1972

Stratigraphy, genesis, and economic potential of the southern part of the Florida land-pebble phosphate field

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STRATIGRAPHY, GENESIS, AND ECONOMIC POTENTIAL OF THE SOUTHERN PART OF THE FLORIDA LAND-PEBBLE PHOSPHATE FIELD

by

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A DISSERTATION

Presented to the Faculty of the Graduate School of the

UNIVERSITY OF MISSOURI-ROLLA

In Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

in

GEOLOGY

1972

Approved by:

Advisor

ABSTRACT

The important and highly productive Florida land-pebble phosphate field is located in west central peninsular Florida in portions of Hillsborough, Polk, Hardee, and Manatee counties. The Pine Level phosphate area, described in detail in this report, is south of the previously known and mined deposits and occurs in portions of Manatee, Sarasota, and De Soto counties. Results of the current geologic study of the Pine Level phosphate deposit and the evaluation of the overall potential of this southern part of the land-pebble field are presented.

The entire southern part of the phosphate field is underlain by more than 15,000 feet of Cretaceous and Tertiary carbonate strata. Phosphate deposits are confined to a thin clastic veneer of sediments that overlie the carbonate strata, and include the upper clastic member of the Hawthorn Formation of Miocene age, the Bone Valley Formation of Pliocene age, and unnamed strata of Pleistocene age. The total thickness of the phosphatic veneer is somewhat more than 100 feet.

The Pine Level phosphate deposit, characteristic of the heretofore undescribed phosphate deposits in the southern part of the Florida land-pebble phosphate field, is compared with the deposits of the main producing area in the northern part of the field. The Pine Level deposit differs markedly from the deposits in the main producing district. The differences include the more localized and erratic distribution of mineable phosphate concentrations, inclusion of portions of the upper clastic member of the Hawthorn Formation within the mineable unit, origin and age of the deposits, significant contrasts in pebble and concentrate quality and quantity related to the mode of origin, the lack of development of the aluminum phosphate zone, and the enrichment of the contained carbonate

fluorapatite by replacement processes.

Very gentle scarps, representing Pleistocene sea standstills, divide the land-pebble field into several physiographic subdivisions. The physiographic provinces of the land-pebble field and the origin of the Pine Level deposit are related to three, and possibly four, Pleistocene interglacial marine advances that have reworked and recycled the apatite particles of the Bone Valley and Hawthorn Formations into new lower-level Pleistocene deposits that surround and flank buried remnant paleo-islands of the Bone Valley Formation.

Field relations, chemical analyses and petrographic studies of a series of apatite pebbles ranging from deeply buried, low-grade, black, impure apatite to shallow, high-grade, relatively pure, white apatite, indicates that high-grade white apatite in the Pine Level deposit is derived from initial low-grade black apatite. The alteration occurs by progressive replacement of mineral impurities within the black apatite as erosion continually reduces the depth of burial and the black apatite is subjected to increasingly acidic and oxidizing ground water activity.

Simplified evaluation criteria that serve to identify economically valuable deposits of the Pine Level phosphate type are described. These criteria are easily and readily determinable by the exploration geologist or engineer in search of such deposits.

The slimes (clay) content of the Pine Level phosphate deposit is much lower than in the deposits of the main producing area and provides the basis for a new method of land reclamation that may eliminate the expensive and difficult conventional method of slimes disposal in permanent storage reservoirs.

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I. INTRODUCTION

A. Outline of the Problem

The phosphate occurrences and deposits of Manatee, Hardee, Sarasota, De Soto, and Charlotte counties, Florida, are the subject matter of this dissertation. The general area is south of the main producing district of the important Florida land-pebble phosphate field, but is partly included within the known extent of the southern part of the field. Phosphate exploratory work conducted in the area by the author resulted in the discovery of a heretofore unreported type of phosphate rock deposit in the Pine Level area of northwestern De Soto County and the adjacent portion of Manatee County.

It was evident at an early stage of the exploratory work that the occurrences of phosphate in this southern area differed markedly from the deposits of the main producing district. The major differences exhibited by these occurrences are:

1. the unexpected distribution of phosphatic units within a much thicker portion of the stratigraphic section;

2. the lack of characteristic widespread blanket-type continuity of the deposits;

3. sudden inexplicable changes in thickness or stratigraphic position of certain phosphatic strata within short distances;

4. the variable, and often marginal, quality of the phosphate rock in many of the samples;

5. common deleterious carbonate contamination of phosphatic sand strata by abundant shell fragments, limestone pebbles, or thin beds of limestone or dolomite; and,

6. the apparent absence or decrease of the very important

weathering and leaching processes that have altered the phosphatic rocks of the main producing district.

In short, these southern deposits and occurrences differ notably from the deposits in the northern portion of the land-pebble field. The geological events that led to their formation are evidently different.

B. Purpose of This Study

The purpose of this study is:

1. to present the geologic results of a detailed investigation of a previously unreported type of phosphate deposit, herein designated the Pine Level deposit, south of the main producing district of the Florida land-pebble phosphate field;

2. to evaluate the detailed geologic data and suggest the mode of origin of this unique phosphate deposit;

3. to examine the effects of weathering and leaching of selected phosphate rock samples and define their relationships to the economically valuable Pine Level phosphate deposit;

4. to compare the origin and geologic history of this deposit with the main producing district of the land-pebble field and determine the significant geologic events responsible for the differences in the phosphate occurrences of the two areas;

5. to indicate whether other deposits of the Pine Level type are present in the southern part of the land-pebble field;

6. to indicate some of the economic factors which must be considered in the evaluation of phosphate deposits of the Pine Level type;

7. to offer suggestions for future geologic exploration in the southern part of the land-pebble field including a discussion of the

relative favorability of the different physiographic subdivisions; and,

8. to indicate the ecological and land reclamation advantages of a deposit of the Pine Level type and to relate these advantages to the grain size distribution and sedimentation characteristics of the clastic components of the mineable phosphate strata.

C. Scope and Methods of This Study

During the exploration period a total of 1,644 shallow exploration core holes, varying from about 25 to 100 feet in depth, were drilled on 102,000 acres in the Pine Level and adjacent areas. A descriptive lithologic log of each drill hole was prepared, and about 2,200 phosphatic intervals in the drill cores were sampled. These samples were all laboratory processed, and several different screened fractions of the recovered phosphate rock from each sample were analyzed for phosphate and several other important constituents.

About 1,800 of the total samples and 1,308 of the total drill holes are concentrated in the Pine Level area. These data were part of the intensive exploration effort to delineate and determine mineable ore reserves, to justify possible acquisition costs, and to obtain geologic information for subsequent engineering studies. The geologic data provided by this intensive phase of the exploration program is the basis for this detailed study of the geology of the Pine Level deposit. More general remarks regarding the entire southern portion of the land-pebble field are mainly based on interpretations of the geologic data from the other 336 drill holes.

This study consisted of the following phases:

1. A review of the geology, mineralogy, history, origin, and

production methods of the main phosphate producing district and a brief compilation of this review to serve as a background framework against which the detailed geologic data of the Pine Level area may be compared.

2. Correlation of the stratigraphic units in the Pine Level area from an interpretation of the 1,308 lithologic logs and sample data.

3. Study of the physiography of the area and the relationship of certain physiographic features to the geological events that resulted in the Pine Level deposit.

4. Interpretation of the Pleistocene paleogeography of the Pine Level area and the relationship of certain of these features to the genesis of the deposit.

5. Chemical, geochemical, and petrographic studies of selected phosphate rock samples to determine the nature, extent, and history of weathering of the phosphate rock and its relationship to the formation of mineable phosphate deposits of this type.

6. Study and interpretation of the engineering and economic data of the Pine Level deposit and the correlation of these data with various determinable geologic features that may serve as simple guides in the continued exploration for additional deposits of the Pine Level type.

7. Study of the major ecological and land reclamation problem of the phosphate industry, and the relationship of unique geologic features of the Pine Level deposit that may be advantageous in the solution or mitigation of this serious problem.

8. Preparation of selected maps, cross sections, and tables to effectively depict the salient and most important geologic features of the Pine Level deposit.

D. General Geography

1. The Florida Land-Pebble Field

The Florida land-pebble phosphate field is in the west central portion of the Florida peninsula in Polk, Hillsborough, Hardee, and Manatee counties (Fig. 1). All phosphate rock production to date has been localized in southwestern Polk County and the adjacent southeastern portion of Hillsborough County.

The producing area is approximately 50 miles by rail from the port of Tampa, on the Gulf Coast, where special tidewater terminals are maintained for loading phosphate rock for seaborne shipments. The entire area is easily accessible by an extensive network of federal, state, and county roads. The area is drained to the south by the Peace River and a major tributary, Horse Creek; to the southwest by the Manatee River; and to the west by the Alafia River.

2. The Pine Level Area

The Pine Level area is south of the previously known extent of the land-pebble field and encompasses about 100 square miles in northwestern De Soto County, southeastern Manatee County, and an adjoining part of Sarasota County (Fig. 1). Florida State Highway 72 from Sarasota passes through the southern part of the area, and Florida State Highway 70 from Tampa crosses the north part. These two roads are connected by several north-south county roads within the area. United States Highway 17, connecting Punta Gorda and Bartow, passes a few miles to the east and joins highways 70 and 72 at Arcadia.

Ranching is the principal commercial activity of the area. A few ranchers maintain citrus groves, but citrus production is not an important factor in the local economy. Arcadia, the county seat of

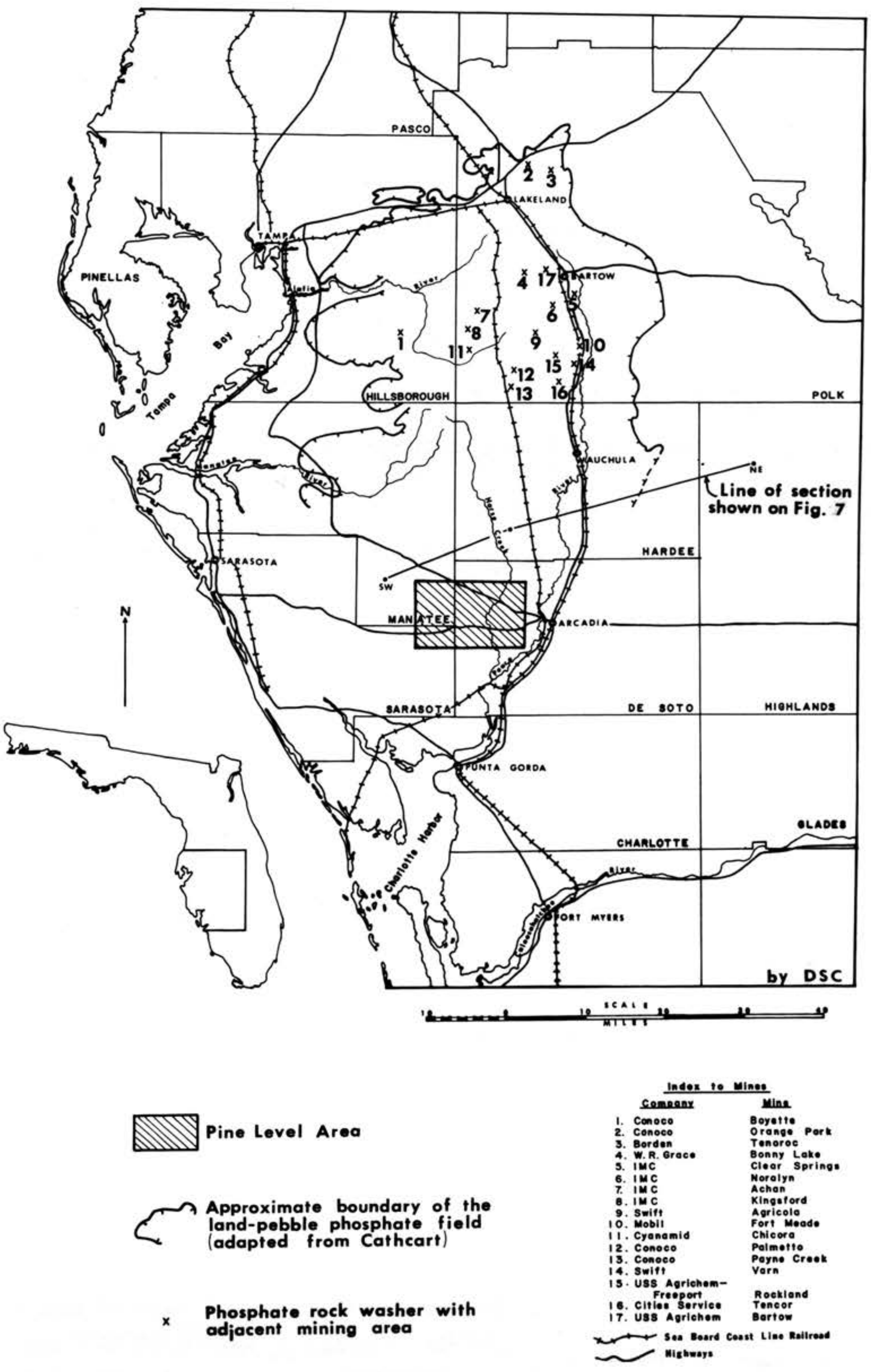


Figure 1. Index map of the west central Florida peninsula.

De Soto County, is the commercial center and largest city in the vicinity with a population of about 6,000.

The climate is subtropical with a mean temperature of about 72° F. Below freezing temperatures occasionally occur during the winter. The average annual rainfall is approximately 55 inches. About 60 percent of the yearly precipitation occurs between June 1 and September 30 during thunder showers or occasional hurricanes.

The eastern part of the area is drained by Horse Creek and its tributaries, and the western part by Big Slough Canal. The stream valleys are generally shallow with gradual slopes to the interstream divides, and are characterized by swamps or marshes with streams that readily overflow their poorly defined channels during the rainy season. Cypress and live oak are common trees along the streams. The interstream areas are dotted by small depressions called bay heads, heads, or ponds, and are sparsely covered by longleaf pine, with abundant palmetto and wire grass as undergrowth. Elevations in the area range from about 30 to 75 feet.

E. Summary of Previous Work

No detailed investigations of the phosphate deposits of the Pine Level area have been made prior to the present study. However, several short stratigraphic and ground water studies include all or portions of the area. Some of the more informative papers are described below.

The early paper by Matson and Sanford (1913) contains general information on De Soto County. A report on the geology of Florida by Cooke and Mossom (1929) also contains references to the general geology of the area. Important papers on artesian water in peninsular Florida, by Stringfield, were published in 1933 and 1936. A report on Pleistocene shorelines by MacNeil (1950) contains references to the general area. Bergendahl (1956) refers to the general geology and phosphate reserves of De Soto County in an important paper. The ground water resources and stratigraphy of the Manatee County portion of the area are discussed by Peek (1958). Puri and Vernon (1964) include references to the stratigraphy and paleontology of the general area. The very important recent physiographic study by White (1970) contains important references to the Pine Level area.

The geology, mineralogy, or descriptions of the phosphate deposits of the northern portion of the land-pebble field have been reported in more or less detail in the papers mentioned below.

The term Bone Valley was introduced by Matson and Clapp (1909) in a paper discussing commercial phosphate mining activities in Polk County. Matson (1915) described the phosphate deposits of Florida, including the land-pebble field. The potential phosphate reserves of Florida are discussed by Mansfield (1942). Altschuler, Cisney, and Barlow (1952) conducted x-ray studies of sedimentary apatite from the land-pebble field; and Altschuler, Jaffe, and Cuttita (1956) reported on the occurrence of uranium in the aluminum phosphate zone of the Bone Valley Formation. Cathcart (1956) summarized the distribution of uranium in the calcium phosphate zone of the land-pebble field while Altschuler, Clarke, and Young (1958) investigated the geochemistry of uranium in the phosphate deposits. Cathcart and McGreevy (1959) reported on the results of wide-spaced exploratory drilling conducted by the U. S. Geological Survey in 1953. The most important and detailed studies of the phosphate deposits of the land-pebble field have been published by Cathcart (1963a, 1963b, 1963c, 1964, 1966).

Specific references are made at appropriate places in the text to additional pertinent publications that are listed in the bibliography.

F. Glossary of Specialized Florida Phosphate Industry Terms

The Florida phosphate deposits, as may be seen in the previous section of this paper, have received scant attention from the more renowned economic geologists of earlier times. This is undoubtedly a reflection of the widespread extent and shallow depth of burial of the phosphate deposits that promoted, in the early years, their simple and easy discovery. Exploration, development, and even mining, were all generally conducted by persons with little or no geological or engineering training. As a result of this early isolation from the mainstream of developments in economic geology a unique colloquial vocabulary evolved. This terminology is still in standard use within the Florida phosphate industry.

Though it is an inconvenience to the general reader to use this specialized terminology, all of the laboratory data are reported in these terms, and because this paper will be most useful to the Florida phosphate industry, it is necessary that these terms be defined here for use at appropriate places in the subsequent discussion.

1. Mining Terms

Overburden - includes all of the covering strata that must be removed prior to actual mining of the underlying phosphate deposit.

Aluminum Phosphate Zone - an irregular zone of leaching characterized by a white color and the presence of aluminum phosphate minerals. The zone is included in the overburden.

Matrix - that part of the stratigraphic section that can be mined. It is synonymous with "ore" in the usual sense of that word. Often used more freely, it designates a highly phosphatic sand unit, even though the unit has not actually been determined to be ore in the strict sense.

2. Processing Terms

Pebble - a coarse phosphate product, +14 mesh (+1.17 mm) in size. In this paper, "pebble" denotes phosphate particles that are coarser than this mesh size.

Feed - the -14/+150 mesh (-1.17 to 0.104 mm) portion of the matrix that must be treated by flotation methods to separate the phosphate particles from admixed quartz sand.

Concentrate - the fine phosphate product, -14/+150 mesh, recovered from the feed by flotation. In this paper the term "pellet" will be used to denote the phosphate particles in this size range, and the term "concentrate" will be reserved for use in describing a marketable product of this size range.

Phosphate Rock - various combinations of the pebble and concentrate products, depending upon customer requirements, are marketed as "phosphate rock".

Tailings - the -14/+150 mesh quartz sand fraction of the feed. This material has no economic value and is disposed of in previously mined areas.

Slime - the slime (or slimes) is that portion of the matrix that is -150 mesh (-0.104 mm) in size. It is also a waste product and presents a very serious and expensive disposal problem.

3. Chemical Terms

BPL - is bone phosphate of lime or tricalcium phosphate, $Ca_3(PO_4)_2$, and is equal to percent P_2O_5 x 2.185. All industrial analyses in the Florida phosphate field are reported as percent BPL.

I & A - is the combined analysis of iron oxide (Fe_2O_3) and aluminum oxide (Al_2O_3). Most industrial analyses report these combined oxides as percent I & A.

Insoluble Residue or Insol - is the acid insoluble residue remaining after digestion of a phosphate rock sample in acid by a standard industry procedure. Generally the percent insoluble residue is very near the actual SiO_2 content.

G. Acknowledgments

The original exploration program was conducted under the supervision of Dr. C. N. Holmes; Manager, Minerals Division; Phillips Petroleum Company. His encouragement and direction contributed to the success of that phase of the project. The occasional and timely assistance of other company employees was also most helpful at that time. Specific credit must be given to Donald E. Fryhofer, William J. Rice, and Horacio A. Franco.

This interpretive geologic and petrographic study was conducted in the laboratories of the Geology Department of the University of Missouri-Rolla. Acknowledgment is made to the committee members and to my advisor, Dr. Paul D. Proctor, for direction and assistance given.

Lastly, the deepest appreciation is expressed to Phillips Petroleum Company for permission to use the information presented in this paper, especially for the use of the extensive drill hole data.

II. REVIEW OF THE FLORIDA LAND-PEBBLE FIELD

A. General Statement

The Florida land-pebble field is one of the great mining districts of the world. The district annually produces approximately one-fourth of the world's phosphate rock requirements from seventeen separate producing operations in Polk and Hillsborough counties (Fig. 1). Production statistics are shown in Table I. The figures shown in the table include about 4,000,000 tons per year produced from north Florida and North Carolina since 1966.

Table I. Phosphate Rock Production Statistics for Florida and North Carolina (from Minerals Yearbook, U. S. Bureau of Mines).

Year	Production (tons)	Value (dollars)	Value/ton	% of U. S. Production	% of World Production
1969	28,835,000	155,197,000	$5.38	76	--
1968	29,571,000	173,190,000	5.86	72	32
1967	29,796,000	193,283,000	6.49	75	35
1966	28,043,000	184,075,000	6.56	72	29
1965	21,388,000	138,744,000	6.49	73	25
1964	16,252,000	115,513,000	7.11	71	28
1963	14,377,000	100,749,000	7.01	72	29
1962	13,624,000	93,669,000	6.88	70	29
1961	12,667,000	88,395,000	6.98	68	28

The industry employs several thousand people and supports an extensive attendant business providing mining equipment, repair facilities, engineering services, transportation, and operating necessities. The industry is an important factor in the economy of Florida.

A brief description of the general geology, mineralogy, chemistry, origin, and production practices of the deposits in the main production area is presented here to provide a background against which pertinent geologic features of the Pine Level deposit may be compared in subsequent sections of this paper.

B. Structure and Geologic Setting

Both the Pine Level area and the land-pebble field are within the Florida Peninsula sedimentary province of the eastern Gulf of Mexico sedimentary basin (Pressler, 1947, p. 1851). The Province is characterized by a very thick, predominately carbonate sedimentary sequence overlain by a thin clastic cover of late Tertiary and Quaternary age. The important phosphate deposits are confined to this thin veneer of clastic sediments.

Formations in the area dip gently southward a few feet per mile from the Ocala uplift toward the South Florida embayment. Figure 2, reproduced from Puri and Vernon (1964), shows the relationship of the land-pebble field and the Pine Level area to the major structural and sedimentary features of Florida.

C. General Geology

The land surface in the main producing area of Polk and Hillsborough counties is a gently rolling upland about 80 to over 150 feet above sea level. Pleistocene sand mantles the greater part of the area and unconformably overlies the Pliocene Bone Valley Formation, which, in turn, unconformably overlies the Miocene Hawthorn Formation. The geologic structure of the area, as noted, is relatively simple. The formations dip very gently toward the south away from the Ocala uplift.

The Hawthorn Formation underlies the area at shallow depths and consists of tan, cream, or white, sandy, argillaceous, phosphatic limestone or dolomitic limestone. The top few feet of the limestone is locally altered to a phosphate-rich, calcareous clay residuum. Very locally a few feet of an upper noncalcareous clastic member overlies the limestone (Cathcart, 1963c, p. 12; 1964, p. 13; 1966, p. 11). It

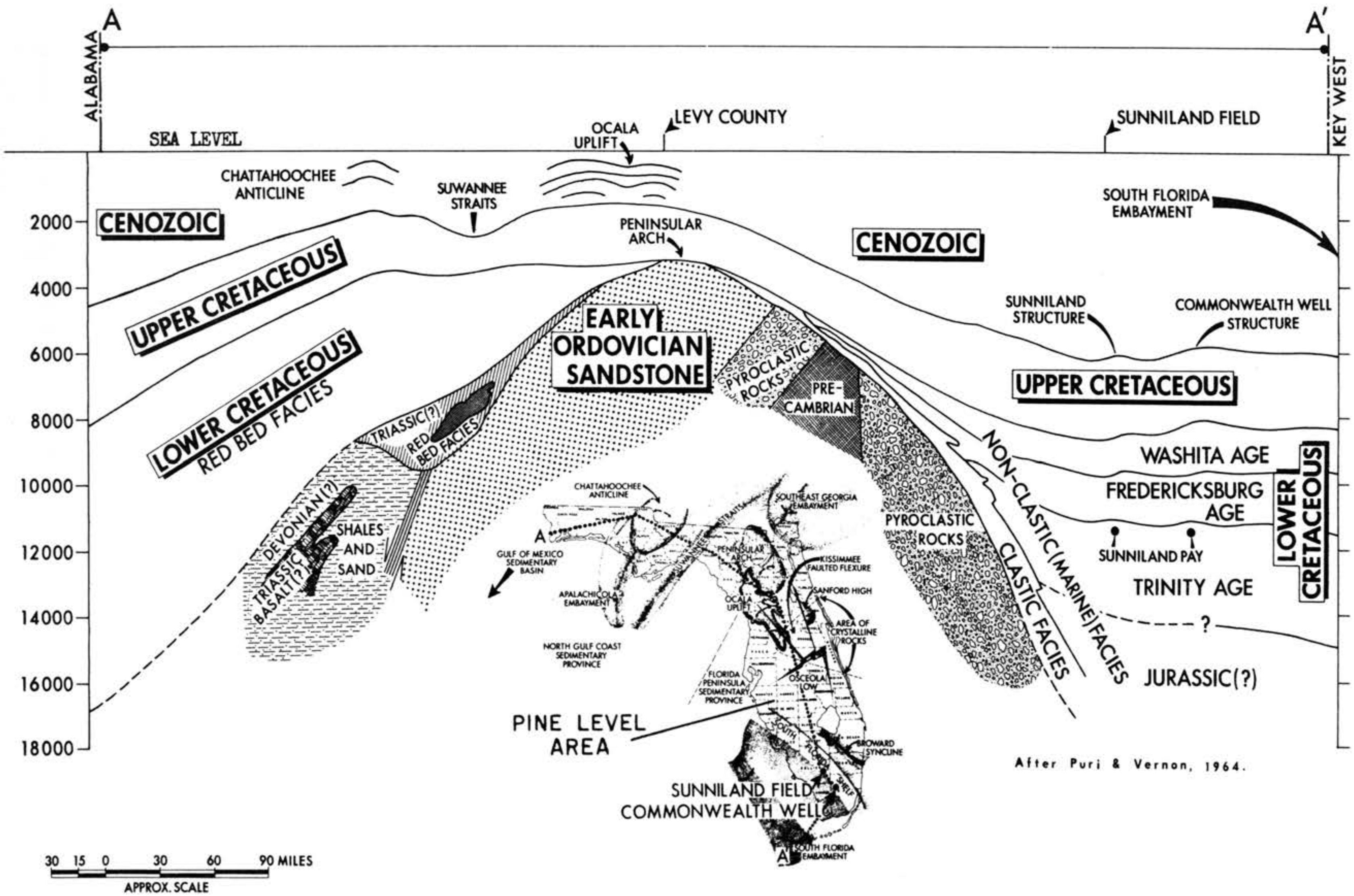


Figure 2. Principal geologic structures of Florida.

consists of a dark grayish green, olive-green, yellowish green, or brownish-green clayey sand that contains traces to moderate amounts of brown or black phosphate pellets.

The Bone Valley Formation consists of two conformable members of variable thickness: a lower phosphatic unit and an upper, clayey, very slightly phosphatic sand member.

The overlying Pleistocene deposits are loose, incoherent, non-clayey sand of quite variable thickness. Local sand-filled channels are present that have eroded and removed all of the underlying Bone Valley Formation.

The mineable phosphate bed, or matrix, may consist of portions of either, or both, of the lower member of the Bone Valley Formation and the residuum of the underlying Hawthorn Formation. Where the aluminum phosphate zone is absent or poorly developed the matrix may include all of the lower member of the formation along with the underlying Hawthorn residuum, if it is present. Where the zone is well developed the upper portion or, perhaps, most of the lower member may be unmineable. Where it is intensely developed the entire phosphatic section, including both the lower member of the Bone Valley and the Hawthorn residuum, may be unmineable. The matrix is thus seen to be confined to a stratigraphic position immediately adjacent to the Hawthorn-Bone Valley unconformity; and may include part or all of the lower member of the Bone Valley Formation; part or all of the Hawthorn residuum; or a combination of the residuum and part or all of the lower member of the Bone Valley. The greater bulk of the phosphate is contained within the lower member of the Bone Valley Formation.

The matrix unit in the main producing area is fairly continuous, relatively flat-lying, unconsolidated, generally about 10 to 25 feet thick, and consists of fine to coarse recoverable phosphate particles (pebbles and pellets) mixed with quartz sand and clay which contains phosphate particles of micron and submicron size. The matrix normally consists of roughly equal parts of recoverable phosphate, quartz sand, and interstitial clay. The phosphate content of the clay fraction is not recoverable by present processing methods.

The recoverable phosphate particles are rounded, oval-shaped, somewhat flattened, shiny, structureless, highly polished, white, gray, brown, or black particles of sedimentary apatite ranging in size from about $\frac{1}{2}$ inch in diameter to very fine sand.

D. Mineralogy

The mineral assemblage of the matrix is basically simple and consists, as noted above of quartz sand, interstitial clay, and the phosphate mineral carbonate-fluorapatite (Altschuler *et al.*, 1953). The apatite particles are aggregates of micron-sized crystals. The index of refraction ranges from 1.575 to 1.625 and is typically about 1.605. The mineral appears isotropic in thin section, but fibrous varieties show slight birefringence, positive elongation, and parallel extinction. The specific gravity of pure apatite particles is 2.96 to 2.99.

The apatite is demonstrably smaller in unit-cell dimensions than igneous fluorapatite. Structural differences revealed by x-ray studies are best explained by chemical variations which can be expressed by the formula $Ca_{10}(PO_4CO_3)_6F_{2-3}$ (Altschuler *et al.*, 1953).

The interstitial clay in the matrix is mainly iron-rich montmorillonite but minor attapulgite has been reported (Berman, 1953).

Altschuler et al. (1956, p. 496) indicate that the clay in the upper part of the Hawthorn Limestone, normally montmorillonite, has been transformed to attapulgite in areas where the limestone has been irregularly dolomitized.

The phosphate particles in the aluminum phosphate zone are white, vesicular, friable, light in weight and consist of the secondary aluminum phosphate minerals wavellite, $Al_3(PO_4)_2(OH)_3 \cdot 5\ H_2O$; crandallite, $CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$; and, locally, millisite, $(NaK)CaAl_6(PO_4)_4(OH)_9 \cdot 3H_2O$ (Altschuler et al., 1956, p. 496). The interstitial montmorillonite has been converted to kaolinite.

E. Chemical Composition of the Phosphate Rock

Gulbrandsen (1969, p. 370) uses the basic formula $Ca_5(PO_4)_3F$ for marine apatite, but notes that the formula is modified by significant substitutions. Carbonate substitution for phosphate (PO_4) is ubiquitous and occurs in amounts that commonly range from a few tenths of a percent to several percent equivalent CO_2 (Altschuler et al., 1952; Altschuler et al., 1958). Paired substitution of sodium and sulfate for calcium and phosphate, respectively, appears to occur also in about the same magnitude as carbonate substitution (Gulbrandsen, 1960). Fluorine is generally present in amount greater than the apparent structural requirement, and the excess is probably combined with carbonate in substitution for phosphate (Gulbrandsen, 1969). Characteristic lesser substitutes are strontium, rare earths, uranium, and thorium for calcium.

The typical analytical variability of marketable phosphate rock from the land-pebble field, courtesy of Wellman-Lord, Inc., Lakeland, Florida, is shown below:

Constituent	Percent
P_2O_5	30-35
CaO	46-50
CaO/P_2O_5 ratio	1.45-1.55
F	3.3-4.0
Fe_2O_3	0.7-2.6
Al_2O_3	0.7-2.6
Na_2O	0.5-0.6
K_2O	0.5-0.6
SiO_2	5-10
MgO	0.20-0.50
Cl	0.003-0.03
CO_2	1.5-4.4
Organic Carbon	0.25-0.40

F. Mineral Contaminants

The chemical analysis indicates a variety of constituents are present that are not accounted for by substitutions. These include Fe_2O_3, Al_2O_3, K_2O, SiO_2, MgO, Cl, and organic carbon. These impurities are contained in other minerals that form surface coatings and inclusions on and within the apatite particles.

These minerals include various clays, iron and aluminum oxides and phosphates, limestone, dolomite, pyrite or marcasite, carbon, and quartz. These minerals usually occur as microcrystalline aggregates within similar apatite aggregates, and study of natural marine apatites has been plagued by the extreme difficulty of separating the apatite from the intimately mixed impurities. Interpretations based on chemical determinations of composition are always uncertain because of these impurities (Gulbrandsen, 1969, p. 370).

G. Origin of the Deposits

The source of the high phosphatic content of the lower member of the Bone Valley Formation begins with the Hawthorn-Bone Valley erosional interval. Erosion during this period removed all but a few remnants of the upper clastic member of the Hawthorn Formation (Cathcart, 1964, p. 41). This exposed the underlying limestone member to chemical weathering which formed an irregular karst surface with a residual calcareous clay mantle containing abundant pellets of phosphate and secondary phosphatized limestone pebbles. Marine transgression during Pliocene time dolomitized the weathered limestone, and reworked the clastic residuum into the Bone Valley Formation, at the same time adding unknown amounts of quartz, clay, and phosphate (Altschuler et al., 1956, p. 496). According to Cathcart (1964, p. 41) "Phosphate was precipitated, limestone fragments were phosphatized, and the phosphate in the residual mantle was enriched, sorted, and concentrated". The deposition of the lower member was suceeded without interruption, except locally at the northern edge of the land-pebble field, by the upper member.

Another period of erosion and weathering occurred between the retreat of the Bone Valley sea and the deposition of the overlying loose sand of the Pleistocene.

Critical points in the above interpretation that are stressed for future discussion are: (1) the upper clastic member of the Hawthorn Formation did not contribute any detrital phosphate to the Bone Valley deposits, (2) the phosphate pellets are derived from the reworked residuum of the Hawthorn Limestone, (3) the pebbles in the deposits are phosphatized Hawthorn limestone pebbles, and (4) marine apatite was actively precipitated in the Bone Valley sea and it enriched the previously existing apatite particles and phosphatized limestone pebbles.

Evidence in the Pine Level area suggests alternative conclusions.

H. Effects of Weathering

At least two major periods of weathering have altered the phosphatic sediments of the land-pebble field (Cathcart, 1966, p. 23). The first, during the Hawthorn-Bone Valley erosion interval, formed the phosphatic rich calcareous clay residuum on top of the Hawthorn Limestone. A later period of intense lateritic weathering caused the development of the aluminum phosphate zone with the alteration of apatite to the aluminum phosphate minerals and alteration of montmorillonite to kaolinite (Altschuler et al., 1956).

The weathering was accomplished by downward percolating acid ground water. The alteration stopped at the water table or at impervious clay beds. Therefore, the base of the alteration is at different stratigraphic positions throughout the area. In general, the alteration is most intense in areas of thinnest cover, such as in the Alafia and Peace River drainage basins; and is poorly developed in interstream areas with thicker cover. Cathcart notes (1966, p. 24) that the alteration of montmorillonite to kaolinite releases MgO, and suggests that the dolomitization of the top of the Hawthorn Limestone took place during this weathering period.

It has been pointed out that the geochemistry, mineralogy, and petrology of the alteration processes resulting in the formation of the aluminum phosphate minerals have been studied in some detail. The starting point in all of these studies is the relatively high grade apatite of the matrix. Did the downward leaching process also significantly alter the apatite of the underlying matrix? Was it initially a relatively low grade apatite with abundant mineral contaminants that were partially removed by lessened but continued activity of the same downward leaching that formed the aluminum phosphate zone? Was the enrichment of the apatite particles in the matrix unrelated to precipitation of apatite in the Bone Valley sea as suggested by Cathcart? Evidence from the Pine Level area bearing on these questions will be discussed later in this paper.

I. Mining Procedure

The Florida phosphate industry, because of the shallow depth of the phosphate deposits, the lithologic character, and other geologic features of the phosphate deposits, utilizes large-scale earth-moving production techniques in the mining operations. The overburden is stripped by large walking draglines equipped with buckets ranging in size from 16 to 42 cubic yards. The overburden, normally 20 to 50 feet thick, is dumped as a linear ridge in the adjacent, previously mined cut. The width of a mining cut depends on the boom length of the dragline, but is normally about 200 feet wide. The length of the cut is dependent on the distribution of the matrix and the property boundaries, but commonly may be a mile or more. After a suitable area of matrix is uncovered, it is immediately dug by the dragline and deposited at a pit sump on top of the bench near the dragline. Here the matrix is slurried to about 25 percent solids by hydraulic monitors, and pumped in 16 to 20 inch lines to the washing and flotation plant for recovery of the contained phosphate. The dragline continues advancing along the cut until the pit sump can no longer be reached. At this point the pit sump is moved ahead, and mining of the cut then continues. Matrix pumping lines several miles in length are common.

J. Processing Methods

At the treatment plant the matrix slurry is passed over a series of 14 mesh vibrating screens. The +14 mesh material obtained is all marketable phosphate pebble. The remaining matrix slurry is deslimed at 150 mesh in a series of cyclones. The cyclone overflow contains the -150 mesh slimes which consist mainly of montmorillonite clay, but often contain some clay-size phosphate as well as an amount of very fine sand and silt size particles. The slime slurry is pumped to a specially constructed storage area for disposal.

The cyclone underflow contains the -14/+150 mesh deslimed flotation feed. The feed is dewatered, conditioned for flotation, and the marketable concentrate recovered in a two-step flotation process. Variations in the processing techniques used by the different companies have been recently discussed by Aparo (1970). The waste sand tailings, left after the phosphate has been removed, are pumped back into previously mined cuts where they are utilized in land reclamation. All of the operating companies routinely reclaim mined areas.

III. PHYSIOGRAPHY OF THE LAND-PEBBLE FIELD AND THE PINE LEVEL AREA

A. Pleistocene Shorelines

The Florida peninsula and the land-pebble field have been subjected to repeated inundations by different stands of the sea during the Pleistocene interglacial stages. A number of ancient shoreline terraces associated with these former sea standstills have been recognized. Different investigators have assigned different elevations and ages to some of them. Table II summarizes some of the interpretations that have been presented to date.

The Florida peninsula is underlain by limestone. This has been dissolved and has resulted in differential sagging of the overlying surface. Sellards (1914), using data on flow of large springs and the dissolved mineral content of their waters, estimated that the surface of central peninsular Florida is being lowered by solution at an average rate of one foot in 5,000 or 6,000 years.

The older, higher shorelines have been subjected to a long period of erosional dissection, coupled with underlying limestone solution, and are difficult to recognize and correlate in the field. The use of key contour lines on topographic maps to depict them may be significantly in error in areas of considerable sagging. The younger, lower, more recent shorelines are more readily recognized--particularly in areas underlain by clastic rocks where subsurface solution has not been so active.

Inasmuch as several higher ridges in Polk County slightly exceed 150 feet in elevation, it can be concluded that the entire land-pebble field was covered by the Coharie sea, and all but the small ridge areas were covered during the Okefenokee advance. The Wicomico advance covered

Table II. Marine Terraces in Florida.

Terrace	Elevation	Age
	After Cooke (1945)	
Brandywine	270 feet	Aftonian
Coharie	215 feet	Yarmouth
Sunderland	170 feet	Yarmouth
Wicomico	100 feet	Sangamon
Penholoway	70 feet	Sangamon
Talbot	42 feet	Sangamon
Pamlico	25 feet	Wisconsin
	After MacNeil (1950)	
Okefenokee	150 feet	Yarmouth
Wicomico	100 feet	Sangamon
Pamlico	25 to 35 feet	Wisconsin
Silver Bluff	8 to 10 feet	Recent
	After Vernon (1951)	
Coharie	220 feet	Aftonian
Okefenokee	150 feet	Yarmouth
Wicomico	100 to 105 feet	Sangamon
Pamlico	25 to 30 feet	Wisconsin
	After Puri & Vernon (1964)	
Erosion		Nebraskan Glacial
Coharie	220 feet	Aftonian Interglacial
Erosion		Kansan Glacial
Okefenokee	150 feet	Yarmouth Interglacial
Erosion		Illinoian Glacial
Wicomico	100 feet	Sangamon Interglacial
Erosion		Early Wisconsin Stadial
Pamlico	30 feet	Peorian Interstadial
Erosion		Late Wisconsin Stadial
Silver Bluff	8 feet	Late Wisconsin Interstadial
	After Alt & Brooks (1965)	
	215 to 250 feet	Upper Miocene
	90 to 100 feet	Pliocene
Insignificant Stand	70 to 80 feet	Pliocene or Pleistocene
Insignificant Stand	45 to 55 feet	Pliocene or Pleistocene
	25 to 30 feet	Pleistocene

the Pine Level area but not the northern portion of the land pebble field. The Pamlico sea probably reached the extreme southwestern corner of the Pine Level area.

B. Physiographic Subdivisions

Figure 3 shows that the land-pebble field is included within portions of the Polk Upland, and the De Soto Plain; and the Pine Level area occupies portions of the De Soto Plain, a northwestern continuation of the Caloosahatchee Incline, and the Gulf Coastal Lowlands.

1. Polk Upland

The ground surface in the Polk Upland, except for the somewhat higher Lakeland and Lake Henry Ridges, generally ranges between 100 and 130 feet in elevation. An inconspicuous but persistent south-facing scarp separates the Polk Upland from the De Soto Plain on the south. The toe of the scarp is some 80 to 90 feet in elevation. The crest is somewhat more variable in elevation, but is generally slightly above 100 feet.

The Bone Valley Formation underlies a large part of the Polk Upland. Its siliceous character has hindered karst development and the effects of solution are not as intense as they are throughout much of the Florida peninsula. There is much better development of surface streams in the Polk Upland. The Peace, Manatee and Alafia Rivers all head in the Polk Upland with widely branching tributaries. Topographic dissection in the Upland generally amounts to some fifty feet.

2. De Soto Plain

The northern edge of the De Soto Plain is at the foot of the scarp that forms the south boundary of the Polk Upland. The southern edge

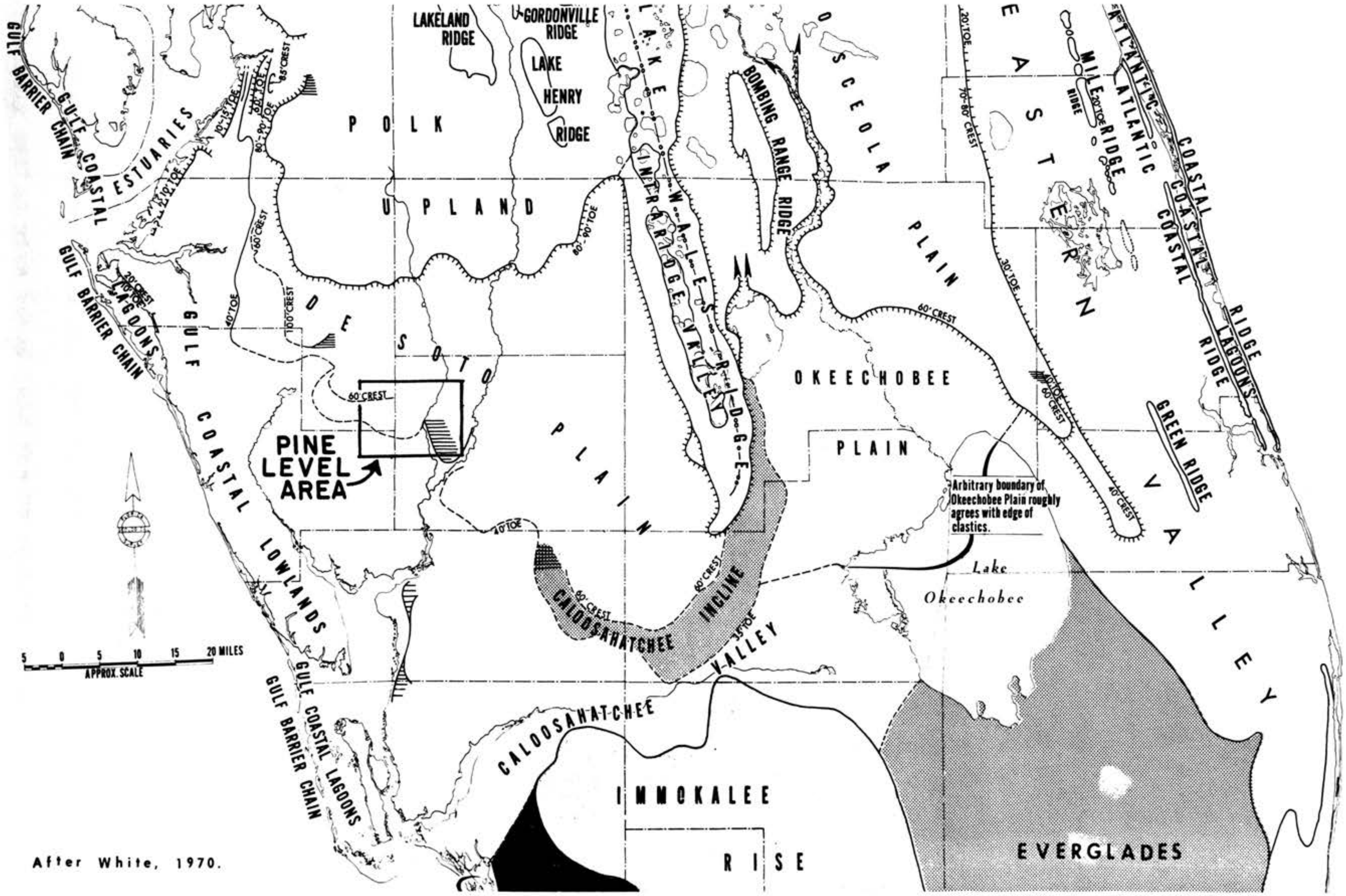


Figure 3. Physiographic map of the central Florida peninsula.

of the Plain, some thirty odd miles to the south at the crest of the northwest extension of the Caloosahatchee Incline, is only 20 to 30 feet lower at an elevation of 60 feet. The De Soto Plain is thus seen to be very flat with an average drop in elevation to the south of about one foot per mile or less. Figure 4A is a typical view of the De Soto Plain in the Pine Level area. Relief along stream valleys, such as the entrenched Peace River, may locally exceed 30 feet. The De Soto Plain, like the Polk Upland, is also underlain by predominately siliceous rocks and karst development does not exist. Drainage, compared to most of peninsular Florida, is well developed.

The portion of the Pine Level area within the De Soto Plain is dotted with small ponds or bay heads that are interconnected to Horse Creek or Big Slough Canal by fairly well defined drainage channels that permit fairly rapid runoff during periods of heavy rainfall.

3. Caloosahatchee Incline

The Caloosahatchee Incline and its northwest continuation into the Pine Level area has a toe elevation of about 40 feet, and rises northward to a crest elevation of about 60 feet within a distance of approximately four miles. The surface inclination therefore is about 5 feet per mile, or more than five times the average slope of the De Soto Plain.

This gentle scarp separates two of the largest and flattest plains of Florida. It divides the vast lowland to the south which comprises the Okeechobee Plain, the Immokalee Rise, the Everglades, and the Gulf Coastal Lowlands; none of which exceed the toe elevation of the scarp; from the higher, but equally flat, De Soto Plain.

The Caloosahatchee Incline, in the Pine Level area, is much more profusely dotted with ponds than the De Soto Plain portion, but due to

A. View of the De Soto Plain in the Pine Level area.

B. View of the Caloosahatchee Incline. Note shallow pond in center of picture behind live oak tree and fence.

Figure 4. Typical views in the Pine Level area.

the greater surface slope, it is also fairly well drained. Figure 4B is a view of the Caloosahatchee Incline in the Pine Level area.

4. Gulf Coastal Lowlands

The Gulf Coastal Lowlands vary from an elevation of 40 feet at the toe of the Caloosahatchee Incline to sea level some twenty miles or so to the southwest along the Gulf Coast. The average slope is very flat for a few miles to the crest of the Pamlico scarp. It then steepens to the toe of the scarp, and then continues with very slight inclination to the coast. The Lowlands are very profusely dotted with ponds, and are very poorly drained. A heavy summer shower of several inches may result in the accumulation of water over the ground surface that may take several days to dissipate. Figure 5 is an aerial view of a portion of the Gulf Coastal Lowlands in the Pine Level area.

C. Origin of the Physiographic Subdivisions

The Polk Upland is a relatively mature upland that has been dissected by a well defined drainage system. The Pleistocene sediments, covering most of the Upland, are deposits resulting from the Coharie and Okefenokee seas.

White (1970, p. 133) concludes that the southern bounding scarp of the Polk Upland is most probably an erosional marine shoreline made by a standstill of the Wicomico sea. It is not known if the scarp represents the actual maximum advance of the Wicomico sea, but the development of the scarp is indicative of a prolonged standstill.

The De Soto Plain is considered to be a submarine shoal plain developed during the Wicomico standstill; and the Caloosahatchee Incline and its northwest continuation is regarded as a depositional feature,

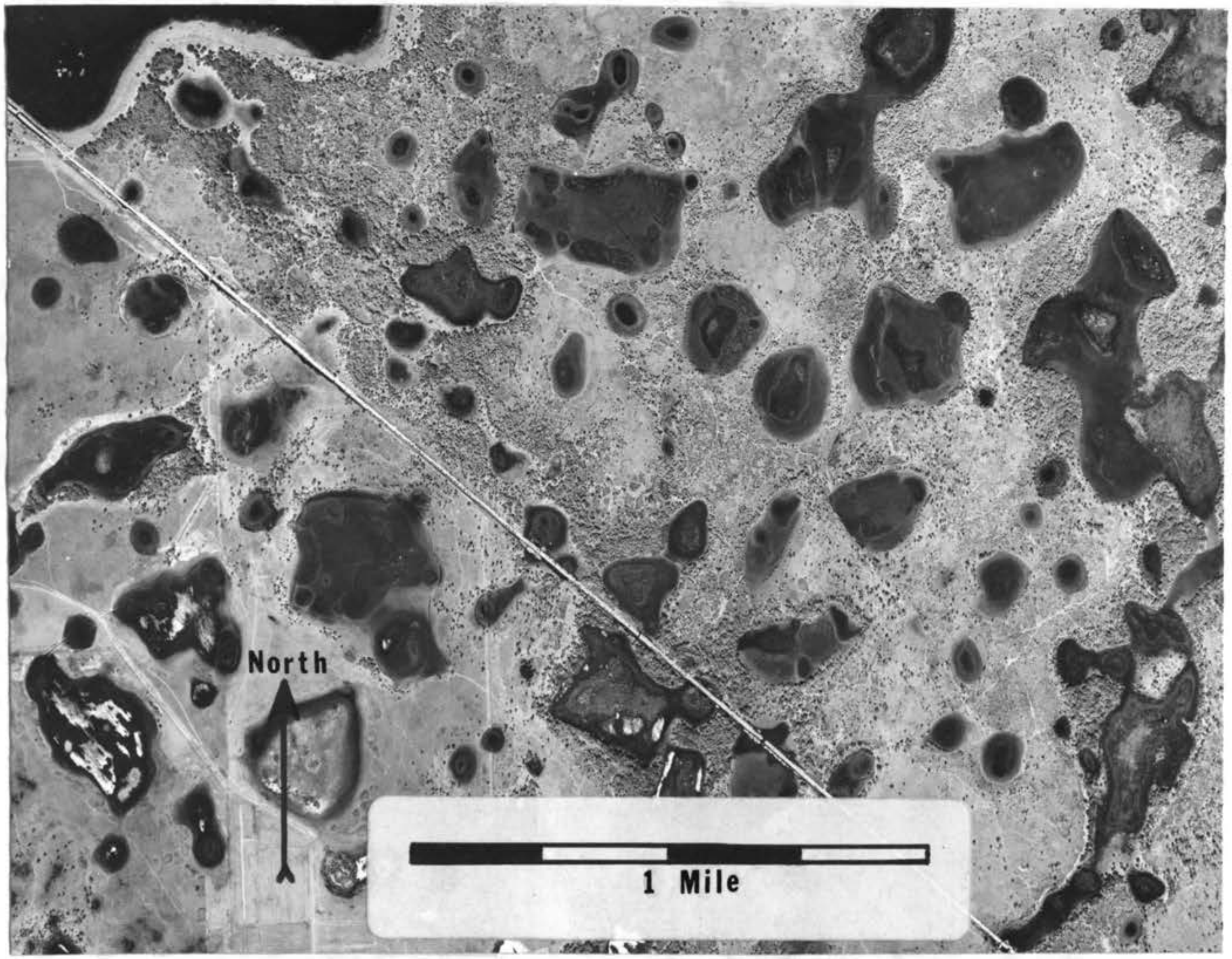


Figure 5. Aerial view of a portion of the Gulf Coastal Lowlands in the Pine Level area.

at the distal or down-current end of the submarine shoal, that has been uniquely preserved by virtue of emerging through the protected waters of a low energy coast (White, 1970, p. 141).

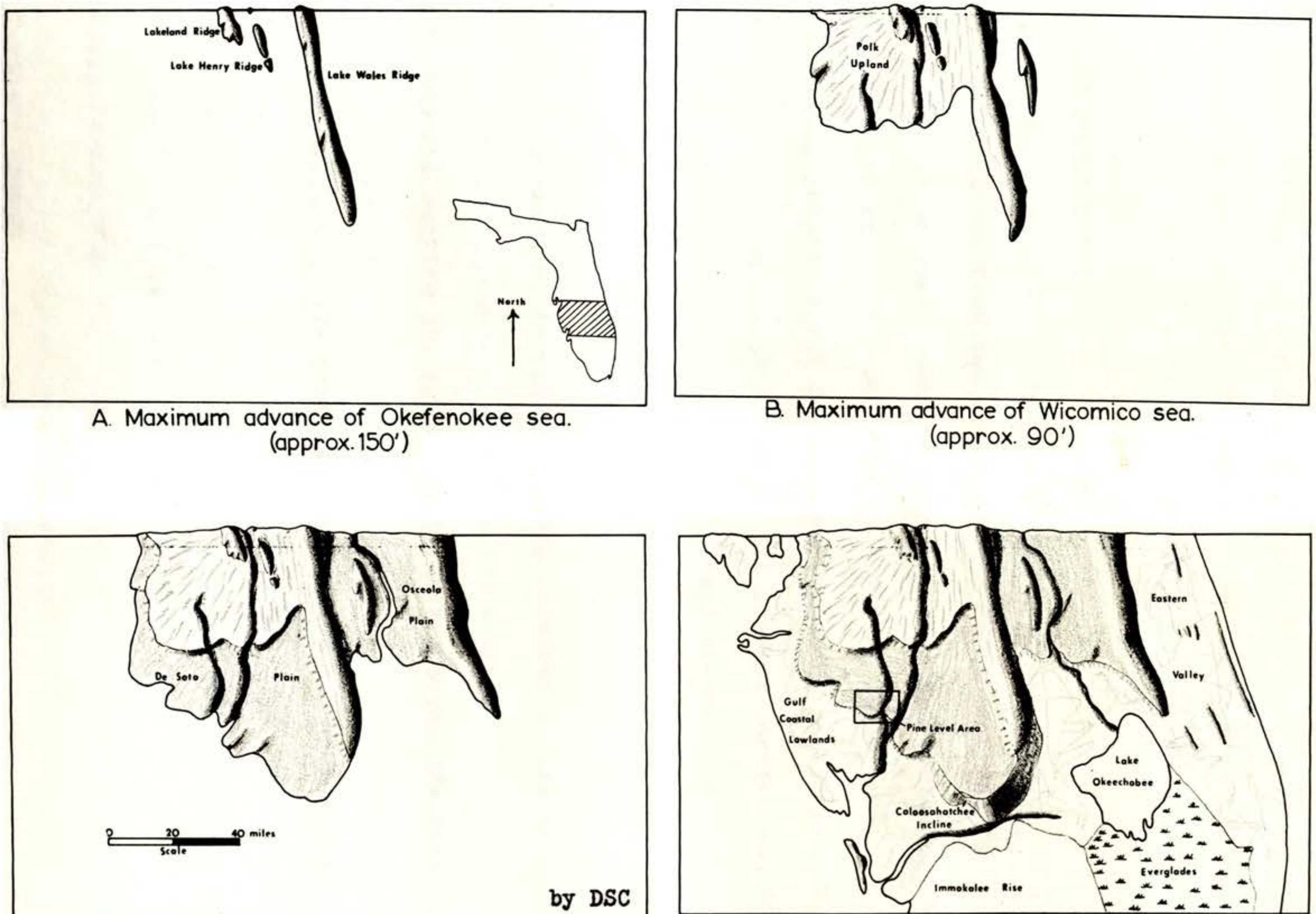
According to White's interpretation an elevation of about 40 feet should define the top of the Wicomico transgressive sequence in the Pine Level area. The remaining sediments above an elevation of 40 feet should consist of the submarine shoal deposits. The stratigraphic sequence in the Pine Level area does not support this interpretation.

Cooke is the only other worker to recognize a scarp at about the forty foot level (Table II), but his interpretation is at considerable variance with that of White. According to Cooke, the toe of the above described scarp at about 40 feet records the maximum advance of a Talbot sea; the scarp itself is considered to be the Penholoway terrace; the ground between 60 and 70 feet in elevation is the Penholoway scarp; and the area above 70 feet is the southern end of the Wicomico terrace. This is certainly tenuous at best.

The writer believes that the northwest extension of the Caloosahatchee Incline is an erosional marine shoreline developed during a somewhat transient sea standstill at about 60 feet. Whether it developed during a temporary pause in the regression of the Wicomico sea; during a brief temporary higher advance of the Pamlico sea; or during a separate Penholoway or Talbot sea transgression in Sangamon time, as indicated by Cooke, has not been determined. The abundant ponds in the Gulf Coastal Lowland and the northwest extension of the Caloosahatchee Incline are evidence of a shallow, relatively late, emergent coastal sea floor.

In summary, the Polk Upland has been subjected to two Pleistocene marine invasions (Coharie and Okefenokee); the De Soto Plain to three (Coharie, Okefenokee, and Wicomico); the Pine Level area to three or, possibly, four (Coharie, Okefenokee, Wicomico, and, possibly, Pamlico); and the Gulf Coastal Lowlands to five (Coharie, Okefenokee, Wicomico, Pamlico, and Silver Bluff). Development of the physiographic divisions discussed and their relationships to the various sea standstills are depicted in Figure 6.

This rather protracted discussion of physiography and Pleistocene marine transgressions bears on the fact that all of the Florida phosphate rock produced to date from the land-pebble field has been obtained from the Polk Upland above the Wicomico scarp (Figs. 1 and 3). This is not merely a coincidence.



A. Maximum advance of Okefenokee sea. (approx. 150')

B. Maximum advance of Wicomico sea. (approx. 90')

C. Standstill during formation of Caloosahatchee Incline. (approx. 60')

D. Present sea level.

Figure 6. Physiographic diagrams depicting central peninsular Florida during various sea standstills.

IV. STRATIGRAPHY

Deposits of late Pleistocene age completely mantle the entire Pine Level area. Information pertaining to the underlying covered formations is derived from the shallow exploration core holes, and the logs of several water wells and two deep oil-test wells in adjoining counties.

A. Pre-Tertiary Rocks

Rocks older than middle Eocene in the general vicinity of the Pine Level area are known from two deep oil-test wells in adjoining counties. The data from these wells indicate that rocks of Cretaceous age should occur at a depth of about 5,000 feet in the Pine Level area.

One well, located about 25 miles northwest of the Pine Level area in the NW¼ Section 14, T. 35 S., R. 19 E., Manatee County, was drilled by Magnolia Petroleum Corporation. This well entered the Upper Cretaceous at 5,120 feet below sea level and ended in Cretaceous rocks at more than 10,000 feet below sea level (Peek, 1958, p. 14). The Cretaceous rocks consist of interbedded shale, limestone, and anhydrite.

The other well, located about 50 miles southeast of the Pine Level area in the NW¼ Section 34, T. 38 S., R. 29 E., Highlands County, was drilled to a depth of 12,985 feet by Humble Oil and Refining Company. According to Applin (1951) this well penetrated Cretaceous limestone, dolomite and anhydrite between 5,096 and 12,618 feet. The lower 367 feet (below 12,618 feet) penetrated basalt, rhyolite porphyry, and related volcanic rocks tentatively classified as early Paleozoic, or possibly, Precambrian.

B. Tertiary System

The formations of Tertiary age in the Pine Level area, and their approximate thicknesses are listed in Table III. The formations penetrated by the water wells (Fig. 7) are briefly described in the following sections.

1. Eocene Series

Avon Park Limestone: The upper part of the late middle Eocene in Florida was named the Avon Park Limestone by the Applins (1944, p. 1680, 1686). It crops out to the north in Citrus and Levy Counties and is the oldest formation exposed at the surface in Florida. It is also the oldest formation penetrated by water wells in the vicinity of the Pine Level area.

Lithologically the Avon Park in the Manatee County well (Fig. 7) varies from white to tan, fairly soft, coquinoid or granular limestone, to dark brown, hard, crystalline dolomite. Most of the limestone beds are dolomitic. The formation contains a prolific, distinct middle Eocene microfauna (Puri and Vernon, 1964, p. 52).

The Avon Park Limestone thins from about 700 feet in Manatee County (Peek, 1958, p. 16) to about 300 feet in Highlands County, and is evidently about 600 feet thick under the Pine Level area.

Ocala Group: The term Ocala Limestone was first used by Dall (1892, p. 103-104) to describe exposures in the vicinity of Ocala, Marion County, Florida. Puri and Vernon (1964, p. 57) discuss the subsequent revisions of the Ocala Limestone. The Florida Geological Survey now recognizes the Ocala Group as subdivided into three formations which, in ascending order, are the Inglis, Williston, and Crystal River Formations.

The Ocala Group lies unconformably on the Avon Park Limestone and is about 300 feet thick. The upper part in Manatee County consists of cream, tan, and grayish-tan, soft, chalky, highly fossiliferous lime-

Table III. Geologic Formations in the Pine Level Area

System	Series	Formation	Characteristics	Thickness (feet)
Quaternary	Recent		Soil, gravel, peat, muck, hardpan.	0-10
	Pleistocene	Upper Pleistocene Sand	Tan, light gray, or brownish gray, fine- to coarse-grained, clayey to loose, incoherent sand.	0-33
		Lower Pleistocene Sand	Gray, fine- to coarse-grained, incoherent, phosphatic sand with thin beds of dark green sandy clay or marly limestone.	0-50
Tertiary	Pliocene	Bone Valley Formation	Brownish gray, fine- to coarse-grained, cohesive, clayey, phosphatic sand.	0-16
	Miocene	Hawthorn Formation	Upper clastic member of gray, fine-grained phosphatic sand and interbedded green clay. Lower member of tan, sandy, phosphatic limestone.	±300
		Tampa Formation	White, gray, and tan, hard, dense, sandy limestone with thin chert beds. Locally phosphatic.	±100
	Oligocene	Suwannee Limestone	Creamy white to tan, granular, porous limestone with some beds of crystalline dolomitic limestone.	±150
	Eocene	Ocala Group	Cream, tan, and grayish tan, soft, chalky, highly fossiliferous limestone.	300
		Avon Park Limestone	White to tan, fairly soft, coquinoid, granular limestone or dark brown, hard, dolomite.	600
		Lake City Limestone	Cream and tan, chalky to granular, fossiliferous, dolomitic to gypsiferous limestone.	500
		Oldsmar Limestone	Tan and brown, granular, porous limestone interbedded with chert, anhydrite, and tan, crystalline dolomite.	950
	Paleocene	Cedar Keys Formation	Cream to tan, fairly hard, granular, gypsiferous limestone and tan to brown, crystalline dolomite.	2,000

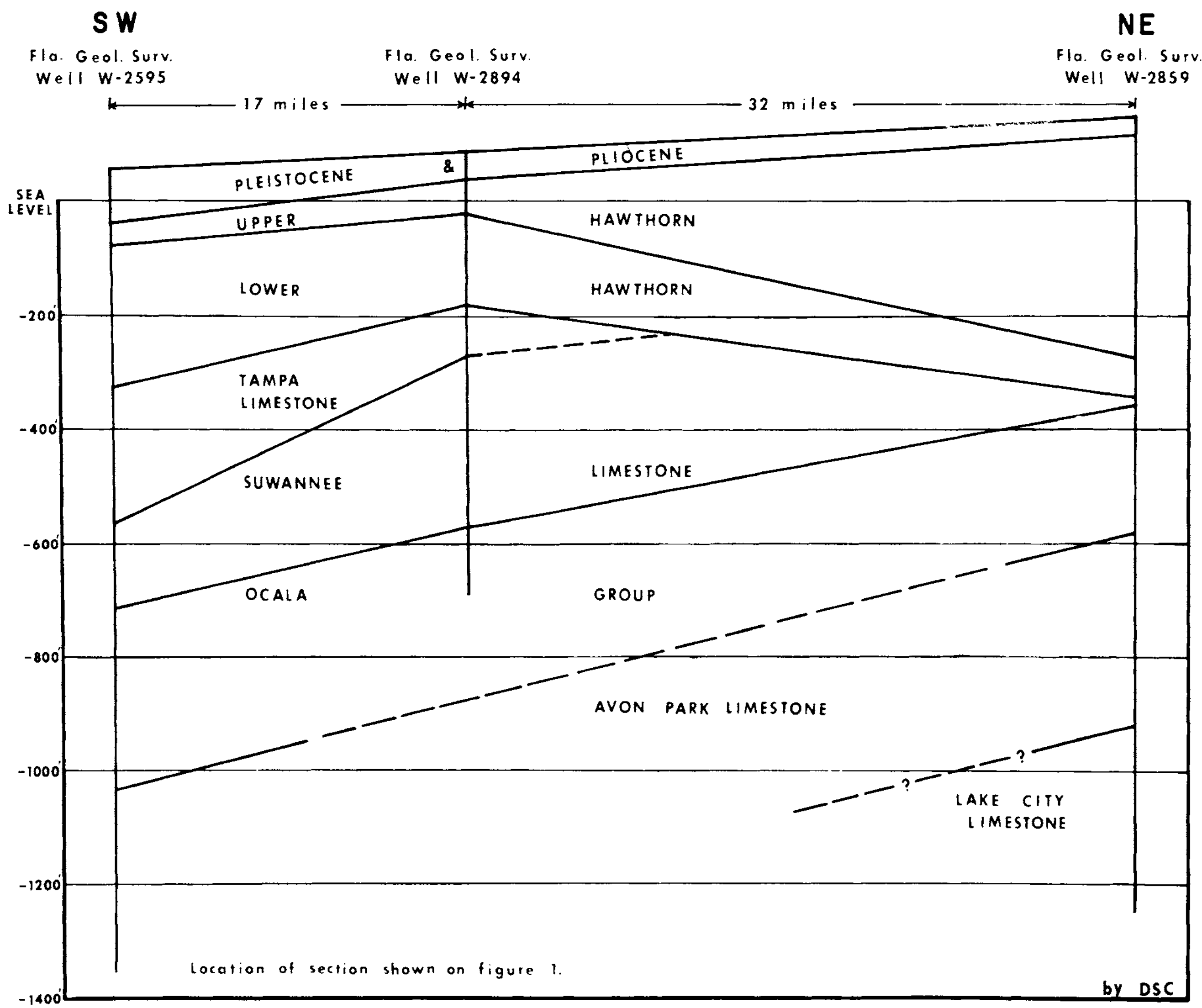


Figure 7. Cross section of geologic formations penetrated by water wells in the vicinity of the Pine Level area.

stone. The lower part is similar but contains beds of brown and tan, hard, crystalline dolomite and dolomitic limestone.

2. Oligocene Series

Suwannee Limestone: The name Suwannee Limestone was proposed by Cooke and Mansfield (1936, p. 71) for the yellowish limestone exposed along the Suwannee River in Hamilton and Suwannee Counties in northern peninsular Florida. The formation is differentiated from the underlying Eocene formations and the overlying Miocene formations on the basis of lithology and faunal content, and is separated from these formations by unconformities.

The Suwannee Limestone is not continuous in the subsurface of peninsular Florida. As shown in Figure 7 the formation is about 125 feet thick in the Manatee County well, 300 feet thick in the Hardee County well, and 15 feet thick in Highlands County. The formation is missing in eastern Highlands County (Bishop, 1956, p. 23).

The formation is a creamy-white to tan, soft to hard, granular, porous limestone with some beds of crystalline and dolomitic limestone. It contains many echinoids, mollusks, and foraminifers.

3. Miocene Series

The deposits of Miocene age in the Pine Level area are referred to the Tampa Formation of early Miocene age (Cooke, 1945, p. 107), and the Hawthorn Formation of middle and late Miocene age. Both of the formations are of marine origin, but they represent different depositional environments and are probably separated by an unconformity.

Tampa Formation: The Tampa Formation lies unconformably on the Suwannee Limestone and consists of white, gray, and tan, hard, dense, sandy limestone which locally contains fine-grained phosphorite. The limestone is crystalline and dolomitic, and contains thin beds of chert. It is generally fossiliferous and contains echinoid plates and spines, ostracods, foraminifers, and mollusks.

The formation, like the Suwannee, is not continuous in the subsurface. It is about 140 feet thick in the Manatee County well, 90 feet thick in Hardee County, and missing in Highlands County. It is probably about 100 feet thick in the Pine Level area.

Hawthorn Formation: The term "Hawthorn Formation" has a complex history in Florida. Originally, the name "Hawthorne" was given by Dall (1892, p. 107) to the phosphatic limestone believed to be of "older" Miocene age near the town of Hawthorne in Alachua County. Younger than the Hawthorne "beds", but still of "older" Miocene age, were the Tampa, Chipola, and Alum Bluff "beds", which were assigned by Dall (1892, p. 112) to the Tampa group. Later, due to a readjustment of the Oligocene-Miocene boundary, the Tampa group was regarded as Oligocene by Dall and others.

Matson and Sanford (1913, p. 87-88) shortened the name "Hawthorne" to "Hawthorn". They believed that the land-pebble phosphate deposits lie upon an eroded surface of the Alum Bluff Formation.

According to Sellards (1915, p. 34-35), the Alum Bluff Formation was the parent rock from which the land-pebble phosphates were derived. Sellards (1916, p. 91-92) later introduced evidence of a Miocene vertebrate fauna in the Alum Bluff Formation. The opinion that the Alum Bluff Formation should be considered Miocene was generally accepted by later workers.

Gardner (1926, p. 1-2) recognized three distinct marine faunas of Miocene age, and, on the basis of these faunas, she raised the Alum

Bluff of western Florida to the rank of a group divided into three formations, each of which was characterized by a separate fauna. In descending order these were: Shoal River Formation, Oak Grove Sand, and Chipola Formation.

Cooke and Mossom (1929, p. 98) retained Gardner's Alum Bluff Group but reinstated the Hawthorn Formation as a lateral equivalent in peninsular Florida of the Alum Bluff Group in western Florida. Within the Hawthorn Formation, Cooke and Mossom (1929, p. 115) included the earlier Alum Bluff Formation of Matson and Clapp (1909, p. 91) and the original Hawthorne "beds", the Manatee River Marl, the Sopchoppy Limestone, and the Jacksonville Limestone of Dall. In general, Cooke (1945, p. 144) retained this classification, but he tentatively transferred to the Duplin Marl some beds of late Miocene age that Cooke and Mossom (1929, p. 115) assigned to the Hawthorn Formation.

As a result of the above investigations, the Florida Geological Survey considers the Hawthorn Formation of peninsular Florida to be a facies equivalent of the western Alum Bluff Group of middle Miocene age (Puri and Vernon, 1964, p. 117). However, Cathcart reports (1964, p. 20) that MacNeil, in a personal communication, suggest that the upper part of the formation in the northern part of the land-pebble field is either late middle Miocene or early upper Miocene. Also, Bergendahl (1956, p. 73-79) has described a "sand of late Miocene age" that underlies all of De Soto County, which, based upon stratigraphic position and lithologic similarity, is equivalent to the upper part of the Hawthorn Formation in the northern part of the land-pebble field. The formation in the land-pebble field thus apparently ranges from middle into upper Miocene, and the upper part of the formation is evidently younger than the Alum Bluff Group of the Florida panhandle.

It is recognized that the inclusion of Bergendahl's "sand of late Miocene age" in the Hawthorn Formation properly requires a redefinition of the Hawthorn Formation or a revision of the upper age limits of the Alum Bluff Group. The clear lithologic similarity of the "sand of late Miocene age", the upper clastic member of the land-pebble field, and the phosphatic Hawthorn Formation of northern peninsular Florida indicates a revision of the Alum Bluff Group is required. This must await a comprehensive regional study of the paleontology of the upper part of the Hawthorn Formation south of the Polk Upland.

The strata assigned to the Hawthorn Formation in this paper follows the usage of Cathcart (1964) and includes all deposits of Miocene age that are younger than the Tampa Formation; and, again following Cathcart, the formation is divided into a lower limestone member and an upper unnamed clastic member.

The lower Hawthorn Limestone Member underlies, except very locally, the entire land-pebble field and the Pine Level area. Details of the distribution, lithologic variations, and thickness must be obtained from well data. In the main producing district it forms the "basement" or "bedrock" under all of the mineable phosphate deposits.

The lower member consists essentially of white, gray, and tan, soft to hard, sandy, crystalline limestone with numerous thin interbeds of white calcareous clay or sandy marl. The member contains sparse to locally abundant phosphate pellets and pebbles. The thickness apparently ranges from about 250 feet in Manatee County to 160 feet in Hardee County, and 70 feet in Highlands County (Fig. 7).

The upper clastic member of the Hawthorn Formation crops out or underlies, at relatively shallow depth, a large part of the northern Florida peninsula (Vernon and Puri, 1964). It has mostly been removed by erosion from the northern part of the land-pebble field and the area of the Ocala uplift (Fig. 2).

The detailed stratigraphic relations between the upper clastic member of this paper and the phosphatic Hawthorn Formation north of the land-pebble field are not known. Similar fine- to medium-grained phosphatic sands are widespread and are being mined by Occidental Minerals Corporation of Florida in Hamilton County. Pirkle (1967, p. 238) shows the location of several other potential deposits in the Hawthorn Formation of the northern Florida peninsula; and Espenshade and Spencer (1963, p. 54) discuss areas favorable for prospecting.

In the main producing district the upper clastic member is locally present in the southeastern part of the Lakeland quadrangle where it has a maximum thickness of about 10 feet (Cathcart, 1964); it has been noted at several localities in the northwestern part of the Fort Meade quadrangle where it is also about 10 feet thick (Cathcart, 1966); and thin isolated remnants up to five feet thick are occasionally noted in the Keysville quadrangle (Cathcart, 1963a). In northeastern Manatee County the member begins thickening toward the south and reaches a thickness of 70 feet in the southern part of the Chicora quadrangle (Cathcart, 1963c)

The member was probably once continuous over the land-pebble field but was probably much thinner than to the north and the south as a result of deflection around the southern end of the Ocala uplift (Cathcart, 1963b, p. 22). The present thickness and erratic distribution of the member in the northern part of the land-pebble field is the result of post depositional erosion.

The upper clastic member underlies the entire Pine Level area (Fig. 8) and is a dark gray, brownish-gray, or greenish-gray, fine- to very fine-grained phosphatic sand; interbedded green clay; and minor thin, light gray, soft phosphatic limestone or marl beds. Sand constitutes about 60 to 70 percent of the member penetrated by the exploration core holes, and clay about 30 to 40 percent, although most of the sand units contain varying amounts of interstitial clay. The thin limestone or marl beds constitute a minor part of the member.

The phosphate content of the sand units varies from traces to as much as 25 percent of the total weight of the unit. Particulars of the phosphate content are discussed in detail in a succeeding section of this paper.

The top of the upper clastic member is an irregular erosion surface that ranges from 41 feet above sea level to 31 feet below sea level in the Pine Level area. Figure 9 is partially a subsurface contour map of the buried Hawthorn erosional surface in the area. The erosional relief on the Hawthorn surface in Manatee County is about 60 feet and ranges from 10 feet above sea level to 50 feet below sea level (Peek, 1958, p. 21).

The thickness of the upper clastic member is about 40 feet in the Manatee County well, and thickens to 300 feet in Highlands County (Fig. 7). Only the uppermost part of the member has been penetrated and sampled by the exploration core holes in the Pine Level area. The thickness of the member in the Pine Level area was consequently not determined during the exploration program but it is estimated, by inference, to be about 100 feet thick. The member is thus seen as a south-thickening

Figure 8. Geologic map and index to cross sections, Pine Level area; De Soto, Manatee, and Sarasota counties, Florida.

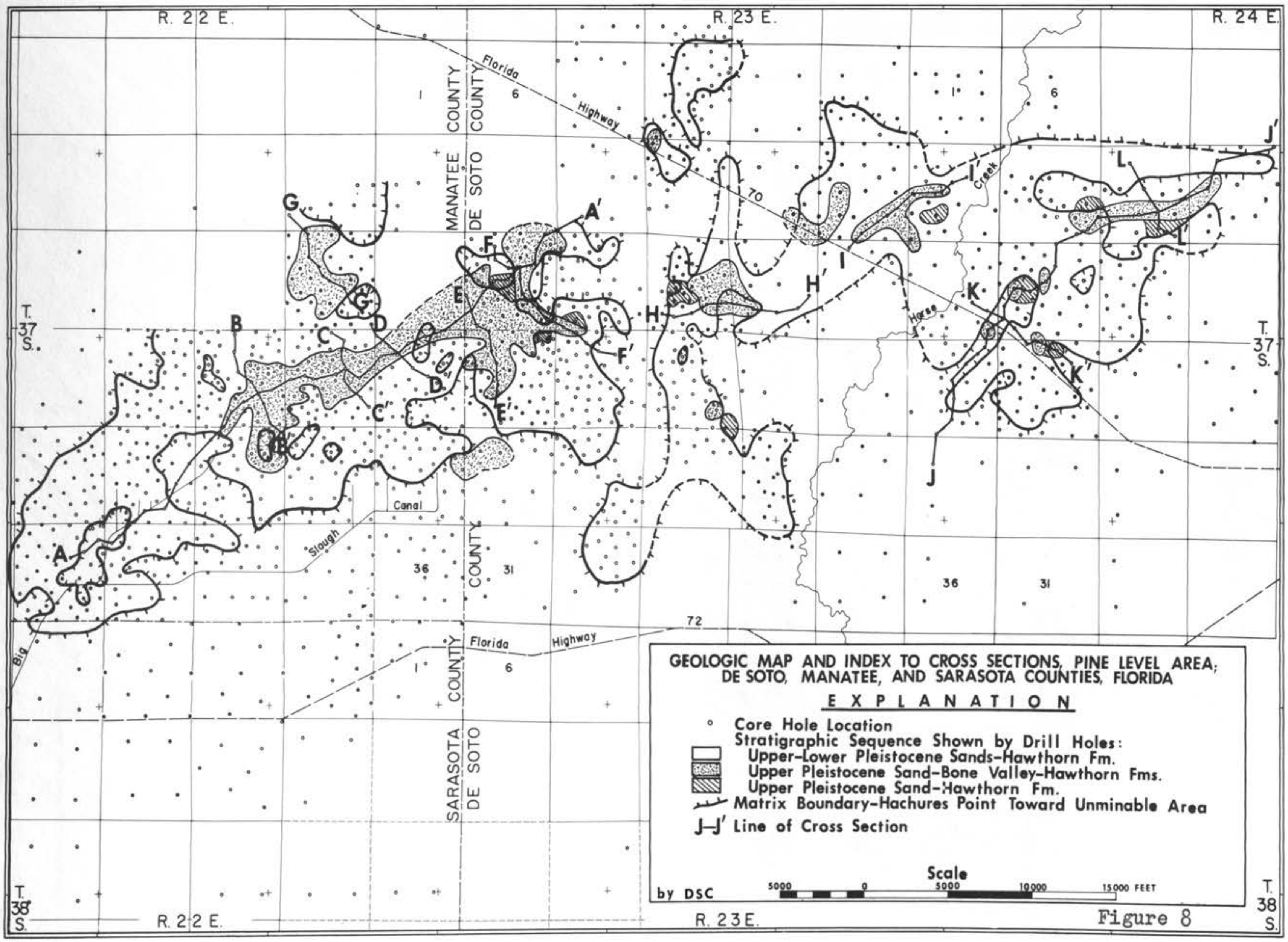

GEOLOGIC MAP AND INDEX TO CROSS SECTIONS, PINE LEVEL AREA; DE SOTO, MANATEE, AND SARASOTA COUNTIES, FLORIDA
EXPLANATION
Core Hole Location
Stratigraphic Sequence Shown by Drill Holes:
Upper-Lower Pleistocene Sands-Hawthorn Fm.
Upper Pleistocene Sand-Bone Valley-Hawthorn Fms.
Upper Pleistocene Sand-Hawthorn Fm.
Matrix Boundary-Hachures Point Toward Unminable Area
J–J′ Line of Cross Section
Scale
5000 0 5000 10000 15000 FEET
by DSC
R. 22 E.
R. 23 E.
R. 24 E.
T. 37 S.
T. 38 S.
MANATEE COUNTY
DE SOTO COUNTY
SARASOTA COUNTY
DE SOTO COUNTY
Florida Highway 70
Florida Highway 72
Horse Creek
Big Slough
Canal
A A′ B C C′ D D′ E E′ F F′ G G′ H H′ I I′ J J′ K K′ L L′
1 6 36 31
Figure 8

Figure 9. Paleotopographic map of the Pliocene-Pleistocene erosion surface in the Pine Level area; De Soto, Manatee, and Sarasota counties, Florida.

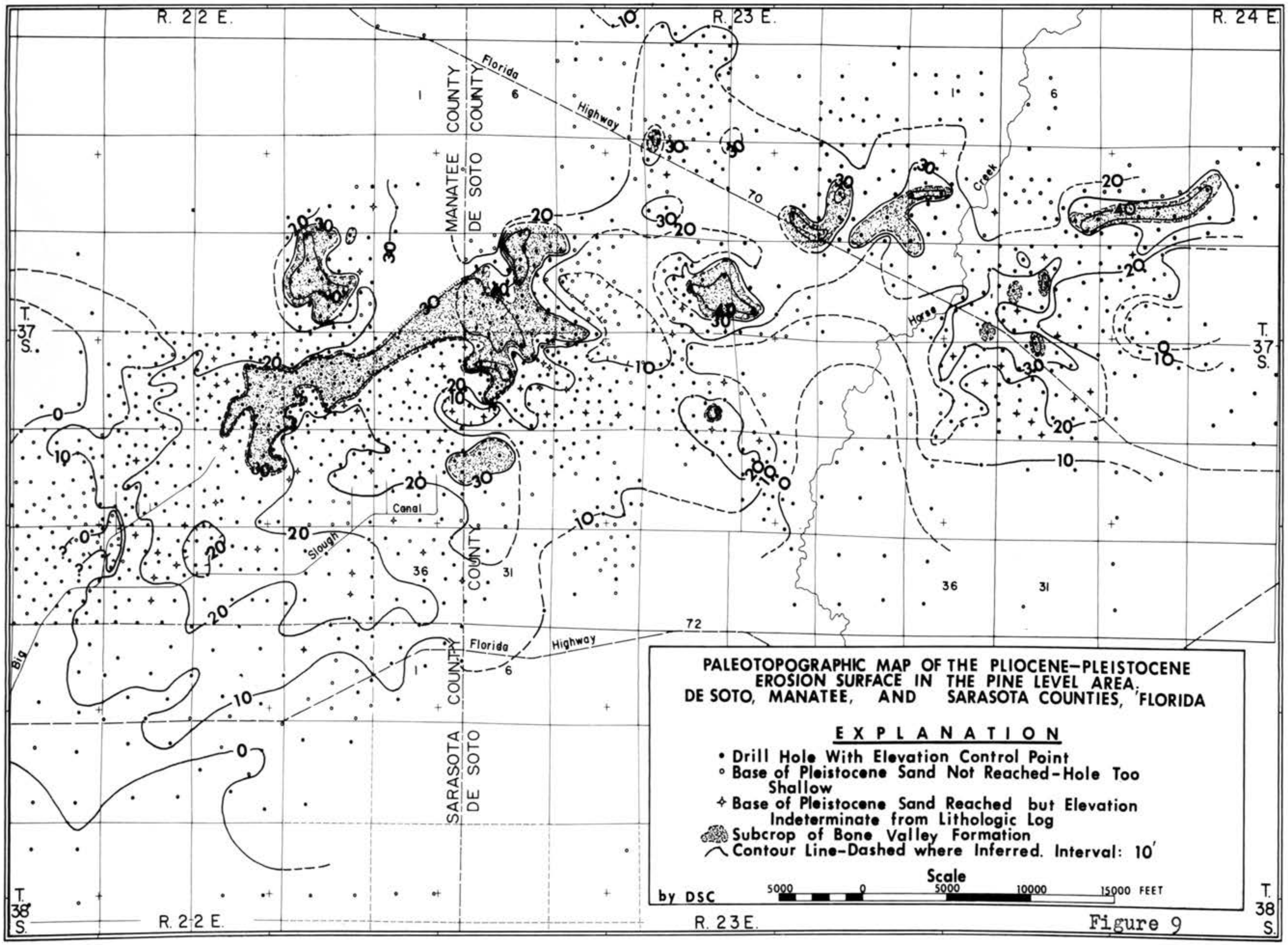

PALEOTOPOGRAPHIC MAP OF THE PLIOCENE–PLEISTOCENE EROSION SURFACE IN THE PINE LEVEL AREA, DE SOTO, MANATEE, AND SARASOTA COUNTIES, FLORIDA
EXPLANATION
• Drill Hole With Elevation Control Point
◦ Base of Pleistocene Sand Not Reached–Hole Too Shallow
✧ Base of Pleistocene Sand Reached but Elevation Indeterminate from Lithologic Log
Subcrop of Bone Valley Formation
Contour Line–Dashed where Inferred. Interval: 10′
Scale
5000
0
5000
10000
15000 FEET
by DSC
R. 22 E.
R. 23 E.
R. 24 E.
T. 37 S.
T. 38 S.
MANATEE COUNTY
DE SOTO COUNTY
SARASOTA COUNTY
DE SOTO COUNTY
Florida Highway 70
Florida Highway 72
Horse Creek
Big Slough Canal

Figure 9

wedge of clastic sediments that varies from a few feet in thickness in the south part of the main producing area to a thickness of, perhaps, 100 feet in the Pine Level area.

Citronelle Formation: A discussion of the regional stratigraphic relationships and the interpretation of the regional geologic history, to which the Pine Level deposit is related, requires the brief consideration of an additional important geologic feature of the Florida peninsula, and another formation not now present in the land-pebble field. These are the Lake Wales Ridge and the Citronelle Formation.

The Lake Wales Ridge is present in central peninsular Florida. It trends in a general north-south direction from Highlands County on the south into Clay County to the north along a distance of about 200 miles, and divides the peninsula into two nearly equal parts. The southern portion of the Ridge is shown on Figure 3. The Ridge forms the high elevation "backbone" of the Florida peninsula and attains elevations of near 300 feet in southern Polk County.

The Lake Wales Ridge is covered by a blanket of loose to slightly indurated surface sands. The surface sands are underlain by clastic deposits of the Citronelle Formation which, in turn, rest upon sands, clays, marls, limestone, dolomite, and phosphate concentrations of the Hawthorn Formation. The Citronelle consists of cross-bedded, coarse, fluvial deposits of quartz sand, quartz granules, and interstitial kaolinitic clay. The Citronelle Formation has been dated by invertebrate fossils as late Miocene by Ketner and McGreevy (1959, p. 49).

The Citronelle sediments are thought to have been deposited as part of a prograding delta that built southward into the present area of Florida (Pirkle et al., 1964, p. 1131). Considerable parts of such deposits have been removed by stream erosion and advancing Pleistocene seas, leaving the higher parts of the delta as a remnant ridge, the Lake Wales Ridge. Presumably the eastern part of the land-pebble field, at least, may have been blanketed at the close of Miocene time by some unknown thickness of Citronelle sediments.

Alachua Formation: In addition to the Hawthorn phosphate deposits of the northern Florida peninsula and the Bone Valley deposits of the land-pebble field, another group of deposits has contributed to Florida phosphate rock production in the past. These are the hard-rock deposits of the Alachua Formation. A brief description of these deposits is recounted here because the author suggests that the origin of these deposits may be related to the origin of the phosphate pebbles in the Bone Valley Formation.

The hard-rock phosphate deposits occur in a linear belt that extends northwest about 110 miles from southern Hernando to southern Suwannee County along the crest of the Ocala uplift (Fig. 2). The deposits characteristically are a rubble of platy fragments and botryoidal masses of hard apatite with soft white claylike apatite, clay, sand, chert, and limestone. The deposits are highly irregular in shape and size and are several feet to more than 100 feet in thickness and a few hundred square feet to more than 40 acres in area (Espenshade and Spencer, 1963, p. 32). The phosphate deposits rest upon Avon Park, Ocala, or Suwannee limestone that is intricately pitted by ground water solution; pinnacles of limestone may project 20 to 30 feet above the general surface of the limestone up into the phosphate deposit, or the phosphatic rubble may fill old sink holes to considerable depths.

These highly irregular rubble deposits, along with some clay and sand have generally been assigned to the Alachua Formation (Sellards, 1913; Matson, 1915). Pirkle (1956) summarizes the nomenclature of the Alachua Formation and believes that strata of both the Hawthorn Formation and Pleistocene sediments have been included in the Alachua. Espenshade and Spencer (1963, p. 38) conclude that the deposits formed somewhere in the range between middle Miocene and early Pliocene.

According to Espenshade and Spencer (1963, p. 40-45) phosphatic strata of the Hawthorn Formation evidently once covered all or most of the hard-rock district. Uplift during early Pliocene time exposed the area to subaerial erosion. A surface drainage system of brief duration developed, but was soon succeeded by the underground drainage system which now predominates.

Development of the underground drainage system accelerated the leaching of phosphate and carbonate from the overlying and enclosing strata. Calcium carbonate was first leached by descending acidic water; after its removal, phosphate was gradually dissolved and carried downward, and perhaps laterally, to be deposited as secondary apatite in the zone where limestone was being actively dissolved and the acidic water was being neutralized.

Solution slumping took place repeatedly, causing brecciation of secondary apatite and mixing it with other materials. Phosphate deposition was discontinuous, and several generations of secondary apatite are commonly evident. The process resulted in an irregular chaotic rubble breccia consisting of portions of phosphate particles from the overlying Hawthorn Formation, secondary apatite plates and botryoidal masses, limestone fragments, sand, and clay. Considerable erosion has taken place since the formation of the hard-rock deposits.

4. Pliocene Series

Bone Valley Formation: The Bone Valley Formation was first called the Bone Valley gravel (Matson and Clapp, 1909) for phosphate beds west of Bartow, Polk County, where the beds were being mined commercially for phosphate. It originally included all of the mineable phosphate plus the overlying clayey sand containing traces of phosphate, but it excluded the underlying lower limestone member of the Hawthorn Formation, and the overlying loose Pleistocene sand. Cooke (1945, p. 203) discarded the term "gravel" because only a small part of these deposits is really gravel, and used the term Bone Valley Formation. Cathcart (1963a, p. 15) has shown that the lower part of the mineable phosphate bed is in some places a residuum of the underlying lower limestone member of the Hawthorn Formation. The lower phosphatic member of the Bone Valley Formation in the main portion of the field thus does not necessarily include all of the mineable phosphate.

Riggs and Freas (1965) proposed a revision of the Bone Valley Formation. They applied the name Bone Valley to the upper clastic member of the Hawthorn, and called the Bone Valley Formation proper an "unnamed" Pliocene and Pleistocene formation. Their proposal has not been taken seriously.

The Bone Valley Formation, as shown by Cathcart's geologic maps, entirely underlies almost all of the Polk Upland portion of the land-pebble field. There are small, local areas of Pleistocene channeling where the formation has been removed, and recycled into the Pleistocene channel-fill deposits (Cathcart, 1966, Fig. 4). Also several streams and rivers have downcut through the formation and redistributed the phosphate particles downstream into Recent "river pebble" deposits.

The upper clayey sand member between the loose Pleistocene sand and the lower phosphatic member is not recognized in the Pine Level area. The Bone Valley Formation has been largely removed from the Pine Level area by Pleistocene erosion. The subsurface distribution of the uneroded remnants of the lower phosphatic member of the formation are shown on Figure 8. The lower member is recognized on the basis of stratigraphic position, a relatively uniform basal elevation, and lithologic similarity to the formation in the quadrangles studied by Cathcart.

The Bone Valley Formation in the Pine Level area is a brownish-gray, fine- to coarse-grained, cohesive, clayey, phosphatic sand. The phosphate content varies from about 15 to 40 percent by weight, and will be discussed in more detail in a later section. The thickness of the formation ranges from 0 to about 16 feet.

Cathcart summarizes the evidence bearing on the age of the Bone Valley Formation and concludes the vertebrate fossils and large avifauna indicate the age is Pliocene (1966, p. 16).

5. Hawthorn-Bone Valley Unconformity

The upper surface of the Hawthorn Formation in the Polk Upland is a very irregular erosional surface that has been modified by, at least, two periods of erosion. The first occurred after deposition of the Hawthorn Formation but before the deposition of the overlying Bone Valley Formation. The second is apparently related to a more recent erosional cycle for the streams and major rivers, such as the Peace and Alafia, are entrenched into the Hawthorn surface. There are some exceptions, but, in general, the present drainage pattern is similar to the ancestral stream patterns (Cathcart, 1963a, p. 20). The upper member of the Hawthorn was eroded and removed during the earlier cycle of erosion.

Cathcart's contour maps show the present surface of the Hawthorn varies from about 150 feet above sea level to ten feet below sea level, and is a very irregular karst surface that was formed by chemical weathering after the removal of the upper member. The greatest local relief is along present day streams, so the actual relief on the Hawthorn surface immediately prior to the deposition of the Bone Valley Formation was more moderate than indicated by the present surface. This period of chemical weathering formed the phosphate-rich, calcareous clay residuum on the Hawthorn Limestone surface.

The Hawthorn-Bone Valley contact in the Pine Level area is best shown in cross sections A-A' (Fig. 10) and J-J' (Fig. 13). It can be seen that the contact is at an elevation of about 30 feet in the remnant area near the Manatee-De Soto county line and appears to increase some eight miles to the northeast to an elevation of around 40 feet in Section 8, T. 37 S., R. 24 E. in De Soto County (Fig. 8). Local relief on the contact appears to be on the order of, at most, several feet.

The difference in the basal elevation of the two remnants indicates a westerly dip of approximately one foot per mile. Cathcart (1963a, p. 40) has commented that Tampa Bay and Charlotte Harbor on the Florida west coast are typical drowned river valleys while the straight east coast of Florida resembles a coast line of emergence. From this relationship and an evident west dip of the Hawthorn surface in the Keysville quadrangle, he concludes that westward tilting of the Florida peninsula may have occurred after the development of the erosion surface. The ten foot difference in elevation discussed above could be

Figure 10. Cross section A-A'.

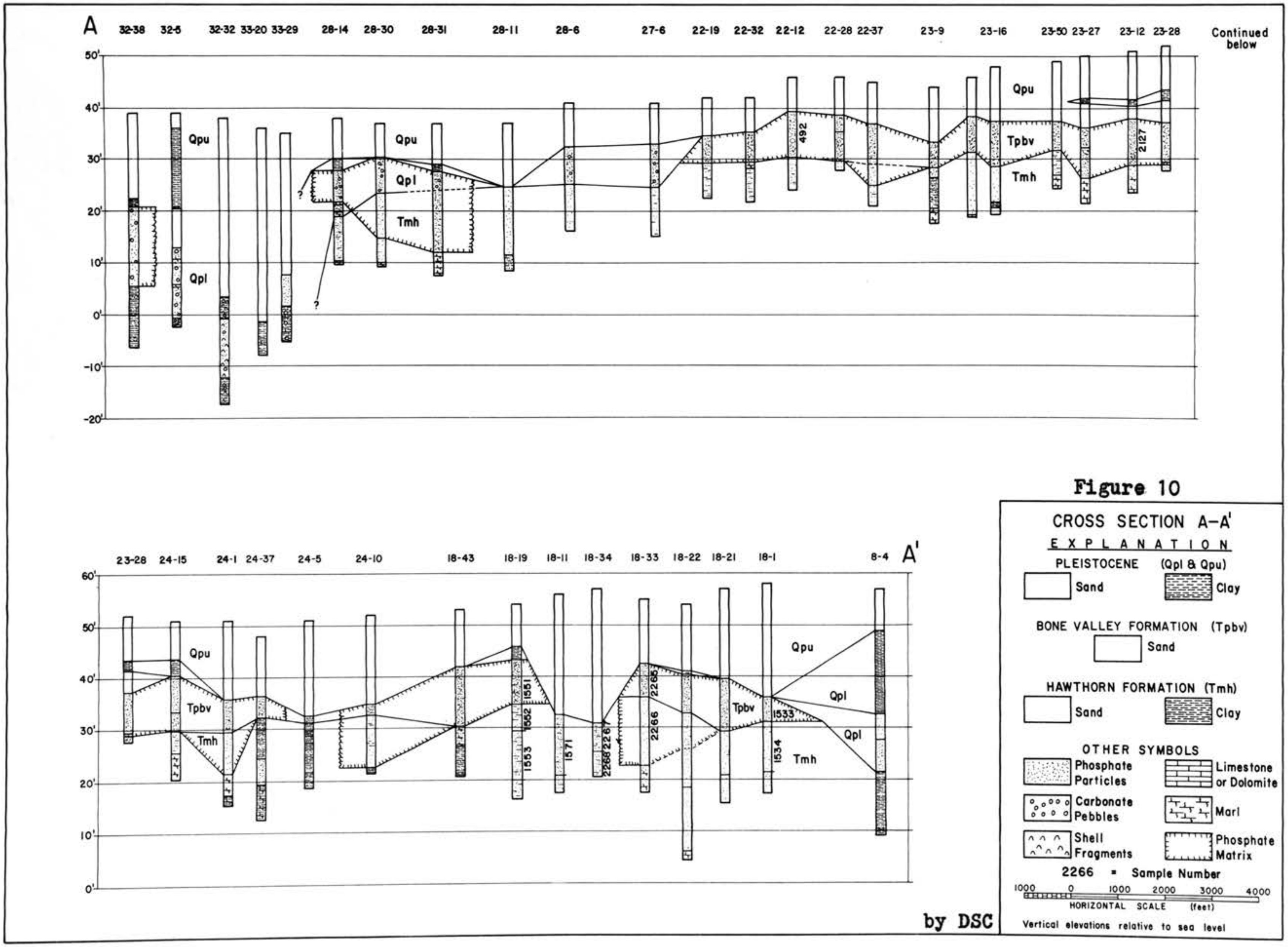

A
32-38 32-5 32-32 33-20 33-29 28-14 28-30 28-31 28-11 28-6 27-6 22-19 22-32 22-12 22-28 22-37 23-9 23-16 23-50 23-27 23-12 23-28
Continued below
50'
40'
30'
20'
10'
0'
-10'
-20'
Qpu
Qpl
Tmh
Tpbv
492
2127
23-28 24-15 24-1 24-37 24-5 24-10 18-43 18-19 18-11 18-34 18-33 18-22 18-21 18-1 8-4
A'
60'
1551
1552
1553
1571
2267
2268
2265
2266
1533
1534
CROSS SECTION A–A'
EXPLANATION
PLEISTOCENE (Qpl & Qpu)
Sand
Clay
BONE VALLEY FORMATION (Tpbv)
Sand
HAWTHORN FORMATION (Tmh)
Sand
Clay
OTHER SYMBOLS
Phosphate Particles
Limestone or Dolomite
Carbonate Pebbles
Marl
Shell Fragments
Phosphate Matrix
2266 = Sample Number
1000 0 1000 2000 3000 4000
HORIZONTAL SCALE (feet)
Vertical elevations relative to sea level
by DSC

Figure 10

Figure 11. Cross sections B-B' through F-F'.

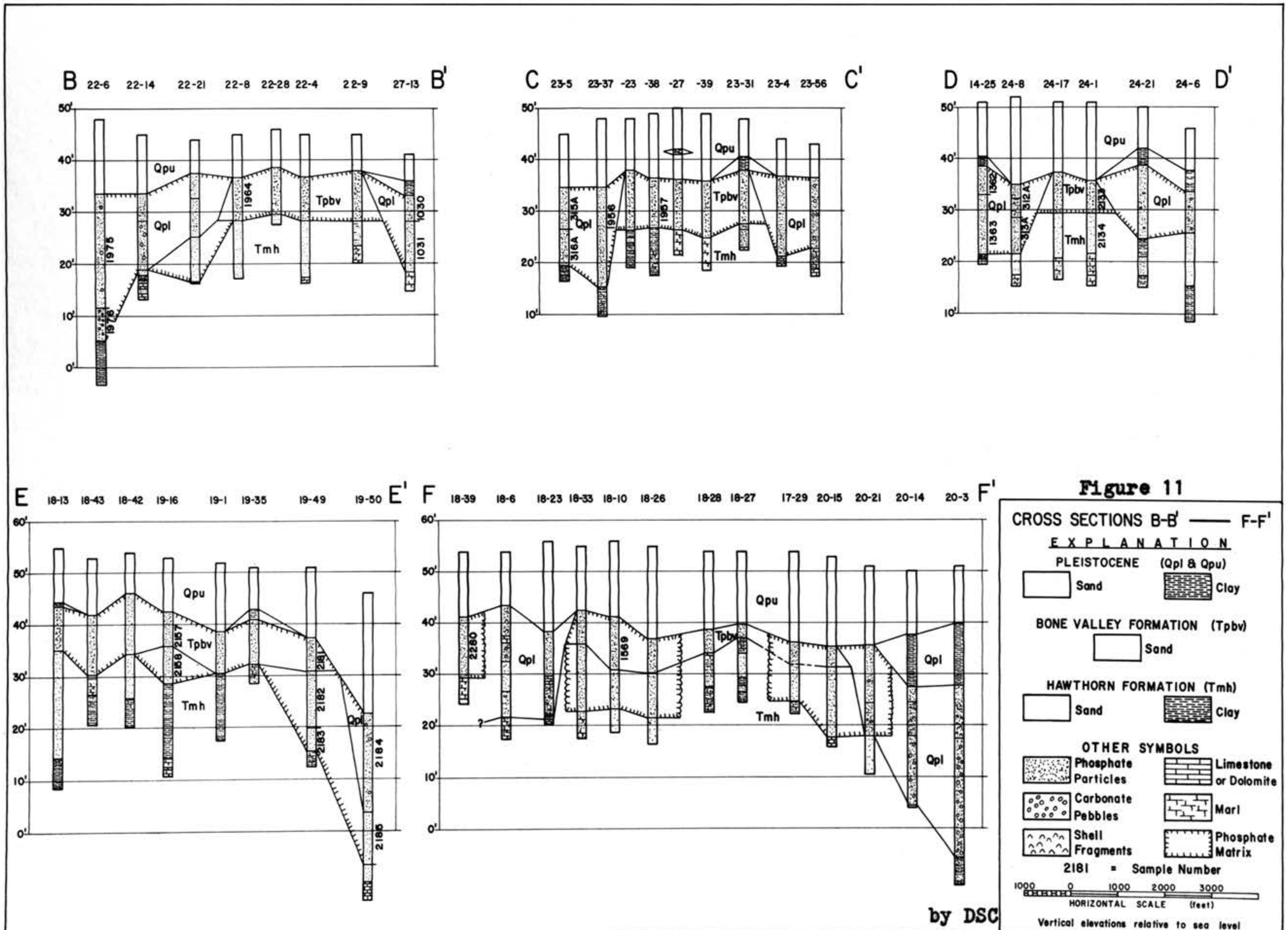


Figure 11

CROSS SECTIONS B-B' —— F-F'

Figure 12. Cross sections G-G' through I-I'.

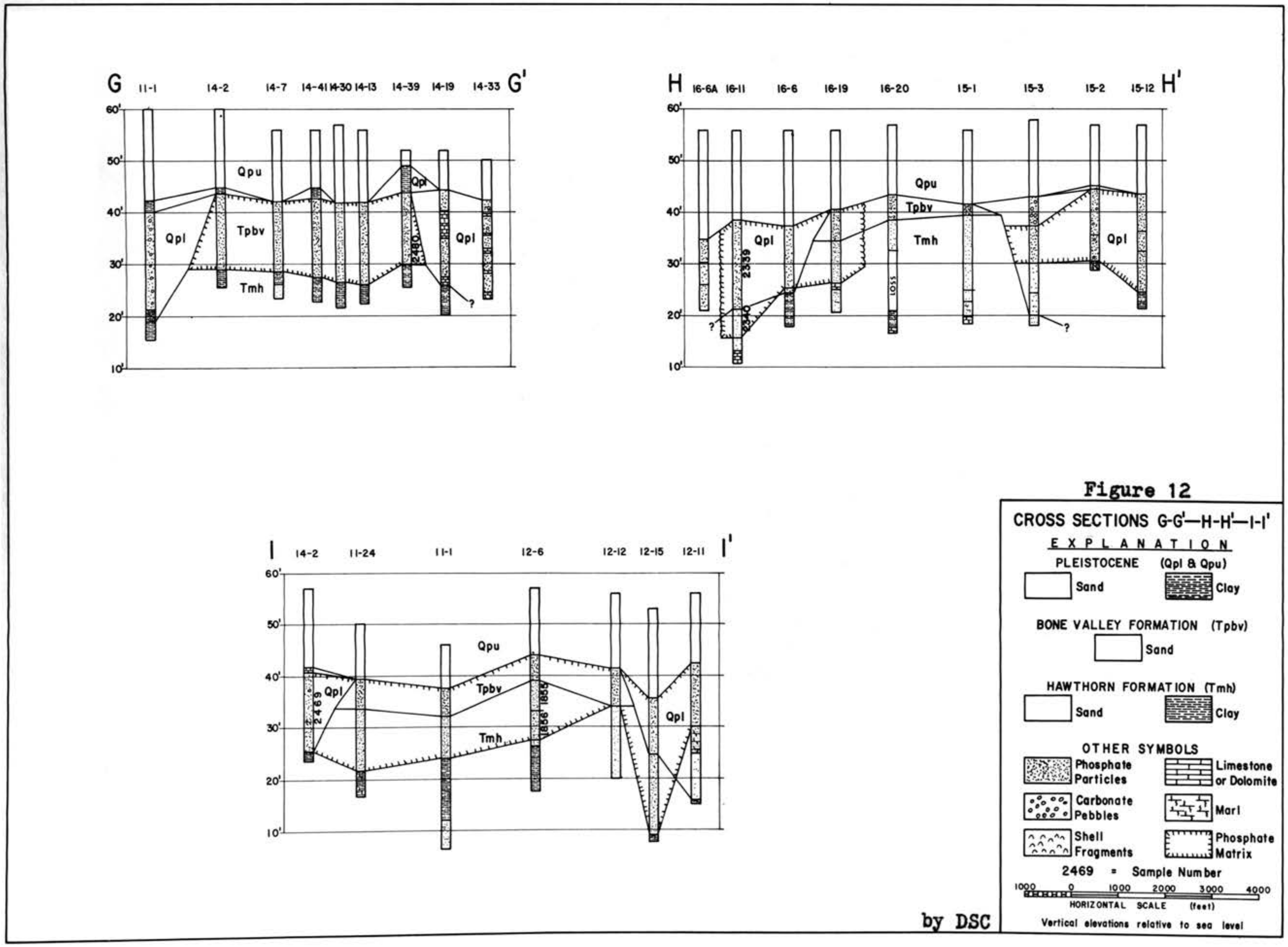


Figure 12

CROSS SECTIONS G-G'—H-H'—I-I'

Figure 13. Cross sections J-J' through L-L'.

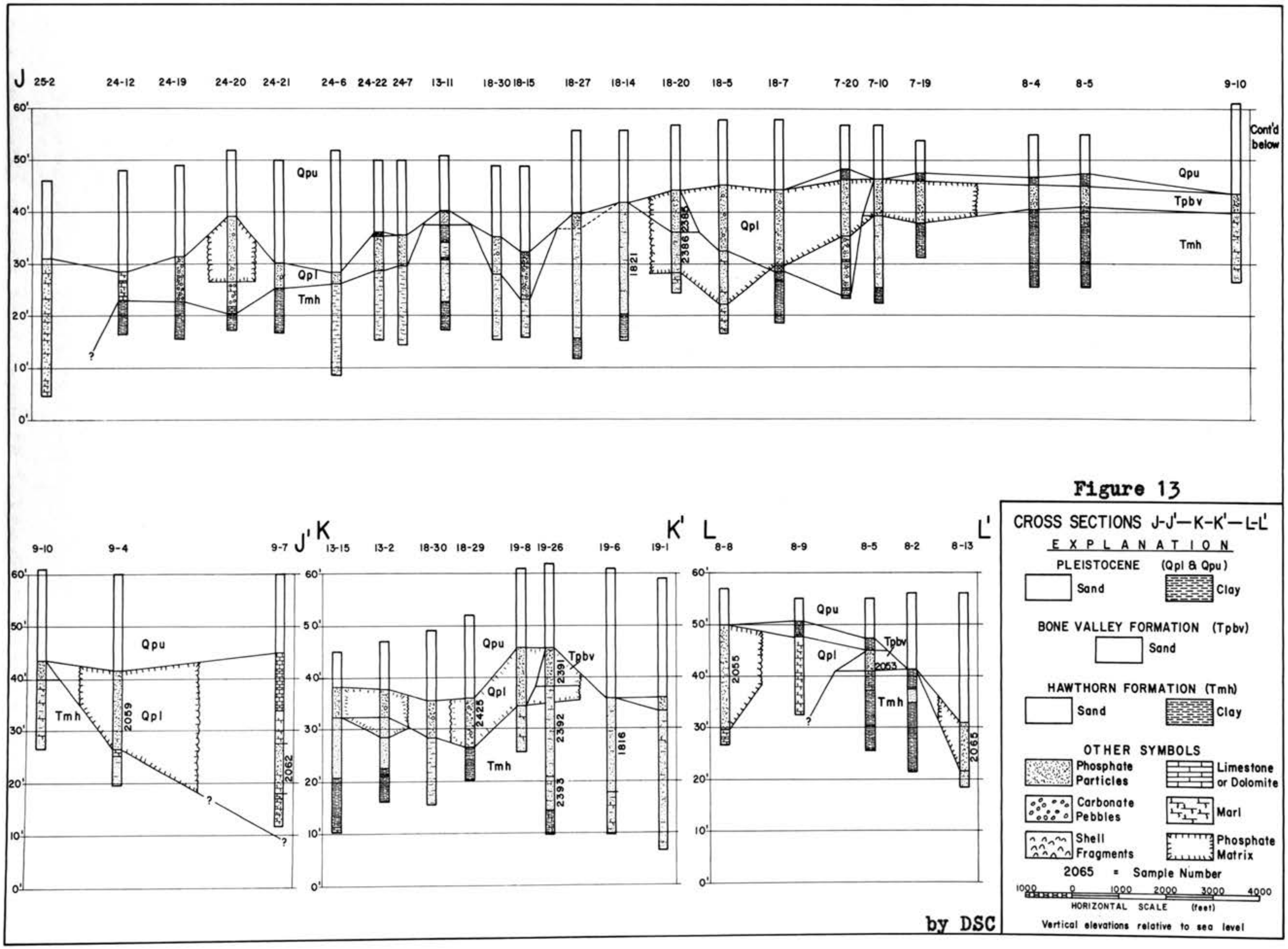


Figure 13

CROSS SECTIONS J-J'—K-K'—L-L'

accounted for by such westward tilting, however, such a minor difference in elevation is more readily explained as a gentle surface of low relief upon which the Bone Valley Formation was deposited.

The small size and limited areal extent of the Bone Valley erosional remnants do not supply sufficient definite information regarding the possible configuration of the Hawthorn-Bone Valley surface in the Pine Level area.

Bergendahl's (1956) "sand of late Miocene age" indicates that deposition of the upper clastic member continued for a much longer period of time in the Pine Level area, and the erosional interval that stripped the member from the Polk Upland was of much more limited duration. The apparent gentle surface suggests that the period of erosion following the deposition of the Hawthorn may have been of much less severity in the Pine Level area. Certainly the period of chemical weathering that formed the phosphate-rich residual source of the Bone Valley phosphate pellets in the Polk Upland could not have had the same result in the clastic terrain of the Pine Level area. A phosphate-rich mantle and reworked, phosphate-rich fluvial deposits most likely developed on the underlying phosphatic sands of the upper member of the Hawthorn Formation in the Pine Level area during the interval.

C. Quaternary System

1. Pleistocene Series

The principal difference in the Pleistocene deposits of the Polk Upland and the Pine Level area is related to recycling of sediments by the successive marine inundations.

The sedimentary deposits under the Lakeland and Lake Henry Ridges are generally coarse sand deposits (Altschuler and Young, 1960, Fig.

89.2; Pirkle et al., 1967, p. 253) that are most likely erosional remnants of Coharie deposits derived, in large part, from the Citronelle Formation.

The remainder of the Pleistocene deposits above the Wicomico scarp in the Polk Upland are Okefenokee sediments that have probably been mainly derived from both the upper member of the Bone Valley Formation and recycled Coharie deposits.

The Wicomico deposits under the De Soto Plain appear to be essentially composed of materials recycled from both the Bone Valley and Hawthorn Formations. Phosphate particles in the Wicomico deposits are ever present and locally very abundant.

The Pamlico deposits appear to be mainly recycled Wicomico deposits. They appear, in general, to contain somewhat less phosphate than the Wicomico deposits with the more abundant addition of broken shell fragments.

The Pine Level area, as noted in the section on physiography, has apparently been subjected to at least three Pleistocene marine transgressions separated by periods of subaerial erosion. Each succeeding marine invasion probably reworked part or all of the deposits of the previous cycle so that reconstruction of the detailed geologic history is not possible from the information available. The difficulty is further compounded by the fact that only sediments lowest in elevation and youngest in age (Pamlico and Silver Bluff) contain identifiable fossils of a marine environment (Puri and Vernon, 1964, p. 286). The writer recognizes two lithologically distinct deposits of apparent Pleistocene age in the Pine Level area: a lower, phosphatic, transgressive marine sand, and an upper, marginal marine to fluvial, regressive sand that blankets the entire area. The Pleistocene age assignment is indicated by stratigraphic position and a genesis related to regional Pleistocene history.

The two units are herein designated lower and upper Pleistocene on the basis of stratigraphic position. They may contain reworked deposits of several different Pleistocene marine invasions so the lower and upper designation does not denote any age significance.

Lower Pleistocene Sand: This unit consists of medium to very dark gray, fine- to coarse-grained, incoherent, loose, slightly clayey, phosphatic sand with minor thin intercalated beds of dark green sandy clay. Well rounded to subrounded, gray limestone granules and pebbles are characteristic and locally abundant, as are broken pelecypod fragments. Gray limestone, often partially decomposed by ground water so as to form a clayey rubble or marl, occurs in thin beds and may locally constitute as much as ten percent of the unit. The upper part of the unit is a local, erratically distributed orange-green mottled clay that varies from 0 to several feet in thickness.

The top of the sand occurs at an elevation approximating 20 feet above sea level in the Gulf Coastal Lowland portion of the Pine Level area, and at an elevation of 30 to 50 feet above sea level under the De Soto Plain portion. The sand does not now overlap or cover the Bone Valley Formation, but surrounds it at lower elevations (Figs. 8, 10, 11, 12, 13). The unit varies from a feather edge to more than 50 feet in thickness.

Most of the phosphate reserves of the Pine Level area, in marked contrast with the main producing area of the land-pebble field, occur in this lower Pleistocene sand. Details of the distribution and occurrence of phosphate within the unit will be discussed in a following section.

Upper Pleistocene sand: The upper Pleistocene sand blankets and covers the entire Pine Level area. It is a tan, light gray, or brownish-gray, fine- to coarse-grained, slightly clayey to loose, incoherent sand. The relationships of the clayey sand and the loose sand indicate that the loose sand appears to occur as channel fill; it is locally very coarse-grained; and it may represent a fluvial deposit that is younger than the clayey sand. The thickness of the upper Pleistocene unit varies from a few feet to more than 33 feet in thickness.

2. The Pliocene-Pleistocene Unconformity

Erosional relief on the base of the Pleistocene surface in the main producing area is not known in detail. One of Cathcart's cross sections (1963c, Fig. 3) shows local relief in this section is about 50 feet. Most of his other sections commonly show a variation on the base of the Pleistocene terrace sand of 10 to about 30 feet.

Figure 9 is a subsurface contour map of the pre-Pleistocene erosional surface (the surface formed by the transgressive marine erosion) in the Pine Level area. Both the lower transgressive phosphatic sand and the upper regressive sand are variable in thickness. The elevation of the base of the phosphatic sand varies from 31 feet below sea level in the SW$\frac{1}{4}$ Section 36, T. 37 S., R. 23 E. to 32 feet above sea level (Fig. 13, section J-J', hole 18-5). The base of the upper sand varies from near sea level in the SW$\frac{1}{4}$ Section 36, T. 37 S., R. 23 E. to 48 feet above sea level in Section 8, T. 37 S., R. 24 E. Maximum relief on the erosional surface is therefore 79 feet at the present time.

3. Recent Deposits

Phosphate sand and fine gravel deposited in bars along Horse Creek, muck and peat deposits in swamps and ponds, and iron-cemented "hardpan" a few feet beneath the surface constitute deposits of Recent age in the Pine Level area. The deposits are thin and erratic in distribution and have not been designated on the geologic map (Fig. 8). It is possible that the channel fill deposits, discussed above, may be of Recent age.

V. PLEISTOCENE PALEOGEOGRAPHY OF THE PINE LEVEL AREA

A. Introductory Comment

The configuration of the basal Pleistocene surface allows some interpretations pertaining to the paleogeography of the Pine Level area during the Wicomico transgression (Fig. 9). Additional geologic criteria related to such interpretations include the location and configuration of the Bone Valley erosional remnants, the general elevation of these remnants, the surrounding and flanking relationship of the lower Pleistocene sand, and the distribution of the matrix. These data indicate a variety of marine landforms were formed by the transgressive sea. These include a series of islands, several tidal passes, a low energy tidal terrace area, and areas of scouring by more active currents.

B. Bone Valley Islands

One of the more interesting and obvious features indicated by Figure 9 is that the erosional remnants of the Bone Valley Formation occupy the greater proportion of the total area above an elevation of about 30 feet above sea level (see stippled areas on Fig. 9). Below this elevation; except for the very small, local areas shown on Figure 8 where the upper Pleistocene sand fills channels scoured into the underlying Hawthorn; the lower Pleistocene sand rests directly on the Hawthorn Formation. Above this elevation the lower Pleistocene sand is not present, and the upper Pleistocene sand rest directly on the Bone Valley Formation. The contours within the stippled areas (Fig. 9) are therefore drawn on the contact between the upper sand and the Bone Valley Formation; and the contours outside of the stippled areas are consequently drawn on the lower Pleistocene sand-Hawthorn contact.

These relationships clearly indicate the present Bone Valley remnants were islands that stood above the advancing Wicomico sea during a temporary standstill where high tide reached an elevation of about 30 feet. The Bone Valley Formation outside of the stippled areas was eroded, winnowed, and recycled into the surrounding and flanking lower Pleistocene sand. The Hawthorn sediments between this elevation and the present base of the lower Pleistocene sand suffered similar erosion and redistribution.

It may also be noted that the base of the Bone Valley remnants, which represent the high tide mark of this temporary Wicomico standstill, increases from about 28 feet in Section 22, T. 37 S., R. 22 E.; to near 35 feet in Section 11, T. 37 S., R. 23 E.; and then to nearly 40 feet in Section 8, T. 37 S., R. 24 E. This could indicate that the Pine Level area has in fact been tilted westward approximately one foot per mile since this Wicomico standstill.

C. Tidal Passes

The distribution of the lower Pleistocene matrix is indicative of the presence of an active tidal pass trending in an arcuate north-south direction from Section 31 through the east part of Section 17 into Section 5, all in T. 37 S., R. 23 E. Further evidence, in addition to the north-south extended distribution of the matrix along this trend (Fig. 8), supports this interpretation. The depression or scour in Sections 17 and 20 is indicative of active current movement through this area, and the phosphate content of the sediments in this pass area is quite minor with an abundance of shell fragments and limestone pebbles (Fig. 11, section F-F', hole 20-3). Further, the pass area remained a low swale after the continued advance of the Wicomico sea, and it subsequently became filled with green clay that was eroded from the Hawthorn

Formation to the north and carried south into quiet water where it settled into and filled the swale. The thickest and most persistent occurrence of the green clay in the top portion of the lower Pleistocene sand occurs within this tidal pass area (Fig. 10, section A-A', hole 8-4; Fig. 11, section F-F', hole 20-3). The scour in Sections 24, T. 37 S., R. 22 E. and Section 19, T. 37 S., R. 23 E. indicates the tidal flow, in part or at one time, passed through this area.

The configuration of the matrix from the southwest corner of Section 32 to the southeast part of Section 14, T. 37 S., R. 22 E., is again indicative of redistribution of phosphate by tidal activity through a pass in the extreme northern part of Section 23. The pass appears to be rather shallow from Section 14 toward the southwest to the center of Section 28. At this point the Hawthorn surface steepens rather abruptly into an apparent scour that contains a considerable thickness of sand similar to the upper Pleistocene sand (Fig. 10, section A-A'). The abruptness may be related to some older small wave cut clifflike feature that formed when the sea stood at a lower level, but an explanation for the local thick section of nonphosphatic sand is not apparent.

The relationship at the extreme west part of the Pine Level area is not well understood and probably results, for the most part, from a lack of definitive lithologic information in the northwest part of the map area.

The presence of the passes implies that the northernmost part of the Pine Level area was occupied by a lagoon or embayment which restricted tidal action. The position of the actual shore line was evidently north of the Pine Level area at this time. The limited number of drill holes in Sections 1 and 2, T. 37 S., R. 23 E., and Section 20, T. 37 S.,

R. 22 E. contain a higher proportion of clay and clayey sand in the lower Pleistocene deposits and provides evidence of deposition in a much lower energy environment.

D. Beach Terrace

The large area between 20 and 30 feet in elevation in the southeastern corner of Manatee County evidently represents a lower energy wave cut terrace area that was protected from the more erosive activity of tidal or longshore currents.

This area is covered by a relatively thin and uniform veneer of lower Pleistocene sand (Fig. 10, section A-A'). The recovered +14 mesh pebble in this area contains, in general, a greater amount of coarser limestone pebbles than in most areas. Most of these limestone pebbles can be separated from the phosphate pebbles by a secondary screening at 6 or 8 mesh.

VI. DESCRIPTION OF THE PINE LEVEL MATRIX

A. General Description

The mineable phosphate zone, or matrix, of the Pine Level area may consist of any one of five different combinations of three different stratigraphic units: (1) only the Bone Valley Formation (Fig. 10, section A-A', hole 24-15), (2) only some portion or all of the lower Pleistocene sand (Fig. 10, section A-A', hole 28-6), (3) the Bone Valley Formation and a portion of an underlying phosphatic sand of the Hawthorn Formation (Fig. 10, section A-A', hole 22-37), (4) a combination of all or the basal part of the lower Pleistocene sand and underlying phosphatic sand of the Hawthorn Formation (Fig. 10, section A-A', hole 28-30), and (5) only a phosphatic sand unit of the Hawthorn Formation. The stratigraphic composition of the matrix thus varies from place to place throughout the Pine Level area.

The matrix ranges from 5 feet to over 40 feet in thickness and averages 14 feet. The thickness of the overburden also averages 14 feet. The basal elevation of the matrix varies from near sea level in Section 32, T. 37 S., R. 22 E. to about 40 feet above sea level in Section 8, T. 37 S., R. 24 E. The largest recoverable tonnage of phosphate rock occurs in the lower Pleistocene sand, and the actual reserve tonnage in the Hawthorn Formation is relatively minor.

B. Lower Pleistocene Matrix

The lower Pleistocene sand contains an incredible abundance of phosphate particles reworked from both the Hawthorn and Bone Valley Formations, but it is not everywhere economically mineable. In a large part of the area the phosphatic section is too thin (Fig. 10, section A-A', hole 33-29) or replaced by other sediments (Fig. 13, section J-J', hole 24-12), the phosphate content is too meager (Fig. 12, section H-H', hole 16-6A), or the phosphatic portion is too contaminated by calcium carbonate in the form of limestone pebbles or shell fragments to be useful (Fig. 10, section A-A', holes 32-5, 32-32, 28-6, and 27-6).

The actual lower Pleistocene matrix is generally restricted to the areas immediately adjacent to the Bone Valley remnants (Fig. 8), and as the distance from these remnants increases, becomes increasingly contaminated with limestone pebbles and shell fragments. The higher energy currents closely adjacent to the remnants winnowed and removed more of the materials of lighter specific gravity, and left a concentration of the fluorapatite particles.

The limestone pebbles are unusual in that in many local areas, because of the round shape, the difference in specific gravity, and their response to the energy of the depositional environment, they are often larger in size than the phosphate pebbles. In a great number of samples the use of a secondary coarse screening will remove all of the limestone pebbles from the +14 mesh fraction with minor loss of the phosphate content. The flat shell fragments, on the other hand, having exposed only surface edges to current flow, are much more varied in size. Moreover, the normal agitation of processing further breaks them into smaller fragments which eventually contaminate the flotation concentrate.

The lower Pleistocene matrix may constitute the entire thickness of the lower Pleistocene sand (Fig. 11, section B-B', hole 22-14), may occur at the top of it (Fig. 12, section I-I', hole 12-11), or may be restricted to the middle portion (Fig. 12, section H-H', hole 15-3). The top of the Pleistocene matrix normally forms a relatively uniform surface locally whereas the base, lying on the Hawthorn erosion surface and flanking the

Bone Valley remnants, is considerably more irregular (Fig. 11, sections B-B' and C-C').

Table IV presents the laboratory assay data for 20 Pleistocene matrix samples from 15 drill holes. The field lithologic logs of the 15 drill holes are included in the Appendix. The chemical analyses in Table IV and in all subsequent tabulations of analytical data were obtained commercially from Thornton Laboratories, 1145 East Cass Street, Tampa, Florida. The weighted average figures shown are derived from the actual weights of the sample fractions.

The apatite pebbles and pellets of the Pleistocene matrix are almost always black to dark brown. The +14 mesh pebble is low in BPL content, and relatively high in CaO and acid insoluble residue. Fortunately the pebble content of the matrix is relatively low, and the concentrates sufficiently high in BPL content and low in CaO, so that blending the pebble with the concentrate results in a marketable product. Sample 2062 (Table IV) is an example of an uneconomic sample highly contaminated by carbonate.

As shown by Table IV, the pebble content varies from about 2 to 12 percent of the matrix and averages about 5 percent, the feed content varies from about 70 to 90 percent, and averages about 83 percent, and the slimes content varies from about 6 to 24 percent and averages about 12 percent. The recoverable phosphate rock content is in excess of 20 percent of the matrix. An important fact, not shown by Table IV, is that approximately 50 percent of the slimes actually occur in the silt size range. The actual clay content of the Pleistocene matrix is very low. As a consequence, with little clay to serve as a "binder", the matrix is usually quite loose, incoherent, and unconsolidated.

Table IV. Lower Pleistocene Matrix Samples*

CROSS SECTION	HOLE #	SAMPLE #	+14 MESH PEBBLE				-14+150 MESH FEED		-150 MESH SLIMES	-14+150 MESH CONCENTRATES		
			% of Sample	% BPL	CaO/P_2O_5	% Insol.	% of Sample	% BPL	% of Sample	% BPL	CaO/P_2O_5	% Insol.
B-B'	22- 6	1975 + 1976	5.14	60.53	1.55	12.66	85.10	19.80	9.75	68.75	1.50	4.76
	27-13	1030 + 1031	4.74	63.79	1.55	8.11	82.40	17.48	12.86	68.47	1.54	5.01
C-C'	23- 5	315A + 316A	5.29	61.91	1.59	10.89	88.49	20.06	6.21	67.56	1.55	6.92
	23-37	1956	2.54	63.98	1.53	9.20	85.82	18.20	11.64	71.10	1.47	3.89
D-D'	14-25	1362 + 1363	4.67	62.32	1.46	13.59	72.13	23.20	23.50	72.31	1.45	3.82
	24- 8	312A + 313A	3.42	62.04	1.56	11.46	84.12	22.45	12.46	68.35	1.49	6.71
E-E'	19-50	2184	6.75	66.27	1.57	5.15	71.86	19.38	21.40	71.90	1.52	0.91
F-F'	18-39	2280	6.32	63.32	1.54	10.05	84.04	21.55	9.64	70.84	1.49	2.14
H-H'	16-11	2339	3.73	64.22	1.51	12.02	84.83	19.20	11.44	73.47	1.46	1.73
I-I'	14- 2	2469	2.17	68.32	1.53	4.95	87.86	17.18	9.97	70.86	1.50	3.00
J-J'	9- 4	2059	3.63	64.82	1.49	10.60	89.82	18.83	6.55	72.31	1.46	2.79
	9- 7	2062	11.83	47.28	1.87	10.20	76.38	19.61	11.79	66.73	1.56	3.60
K-K'	18-29	2425	10.57	61.92	1.57	8.75	70.38	22.12	19.05	67.65	1.59	5.64
L-L'	8- 8	2055	3.66	65.06	1.50	10.36	89.94	20.23	6.40	69.96	1.47	6.02
	8-13	2065	5.54	62.34	1.51	12.59	82.69	20.11	11.77	70.50	1.46	4.18
	Weighted Average:		4.95	61.76	1.57	10.07	82.92	19.92	12.13	70.11	1.50	4.23

* Analyses by Thornton Laboratories, Tampa, Florida.

C. Bone Valley Matrix

The Bone Valley Formation in the Pine Level area is preserved as a series of erosional remnants that were not destroyed and reworked by the transgressive Wicomico sea. The upper barren member of the Bone Valley Formation, if it was formerly present in the Pine Level area, has been completely stripped from the area by the Wicomico transgression. In addition, part of the upper portion of the lower phosphatic member has probably been removed. The Bone Valley Formation in several areas is too thin to be mineable and contains a very high proportion of pebble (Fig. 13, section J-J', hole 9-10 and section L-L', hole 8-5). It appears as if the pebble is a residual concentration remaining after the removal of the finer portions of the matrix by the winnowing currents of the Wicomico sea.

The Bone Valley matrix, except where it is too thin as noted, is minable for its full thickness wherever it occurs (Fig. 10, section A-A', Fig. 11, sections B-B' and C-C', Fig. 12, section G-G'). The Bone Valley rests with slight unconformity on the upper member of the Hawthorn Formation, and the base of the matrix forms a surface of very low relief. The upper surface is also relatively gentle except where the overlying upper Pleistocene sand has channeled down into or through it (Fig. 10, section A-A', holes 24-5, 24-10, 18-11, 18-34). The average thickness of the matrix normally varies between 12 and 15 feet. The matrix does not contain any detrital limestone pebbles or shell fragments.

Table V presents the laboratory assay data for 15 Bone Valley matrix samples from 15 drill holes. The field lithologic logs of the 15 holes are included in the Appendix.

The apatite pebbles and pellets from the Bone Valley matrix are

Table V. Bone Valley Formation Matrix Samples *

CROSS SECTION	HOLE #	SAMPLE #	+14 MESH PEBBLE				-14+150 MESH FEED		-150 MESH SLIMES	-14+150 MESH CONCENTRATES		
			% of Sample	% BPL	CaO/P_2O_5	% Insol.	% of Sample	% BPL	% of Sample	% BPL	CaO/P_2O_5	% Insol.
A-A'	22-12	492	8.92	63.43	1.50	9.06	80.01	18.05	11.07	70.83	1.49	0.92
	23-12	2127	4.62	67.30	1.50	6.74	87.14	18.75	8.24	72.79	1.46	1.59
	18-19	1551	11.18	66.84	1.53	6.49	75.45	19.87	13.37	73.53	1.46	1.54
	18-33	2265	13.93	65.87	1.53	6.63	74.95	25.00	11.11	71.13	1.44	1.34
	18- 1	1533	18.46	66.63	1.48	8.74	75.73	21.42	5.82	74.53	1.42	1.83
B-B'	22- 8	1964	9.84	66.08	1.50	7.58	77.66	22.80	12.50	71.30	1.49	2.88
C-C'	23-38	1957	3.47	65.50	1.50	9.65	81.16	19.15	15.37	72.98	1.50	2.59
D-D'	24- 1	2133	5.14	66.79	1.52	6.83	75.92	15.62	18.94	73.16	1.45	1.70
E-E'	19-16	2157	9.74	64.88	1.52	8.83	74.12	30.60	16.14	71.87	1.49	2.51
	19-49	2181	7.15	68.88	1.52	4.88	83.42	20.50	9.43	73.74	1.49	1.01
F-F'	18-10	1569	6.12	64.01	1.50	10.66	78.55	22.77	15.34	71.63	1.50	1.91
G-G'	14-39	2480	4.04	65.66	1.51	7.62	86.43	20.78	9.53	71.95	1.50	1.48
J-J'	18-20	2385	20.17	64.86	1.53	8.97	65.36	24.67	14.47	70.36	1.48	4.00
K-K'	19-26	2391	22.29	66.24	1.53	7.44	50.59	23.67	27.12	70.71	1.50	3.67
L-L'	8- 5	2053	5.24	64.49	1.52	8.84	81.56	19.07	13.20	70.75	1.50	3.25
	Weighted Average:		9.38	65.72	1.52	7.98	77.32	21.30	13.30	72.03	1.48	2.09

* Analyses by Thornton Laboratories, Tampa, Florida.

white, tan, light gray, and brown. The +14 mesh pebble is of nominal BPL, CaO, and insoluble residue content. The concentrates are high quality, and the blend of the pebble and concentrate is good, marketable phosphate rock.

The pebble content varies from about 3 to 22 percent and averages about 9 percent, the feed content varies from about 50 to 87 percent and averages about 77 percent, and the slimes content varies from about 6 to 27 percent and averages about 13 percent. The recoverable phosphate rock content is in excess of 20 of the matrix. The slimes content of the Bone Valley matrix is predominately clay. The amount of silt size particles in the slimes is minimal, and the interstitial clay "binds" the matrix so that it is coherent.

D. Hawthorn Matrix

The Hawthorn surface, as discussed, is an irregular erosional surface with at least 72 feet of relief in the Pine Level area, and is either overlain by the Bone Valley Formation, the lower Pleistocene sand, or the upper Pleistocene sand. The upper part is lithologically variable and may change from a rich phosphatic sand to clay or sandy clay within a relatively short distance (Fig. 11, section F-F', holes 18-26, 18-28). These circumstances have foiled repeated attempts to develop a systematic stratigraphic sequence for that part of the member penetrated by the exploration core holes.

The Hawthorn Formation, like the lower Pleistocene sand, contains an abundance of apatite. However, unlike the lower Pleistocene sand, the quantity is rarely sufficiently high for the phosphatic sand to be economically mined by itself. In a few local areas, where the phosphate content is relatively high, it is economically mineable. More often it must be mined in conjunction with the overlying Bone Valley or lower Pleistocene matrix (Fig. 10, section A-A', hole 24-1; Fig. 11, section B-B', hole 22-21). It is most often under these circumstances that the phosphatic sand of the upper clastic member of the Hawthorn Formation in the Pine Level area may be designated matrix in the strict sense of the term.

Table VI presents the laboratory assay data for 20 Hawthorn matrix samples from 15 drill holes. The term "matrix" is here used more freely. The field lithologic logs of the 15 drill holes are included in the Appendix.

The apatite pebbles and pellets of the Hawthorn matrix are white, tan, brown, or black. The +14 mesh pebble is very low in BPL content, and very high in CaO and acid insoluble residue. The concentrate is marketable phosphate rock with a nominal BPL and CaO content.

The Hawthorn matrix is always fine- to very fine-grained with a very low pebble content. As shown by Table VI, the pebble content never exceeds 1.5 percent of the matrix by weight. The feed content varies from about 78 to 95 percent of the matrix and averages about 86 percent, and the slimes content varies from about 9 to 15 percent and averages about 14 percent. The recoverable phosphate rock content is less than 20 percent. The slimes content of the Hawthorn matrix may vary from silt size particles to mostly clay. Normally the clay content reported in the slimes occurs as thin green clay seams in the matrix. The phosphatic sand rarely contains much interstitial clay, and is often loose, incoherent, and unconsolidated.

E. Summary of Distinguishing Matrix Characteristics

The Hawthorn matrix is readily and easily distinguished in field

Table VI. Hawthorn Formation "Matrix" Samples*

CROSS SECTION	HOLE #	SAMPLE #	+14 MESH PEBBLE				-14+150 MESH FEED		-150 MESH SLIMES	-14+150 MESH CONCENTRATES		
			% of Sample	% BPL	CaO/P_2O_5	% Insol.	% of Sample	% BPL	% of Sample	% BPL	CaO/P_2O_5	% Insol.
A-A'	18-19	1552 + 1553	0.94	61.18	1.61	8.19	77.60	9.47	21.46	72.45	1.48	1.60
	18-11	1571	0.46	58.93	1.71	13.84	87.73	10.23	11.81	71.54	1.48	1.83
	18-34	2267 + 2268	0.18	51.44	1.68	14.11	86.38	10.83	13.44	70.57	1.51	1.32
	18-33	2266	0.78	63.26	1.54	9.74	92.70	14.95	6.52	69.60	1.51	2.90
	18- 1	1534	0.91	63.94	1.49	9.71	90.44	10.91	8.65	72.65	1.46	1.36
D-D'	24- 1	2134	0.19	60.25	1.56	11.91	90.33	10.80	9.48	73.62	1.44	1.12
E-E'	19-16	2158	0.20	58.81	1.61	9.60	77.87	14.72	21.93	67.38	1.54	4.30
	19-49	2182 + 2183	0.61	57.95	1.66	7.73	80.05	18.93	19.34	69.31	1.54	1.77
	19-50	2185	0.12	49.39	1.63	18.04	95.36	14.15	4.51	68.57	1.53	1.39
H-H'	16-11	2340	0.77	61.18	1.56	9.61	82.32	13.60	16.91	70.86	1.51	1.13
I-I'	12- 6	1855 + 1856	0.45	59.49	1.52	17.23	81.10	12.95	18.45	72.93	1.48	1.60
J-J'	18-14	1821	1.20	63.51	1.50	11.12	84.57	14.95	14.23	70.61	1.48	2.23
	18-20	2386	0.86	52.54	1.58	20.11	79.70	14.73	19.45	67.37	1.52	5.01
K-K'	19-26	2392 + 2393	1.21	35.66	1.84	29.75	86.16	14.85	12.63	67.56	1.54	3.88
	19- 6	1816	1.11	61.21	1.44	15.00	89.81	12.91	9.08	70.95	1.47	2.58
	Weighted Average:		0.78	55.78	1.60	15.61	85.65	13.55	13.57	69.93	1.51	2.48

* Analyses by Thornton Laboratories, Tampa, Florida.

samples on the basis of the lean phosphate content, interstratified green clay seams, lack of pebble, and fine grain. The Bone Valley matrix can usually be distinguished by the color of the apatite, the high apatite content, the greater abundance of pebble, the elevation of the Hawthorn-Bone Valley contact, and the cohesiveness resulting from the interstitial clay. The Pleistocene matrix is distinguished by the color of the apatite, the high apatite content, the sparser amount of pebble, the possible presence of detrital limestone and shell fragments, the incoherence resulting from the lack of interstitial clay, and the elevation of the base of the matrix. If the assignment as Bone Valley or Pleistocene matrix cannot be made in the field, the laboratory data will normally resolve the problem.

F. Chemical Quality of the Phosphate Rock

A large bulk sample of matrix was prepared from drill hole samples collected in six sections in T. 37 S., R. 22 E. It is believed that the sample is representative of at least several million tons of the Pine Level phosphate rock. The detailed analysis of the phosphate rock obtained from this sample is shown in Table VII. The analysis is nominal for Florida phosphate rock.

Table VII. Analysis of Phosphate Rock from Composite Sample *

Constituent	Percent
Phosphorus Pentoxide (P_2O_5)	31.49
Equivalent BPL = 68.81	
Calcium Oxide (CaO)	46.87
Iron Oxide (Fe_2O_3)	1.72
Aluminum Oxide (Al_2O_3)	0.80
Acid Insoluble (including SiO_2)	5.53
Silica (SiO_2) = 4.91	
Carbon Dioxide (CO_2)	4.92
Organic Matter (C)	0.17
Combined Water (H_2O)	2.68
Fluorine (F)	2.07
Total Sulfur (as SO_3)	1.55
Magnesium Oxide (MgO)	0.30
Sodium Oxide (Na_2O)	0.79
Potassium Oxide (K_2O)	0.21
Chlorides (Cl)	0.01
Total	99.11

Analysis by Thornton Laboratories, Tampa, Florida.

VII. EFFECTS OF WEATHERING

A. General Statement

Alteration phenomena associated with several different periods of weathering have profoundly altered the phosphatic sediments of Florida. Alteration and weathering have played a major role in the formation of the economic deposits of the main producing area (Cathcart, 1966, p. 23). The role of leaching and redeposition of phosphate by ground water in the hard-rock field, and the formation of the aluminum phosphate zone by the alteration activity of acidic ground water in the land-pebble field have been previously discussed. The Pine Level deposit, due to the much more limited time that it has been exposed to weathering processes, has a different history of weathering and alteration, but the results are equally important. If it were not for the favorable consequences of these activities the Pine Level deposit would not be economically mineable today.

B. Depth of Burial and Apatite Quality Relationships

1. Apatite Color Changes

One of the most obvious features of the apatite in the Pine Level deposit is the invariable color change with increasing depth. The color change is equally pronounced in all three of the matrix units and is distinctly and positively related to the depth of burial.

The entire color change range is rarely exhibited in any one drill hole. The normal color range in a single hole is usually less than half of the total range. The color range scale is therefore composited from a number of drill holes in different areas.

The composited color change progression in the apatite particles with increasing depth, from near surface to those most deeply buried, is as follows:

1. White (N9)
2. Very light gray (N8) to pinkish gray (5 YR 8/1)
3. Light brownish gray (5 YR 6/1) to pale yellowish brown (10 YR 6/2)
4. Brownish gray (5 YR 4/1) to dark yellowish brown (10 YR 4/2)
5. Dark brownish gray (5 YR 3/1) to dusky yellowish brown (10 YR 2/2)
6. Brownish black (5 YR 2/1) to dusky yellowish brown (10 YR 2/2)
7. Grayish black (N2)

The BPL content of the white apatite is the highest and that of the black apatite the lowest, and the BPL content is positively correlated with the color changes. This relationship is discussed in detail in a later section of this chapter.

2. Water Table Level

A well defined color change in the sediments, commonly around 25 or 30 feet in depth, is encountered in most of the drill holes. The color contact is variable in depth from area to area and usually occurs over a four or five foot interval. Immediately above the color contact the phosphatic sands are generally medium to dark brownish gray with brown apatite particles. Immediately below the contact the sands are very dark gray to grayish black with grayish black apatite particles. Clays in the Hawthorn Formation or in the lower Pleistocene sand commonly change across the gradational contact from a light to medium grayish green to a very dark green.

The Bone Valley Formation, by virtue of its occurrence in the higher elevation island remnants, is always above this color change. The change, in areas where the Bone Valley occurs, is generally ten feet or so below the base of the Bone Valley in the upper portion of the

Hawthorn. The color change is deeper and more variable in depth in the areas away from the Bone Valley island remnants. The clays in the Hawthorn, under the island remnants, have served as a permeability barrier that prevented any deeper downward development of the color change.

When two or more samples are obtained from the same drill hole and are separated by this contact, the upper sample invariably contains better quality apatite. This relationship is indicated by Tables VIII and IX. Clearly, some deleterious impurities from above this contact have been removed.

These data suggest the color contact represents the maximum depth of alteration by the present fluctuating ground water table, and the upper samples in Tables VIII and IX have been beneficially altered by this descending ground water.

3. Depth of Burial

As a general but reasonable approximation it can be stated that the Bone Valley matrix occurs at the highest overall elevation, the lower Pleistocene matrix at an intermediate elevation, and the Hawthorn matrix at the generally lowest overall elevation. As a further broad generalization, all of the Bone Valley matrix is above the color change related to the water table, the lower Pleistocene matrix is partly above and partly below it, and most of the Hawthorn samples are below it. The differences in the weighted average analyses shown in Tables IV, V, and VI are readily explained by the above relationship at the water table color change.

C. General Mineralogical Aspects of Possible Leaching Mechanism

The quantitative chemical relationships that could be involved in

Table VIII. Comparison of Upper and Lower Pleistocene Matrix Samples in the Same Drill Hole*

	CROSS SECTION	HOLE #	SAMPLE #	+14 MESH PEBBLE			-14+150 MESH CONCENTRATES		
				% BPL	CaO/ P_2O_5	% Insol.	% BPL	CaO/ P_2O_5	% Insol.
UPPER	B-B'	22-6	1975	61.11	1.55	12.44	69.79	1.48	4.83
UPPER	C-C'	23-5	315A	63.12	1.62	9.33	67.32	1.55	8.07
UPPER	D-D'	24-8	312A	65.77	1.53	8.93	69.79	1.46	6.20
	Weighted Average:			61.95	1.56	11.52	69.23	1.49	5.81
LOWER	B-B'	22-6	1976	51.77	1.66	16.13	64.79	1.58	4.49
LOWER	C-C'	23-5	316A	61.16	1.57	11.85	67.80	1.54	5.82
LOWER	D-D'	24-8	313A	59.37	1.58	13.26	66.93	1.51	7.21
	Weighted Average:			59.70	1.58	12.69	66.76	1.54	5.99

* Analyses by Thornton Laboratories, Tampa, Florida.

Table IX. Comparison of Upper and Lower Hawthorn Formation Samples in the Same Drill Hole *

CROSS SECTION	HOLE #	SAMPLE #	+14 MESH PEBBLE			-14+150 MESH CONCENTRATES		
			% BPL	CaO/ P_2O_5	% Insol.	% BPL	CaO/ P_2O_5	% Insol.
A-A'	18-34	2267		None		72.18	1.50	0.88
E-E'	19-49	2182	65.74	1.54	6.28	70.99	1.53	1.53
I-I'	12- 6	1855	63.27	1.53	11.79	73.67	1.48	1.33
Weighted Average:			64.89	1.54	8.17	71.84	1.51	1.36
A-A'	18-34	2268	51.44	1.68	14.11	69.00	1.52	1.74
E-E'	19-49	2183	39.96	2.07	11.03	66.68	1.57	2.15
I-I'	12- 6	1856	55.27	1.51	22.92	72.23	1.49	1.85
Weighted Average:			48.07	1.78	15.68	68.89	1.53	1.96

* Analyses by Thornton Laboratories, Tampa, Florida.

the beneficial alteration of the Pine Level apatite by ground water is shown by a series of four weighted average analyses calculated for four grades of pebble selected from the approximately 1,800 sample analyses. The four analyses are calculated from samples in each of the grade ranges: 50-55 percent BPL, 55-60 percent BPL, 60-65 percent BPL, and 65-70 percent BPL. Ten, large volume, randomly selected pebble samples were used to derive the weighted average composite analysis in each grade range. Each composite analysis represents a significant amount of the total available pebble in the Pine Level deposit within that grade range, and the calculated composites are therefore believed to be representative. The four calculated analyses are given in Table X. The column labeled "unanalysed constituents" represents the difference between 100 percent and the sum of the constituents reported in the other columns.

It can be seen that the lowest grade pebble (composite 1) is relatively low in P_2O_5 and relatively high in every other constituent. The highest grade pebble (composite 4) is nominal, commercial quality phosphate rock that is relatively high in P_2O_5 content and relatively low in the other constituents. These data indicate that the major impurities in composites 1, 2, and 3 may be quartz, calcite, dolomite, and other unidentified minerals. These analyses, coupled with the color changes and the decreasing quality with depth, previously discussed, strongly indicate that the mineral contaminants are removed by some method, most probably by some mechanism involving ground water activity, so that low grade apatite is beneficially altered to nominal commercial quality phosphate rock.

Table X. Calculated Weighted Average Analyses of Composite Pebble Samples. *

Sample	BPL	P_2O_5	I&A	Insol	MgO	CaO	CaO/P_2O_5	Unanalyzed Constituents
	Percent							
1	52.39	23.98	3.06	10.90	2.79	41.21	1.72	18.06
2	57.84	26.47	2.75	10.24	1.63	42.54	1.61	16.37
3	62.80	28.74	2.64	9.00	0.71	44.72	1.56	14.19
4	67.59	30.93	2.32	6.19	0.41	46.78	1.51	13.37

Weighted average composite of ten random large volume pebble samples in:

1 = 50-55 % BPL range (22.9-25.2 % P_2O_5)

2 = 55-60 % BPL range (25.2-27.5 % P_2O_5)

3 = 60-65 % BPL range (27.5-29.7 % P_2O_5)

4 = 65-70 % BPL range (29.7-32.0 % P_2O_5)

* **Analyses by Thornton Laboratories, Tampa, Florida.**

D. The Aluminum Phosphate Zone in the Pine Level Area

Evidence of the intense lateritic weathering that formed the aluminum phosphate zone in the main producing area is not abundant in the Pine Level area. In many places, where the overburden is thin or apparently more permeable, sparse apatite pebbles in the basal portion of the upper Pleistocene sand may be altered to soft, white, chalky aluminum phosphate minerals (see Appendix-Field Logs of Selected Drill Holes). Also, the uppermost few inches of the matrix may be similarly altered. The period of lateritic weathering that profoundly altered the Bone Valley apatite in the main producing district was less intense in the Pine Level area.

E. Detailed Study of Selected Samples

To examine the mechanism of the mineralogical and chemical changes in the alteration process, a set of four pebble samples has been studied in more detail. The four samples were prepared by hand sorting four color phases of apatite pebbles in the 0.05 to 0.20 inch size range from a large volume of pebble samples. The four selected color phases are white, gray, brown, and black. These colors very well represent the entire range of apatite pebbles in the Pine Level deposit. The white pebbles are characteristic of shallow apatite that has been most intensively altered, the gray pebbles are characteristic of the zone above the water table color change, the brown pebbles represent apatite within or slightly below the horizon of the color change, and the black pebbles represent deeply buried unaltered apatite from well below the color change zone.

X-ray diffractometer patterns of the four colored samples are shown in Figure 14. Carbonate fluorapatite is the most abundant mineral in

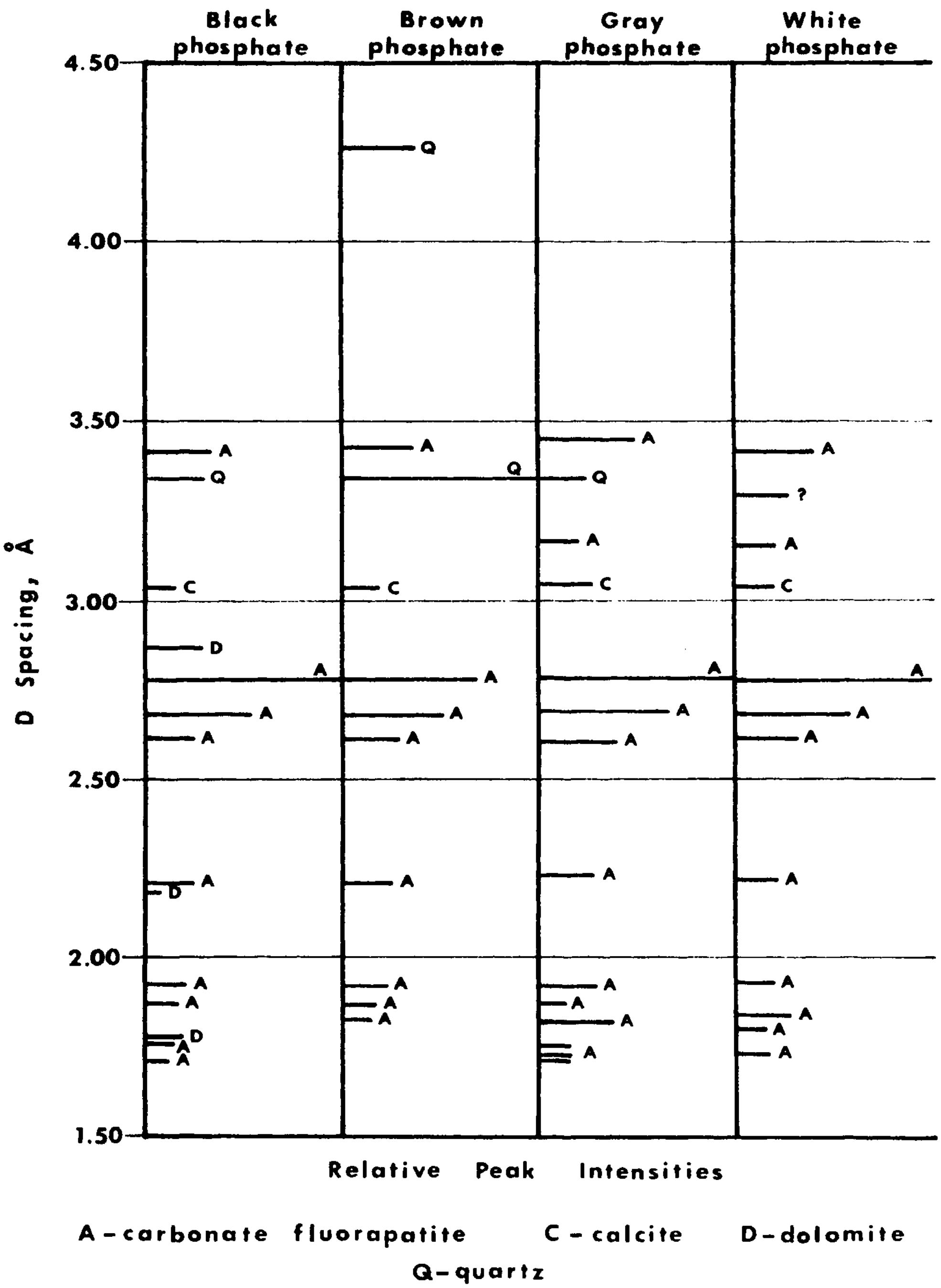


Figure 14. X-ray diffractometer patterns of phosphate rock samples (copper K-alpha radiation).

all of the samples. Calcite also is present in all of the samples. Quartz is identified in all but the white phosphate rock, and dolomite is only identifiable in the black phosphate.

1. Petrographic Relationships

Thin sections of the four samples were prepared for petrographic study. The apatite in the thin sections appears to be amorphous, isotropic, and consists of microcrystalline aggregates of crystals too small to be resolved by the microscope (Russel and Trueman, 1971, p. 1206). A few pebbles or portions of pebbles consist of fibrous apatite that exhibits slight birefringence. At least two stages of apatite, based on a different appearance as the result of impurity inclusions, can be distinguished in plain transmitted light. The earlier stage generally contains submicroscopic inclusions that impart a "dusty" appearance to the apatite while the later stage is clear and appears to be completely amorphous. It commonly fills cracks and fractures, occurs as a rim completely encasing the earlier variety, or embays and replaces other minerals.

The thin sections of the black pebbles (Figs. 15 and 16) contain abundant subhedral, angular grains of calcite that range from submicroscopic in size to nearly a millimeter in the longest dimension. The calcite grain boundaries are generally very sharp and distinct. The apatite is predominately the "dusty" variety containing abundant birefringent microcrystalline impurities that impart a deep, intense bronze sheen under crossed nicols. Several pebbles have pronounced thin rims of black amorphous apatite that appears to be later than the core. Pyrite and quartz were not identified in the thin sections, but were noted in crushed material examined under the binocular microscope.

Figure 15. Thin section of black phosphate rock pebble. Rock is characterized by large angular inclusions of calcite (white) in a groundmass of carbonate fluorapatite. Plain light, X85.

Figure 16. Same view as above with crossed nicols. Note large calcite grains, finger-like slightly birefringent apatite grain at lower left, abundant birefringent impurities in apatite at upper right, and scattered impurities in isotropic apatite throughout remainder of section.

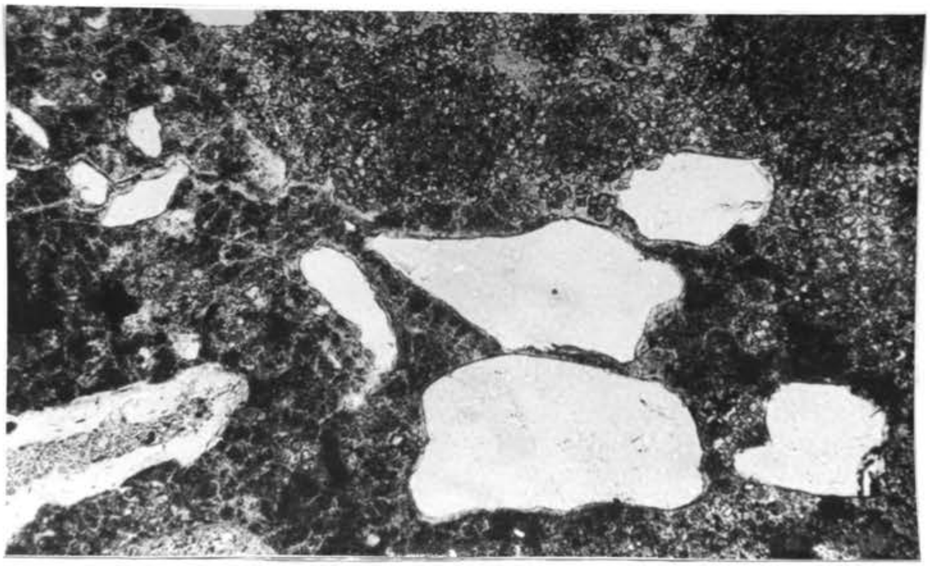
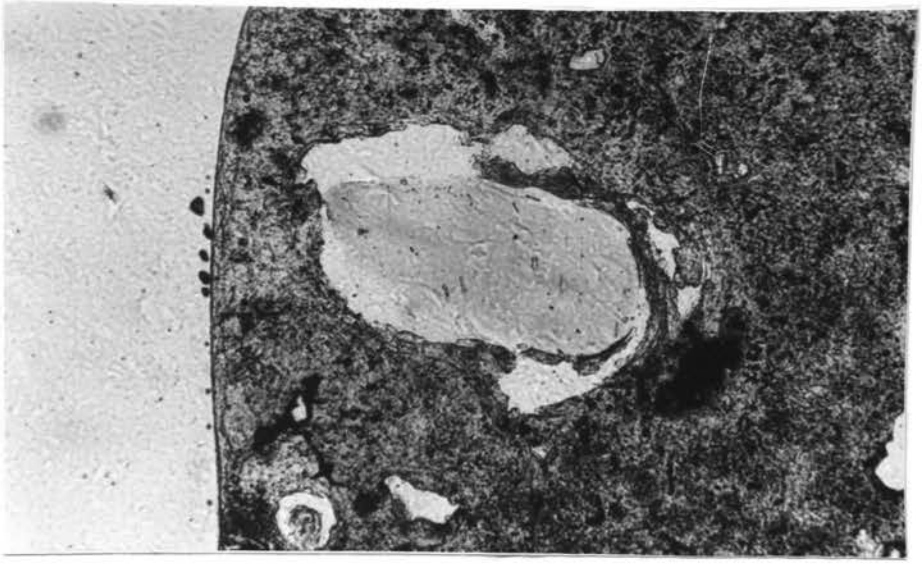


Figure 17. Thin section of brown phosphate rock pebble. Groundmass of carbonate fluorapatite (dark gray) contains large rounded calcite grain (medium gray) partially replaced by clear apatite (white). Smaller grains of former calcite (white) have been entirely replaced by clear apatite. Irregular opaque splotches are colloidal iron oxide apparently derived from pyrite. Plain light, X85.

Figure 18. Same view as above with crossed nicols. Note diffused boundaries of remaining calcite.



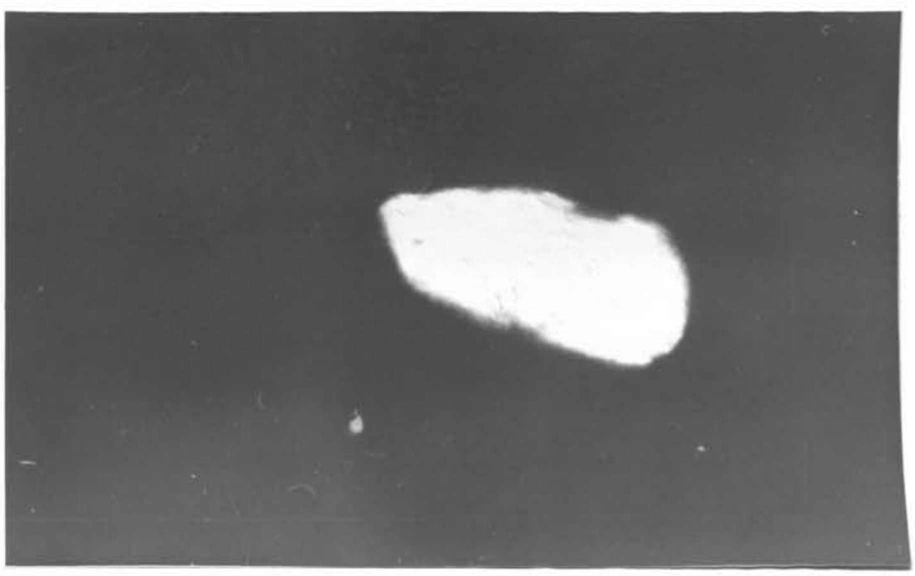


Figure 19. Thin section of gray phosphate rock pebble (approximately upper two-thirds of view). Groundmass of carbonate fluorapatite (light gray) contains secondary apatite (dark gray) that has replaced former calcite grains. Plain light, X85.

Figure 20. Same view as above with crossed nicols. Note general reduction of contained birefringent impurities as compared to previous figures.

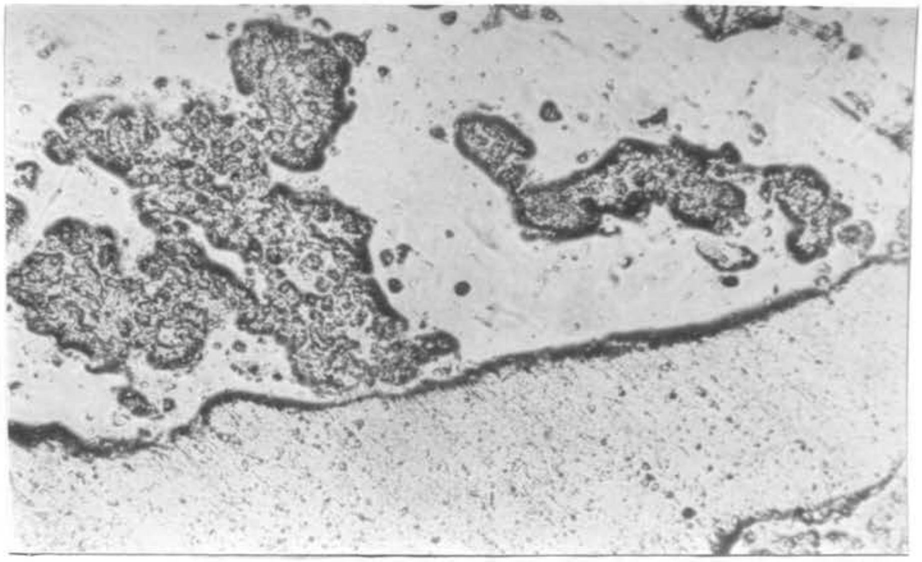


Figure 19

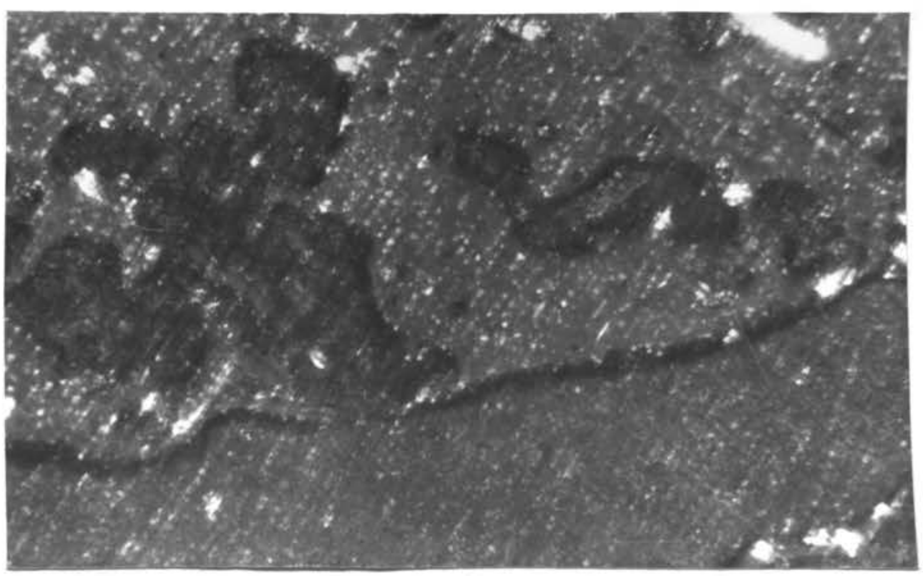


Figure 20

Figure 21. Thin section of white phosphate rock pebble. Entire section is groundmass of carbonate fluorapatite. Note apparent diffused boundary between two stages of apatite in left portion of the view. Plain light, X85.

Figure 22. Same view as above with crossed nicols. Note continued reduction of birefringent impurities.

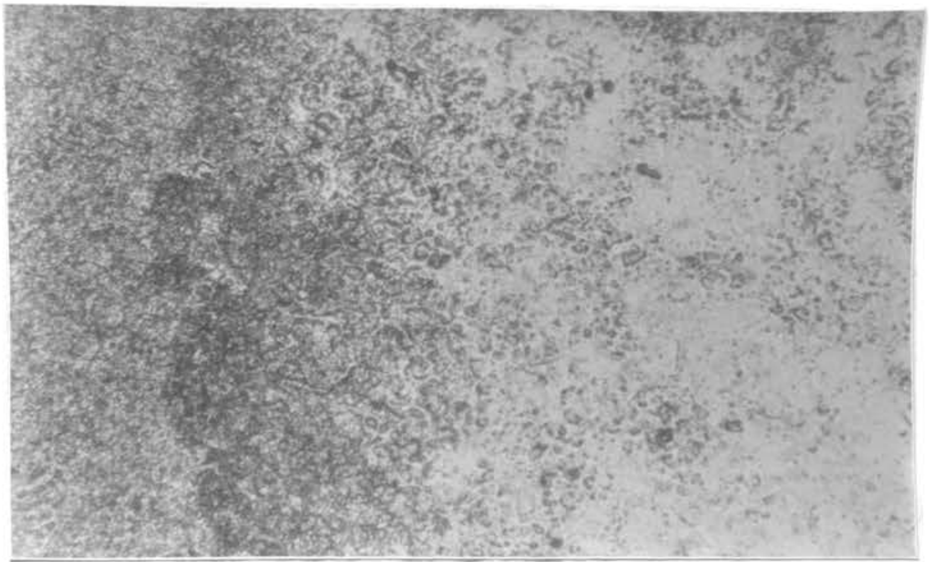


Figure 21

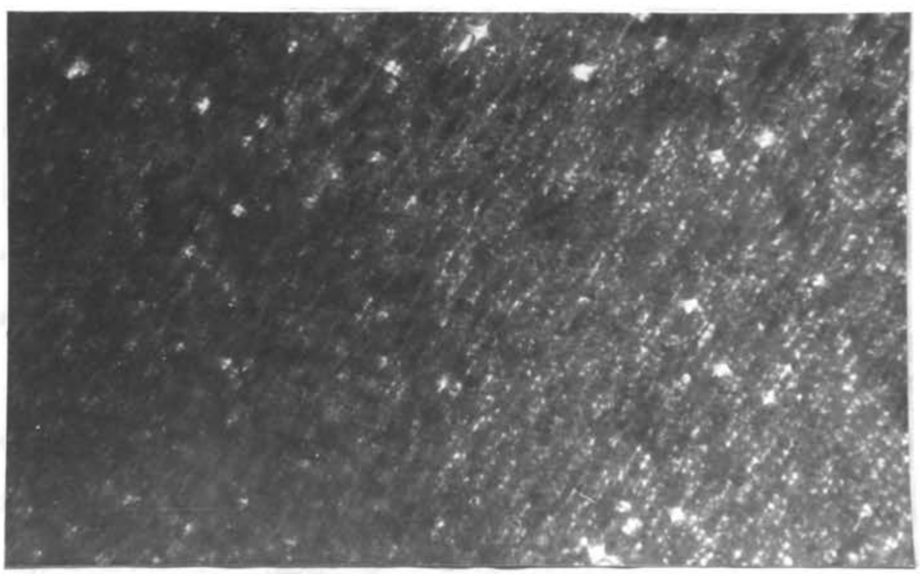


Figure 22

The brown pebbles contain much less calcite, and the grain boundaries are corroded, embayed, and partially replaced by amorphous apatite (Figs. 17 and 18). The pyrite of the black pebbles now appears to have been altered to amorphous iron oxide which imparts the brown color to the pebbles. Again, quartz was not noted in the thin sections.

Calcite grains in the gray pebbles (Figs. 19 and 20) are seen to be largely replaced by amorphous apatite. Impurities of both iron oxide and minute birefringent minerals are relatively minor.

Thin sections of the white pebbles (Figs. 21 and 22) are almost completely amorphous apatite. Calcite has been almost entirely replaced and only the centers of a few pebbles contain remnant concentrations of iron oxide. Other impurities are not recognizable.

2. Chemical Relationships

Detailed chemical analyses of the important constituents in the four color phases are given in Table XI. Analyses of the minor constituents; essentially water, chlorine, sulfate, and sodium; were not obtained and are reported as "Not Assayed" in the table.

The chemical analyses appear to correlate quite well with the petrographic and x-ray observations. The decreasing $CaO:P_2O_5$ ratio, coupled with the abrupt decrease in CO_2 content from the black to the brown samples, clearly indicates an increase in apatite at the expense of calcite. The decreasing insoluble residue content also indicates an increase in apatite at the expense of silicate (?) impurities. The color of the black pebbles is explained by the high organic carbon content and finely disseminated pyrite.

Table XI. Analyses of Selected Colored Samples

Constituent	Color: Black	Brown	Gray	White
P_2O_5	25.65	29.64	30.71	32.19
CaO	43.16	46.00	46.16	47.38
CaO/P_2O_5 Ratio	1.68	1.55	1.50	1.47
Fe_2O_3	1.83	2.47	0.92	0.76
Al_2O_3	0.74	0.84	1.81	1.89
CO_2	8.74	4.96	4.74	4.67
C (Organic)	0.66	0.24	0.28	0.20
Insoluble Residue	5.99	4.67	3.63	3.50
F	2.88	3.38	3.53	3.69
MgO	2.40	0.52	0.58	0.31
Not Assayed	7.95	7.28	7.64	5.41
Total	100.00	100.00	100.00	100.00

Precise sample colors based on the Geological Society of America Rock Color Chart:

Black = Grayish Black (N2)
Brown = Grayish Brown (5 YR 4/2)
Gray = Light Brownish Gray (5 YR 6/1)
White = Light Pinkish Gray (5 YR 9/1)

3. Chemistry of Replacement

The analyses of Table XI provide the basis for a semiquantitative estimation of the progressive mineralogical changes that occur in the formation of the white apatite pebbles from the impure black pebbles. Such an estimate requires some simplifying assumptions regarding the unidentified mineral inclusions that detract from the precision of the estimate, but, nevertheless, should yield useful general information on the course of the overall replacement process.

To pursue this examination the following simplifying assumptions are used:

(1) The 0.74% Al_2O_3 in the black pebble is present in an unaltered, unidentified mineral impurity, and the excess of this amount in the remaining samples is present in crandallite that has altered from apatite with the formula $CaAl_3(PO_4)_2(OH)_5\ H_2O$. The stoichiometric ratios are % Al_2O_3 x 2.707 = crandallite, x 0.367 = % CaO, and x 0.928 = % P_2O_5. It is assumed that the excess Al_2O_3 in the brown, gray, and white samples has been added from an external source.

(2) The carbonate anion substitutes for the phosphate anion in the apatite in such an amount that the formula can be artificially expressed, based on an "average" amount of substitution, as $Ca_{11}(PO_4)_6(CO_3)F_{2-3}$. This is a simplification of the formula $Ca_{4.967}Na_{0.033}(PO_4)_{2.899}(CO_3)_{0.122}(SO_4)_{0.019}F_{1.116}(OH)_{0.050}$ calculated by Russel and Trueman (1971, p. 1210) for Florida phosphate rock. The ratios are therefore % P_2O_5 x 2.603 = % apatite, x 1.440 = % CaO, x 0.1034 = % CO_2, and % apatite x 0.0892 = % F.

(3) The excess fluorine shown by Table XI over the amount required above is present in the apatite (Gulbrandsen, 1969, p. 370).

(4) The remaining excess Cao over the amount required for calcite, crandallite, and apatite is present in other unidentified minerals, and

(5) The 0.31% MgO of the white sample is present in unidentified minerals since it is assumed that all MgO in dolomite would have been replaced during the formation of the white sample. The excess of this amount in the remaining samples is present as $MgCO_3$ (in dolomite) so that % MgO x 2.092 = % $MgCO_3$.

Table XII presents the calculated mineralogical composition of the four samples based on the above assumptions. It is, of course, realized that the data can be subjected to many different interpretations. For example, Al_2O_3 could logically be at least partly assigned to kaolinite, and SiO_2 is probably not entirely present as quartz but in unidentified silicate minerals. The purpose is not to precisely determine these details but to clearly indicate that all of the other minerals have been progressively replaced by apatite during the process of forming high grade light colored apatite from the low grade, impure black apatite

4. Conclusions

The data presented in this section demonstrates that the commercial quality apatite of the Pine Level area has most likely formed since the retreat of the Wicomico sea with the consequent exposure of the sediments to weathering and erosion. It appears that descending, slightly acidic ground water leached phosphate from overlying Pleistocene sediments and carried it downward where apatite has systematically replaced mineral impurities in the underlying phosphate particles. That apatite, or rather the phosphate ion, is mobile in slightly acidic ground and surface water is shown by Kaufman (1969). The initial replacement of dolo-

Table XII. Calculation of Mineral Constituents of Selected Colored Samples

		Color			
		Black	Brown	Gray	White
1.	Surplus Al_2O_3 (+0.74%)	0.00	0.10	1.07	1.15
2.	% Crandallite (1 x 2.707)	0.00	0.27	2.90	3.11
3.	Contained CaO in 2 (1 x .367)	0.00	0.04	0.39	0.42
4.	Contained P_2O_5 in 2 (1 x .928)	0.00	0.09	0.99	1.07
5.	Balance CaO (Assay - 3)	43.16	45.96	45.77	46.96
6.	Balance P_2O_5 (Assay - 4)	25.65	29.55	29.72	31.12
7.	% Apatite (6 x 2.603)	66.77	76.92	77.36	81.01
8.	Contained F in 7 (6 x .0892)	2.29	2.64	2.65	2.78
9.	Surplus F (Assay - 8)	0.59	0.74	0.88	0.91
10.	Adjusted % Apatite (7 + 9)	67.36	77.66	78.24	81.92
11.	Contained CaO in 10 (6 x 1.449)	37.17	42.82	43.06	45.09
12.	Contained CO_2 in 10 (6 x .1034)	2.65	3.05	3.07	3.22
13.	Balance CaO (5 - 11)	5.99	3.14	2.71	1.87
14.	Surplus CO_2 (Assay - 12)	6.09	1.91	1.67	1.45
15.	Surplus MgO (+ 0.31%)	2.09	0.21	0.27	0.00
16.	% $MgCO_3$ (15 x 2.092)	4.37	0.44	0.56	0.00
17.	Balance CO_2 (14 -(16 - 15)	3.81	1.68	1.38	1.45
18.	% $CaCO_3$ (17 x 2.274)	8.66	3.82	3.14	3.30
19.	Balance CaO (13 -(18 - 17)	1.14	1.00	0.95	0.02

Summary

	Black	Brown	Gray	White
% Apatite	67.36	77.66	78.24	81.92
% Crandallite	0.00	0.27	2.90	3.11
% $MgCO_3$	4.37	0.44	0.56	0.00
% $CaCO_3$	8.66	3.82	3.14	3.30
% SiO_2 (Insol assay)	5.99	4.67	3.63	3.50
% Other Mineral Constituents	13.62	13.14	11.53	8.17
% Total Apatite	67.36	77.66	78.24	81.92
% Total Other Mineral Constituents	32.64	22.34	21.76	18.08

mite and calcite was rapid and probably resulted from simple neutralization of acidic water by the carbonates. Alteration of pyrite to iron oxide is also apparently an early alteration process. Replacement of the other minerals appears to follow calcite replacement and apparently occurs later at shallower depths where oxidation-reduction processes are evidently more prevalent.

VIII. GEOLOGIC HISTORY OF THE LAND-PEBBLE FIELD AND PINE LEVEL AREA

A. Introduction

Various events in the geologic history of central peninsular Florida have been discussed, necessarily, in previous portions of this paper, so the treatment of the subject here entails a certain amount of redundancy. However, a recapitulation, in proper chronological sequence, serves to relate the events to one another in a more coherent manner. Further, it provides a means for emphasizing the interrelated events that are most important in the development of the phosphate deposits of the land-pebble field and the Pine Level area.

B. Early Tertiary Events

The early Tertiary sedimentary rocks, from the Paleocene Cedar Keys Formation through the middle Miocene lower limestone member of the Hawthorn Formation, are characterized by an unconformable assemblage of carbonate strata deposited in the Florida Peninsula sedimentary province. These sedimentary deposits record shallow water, offshore marine environments, with the shore line far to the north. The Florida peninsula was a shallow shelf area that continued to develop by the accretion of carbonate strata over the older Peninsular Arch.

The numerous unconformities and variable distribution of these carbonate strata indicate the peninsular area was structurally very unstable with numerous periods of erosion and tilting. During these times portions of the area were above the sea and formed an insular system surrounded by shallow limestone marine banks. This long period of alternate shallow water marine carbonate deposition and erosion was terminated by the closing stages of the Ocala uplift.

C. The Upper Member of the Hawthorn Formation

Movement of the Ocala uplift apparently terminated during middle Miocene time. The present location and configuration of the uplift indicates it is a relatively local feature confined to the west central part of the Florida peninsula (Fig. 2). The actual uplift, however, affected all of the Florida peninsula, which, for the first time, received clastic sediments derived from the continental land mass. These deposits are represented by the upper clastic member of the Hawthorn Formation of middle Miocene age, and, according to Bergendahl (1956, p. 73-79), of upper Miocene age in the Pine Level area.

The fine-grained, clastic, phosphatic materials of the Hawthorn Formation were moved southward from the continental land mass and were deposited in a shallow, marine environment with sufficient fluctuating energy to, at times, transport fine- to medium-grained phosphatic sands. At other times current activity was minimal and lenses and beds of clay were deposited in quiet water.

The distribution of the clastic Hawthorn sediments indicates the presence of a massive delta along the Georgia, Alabama, and Florida lines that possibly extended down the peninsula (Puri and Vernon, 1964, p. 153). The southward extending distributary system from this delta furnished the materials that compose the clastic deposits of the Hawthorn.

The Hawthorn deposits probably covered most of the Florida peninsula but may have been thin or more sporadically distributed over the Ocala uplift. The land mass created by the Ocala uplift probably stood as a shallow, broad submarine plain, a series of undulating hills forming a large insular area, or as a narrow peninsula that extended south from Georgia along the west part of peninsular Florida (Vernon, 1951, p. 181-184).

D. The Citronelle Formation

During late Miocene time the southward migration of the delta distributary system reached, at least, into the vicinity of the land-pebble field. The continuous southward extension of the system was evidently accompanied by shoaling, and finally complete withdrawal of the surrounding seas, so that deposition of the characteristic phosphatic upper member of the Hawthorn Formation was terminated from north to south in response to the southward growth of the delta. Deposition apparently ceased in the area of the hard-rock phosphate deposits by the end of middle Miocene time, but continued in the Pine Level area to well into the upper Miocene.

The deltaic sediments eventually extended as far south as the southern terminus of the Lake Wales Ridge in Highlands County (Fig. 3). The uneroded remnants of these deltaic sediments are preserved as the Citronelle Formation comprising the body of sediments in the Lake Wales Ridge.

Miocene time closed with gentle uplift of the Florida peninsula and a cessation of the unusual conditions that resulted in the deposition of the clastic Hawthorn deposits and the related deltaic Citronelle Formation. Figure 23A depicts the land-pebble field and the Pine Level area at the end of Miocene time.

E. Post-Miocene Period of Erosion

The erosional interval between the retreat of the Miocene sea and the deposition of the Pliocene Bone Valley Formation occurred at different

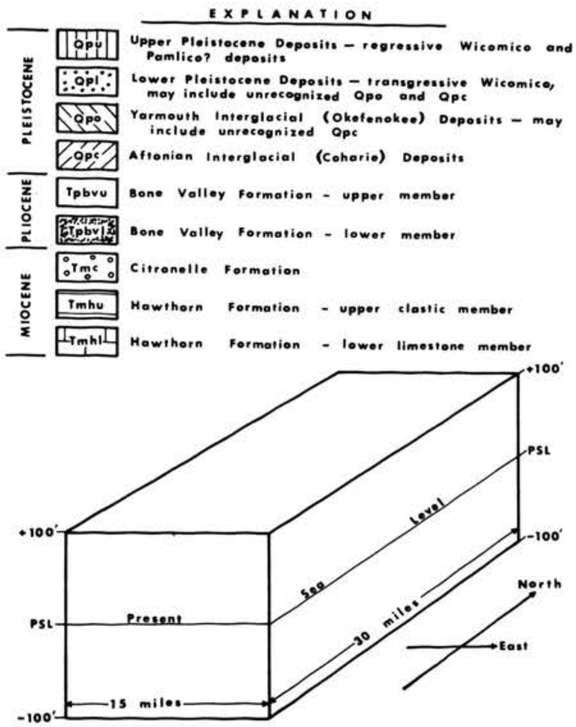
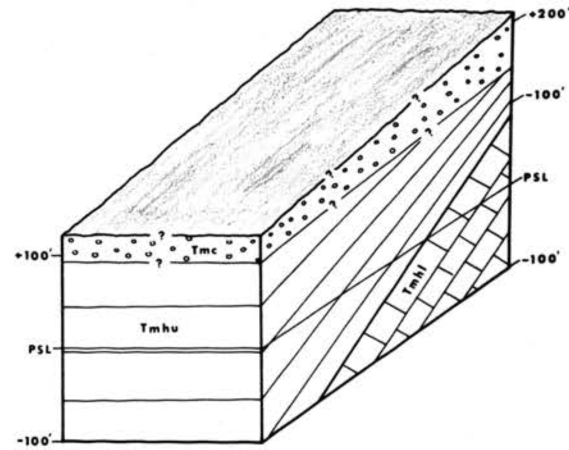
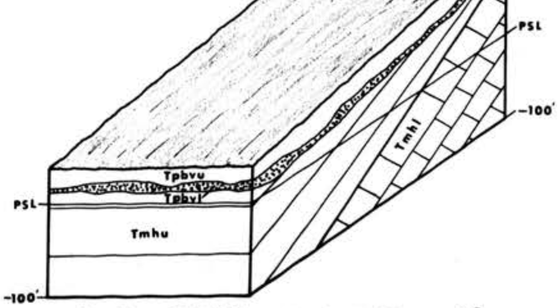


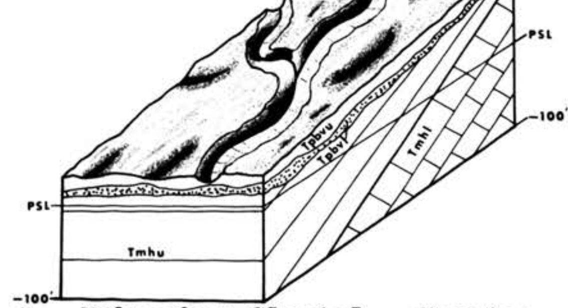
Figure 23. Physiographic diagrams depicting geologic events, Pine Level and adjacent area, Florida (diagrams A through K, following).



A. End of Miocene age. Diagram indicates Citronelle Formation may have extended into the area.

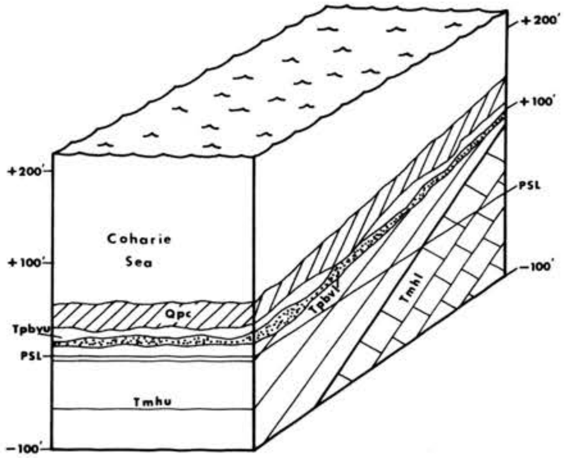


B. End of Pliocene age. Advance and retreat of sea, removal of Citronelle, some Hawthorn sediments, and deposition of Bone Valley Formation.

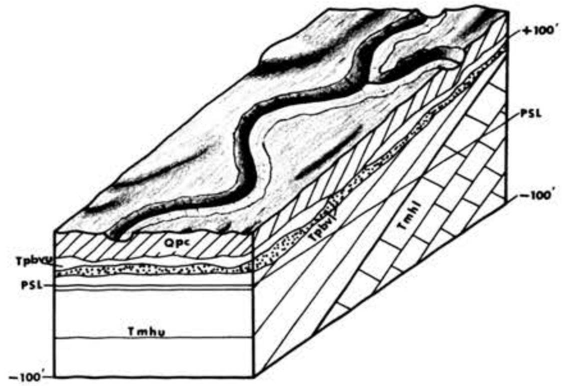


C. Nebraskan Glacial. Erosion and weathering.

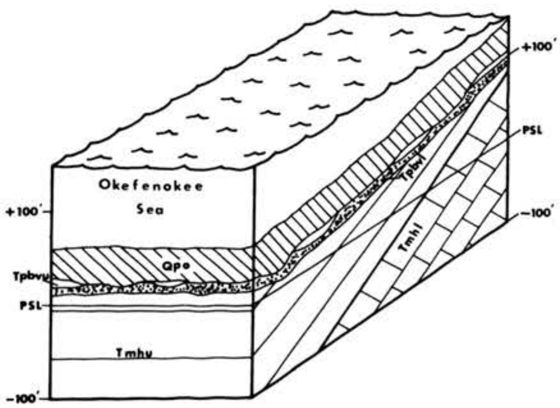
by DSC



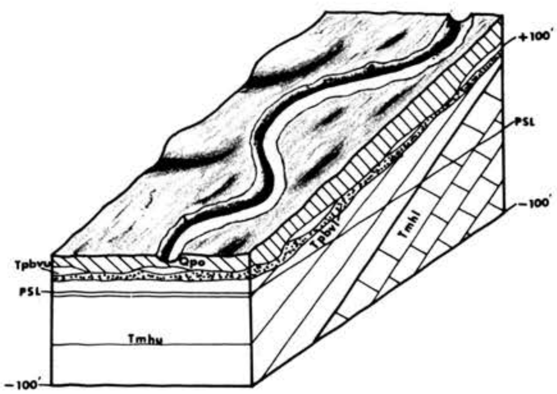
D. Aftonian Interglacial. Advance and retreat of Coharie sea, and reworking of earlier sediments into Coharie deposits.



E. Kansan Glacial. Erosion and weathering.



F. Yarmouth Interglacial. Advance and retreat of Okefenokee sea, and recycling of earlier sediments into Okefenokee deposits.



G. Illinoian Glacial. Renewed weathering and erosion.

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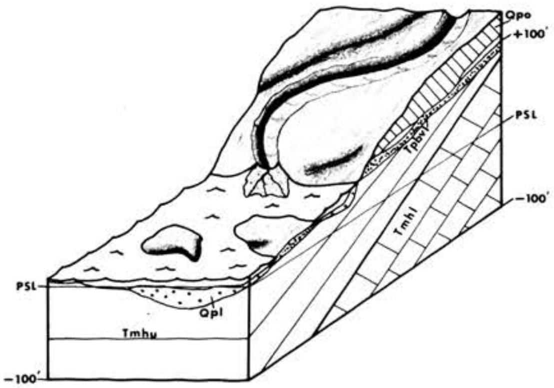
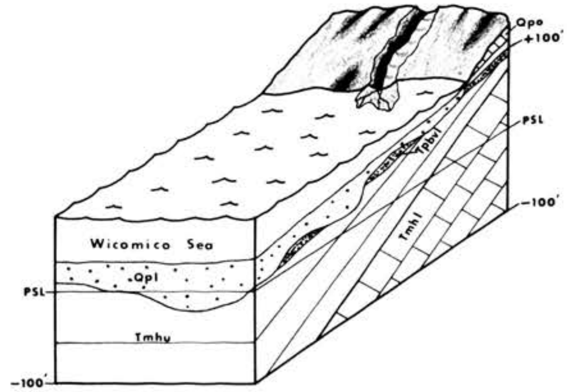
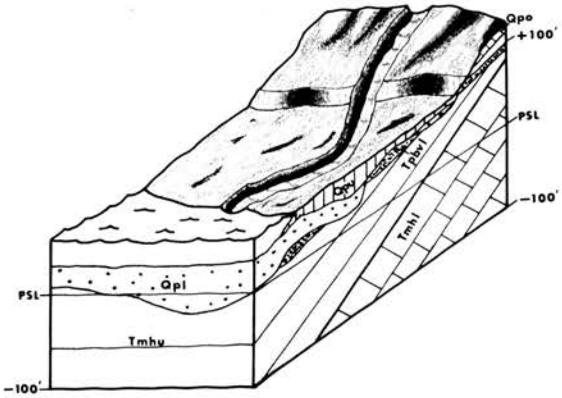


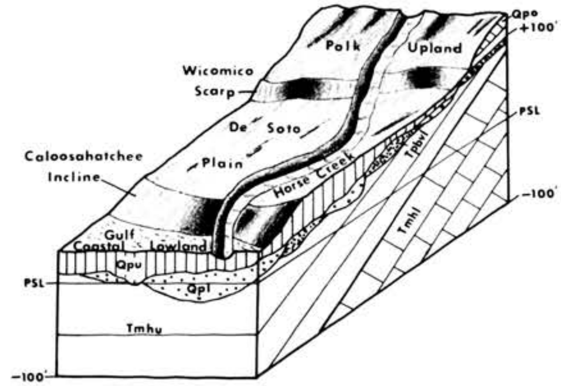
H. Early Sangamon Interglacial. Development of islands of Bone Valley Formation in advancing Wicomico sea.



I. Middle Sangamon Interglacial. Rapid advance of Wicomico sea, recycling of previous sediments, and burial of Bone Valley islands. Transgressive Wicomico deposits probably contain unrecognized uneroded remnants of earlier sediments.



J. Late Sangamon or early Peorian Interglacial. Formation of Caloosahatchee Incline.



K. Present time. Continued weathering and erosion.

by DSC

intervals in various localities in the central Florida peninsula. The area of the hard-rock deposits was evidently emergent during late Miocene and early Pliocene time. The unusual hard-rock deposits were formed during this interval in the manner previously described. Apparently the Citronelle deposits did not reach westward into the area for the hard-rock deposits were being formed during late Miocene deposition of the Citronelle Formation.

In the main producing area of the land-pebble field it seems likely that Citronelle deposits or equivalent sediments probably extended into and covered part of the area. The erosional interval, in this area, probably began with the retreat of the Miocene sea. During this interval the sediments overlying the lower Hawthorn limestone member were removed by erosion. A drainage system developed on the Hawthorn limestone surface, and chemical weathering developed a karst surface and a richly phosphatic, calcareous clay residual mantle (Cathcart, 1963a, p. 20).

The erosional events in the Pine Level area seem to be of less magnitude and appear to indicate a later retreat of the Miocene sea, coupled with a lower elevation that precluded development of the comparable deep drainage system of the main producing area. It is not certainly known if the Citronelle sediments ever extended into the area. Erosion and weathering during the interval developed a phosphate-rich, residual soil mantle on top of the upper clastic member of the Hawthorn.

The preceeding chapter of this paper has discussed the alteration and weathering of the apatite pebble of the Pine Level deposit. The important point must be emphasized here that the apatite in both the Hawthorn Limestone residuum of the main producing district and the phosphate rich mantle of the Pine Level area have most probably been subjected to similar weathering processes during this Miocene-Pliocene erosional interval. The apatite in these residual deposits was, consequently, almost surely a better quality product at this point in time than the apatite in the underlying Hawthorn sediments.

F. Deposition of the Bone Valley Formation

A return to marine depositional conditions in the area of the land-pebble field during Pliocene time is indicated by the advance of a transgressive sea that eroded, winnowed, and sorted the residual materials on top of the two Hawthorn members. The advancing sea reworked the residual materials into a basal conglomerate containing an abundance of apatite pebbles and pellets. The distribution of this deposit; the lower phosphatic member of the Bone Valley Formation; the coarse character and lenticular bedding of the phosphatic sediments, and the presence of land mammal, shark, ray, manatee, and bird remains are indicative of a transgressive marine environment.

The retreat and withdrawal of the sea formed a regressive sand, the upper barren member of the Bone Valley Formation, that probably blanketed the entire land-pebble field, including the Pine Level area. These events are depicted in Figure 23B.

G. Pleistocene Events

The retention and release of tremendous volumes of water during the various glacial and interglacial stages caused extraordinary fluctuations of sea level during Pleistocene time. During periods of relative stability at various interglacial stages, terraces, representing sea standstills, developed at several elevations in Florida (Table II). These old shorelines indicate that the Pine Level area was inundated by these encroaching seas at least three, and possibly four times. The record of the earlier seas in the Pine Level area have been obliterated by the later Wicomico transgression. The inferred sequence of Pleistocene events is depicted in Figures 23C through 23K.

The advancing Wicomico sea stripped and reworked the previous deposits, modified the topography of the Hawthorn surface, and redistributed much of the contained apatite in the lower member of the Bone Valley Formation into new lower level deposits of Pleistocene age. In the Pine Level area, at this time, several higher elevation Bone Valley remnants existed as a series of small offshore islands. These were being subjected to erosion by waves and tidal currents when an apparent increased influx of glacial meltwater to the oceans raised sea level rapidly enough that the islands were completely inundated and spared from further destruction. Schnable and Goodell (1968, p. 19) describe similar circumstances surrounding the inundation and burial of an island, now Dog Island Reef, near Alligator Harbor on the Apalachicola Coast.

As the sea continued advancing toward the Polk Upland the reworked clastic components were moved seaward and completely buried the Bone Valley islands. The finer clay particles, winnowed from both the Bone Valley and the Hawthorn Formations, were settling in deeper, quiet water so that, finally, as the sea neared the Polk Upland, the lower Pleistocene sand of the Pine Level area was covered by green clay. The Wicomico sea apparently reached a maximum elevation of about 100 feet and did not affect the Bone Valley Formation under the Polk Upland.

The retreating Wicomico sea eroded and removed most of the green clay unit, and deposited a regressive sand sequence that completely blanketed and covered the area south of the Polk Upland. The northern extension of the Caloosahatchee Incline into the Pine Level area is thought to represent a temporary standstill in the retreating Wicomico sea. The incursion of the Pamlico and Silver Bluff seas evidently did not reach into the Pine Level area.

H. Pleistocene Periods of Weathering

The Polk Upland portion of the land-pebble field was not affected by the Wicomico transgression and has been undergoing erosion and weathering since the withdrawal of the Okefenokee sea. The Pine Level area, on the other hand, has only been subjected to these processes since the retreat of the Wicomico sea.

It would appear from this fact that the period of intense lateritic weathering, that so altered the phosphatic sediments of the main producing area, but did not affect the Pine Level area, may have started or occurred largely during the time the Pine Level area was covered by the Wicomico sea. If it did occur later, say during Pamlico time, the Pine Level area would have been much closer to sea level, and, perhaps, was so poorly drained that the intense lateritic weathering did not affect the area.

I. Recent Events

It is thought that the lower general elevation, and consequent poor drainage, of the Pine Level area inhibited the development of the important weathering processes. They are therefore believed to be essentially of Recent age with the most extensive leaching and alteration of the Pine Level deposit beginning with the retreat of the Silver Bluff sea.

IX. ORIGIN OF THE LAND-PEBBLE PHOSPHATE DEPOSITS

A. General Origin of Marine Apatite

In spite of the extensive and very detailed studies of the Permian Phosphoria and the Pliocene Bone Valley Formations by the U. S. Geological Survey since 1947, and an almost overwhelming volume of literature by numerous other investigators, there does not yet exist a unifying hypothesis for the formation of marine apatite that is acceptable to all, or even most, investigators. The problem stems from the complex chemical activity of the phosphate ion, and the variety of occurrences of carbonate fluorapatite.

Some common occurrences of apatite in sediments include: microcrystalline aggregates as nodules, pellets, and oolites; microcrystalline aggregates as laminae, beds, and interstitial cement; fish teeth, fish scales, and bones of birds, mammals, and fish; phosphatic shells of certain invertebrates; replacement of calcareous shells and oolites; replacement of limestone; replacement of wood; and coprolites. The pelletal form is the overwhelming mode of occurrence of apatite in the land-pebble field. The various modes of occurrence clearly indicate that a variety of origins are involved in the formation of carbonate fluorapatite. Pellets and oolites are thought by many to represent direct precipitation from sea water; limestone and wood replacements obviously involve secondary mechanisms; and the formation of original bone and certain phosphatic shells is an organic process. The principal lack of consensus in the origin of marine apatite revolves around the phase relationships of phosphorus in sea water, and the possibility of direct precipitation of apatite from sea water.

Perhaps the only point of real agreement is the relationship of organic matter and phosphorus, and the acceptance that the phosphorus in the present deposits is immediately derived from the death and decomposition of organisms. Phosphorus is an essential component of all living matter. It is present in plants and the soft part of animals in generally small amounts, but is a major component of the skeletal parts of vertebrates and of some of the hard parts of invertebrates. Phosphorus is present in organic matter largely as organic and inorganic orthophosphate (PO_4) compounds (Waggeman, 1952, o. 16) and is used in a seemingly endless cycle. The "red tides" of phytoplankton, with the attendant "mass mortalities" that result in the death of thousands of fish, that constantly afflict the west coast of Florida each summer (the summer of 1971 is particularly notable) provides one spectacular example of a mechanism whereby phosphorus is locally concentrated in sea water and might be precipitated under favorable conditions.

The U. S. Geological Survey, as a result of their studies of the extensive "primary" bedded phosphorites of the Phosphoria Formation, has particularly championed the mechanism of direct precipitation. Gulbrandsen (1969) recently summarized the work of the Survey on this problem and presents a simplified physical chemical analysis of the phase relationships of phosphorus in sea water. Gulbrandsen (1969, p. 365) concludes:

> "Optimum conditions for the formation of large amounts of apatite seem to be the coincidence of a special steady supply of phosphate, originally derived from organic matter, and a decreased capacity of sea water for phosphate. These conditions probably prevail in shallow parts of the seas upon continents where large amounts of organic matter accumulate in oxygenated waters of higher than normal temperature, pH, and salinity".

McConnel takes a different point of view and contends (1965, p. 1061) "that the necessary conditions for precipitation probably cannot be evaluated solely by means of inorganic chemical theory". He concludes that most phosphorites have originated by precipitation under biochemical influences in a manner analogous to the formation of teeth and bone. McConnel considers that phosphorite is precipitated from sea water by organisms with the possible aid of an enzyme, carbonic anhydrase. According to his view direct inorganic precipitation of apatite from sea water does not occur.

By contrast, Pevear (1966, 1967) in studies of the Atlantic Coast phosphates concludes (1967, p. 566),

> "Direct inorganic precipitation of carbonate apatite from sea water is probably not possible and no organic or biologic mechanism is presently known to be operative in the marine environment. The replacement process has been observed both in the laboratory and in the field. In the light of the existing data, it appears that inorganic replacement of calcium carbonate by phosphate ions in sea water is the only reasonable mechanism for phosphorite formation".

In summary, current views indicate that marine apatite is formed by direct inorganic precipitation directly from sea water, only by the life processes of organisms, or only by the replacement of calcium carbonate by phosphate ions in sea water. The recycled, clastic deposits of the Pine Level area do not shed any light on this particular problem, but do indicate that some chemical features usually ascribed to "primary" marine apatite may be the result of later phenomena associated with weathering.

B. Summary of the Origin of the Pine Level Deposit

The apatite of the Pine Level deposit has, as its original source, the previously reworked clastic apatite particles of the Hawthorn Formation. Apatite is an abundant component of the upper member of the Hawthorn Formation in the Pine Level area, and is estimated to constitute

10 percent by weight of the member. The following samples from Table VI probably characterize the "initial" or "original" apatite of the upper clastic Hawthorn member: section E-E', hole 19-16, sample 2158; section J-J', hole 18-20, sample 2386; and section K-K', hole 19-26, samples 2392 + 2393.

The Miocene-Pliocene erosional interval developed a phosphate-rich soil mantle on the top of the exposed upper member. The apatite in the mantle was subjected to weathering processes and was beneficially altered to a higher quality apatite than in the unweathered, uneroded portion of the underlying upper member.

The incursion of the Bone Valley sea into the area eroded, sorted, and reworked the above described residual mantle into a basal conglomerate containing a higher proportion of apatite than the underlying Hawthorn Formation. On the basis of the ratio of pebble content (Tables V and VI), a minimum of 12 volumes of the upper Hawthorn member were reworked to provide one volume of the resulting Bone Valley Formation. Much of the Hawthorn clay, fine sand, and fine phosphate pellets were removed from the area by active currents. It is thought that the upper member of the Bone Valley Formation was probably deposited in the Pine Level area, but its presence at this time is not recognized.

The withdrawal of the Bone Valley sea again exposed the area to erosion and weathering but the presumed cover of sediments probably inhibited alteration by ground water leaching. A similar pattern is thought to have continued through early Pleistocene time with the advance and withdrawal of the Okefenokee and Coharie seas. Evidence of the sediments associated with these invasions, and the possible weathering effects associated with their withdrawals have been obliterated by later geologic events.

The Wicomico sea removed any remaining overlying sediments and eroded and destroyed much of the Bone Valley Formation and scoured an irregular surface on the upper member of the Hawthorn Formation. Apatite particles from both the Hawthorn and Bone Valley Formations were reworked into the basal transgressive phosphatic deposits of the Wicomico sea. The combining of about one volume of Hawthorn matrix with an equal volume of Bone Valley matrix would correspond in pebble ratio to the lower Pleistocene matrix (Tables IV, V, and VI).

The following samples from Table IV probably characterize the approximate chemical quality of the apatite of the deposit at this point in time: section C-C', hole 23-5, samples 315A + 316A; section K-K', hole 18-29, sample 2425. The concentrate fraction has been altered slightly from the "original" Hawthorn and the pebble fraction has been considerably upgraded. It is believed that this occurred during the erosional intervals between the retreat of the Hawthorn sea and the advance of the Wicomico sea.

The Pine Level area, while exposed to erosion, remained near sea level during Pamlico and Silver Bluff time, was probably poorly drained, and the effects of weathering probably proceeded very slowly. The more intense weathering effects that have altered the apatite to commercial quality is evidently of Recent age and followed the retreat of the Silver Bluff sea.

C. Comparison With Origin of Polk Upland Deposits

Major differences in the above described origin of the Pine Level deposit and the origin of the Polk Upland deposits according to both Cathcart (1964) and Altschuler *et al*. (1956) are as follows: (1) the upper clastic member of the Hawthorn Formation did not contribute any detrital phosphate to the Bone Valley deposits since the phosphate pellets in the Bone Valley matrix are entirely derived from the chemically weathered Hawthorn Limestone, and the pebbles were originally phosphatized limestone pebbles; (2) marine apatite was actively precipitated in the Bone Valley sea, and it enriched the previously existing pebbles and pellets; and (3) the period of intense lateritic weathering formed the aluminum phosphate zone and developed the present calcareous clay residuum on top of the Hawthorn Limestone, but the effects on the apatite of the matrix are apparently of no consequence. The extraneous pebble source is aimed to account for the fact that the Hawthorn Limestone probably contains insufficient pebbles, and that many of the apatite pebbles in the Bone Valley Formation in the main producing area are phosphatized limestone particles that contain the same fossils as the underlying Hawthorn Limestone.

D. Consideration of Major Differences of Origin

The writer does not argue or contend that the interpretations of Cathcart or Altschuler *et al*. regarding the origin of the Bone Valley deposits of the Polk Upland are incorrect. It is rather suggested that the study of the Pine Level deposit indicates that, perhaps, some alternative factors may warrant additional consideration. The origin of the deposits may be more complicated than has been previously reported. Some of the additional factors that possibly should be considered are discussed below.

1. Source of the Apatite

The Pine Level deposit indicates that the apatite is derived from the underlying clastic member of the Hawthorn Formation. This member originally extended over the main producing area and, most likely, contributed a significant amount of apatite to the Bone Valley Formation. An extraneous derivation of the Bone Valley pebble is not required if the phosphate is derived from the clastic member. Further, the condition that chemical weathering formed a phosphate-rich residuum would not be required. A considerable amount of the fine grained fraction of the clastic member would have to have been removed from the area by streams to provide the present pebble concentration of the Polk Upland deposits.

It may be noted, on the other hand, that the hard-rock deposits of the Ocala uplift area evidently developed prior to the incursion of the Bone Valley sea. They may originally have been sufficiently extensive to have involved the Hawthorn Limestone at the northwestern end of the land-pebble field. Erosion of these deposits in early Pliocene time could have contributed some, or even most, of the pebbles to the present Bone Valley matrix.

2. Marine Apatite Enrichment Versus Alteration by Weathering

The Bone Valley sea is an ideal example of the type of marine environment discussed by Gulbrandsen (1969) wherein apatite might be directly precipitated from sea water. The relative abundance of phosphatized bone and shark teeth attest to the abundance of organic matter which could have furnished more than the required supply of phosphorus. Streams, draining from the phosphatic Hawthorn and hard-rock terrain to the north, could also have contributed more than a sufficient supply of phosphorus to the Bone Valley sea. If it can in fact be shown that apatite was precipitated from the Bone Valley sea, then the apatite particles might indeed have been enriched to their present quality at this time.

This study presents evidence which indicates that alteration by the activity of ground water is the enrichment mechanism in the Pine Level area. It is therefore suggested that apatite may not have been precipitated in the Bone Valley sea, but that enrichment of the Bone Valley apatite most likely occurred subsequent to the deposition of the matrix, probably, in large measure, during the period of intense lateritic weathering.

3. Possible Pleistocene Reworking

The local and regional relief on the base of the Bone Valley Formation as shown by Cathcart's maps and the exposure of the area to two Pleistocene marine invasions (Okefenokee and Coharie) suggest that portions of the Bone Valley Formation might conceivably have been reworked into Pleistocene deposits similar to those of the Pine Level area that have not heretofore been recognized.

E. Unsolved Problems

1. Source of Hawthorn Apatite

Sediments related to Miocene embayments in the Atlantic Coastal Plain from the Brightseat Formation of Maryland to the Hawthorn Formation of the Pine Level area contain billions of tons of detrital apatite. Miocene deposits were formerly mined in the Charleston, South Carolina area; are now being mined along Pamlico Sound in North Carolina, and in north Florida; and are known to be of commercial quality in the Savannah, Georgia area. It seems logical to believe the apatite is probably related to some common origin. The apatite pellets are detrital, oval-shaped, and highly polished. Have they been reworked into these Miocene sediments from some previous sediments? Was the apatite precipitated and formed in this grade, size, and shape, or has it been derived by erosion and attrition from bedded phosphorites or phosphate nodules? Why does the Miocene series of the Atlantic Coastal Plain contain such an abundance of apatite?

Pevear assigns a Miocene age to this apatite and describes a possible origin (1966, pp. 254-255):

> "It seems justified, therefore, to envision sedimentation during Miocene time as having occurred on a coast not dissimilar to that of modern Georgia, with a wide shelf and shoreline embayed by many estuaries. During a period of warm climate and relatively low relief limey sediments accumulated within the sheltered confines of productive coastal estuaries on a broad continental shelf. Cooling climatic conditions resulted in a slackening or withdrawal of limestone-forming conditions and a possible slight increase in productivity due to increased CO_2 solubility. High productivity, especially of marsh grass and benthic algae, raised inorganic phosphorus concentrations to a point where lime mud was replaced by phosphorite. During a period of 60,000 years one foot of phosphorite was produced over most all the estuaries. Small shelf instabilities resulted in significant changes of sea level on the shallow shelf causing the surf zone to transgress over the estuary breaking up and somewhat redistributing the phosphorite. The process of formation and breaking up of the phosphorite layer occurred repeatedly during Miocene time".

Perhaps the Pine Level area represents one of these embayments. If it does not, the detrital apatite may have been transported into the area from north of the Florida state line by the Miocene delta distributary system previously discussed.

2. Pellet and Pebble Differences

The reason for the obvious fact that the pebble fraction in any sample from the land-pebble field contains more impurities than the concentrate fraction has not been determined. The pellets of the concentrate fraction may represent smaller detrital grains derived from broken pebbles from which all impurities have been scrubbed off by attrition; the pellets may have initially formed as small, higher quality particles; or the pellets, as a result of their small size, have allowed rapid and more thorough alteration by groundwater while the pebbles still encase considerable impurities within them.

X. ECONOMIC GEOLOGY

A. Economic Evaluation of Deposits of the Pine Level Type

1. Introductory Statement

The economic evaluation of the Pine Level and similar phosphate deposits differs from the evaluation many other mineral deposits in that various production cost parameters may be somewhat more variable. The The depth of overburden, the matrix thickness, the pebble to concentrate ratio, flotation recovery, and product grade may vary widely within short distances.

In addition, many of the direct production costs are generally inter-related. Some of the direct costs of a producing operation might, for example, be assigned to the following cost centers:

1. Mine overburden stripping
2. Matrix mining
3. Matrix pumping
4. Washing and screening
5. Flotation

It can be seen that the increased production cost of an increased thickness of overborden could be offset by an equal increase in the thick- of matrix, or a reduction in the pumping distance by being closer to the plant, or a higher pebble content which would reduce washing and screening unit costs, or an increase in recoverable flotation concentrate. Similarly a combination of adverse costs might be offset by a combination of favorable costs, or by an increase in the sales price of a higher grade marketable product.

The detailed economic evaluation of this type of phosphate deposit thus embraces a wide variety of disciplines including geology, engineering, and marketing. In the final analysis a team effort is required to properly conduct a detailed economic evaluation. However, a study of the engineering and production cost data developed for the Pine Level deposit in 1969 indicates that most of these cost parameters, as well as certain quality requirements, can be expressed in terms easily determinable by the exploration geologist or engineer.

2. Mining Considerations

Most phosphate rock plants in central Florida produce at an annual rate of about 2,000,000 tons per year of marketable phosphate rock, or are at least capable of such a production rate. Any new facility or company, planning to produce Florida phosphate rock, must plan production at least at this rate to maintain competetive unit costs. If the plant and mining equipment are to be depreciated over a 20 year period, the required phosphate rock reserve is 40 million tons. The period of 20 years is stated because this is the reasonable, expected life of the equipment involved.

Acquisition cost of the reserve, in terms of fee simple purchase, probably should not exceed $0.30 to $0.40 per reserve ton of phosphate rock in the ground. This cost will depend somewhat on the quality of the reserve, the cash position, and immediate and long range capital investment plans of the company contemplating acquisition. An economic analysis is normally required to properly evaluate the sensitivity of this cost item. A deposit that yields an average of 5,000 tons per acre of recoverable phosphate rock will need to underlie 8,000 acres to provide the required reserve, and phosphate land values in Florida vary from about $300 to $2,000 per acre.

The minimum size dragline with the materials handling capability of providing the required 2,000,000 tons per year of production will be in to 20 to 25 cubic yard range if the overburden and matrix thickness are favorable. Such a machine cannot efficiently or economically mine matrix less than three feet thick. Further, the effective working area from one pit sump set-up is determined by the length of the dragline boom. Matrix containing less than 3,500 tons per acre of recoverable phosphate rock will require more frequent moves of the pit sump with an attendant increase in production costs.

If the overburden is too thick an inordinate amount of time will be required for overburden removal and the plant cannot be adequately supplied with matrix from the pit sump set-up. Consequently; unless other alternatives are available, such as two draglines supplying the same plant; the thickness of overburden should not be more than three times greater than the thickness of the matrix.

The matrix slurry from the mine requires treatment at the plant to recover the contained phosphate rock. If the content, or recovery, is too low, the processing cost will be excessive. As a general rule the recoverable product should exceed 350 tons per acre-foot of matrix mined, and the BPL content of the flotation feed should be greater than 15 percent.

Another factor requiring some consideration is the total depth that would be required to mine a given deposit. A 20 cubic yard dragline cannot, for example, mine a deposit with a one-to-one overburden to matrix ratio at a total depth of much over fifty feet without a serious cycle-time sacrifice. An appropriate dragline must be selected with both the deposit and plant requirements in mind.

The concentrate fraction must be recoverable by competitive flotation methods. Some apatite pellets, to cite one example, may be soft and friable, and may "slime" during processing, with the end result that they cannot be economically conditioned for flotation treatment.

3. Chemical Quality Factors

The minimum grade of marketable Florida phosphate rock contains 66 percent BPL (30 percent P_2O_5). In general, higher quality rock commands a premium price and is preferred by distant customers due to the lower freight cost per unit of contained BPL.

Excessive calcium carbonate in the phosphate rock requires costly treatment with additional sulfuric acid in the manufacture of fertilizer. The ratio of the contained CaO to P_2O_5 is a commonly used "yardstick" of expected sulfuric acid consumption. The nominal ratio for marketable rock is about 1.50.

Aluminum oxide and iron oxide (usually reported as combined I & A) are undesirable in rock used to make wet-process phosphoric acid because they form insoluble chemical complexes that settle slowly and create sludge problems. They also create problems in the manufacture of superphosphate and give a poor physical condition upon curing. The combined I & A should not exceed 4.0 percent.

Magnesium will form an insoluble ammonium-magnesium-phosphate complex if it is present in the phosphoric acid used to produce ammonium phosphate fertilizers. The presence of organic matter causes a foaming problem in the manufacture of phosphoric acid. Excess SiO_2, generally reported as "Insol" is undesirable as it detracts from the possible BPL content, and incurs "dead weight" shipping charges.

4. Summary of Minimum Requirements

The foregoing factors are summarized in tabular form below. It must be understood that these are general guidelines that serve, at best, to recognize deposits of merit, are based on 1969 costs, and are not a substitute for the required engineering and economic studies.

1. The minimum reserve required for a proposed mining operation is about 40,000,000 tons, which, at an average recoverable yield of about 5,000 tons per acre, will underlie 8,000 acres.

2. Minimum matrix thickness is 3 feet provided the recoverable phosphate rock exceeds 3,500 tons per acre.

3. The overburden to matrix ratio should not exceed 3 to 1.

4. The recoverable phosphate rock must exceed 350 tons per acre foot in the matrix.

5. The BPL content of the flotation feed must exceed 15 percent.

6. The dragline to be selected must be capable of supplying the plant requirements from the maximum depths that will be encountered in mining the deposit.

7. The concentrate fraction must be amenable to standard, competitive flotation techniques.

8. The minimum grade of marketable phosphate rock contains 66 percent BPL.

9. The CaO/P_2O_5 ratio should be in the nominal 1.50 range.

10. The combined I & A should not exceed 4.0 percent.

11. A MgO content in excess of 0.60 percent will be difficult to market if the rock is used in ammonium phosphate production.

B. Exploration for Other Deposits

1. Polk Upland

The area of the land-pebble phosphate field encompassed by the Polk Upland has been extensively explored (see Cathcart). Most of the entire area has long been owned or controlled by the various phosphate companies. The opportunity to acquire sufficient reserves in this area by an option and exploration procedure is exceedingly limited. New companies that have most recently entered, or have announced their intentions to enter, the phosphate business in this area (United States Steel, Kerr-McGee, and Freeport) have done so by some type of partnership arrangements with other companies that own the reserves.

2. De Soto Plain

During the course of the exploration program about 200 or so holes were drilled on various tracts in the De Soto Plain in eastern Manatee, western Hardee, and northern De Soto counties. These holes were within the land-pebble field between the Polk Upland the the Pine Level area. The holes were concentrated in several different areas and did not systematically or properly sample the entire area under consideration.

However, the drill holes encountered a variety of geologic features similar to the Pine Level area and clearly were indicative of an identical mode of origin. Irregularly distributed subcrop patterns of the Bone Valley Formation, perhaps "island" remnants as in the Pine Level area, were encountered in three different areas; several holes in one area contained as much as 50 feet of lower Pleistocene matrix; and one area contained a commercial quantity of phosphate concentrates in a very thick, but deep, section of the Hawthorn Formation. It is obvious that deposits of the Pine Level type may be present in the De Soto Plain between the Polk Upland and the Pine Level area.

During the period of the exploration program described herein, a number of other companies were also conducting exploration work in the area. Several other reserve acquisition programs, in addition to the Phillips program in the Pine Level area, were completed during this time. These include purchases of acreage by Pittsburgh Plate Glass in Manatee County, Stauffer Chemical and Duval Chemical in Hardee County, and International Minerals in De Soto and Manatee Counties. These purchases clearly prove that other deposits are present in the area under discussion.

The writer believes that the De Soto Plain offers the best opportunity to acquire reserves by the option and exploration method in the land-pebble field. The immediate question, in view of the exploration drilling that has been conducted, concerns the intensity of the exploration coverage. The writer estimates that perhaps half of the total area has been tested by some exploration holes.

In this regard it must be emphasized that deposits of the Pine Level type are stratigraphically irregular and lack the blanket-type continuity of the Polk Upland deposits. Drilling procedures and patterns, quite appropriate in the Polk Upland, may not be adequate in the De Soto Plain. It is not, and has not, been uncommon in the Polk Upland to base a preliminary evaluation program on exploration drill holes located approximately at the center of 160 acre blocks. This is the equivalent of four holes per section. If the four holes all encounter a thick and intense development of the aluminum phosphate zone it can reasonably be concluded that the section is unfavorable and unworthy of additional expenditures. If, on the other hand, the four holes all encounter mineable thicknesses of matrix, it can be almost assuredly concluded that the section is underlain by significant phosphate rock reserves.

The unusual stratigraphic and areal distribution of the matrix in a deposit of the Pine Level type precludes such assured interpretations from a comparable limited exploration drill hole pattern. Some, and perhaps even most, of the exploration efforts conducted to date in the De Soto Plain have been based on previous and long-standing experience in the Polk Upland. The writer believes the validity of such efforts is questionable. Exploration for deposits of the Pine Level type requires an interpretation of the geologic history and environment of deposition of every drill hole. These geologic guides and interpretations form the sole basis for an effective exploration program for phosphate deposits of the Pine Level type in the De Soto Plain portion of the land-pebble field.

3. The Gulf Coastal Lowland

The Gulf Coastal Lowland does not appear to contain phosphate deposits of interest at the present time. This is particularly true of the area in Sarasota, Manatee, and Charlotte counties below the Pamlico shore line. The apatite has been extensively reworked in this area and a great amount of fragmental shell is intermixed with it. Until some economical method of flotation is developed that will separate calcite from apatite, the phosphate concentrations in this area are of no interest. The area is also very low and poorly drained, the apatite is black, not sufficiently altered, and of marginal grade.

C. Ecological Considerations

One of the most troublesome aspects of Florida phosphate rock production is the disposal of slimes. It is a particularly expensive phase of the total operation, and requires constant supervision and maintenance. The accidental introduction of slimes into the Alafia and Peace Rivers on several occasions in recent years has resulted in serious environmental damage.

In a recent instance in 1968, an old slime disposal dam, near the headwaters of the Peace River, accidently ruptured and released a very large quantity of slimes into the Peace River. The slimes flowed down the river to Charlotte Harbor where the clay finally floculated in salt water and settled out. Residents of Arcadia, near the Pine Level area, described the local scene at the time as a "river of pancake batter with thousands of dead fish". The company responsible was required to clean up the river, restock it with fish, and, in addition, was fined $250,000 by the state of Florida.

The Bone Valley matrix, as has been described, consists of about equal parts of recoverable phosphate, sand tailings, and slimes. The -150 mesh slimes contain a very minor proportion of fine sand and silt size particles and predominately consists of montmorillonite. The tailings to slimes ratio is therefore approximately one to one.

The normal method of slimes disposal is within a large perimeter dam 25 feet or so high. The dams are usually constructed around a mined-out area to gain the advantage of the additional space. Most slimes dams encompass several hundreds of acres, and the slimes from the plant are pumped into these ponds for permanent storage and disposal.

The clay particles rapidly settle to where the slimes are about 12 to 15 percent solids, and then settle exceedingly slowly. Many ponds 20 to 30 years old have finally reached a condition where the slimes are somewhat like gelatin and contain a maximum of around 30 percent solids by weight. They thus actually require about the same disposal space as the volume of the original matrix from which they were derived.

The various companies are conducting numerous experimental studies designed to reclaim these areas, and to fine a more effective method of disposal, including the addition of various flocculating agents, and the concentration of the slimes by new ultra-fine flotation techniques. Numerous disposal attempts have been made to blend the sand tailings and slimes in varying proportions in the hope the settling sand would entrap the clay particles and form a reconstituted sediment. These efforts have not been productive, for the clay always remains in suspension.

Recently American Cyanamic (Timberlake, 1969) has reported the encouraging results of a new series of experiements in reconstituting the sediments. Simply, the system involves having the dragline cast a series of spoil banks at right angles to the mining cut, in addition to the normal spoil bank paralleling the cut, as mining along the cut proceeds. After several parallel cuts are mined in this manner the mined area will consist of a series of rectangular unfilled depressions surrounded on two sides by the spoil banks paralleling the cut, and, on the other two side, by the extra spoil banks at right angles. The rectangular depressions are then sequentially filled with a layer of slimes which settles to about 10 to 15 percent solids in a relatively short time. The clear top-water is pumped off and a layer of thickened sand tailings is pumped into each pond. The sequence is repeated several times until the rectangular area is filled. The spoil banks can then be smoothed out and graded and the land is very effectively reclaimed. American Cyanamid has been successful in disposing about one-half of the total slimes by this method, with the other half being routed to conventional disposal. This system has therefore been successfully applied in the case where the sand tailings to slime ratio is 2 to 1.

The Pine Level deposit contains four parts by weight of sand tailings to one part by weight of slimes for a ratio of 4 to 1. The sorting and winnowing action of the Wicomico sea has very effectively removed a large amount of the interstitial clay and greatly enhanced the mineability of the Pine Level deposit.

The best overall reclamation procedure must await actual production experiments and test, but the particle size distribution of the deposit, and the results acheived by American Cyanamid, clearly indicate that the Pine Level deposit is uniquely favorable for complete and attractive reclamation of the mined lands. Of equal importance, the necessity of constructing and maintaining the expensive and dangerous slimes storage areas may be obviated.

XI. CONCLUSIONS

The detailed study of the geology of the Pine Level phosphate deposit and the Polk Upland portion of the land-pebble phosphate field yields the following conclusions:

(1) The deposits of the two areas are significantly different in a number of important respects. These differences are summarized in Table XIII.

(2) The economic phosphate deposit of the Pine Level area is an unusual, unique, unreported type in a transgressive sand deposited by the Pleistocene Wicomico sea that eroded, dissected, and redistributed phosphate from both the Hawthorn and Bone Valley Formations into new recycled clastic deposits of Pleistocene age.

(3) The entire southern portion of the Florida land-pebble field below the Wicomico scarp has been subjected to a similar geologic history. This explains the differences in the deposits north and south of this scarp.

(4) The decrease in quality of the phosphate, coupled with significant color changes, with increasing depth clearly indicates that an upgrading process to commercial quality is dependent upon ground water leaching of undesireable contaminants and replacement by apatite.

(5) There need not have been any actual apatite precipitation in the Bone Valley sea as proposed by Cathcart (1964) and Altschuler et al. (1956). The phosphate particles are more likely recycled from preexisting sources.

(6) The high grade rock of the main producing district was probably not formed by enrichment in the Bone Valley sea but by processes involving ground water leaching and apatite replacement that accompanied

Table XIII. Comparison of the Phosphate Deposits of the Pine Level Area and the Polk Upland.

		Pine Level Area	Polk Upland
1.	Distribution of Bone Valley Formation	Local and erratic	Widespread
2.	Hawthorn clastic member	Present	Absent
3.	Origin	Reworked Hawthorn and Bone Valley Formations	Reworked Hawthorn residuum
4.	Age of deposits	Mainly Pleistocene	Pliocene
5.	Source of apatite pellets	Hawthorn clastic member	Hawthorn limestone member
6.	Source of apatite pebbles	Hawthorn clastic member	Introduced (?)
7.	Enrichment of apatite	By weathering and replacement	Precipitated in the Bone Valley sea
8.	Area of commercial deposits	Small	Very large
9.	Aluminum phosphate zone	Very minor	Widespread and locally intense
10.	Age of weathering	Recent	Okefenokee to Recent
11.	Pebble content	Low	High
12.	Pebble quality	Poor to moderate	Moderate to high
13.	Concentrate content	High	Low to moderate
14.	Concentrate quality	Poor to high	Moderate to very high
15.	Slimes content	Low	High

the period of intense lateritic weathering.

(7) The Pine Level deposit, with a tailings to slimes ratio of 4 to 1 offers a significant advantage in land reclamation over the deposits of the main producing district with a ratio of 1 to 1. The exceedingly serious slimes disposal problem may be eliminated and complete land reclamation acheived at less cost.

(8) Other similar deposits exist in the southern portion of the land-pebble field. Exploration for these deposits requires the thorough application of the basic principles of geology.

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XIII. VITA

Dean Stanley Clark was born May 22, 1925 at Bridger, Montana. He received his primary and secondary education in the Bridger public school system. He enlisted in the U. S. Naval Reserve upon graduation from high school and served three and one-half years on active duty during World War II.

Upon separation from the Naval service he attended the University of Montana at Missoula, Montana. He graduated with honors and received a Bachelor of Arts degree in Geology in June 1950. After one year of employment as geologist and mine foreman with the San Francisco Chemical Company of Montpelier, Idaho, he attended graduate school at Indiana University, Bloomington, Indiana as a teaching assistant. He received the Master of Arts degree in Geology from Indiana University in February 1953.

During the period 1953-1971 he was employed as a mineral exploration geologist with Phillips Petroleum Company, and prior to enrollment toward the Ph. D. degree at the University of Missouri-Rolla was serving as Manager, Eastern Minerals Region. Particular work experience includes the economic geology of metallic and non-metallic mineral deposits.

At the present time he is on a civil leave of absence from Phillips Petroleum Company and is enrolled in a Ph. D. program in the Geology Department of the University of Missouri-Rolla.

XIV. APPENDIX: FIELD LITHOLOGIC LOGS OF SELECTED DRILL HOLES

Explanation of Drill Hole Numbers

The drill hole number is a four-part number such as: 37-24-24-8. The first number indicates the township south, the second number indicates the range east, the third number indicates the section, and the final number is the assigned hole number within the section. In the above example, the drill hole number indicates that the hole is number 8 in Section 24, T. 37 S., R. 24 E. The drill holes included within the appendix are arranged in numerical sequence according to the above numbering system.

Hole # 37-22-14-25

Location: Section 14, T. 37 S., R. 22 E.
Date: October 19, 1965

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	10.6	10.6	Sand: brownish gray, fine- to coarse-grained, soft, incoherent with an estimated 5 percent interstitial clay.
			Lower Pleistocene
10.6	12.3	1.7	Clay: light grayish green.
12.3	18.0	5.7	Sand: dark brownish gray, fine- to coarse-grained with an estimated 10 percent interstitial clay content; phosphatic with an estimated 20 percent white and tan phosphate pebbles and pellets. Sample # 1362.
18.0	29.6	11.6	Sand: dark brownish gray, fine- to coarse-grained, soft and incoherent with no interstitial clay; minor thin seams of grayish green, sandy, phosphatic clay; phosphatic with 15 to 20 percent dark brown phosphate pebbles and pellets. Sample # 1363.
			Hawthorn Formation
29.6	30.5	0.9	Clay: dark grayish green.
30.5	31.5	1.0	Sand: black to very dark gray, medium- to very fine-grained, incoherent with no interstitial clay; estimate 5 to 10 percent fine black phosphate pellets.

Hole # 37-22-14-39

Location: Section 14, T. 37 S., R. 22 E.
Date: June 25, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	3.0	3.0	Sand: light brown, medium-grained, soft and incoherent with an estimated 3 percent interstitial clay content.
			Lower Pleistocene
3.0	8.1	5.1	Clay: light grayish green.
			Bone Valley Formation
8.1	22.2	14.1	Sand: medium grayish green, fine- to coarse-grained, estimated 15 percent interstitial clay; phosphatic with an estimated 25 percent white and tan phosphate pebbles and pellets. Sample # 2480.
			Hawthorn Formation
22.2	26.5	4.3	Clay: brownish green with sparse, thin seams of fine brown sand.

Hole # 37-22-22-6

Location: Section 22, T. 37 S., R. 22 E.
Date: March 26, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	14.1	14.1	Sand: tan to brown, fine- to coarse-grained, estimated 3 percent interstitial grayish green clay.
14.1	14.3	0.2	Sand: tan, fine- to coarse-grained, estimated 3 percent interstitial clay; phosphatic with traces of soft, white aluminum phosphate pebbles.
			Lower Pleistocene
14.3	36.3	22.0	Sand: grayish green, fine- to coarse-grained, phosphatic with 25 percent brown, gray, and white phosphate pebbles and pellets; estimate 15 percent interstitial clay. Sample # 1975.
36.3	42.7	6.4	Sand: dark gray, fine- to coarse-grained, 5 percent interstitial clay; phosphatic with 20 percent dark brown to black phosphate pebbles and pellets. Sample # 1976.
			Hawthorn Formation
42.7	51.3	8.6	Clay: dark grayish green.

Hole # 37-22-22-8

Location: Section 22, T. 37 S., R. 22 E.
Date: March 22, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	7.2	7.2	Sand: light brownish gray, fine- to coarse-grained with 10 percent interstitial clay.
7.2	8.2	1.0	Sand: tan, fine- to coarse-grained with 15 percent interstitial clay and traces of soft, white aluminum phosphate pebbles.
			Bone Valley Formation
8.2	16.5	8.3	Sand: tan, fine- to coarse-grained, phosphatic with estimated 30 percent white, gray, and brown phosphate pebbles and pellets; 15 percent interstitial clay. Sample # 1964.
			Hawthorn Formation
16.5	27.9	11.4	Sand: light brownish green, fine-grained, 10 percent thin seams of grayish green clay and 15 percent interstitial grayish green clay; phosphatic with 5 percent fine, brown phosphate pellets.

Hole # 37-22-22-12

Location: Section 22, T. 37 S., R. 22 E.
Date: December 15, 1964

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	3.6	3.6	Sand: light brown, medium-grained with estimated 3 percent interstitial clay.
3.6	6.8	3.2	Sand: very dark gray, fine- to coarse-grained with 10 percent interstitial clay; phosphatic with traces of white aluminum phosphate pebbles.
			Bone Valley Formation
6.8	13.6	6.8	Sand: dark brown, fine- to coarse-grained, phosphatic with an estimated 25 percent brown phosphate pebbles and pellets; 10 percent interstitial clay. Upper part of Sample # 492.
13.6	15.7	2.1	Sand: brownish gray, fine- to coarse-grained, phosphatic with an estimated 30 percent brown phosphate pebbles and pellets; 10 percent interstitial clay. Lower part of Sample # 492.
			Hawthorn Formation
15.7	22.0	6.3	Sand and clay: interbedded fine- to very fine-grained, brownish gray, slightly phosphatic sand and grayish green clay. Approximately 50 percent of each in alternating thin seams.

Hole # 37-22-23-5

Location: Section 23, T. 37 S., R. 22 E.
Date: October 27, 1964

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	8.0	8.0	Sand: brown, medium-grained with 15 percent interstitial clay.
8.0	9.8	1.8	Sand: dark brown, medium-grained with 10 percent interstitial clay.
9.8	10.3	0.5	Sand: dark brown, medium-grained with 10 percent interstitial clay and traces of brown phosphate pebbles and pellets.
			Lower Pleistocene
10.3	13.3	3.0	Sand: dark brownish gray, fine- to medium-grained with 5 percent interstitial clay; phosphatic with 25 percent white, tan, and green phosphate pebbles and pellets. Sample # 315A.
13.3	15.8	2.5	Sand: dark brownish gray, fine- to coarse-grained with 10 percent interstitial clay; phosphatic with 25 percent brown phosphate pebbles and pellets. Middle part of Sample # 315A.
15.8	18.5	2.7	Sand: brownish gray, fine- to medium-grained with 10 percent interstitial clay; phosphatic with 30 percent brown phosphate pebbles and pellets. Lower part of Sample # 315A.
18.5	25.6	7.1	Sand: brownish gray, fine- to medium-grained with 15 percent interstitial clay; phosphatic with 30 percent brown to dark brown phosphate pebbles and pellets. Sample # 316A.

Continued on next page

Hole # 37-22-23-5-continued

Hawthorn Formation

25.6	26.7	1.1	Clay: dark grayish green.
26.7	27.2	0.5	Sand: brownish gray, fine-grained with 15 percent interstitial green clay; phosphatic with an estimated 10 percent dark brown phosphate pellets.
27.2	28.6	1.2	Clay: dark grayish green with a trace of fine phosphatic sand with black phosphate pellets.

Hole # 37-22-23-12

Location: Section 23, T. 37 S., R. 22 E.
Date: April 25, 1968.

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	9.1	9.1	Sand: tan to brown, fine- to coarse-grained with 5 percent interstitial clay.
9.1	10.6	1.5	Clay: light grayish green.
10.6	13.0	2.4	Sand: very light gray, fine- to coarse-grained with 5 percent interstitial clay; phosphatic with traces of soft, white aluminum phosphate pebbles.
			Bone Valley Formation
13.0	22.1	9.1	Sand: brownish green, fine- to coarse-grained with 10 percent interstitial clay; phosphatic with 20 percent white to brown phosphate pebbles and pellets. Sample # 2127.
			Hawthorn Formation
22.1	27.4	5.3	Sand: very light gray, fine-grained; contains abundant, soft interstitial marl or calcareous clay; slightly phosphatic.

Hole # 37-22-23-37

Location: Section 23, T. 37 S., R. 22 E.
Date: March 21, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	12.1	12.1	Sand: brownish gray, medium-grained with 15 percent interstitial clay.
12.1	13.3	1.2	Sand: gray, fine- to coarse-grained with 10 percent interstitial clay; phosphatic with traces of soft, white aluminum phosphate pebbles.
			Lower Pleistocene
13.3	32.9	19.6	Sand: medium grayish green, fine- to coarse-grained with 15 percent interstitial clay; phosphatic with 20 percent dark gray to dark brown phosphate pebbles and pellets. Sample # 1956.
			Hawthorn Formation
32.9	38.3	5.4	Clay: dark grayish green.

Hole # 37-22-23-38

Location: Section 23, T. 37 S., R. 22 E.
Date: March 21, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	11.5	11.5	Sand: brown, fine- to coarse-grained with 15 percent interstitial clay.
11.5	12.7	1.2	Sand: tan, fine- to coarse-grained with 10 percent interstitial clay; phosphatic with traces of soft, white aluminum phosphate pebbles.
			Bone Valley Formation
12.7	22.2	9.5	Sand: light brownish gray, fine- to coarse-grained with 10 percent interstitial clay and 5 percent clay in thin seams; phosphatic with 20 percent brown, gray, and black phosphate pebbles and pellets. Sample # 1957.
			Hawthorn Formation
22.2	31.5	9.3	Clay: grayish green. Top part contains abundant thin, fine-grained phosphatic sand seams. Lower part very marly.

Hole # 37-22-24-1

Location: Section 24, T. 37 S., R. 22 E.
Date: April 26, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	12.6	12.6	Sand: brown, fine- to coarse-grained with 10 percent interstitial clay.
12.6	15.1	2.5	Sand: tan, fine- to coarse-grained with 15 percent interstitial clay; phosphatic with traces of soft, white aluminum phosphate pebbles.
			Bone Valley Formation
15.1	21.6	6.5	Sand: greenish gray, fine- to coarse-grained with 15 percent interstitial clay and 5 percent clay in thin seams; phosphatic with 20 percent white to brown phosphate pebbles and pellets. Sample # 2133.
			Hawthorn Formation
21.6	27.2	5.6	Sand: greenish brown, fine-grained with 10 percent interstitial green clay and 5 percent thin green clay seams; phosphatic with 10 percent brown phosphate pellets. Sample # 2134.
27.2	29.4	2.2	Sand: tan, fine-grained with sparse interstitial clay; slightly phosphatic.
29.4	33.6	4.2	Clay: tan, very calcareous.
33.6	35.5	1.9	Clay: dark green, very calcareous.

Hole # 37-22-24-8

Location: Section 24, T. 37 S., R. 22 E.
Date: October 27, 1964

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	8.0	8.0	Sand: brown, medium-grained with 15 percent interstitial clay.
8.0	15.5	7.5	Sand: light brown, fine- to medium-grained with 10 percent interstitial clay.
15.5	17.0	1.5	Sand: light gray, medium-grained with 5 percent interstitial clay, soft, incoherent.
			Lower Pleistocene
17.0	19.8	2.8	Sand: brownish gray, fime- to medium-grained with 10 percent interstitial clay; phosphatic with 25 to 30 percent brown phosphate pebbles and pellets. Top part of Sample # 312A.
19.8	20.0	0.2	Clay: grayish green. Middle part Sample # 312A.
20.0	23.4	3.4	Sand: brownish gray, fine- to medium-grained with 5 percent interstitial clay and 5 percent thin clay seams; phosphatic with 30 to 35 percent brown phosphate pebbles and pellets. Lower part of Sample # 312A.
23.4	30.3	6.9	Sand: brownish gray, fine- to medium-grained with 5 percent interstitial clay and 5 percent thin clay seams; phosphatic with 25 percent very dark brown phosphate pebbles and pellets. Sample # 313A.
			Hawthorn Formation
30.3	34.6	4.3	Clay and sand: interbedded dark green clay and fine-grained, slightly phosphatic sand.
34.6	36.9	2.3	Clay: light to medium gray, very calcareous with hard, irregular patches and masses of limestone. Probably a weathered limestone bed.

Hole # 37-22-27-13

Location: Section 27, T. 37 S., R. 22 E.
Date: April 27, 1965

Depth (feet) From	To	Thick. (feet)	Description
		Upper Pleistocene	
0.0	5.0	5.0	Sand: brown.
		Lower Pleistocene	
5.0	7.9	2.9	Clay: very light gray, very calcareous with hard, irregular masses of limestone.
7.9	8.6	0.7	Sand: very light gray, medium-grained, phosphatic with 10 percent white phosphate pebbles and pellets; 50 percent interstitial clay.
8.6	9.3	0.7	Sand: light gray, medium-grained with 5 percent interstitial clay; slightly phosphatic.
9.3	10.8	1.5	Sand: light brownish gray, fine- to coarse-grained with 5 percent interstitial clay; phosphatic with 30 percent white and light brown phosphate pebbles and pellets. Sample # 1030 (continued below).
10.8	16.7	5.9	Sand: brownish gray, fine- to medium-grained with 10 percent interstitial clay; phosphatic with 25 percent brown phosphate pebbles and pellets. Remainder of Sample # 1030.
16.7	22.7	6.0	Sand: brownish gray, fine- to medium-grained with 10 percent interstitial clay; phosphatic with 20 percent brown phosphate pebbles and pellets. Sample # 1031.
		Hawthorn Formation	
22.7	26.3	3.6	Marl: very light gray, soft, very clayey.

Hole # 37-23-12-6

Location: Section 12, T. 37 S., R. 23 E.
Date: January 12, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	11.7	11.7	Sand: brownish gray, fine- to medium-grained with 5 percent interstitial clay, soft, incoherent.
11.7	13.0	1.3	Sand: very light gray, fine- to very coarse-grained with 10 percent interstitial clay; slightly phosphatic with traces of soft, white aluminum phosphate pebbles.
			Bone Valley Formation
13.0	18.0	5.0	Sand: very light grayish green, fine- to very coarse-grained with 15 percent interstitial green clay; phosphatic with 25 percent tan and brown phosphate pebbles and pellets. Sample # 1854.
			Hawthorn Formation
18.0	24.0	6.0	Sand: very light gray, fine- to medium-grained with 15 percent interstitial clay; phosphatic with 10 to 15 percent fine, tan to brown phosphate pellets. Sample # 1855.
24.0	29.7	5.7	Sand: light brown, fime- to medium-grained with 10 percent interstitial clay; phosphatic with 15 to 20 percent brown phosphate pellets. Sample # 1856.
29.7	30.9	1.2	Sand: light brownish gray, very fine-grained, slightly clayey, slightly phosphatic.
30.9	39.5	8.6	Clay: dark grayish green with 20 percent thin, fine-grained, very dark gray, phosphatic sand seams.

Hole # 37-23-14-2

Location: Section 14, T. 37 S., R. 23 E.
Date: June 21, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	15.2	15.2	Sand: dark brown, fine- to coarse-grained. Zone of hardpan from 5 feet to 8.5 feet.
			Lower Pleistocene
15.2	16.1	0.9	Limestone: white
16.1	31.6	15.5	Sand: greenish brown, fine- to coarse-grained with 15 percent interstitial clay; phosphatic with 20 percent brown and gray phosphate pebbles and pellets. Sample # 2469.
			Hawthorn Formation
31.6	33.3	1.7	Clay: dark green.

Hole # 37-23-16-11

Location: Section 16, T. 37 S., R. 23 E.
Date: May 28, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	16.7	16.7	Sand: brown, fine- to very coarse-grained with sparse interstitial clay and minor hardpan.
16.7	17.3	0.6	Sand: tan, fine- to coarse-grained with sparse interstitial clay and traces of white, soft aluminum phosphate pebbles.
			Lower Pleistocene
17.3	34.9	17.6	Sand: tan to brown, fine- to coarse-grained with 10 percent interstitial clay and very minor clay seams; phosphatic with 20 percent white, tan, and brown phosphate pebbles and pellets. Sample # 2339.
			Hawthorn Formation
34.9	40.2	5.3	Sand: gray, fine-grained with sparse interstitial clay and minor thin clay seams; phosphatic with 10 to 15 percent fine, black phosphate pellets. Sample # 2340.
40.2	42.8	2.6	Clay: grayish green.
42.8	45.2	2.4	Limestone: light gray, hard.

Hole # 37-23-18-1

Location: Section 18, T. 37 S., R. 23 E.
Date: June 22, 1966

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	22.0	22.0	Sand: brown to light gray, medium-grained, clayey in basal part.
			Bone Valley Formation
22.0	26.9	4.9	Sand: light brownish gray, fine- to coarse-grained with 10 percent interstitial clay; phosphatic with 25 percent light gray to tan phosphate pebbles and pellets. Sample # 1533.
			Hawthorn Formation
26.9	36.5	9.6	Sand: medium brown, fine-grained with 5 percent interstitial clay; slightly phosphatic with 10 percent brown phosphate pellets. Sample # 1534.
36.5	40.5	4.0	Sand: very dark gray, fine-grained with 5 percent interstitial clay; slightly phosphatic with 5 percent fine, black phosphate pellets.

Hole # 37-23-18-10

Location: Section 18, T. 37 S., R. 23 E.
Date: June 27, 1966

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	14.0	14.0	Sand: light brown, medium-grained.
14.0	14.7	0.7	Sand: medium brown, fine- to coarse-grained with 10 percent interstitial clay and a trace of soft, white aluminum phosphate pebbles.
			Bone Valley Formation
14.7	16.5	1.8	Sand: medium gray, fine- to coarse-grained with 10 percent interstitial clay; phosphatic with 25 percent dark brown to black phosphate pebbles and pellets. Upper part of Sample # 1569.
16.5	25.0	8.5	Sand: medium gray, fine- to medium-grained with 10 percent interstitial clay and minor thin clay seams; phosphatic with 20 percent dark brown to black phosphate pebbles and pellets. Lower part of Sample # 1569.
			Hawthorn Formation
25.0	32.8	7.8	Sand: brownish gray, fine- to very fine-grained with sparse interstitial clay; phosphatic with 10 percent dark brown phosphate pellets. Sample # 1570.
32.8	37.3	4.5	Sand: very dark gray, fine- to very fine-grained with sparse interstitial clay; phosphatic with 5 percent black phosphate pellets.

Hole # 37-23-18-11

Location: Section 18, T. 37 S., R. 23 E.
Date: June 27, 1966

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	23.6	23.6	Sand: light brown to light gray, fine-grained with 15 percent interstitial clay.
			Hawthorn Formation
23.6	28.0	4.4	Sand: light brownish gray, fine-grained with 10 percent interstitial clay; phosphatic with 10 percent white to tan phosphate pellets. Sample # 1571 (continued below).
28.0	35.0	7.0	Sand: light brown, fine-grained with 10 percent interstitial clay; phosphatic with 5 percent dark brown phosphate pellets. Remainder of Sample # 1571.
35.0	38.5	3.5	Sand: dark gray, fine-grained, slightly clayey, slightly phosphatic with 5 percent black phosphate pellets.

Hole # 37-23-18-19

Location: Section 18, T. 37 S., R. 23 E.
Date: June 23, 1966

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	8.0	8.0	Sand: dark brownish gray, fine-grained with 15 percent interstitial clay.
			Lower Pleistocene
8.0	10.8	2.8	Clay: light grayish green.
			Bone Valley Formation
10.8	19.4	8.6	Sand: light brownish gray, fine- to coarse-grained with 15 percent interstitial clay; phosphatic with 25 percent white and tan phosphate pebbles and pellets. Sample # 1551.
			Hawthorn Formation
19.4	24.7	5.3	Sand: light brown, fine- to very fine-grained; very sparse interstitial clay; estimated 50 percent clay in thin seams; phosphatic with 10 percent fine, brown phosphate pellets. Sample # 1552.
24.7	34.0	9.3	Sand: medium brown, fine- to very fine-grained with very sparse interstitial clay; phosphatic with 15 percent brown phosphate pellets. Sample # 1553.
34.0	37.5	2.5	Sand: very dark gray to black, fine- to medium-grained with sparse interstitial clay; phosphatic with 5 percent fine, black phosphate pellets.

Hole # 37-23-18-33

Location: Section 18, T. 37 S. R. 23 E.
Date: May 16, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	12.6	12.6	Sand: brownish gray, fine- to coarse-grained with 10 percent interstitial clay.
			Bone Valley Formation
12.6	19.0	6.4	Sand: greenish gray, fine- to coarse-grained with 15 percent interstitial clay and minor clacareous clay seams; phosphatic with 25 percent brown phosphate pebbles and pellets. Sample # 2265.
			Hawthorn Formation
19.0	32.2	13.2	Sand: greenish tan, fine-grained with 10 percent interstitial clay; phosphatic with 10 to 15 percent fine, brown phosphate pellets. Sample # 2266.
32.2	37.5	5.3	Clay: dark gray, sandy, very calcareous.

Hole # 37-23-18-34

Location: Section 18, T. 37 S., R. 23 E.
Date: May 16, 1968

Depth (feet) From	Depth (feet) To	Thick. (feet)	Description
			Upper Pleistocene
0.0	14.9	14.9	Sand: brown, fine- to coarse-grained with very sparse interstitial clay.
14.9	15.8	0.9	Sand: tan, fine- to coarse-grained with very sparse interstitial clay and a trace of soft, white aluminum phosphate pebbles.
15.8	26.1	10.3	Sand: tan, fine-grained with 5 percent interstitial clay and 5 percent thin green clay seams.
			Hawthorn Formation
26.1	31.5	5.4	Sand: light brown, fine-grained with 5 percent interstitial clay; phosphatic with 5 to 10 percent fine, brown phosphate pellets. Sample # 2267.
31.5	36.4	4.9	Sand; dark gray, fine-grained, like above with very dark gray to black phosphate. Sample # 2268.

Hole # 37-23-18-39

Location: Section 18, T. 37 S., R. 23 E.
Date: May 20, 1968.

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	12.8	12.8	Sand: tan to greenish gray, fine- to coarse-grained with very sparse interstitial clay.
			Lower Pleistocene
12.8	24.7	11.9	Sand: greenish brown, fine- to coarse-grained with 10 percent interstitial clay and minor thin clay seams; phosphatic with 20 percent brown phosphate pebbles and pellets. Sample # 2280.
24.7	28.8	4.1	Clay: greenish gray with minor phosphatic sand, very calcareous with minor irregular masses of hard limestone.
28.8	29.8	1.0	Clay: dark gray, sandy with trace of fine dark gray phosphate pellets.

Hole # 37-23-19-16

Location: Section 19, T. 37 S, R. 23 E.
Date: May 8, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	10.4	10.4	Sand: tan, fine- to coarse-grained, slightly clayey.
			Bone Valley Formation
10.4	17.0	6.6	Sand: greenish gray, fine- to coarse-grained with 10 percent interstitial clay; phosphatic with 35 percent white, gray, and brown phosphate pebbles and pellets. Sample # 2157.
			Hawthorn Formation
17.0	24.4	7.4	Sand: greenish brown, fine- to coarse-grained with 5 percent green clay seams and 5 percent interstitial clay; phosphatic with 15 percent fine brown phosphate pellets. Sample # 2158.
24.4	30.0	5.6	Clay: brownish green with minor thin seams of phosphatic sand.
30.0	38.8	8.8	Clay: grayish green.
38.8	42.1	3.3	Limestone: light gray, clayey, very soft and weathered.

Hole # 37-23-19-49

Location: Section 19, T. 37 S., R. 23 E.
Date: May 5, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	13.5	13.5	Sand: brown to tan, fine- to coarse-grained, very sparsely clayey.
			Bone Valley Formation
13.5	20.0	6.5	Sand: tan, fine- to coarse-grained, sparse interstitial clay; phosphatic with 25 percent white, tan, and brown phosphate pebbles and pellets. Sample # 2181.
			Hawthorn Formation
20.0	31.1	11.1	Sand: grayish green, fine-grained with sparse interstitial clay and 5 percent thin, green clay seams; phosphatic with 15 percent brown to dark brown phosphate pellets. Sample # 2182.
31.1	35.4	4.3	Sand: dark grayish green, fine-grained, sparse interstitial clay, 10 percent thin clay seams; phosphatic with 20 percent dark gray to black, fine phosphate pellets; slightly marly. Sample # 2183.
35.4	38.7	3.3	Clay: dark grayish green.

Hole # 37-23-19-50

Location: Section 19, T. 37 S., R. 23 E.
Date: May 6, 1968

Depth (feet) From	To	Thick. (feet)	Description
		Upper Pleistocene	
0.0	23.3	23.3	Sand: tan, fine- to coarse-grained, very soft and incoherent.
		Lower Pleistocene	
23.3	42.1	18.8	Sand: greenish brown, fine- to coarse-grained with sparse interstitial clay; phosphatic with 20 percent brown phosphate pebbles and pellets. Sample # 2184.
		Hawthorn Formation	
42.1	52.3	10.2	Sand: dark gray, fine- to coarse-grained with very sparse interstitial clay; phosphatic with 20 percent dark gray phosphate pebbles and pellets. Coarse pebble fraction is very minor. Sample # 2185.
52.3	55.6	3.3	Sand: dark greenish gray, fine-grained with 20 percent interstitial clay and sparse, minor calcareous patches; phosphatic with 15 percent dark gray phosphate pellets. Sample # 2186.
55.6	59.1	3.5	Limestone: gray, alternating soft, clayey masses and hard zones.

Hole # 37-24-8-5

Location: Section 8, T. 37 S., R. 24 E.
Date: April 10, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	7.7	7.7	Sand: tan, fine- to coarse-grained.
			Lower Pleistocene
7.7	10.0	2.3	Clay: tan and green mottled.
			Bone Valley Formation
10.0	14.0	4.0	Sand: greenish gray, fine- to coarse-grained with 15 percent interstitial clay; phosphatic with 20 percent brown to gray phosphate pebbles and pellets. Sample # 2053.
			Hawthorn Formation
14.0	17.9	3.9	Clay: white, very calcareous.
17.9	24.7	6.8	Clay: greenish tan with minor seams of fine phosphatic sand.
24.7	29.5	4.8	Clay: grayish green.

Hole # 37-24-8-8

Location: Section 8, T. 37 S., R. 24 E.
Date: April 11, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	5.9	5.9	Sand: tan, fine- to coarse-grained.
5.9	7.1	1.2	Sand: tan, fine- to coarse-grained; phosphatic with a trace of soft, white aluminum phosphate pebbles.
			Lower Pleistocene
7.1	27.4	20.3	Sand: light gray, fine- to coarse-grained with 15 percent interstitial clay; phosphatic with 25 percent white to gray phosphate pebbles and pellets. Sample # 2055.
27.4	30.2	2.8	Marl: light gray, some irregular, hard calcareous masses.

Hole # 37-24-8-13

Location: Section 8, T. 37 S., R. 24 E.
Date: April 12, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	25.2	25.2	Sand: light brown, fine- to coarse-grained, 15 percent interstitial clay.
			Lower Pleistocene
25.2	34.4	9.2	Sand: medium gray, fine- to medium-grained, very clayey and soft; phosphatic with 15 percent brown to gray phosphate pebbles and pellets. Sample # 2065.
			Hawthorn Formation
34.4	37.6	3.2	Sand: grayish green, very fine-grained, soft, incoherent, slightly phosphatic, very clayey (estimate 40 percent clay).

Hole # 37-24-9-4

Location: Section 9, T. 37 S., R. 24 E.
Date: April 11, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	17.6	17.6	Sand: brown, fine- to coarse-grained, minor thin hardpan zone.
17.6	18.4	0.8	Sand: medium brown, fine- to very coarse-grained, slightly clayey; trace of soft, white aluminum phosphate pebbles.
			Lower Pleistocene
18.4	33.5	15.1	Sand: tan to dark gray, fine- to coarse-grained, very slightly clayey, soft, incoherent; phosphatic with 25 percent gray phosphate pebbles and pellets. Sample # 2059.
			Hawthorn Formation
33.5	34.9	1.4	Marl: medium gray, clayey with some hard, irregular calcareous patches.
34.9	40.3	5.4	Sand: dark grayish green, fine-grained, very clayey, sparsely phosphatic.

Hole # 37-24-9-7

Location: Section 9, T. 37 S., R. 24 E.
Date: April 12, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	15.0	15.0	Sand: tan, fine- to coarse-grained.
			Lower Pleistocene
15.0	26.1	11.1	Limestone: light tan, very porous and soft, incoherent.
26.1	32.5	6.4	Sand: brownish gray, fine- to very coarse-grained with 15 percent interstitial clay and 5 percent clay seams, abundant hard calcareous masses, 10 percent black phosphate pebbles and pellets.
32.5	42.0	9.5	Sand: dark gray, fine- to coarse-grained with 10 percent interstitial clay and minor marl; phosphatic with 20 percent black phosphate pebbles and pellets. Sample # 2062.
42.0	43.0	1.0	Sand: very dark gray, fine- to very coarse-grained; similar to above but with abundant hard marl masses.
43.0	48.3	5.3	Sand: As above but sparsely phosphatic.

Hole # 37-24-18-14

Location: Section 18, T. 37 S., R. 24 E.
Date: December 11, 1967

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	12.0	12.0	Sand: brown, fine- to medium-grained.
12.0	14.0	2.0	Sand: tan, fine- to coarse-grained with sparse interstitial clay and a trace of soft white aluminum phosphate pebbles.
			Hawthorn Formation
14.0	35.5	21.2	Sand: light gray, fine-grained, very sparse interstitial clay, 10 percent thin clay seams; phosphatic with 25 percent tan and brown phosphate pellets. Sample # 1821.
35.5	40.6	5.1	Clay: dark grayish green with 10 percent thin, fine-grained, phosphatic sand seams.

Hole # 37-24-18-20

Location: Section 18, T. 37 S., R. 24 E.
Date: June 6, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	12.7	12.7	Sand: brown, fine- to coarse-grained.
			Bone Valley Formation
12.7	20.8	8.1	Sand: brownish gray to greenish gray, fine- to coarse-grained, clayey; phosphatic with 25 percent white and brown phosphate pebbles and pellets. Sample # 2385.
			Hawthorn Formation
20.8	28.8	8.0	Sand: brownish gray, fine-grained with sparse interstitial clay and minor clay seams; phosphatic with 15 percent brown phosphate pellets. Sample # 2386.
28.8	32.4	3.6	Clay: gray, very calcareous, phosphatic.

Hole # 37-24-18-29.

Location: Section 18, T. 37 S., R. 24 E.
Date: June 12, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	16.0	16.0	Sand: tan to brown, fine- to coarse-grained, very slightly clayey, incoherent.
			Lower Pleistocene
16.0	25.6	9.6	Sand: greenish gray, fine- to coarse-grained with 30 percent interstitial clay; phosphatic with 25 percent brown phosphate pebbles and pellets and minor limestone pebbles. Sample # 2425.
			Hawthorn Formation
25.6	31.8	6.2	Clay: brownish green, mottled, with minor, thin seams of fine phosphatic sand.

Hole # 37-24-19-6

Location: Section 19, T. 37 S., R. 24 E.
Date: December 8, 1967

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	25.1	25.1	Sand: dark to medium brown, fine- to coarse-grained, very slightly clayey.
			Hawthorn Formation
25.1	43.2	18.1	Sand: brownish gray, fine- to medium-grained, slightly clayey; phosphatic with 15 percent white, tan, and brown phosphate pellets. Sample # 1816.
43.2	51.3	8.1	Sand: very dark gray, fine-grained, 10 percent interstitial clay, slightly phosphatic, minor irregular patches or masses of marl.

Hole # 37-24-19-26

Location: Section 19, T. 37 S., R. 24 E.
Date: June 7, 1968

Depth (feet) From	To	Thick. (feet)	Description
			Upper Pleistocene
0.0	16.4	16.4	Sand: brown, fine- to coarse-grained.
			Bone Valley Formation
16.4	23.9	7.5	Sand: greenish gray, fine- to coarse-grained, clayey; phosphatic with 25 percent white to brown phosphate pebbles and pellets. Sample # 2391.
			Hawthorn Formation
23.9	41.2	17.3	Sand: brown, fine- to medium-grained, 15 percent interstitial clay; phosphatic with 15 percent brown phosphate pellets. Sample # 2392.
41.2	47.7	6.5	Sand: dark gray, fine- to coarse-grained, slightly clayey; phosphatic with 15 percent black phosphate pellets. Sample # 2393.
47.7	52.4	4.7	Clay: dark grayish green, marly.