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FLORIDA TYPE PHOSPHORITE DEPOSITS--ORIGIN AND TECHNIQUES FOR PROSPECTING

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Introduction

Phosphate particles are widespread in rocks of Cretaceous, Tertiary, and Quaternary ages in the Atlantic and Gulf Coastal Plains of the United States. Sedimentary particles of phosphate are known to occur in rocks of Cretaceous, Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene and Recent ages, but known economic deposits are confined to or were derived from rocks of middle Miocene age. Economic deposits occur only in the Atlantic Coastal Plain from North Carolina to Central Florida (fig. 1). Similar deposits are known at Sechura in Peru in rocks of Miocene age.

The Miocene phosphorite deposits are herein called the "Florida" type, because the deposits of the land-pebble district of Florida are the best known.

The deposits are unconsolidated, flat-lying, ~~have been~~ and reworked in varying degrees, and all are covered by varying thicknesses of non-phosphatic material called overburden. The overburden, in many cases, completely masks the underlying deposits, and discovery of new deposits depends on an understanding of the origin and geology of the already known deposits. Prospecting must be done by drilling in the deeper deposits or by a combination of drilling or trenching in the shallower deposits. Prospecting can be expensive, and the target area has to be limited so that drilling of blank holes can be held to a minimum.

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Clues to the location of possible ore bodies and methods of prospecting, or more precisely, the limiting of areas in which to prospect will be discussed in this paper. The clues may be direct, that is, dependent on the ore body being at or close to the surface, or the clues may be indirect, and dependent entirely on the theory of origin of the deposits.

Some of the geologic factors that control the deposition of the phosphorite ore bodies are the same as ~~the same as~~ those that govern the deposition of the marine phosphorite deposits in miogeosynclinal areas, but other factors are different, and a major difference is that the "Florida" type deposits are economic because they have been reworked and concentrated.

General geology of the Atlantic Coastal Plain

The Atlantic Coastal Plain is a physiographic province of the eastern United States that is bounded by the Piedmont on the west and by the Atlantic Ocean on the east. The Coastal Plain is underlain by Cretaceous and Tertiary sedimentary rocks that, in general, dip very gently east and southeast toward the sea. The sedimentary rocks are unconsolidated or weakly consolidated, outcrops are poor, and a cover of Pleistocene and Recent deposits obscures much of the geology. The general seaward dips are interrupted by broad, gentle anticlinal and basinal folds that have northeast and northwest trends (fig. 1).

Figure 1.--Near here

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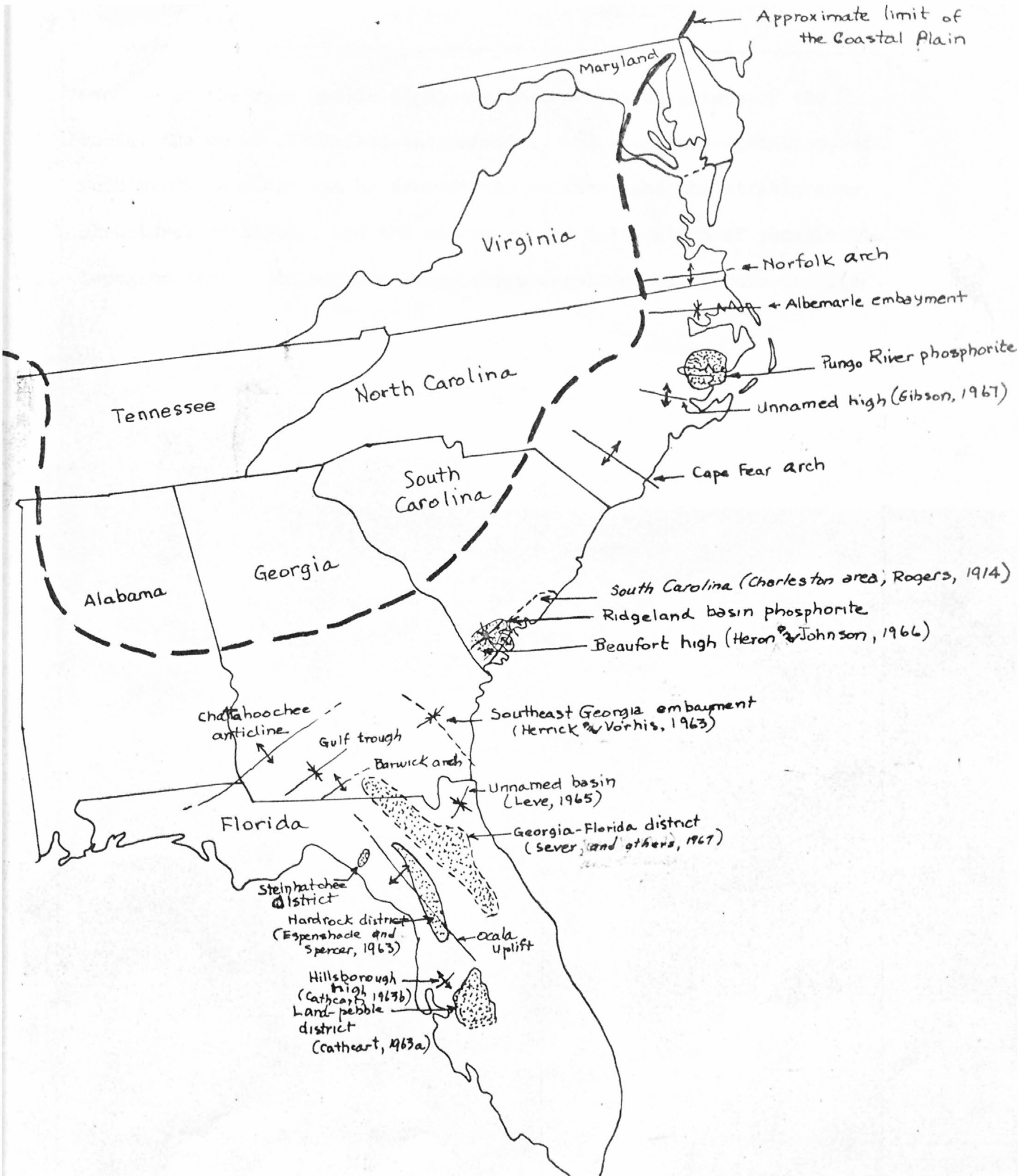

FIGURE 1.--SKETCH MAP OF EASTERN UNITED STATES SHOWING STRUCTURES OF THE COASTAL PLAIN AND PHOSPHORITE DEPOSITS OF TERTIARY AGE

Because of the very gentle dips, the unconsolidated nature of the rocks, the cover of Pleistocene material, and abundant vegetation, not much of the geology can be seen at the surface, and the stratigraphy, structural relations, and the discovery and delineation of phosphorite deposits depend on mapping large areas supplemented by core drilling.

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Stratigraphy

Phosphate pellets are widespread in rocks of Cretaceous, Tertiary, and Quaternary ages in the Atlantic and Gulf Coastal Plains of the eastern United States. A complete discussion of the stratigraphy of the coastal plains is beyond the scope of this paper, but summary data on all known occurrences of phosphate pellets in sedimentary rocks of the Coastal Plains are given on table 1. Table 1 lists the formations

Table 1.--Near here

in which phosphate occurs and is arranged generally according to age and state, but the table is not a correlation chart, and is not intended to show relations between formations.

In general, the phosphatic formations are of two kinds: calcareous and quartzose. The calcareous phosphorites are probably primary, while the quartzose phosphorites have been reworked, at least to some degree.

Phosphatic sedimentary rocks in the Gulf Coast are confined to the Paleocene and the Cretaceous, and in general are found associated with marls and glauconitic sediments. No phosphate deposits are known in rocks of Tertiary age in the Gulf Coastal Plain, and the occurrences of phosphate pellets in these rocks are restricted to a few grains in a few outcrops. A survey of the literature indicates that there is little or no phosphate in rocks of Eocene to Pleistocene age in the Gulf Coast.

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Age	State	Formation	Lithology	P_2O_5 content	References
Recent or Pleistocene	Florida, Georgia, South Carolina	Bars, floodplains along modern rivers	Sand of quartz grains and phosphate pellets 1/	Phosphate pellets 25	Mansfield, 1942; Rogers, 1914
Pleistocene	South Carolina	Ladson Formation	Clay, quartz sand, phosphate pellets 1/	Phosphate pellets 21-29	Malde, 1959
Pliocene	Florida	Bone Valley Formation	Clay, sand, phosphate pellets and nodules 1/	Phosphate grains 30-38	Cathcart, 1963a
Pliocene	North Florida, South Georgia	Unnamed	do. 1/	Phosphate pellets 20-35	Olson, 1966
Miocene	Florida, Georgia, South Carolina	Hawthorn Formation	Clay, sand, calcite, dolomite, phosphate	Phosphate pellets in weathered rock-25-35; in fresh rock-15-25	Olson, 1966; Sever, and others, 1967; Heron and Johnson, 1966; Cathcart, 1963b
	North Carolina	Yorktown Formation	Clay, sand, limestone, some phosphate pellets and granules 1/	Phosphate pellets 30±	Brown, 1958; Kimrey, 1965; Gibson, 1967; Rooney and Kerr, 1967
	North Carolina	Pungo River Formation	Phosphate pellets, sand, dolomite, clay 1/	Phosphate pellets 31	Do.
	Florida, Georgia	Tampa Limestone	Limestone, clay, sand, some phosphate pellets	Phosphate pellets--10-20; Whole rock--2-4	Sever and others, 1967; Carr and Alverson, 1959
Oligocene	South Carolina	Cooper Marl	Marl, minor phosphate pellets	Phosphate pellets 10-20; Whole rock--2-9	Malde, 1959
Eocene	North Carolina	Castle Hayne Limestone	Limestone, some phosphate pellets and granules	Phosphate pellets 30; Whole rock--6-7	Dabney, 1885
	Georgia	Tallahata Formation	Quartz sand, some phosphate grains 1/	No data	Owen, 1963
	Alabama	Claiborne Group	Phosphatic shell marl	Phosphate pellets 20	Smith, 1892
	Texas	Midway Group	Phosphate pellets in greensands and marls	Phosphate pellets--20; Matrix--1-2	Weaver and others, 1963
Paleocene	Maryland	Brightseat Formation	Phosphate pellets in calcareous sand 1/	No data	Adams and others, 1961
Cretaceous	Alabama, Mississippi, Georgia	Prairie Bluff Formation of Selma Group and equivalents	Phosphate pellets in chalk	Phosphate pellets--30; matrix 2-4	Smith, 1892; McCallie, 1896; Monroe, 1941; Stephenson & Monroe, 1940
	Texas	Eagle Ford Formation	Phosphate conglomerate at base of shale 1/	Phosphate--24; Whole rock--5-10	Weaver and others, 1963

1/ Reworked, at least in part, from older rocks.

Economic phosphorite deposits of the "Florida" type are found only in the Atlantic Coastal Plain and in rocks of middle miocene age, or in younger rocks in which the phosphate was derived from rocks of middle Miocene age. Generalized stratigraphy of the phosphate deposits of the Atlantic Coastal Plain is shown on Table 2.

Table 2.--Near here

The phosphorite deposits of North Carolina are in the Pungo River Formation of middle Miocene age. The underlying Castle Hayne Limestone contains a few phosphate nodules, and the overlying Yorktown Formation contains some phosphate pellets in the base of the formation, that have been reworked from the Pungo River Formation. The Pungo River Formation consists of phosphate pellets, quartz sand, minor clay, and interbeds of dolomite, diatomaceous clay, and sand. The phosphate pellets show evidence of having been reworked (Rooney and Kerr, 1967).

The phosphorite of the Charleston area, South Carolina, is in the base of the Ladson Formation of Pleistocene age (Malde, 1959) and consists of boulders of reworked, phosphatized Cooper Marl in a clayey sand. Malde does not propose any source for the solutions that phosphatized the surface of the Cooper Marl. The Hawthorn Formation is present just to the south of the Charleston area, where it contains abundant phosphate (Heron and Johnson, 1966). The source of the P_2O_5 that phosphatized the Cooper Marl probably was phosphate pellets in the Hawthorn Formation.

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		NORTH CAROLINA	SOUTH CAROLINA Charleston area	SOUTH CAROLINA Beaufort County	SOUTH GEORGIA NORTH FLORIDA	SOUTH FLORIDA
Pleistocene		Surficial sand	Surficial sand and Ladson Formation (phosphorite)	Surficial sand	Surficial sand	Surficial sand
Pliocene					Unnamed unit (phosphorite)	Bone Valley Formation (phosphorite)
Miocene	Upper	Yorktown Formation (trace phosphate)				
	Middle	Pungo River Formation (phosphorite)		Hawthorn Formation (phosphorite)	Hawthorn Formation (phosphorite)	Hawthorn Formation (phosphate pellets abundant)
	Lower				Tampa Formation (trace phosphate)	Tampa Limestone (trace phosphate)
Oligocene			Cooper Marl (trace phosphate)	Cooper Marl	Suwannee Limestone	Suwannee Limestone
Eocene	Upper		Jackson, Claiborne, and Wilcox Groups		Ocala Limestone	Ocala Limestone
	Middle	Castle Hayne Limestone (trace phosphate)		Castle Hayne Limestone	Avon Park Limestone	Rocks of Claiborne age
References		Gibson (1967)	Malde (1959)	Heron and Johnson (1966)	Olson (1966) Sever, Cathcart, and Patterson (1967)	Cathcart (1963a, b)

The phosphorite deposits of Beaufort County South Carolina are in the Hawthorn Formation, which is underlain by the Cooper Marl, and is overlain by surficial sand of probable Pleistocene age (Heron and Johnson, 1966).

The North Florida-South Georgia deposits are in the Hawthorn Formation and in rocks of probable Pliocene age. According to Olson (1966, p. 79) the phosphorite deposit at the mine of the Occidental Corporation of Florida is Pliocene in age, but the phosphate probably was derived from pre-existing Miocene beds. Much of the phosphorite in this area is in rocks of the Hawthorn Formation (Sever, Cathcart, and Patterson, 1967).

The very large phosphorite deposit of South-Central Florida is in the Bone Valley Formation of Pliocene age (Cathcart, 1963a,b; Altschuler, Cathcart, and Young, 1964), but much of the phosphate in the deposit was reworked from the Hawthorn Formation. Some phosphate is mined from the Hawthorn Formation.

Structure

The structure of the Atlantic Coastal Plain is a gentle, seaward-dipping homocline, but the general seaward dip is interrupted by a series of very gentle anticlines and synclines that strike either to the northwest or the northeast (fig. 1). The phosphate deposits are related to the structures in the Coastal Plain (Cathcart and Osterwald, 1954). Each of the deposits is in a basin on the flank of an anticline, and the anticlinal structures were rising at the time of deposition. The northernmost phosphate deposit (in North Carolina) is in a basin on the flank of an unnamed high; the deposit in Beaufort County, South Carolina, is in the Ridgeland basin on the flank of the Beaufort high; the northern Florida-southern Georgia deposits are on the flanks of the Barwick Arch and the Ocala Uplift; and the central Florida deposits are on the flanks of the Ocala Uplift and the Hillsborough high. Each of the deposits is in a position such that deposition could have been from southward flowing ocean currents. The rising domes could have acted as barriers to the southward flow of the currents, possibly leading to deposition in the basins.

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Phosphorite

Phosphate pellets

The phosphate pellets of all the deposits and occurrences are very similar. They include internal casts and molds of fossils, phosphatized bone fragments and teeth (particularly shark's teeth), phosphatized limestone fragments, elongate grains that may be fecal pellets, and rounded, zoned particles that have formed by precipitation around a nucleus. Many of the particles show evidence of reworking--there are compound pellets, broken and rerounded pellets, phosphatized fossils that have a rim of later phosphate, and so on. The phosphate particles are white, gray, tan, brown, red, black, and green. All are rounded, some are spherical, and most have a high luster. Particles that are dull are usually near the surface of the deposit and show evidence of having been altered by solution.

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The pellets range in size from less than 0.1 mm to several centimeters ~~in diameter~~, and in the deposits in Florida and South Carolina some of the phosphate is in the form of boulders that are as much as tens of centimeters in diameter. In the deposits of the land-pebble district in central Florida, the particle size is very important, and the variation in particle size can be mapped. Coarser particles are found on submarine ridges, from which the fines were winnowed by current action, during and after deposition. Screening is necessary to obtain a uniform size feed for the flotation plants that separate quartz and phosphate grains, and the material coarser than 1 mm is separated from the flotation feed. In the land-pebble district, the +1 mm material, called pebble, is a phosphate product. Elsewhere in the Atlantic Coastal Plain, the coarser sizes contain material other than phosphate (quartz, shell material, and limestone or dolomite fragments) and the coarse material is not a product.

Mineralogy

The phosphate mineral of all of the sedimentary phosphorites is a carbonate fluorapatite that has the formula $Ca_{10}(PO_4,CO_3)_6F_{2-3}$ (Altschuler and others, 1958).

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The gangue minerals that occur with the phosphate particles are basically of 2 types--calcareous and quartzose, but even the most calcareous of the host materials also contain abundant quartz grains (table 2). Limestones that contain little or no quartz do not contain any phosphate grains.

Silica is present as detrital grains of quartz of varying size, and in some of the deposits as diatoms. Quartz is most abundant in the reworked phosphorite deposits. In these deposits, quartz and phosphate, with minor amounts of clay, may be the only minerals.

Carbonate minerals are present as major constituents in all of the primary phosphatic sedimentary rocks in the Atlantic Coastal Plain of the United States. Dolomite is the principal carbonate mineral in the phosphorite deposits of North Carolina, while calcite is the principal carbonate mineral in all of the other deposits. Dolomite, probably secondary, is present in the Hawthorn Formation of Florida.

The phosphorite deposits also contain one or more clay minerals--illite, montmorillonite, attapulgite, and sepiolite. Where the rocks are weathered, kaolinite is a prominent clay mineral.

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The clay minerals of the phosphorite deposits of the eastern United States are different in each of the deposits. The clay minerals in the phosphorite of North Carolina are illite and montmorillonite (Rooney and Kerr, 1967); in the phosphorite of the Hawthorn Formation in Beaufort County, South Carolina, the clay minerals include abundant sepiolite and montmorillonite, and minor illite (Heron and Johnson, 1966); in the phosphorite of South Georgia-North Florida, the clay minerals are predominantly montmorillonite and attapulgite (Olson, 1966); and in the phosphorite deposits of the land-pebble district of Florida, the principal clay mineral in the Bone Valley Formation is montmorillonite but the underlying Hawthorn Formation contains some attapulgite in addition to montmorillonite (Altschuler, Cathcart, and Young, 1964).

Iron minerals are also present in all of the phosphorite deposits in small amounts. The iron minerals include pyrite, and the iron oxide minerals--hematite, goethite, limonite, and in the weathered zones in Florida, the iron phosphate minerals, vivianite and dufrenite.

Glauconite, a trace constituent in many of the deposits, is found almost entirely within the phosphate pellets.

Trace amounts of "heavy" minerals--ilmenite, zircon, rutile, staurolite, sillimanite, tourmaline, and several others--are present in most or all of the deposits.

Clinoptilolite, a zeolite mineral, that possibly formed as an alteration of volcanic ash (Rooney and Kerr, 1967) is present in small amounts in the Pungo River Formation of North Carolina, and has been reported in one sample from South Carolina (Heron and Johnson, 1966).

Aluminum phosphate minerals (wavellite and crandallite) are important secondary minerals in the Florida deposits.

Origin

Phosphate pellets are found in the Gulf and Atlantic Coastal Plains of the eastern United States in marine sedimentary rocks of Cretaceous to Recent age. In the Gulf Coastal Plain, phosphatic sediments are known only in rocks of Cretaceous and Paleocene age, whereas in the Atlantic Coastal Plain, phosphatic sedimentary rocks are known from rocks of all ages from Cretaceous to Recent.

Rocks of Cretaceous age contain phosphate pellets only in the southern part of the outcrop belt in Georgia, Alabama, Mississippi, and Texas. In the northern part of the outcrop belt, in New Jersey, Virginia, and Tennessee, and in a part of Texas, the sedimentary rocks contain abundant glauconite, and only trace amounts of phosphate. No economic deposits of phosphorite are known in rocks of Cretaceous age. Rocks of Paleocene age on the Gulf Coast contain abundant glauconite and only minor phosphate.

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Phosphate in rocks of Eocene to Recent age is known only from the Atlantic Coastal Plain. Glauconitic sedimentary rocks are present in the northern states of the Atlantic Coastal Plain from Virginia to New Jersey, and in this area, phosphate pellets are scarce. From North Carolina south to the southern tip of Florida, phosphatic sediments are widespread, and glauconite is present only in minor amounts.

The economic deposits of phosphorite are all structurally controlled. The deposits are in basins that are on the flanks of domes or anticlines that were rising at the time of deposition. Depth of water is evidently an important factor in the deposition of the phosphorites.

All of the deposits are in areas where deposition of clastic material was at a minimum. They are ~~either~~ far from a source of clastic sediment as in south Florida, or ~~are~~ adjacent to very low-lying land masses.

The phosphate pellets in all of the deposits have very similar forms, and all were deposited in marine sediments, except for the deposits in Pleistocene and Recent sediments, and in these rocks, the phosphate particles were derived from older rocks and were redeposited and concentrated in either marine or continental environments.

Phosphate pellets in the surficial materials under the Atlantic Ocean are thought to have been derived from older rocks (Pilkey and Luternauer, 1967).

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During middle Miocene time abundant phosphate was deposited over most of the Atlantic Coastal Plain, but none was deposited on the Gulf Coastal Plain. The geographic distribution of phosphate is consistent with the source of the phosphorus being currents that moved southward along the Atlantic coast. These were cool, temperate waters, different from the waters of late Miocene and the present (Gibson, 1967), and were probably cooler than the northward moving Gulf Stream. The cooler southerly currents, diverted by the rising anticlinal structures of the Coastal Plain (fig. 1), might have been mixed with the warmer Gulf stream, causing phosphate to precipitate.

Pevear (1966) has suggested that the phosphorites of the eastern United States were deposited in an estuarine environment, and it seems likely that the nutrient-laden waters typical of estuaries may have been the loci for the start of precipitation of phosphate. Certainly a part of the land-pebble phosphorite of Florida was deposited in an estuary (Cathcart, 1950). The estuarine environment, however, cannot account for the vast, widespread phosphorite of the middle Miocene throughout the Atlantic Coastal Plain.

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Both Gibson (1967) and Rooney and Kerr (1967) attach great significance in the origin of the phosphorite of North Carolina to clinoptilolite derived from volcanic ash. For example, Rooney and Kerr (1967, p. 747) suggest that: "Widespread ash falls of long duration killed large numbers of marine organisms whose subsequent decay contributed phosphate." Neither report, however gives any data regarding the amount of clinoptilolite. Work by the present writer shows that over the whole deposit clinoptilolite is present in small amounts and is only in the fine fraction (-200 mesh) of the phosphorite. The -200 mesh fraction averages 16 percent, by weight of the total rock, and the amount of cliniptilolite in the -200 mesh fraction (based on X-ray diffraction patterns) ranges from a trace to about 30 percent. The amount of clinoptilolite in the whole rock, therefore, ranges from nil to about 5 percent.

Elsewhere in the Atlantic Coastal Plain, clinoptilolite has been reported only from one sample from South Carolina (Heron and Johnson, 1966). It has not been reported from the offshore deposits in the Atlantic. A 9.0Å peak, present in X-ray diffractometer patterns run by the writer from samples of -200 mesh material from offshore Baja California, may represent clinoptilolite.

It seems likely that the small amount of clinoptilolite in the North Carolina phosphorite deposit is merely coincidental and has no necessary relation to the origin of the phosphorite deposits.

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To briefly recapitulate--phosphorite deposits are restricted to rocks of middle Miocene age and were probably precipitated from sea water in areas of favorable structural positions, that is, in basins on the flanks of anticlines that were rising at the time of deposition. Deposits are present only on the Atlantic Coastal Plain because of southerly moving, cool, oceanic currents that were turbulently mixed with warmer waters around the structural highs. The southerly currents could not have moved into the Gulf Coast area of North America, because of the position of the Floridian plateau, which caused the current to move south and east, away from the Caribbean. This accounts for the absence of phosphate deposits or even occurrences on the Gulf Coast.

The deposits are on the stable shelf or foreland, which was low-lying at the time of deposition, and therefore, was not deluged with large amounts of clastic sediments.

Many of the deposits are economic only because of later reworking and concentration of the phosphate pellets, and all of the deposits show some evidence of reworking.

Prospecting techniques

Phosphorite deposits of the "Florida" type are concealed by variable thicknesses of barren overburden, and prospecting must be by some form of drilling or trenching. Actual prospecting is simple, except that core drilling of unconsolidated sediments requires an experienced driller. Trenching of shallow deposits is not a problem in terms of technique, but deposits that are covered by more than a few feet of overburden probably cannot be trenched. The problem in prospecting is to pick the area that is to be examined.

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A generally favorable area might be picked on the basis of a knowledge of the details of local geology, based on the theory of origin of the deposits. That is, the area is structurally favorable, and the knowledge of paleogeography is such that it is possible that upwelling or laterally moving oceanic currents are known to have been operative during the time the structures were being formed. This area might be a basin on the flank of the rising dome, and in the proper relation to the lateral or upwelling currents, so that it might be restricted enough so that prospecting could be started on a broad pattern that would ensure discovery of a deposit.

If the local geology is not well enough known to predict this type of area, there are certain other techniques that can be used to determine a possibly favorable area.

A traverse of all of the streams can be made to determine if there is any concentration of phosphate particles as bars along the courses of the river. These are the so-called river-pebble deposits, and they are characteristic of all of the Coastal Plain phosphorite deposits of the eastern United States that are covered by thin overburden. The presence of river-pebble deposits may indicate an economic phosphorite deposit under the interstream divides.

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All known marine phosphate deposits contain uranium. The uranium is present in amounts that are large enough to cause radioactive anomalies. Thus, search for deposits of phosphorite can be made with radiation detection equipment. Airborne scintillometers are effective in the detection of the anomalous radiation caused by a phosphorite deposit, provided the deposits crops out. The thickness of overburden sufficient to mask the radiation is only a few feet.

If the deposits are too deeply buried to be detected with surface radiation equipment, gamma-ray logging of drill holes is an effective method of locating possible phosphate deposits. This is the method used on the deposits of North Carolina, which are so deeply buried that there is no surface indication of their presence. There must be some drill holes in the area that can be logged, however. Gamma-ray logs of all test holes (water wells, oil wells, and so on) should be made, or examined, to determine whether there is any indication of anomalous radioactivity.

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Reconnaissance work by the writer and P. F. Fix of the Geological Survey clearly indicated that acid streams that drain phosphatic terrains contain anomalous amounts of uranium in solution, and Odum (1953) showed that these acid streams also contain anomalous amounts of P_2O_5 in solution. Stream sampling may be an effective way to outline a potential area that contains a phosphorite deposit. There are disadvantages, however. The analytical techniques required to determine extremely small amounts of uranium and phosphorus are difficult and require special training. Anomalous uranium may indicate concentrations of uranium minerals rather than phosphate minerals, and anomalous phosphate contents may indicate large areas of sedimentary rock that contain small amounts of phosphate nodules, rather than a phosphorite deposit. In either case, anomalies must be followed by other prospecting to determine the source of the phosphorus and uranium. The technique will be effective only in areas of acid groundwaters, because the phosphate mineral, that contains the uranium, is soluble only in acid solutions.

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The phosphorite deposits of the "Florida" type do not have the unique suite of rock types (black shale and chert) that are associated with marine phosphorites of the geosynclinal type. The phosphatic sedimentary rocks that form the source of the phosphorite deposits are all marls or impure (sandy and clayey) limestones. Some of the deposits contain beds of diatomaceous earth (North Carolina, USA, and Sechura, Peru), and the presence of diatomaceous material in the section may be a clue to the location of the deposits. The phosphorite deposits are always in sections that are thin--the total thickness of the rocks that contain phosphate grains seldom is measured in more than scores or hundreds of feet, while non-phosphatic sections of the same age may measure thousands of feet. Thus, prospecting in areas where the beds are very thick might be unproductive, and prospecting should be restricted to areas where the beds are thin.

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