Project Report No. 7
South Georgia Minerals Program

Georgia
State Division of Conservation
Department of Mines, Mining and Geology

A. S. Furcron, Director

PHOSPHATE DEPOSITS OF SOUTH-CENTRAL GEORGIA AND NORTH-CENTRAL PENINSULAR FLORIDA

By

Charles W. Sever, James B. Cathcart,
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Responsibility of Authorship

This report was prepared by three geologists while employed by the U. S. Geological Survey. Most of the stratigraphy and the structural geology related to southern Georgia was contributed by C. W. Sever, before he resigned in the fall of 1966 to become a private consultant. His knowledge of southern Georgia was gained while working on ground-water projects carried on in cooperation with the Georgia Department of Mines, Mining and Geology. The principal contributions of the two junior authors were in the discussions related to economic geology, deposits in Florida, and the relations of the Georgia-Florida field to the regional geology.

The junior authors did not have the opportunity of reviewing the geologic observations on which several of Sever's conclusions are based, and, therefore, their joint-authorship positions are not to be interpreted as meaning that they are responsible for all ideas presented. The conclusions for which Sever alone is responsible include those in the text and figures relating to the subdivisions and stratigraphy of the "Hawthorn Formations," the stratigraphy of late Miocene and Pliocene beds, the existence of the Barwick arch and Ochlockonee fault, and the distribution of phosphate pellets in southern Georgia.

Cathcart's principal contributions relate to the geology of deposits in Florida and the mineralogy, chemical composition, origin, and resources of phosphate. Patterson recognized the value of Sever's and Cathcart's knowledge and arranged for them to write the report. He assisted Sever in organizing and evaluating his ideas and was required to take an active part in completing the report when others could not devote the time to do so.

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PHOSPHATE DEPOSITS OF SOUTH-CENTRAL GEORGIA AND NORTH-CENTRAL PENINSULAR FLORIDA[1]

By Charles W. Sever,[2] James B. Cathcart,[3] and Sam H. Patterson[4]

ABSTRACT

Phosphate deposits are scattered throughout a large area in south Georgia and northern peninsular Florida. The best deposits are in beds of early and middle Miocene age, but valuable phosphate may also occur in clastic sediments of late Miocene age. The phosphate is chiefly of the pebble type, and most of it occurs as pellets in sand beds. Carbonate-fluorapatite is the only phosphate mineral in the deposits. A leached aluminum phosphate zone above the carbonate-fluorapatite has been identified in northern Florida, but, as yet, has not been recognized in Georgia.

The phosphate occurs in irregularly distributed deposits that may have formed in local basins or estuaries northeast or east of broad low anticlines. Phosphate may have been present in higher than normal concentrations in these restricted environments, or it may have been introduced by ocean currents moving from the northeast or east and was precipitated because of turbulent mixing and warming.

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[1]Publication authorized by the Director, U. S. Geological Survey.

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INTRODUCTION

Increased demands for phosphate have caused numerous companies to become interested in deposits in south-central Georgia and north-central peninsular Florida. One company, the Occidental Agricultural Chemicals Corp., began operating a mine and flotation concentrate plant at Purvis Still, 5 miles north of White Springs, Hamilton County, Fla., in 1965. The plant was operating in 1966 with a rated capacity of 1.5 million short tons of phosphate rock per year. Construction to double capacity was scheduled for completion in 1966, and a chemical complex to produce triple superphosphate and diammonium phosphate was scheduled to be completed early in 1967 (Beall and Merritt, 1966, p. 88, 98). The operation not only marked the opening of a new phosphate district but stimulated much of the interest in south Georgia deposits, which are located only a few miles north of the plant.

The area of most intense phosphate exploration is a belt 175 miles long and 25 to 50 miles wide (fig. 1), here referred to as the Georgia-Florida phosphate field, extending from Echols and Lowndes Counties, Ga., to the eastern part of Alachua County, Fla. The phosphate occurs in lenticular and irregularly shaped bodies scattered throughout the field. Some bodies or groups of bodies cover as much as 30,000 acres and contain 70 to 75 million tons of phosphate reserves. The Georgia-Florida field lies to the east of the main hard-rock phosphate mining district and a considerable distance north of the productive land pebble district located in the region east of Tampa Bay. Phosphate has been known to occur in the Georgia-Florida field since the late 1880's (McCallie, 1896; Eldridge, 1893) and was mined in Alachua County, Fla., as early as 1883 (Sellards, 1913, p. 41). However, production of phosphate

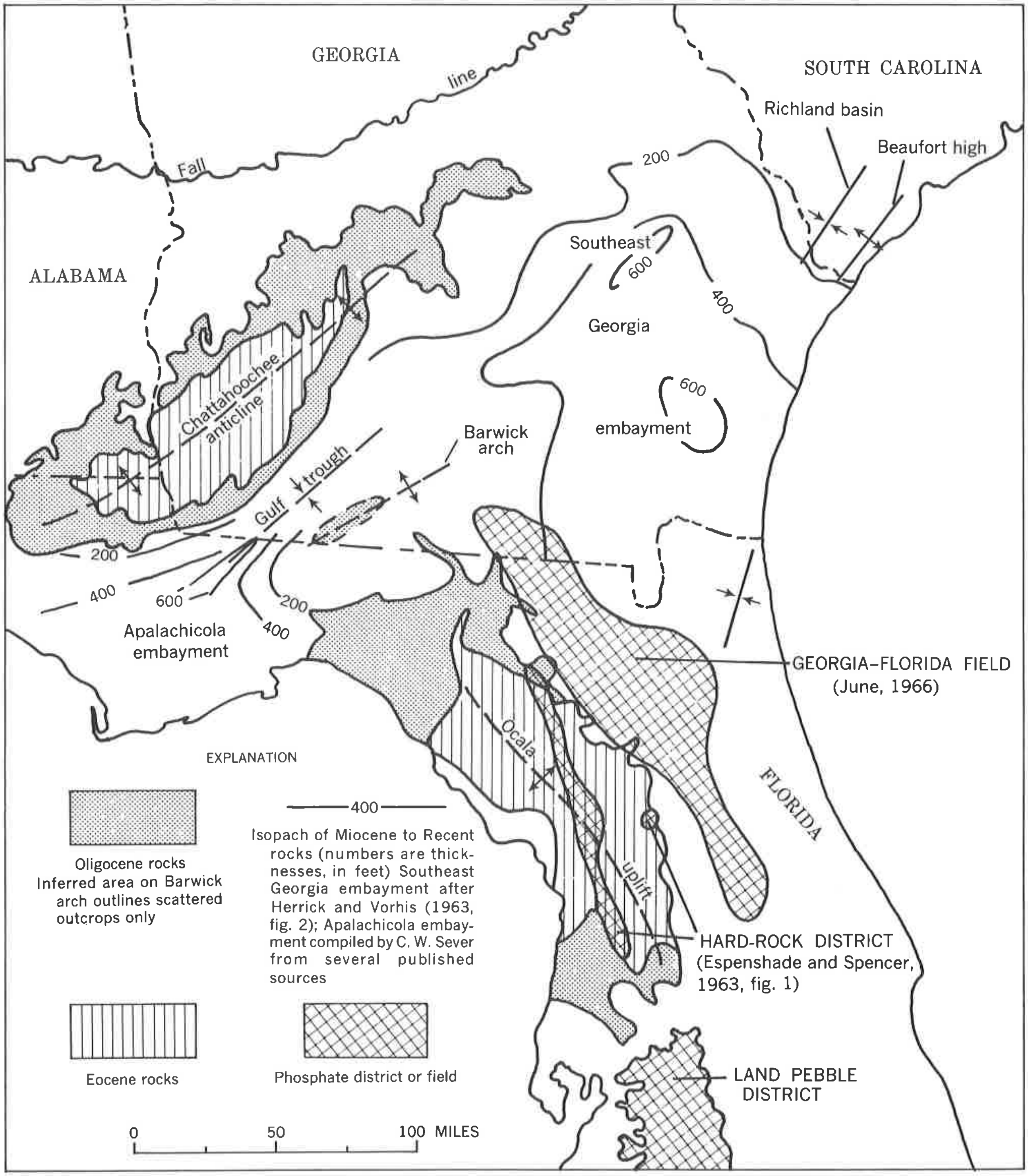


Figure 1. Map Showing the Relation of the Georgia-Florida Phosphate Field to the Regional Geology.

from the field was negligible until the Occidental Agricultural Chemicals Corp. began mining in 1965. Mr. Wayne Thomas (quoted in G. R. Mansfield, 1942, p. 5-11) clearly pointed out the potential value of the Florida part of the Georgia-Florida field in a brief presented to the Congressional Phosphate Hearing in 1938, and from time to time through the mid-1950's the south Florida phosphate companies prospected the area. Difficulties in obtaining leases and mineral rights, however, delayed development.

The Mineral Engineering Group, Engineering Experiment Station, Georgia Institute of Technology, and the Georgia Department of Mines, Mining, and Geology in 1965 and 1966 (Georgia Department of Mines, Mining, and Geology, 1966a, 1966b) investigated the deposits in Echols County and carried on reconnaissance drilling in several other south Georgia counties (the counties in south Georgia are shown on fig. 5), as part of a program to evaluate mineral resources in the southern part of the state. Deposits in southern Georgia have also been investigated by the Southern Railway System (Olson, 1966b). Deposits in the "Hawthorn Formation" at 35 localities in Florida, east of the main hard-rock district, were reconnoitered by Espenshade and Spencer (1963), who recommended additional prospecting in the eastern parts of Alachua and Marion Counties, southern Union County, and in west-central Columbia County. Deposits at several localities in the Florida part of the Georgia-Florida field were discussed by G. R. Mansfield (1942, p. 31-33, 61), and he listed possible reserves for Hamilton, Clay, and Bradford Counties. The geology of phosphate deposits in Alachua County, Fla., was also investigated by Pirkle (1957).

The purpose of this report is to summarize existing information on the geology of the phosphate deposits in the Georgia-Florida field and to present some heretofore unpublished geological data. Most of the new information on structure and stratigraphy in Georgia and much of that on the economic geology of deposits in southern Georgia resulted from the senior author's investigations of ground-water resources in 1961-66, undertaken as part of a cooperative program conducted by the Georgia Department of Mines, Mining, and Geology and the U. S. Geological Survey. Some of the information was obtained during a reconnaissance augering program at scattered localities in the region in 1952 and 1953 (Cathcart, 1954) to investigate anomalies found in an airborne radioactivity survey (Moxham, 1954; Espenshade, 1958). Virtually all of the report was completed prior to the senior author's resignation from the U. S. Geological Survey in September 1966.

Several terms are used in this report in conformance with accepted usage in the phosphate industry. Inasmuch as some of them are used with different meanings in geologic literature, the following definitions are listed to avoid misunderstanding.

Apatite

More than one apatite mineral is known to exist, but carbonate-fluorapatite is the only form occurring in sedimentary phosphate deposits in southeastern United States, and wherever apatite is used this form is the intended meaning.

BPL

Bone phosphate of lime ($Ca_3(PO_4)_2$). Equals percent P_2O_5 x 2.185.

Concentrate

Fine phosphate product -1 mm to +0.1 mm in size, separated from quartz by flotation.

Matrix

That part of the calcium phosphate zone from which phosphate particles can be economically recovered; equal to "ore."

Nodule

Rounded, irregular mass of any size. The term may apply to rock fragments as well as apatite particles.

Overburden

All rock overlying the matrix.

Pebble

Coarse phosphate product, +1 mm in size.

Pellet

General term for rounded oviform sedimentary apatite particle of any size.

Phosphorite

Rock containing substantial amounts of sedimentary apatite.

Slime

Material less that 0.1 mm in diameter. Includes clay minerals, quartz, and phosphate minerals.

An adequate discussion of the atomic structure and chemical composition of phosphate and clay minerals is beyond the scope of this report. Information on the phosphate minerals can be found in Altschuler, Jaffe, and Cuttitta (1956) and Altschuler, Clarke, and Young (1958). Clay minerals are discussed in detail by Grim (1953).

ACKNOWLEDGMENTS

The authors are grateful to several companies and individuals who assisted in gathering information leading to this report. Mr. R. N. Saunders of the American Cyanamid Company, Bradley, Fla., arranged for the logging of a drill hole and supplied analyses of samples. Similar assistance was given by Mr. William Collette of Monsanto Chemical Company, White Springs, Fla. Mr. J. L. Weaver of Wayne Thomas Inc., Tampa, Fla., obtained chemical analyses of samples collected by the senior author. Mr. J. R. Landrum of the Georgia Department of Mines, Mining, and Geology analyzed two samples of phosphatic carbonate rock. Dr. A. S. Furcron and Mr. Samuel M. Pickering, Jr. of the Georgia Department of Mines, Mining, and Geology read this report when it was in manuscript form and made several helpful suggestions.

STRATIGRAPHY

Rocks exposed in southern Georgia and northern Florida range in age from Eocene to Recent. Rocks of Eocene and Oligocene age are composed chiefly of carbonate rock (mostly limestone but some dolomite) and contain only minor to trace amounts of clastic material (clay and sand). Miocene and younger rocks, however, contain abundant clastic material and only minor amounts of carbonate rock. The marked changes in environment recorded by the clastic Miocene sediments were accompanied by widespread deposition of phosphate.

Tertiary System

Eocene Series

Formations of Eocene age include the Avon Park Limestone (middle Eocene) and Ocala Limestone (late Eocene) which crop out in the central parts of the Ocala uplift and the Chattahoochee anticline (fig. 1). Most of the outcrop belt of Eocene rock is formed by the Ocala Limestone. The Ocala Limestone is missing from a few places in the central parts of the Ocala uplift where the Avon Park Limestone crops out and thickens markedly in the Gulf trough and Southeast Georgia embayment. The Ocala is a very pure limestone. Mossom (1925, p. 69) points out that "The rock is extremely uniform in texture and chemical purity, and it has been known to run as high as 99.6 percent $CaCO_3$."

The Ocala unconformably overlies all older rocks (Cooke, 1945, p. 56) and is unconformably overlain by several younger formations (Vernon, 1951).

Oligocene Series

Formations of Oligocene age include the Byram Formation (middle Oligocene) and the Suwannee Limestone (late Oligocene), which crop out on the north and south ends of the Ocala uplift, the east flank of the Chattachoochee anticline, and at a few places on the crest of the Barwick arch (fig. 1). Most of the outcrop area of Oligocene rocks is formed by the Suwannee Limestone. The Suwannee Limestone and Byram Formation are missing from the crests of the Ocala uplift and the Chattachoochee anticline because of removal by erosion. Oligocene rocks range in thickness from 0 to about 500 feet.

Miocene Series

Tampa Formation

The name "Tampa Formation" appears to have first been used by Johnson (1888, p. 235). Cooke and Mossom (1929, p. 78) changed the name to Tampa Limestome and redefined the formation to include much of the Chattachoochee Formation of Veatch and Stephenson (1911). Vernon (1942, p. 68) in describing rocks in Washington and Holmes Counties, Fla., exposed on the southwest end of the Chattahoochee anticline (fig. 1) returned to the original designation--Tampa Formation. His Tampa Formation includes "all sediments lying above the Suwannee Limestone and below the Alum Bluff Group," and he describes the formation as consisting predominantly of limestone in the upper part, but containing sand, silt, marl, and clay in the lower part. Tampa Formation is used in this report because the formation contains appreciable quantities of rock other than limestone.

In south Georgia, the Tampa Formation consists of two members. The lower member in the Gulf Trough is composed dominantly of yellowish-gray sandy marl and greenish-gray argillaceous sand, interbedded with white sandy limestone. In the southeast Georgia embayment, the lower member is chiefly greenish-gray phosphatic clayey sand that contains abundant large shell fragments in its lower part. Wherever the upper member is present, it is composed of gray to brown, sandy, dense phosphatic dolomite or dolomitic limestone. The upper member is equivalent to the uppermost beds of the Chattahoochee Formation of Veatch and Stephenson (1911, p. 235). It can be distinguished from other Miocene limestones (Sever, 1966) by its color, sand content, and dense chertlike texture. The upper member can be recognized in electric logs by high resistivity probably caused by its high density and low permeability, and in gamma ray logs by a distinctively high anomaly caused by uraniferous phosphate grains (fig. 2). The upper member contains the foraminifer *Archaias floridanus* and a distinctive molluscan fauna described by W. C. Mansfield (1937). A number of other genera that are characteristic of a warm (20° - 30°C) inner neritic environment have been recognized in the Tampa Formation (Puri, 1953, p. 45).

In Florida, the Tampa Formation wedges out against the flanks of the Ocala uplift and is absent from its crest (Vernon, 1951, p. 181). It is as much as 40 feet thick on the north end of the uplift along the Georgia-Florida line, and thickens toward the central parts of the Gulf trough and the Southeast Georgia embayment. The maximum thickness of the lower member is approximately 200 feet and that of the upper member is about 80 feet. The top of the formation ranges from 200 to 400 feet below the surface in central parts of the Gulf trough and the Southeast Georgia embayment. The outcrops of the upper member of the Tampa Formation in south Georgia extend along a narrow belt on the east flank of the Chattahoochee anticline (Cooke, 1943, pl. 1), scattered localities along the axis of the Barwick arch (Sever, 1966, fig. 2), and along the Alapaha and Withlacoochee Rivers near the Georgia-Florida line (MacNeil, 1947). The lower member of the Tampa Formation probably wedges out against the flanks of the Gulf trough and the Southeast Georgia embayment, as no outcrops of this member have been found.

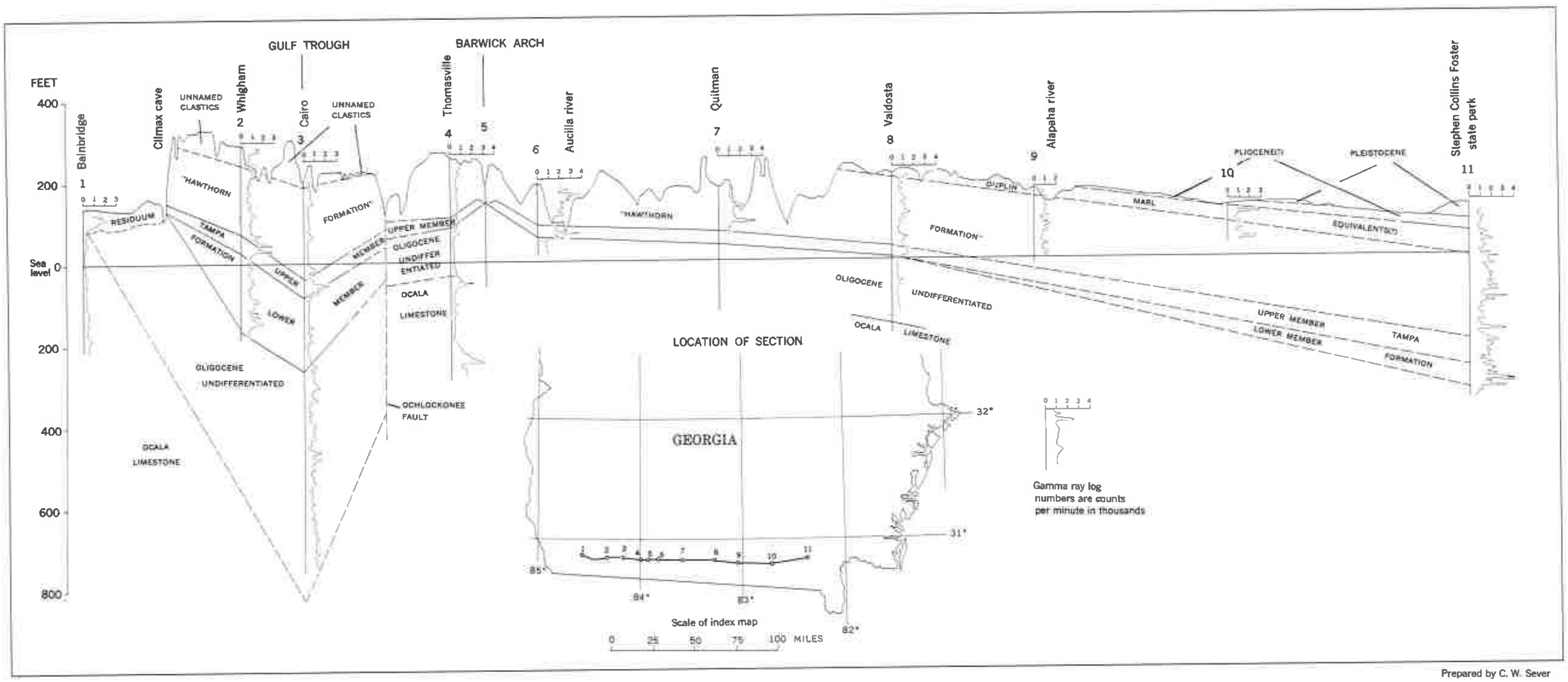


Figure 2. Geologic Section of Tertiary and Quaternary Rocks in South Georgia.

"Hawthorn Formation"

The "Hawthorn Formation," as noted by Puri and Vernon (1964, p. 145), ". . . perhaps is the most misunderstood formational unit in southeastern United States. It has been the dumping ground for alluvial, terrestrial, marine, deltaic, and pro-deltaic beds of diverse lithologic units in Florida and Georgia, that are stratigraphic equivalents of the Alum Bluff Stage." After considering nomenclature problems involving the Hawthorn Formation in northern Florida, Espenshade and Spencer (1963, p. 26) applied this name to the entire phosphatic sequence that is younger than the Tampa Formation of Miocene age. Cooke (1943, p. 89) noted in his text that the Hawthorn in Georgia is stratigraphically equivalent to one of the formations in the Alum Bluff Group in Florida. He also noted that some of the fossils in the Hawthorn are similar to those in the Chipola Formation. The lower part of the Hawthorn as mapped by Cooke was shown as undifferentiated Chipola Formation and Tampa Limestone by MacNeil (1947), and the upper part of Cooke's Hawthorn was shown as Duplin Marl and Hawthorn Formation undifferentiated. From their descriptions of the rocks at several localities in southern Georgia, it is clear that Veatch and Stephenson (1911, p. 342-366) applied the term "Alum Bluff Formation" to rocks that Cooke and MacNeil considered to be Chipola Formation but were unable to map as a separate unit.

The authors are in agreement with those who regard the Miocene beds overlying the Tampa Formation as being essentially the equivalent of the Chipola Formation. However, we cannot rule out the possibility that other formations in the Alum Bluff Group may also be present in southern Georgia, and cannot be distinguished from Chipola equivalents. Because of this difficulty and because the name Hawthorn Formation is used for Miocene phosphatic rocks in Florida, this formational term is retained in this report and included within quotation marks to show that it is not equivalent to all of the beds at the type section near Hawthorne, Fla.

The "Hawthorn Formation" crops out around the north and south ends of the Ocala uplift (Puri and Vernon, 1964, pl. 2), in a broad irregular belt east of the Ocala uplift (Espenshade and Spencer, 1963, pl. 1), and in a broad northeast trending belt across the Georgia Coastal Plain east of the Chattahoochee anticline and west of the Pliocene(?) and Pleistocene terraces (MacNeil, 1947; Cooke, 1943, pl. 1). The "Hawthorn Formation" ranges in thickness from 0 to 500 feet. Probably the thickest exposed section of "Hawthorn" beds is the one at Devils Mill Hopper about 6 miles northwest of Gainsville, Fla., measured by Pirkle (1956, p. 215-216), where beds 123 feet thick crop out. Most of the information on this formation where it is more than 100 feet thick has come from studies of drill cuttings and core (Herrick, 1961; Espenshade and Spencer, 1963, p. 21-25; Herrick and Vorhis, 1963, p. 10; Sever, 1966).

The "Hawthorn Formation" in south Georgia consists chiefly of unconsolidated sand, but it also contains appreciable quantities of clay and minor amounts of carbonate. The senior author has divided the formation into four zones in south Georgia on the basis of lithologic characteristics, recognized chiefly in well cuttings.

Zone 1

The basal zone of the "Hawthorn Formation" is of early Miocene age and is higher in carbonate than the other zones. In the Gulf trough, zone 1 consists chiefly of white sandy marl that contains sparse phosphate pellets and is locally fossiliferous. In the southeast Georgia embayment, zone 1 consists of green, well-sorted fine-grained, calcareous, silty sand interbedded with thin (less than 1 foot thick) lenses of brown saccharoidal dolomite. Phosphate pellets are present in both the sand and dolomite beds, but are abundant only locally in a zone about 10 to 20 feet above the base of the zone. The zone can be identified in gamma ray logs by its distinctively low radiation intensity. Zone 1 is as much as 100 feet thick in the central part of the Gulf trough (fig. 1) but wedges out within a few miles both east and west of the axis of the trough.

Zone 2

The beds of zone 2 occur only in the Gulf trough and the southeast Georgia embayment where they range in thickness from 0 to about 50 feet. Zone 2 consists chiefly of very silty, fine grained calcareous sandstone. Although the beds of zone 2 contain no visible phosphate pellets, a moderately high gamma-ray anomaly associated with these beds is thought to be caused by silt-sized phosphate grains.

Zone 3

Zone 3 is thickest and most persistent in the Gulf trough and the southeast Georgia embayment where it reaches a maximum thickness of about 100 feet. The zone thins sharply or is missing on the flanks of the Barwick arch, the Chattahoochee anticline and the Ocala uplift. The zone consists of lenticular beds of very clayey sand and silt, clay, and minor dolomite or dolomitic limestone. The clay beds include the commercial fuller's earth deposits that are chiefly attapulgite, but also contain sepiolite, montmorillonite, amorphous silica, and radiolaria (Gremillion, 1965; McClellan, 1964). The thicker and purer clays are in a belt extending along the central part of the Gulf trough, where deposits mined are as much as 25 feet thick. Impure, thin beds of clay of similar mineral content occur in the southeast Georgia embayment and in northern Florida (Espenshade and Spencer, 1963, p. 17). Phosphate pellets are sparse and are very fine grained in zone 3 in the Gulf trough. They are sparse to abundant in Cook and Lowndes Counties, and are common to abundant in the southeast Georgia embayment.

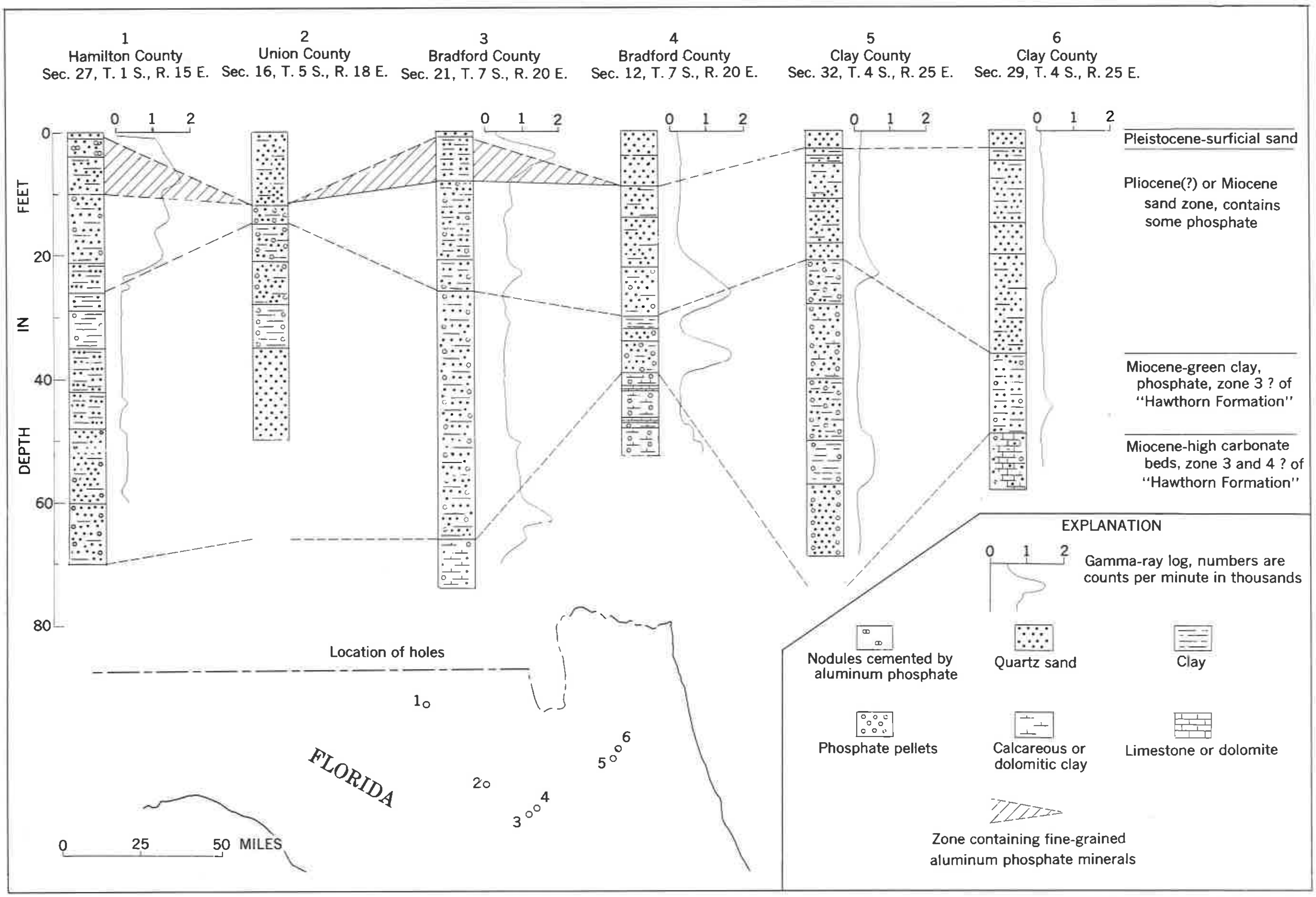
Fossiliferous beds in zone 3 exposed in a fuller's earth pit 4.5 miles south-southwest of Attapulgus, Ga., contain diverse suites of fossils which were studied by paleontologists of the U. S. Geological Survey (Olson, 1966a, p. 64-65). Druid Wilson examined the macro-fossils, S. M. Herrick the foraminifer, and J. E. Hazel the ostracods. All three types of fossils contain diagnostic species of early Miocene age (Chipola equivalent). Based on the presence of the foraminifera _Ammonia beccarii_ and three species of _Elphidium_, Herrick concluded that these beds were deposited in a near-shore, brackish shallow-water environment.

Zone 4

Zone 4, the uppermost zone of the "Hawthorn Formation," is probably middle Miocene in age, and ranges in thickness from 0 to about 100 feet. Zone 4 is of variable lithology and probably was deposited during a period of regression of the sea. Rocks of zone 4 are present throughout most of southern Georgia, but are missing in the structurally high parts of the Barwick arch and they have been eroded from the valley of the large modern streams. This zone is as much as 100 feet thick in the central part of the southeast Georgia embayment.

In southwest Georgia, zone 4 consists of medium to very coarse grained poorly sorted sand interbedded and crossbedded with light-gray clay layers that are rarely as much as 2 inches thick. These beds are believed to have been deposited in a terrestrial or very nearshore environment. In a belt lying east and north of the Barwick arch (fig. 1), beds of zone 4 consist of interbedded sandstone and clay typical of nearshore and shallow marine deposition. Some of the thicker sand layers are crossbedded, but most thinner layers of interbedded clay and sand are horizontally bedded. At places the interbedded clay and sand layers are no more than 1 inch thick. The sand layers in zone 4 commonly contain abundant phosphate pellets, and the most valuable phosphate deposits are in this zone. Shark's teeth and marine microfossils are locally common in this zone.

The information available on the "Hawthorn Formation" in northern Florida, other than that outlined in the reconnaissance by Espenshade and Spencer (1963), is based primarily on scattered auger holes put down by Cathcart in 1952-1953 and observations of samples from a few company drill holes. A section (fig. 3) from Hamilton County on the west to Clay County on the east shows the possible correlations. Beds we are certain are part of the "Hawthorn Formation" occur only at depth. They are overlain by a phosphatic sand unit of unknown relationship to beds in south Georgia. Perhaps it correlates with zone 4 in the "Hawthorn", the Duplin Marl equivalents(?) of late Miocene age (p. 34), or still younger beds of Pliocene age. The surficial sands are considered to be of Pleistocene age chiefly because of their stratigraphic position.



Prepared by J. B. Cathcart

Figure 3. Geologic Section in Northern Peninsular Florida.

The lowermost beds in the "Hawthorn Formation" are chiefly limestone and dolomite, but they also contain minor amounts of phosphate particles. Little information on this zone is available, because most prospect holes for phosphate are terminated at the top of it or penetrate it only a few feet. Logs of deep wells in northern Florida indicate that most lower "Hawthorn" beds are composed of carbonate rock. These beds may be a carbonate facies of zones 1 and 2 in south Georgia, but the data available are inadequate to make this correlation.

The upper part of the unquestioned "Hawthorn Formation" consists of interbedded green or grayish-green clay, sandy clay, and sand. It contains some carbonate material, and phosphate particles are abundant locally. This zone (referred to as the green clay and phosphate zone in fig. 3) ranges in thickness from 5 to about 50 feet. It has most of the lithologic characteristics of zone 3 in south Georgia and is tentatively correlated with it. The green clay is a mixture of attapulgite and montmorillonite. The phosphate particles are mostly fine grained; concentrate-size particles (-1 to 0.1 mm) are much more abundant than pebble size (1 mm). The P_2O_5 content of particles in this zone is lower than in particles in the overlying sand, due chiefly to the diluent effect of carbonate and quartz in the particles.

Beds in the upper part of the "Hawthorn Formation" and younger formations are penetrated in phosphate drill holes which are rarely more than 50 feet deep. The stratigraphic assignments made from drill core are based on lithology because no diagnostic macrofossils are present. The beds described in the following drill-hole logs are typical of those in the Florida part of the Georgia-Florida field.

Log of hole drilled by Monsanto Chemical Co., Hamilton County, Fla., about 1/2 mile south of the Georgia state line, and about 1/2 mile west of U.S. Highway 129. Lithologic log by J. B. Cathcart, used with the permission of the company.

	Thickness (feet)
Pleistocene	
Sand, loose, fine- to medium-grained, contains some black organic material in top foot	5
Total Pleistocene	5
Miocene (probably zone 4, "Hawthorn Formation")	
Sand, clayey, white to light-gray (leached)	3
Sand, clayey, gray, trace amounts of white, soft, phosphate grains (leached). X-ray of -200 mesh fraction indicates quartz, feldspar, minor apatite and montmorillonite, and a trace amount of kaolinite and wavellite	5
Sand, clayey, gray-white. Contains fine-grained black, brown, white, and gray phosphate pellets. The amount of phosphate increases toward the base of the interval	7
Sand, clayey, gray. Contains more clay than unit above, and in addition to the fine-grained phosphate pellets, some pebble size	8
Miocene (zone 3 "Hawthorn Formation")	
Clay, silty, blue-green, dolomitic. Contains a few white phosphatized dolomite fragments or pebbles. X-ray of -200 mesh shows quartz, dolomite, attapulgite and minor montmorillonite	7
Total Miocene	30
Total depth	35

The hole bottomed in hard dolomite or dolomitic limestone. The bottom bed of blue-green silty dolomitic clay is probably the top bed of zone 3 of the "Hawthorn Formation," as indicated by the presence of attapulgite as the principal clay mineral, and the bed of hard limestone or dolomite on which the hole was completed.

Log of drill hole in Alachua County, Fla. by the American Cyanamid Co. Lithologic log by J. B. Cathcart and chemical analyses by the company, used with permission. Drilled by power auger and thicknesses of units are approximate.

	Thickness (feet)
Pleistocene	
Sand, loose, black and brown, contains organic material	3
Sand, loose, white	3
Sand, light-brown, iron-stained, grading to loose tan sand at the base of the interval	9
Total Pleistocene sand	15
Pliocene(?) (may be "Hawthorn Formation")	
Sand, slightly clayey, light-gray, leached	18
Sand, very clayey, light-gray. Contains brown coarse (pebble) and fine-grained (concentrate) phosphate grains. The +20 mesh fraction contains 26.6 percent P_2O_5 and 16.7 percent acid insoluble. The -20+150 mesh fraction (concentrate) contains 31.3 percent P_2O_5 and 3.6 percent insoluble. The ratio of the +20 mesh to the -20+150 mesh is 1.1 to 1	7
Total Pliocene(?)	25
Miocene (zone 3 of the "Hawthorn Formation")	
Clay, silty, light gray-green. Contains fine-grained black phosphate grains. The +20 mesh fraction contains 18.4 percent P_2O_5 and 13.7 percent acid insoluble. The -20+150 mesh concentrate contains 28.8 percent P_2O_5 and 4.1 percent acid insoluble. The ratio of +20 mesh to -20+150 mesh is 0.7 to 1 . .	30
Total Miocene	30
Total depth	70

The bottom sample of gray-green clay is considered to be in zone 3 of the "Hawthorn Formation" because of its lithology. The clay is typical of the attapulgite clay of zone 3, and probably contains carbonate, as indicated by the analytical data for the coarse phosphate fraction. The very low P_2O_5 content, plus the low acid insoluble content, indicates that carbonate (either calcite or dolomite) is the principal diluent in this fraction. Also, the fine phosphate fraction (concentrate) is much more abundant than the coarse phosphate.

The gray clayey sand just above the green clay is Pliocene(?) or post-middle Miocene. The coarse phosphate fraction is more abundant than the fine fraction, typical of rocks of post-Miocene age, and in places in Alachua County, there is a conglomerate of phosphate nodules at this stratigraphic horizon. The analytical data are much different than in the green clay. The phosphate is much higher in P_2O_5 content and obviously contains much less carbonate.

The surficial sands are placed in the Pleistocene, chiefly because of their stratigraphic position.

Log of drill hole south of Lake Park, Georgia, near the Florida state line. Drilled with power auger, October, 1952 by J. B. Cathcart.

	Thickness (feet)
Pleistocene and/or Pliocene	
Sand, slightly clayey, black, contains organic material	13
Total Pleistocene and/or Pliocene	13
Miocene (zone 4 of the "Hawthorn Formation" or Duplin Marl equivalents(?))	
Sand, clayey, gray, contains some tan phosphate	8
Miocene (zone 3 of the "Hawthorn Formation")	
Clay green, calcareous or dolomitic, contains traces of phosphate	24
Total Miocene	32
Total depth	45

The phosphatic material in the gray clayey sand 8 feet thick in the above section was sampled. Coarse phosphate (+20 mesh) contains 15.1 percent P_2O_5 and 20.6 percent acid insoluble; the -20+48 mesh (coarse concentrate) contains 29.6 percent P_2O_5; and the -48+150 mesh (fine concentrate) contains 14.3 percent P_2O_5 and 1.8 percent acid insoluble. The light fraction of the fine concentrate separated by bromoform (Sp. Gr. 2.86) contains abundant foraminifera. The heavy fraction consisting chiefly of phosphate grains contains 27.3 percent P_2O_5. A composite of all phosphate fractions contain 0.017 percent uranium. The phosphate particles are not abundant in any of the fractions, but both the coarse and fine concentrates were much larger than the pebble fraction.

Log of drill hole, Union County, Florida, sec. 9, T. 5 S., R. 18 E.

Drilled with power auger, October, 1952 by J. B. Cathcart.

	Thickness (feet)
Pleistocene	
Sand, slightly clayey, gray and tan	12
Total Pleistocene	12
Pliocene(?) or Duplin Marl equivalents(?)	
Sand, clayey, gray. Contains mostly fine-grained phosphate; black, brown, tan, and abundant white	3
Sand, very clayey, gray. Contains some phosphate, like the above sample	6
Sand, slightly clayey, gray-green. Trace phosphate	7
Total Pliocene(?) or Duplin Marl equivalents(?)	16
Miocene (zone 3 "Hawthorn Formation")	
Clay, silty, green. Contains some phosphate, both pebble and concentrate size. Pebble fraction contains 2.6 percent P_2O_5; concentrate contains 26.2 percent P_2O_5; both fraction are high in carbonate	7
Sand, gray-green, practically no clay (very fast drilling, very poor sample recovery)	15
Total Miocene	22
Total depth	50

Duplin Marl equivalents(?)

In southeastern and south-central Georgia the "Hawthorn Formation" is overlain unconformably by late Miocene marine beds of variable lithology, herein called the Duplin Marl equivalents(?). The formational name Duplin Marl has been used in south Georgia by Cooke (1943, p. 98-100), but we believe that late Miocene beds in this area should be considered only as the questionable equivalents of this formation. Marl is rare in these beds and marine fossils of the type described as diagnostic of the Duplin (Malde, 1959, p. 28-34) have not been found at many localities in south Georgia.

The Duplin Marl equivalents(?) near the Atlantic Coast in south Georgia consist of micaceous clay (Herrick, 1965, p. 7, fig. 2) about 100 feet thick. To the west, these beds thin and interfinger with sand layers. In the eastern parts of Clinch and Echols Counties, they are rarely more than 50 feet thick and consist of interbedded green clay and clayey sand, in which phosphate particles are abundant locally. In the western parts of Clinch and Echols Counties and in Lanier and Cook Counties, the formation consists of loose, massive white to brown sand. Beds that range in thickness from 5 to 10 feet in the lower part of this sand contain as much as 20 percent white and brown phosphate pellets, some of which are polished and others are chalky and appear to have been weathered. Some of this phosphate has probably been reworked from the underlying "Hawthorn Formation." The Duplin Marl equivalents(?) are missing from the crest of the Barwick arch, and west of this arch unnamed clastic beds occur in the stratigraphic position of this formation.

Fossils or other means of dating the beds penetrated in the drilling in northern Florida (fig. 3) were insufficient to establish the presence of late

Miocene marine rocks; however, beds of Duplin age may be present in this area. Beds of late Miocene age do occur in northern Florida, as the senior author found fossil teeth identified by S. J. Olsen (1963) as *Merychippus* sp. and *Diceratherium* sp. of this age. These fossils occur in complex deltaic and terrestrial rocks in Jefferson County, Fla.

According to Yon (1965), these rocks are a part of a unit referred to as the "upper Miocene clastics" by Puri and Vernon (1964, fig. 14). Probably the upper Miocene deltaic and terrestrial beds grade eastward into marine strata that are difficult to distinguish from the "Hawthorn Formation" and are likely to contain phosphate.

Unnamed clastics

A coarse clastic unit of questionable relationship to beds in other areas overlies the "Hawthorn Formation" in southwestern Georgia (fig. 2). The unit consists chiefly of medium and coarse red and reddish-brown sand. Locally, they contain lenticular deposits of sandy gravel and a few thin kaolinitic clay deposits. Part of this unit, particularly the lower beds, is probably a nonmarine facies of the Duplin Marl equivalents(?) and is, therefore, likely to be of late Miocene age. This tentative correlation of the clastics agrees with that of Puri and Vernon (1964, fig. 14), who show a clastic unit of late Miocene age in northern Florida grading eastward into their Miccosukee Formation, which may be more or less the same age as the Duplin Marl equivalents(?) as used in this report. The upper beds of the unnamed clastics unit may be of Pliocene age, but as no diagnostic fossils have been found this possibility cannot be evaluated. In some parts of Toombs, Jeff Davis, and Telfair Counties, Ga., the unnamed clastics unconformably overlie the Duplin Marl equivalents(?).

Pliocene(?) Series

The identification and mapping of beds of Pliocene age in south Georgia and northern Florida have been attempted by only a few geologists. Beds of fine sand, locally fossiliferous clay and coquina-like limestone thought to be of Pliocene age were named the Charlton Formation by Veatch and Stephenson (1911, p. 392-400). This formation was shown on a map by MacNeil (1947) to be present in a few places in the southeast part of the state.

According to Herrick (1965, p. 7), the beds containing probable Pliocene fossils underlie parts of Brantly, Charlton, and Glynn Counties, and they may extend westward into the northern part of the Georgia-Florida phosphate field. They crop out at a few places along the Satilla and St. Marys Rivers in Camden County. At most places where beds of Pliocene(?) age are present in south Georgia, they are less than 50 feet thick (Herrick, 1965, fig. 2).

Quanternary System

Pleistocene Series

Sedimentary rocks of Pleistocene age along the Georgia-Florida line have a maximum thickness of about 65 feet (Herrick, 1965, fig. 2). They are thickest near the coast, and are covered by a veneer of sediments of Recent age. Sediments of Pleistocene age consist of fine- to medium-grained arkosic sparsely phosphatic sand and minor amounts of sandy micaceous kaolin. Near the coast, black, lignitic, sandy clay occurs in the middle part of the Pleistocene, and the basal part is chiefly sand and gravel.

Recent Series

Sedimentary deposits of Recent age in south Georgia and northern Florida consist chiefly of alluvium in the bottoms of major stream valleys and alluvium and wind-blown deposits in a belt along the coast. The deposits consist mainly of sand, silt, and clayey silt. They are rarely more than 30 feet thick. Phosphate reworked from older formations occurs in Recent deposits at scattered localities, and river pebble deposits were once mined on a small scale in northern Florida (Mansfield, 1942, p. 24). Phosphate pellets were observed by the senior author in Recent alluvium along the Alapaha River in Lanier and Echols Counties, Ga. Most of the alluvium along rivers in Georgia and Florida is in narrow belts and is blanketed by dense vegetation and swamps. Probably all phosphate in Recent alluvium occurs in small deposits. If large ones are present, they would be costly to prospect and mine because of the dense vegetation and swamps in the river bottoms.

STRUCTURE

The dominant structural features in the rocks of Cenozoic age in the north Florida - south Georgia area are the broad, gently dipping anticlines and synclines--the Ocala uplift, the Chattahoochee anticline, the Southeast Georgia embayment, and the Apalachicola embayment (fig. 1). The broad Peninsular arch (Applin, 1951) is probably the largest structure, but this is an early structure and has no known relationship to the phosphate deposits.

Ocala uplift

The Ocala uplift is a broad, northwest-trending dome whose crest is west of the older Peninsular arch. The two anticlines are apparently unrelated. The uplift of the Ocala arch began in early Miocene time (Vernon, 1951, p. 62) and may have continued throughout this period. Ketner and McGreevy (1959, p. 75) indicate that horizontal beds of possible late Miocene age in the southern part of the uplift overlie upwarped beds of earlier Miocene age, suggesting the deformation may have ended before late Miocene time.

A zone of northwest-trending faults extends along the axis of the Ocala uplift (Vernon, 1951, pl. 2), and the flanks and ends of the arch are modified by minor folds. The most prominent of these folds is a low anticline that splits from the main axis and extends through Live Oak area, Florida, and possibly into Georgia.

Apalachicola embayment

The Apalachicola embayment is a southwest-plunging basin in the eastern part of the Florida panhandle (Pressler, 1947, fig. 1). It lies south of the Chattachoochee anticline and northwest of the Ocala uplift.

According to Murray (1961, p. 103), "Magnitude of the basin increases with depth thereby indicating a long and continued development." The basin received sediment during the early Paleozoic, late Mesozoic, middle Cenozoic (Oligocene and Miocene) and probably in other periods.

Chattahoochee anticline

The Chattahoochee anticline is a broad low dome that trends northeasterly from near the point on Chattahoochee River where the Georgia-Florida-Alabama boundaries meet. West of the tri-state point the axis of the anticline flexes to a west-southwest trend (Sever, 1965, fig. 5) that may even be more westerly than shown on figure 1.

The foregoing description of this anticline is based on outcrop patterns of Eocene and Oligocene rocks as shown on the geologic map of the United States. Other geologists (Stringfield, 1966, p. 73, fig. 22) follow an earlier interpretation by Veatch and Stephenson (1911, p. 58) that the axis extends in a north-south direction and is located near the Chattahoochee River. Hendry and Yon (1958, p. 20, 21) note that this anticline has been called the Decatur arch and give a summary of the problems related to the recognition of this structure.

Gulf trough

The Gulf trough is a structural depression between the Chattahoochee anticline and the Barwick arch. It is only about 10 miles wide at its narrowest point in southern Georiga, where it is bounded on the southeast by the Ochlockonee fault (Sever, 1966, p. C12). The trough broadens and plunges southwestward into the Apalachicola embayment, and it broadens northeastward into the Southeast Georgia embayment. According to Sever (1964, p. B118; 1966, p. C14), the Gulf trough was downwarped at least twice during the Miocene Epoch, once when the lower member of the Tampa Formation was being deposited and again while the "Hawthorn Formation" was accumulating.

Southeast Georgia embayment

A broad depositional basin in the Coastal Plain of Georgia was named the Southeast Georgia embayment by Toulmin (1955, p. 29, fig. 2), and the name was used by Puri and Vernon (1964, fig. 2). This embayment also has been referred to as the Okefenokee embayment (Pressler, 1947, p. 1856) and as the Atlantic embayment of Georgia (Herrick and Vorhis, 1963, p. 55). The name Southeast Georgia embayment is preferred here, because the Okefenokee embayment was described as small and filled primarily with Cretaceous sediments, and Herrick and Vorhis' term seem cumbersome.

The Southeast Georgia embayment extends across the entire coastal area of Georgia and into adjoining parts of South Carolina and Florida (fig. 1). It originated in middle Eocene time and continued as a depositional basin intermittently through Miocene time (Herrick and Vorhis, 1963, p. 55). Miocene rocks in the central part of this embayment are nearly 600 feet thick.

Other structures

Lesser structures occur on the flanks and noses of the large anticlines or are widely separated and apparently unrelated to them. The Barwick arch in southern Georgia (fig. 1) is one of the more prominent of these structures. The axis of the arch trends northeasterly, approximately parallel to the Gulf trough and nearly perpendicular to the axis of the Ocala uplift. The upper member of the Tampa Formation is approximately of normal thickness on the Barwick arch, except where cut by pre-"Hawthorn" or more recent subsurface solution, as at the site of well 5 (fig. 2). Beds of the lower member of the Tampa Formation and of the lower part of the "Hawthorn Formation" thin appreciably or are absent over the crest of the arch, and the arch must have been upwarped during early Miocene time. Another structure is a northeasterly trending unnamed basin in northeast Florida (Leve, 1965, fig. 5). The axis of this basin is alined generally with the axis of the Ridgeland basin and Beaufort high in South Carolina (Heron and Johnson, 1966).

PEBBLE PHOSPHATE DEPOSITS

Most of the phosphate in the Georgia-Florida field occurs as rounded pellets, but angular grains, phosphatized teeth and bone fragments, and phosphatized molds and casts of fossils are also present. The phosphate pellets range in size from less than 0.1 mm to as much as 25 mm in diameter. In most deposits, the quantity of the concentrate (-1 to +0.1 mm) fraction is larger than the pebble (+1 mm) fraction. The angular grains appear to have been broken from larger phosphate pellets or masses. Fresh phosphate pellets are white, tan, brown, or black, and have a high polish. Weathered grains near the surface are bleached and dull or earthy. The phosphate pellets vary in P_2O_5 content because of inclusions of silt-sized quartz, carbonate, or clay minerals. Quartz is the principal diluent in the phosphate pellets that are found in the deposits in zone 1 of the "Hawthorn Formation" and in younger beds; calcite or dolomite is the main diluent in deposits in the lower parts of the "Hawthorn Formation" and in the Tampa Formation.

An aluminum phosphate zone overlies some of the phosphate deposits in the southern part of the Georgia-Florida field (Espenshade and Spencer, 1963, p. 16) and has been traced northward to a point a few miles south of the Georgia line (fig. 3). It presumably is the same type as the weathered and leached zone occurring extensively in the land-pebble district (Altschuler, Jaffe, and Cuttitta, 1956). At most places in that district, the aluminum phosphate zone is 6 to 7 feet thick and consists chiefly of kaolinite, quartz, and the phosphate minerals crandallite, millisite, and wavellite. Aluminous phosphatic rock probably overlies some of the deposits in south Georgia, but geologic and mineralogic work is insufficient to establish its presence there.

Mineralogy

The suite of rocks in which the phosphate occurs include sand, clay, and dolomite, almost always mixed--so that the rocks are described in the field as sandy clay or clayey sand, sandy or clayey limestone (or dolomite) or calcareous or dolomitic sandy clay or clayey sand. The calcareous (or dolomitic) rocks are light-colored--white, gray, or cream. The more clayey materials are greenish when they are unaltered and are light-colored, white, or gray at the surface or are stained red or brown by the development of iron oxide.

Quartz is ubiquitous. It is found in varying amounts in all samples and is present as inclusions in the hand-separated phosphate particles as a minor or trace constituent.

Clayey sand or sandy clay

Green, olive-green, or gray-green clayey sand or sandy clay contain attapulgite and montmorillonite as the major clay mineral; some samples also contain sepiolite. Apatite is present as rounded nodules and pellets, and some apatite is present in trace to minor amounts in the slime fraction. Minor to trace amounts of dolomite are present in a few samples. Pyrite and minor to trace amounts of feldspar are present in some samples. Surficial samples of clayey sand may be red or brown or may be white, depending on the amount of iron oxide present.

White clayey sand at the surface in one sample contained only kaolinite and quartz. Where phosphate grains are present in the surficial samples, the apatite mineral is altered to the aluminum phosphate minerals, crandallite and wavellite. The surficial weathering does not seem to have been as severe as it is in southern Florida. Almost all surficial samples contain apatite as the principal phosphate mineral, and either montmorillonite, attapulgite, and in some places, sepiolite, as the major clay mineral, although minor to trace amounts of kaolinite, crandallite, and wavellite are present.

Where the surficial samples are brown or red-brown clayey sand, the mineralogy is the same except for the addition of an iron oxide mineral (usually limonite, but some hematite was noted) and an iron-phosphate mineral (probably dufrenite).

Dolomite

Samples described in the field as white, gray, or cream sandy and clayey limestone or calcareous sandy clay or clayey sand all contain dolomite as a major mineral phase. None contained any calcite. The samples that were X-rayed were from outcrop (two samples) or from drill holes--six samples that ranged in depth from 45 to 195 feet (below the surface). The most abundant clay mineral in all samples is attapulgite, but montmorillonite was present in all samples, and one sample contained a trace amount of sepiolite. Cristobalite was present in two samples of dense, hard sandy dolomite. Trace amounts of clinoptilolite may be present in these two samples, but positive identification could not be made. The dolomite or dolomitic clay samples all contain varying amounts of phosphate grains or nodules, but the slime fraction of only one of these samples contains sufficient apatite for positive identification.

Phosphate particles

The common beneficiation practice in the phosphate industry in eastern United States is to screen at about 1 mm and 0.1 mm. The +1 mm fraction is called pebble, the -1 to +0.1 fraction is the flotation feed, and the -0.1 mm fraction is the slime. The flotation feed is usually further divided into a coarse (spiral, table, belt) feed and fine (cell) feed.

In the Georgia-Florida field, the pebble fraction contains quartz and rock fragments (limestone or dolomite) in addition to the phosphate particles and is too low in P_2O_5 content to be economic. However, particles and nodules of phosphate can be easily hand picked for X-ray and chemical analyses.

The highly polished phosphate nodules contain carbonate fluorapatite (called apatite throughout the report) as the only major mineral phase regardless of color. Quartz is present in all samples, ranging in amount from a slight trace to as much as 10 percent. Quartz is present as silt-size grains within the phosphate nodule and is the principal diluent. Pyrite is present in minor to trace amounts in the brown and black nodules; it is not present in the white nodules. In some of the brown and black samples, the high background indicates the presence of an iron oxide mineral, not otherwise identified.

Orthoclase is present in trace amounts in a few samples, and trace amounts of the clay mineral attapulgite were noted in one or two samples.

The X-ray patterns for brown, black, and white phosphate nodules are shown on figure 4. The white nodules (34.1 percent P_2O_5) contain apatite and trace amounts of attapulgite. The brown nodules (32.7 percent P_2O_5) contain much more quartz than the white and a trace of pyrite and feldspar. The black nodules (26.4 percent P_2O_5) contain about the same amount of quartz as the brown nodules and a trace amount of attapulgite. The black nodules contain iron oxide mineral, as indicated by the high background on the X-ray diffraction trace.

Analytical data

The few pebble samples from southern Georgia analyzed were hand-sorted phosphate particles, and range from 27.5 to 34.1 percent P_2O_5 (60.0-74.5 percent BPL) and from 0.006 to 0.012 percent U (table 1). Company prospecting data show that the pebble fraction is low grade--the fraction ranges from

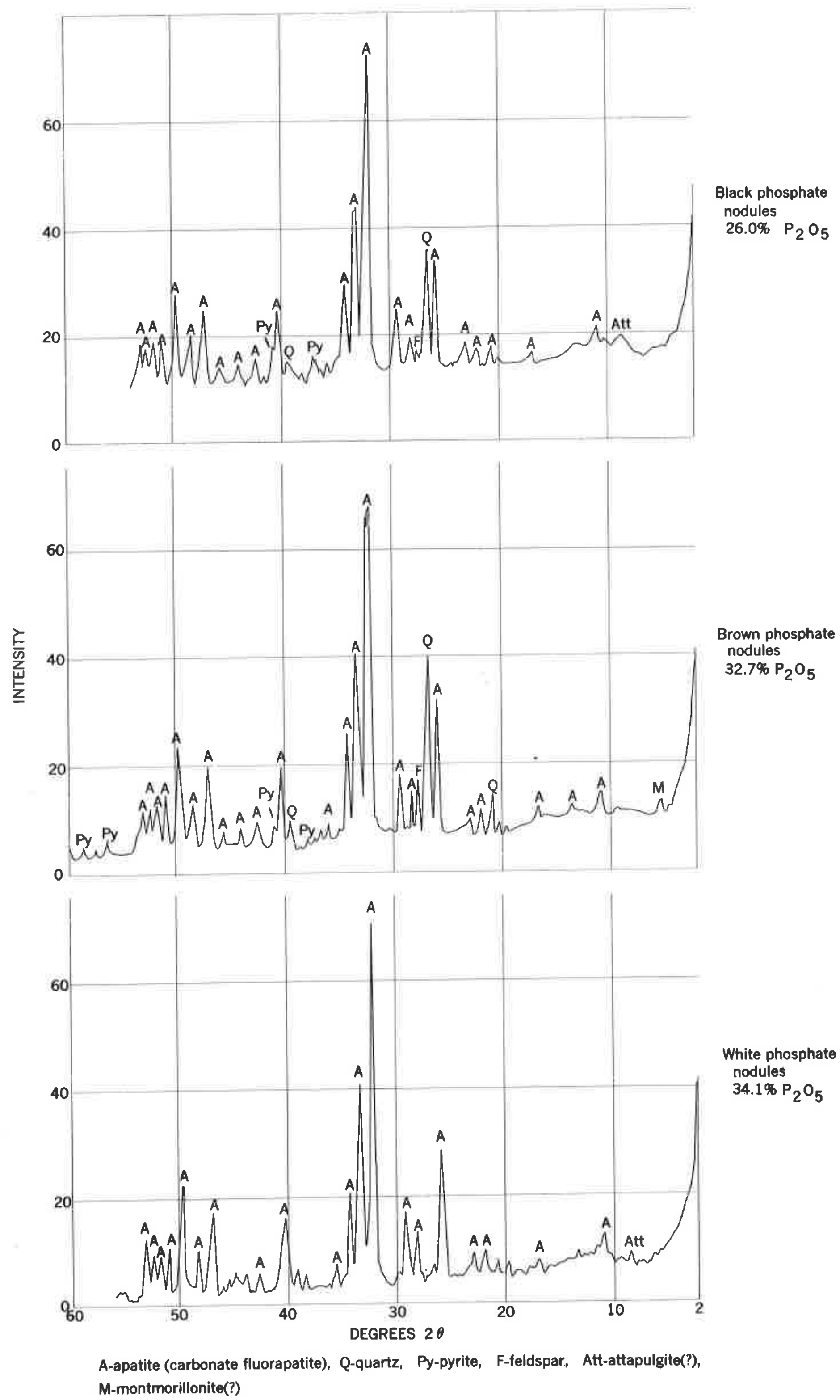


Figure 4. X-ray Diffractometer Traces of Hand-picked Phosphate Particles from Several Drill Hones in Echols County, Georgia.

TABLE 1. PHOSPHORUS PENTOXIDE, URANIUM, AND EQUIVLANENT URANIUM ANALYSES, IN PERCENT, OF PEBBLE PHOSPHATE SAMPLES FROM SOUTH GEORGIA.

Sample no.	P_2O_5	U	eU	Laboratory no.
1	29.1	0.009	0.011	D118546
2	26.0	.006	.009	D118547
3	34.1	.009	.016	D118548
4	32.7	.009	.009	D118549
5	33.7	--	--	--
6	27.5	.012	.012	D123678
7	3.63	--	.002	D123680
8	1.10	--	< .001	D123679
9	4.13	--	.001	D123681
10	5.94	--	.002	D123682
11	7.17	.004	.004	D123683

P_2O_5 analyses by L. F. Radar and O. M. Parker; uranium analyses by E. J. Fennelly and O. M. Parker.

1-4 Hand-sorted phosphate from +20-mesh fraction of composite samples taken from several drill holes in Echols County, Ga. 1--composite of black, white, and brown nodules; 2--black nodules; 3--white nodules; 4--brown nodules.

5 Angular brown nodules washed from clay bed penetrated in drilling near Statenville, Ga.

6 Coarse pellets (up to 30 mm diameter) from bed 7, near Statenville, Ga. section (p. 42).

7-9 Whole samples of phosphatic beds measured near Statenville, Ga., (p. 42); 7--bed 4, 8--bed 5,9--bed 7.

10-11 Whole samples of phosphatic beds exposed on the Strickland farm (p. 43) 10--beds exposed along trail to farm pond, 11--bed exposed upstream from pond.

9.7 to 30.8 percent P_2O_5 (21.3-67.3 percent BPL). The acid insoluble content of the pebble fraction varies inversely with the BPL, and ranges from 10.0 to 57.8 percent, most of the diluting material is the silica. Silt-sized quartz is the principal diluent in the coarse nodules. Two samples of hand-sorted phosphate nodules, one containing about 20 percent and the other about 30 percent P_2O_5, were crushed and then treated by flotation methods. The concentrate fractions of both samples contained about 32 percent P_2O_5. Quartz, separated as the tailing fraction, formed about half of the first sample and about a third of the second.

Flotation concentrate samples range from about 30.0 to 35.0 percent P_2O_5 (66 to 76.5 percent BPL) and probably average about 33 percent P_2O_5 (73 percent BPL).

The whole samples (table 1, samples 7-11) are from outcrops and are probably not representative of deposits under overburden which may be of better grade. P_2O_5 analyses of the deposits most favorable for mining in south Georgia are not available.

One sample of hand-sorted phosphate pebble was analyzed by a six-step semiquantitative spectrographic method (table 2). The results are typical of marine phosphate, except that the sample is somewhat lower than the average for rare earths. Waring and Mela (1952, table 3), for example, show considerably greater amounts of rare earths in a sample from the Florida land-pebble district, and Altschuler and others (1967) also show greater amounts of rare earths from the land-pebble district and several other marine phosphate deposits.

Phosphate in the Tampa Formation

Phosphate pellets are present in varying amounts in both members of the Tampa Formation throughout most of southern Georgia, as indicated by the peaks

TABLE 2. SIX-STEP SPECTROGRAPHIC ANALYSIS OF +20 MESH PHOSPHATE OF SAMPLE 6, TABLE 1.

[Results are reported in percent to the nearest number in the series: M-major constituent--greater than 10 percent, 1, 0.7, 0.5, 0.3, 0.2, 0.15, and 0.1, etc; which represent approximate midpoints of group data on a geometric scale. The assigned group for six-step results will include more accurately determined values about 30 percent of the time.]

Analyst: Harriet Neiman. Laboratory number D123678

Si	2.	Cr	.003
Al	1.	Cu	.0007
Fe	1.5	La	.002
Mg	1.	Mo	.001
Ca	M	Ni	.001
Na	.7	Pb	.0015
K	.7	Sr	.15
Ti	.1	V	.007
P	M	Y	.002
Mn	.02	Yb	.0002
Ba	.01	Zr	.003
Co	.0005		

Looked for but not detected: Ag, As, Au, B, Be, Bi, Cd, Ce, Ga, Ge, Hf, Hg, In, Li, Nb, Pd, Pt, Re, Sb, Sc, Sn, Ta, Te, Th, Tl, U, W, Zn, Nd, Sm, Eu.

TABLE 3. CHEMICAL ANALYSES, IN PERCENT, OF PHOSPHATIC LIMESTONE IN THE UPPER PART OF THE TAMPA FORMATION, IN SOUTHERN GEORGIA.

Location	P_2O_5	SiO_2	CaO	MgO
Thomas County				
Spence Farm[1]	0.50	9.0	--	--
Original Pond[1]	0.20	4.20	--	--
Brooks County				
Withlacoochee River[1, 2]	5.30	12.00	--	--
Cook County				
Test well GGS996[3]				
160-170 feet	0.36	40.80	29.68	0.40
190-200 feet	0.38	36.80	22.40	8.00

[1] Analysis used by permission of Wayne Thomas, Inc.

[2] Sample from poorly exposed dolomitic rock in river bed which might be younger than Tampa Formation.

[3] Analysis of well sample by J. R. Landrum, Georgia Department of Mines, Mining, and Geology.

in gamma logs of water wells (fig. 2). Loose phosphate pellets are abundant in well cuttings from some of the sandy and clayey beds in the lower member in the southeast Georgia embayment. Pellets are loose in cuttings taken from the upper dolomitic member in some wells, but most are firmly cemented in carbonate rock. The lower member occurs only at depth. The upper member is under overburden less than 75 feet thick on the crest of the Barwick arch and in a few stream valleys east of this structure.

Phosphate in the upper part of the Tampa Formation crops out in a few places in south Georgia. Samples from outcrops analyzed (table 3) were collected at Spence Farm and Original Pond, Thomas County (fig. 5, localities 1 and 3). A poorly exposed phosphatic dolomite in the bed of the Withlacoochee River, Brooks County (fig. 5, locality 4), is probably also part of the Tampa Formation, but may be younger. The analyzed subsurface samples came from only one test well (GGS 996) at Adel, Ga. The abundance of phosphate pellets in these samples, as estimated with the aid of a microscope, is more or less typical of that in much of the Tampa Formation.

Phosphate in the "Hawthorn Formation"

Lenticular phosphorite beds occur throughout the "Hawthorn Formation" and are generally more abundant in the upper part of the formation (zones 3 and 4) than in the lower part (zones 1 and 2). The phosphorite lenses in the upper part are as much as 20 feet thick; those in the lower part are ordinarily only a few inches thick.

Exposures of phosphorite beds in southern Georgia are very rare, because deposits occur in areas where interstream uplands are cultivated or forested, and valleys are shallow, swampy, and blanketed by dense vegetation. The best exposure known to the authors is in the overflow ditch of a small pond a quarter mile northwest of Statenville, Echols County, on land owned by Dick Davis. This artificial exposure is in the vicinity of deposits described by McCallie (1896, p. 80, fig. 3). The following section was measured at this locality. All units described are lenticular. The P_2O_5 and U content of whole samples and hand-picked samples of pellets from some units are listed in table 1.

	Thickness (feet)
1. Clay, yellowish-gray, thin-bedded	2
2. Siltstone, light-yellowish-brown, clayey, contains sparse silt-size phosphate nodules	3
3. Covered	3
4. Sand, dusky yellow to green, crossbedded, medium- to coarse-grained, subrounded, fairly well sorted; contains minor quantities of clay; rounded, brown to black phosphate pellets abundant, and shark teeth are common. Sand is chiefly quartz and contains minor attapulgite, montmorillonite, feldspar, hematite, and apatite	5
5. Clay and sand interbedded; clay is greenish-gray, plastic, occurring in beds as much as 1 inch thick in lower part and in thinner beds in upper part; sand is brown, silty, in beds one-quarter-inch thick, mostly fine to coarse grained, fairly well sorted; medium- to coarse-grained polished phosphate pellets make up approximately 10 percent of sand beds. The green clay beds are chiefly a mixture of dolomite, attapulgite, and quartz, but they also contain minor quantities of an iron phosphate (probably dufrenite) and montmorillonite	4
6. Covered	1
7. Sand and gravel, yellowish-brown, crossbedded, ranges from medium-grained sand to fine pebble gravel; sand grains are mostly subangular, gravel is subrounded; contains a few lumps of cream-colored claylike material; white, brown, and black polished phosphate pellets make up approximately 10 percent of the rock, most pellets are 0.5 to 5 mm in diameter, but some are as much as 25 mm in longest dimension; phosphatic shark teeth common. Hand-picked samples of white, brown, and black pellets consist chiefly of apatite, but all three contain minor quartz and attapulgite. Cream-colored lumps are chiefly dolomite, but they contain minor quartz and attapulgite	3
8. River level (water was at bankfull stage when section was measured)	3

Phosphate in the Duplin Marl equivalents (?)

Scattered lenticular deposits of phosphate occur in the lower 5 to 20 feet of beds in the clastic sediments of late Miocene age referred to as the Duplin Marl equivalents (?) in this report. These deposits are in the southern part of the Southeast Georgia embayment. Some phosphatic lenses are associated with clay, sandy clay, and silt that probably were deposited in a shallow-marine environment, whereas others are associated with medium to coarse cross-bedded sand that probably accumulated either very near shore or as beach and bar deposits. Many of the phosphate particles in the Duplin Marl equivalents (?) are angular, and most are light gray or white. Probably most of the angular fragments are broken pellets. Most likely some of the phosphate in this formation has been reworked from the "Hawthorn Formation."

The belt in which scattered deposits of phosphate are known to occur in the Duplin Marl equivalents (?) extends from southern Echols County, Ga., northward into the eastern part of Lowndes County and much of Lanier County (fig. 5). Deposits in this formation may also occur in eastern Lowndes County and Clinch County. Phosphate deposits of late Miocene age may also occur in Florida, but sufficient geologic work to establish their presence there has not been done.

The phosphate deposits in the Duplin Marl equivalents (?) crop out at only a very few places. The best exposure known to the authors is along a small stream flowing westward into the Alapaha River at a point 0.1 mile north of the Florida-Georgia line (fig. 5, loc. 2) on property owned by Mr. Roy Strickland. A grayish-brown, medium to coarse sand 3 to 6 feet thick is exposed in a trail to a farm pond. The sample contained 5.94 percent P_2O_5 and 0.002 percent eU. Yellowish-brown medium- to coarse-grained sand about 4 feet thick is exposed in the stream bottom about 400 feet upstream from the dam forming the pond. This material contained 7.17 percent P_2O_5. The phosphate pellets in this sand are gray, brown, and white, and phosphatized fish remains are common.

A bed of pale-yellowish-brown to white, medium- to coarse-grained phosphatic sand that is probably in the Duplin Marl equivalents (?) crops out on the east bank of the Alapaha River 4 miles southeast of Lakeland, Ga. (fig. 5, loc. 1). White and brown phosphate pellets are abundant in the sand.

Transported phosphate deposits of Pliocene to Recent age

Phosphate pellets eroded from Miocene phosphate deposits and redeposited in beds of Pliocene to Recent age are scattered through southern Georgia and northern Florida. The deposits are small, lenticular, and irregularly distributed in the flood plains of the Withlacoochee, Alapaha, Suwannee, and Santa Fe Rivers and Olustee and Black Creeks. These deposits are the so-called river-pebble type. Deposits of this type were mined in south Florida, along the Peace and Alafia Rivers prior to 1908 (G. R. Mansfield, 1942, p. 8), and they were also mined on a small scale along Black Creek, Clay County, Fla., in the Georgia-Florida field (G. R. Mansfield, 1942, p. 24). Known deposits of transported phosphate are small, scattered, and low grade, and prospects for finding large commercial deposits are not good.

Transported and perhaps primary deposits of Pliocene to Recent age occur in the coastal areas of Georgia and on the Continental shelf off the coast. These deposits are east of the area of investigation of this report and will not be discussed. They have been investigated by the Marine Institute, University of Georgia, and are described by Pevear (1966, p. 255) and Pevear and Pilkey (1966).

HARD-ROCK PHOSPHATE DEPOSITS

Phosphate of the hard-rock type described by Espenshade and Spencer (1963, p. 32-44) occurs at a few places in southern Georgia. The phosphate is in the form of irregular nodules and concretions that range in size from small nodules up to masses more than a foot in longest dimension (McCallie, 1896, p. 61). These nodules and concretions are scattered throughout cherty and clayey residuum on the Tampa Formation. They presumably formed by precipitation from ground water in vugs and joints in limestone, and some masses have a blocky appearance, suggesting that they are replacements of limestone. The phosphate remained in the residual material after the limestone was eroded, resulting in its present rubbly appearance. This theory of origin of the hard-rock deposits is similar to that proposed by several geologists (Espenshade and Spencer, 1963, p. 38-45).

One or two carloads of hard-rock phosphate were mined approximately 4 miles west-northwest of Boston, Thomas County, Ga. (fig. 5), in 1889 or 1890 (McCallie, 1896, p. 61). The only available analyses more recent than McCallie's original ones from this locality are of three hand-picked samples from the dump of the old mine near Boston that were collected by Cathcart in 1952. The analyses of these samples follows:

		BPL	Insolubles
(1)	Light-colored fragments	63.15	16.31
(2)	Dark-colored fragments	71.89	6.22
(3)	Large limestone replacement fragments	76.58	0.66

Two or three of the companies involved in the phosphate exploration in Georgia and Florida have drilled in the vicinity of the hard-rock phosphate

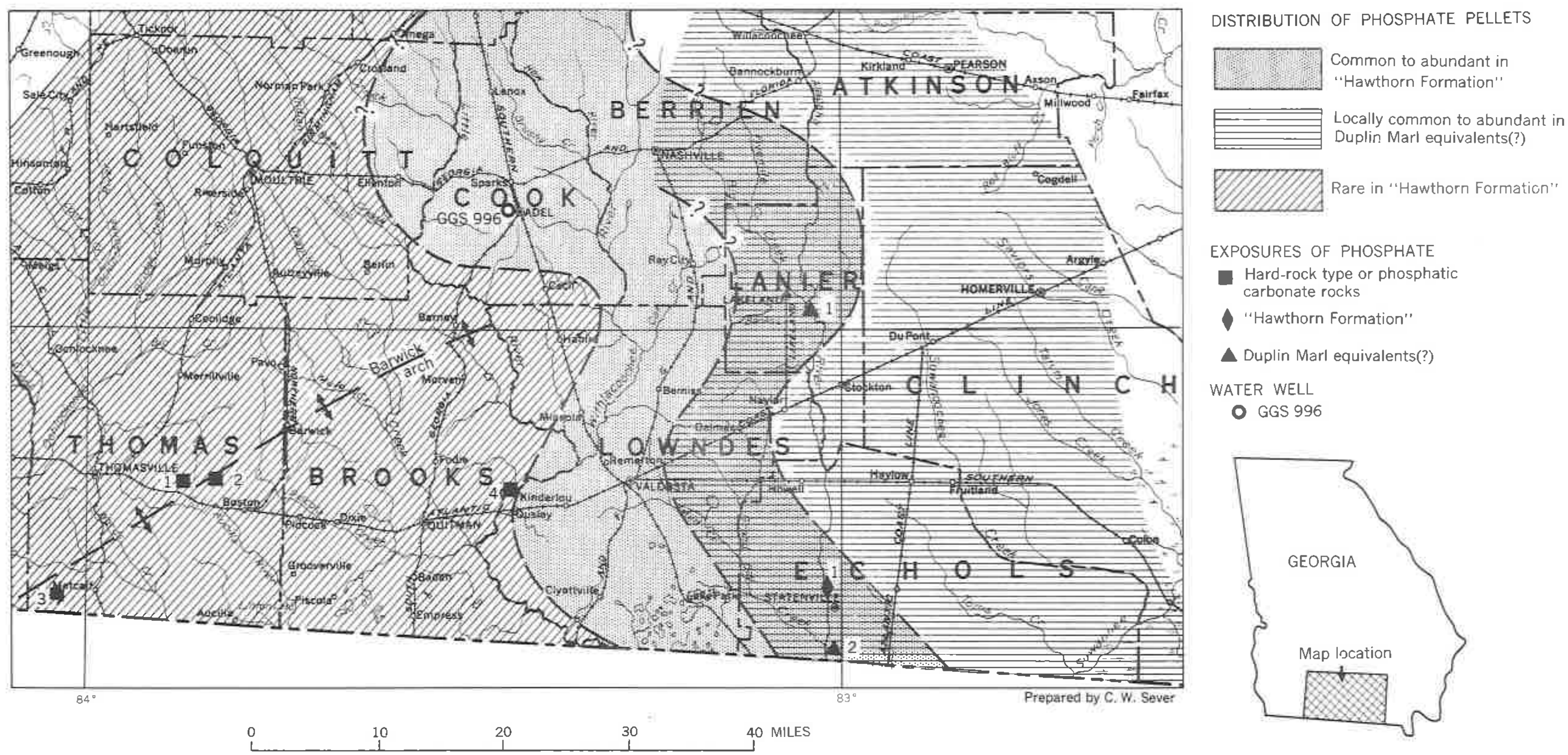


Figure 5. Map Showing the Distribution of Phosphate and Areas Favorable for Prospecting in Southern Georgia.

deposits near Boston and probably in the vicinity of the outcrop along the Withlacoochee River. The results of this drilling are not available, and, insofar as the authors are aware, no deposits favorable for mining have been discovered. A hole was drilled by Cathcart in 1952 near the old hard-rock pit at Boston, Georgia, using a power auger. No phosphate was found in the cuttings. Also, no hard-rock phosphate was present in a hole drilled as part of the South Georgia Minerals Program near the old phosphate mine northwest of Boston (Georgia Department of Mines, Mining and Geology, 1966 b, p. 60-63). Probably hard-rock deposits in southern Georgia are too small to be of value. The very low P_2O_5 content of the Tampa Formation would require the residual accumulation from great thicknesses to form large deposits of the hard-rock type, and all available geologic evidence suggests that no great thickness of limestone residuum accumulated in this region.

RELATION OF DEPOSITS TO REGIONAL STRUCTURE

All significant concentrations of phosphate in southern Georgia and northern Florida are related to the prominent anticlines of the region. The secondary hard-rock deposits of Florida (fig. 1) are in a structurally high area on the Ocala uplift, and the hard-rock deposit near Boston, Ga., (fig. 5) is near the axis of the Barwick arch. It is in these structurally high areas that maximum weathering and erosion took place, phosphate particles were dissolved by acid ground water, and the P_2O_5 in solution moved downward and was precipitated at the limestone or dolomite contact, where the pH of the water was raised by ions from carbonate minerals.

All the pebble phosphate deposits in the Florida part of the Georgia-Florida field are east and northeast of and structurally lower than the carbonate rocks exposed on the Ocala uplift. Phosphate concentrations not yet proved commercial occur in Georgia northeast of the Barwick arch. Though phosphate is present throughout much of southern Georgia and northern Florida, commercial deposits are not known to exist west of the Ocala uplift or northwest of the Barwick arch and the Chattahoochee anticline.

The structural control of pebble phosphate deposits in the eastern United States was noted by Cathcart and Osterwald (1957) who pointed out that phosphate was deposited on the flanks of anticlines or domes contemporaneously with upwarping and that water depth was a very important factor. The general hypothesis seems to be confirmed in the Georgia-Florida field. Deeper water, east and northeast of shallows formed by the upwarping, is a favorable area for phosphate deposition, assuming that the phosphate was introduced by currents from the Atlantic Ocean.

The structural-water-depth control explains the restriction of deposits in the lower member of the Tampa Formation to the now moderately deep parts of the Southeast Georgia embayment and those of "Hawthorn" age to the position in structurally low areas east and northeast of the Ocala uplift. The fact that phosphate is not known to the west and northwest of the Ocala uplift and Chattahoochee anticline is an indication that phosphatic waters did come from the Atlantic and that these positive areas acted as barriers and phosphatic material was removed from these waters in the favorable areas east of the highs.

ORIGIN OF THE PEBBLE DEPOSITS

Kazakov (1937) first presented the idea that marine phosphorites are deposited in areas of upwelling deep ocean waters. His ideas have been expanded by McKelvey (1963) and Sheldon (1964), and they can be applied to an explanation of origin of many marine phosphorites. The theory is based on the assumption that apatite, the mineral forming most marine phosphorite, will be deposited wherever there is a warming and decrease in pressure of cold phosphorus-rich waters. The deposition is believed to be related to a rise in the pH of sea water brought about by the driving off of CO_2 as the water warms; however, the manner in which phosphate minerals actually form is poorly understood (McConnell, 1966). Cold oceanic water is warmed where dynamic upwelling occurs. It may also be warmed where two currents meet; an example of this is the intersection of the Labrador current and the Gulf Stream off the east coast of North America (Sheldon, 1964, fig. 3), and phosphate will precipitate where there is turbulent mixing along the inert edge of warm density currents that occur on the western margins of the oceans (McKelvey, 1966, p.3).

The abundance of phosphate pellets on the northeast flanks of the Ocala uplift and the Barwick arch and the absence of phosphate on the western flanks of these structures together with the likelihood that a higher energy environment existed east of the anticlines during phosphate deposition suggests that the source of the phosphatic material was from the east or northeast. Perhaps cool water flowing toward the southeast caused turbulent mixing with the warm currents. Phosphate then might have precipitated where phosphorus-rich cold water was warmed and where the pH changed in the proper water depth, against the flanks of the rising Ocala uplift and the Barwick arch.

Pevear (1966) has suggested that Tertiary phosphorite deposits of the

Atlantic Coastal Plain may have formed in estuaries, which have a large supply of inorganic phosphorus, and that dynamic upwelling is not necessary to explain the origin of these phosphorites. The phosphorite deposits of the Georgia-Florida field are in local basins on the flanks of low anticlines, and these basins may have been estuaries, as suggested by Pevear.

It seems likely that a combination of turbulent mixing caused by interaction of warm currents and colder currents moving to the southeast and the estuarine origin suggested by Pevear may account for the origin of the phosphorite deposits of the Georgia-Florida field.

RECOMMENDATIONS FOR PROSPECTING

The most intense prospecting for phosphate in southern Georgia and northern Peninsular Florida has been within the limits of the Georgia-Florida field, and virtually all the field (fig. 1) is worth prospecting. The southern and western edge of the Southeast Georgia embayment, east and north of the Georgia-Florida field, may contain shallow phosphate deposits. A belt on the east and north flanks of the Barwick arch (fig. 5) is favorable for phosphate deposits under overburden less than 100 feet thick. Similar areas may be present east of the Miocene outcrops in central Georgia, but geologic information in this part of the State is insufficient to support more than speculation on the possibilities of finding phosphate.

Should technical advances make it feasible to mine phosphate at appreciable depths, then the entire Southeast Georgia embayment would be worth prospecting, because phosphate is known to occur at depth at several places in this basin. For example, during studies of well cuttings, abundant phosphate pellets were found in samples from depths of 55 to 200 and 320 to 430 feet in a well (GGS 455) drilled 1 mile east of Tarboro, Camden County, Ga. (Herrick, 1961, p. 68), and from 119 to 150 feet in a well at Savannah (GGS 563) (Herrick, 1961, p. 108).

ECONOMIC FACTORS IN EVALUATING DEPOSITS

The factors involved in determining the economic value of unconsolidated phosphorite deposits are varied and interrelated, so that accurate evaluations are difficult to make. The factors have been discussed in detail by Cathcart and McGreevy (1959); Cathcart (1963); and Altschuler, Cathcart, and Young (1964). In general terms, the economic factors are as follows:

1. Phosphate particles should contain more than 66 percent BPL (=30 percent P_2O_5).

2. The phosphate particles should contain less than about 5 percent combined Fe_2O_3 and Al_2O_3.

3. The recoverable phosphate should exceed about 400 long tons per acre foot, which corresponds approximately to 20 percent phosphate particles by volume.

4. The thickness of the material mined must be greater than about 3 feet--the least thickness that can be mined profitably with large equipment.

5. The volume of material mined should be less than 25 cubic yards per ton of product recovered.

6. The thickness of the overburden must be less than a certain maximum that can be profitably removed. This is calculated as a part of the ratio of cubic yards of rock moved per ton of product.

7. The maximum depth to which deposits can be mined is a function of the capabilities of the dragline, and deeper deposits can be mined only by putting the dragline on a lower previously mined bench--a generally prohibitive requirement.

8. The amount of excess CaO (as the mineral calcite) is important in chemical processing, but no limits have been established, except that it

should be as low as possible. The ratio of CaO to P_2O_5 in carbonate-fluorapatite nodules is about 1.4:1, and the total CaO in most phosphate concentrate produced in the eastern United States is no more than 1.5 times the P_2O_5 content. This percentage of CaO can be taken as the probable maximum for most economic deposits.

9. A high content of organic material can be deleterious in chemical processing, but no limits have been established. Most phosphate particles in the sedimentary rocks of the eastern United States contain only small amounts of organic material, and such material rarely causes difficulties.

10. Excess fluorine can be a problem in processing, as fluorine is present in the stack gases from the plants and may cause an air pollution problem. In the southeastern deposits, fluorine is known to occur only as an integral part of the phosphate mineral; therefore, no limits for fluorine can be established. A phosphate ore that contained excess fluorine might have to be treated in a somewhat different manner than ore containing 3 to 4 percent fluorine, the typical quantity.

RESOURCES

Reserves of phosphate of the land-pebble type in the Florida part of the Georgia-Florida field were summarized by Mansfield (1942, p. 61) as follows:

	Acres	Known	Probable	Possible
Hamilton County	14,000	1,000,000	24,000,000	25,000,000[1]
Clay County	--	--	--	90,000,000[1]
Bradford County	--	--	--	55,000,000[2]
Lake and Orange Counties	--	--	--	100,000,000[3]

[1] 77 percent grade possible by crushing and flotation.
[2] Grade probably under 70 percent.
[3] Grade 55 percent or better.

Extensive exploration programs have been carried out in north Florida and south Georgia by several companies in the last decade, and the reserves developed are known to be much larger than the totals given by Mansfield. Although detailed data on reserves are company confidential, some general information is available. For example, Olson (1966a, p. 83) states that reserves in an area of about 30,000 acres controlled by one company are about 70-75 million tons, and it is reported in the Engineering and Mining Journal (1966, p. 138) that an adjacent area of 10,000 acres contains 70 million tons of phosphate rock with an average content of 71 percent BPL. These reserves are in Hamilton County, Fla., and the size of other scattered ore bodies found in north Florida and south Georgia in recent years is not known.

The total resources of phosphate rock of all grades and in all deposits (some of which are below the present limits of profitable mining) in the Georgia-Florida field are probably several times the 140 million tons on the two tracts in Hamilton County, Fla. The total phosphate rock in the Georgia-Florida field may amount to billions of tons, as deposits are scattered throughout the field having an area of more than 5,000 square miles. The phosphorite deposits occur as isolated bodies rather than as a continuous blanket, and known occurrences are widespread, thus prospects for finding other deposits similar to those now known in Hamilton County are favorable.

REFERENCES CITED

Altschuler, Z. S., Berman, Sol, and Cuttitta, Frank, 1967, Rare earths in phosphorites--economic geochemistry and potential recovery: U.S. Geol. Survey Prof. Paper 575-B, p. B1-B7.

Altschuler, Z. S., Cathcart, J. B., and Young, E. J., 1964, The geology and geochemistry of the Bone Valley Formation and its phosphate deposits, west-central Florida; Guidebook, field trip no. 6, Geological Society of America, annual meeting, Miami Beach, Nov. 1964: [New York, Geol. Soc. America] 68 p.

Altschuler, Z. S., Clarke, R. S., Jr., and Young, E. J., 1958, The geochemistry of uranium in apatite and phosphorite: U.S. Geol. Survey Prof. Paper 314-D, p. 45-86.

Altschuler, Z. S., Jaffe, E. B., and Cuttitta, Frank, 1956, The aluminum phosphate zone of the Bone Valley Formation, Florida, and its uranium deposits: U.S. Geol. Survey Prof. Paper 300, p. 495-504.

Applin, P. M., 1951, Preliminary report on buried pre-Mesozoic rocks in Florida and adjacent states: U.S. Geol. Survey Circ. 91, 28 p.

Beall, J. V., and Merritt, P. C., 1966, Phosphate and potash minerals to feed the world: Mining Eng., v. 18, no. 10, p. 75-114.

Cathcart, J. B., 1954, Drilling of airborne radioactivity anomalies in Florida, Georgia, and South Carolina: U.S. Geol. Survey open-file report, 10 p.

_____ 1963, Economic geology of the Keysville quadrangle, Florida: U.S. Geol. Survey Bull. 1128, 82 p.

Cathcart, J. B., and McGreevy, L. J., 1959, Results of geologic exploration by core drilling, 1953, land-pebble phosphate district, Florida: U.S. Geol. Survey Bull. 1046-K, p. 221-298.

Cathcart, J. B., and Osterwald, F. O., 1957, Relation of phosphatic sediments to tectonics of the eastern United States [abs.]: Am. Inst. Mining Metall. Eng., Tampa Industrial Minerals Div. Meetings, Oct. 1957.

Cooke, C. W., 1943, Geology of the Coastal Plain of Georgia: U.S. Geol. Survey Bull. 941, 121 p.

_____ 1945, Geology of Florida: Florida Geol. Survey Bull. 29, 339 p.

Cooke, C. W., and Mossom, Stuart, 1929, Geology of Florida: Florida Geol. Survey, 20th Ann. Rept., 1927-1928, p. 31-227.

Eldridge, G. H., 1893, A preliminary sketch of the phosphates of Florida: Am. Inst. Mining Engineers Trans., v. 21, p. 196-231.

Engineering and Mining Journal, 1966, Florida: Eng. and Mining Jour., v. 167, no. 12, p. 138.

Espenshade, G. H., 1958, Geologic features of areas of abnormal radioactivity south of Ocala, Marion County, Florida: U.S. Geol. Survey Bull. 1046-J, p. 205-219.

Espenshade, G. H., and Spencer, C. W., 1963, Geology of phosphate deposits of northern Peninsular Florida: U.S. Geol. Survey Bull. 1118, 115 p.

Georgia Department of Mines, Mining, and Geology, 1966a, Project report no. 2, South Georgia minerals program, Echols County: Georgia Dept. Mines, Mining, and Geology, Rept. No. 2, Project A-880, 79 p.

Georgia Department of Mines, Mining, and Geology, 1966b, Project report no. 3, South Georgia minerals program: Georgia Dept. Mines, Mining, and Geology, Rept. No. 3, project A-880, 68 p.

Gremillion, L. R., 1965, The origin of attapulgite in the Miocene strata of Florida and Georgia: Florida State Univ., Ph.D. thesis, 139 p.

Grim, R. E., 1953, Clay mineralogy: New York, McGraw-Hill, 384 p.

Hendry, C. W., Jr., and Yon, J. W., Jr., 1958, Geology of the area in and around the Jim Woodruff Reservoir (Florida and Georgia): Florida Geol. Survey Rept. Inv. 16, p. 1, p.1-52.

Heron, D. S., Jr., and Johnson, H. S., Jr., 1966, Clay mineralogy, stratigraphy, and structural setting of the Hawthorn Formation, Coosawhatchie district, South Carolina: Southeastern Geology, v. 7, no. 2, p. 51-61.

Herrick, S. M., 1961, Well logs of the Coastal Plain of Georgia: Georgia Dept. Mines, Mining and Geol. Bull. 70, 461 p.

_____ 1965, A subsurface study of Pleistocene deposits in coastal Georgia: Georgia Dept. Mines, Mining, and Geol. Inf. Circ. 31, 8 p.

Herrick, S. M., and Vorhis, R. C., 1963, Subsurface geology of the Georgia Coastal Plain: Georgia Dept. Mines, Mining, and Geol. Inf. Circ. 25, 67 p.

Johnson, L. C., 1888, The structure of Florida: Am. Jour. Sci., 3d ser., v. 36, p. 230-236.

Kazakov, A. V., 1937, The phosphorite facies and the genesis of phosphorites, in Geological investigations of agricultural ores U.S.S.R.: Sci. Inst. Fertilizers and Insectofungicides Trans. (U.S.S.R.), no. 142, p. 95-113. [Special issue in English published for 17th Internat. Geol. Cong.]

Ketner, K. B., and McGreevy, L. J., 1959, Stratigraphy of the area between Hernando and Hardee Counties, Fla.: U.S. Geol. Survey Bull. 1074-C, p. 49-124.

Leve, G. W., 1965, Ground water in Duval and Nassau Counties, Florida: U.S. Geol. Survey open-file report, 102 p.

McCallie, S. W., 1896, A preliminary report on a part of the phosphates and marls of Georgia: Georgia Geol. Survey Bull. no. 5-A, 101 p.

McClellan, G. H., 1964, Petrology of attapulgus clay in north Florida and southwest Georgia: Univ. Illinois, Ph.D. thesis, 119 p.

McConnell, Duncan, 1966, Shallow-water phosphorites: Econ. Geology, v. 61, no. 5, p. 967-968.

McKelvey, V. E., 1963, Successful new techniques in prospecting for phosphate deposits: Science, technology, and development, United States papers prepared for the United Nations Conference on the application of science and technology for the benefit of the less developed areas, v. II, p. 163-172.

_____ 1966, Successful new techniques in prospecting for phosphate deposits: Australian Mining, v. 58, no. 3, 4 p.

MacNeil, F. S., 1947, Geologic map of the Tertiary and Quaternary formations of Georgia: U.S. Geol. Survey Oil and Gas Inv. Prelim. Map 72.

Malde, H. E., 1959, Geology of the Charleston phosphate area, South Carolina: U.S. Geol. Survey Bull. 1079, 105 p.

Mansfield, G. R., 1942, Phosphate resources of Florida: U.S. Geol. Survey Bull. 934, 80 p.

Mansfield, W. C., 1937, Mollusks of the Tampa and Suwannee limestones of Florida: Florida Geol. Survey Bull. 15, 334 p.

Mossom, Stuart, 1925, A preliminary report on the limestone and marls of Florida: Florida Geol. Survey 16th Ann. Rept., p. 28-203.

Moxham, R. M., 1954, Airborne radioactivity surveys for phosphate in Florida: U.S. Geol. Survey Circ. 230, 4 p.

Murray, G. E., 1961, Geology of the Atlantic and Gulf Coastal Province of North America: New York, Harper and Brothers, 575 p.

Olsen, S. J., 1963, An upper Miocene fossil locality in north Florida: Florida Acad. Sci. Journ., v. 26, no. 4, p. 308-314.

Olson, N. K. (ed.), 1966a, Geology of the Miocene and Pliocene series in the north Florida - south Georgia area: Atlantic Coastal Plain Geol. Assoc. and Southeastern Geol. Soc., 12th Ann. Field Conf., 94 p.

_____ 1966b, Phosphorite exploration in portions of Lowndes, Echols, Clinch, and Charlton Counties, Georgia: Georgia Dept. Mines, Mining, and Geol. Project report no. 4, South Georgia Minerals Program, 113 p.

Pevear, D. R., 1966, The estuarine formation of United States Atlantic Coastal Plain phosphorite: Econ. Geology, v. 61, no. 2, p. 251-256.

Pevear, D. R., and Pilkey, O. H., 1966, Phosphorite in Georgia Continental Shelf sediments: Geol. Soc. America, Bull. v. 77, no. 8, p. 849-858.

Pirkle, E. C., 1956, The Hawthorne and Alachua formations of Alachua County, Florida: Florida Acad. Sci. Quart. Jour., v.19, p. 197-240.

_____ 1957, Economic considerations of pebble phosphate deposits of Alachua County, Florida: Econ. Geology, v. 52, p. 354-378.

Pressler, E. D., 1947, Geology and occurrence of iol in Florida: Am. Assoc. Petroleum Geol. Bull., v. 31, p. 1851-1862.

Puri, H. S., 1954, Contribution to the study of the Miocene of the Florida Panhandle: Florida Geol. Survey Bull. 36, 345 p.

Puri, H. S., and Vernon, R. O., 1964, Summary of the geology of Florida and a guidebook to the classic exposures: Florida Geol. Survey Spec. Pub. 5, revised, 312 p.

Sellards, E. H., 1913, Origin of the hard-rock phosphates in Florida: Florida Geol. Survey Fifth Ann. Rept., p. 23-80.

Sever, C. W., 1964, Relation of economic deposits of attapulgite and fuller's earth to geologic structure in southwestern Georgia: U.S. Geol. Survey Prof. Paper 501-B, p. B116-B118.

_____ 1965, The Chattahoochee anticline in Georgia: Georgia Dept. Mines, Mining, and Geology, Georgia Mineral Newsletter, v. 17, p. 39-43.

_____ 1966, Miocene structural movements in Thomas County, Georgia: U.S. Geol. Survey Prof. Paper 550-C, p. C12-C16.

Sheldon, R. P., 1964, Paleolatitudinal and paleogeographic distribution of phosphate: U.S. Geol. Survey Prof. Paper 501-C, p. C106-C113.

Stringfield, V. T., 1966, Artesian water in Tertiary limestone in Southeastern States: U.S. Geol. Survey Prof. Paper 517, 226 p.

Toulmin, L. D., 1955, Cenozoic geology of southeastern Alabama, Florida and Georgia: Am. Assoc. Petroleum Geologists Bull. 39, no. 2, p. 207-235.

Veatch, Otto, and Stephenson, L. W., 1911, Preliminary report on the geology of the coastal plain of Georgia: Georgia Geol. Survey Bull. 26, 456 p.

Vernon, R. O., 1942, Geology of Holmes and Washington Counties, Florida: Florida Geol. Survey Bull. 21, 161 p.

_____ 1951, Geology of Citrus and Levy Counties, Florida: Florida Geol. Survey Bull. 33, 256 p.

Waring, C. L., and Mela, Henry, Jr., 1952, The determination of small amounts of rare earths in phosphate rocks: U.S. Geol. Survey Trace Elements Inv. Rept. 239, issued by Oak Ridge Tech. Inf. Service, 20 p.

Yon, J. W., 1965, The stratigraphic significance of an upper Miocene fossil discovery in Jefferson County, Florida: Southeastern Geology, v. 6, no. 3, p. 167-175.