



28th International Geological Congress

Florida Phosphate Deposits

Field Trip Guidebook T178

Leaders:

Thomas Scott and James Cathcart



**Tampa to Jacksonville, Florida
June 30–July 7, 1989**

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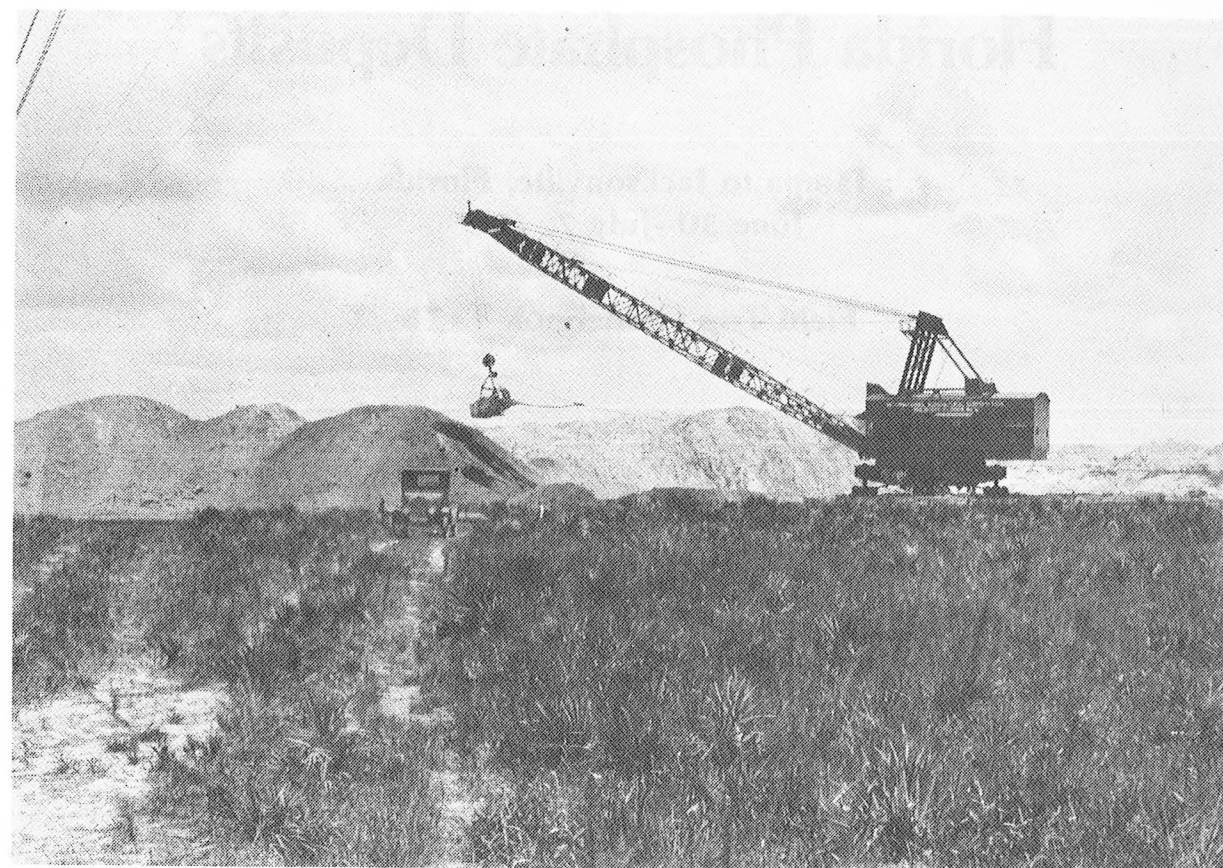
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COVER 1940's photograph of mining in the central Florida phosphate district.

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The editorial efforts of the following geologists with the Florida Geological Survey enhanced the quality of the guidebook: Mr. Ken Campbell, Mr. Jon Arthur, Dr. Walt Schmidt, Ms. Paulette Bond, Ms. Jackie Lloyd, and Mr. Frank Rupert.

INTRODUCTION

Welcome to the International Geological Congress Field Trip T178 Florida Phosphate Deposits. We hope you will enjoy this excursion in Florida. The trip will visit active phosphate mines in central and northern Florida and a limestone mining operation.

Phosphorites deposited in the southeastern United States during the Miocene have attracted the attention of geologists for many years. Numerous studies have investigated the genesis, diagenesis, stratigraphy, mineralogy and extent of these deposits, however, questions concerning the phosphorites and the associated sediments remain. The interest in the phosphorites has resulted in the development of this field trip and guidebook.

The phosphorites of Florida are a part of a larger phosphogenic province which includes much of the Atlantic Coastal Plain from Virginia to Florida. This guidebook provides a brief overview of the geology of the Florida phosphorites and the associated

sediments. In depth discussions of specific details mentioned in this text are available from the many references cited.

The authors of this guidebook have shared an interest in phosphorites for many years. Along with many other geologists we share an enthusiasm for continued research in this area. We hope that you will gain a better understanding of the complex nature of the sediments and the phosphogenic system through participation in this field excursion.

During this field excursion, please keep in mind that the July heat and humidity can be dangerous, especially for those not acclimated to this climate. Remember to drink plenty of fluids and notify the field trip leaders if you begin to feel the effects of the heat. Your cooperation will help make this a safe and enjoyable trip.

Thomas M. Scott
and
James B. Cathcart

THE GEOLOGY OF CENTRAL AND NORTHERN FLORIDA WITH EMPHASIS ON THE HAWTHORN GROUP

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INTRODUCTION

Phosphogenic episodes are an uncommon occurrence in geologic history. Where and when they occur can be documented in the geologic record. Why these episodes occurred and how it happened is not thoroughly understood. What we do know is that the antecedent topography of the ocean bottom appears to be a significant factor, as does the occurrence of bottom water upwelling. Knowledge of the geology of Florida aids in developing a better understanding of the occurrence of the phosphatic sediments.

This paper presents a brief overview of Florida's Cenozoic geologic framework and includes an in depth discussion of the Hawthorn Group sediments which contain vast reserves of phosphate.

GEOMORPHOLOGY

Many geologists have noted the coast paralleling trends of the geomorphic features in peninsular Florida. The development of these trends suggests a strong influence by coastal marine processes which affected this area during higher sea level stands in the Pleistocene. White (1970) thoroughly discussed the geomorphology of the peninsular area. Figure 1 outlines the geomorphic features described by White (1970) with minor modifications.

The Central Florida Phosphate District (Figure 2) lies on part of the Lakeland Ridge and the Polk Upland (Figure 1). The Lake Henry and Winter Haven Ridges form the eastern limits of the district. Mining operations are predicted to move further south as the higher grade deposits are depleted. As they move southward, the mines will be on the DeSoto Plain and the southern edge of the Polk Upland.

The limestone mines visited on this field trip are located on the Brooksville Ridge (Figure 1). Hard rock phosphate mining (the Hard Rock Phosphate District) (Figure 2) occurred along the eastern flank of the Brooksville Ridge.

Occidental Chemical Company's phosphate mining operation in the North Florida Phosphate District occurs in the Northern Highlands (Figures 1 and 2). This district generally trends northwest-southeast paralleling the trends of the peninsula's major geomorphic features.

GEOLOGIC STRUCTURE

The geologic structures of peninsular Florida have played an important role in the geologic history of the State. These features affected the depositional environments and the post-depositional occurrence of the Hawthorn Group sediments. Due to the nature of the Tertiary sediments in peninsular Florida, it is difficult to ascertain a true structural origin for some of these features. Depositional and erosional processes may have played a role in their development.

The most prominent of the structures in peninsular Florida is the Ocala Platform (often referred to as the Ocala Arch or Uplift) (Figure 3). Vernon (1951) described it as a gentle flexure developed in Tertiary sediments with a northwest-southeast trending crest. He believed that the crest of the platform has been flattened by faulting. Vernon (1951) dated the formation of the platform as being Early Miocene based on the involvement of basal Miocene sediments in the faulting and the wedging out of younger Miocene sediments against the flanks of the platform.

Riggs (1979 a, b) stated that the Ocala Upland (his term for the Ocala Platform) was a major structural feature controlling the formation and deposition of the phosphorites in the Florida Miocene.

The Sanford High is another important positive feature in the northern half of peninsular Florida (Figure 3). Vernon (1951) proposed the name for a feature located in Seminole and Volusia Counties, Florida. He describes the feature as "a closed fold that has been faulted, the Sanford High being located on the upthrown side." The Miocene Hawthorn Group and the Upper Eocene Ocala Group are missing from the crest of the Sanford High. The Middle Eocene Avon Park Formation lies immediately below post-Hawthorn sediments. The missing section presumably was removed by erosion. Vernon (1951) believed the feature to be a pre-Miocene structure. Riggs (1979 a, b) considered the Sanford high the "other positive element of extreme importance" in relation to phosphorite deposition.

Extending from the Sanford High are the

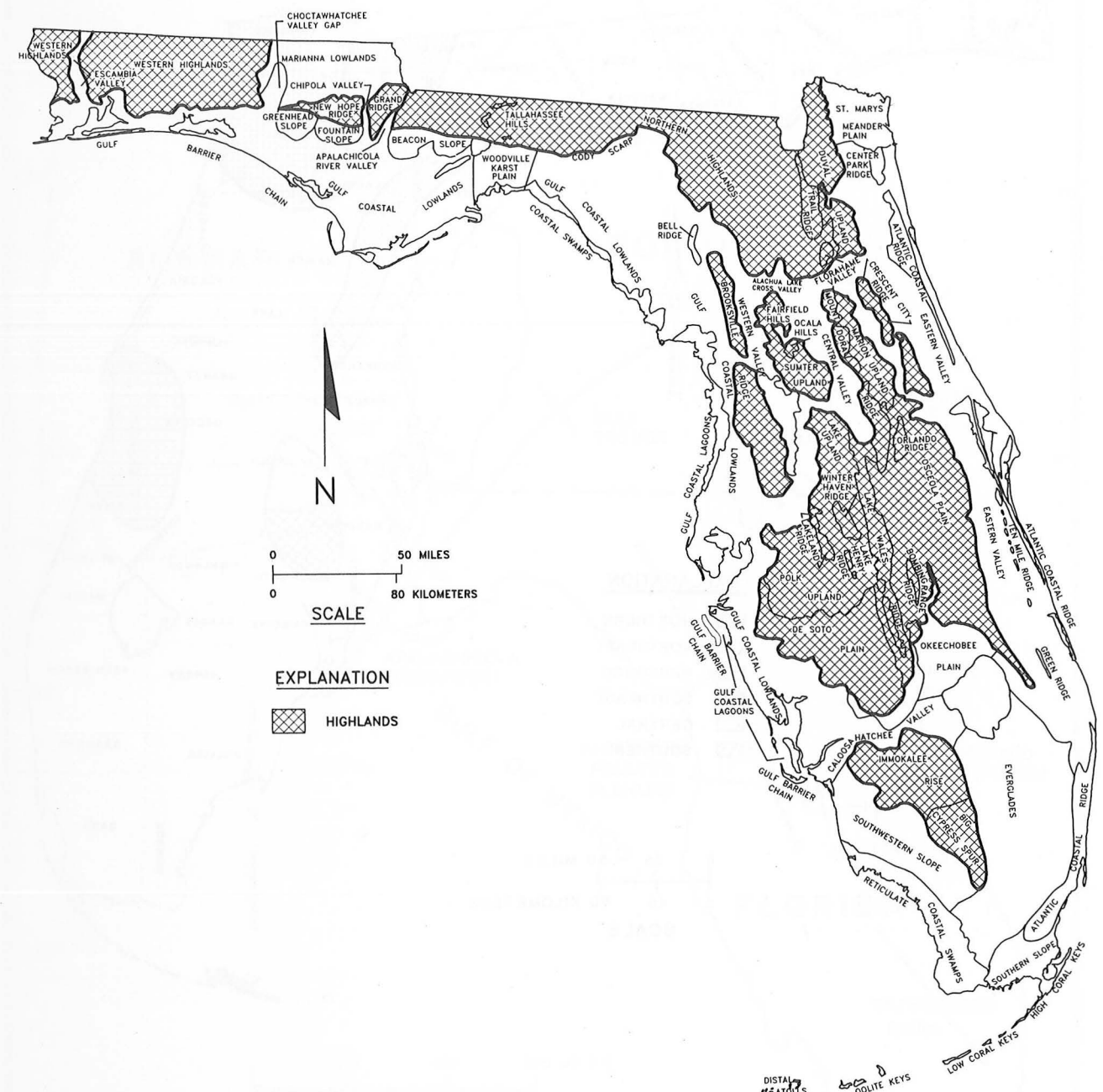


Figure 1: Geomorphology of the Florida peninsula (modified after White, 1970).

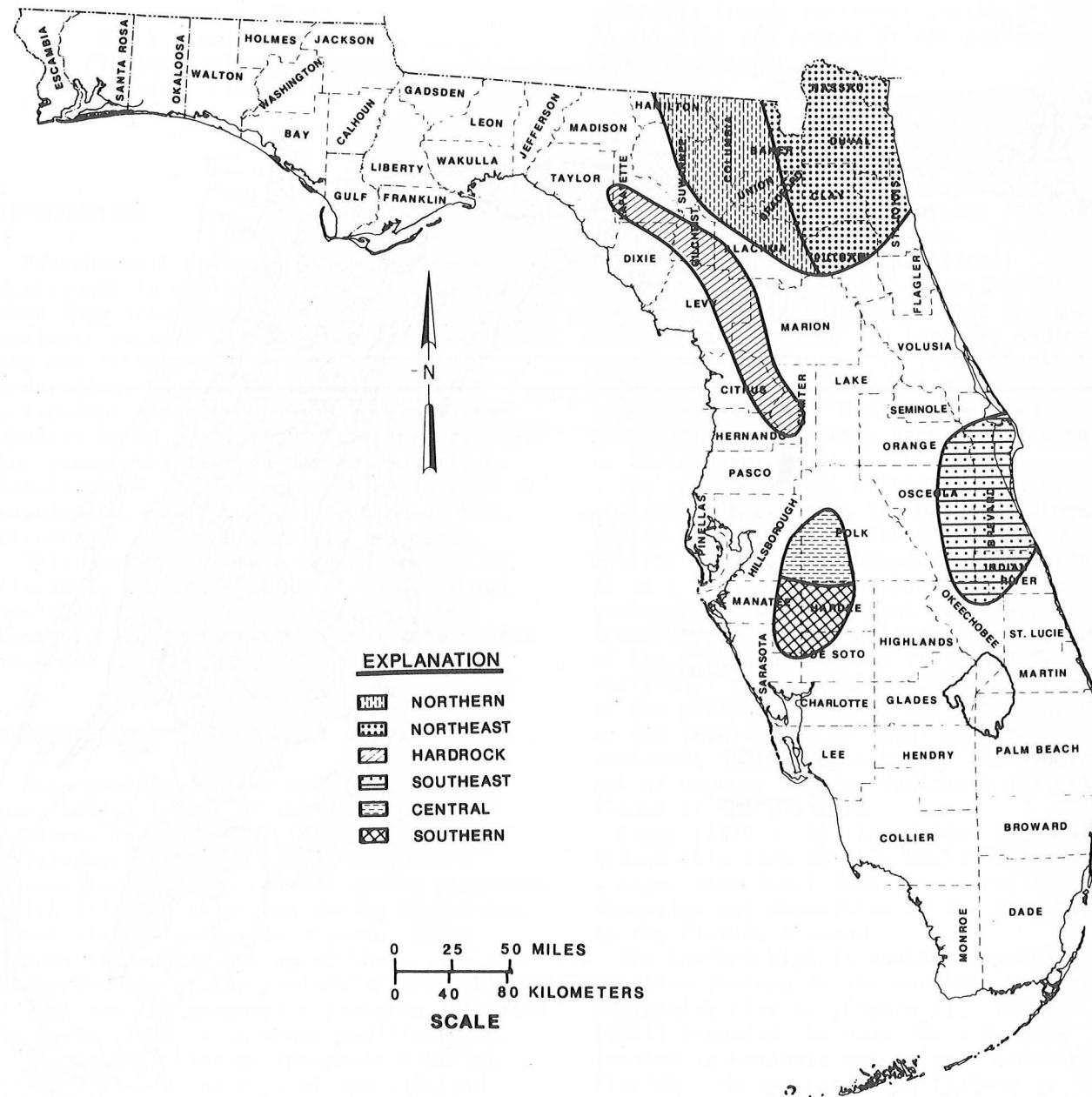


Figure 2: Florida phosphate districts.

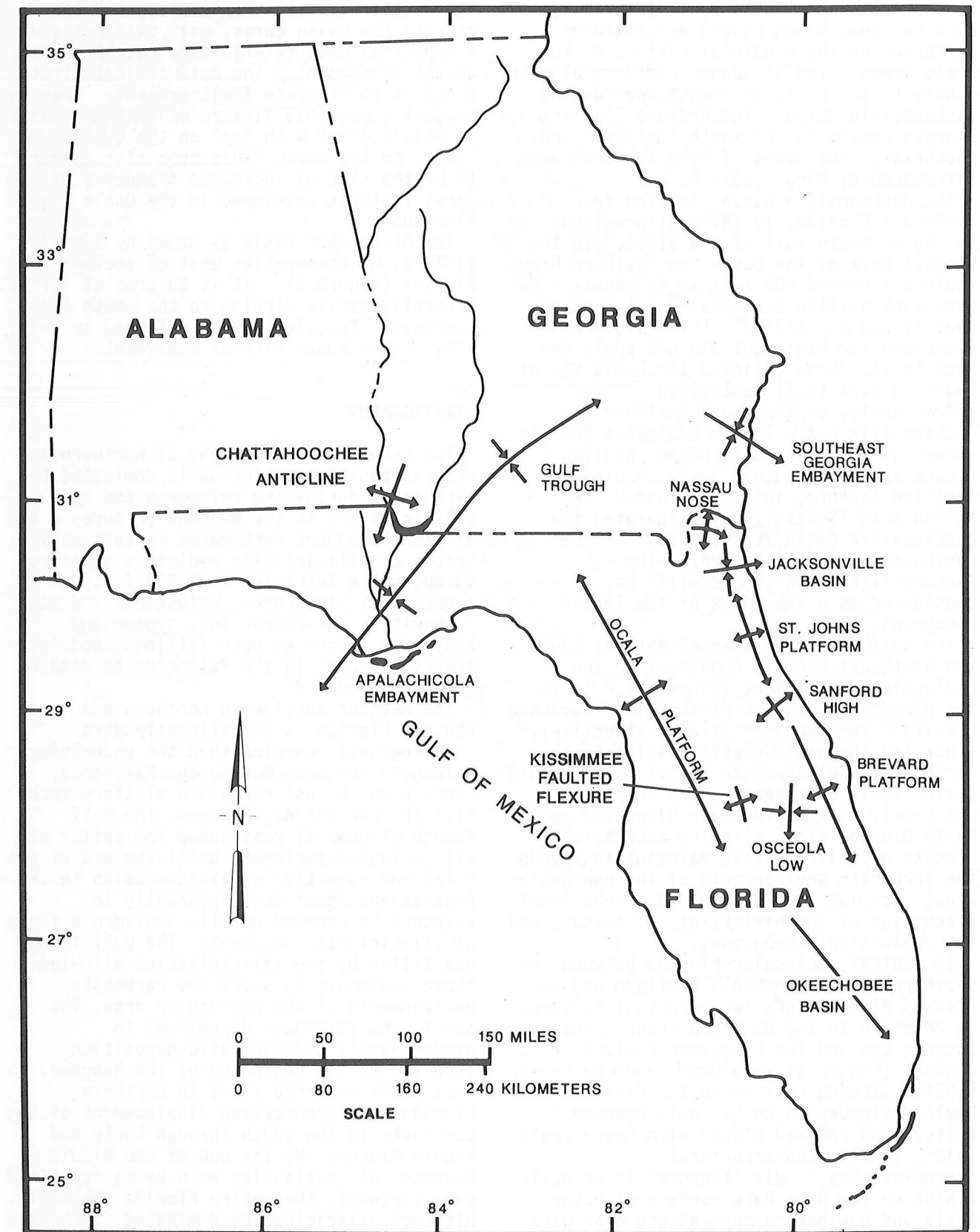


Figure 3: Structural elements of the Florida peninsula.

St. Johns Platform to the north and the Brevard Platform to the south (Figure 3). Both are low, broad ridges or platforms expressed on the erosional surface of the Ocala Group. The St. Johns Platform plunges gently to the north-northwest towards the Jacksonville Basin. The Brevard Platform plunges gently to the south-southeast and southeast. The names of both features were introduced by Riggs (1979 a, b).

The Jacksonville Basin, located in northeast Florida, is the most prominent low in the northern half of the state. In the deepest part of the basin the Hawthorn Group sediments exceed 500 feet in thickness. The name Jacksonville Basin was first used by Goodell and Yon (1960). Leve (1965) discussed the basin but did not apply any name to it. Leve believed the basin was at least in part fault controlled.

Previously, many authors included the Jacksonville Basin in the Southeast Georgia Embayment. As more data became available it became apparent that an eastward dipping positive feature, informally named the Nassau Nose (Scott, 1983), separated the Jacksonville Basin from the rest of the Southeast Georgia Embayment. The Jacksonville Basin should still be considered as a sub-basin of the larger embayment.

The Gulf Trough or Channel extends from the Southeast Georgia Embayment to the Apalachicola Embayment (Figure 3). It is the Miocene expression of the older Suwannee Straits. The Suwannee Straits effectively separated the siliciclastic facies to the north from the carbonate facies to the south during Early Cretaceous. The Gulf Trough was nearly full by the Late Oligocene and Early Miocene time, allowing increasing amounts of siliciclastic material to invade the carbonate environments of the peninsular area. Schmidt (1985) provided an excellent discussion of the history of the feature and the Apalachicola Embayment.

In central peninsular Florida between the southern end of the Ocala Platform and the Brevard Platform are two important features in relation to the Hawthorn Group. The Osceola Low and the Kissimmee Faulted Flexure (Figure 3) were both named by Vernon (1951). Vernon considered the Kissimmee Faulted Flexure to be "a fault-bounded, tilted, and rotated block" with "many small folds, faults, and structural irregularities." His "flexure" is actually a high on the Avon Park surface with the Ocala and Hawthorn groups absent over part of it due to erosion.

The Osceola Low, as described by Vernon (1951), is a fault-bounded low with as much

as 350 feet of Miocene sediments (Figure 4). This author (Scott) has investigated the Osceola Low using cores, well cuttings and geophysical data (Florida Geological Survey, unpublished data). The data indicate that there is no discrete fault present. They do suggest a possible flexure or perhaps a zone of displacement with "up" on the east, "down" on the west. This zone also appears to be the site of increased frequency of karst features developed in the Ocala Group limestone.

The Okeechobee Basin as named by Riggs (1979 a, b) encompasses most of southern Florida (Figure 3). It is an area of strata generally gently dipping to the south and southeast. Pressler (1947) referred to this area as the South Florida Embayment.

STRATIGRAPHY

The Cenozoic stratigraphy of northern and central peninsular Florida is dominated by carbonates during the Paleogene and by siliciclastics in the Neogene (Figures 5 and 6). The Paleogene carbonates contain only traces of siliciclastic sediments scattered throughout a thick (up to 3,000 feet) sequence of limestones, dolostones and some evaporites. The evaporites, gypsum and anhydrite, occur as pore fillings, nodules, lenses and beds in the Paleocene to Middle Eocene carbonates.

The Neogene section in northern and central Florida is significantly more lithologically complex than the underlying Paleogene section. During the Paleogene, Florida was a vast carbonate platform much like the present day Bahamas. The Gulf Trough (Figure 3) restricted the influx of siliciclastic sediments until the end of the Paleogene. Greatly increased erosion in the Appalachian Mountains, apparently in response to renewed uplift, provided a flood of siliciclastic sediments. The Gulf Trough was filled by the siliciclastics allowing these sediments to enter the carbonate environments of the peninsular area. The shift from carbonate deposition to predominantly siliciclastic deposition occurred at the beginning of the Neogene. This shift occurred first in northern Florida with progressive displacement of the carbonate to the south through Early and Middle Miocene. By the end of the Middle Miocene, siliciclastics were being deposited over virtually the entire Florida peninsula. Although siliciclastics dominated, carbonate deposition continued in limited areas as is shown by the scattering of carbonate beds and carbonate cements in the Neogene

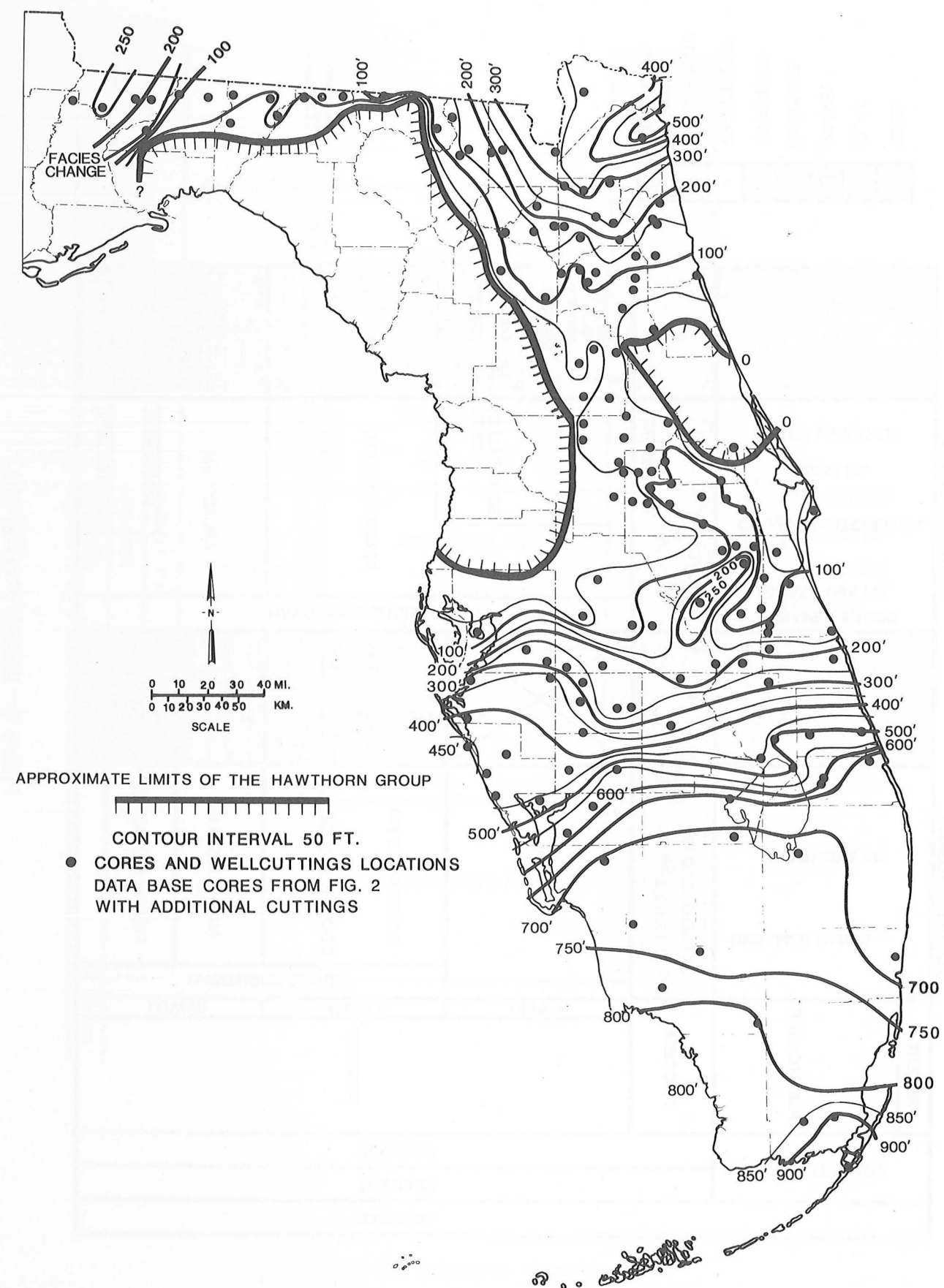


Figure 4: Isopach of the Hawthorn Group in Florida.

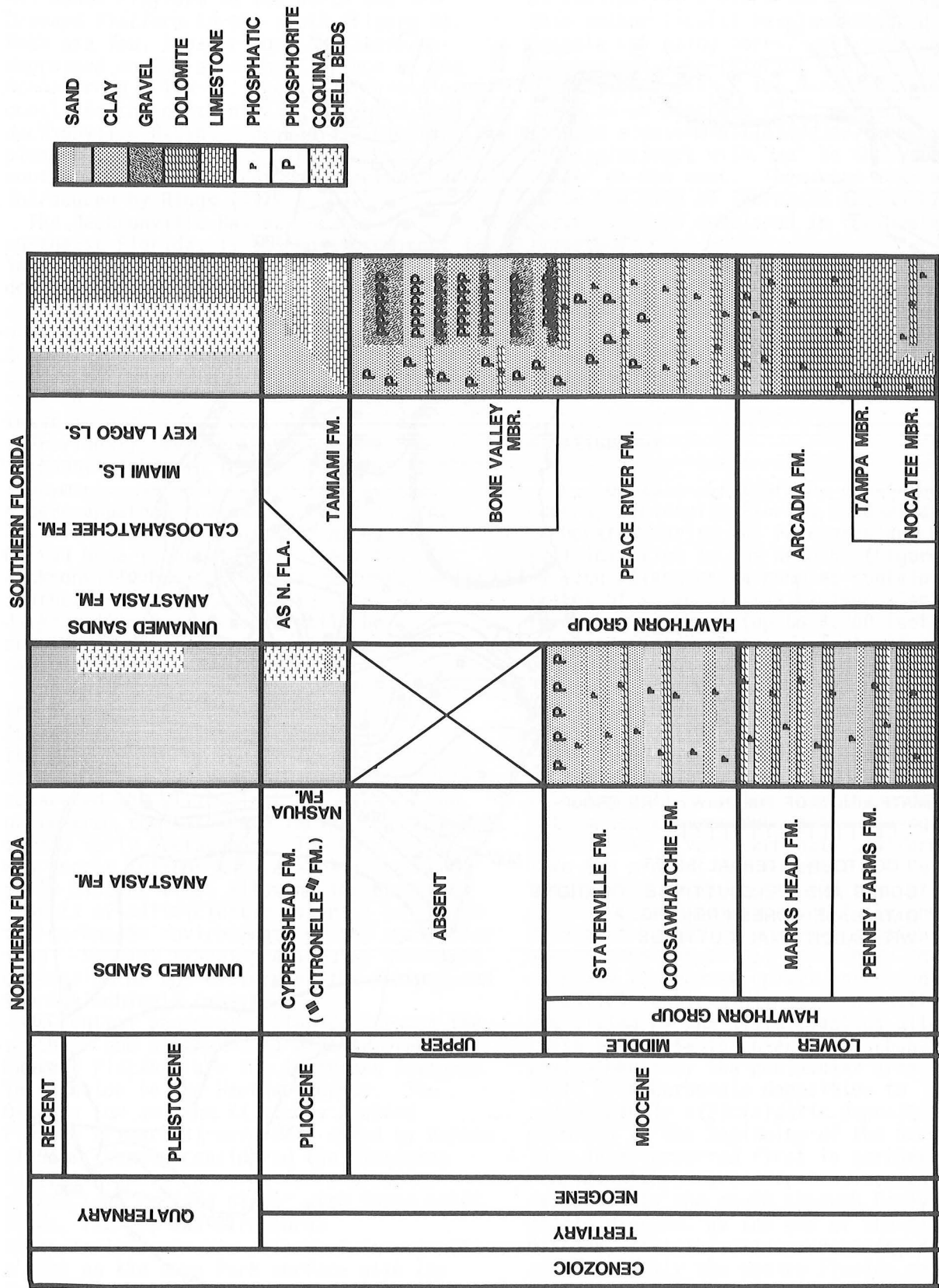


Figure 5: Neogene stratigraphy.

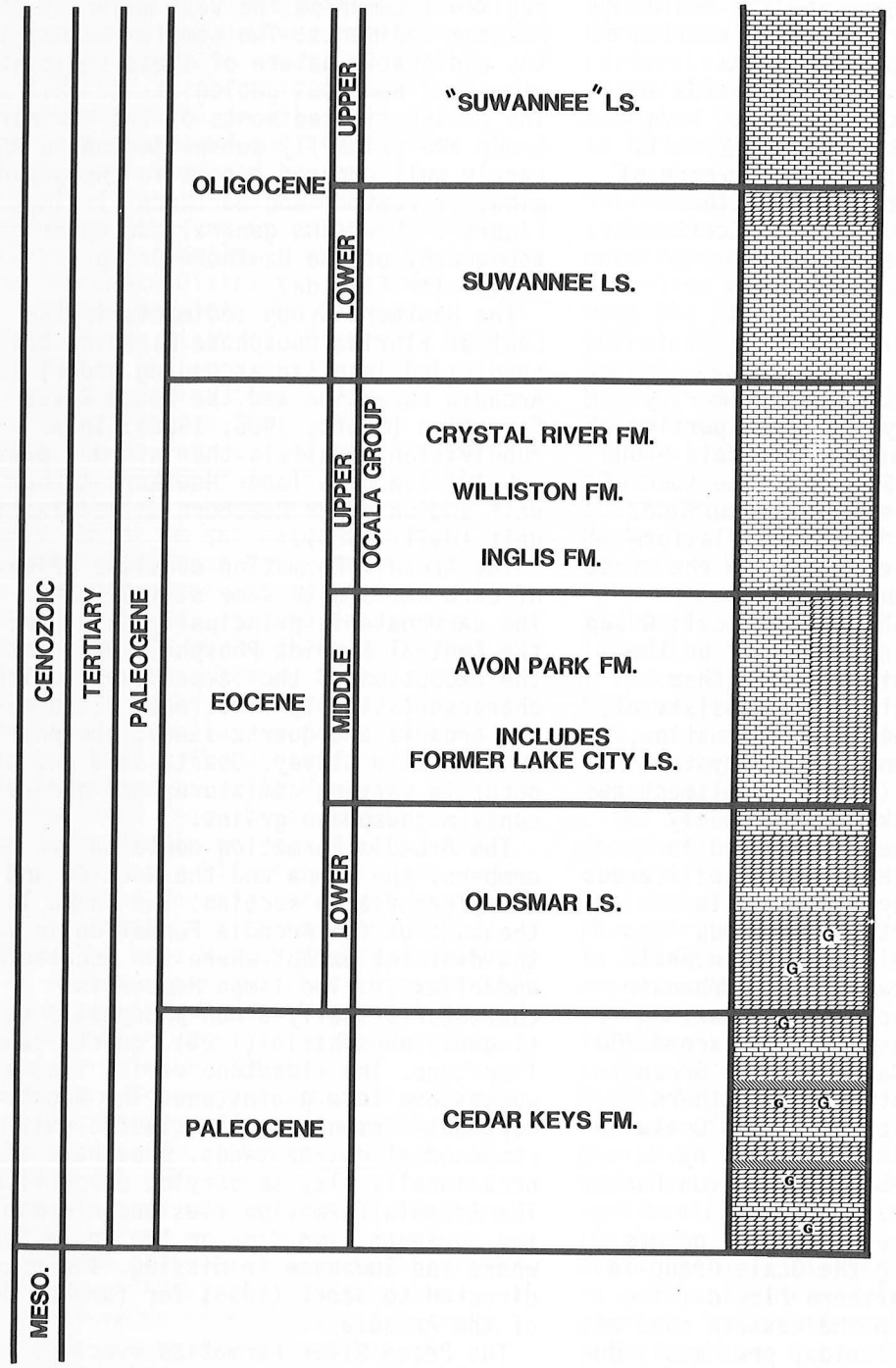


Figure 6: Paleogene stratigraphy.

sediments (Figure 6).

The end of the Paleogene and the beginning of the Neogene also marked the initiation of a major phosphogenic episode in the southeastern United States. In Florida and Georgia, these phosphatic sediments have been placed in the Hawthorn Group (Scott, 1988; Huddleston, 1988). The occurrence of the phosphatic sediments provided the impetus for many investigations. Scott (1988) provides a review of these investigations.

Paleogene Carbonates

The Paleogene carbonates are primarily subsurface units. Only the upper portion of the Avon Park Formation and the Ocala Group of Eocene age and the Suwannee Limestone of Oligocene age are exposed at the surface. This is in response to the Ocala Platform (Figure 3). These units crop out on the crest and on the flanks of this feature.

Field trip stops will show the Ocala Group and Suwannee Limestone. These will be the only Paleogene units discussed further.

The Upper Eocene Ocala Group consists of, in ascending order, the Inglis Formation, the Williston Formation and the Crystal River Formation (Puri, 1957). The limestones are grainstones to wackestones, poorly indurated varying to well indurated in limited areas and thicknesses, fossiliferous and white to light gray in color. In general, the lower part of the group is generally a grainstone to packstone while the upper portion contains more carbonate mud and ranges to a wackestone. Maximum thickness of the Ocala Group may exceed 200 feet in central Florida. The Ocala Group is present throughout central and northern Florida except on the crest of the Ocala Platform where it has been removed by erosion. Where it is absent, the Avon Park Formation crops out.

The Oligocene Suwannee Limestone occurs unconformably overlying the Ocala Group in part of central and northern Florida. The Suwannee is absent from the eastern part of central and northern Florida, presumably due to erosion. Where it does occur, the Suwannee varies from grainstone to wackestone, poorly indurated to well indurated in highly recrystallized zones, fossiliferous, and white to light gray in color. The upper part of the Suwannee, when present, may be highly recrystallized and very hard. The maximum thickness of the Suwannee in this area approaches 100 feet.

Neogene Sediments

Within the area of the field trip, Miocene sediments comprise the vast majority of the Neogene sediments. The complex nature and the phosphatic nature of these sediments has attracted numerous geologists to this area. The phosphatic sediments of the Hawthorn Group are primarily subsurface units and are rarely well exposed except in the phosphate mines of central and northern Florida. Figure 7 shows the generalized upper surface topography of the Hawthorn Group in peninsular Florida.

The Hawthorn Group sediments in the Central Florida Phosphate District have been subdivided into (in ascending order) the Arcadia Formation and the Peace River Formation (Scott, 1985; 1988). This subdivision parallels the informal previous subdivision of a lower Hawthorn carbonate unit and an upper Hawthorn siliciclastic unit (Hall, 1983).

The Arcadia Formation consists primarily of carbonates with some siliciclastic beds. The carbonate is principally dolostone in the Central Florida Phosphate District with the exception of the Tampa Member which is characteristically limestone. Carbonates of the Arcadia are quartz sandy, phosphatic and occasionally clayey. Quartz sand and clay occur in varying admixtures and generally contain phosphate grains.

The Arcadia Formation contains two named members, the Tampa and the Nocatee and an undifferentiated section. The Tampa lies at the base of the Arcadia Formation in much of the district except where the Nocatee Member underlies it. The Tampa Member is characteristically a non-phosphatic to only slightly phosphatic (1-2%), quartz sandy limestone. The limestone varies from a wackestone to a grainstone. The Nocatee is a carbonate cemented siliciclastic unit composed of quartz sands, phosphate and occasionally clay in varying proportions. The Arcadia Formation lies unconformably on the Suwannee Limestone or the Ocala Group where the Suwannee is missing. The reader is directed to Scott (1988) for further details of the Arcadia.

The Peace River Formation overlies the Arcadia unconformably. It is predominantly a siliciclastic unit composed of clayey, dolomitic, variably phosphatic quartz sands and quartz sandy, phosphatic, dolomitic to non-dolomitic clays. Carbonate beds, usually dolostones, occur sporadically and increase in abundance near the base of the section in the southern part of the district.

The Peace River Formation contains one named member, the Bone Valley, and an undifferentiated section. The Bone Valley, the most important phosphorite in the

Central Florida Phosphate District, is of limited areal extent and grades into the undifferentiated Peace River Formation both laterally and, in some areas, vertically. The Bone Valley is characteristically a mixture of phosphate gravel, sand-sized phosphate, quartz sand and clay. The lithologic variation and facies relationships within the member are complex. Figure 8 from Webb and Crissinger (1983) demonstrates the complexities in the Central Florida Phosphate District. The Bone Valley Member pinches out into the southern extension of the district (Figure 9) both depositionally and erosionally. The lithologic and facies complexity is significantly less in the southern extension. It is interesting to note that when the gravelly beds in the Bone Valley Member are absent, the Bone Valley age sediments cannot be separated from the undifferentiated Peace River sediments.

Ages of the Hawthorn Group in central Florida are based on limited data except in the Bone Valley Member and are indicated in Figure 10. The Tampa Member of the Arcadia Formation is thought to be early Early Miocene based on molluscan fauna (Hunter, pers. comm. 1985). The undifferentiated Arcadia Formation is Early Miocene. The undifferentiated Peace River Formation appears to be Middle to Late Miocene and possibly very early Pliocene based on diatoms, limited foraminiferal data and physical correlation with the Bone Valley sediments. The Bone Valley Member contains a prolific vertebrate fauna that suggests that the age ranges from Middle Miocene to very latest Miocene or very earliest Pliocene (Webb and Crissinger, 1983).

The Hawthorn Group in northern Florida is distinctly different from the Hawthorn in central Florida. The lithostratigraphy of the northern Florida Hawthorn is significantly more complex due to the more rapid interbedding and intermixing of carbonates and siliciclastics. Scott (1988) and Huddleston (1988) investigated the Hawthorn sediments of Florida and Georgia, respectively, recognizing a number of separate formations. In northern Florida, Scott (1988) recognized, in ascending order, the Penney Farms Formation, the Marks Head Formation, the Coosawhatchie Formation and the Statenville Formation. Figure 10 indicates the ages of these units. The relationship of the units in the Hawthorn Group can be seen in Figure 11, an east-southeast to west-northwest cross section.

The Penney Farms Formation consists of interbedded phosphatic, quartz-sandy dolostones and siliciclastics with the

amount of siliciclastics increasing upsection. The Penney Farms lies unconformably on Upper Eocene or Oligocene carbonates. Based on lithostratigraphic correlations with fossiliferous sediments in Georgia, the age of the Penney Farms appears to be early Early Miocene.

The Marks Head Formation is a complexly interbedded sequence of phosphatic carbonates, sands and clays. It unconformably overlies the Penney Farms and underlies the Coosawhatchie Formation. As with the Penney Farms, the Marks Head correlates with fossiliferous sediments in Georgia that suggest an age of late Early Miocene (Huddleston, 1988).

The Coosawhatchie Formation is primarily a siliciclastic unit composed of phosphatic, dolomitic quartz sands and clays with scattered carbonate beds. It overlies the Marks Head unconformably and is unconformably overlain by Cypresshead Formation or undifferentiated Pleistocene sediments. The Coosawhatchie grades laterally into the Statenville Formation (Figure 10). In the area of transition, the Statenville may overlie the Coosawhatchie and grade vertically into it. The Coosawhatchie Formation is Middle Miocene in age (Huddleston, 1988).

The Statenville Formation consists of phosphatic to very phosphatic sands and clays with few carbonate beds. The Occidental Chemical Company mines phosphorite from the Statenville Formation in Hamilton County, Florida. The Statenville overlies the Marks Head unconformably in some areas and the Coosawhatchie conformably in others. The Statenville Formation appears to be the same age as the Coosawhatchie, Middle Miocene. There is a reworked zone at the top of the Statenville exposed in the phosphate mines in north Florida. This zone appears to be Late Miocene based on the vertebrate fossils recovered from it (Cathcart, pers. comm., 1985). The Statenville is limited in its known extent in northern Florida. It is unconformably overlain by undifferentiated sediments.

The Hawthorn Group sediments in Florida are overlain by Pliocene and Pleistocene sediments except where exposed by erosion. In part of southern Florida, the Hawthorn is unconformably overlain by Tamiami Formation or unnamed Plio-Pleistocene sediments (Figure 6). Previously held assumptions that the Tamiami was the marine equivalent of the Bone Valley are not currently accepted. In Northern Florida, it is unconformably overlain by Cypresshead Formation, Nashua Formation and unnamed sediments (Figure 6).

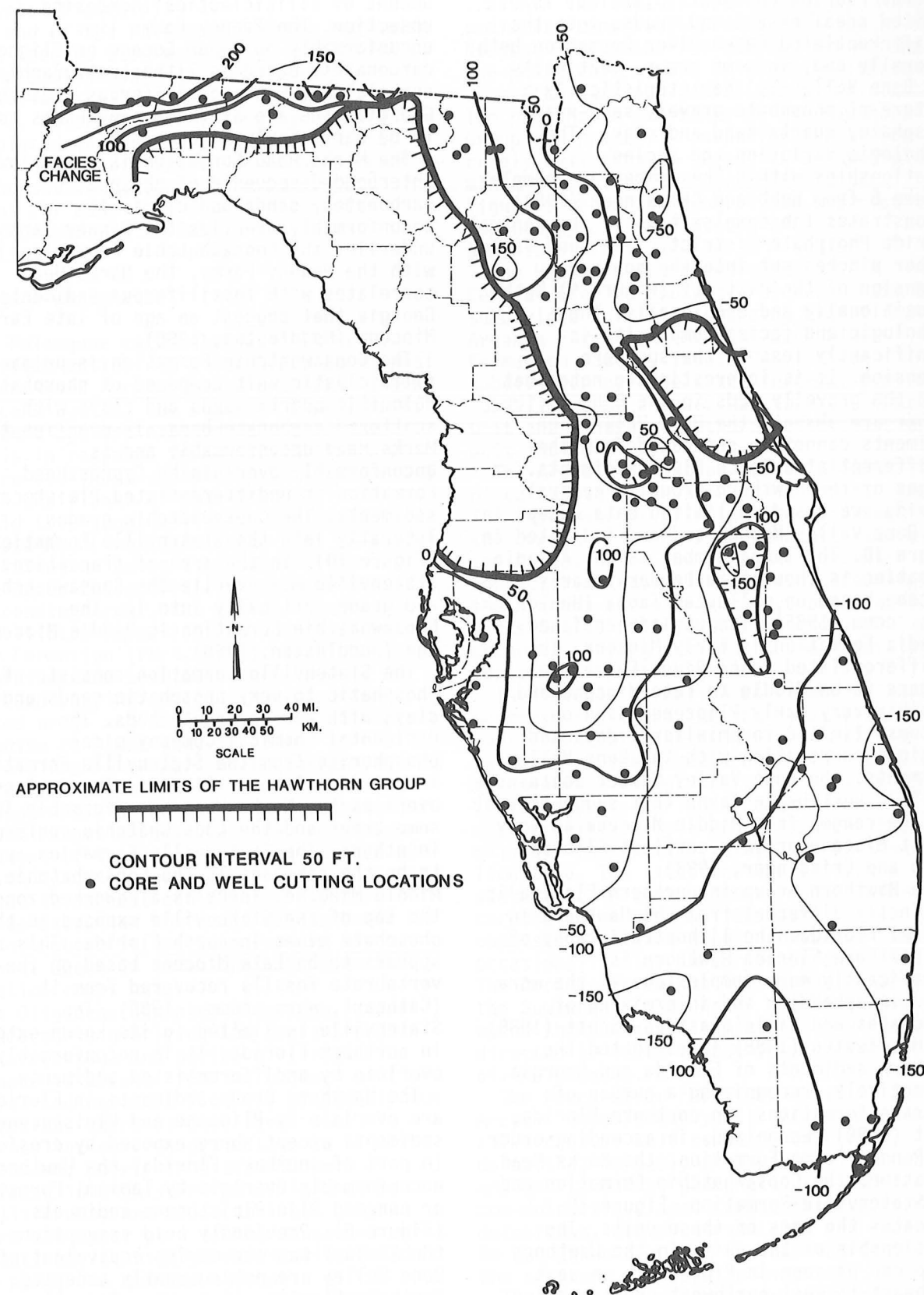


Figure 7: Top of the Hawthorn Group in Florida.

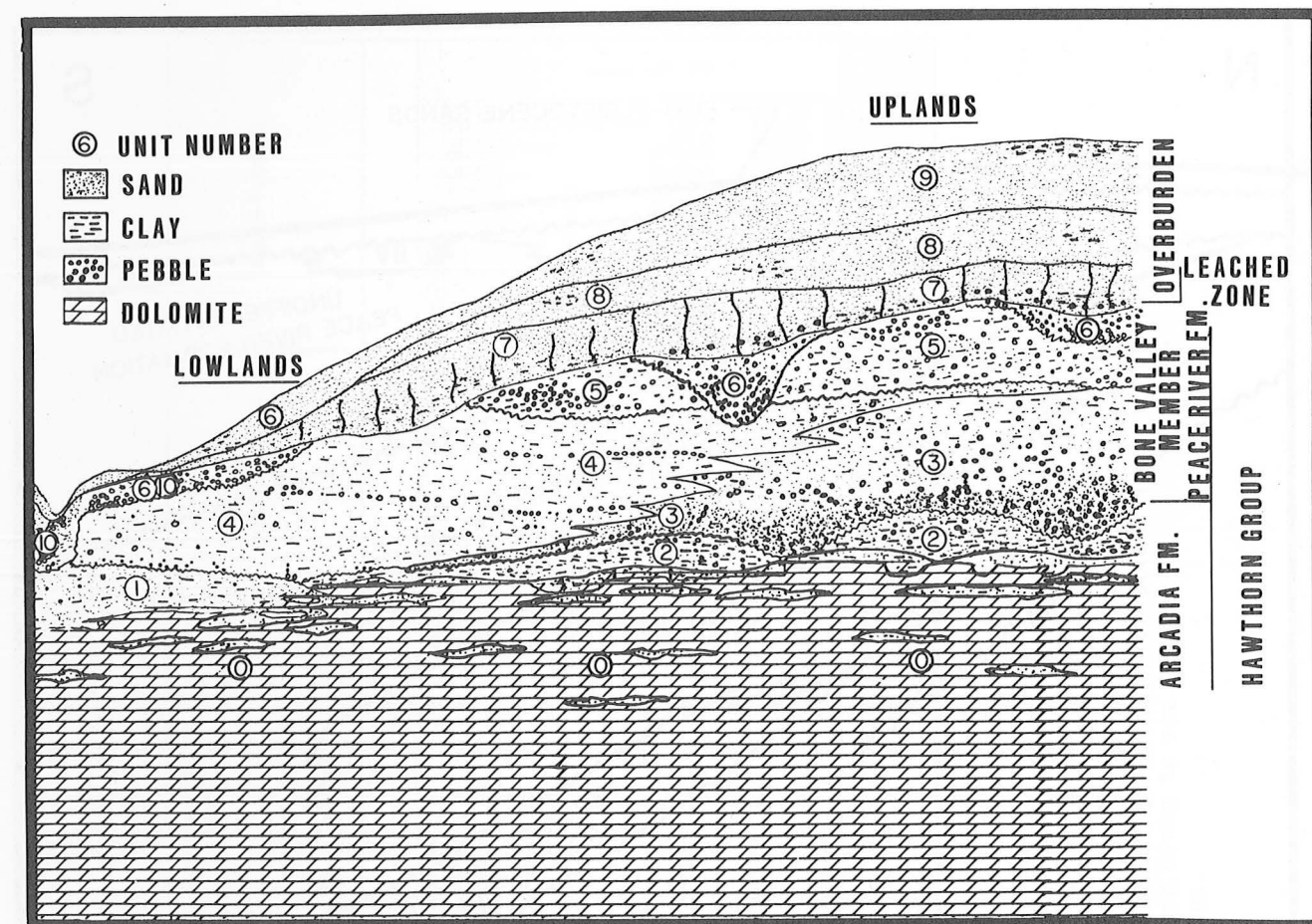


Figure 8: Relationship of facies within the Hawthorn Group in the Central Florida Phosphate District (bed numbers refer to numbers assigned by Webb and Crissinger, 1983).

HYDROGEOLOGY

The vast majority of Florida's water supply comes from subsurface sources. As such, this resource has been intensively studied. Laws regulating ground water in this state are some of the most rigorous in the country since these resources are so valuable. The following discussion of the ground water system in the Central Florida Phosphate District is modified after and excerpted from Upchurch (1985).

There are four hydrostratigraphic horizons in the district. The water chemistry of each reflects the composition of the host rock. The surficial, unconfined aquifer system is predominantly quartz sand and aquifer water is usually slightly acid, and iron and organic-rich. The surficial aquifer system is separated from the uppermost artesian aquifer by the clay-rich sediments of the Bone Valley Member of the Peace River Formation, Hawthorn Group. The uppermost artesian aquifer, part of the intermediate

aquifer system and confining system, is a highly localized series of permeable, sandy strata within the Bone Valley Member. Water quality is highly variable and phosphorus, fluorides and radionuclides are of concern. The uppermost artesian aquifer is separated from the secondary artesian aquifer (upper Floridan aquifer system) by clays and silts of the Bone Valley Member and the undifferentiated Peace River Formation. The upper Floridan aquifer system consists of limestones and dolostones in the lower Hawthorn Group (Arcadia Formation). The Floridan aquifer system lies below a regionally persistent clay horizon in the Tampa Member of the Arcadia Formation, Hawthorn Group. The Floridan aquifer system consists of lower Arcadia, Suwannee, Ocala and Avon Park Formations. Floridan aquifer system horizons are karstic and water quality is typical of carbonate aquifers.

Prior to the environmental concerns of the present, phosphate mining operations employed drainage wells to alleviate the

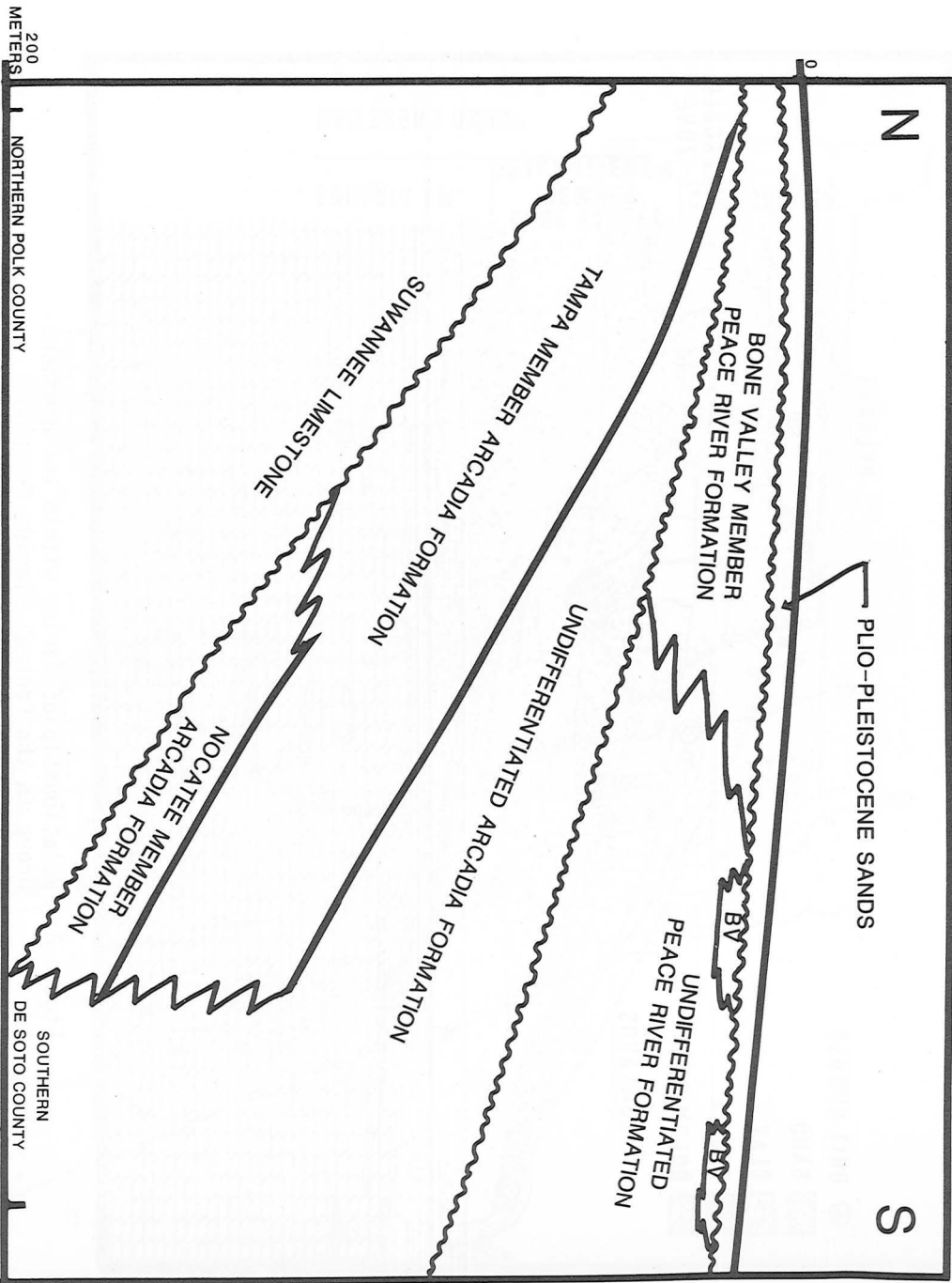


Figure 9: Diagrammatic north to south section of the Hawthorn Group in southern Florida.

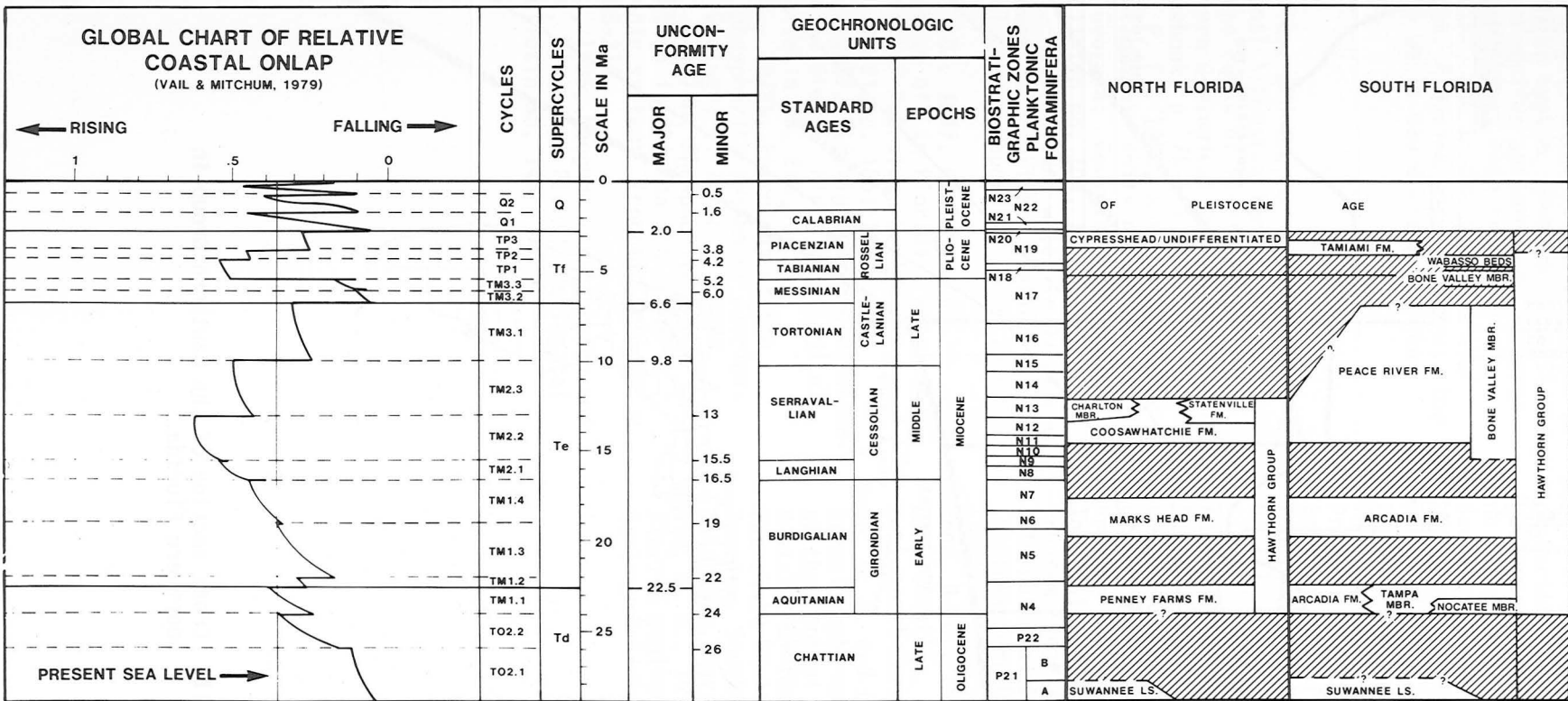


Figure 10: Relationship of ages of the formations in the Hawthorn Group to sea level fluctuations.

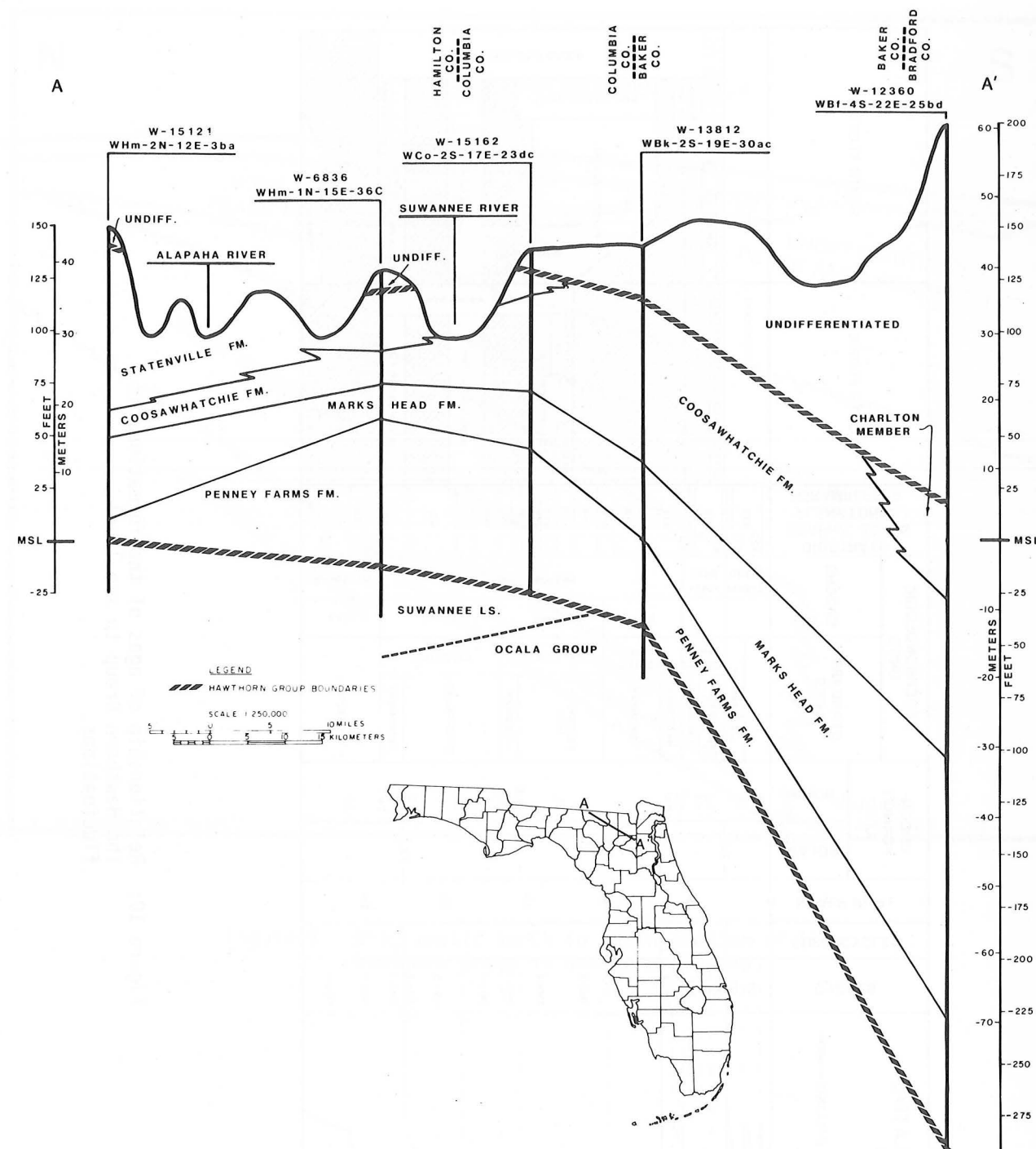


Figure 11: Cross section of the Hawthorn Group in northern Florida.

problems caused by water in the surficial or shallow aquifer system. These wells utilized the Floridan aquifer system as a "recharge zone" for the waters from the shallower zones. However, due to the concerns over radionuclides, fluorine and phosphorus, the use of these wells has declined to near zero.

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ECONOMIC GEOLOGY OF THE LAND PEBBLE PHOSPHATE DISTRICT OF FLORIDA AND ITS SOUTHERN EXTENSION

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INTRODUCTION

The land-pebble phosphate district of Florida, also called the Central Florida Phosphate District, is a part of a phosphogenic province in the Atlantic Coastal Plain of the United States that extends from the southern tip of Florida into the southern part of Virginia and includes deposits both on the land and in the adjacent part of the Continental Shelf of the Atlantic Ocean.

Total resources of phosphate in the province are enormous, aggregating scores of billions of tons of phosphate pellets that contain an average of about 25 percent P_2O_5 . Identified resources in Florida, Georgia, and North Carolina total about 8 billion metric tons of recoverable phosphate pellets with an average content of about 30 percent P_2O_5 (Cathcart et al., 1984).

Although phosphate pellets are known to be present in rocks of Cretaceous to Holocene age in the Atlantic Coastal Plain, potentially economic deposits are confined to rocks of Miocene age or to younger rocks, in which much of the phosphate has been derived by reworking from the Miocene rocks.

The land-pebble phosphate district is in eastern Hillsborough and western Polk Counties, Florida, and extends to the south into the northern parts of Hardee and Manatee Counties (Figure 1). All of the past and current production of phosphate is from this district and is largely from the Bone Valley Member of the Peace River formation, Hawthorn Group. The district is

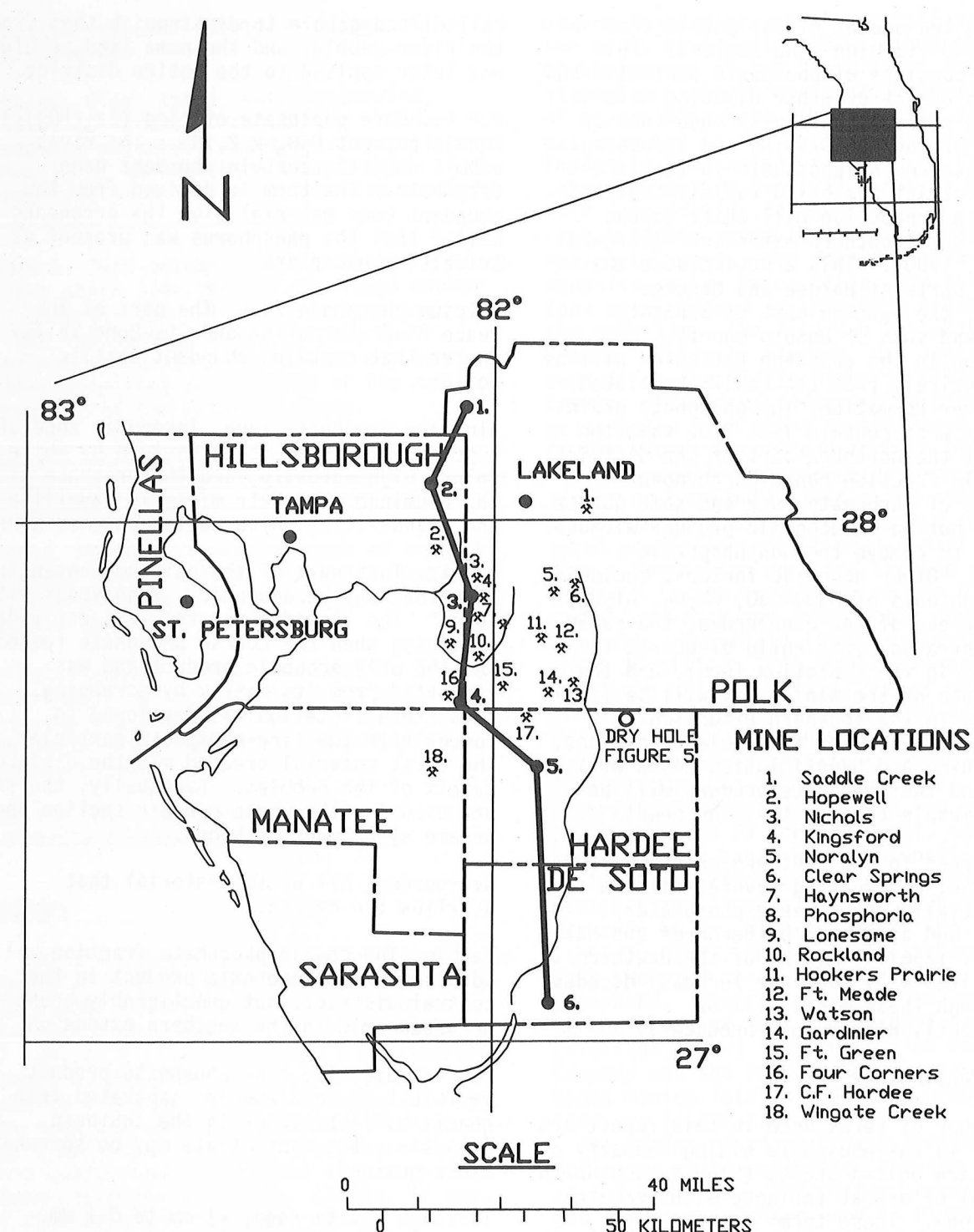


Figure 1. Map showing the Land Pebble Phosphate District, its southern extension and location of mining operations.

unique in the amount of the pebble fraction (>1 mm) and its high P_2O_5 content. This fraction consists of phosphate particles and almost no quartz or other diluting material. Thus, the coarse fraction is made into an economic product by washing and screening.

The reserves of phosphate in the land-pebble district are being rapidly depleted and future production will shift to the south to the "southern extension" (Bernardi and Hall, 1980). This area includes the southern parts of Hardee and Manatee Counties, the eastern part of Sarasota County, and much of DeSoto County. Production in the southern extension will be almost entirely from the undifferentiated Peace River Formation. The phosphate grains from this area contain less P_2O_5 than the grains of the northern part of the district. The pebble fraction contains abundant fragments of carbonate rock and some quartz and will not be an economic product without treating to remove the nonphosphatic material. Other economic factors, including higher contents of MgO , CaO , Fe_2O_3 , Al_2O_3 , the thickness of the overburden, the ratio of concentration (the ratio of quartz to phosphate in the flotation feed), and the total depth of the mining pit will be less favorable in the southern extension. Because of these less favorable conditions, total mining and beneficiation costs will be higher and the phosphate product will be less desirable than in the land-pebble district.

Resources in the southern extension are very large, aggregating several billion tons of potentially recoverable phosphate pellets, and as stated by Bernardi and Hall (1980, p. 1256): "Mining of the Hawthorn phosphorites will continue for many decades even though these mines will be significantly higher-cost producers."

Mining Terminology

A number of terms used in this report are peculiar to the phosphate mining industry of the eastern United States (Florida and North Carolina) or are at variance with accepted terminology. These terms are briefly defined below and are defined in more detail by Cathcart (1963, p. 7-12) and by Altschuler et al., (1958, p. 50).

Land Pebble. The first mining of phosphate was from bars of coarse pebble in the rivers. This material was naturally called river-pebble. When these deposits began to be depleted, prospect drilling away from the rivers located phosphate deposits that were

called land-pebble to distinguish them from the river-pebble, and the name land-pebble was later applied to the entire district.

B.P.L.. Bone phosphate of lime ($Ca_3(PO_4)_2$). Equals percent $P_2O_5 \times 2.185$. The river pebble deposits contain abundant bone fragments. The term is derived from the abundant bone material plus the erroneous belief that the phosphorus was present as tricalcium phosphate.

Calcium phosphate zone. The part of the Peace River Formation and its Bone Valley Member that contains abundant apatite pellets.

Aluminum phosphate zone. Irregular zone of supergene leaching characterized by white color, high porosity, and the presence of the aluminum phosphate minerals wavellite and crandallite. Also called leached zone.

Matrix. That part of the calcium phosphate zone that may be economic. Synonymous with "ore." The term derives from the early days of mining when the coarse phosphate (pebble) was the only economic product and was separated from its matrix by screening. When froth flotation was developed to concentrate the fine-phosphate particles, the first material treated was the discarded matrix of the pebbles. Eventually, the term was used for the whole minable section and became synonymous with ore.

Overburden. All of the material that overlies the matrix.

Pebble. The coarse phosphate fraction, >1 mm id diameter. An economic product in the central district, but questionably economic or uneconomic in the southern extension.

Concentrate. The fine phosphate product, <1 mm to 0.1 mm in diameter, separated from quartz by flotation. In the southern extension, the concentrate may be somewhat finer grained.

Tailing. Quartz sand, <1 mm to 0.1 mm, separated from phosphate grains by flotation.

Slime. Material less than 0.1 mm in diameter. In the land-pebble district, includes clay minerals (kaolinite, smectite, palygorskite), quartz, and phosphate minerals (apatite, wavellite, crandallite). In the southern extension, the slime

fraction includes smectite, palygorskite, and sepiolite.

Bedclay. Clay, sandy, water-saturated, dolomitic, "greasy," containing abundant phosphate pellets. Residuum of argillaceous dolomite of the Hawthorn Group. Not recognized in drill cores from the southern extension.

Bedrock. Hard dolomite of the Hawthorn Group except where limestone of the Tampa Member may underlie the matrix in the northern part of the land-pebble district. In the southern extension, the bedrock may be either limestone or dolomite of the Arcadia Formation of the Hawthorn Group.

Phosphorite (also phosphate rock). Used to denote a rock containing substantial amounts of pelletal apatite.

Nodule. Rounded, irregular mass of any size, but used herein only to designate masses (either phosphate or carbonate) that are coarser than 1 mm in diameter.

Pellet. Rounded sedimentary apatite grain, less than 1 mm in size. May be spherical or disc-shaped, but most commonly irregular. A few pellets may be oolitic but most are structureless.

Apatite. Used herein to mean the mineral carbonate fluorapatite (francolite).

HISTORY

The discovery of phosphate in Florida was probably in 1879 (Day, 1886; Wright, 1893). Day (1886) states that Dr. C. A. Simmons discovered that the "principal building rock of central Florida contained a considerable amount of phosphoric acid. In 1879, he located a quarry and in 1883 began mining the rock and converting it into fertilizer." Day (1886) also reported that the rock from this quarry contained about 45 percent BPL (bone phosphate of lime). Little, if any, of this rock was sold, but it was used as fertilizer for at least a few years.

River-pebble deposits were discovered by Capt. J. Francis Le Baron in 1881. Le Baron (1892), states that he began a survey of Peace Creek at Fort Meade in May 1881, for the U. S. Army Corps of Engineers. He found many fossils below Little Charley Apopka Creek in "drift gravel overlying limestone." Le Baron left Florida and did not return until 1886, at which time he found abundant phosphate gravel in a bar on the west side

of the Peace River about one-half mile below the ferry at Arcadia. Bars along the rest of the course of the Peace River and on Horse Creek also were composed predominantly of coarse phosphate pebbles. The discovery was reported to the public; the Arcadia Phosphate Company was formed, and the company made the first shipment of phosphate rock from Florida in May 1888.

Day (1889) noted that the Arcadia Phosphate Company was developing the deposits on the Peace River, and that 3,000 tons were shipped in 1888 from Arcadia. At the same time, the Peruvian Phosphate Company of Tampa, Florida, was operating a deposit on the Alafia River in Hillsborough County. Mining of river-pebble phosphate, principally from mines on the Peace and Alafia Rivers, continued through 1908, although small tonnages were shipped from stocks on hand until 1914. The peak annual production was about 120 thousand tons and total production was about 1.3 million long tons. Production declined because of the increase in the production of the higher grade hard-rock and land-pebble phosphate deposits. Mansfield (1942) estimated that about 50 million long tons of river-pebble phosphate still remained, but of this only 5 million long tons was considered as "known." It is unlikely that there will ever be any further mining of the river-pebble phosphate deposits because of environmental restrictions coupled with the low grade (average about 25 percent P_2O_5), small size, and irregular habit of the deposits.

The first discovery of high-grade phosphatized limestone (hard-rock phosphate) was made by Mr. Albertus Vogt, who, while sinking a well, found a white subsoil, which when analyzed was determined to be high in phosphate. The discovery was reported to be at the close of 1888 (Day, 1889) or in 1889 (Eldridge, 1892). The Dunnellon Phosphate Company and the Baldwin Fertilizer Company began mining late in 1889, and production in 1890 was 11,000 tons.

The mining of river-pebble phosphate did not cause much excitement, but the discovery of the high- P_2O_5 content hard-rock phosphate set off a prospecting boom in Florida, and by 1892, 80 hard-rock, 7 land-pebble, and 18 river-pebble mines were in operation. The hard-rock mines were in a narrow belt that extended from just north of Polk County in the south almost to Tallahassee in the north, a distance of over 200 mi (Eldridge, 1892, map, p. 197).

The hard-rock phosphate deposits were mined from 1889 to 1966. Production reached a maximum of about 650,000 tons in 1907, then declined as the production of the lower

cost and much more uniform land-pebble increased. The total production of hard-rock phosphate was about 15 million long tons.

Prospecting for the land-pebble deposits began late in 1890 (Eldridge, 1892, p. 16-98), although the term land-pebble was first used by Day (1891, p. 452). The first mining and prospecting for land-pebble was along the headwaters of the Peace River (near Bartow) and the Alafia River (near Mulberry). Day (1891) reports that mining was by dredge. Basins were dug, filled with water, and the dredge was placed in the basin. The mining was in the floodplain of the rivers and most of the material mined in the first few years may have been river-pebble phosphate. Eldridge (1892) shows seven land-pebble phosphate mines, three along the Peace River south of Bartow, the southernmost near the present Polk-Hardee County line. One mine is shown near Mulberry along the Alafia River, two are north of the Alafia River, and one is at Pierce.

Sellards (1909) reports that the first shipment of land-pebble phosphate rock was made in 1891, although development began in 1890. In 1892, production reached 22,000 tons. The rate of increase was gradual at first, then accelerated to 1.1 million tons in 1908, 10 million in 1956, 20 million in 1965, and the maximum of about 42 million tons in 1979. Production has decreased slightly since then due to poor market conditions, and was about 30 million tons in 1986.

The phosphate discoveries attracted foreign as well as domestic companies, and until World War I, French, Belgian, and English companies mined phosphate in Florida. From the start of World War I until the 1970's, the phosphate companies of Florida were all domestic; but in recent years, foreign companies have purchased all or parts of several of them.

The total production of phosphate rock from the land-pebble district of Florida from the inception of production in 1891 through 1986 is about 1.1 billion tons of product, averaging about 32 percent P_2O_5 . At one time, in the early 1900's there were at least 100 phosphate mines in Florida (river-pebble, hard-rock, and land-pebble). Most were small, and over the years, the small companies failed or were purchased by larger companies. Today there are 9 companies mining phosphate in central Florida.

GEOMORPHOLOGY

The surface of peninsular Florida is flat and covered with a blanket of unconsolidated permeable sand; thus, the relatively high rainfall is dissipated by seepage into the porous sand cover and there is little dissection or downcutting by surface streams. The resulting subdued topography is reflected in the relative simplicity of the many geomorphic treatments of Peninsular Florida. See Figure 1 of Scott (this volume) for the geomorphology of the state.

Cooke (1945) subdivided peninsular Florida into the Coastal Lowlands and the Central Highlands, and Vernon's (1951) Terraced Coastal Lowlands and Tertiary Highlands are approximately equivalent to Cooke's divisions. Vernon (1951) also distinguished a third subdivision-River Valley Lowlands.

White (1970) divided the area of the land-pebble district and its southern extension into three geomorphic features: (1) Polk Upland, (2) DeSoto Plain, and (3) Gulf Coastal Lowlands (Figure 2). These subdivisions are divided by scarps or remnants of shorelines formed during major stands of the sea in the Pleistocene. The Polk Uplands and the DeSoto Plain are separated by the 100-foot Wicomico shoreline of Cooke (1945) and MacNeil (1950), while the Coastal Lowland is separated from the DeSoto Plain by the 30-foot Pamlico shoreline. The shorelines are difficult to see because only remnants of the bars, spits, and terrace scarps remain.

The Polk Upland is a poorly drained sand plain that is broken by long narrow, northwest trending ridges that rise rather sharply from the plain (Valrico Ridge, Lakeland Ridge, and Bartow-Winter Haven Ridge). The DeSoto Plain is also a flat poorly drained plain, but does not have the distinct ridges of the Polk Upland. The Polk Upland and the DeSoto Plain are drained by south and southwest flowing streams (the Alafia, Peace, Manatee, and Myakka rivers) that form the River Valley Lowlands of Vernon (1951). The boundaries of these physiographic provinces are not distinct they tend to be gradational on the west and south, however, the Lake Wales Ridge, which forms the eastern boundary of the Polk Upland and the DeSoto Plain, is a distinct topographic feature.

The land-pebble district is almost entirely within the limits of the Polk Upland (Figure 2), while the southern extension falls almost entirely within the DeSoto Plain.

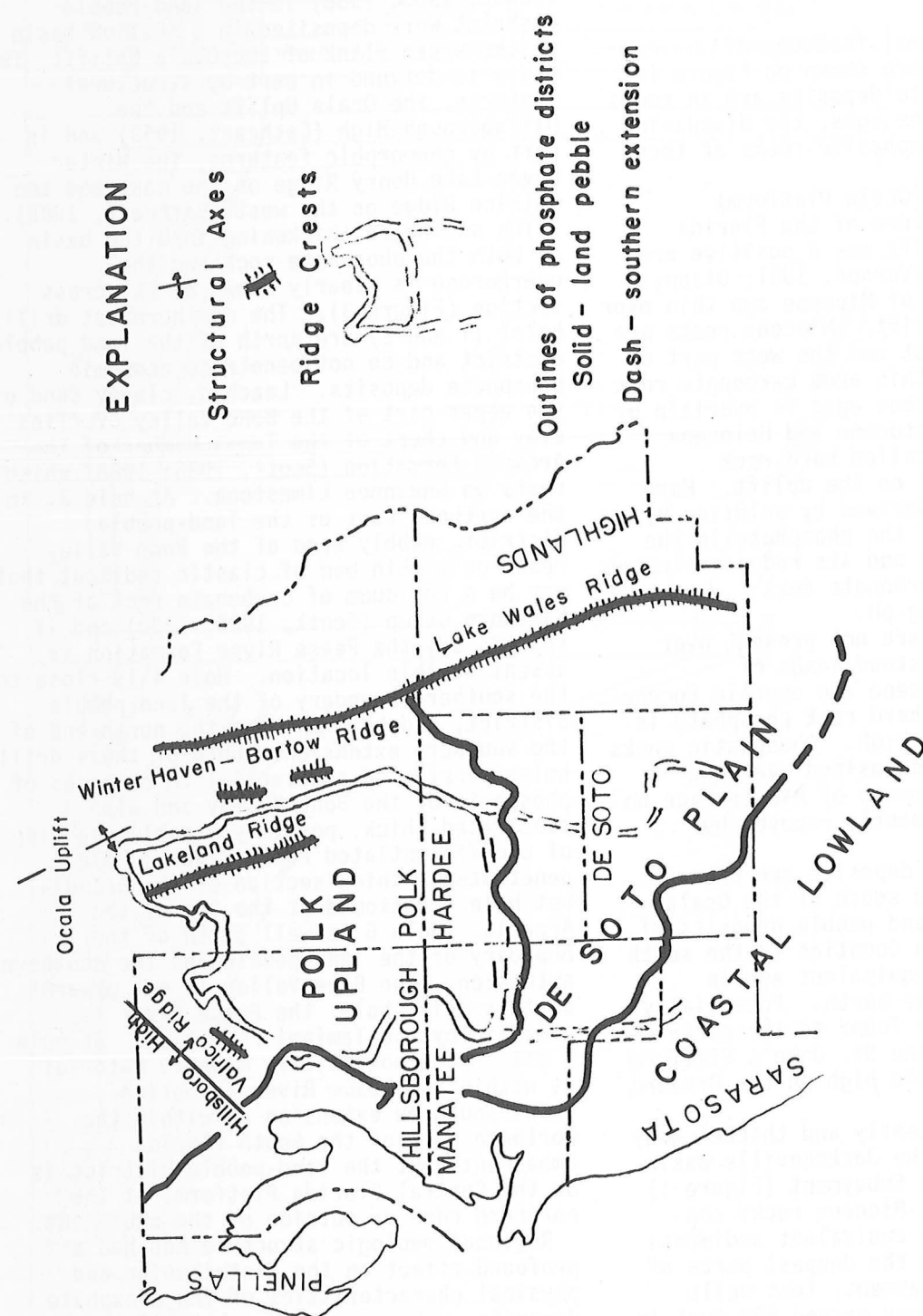


Figure 2. Physiographic divisions, Land Pebble Phosphate District and southern extension.

(After White, 1970)

GENERAL GEOLOGY

Regional Structure

The major structural features of peninsular Florida are shown on Figure 1. Because the phosphate deposits are in rocks of Miocene or younger ages, the discussion of structure will emphasize rocks of these ages.

The Ocala Uplift (Ocala Platform) dominates the structure of the Florida Peninsula. The uplift was a positive area during the Miocene (Vernon, 1951; Olson, 1966) and sediments of Miocene age thin over the crest of the uplift. Miocene rocks are absent from the crest and the west part of the uplift, and in this area carbonate rock of Eocene and Oligocene ages is overlain by unconsolidated Pleistocene and Holocene sand. Only the so-called hard-rock phosphate is present on the uplift. Hard rock phosphate was derived by solution by acid ground water of the phosphate in the rocks of Miocene age and its redeposition on or replacement of carbonate rock accompanying changing pH.

Miocene sediments are not present over the Sanford High, instead sands of Pleistocene and Holocene age overlie Eocene carbonate rock. No hard rock phosphate is known on the Sanford high. Phosphatic rocks may never have been deposited over the Sanford High or sediments of Miocene age on the high were subsequently removed by erosion.

Economic phosphate deposits are present both to the north and south of the Ocala Uplift-the classic land pebble deposits of Polk and Hillsborough Counties to the south and the deposits of equivalent age in Hamilton County to the north. Potentially economic deposits are found to the north of the Sanford high on the St. John's Platform and to the south of the high on the Brevard Platform (Figure 1).

Miocene rocks dip gently and thicken away from the highs. In the Jacksonville Basin and the South Florida Embayment (Figure 1) both Miocene and post-Miocene rocks are markedly thicker than equivalent sediments on the platforms. In the deepest parts of the South Florida Embayment, test wells indicate the Miocene may exceed 600 feet in thickness and post-Miocene sediments may be up to 200 feet thick. Similarly in the deeper parts of the Jacksonville Basin phosphatic rocks of Miocene age and non-phosphatic rocks (overburden) overlying the phosphatic sediments are much thicker than the equivalent rocks on the St. Johns Platform.

The phosphatic deposits of the Bone Valley Member of the Peace River Formation (Scott, 1985; 1988) in the land-pebble district were deposited in a shallow basin on the south flank of the Ocala Uplift. The basin is defined in part by structural features, the Ocala Uplift and the Hillsborough High (Cathcart, 1963) and in part by geomorphic features, The Winter Haven-Lake Henry Ridge on the east and the Valrico Ridge on the west (Cathcart, 1985).

The southward thickening into the basin of both the phosphate rock and the overburden is clearly shown on the cross section (Figure 3). The northernmost drill holes (1 and 2) are north of the land-pebble district and do not penetrate economic phosphate deposits. Leached, clayey sand of the upper part of the Bone Valley overlies clay and chert of the Tampa Member of the Arcadia Formation (Scott, 1985; 1988) which rests on Suwannee Limestone. At hole 3, in the northern part of the land-pebble district, pebbly sand of the Bone Valley rests on a thin bed of clastic sediment that may be a residuum of carbonate rock of the Hawthorn Group (Scott, 1985; 1988) and if this is so, the Peace River Formation is absent at this location. Hole 4 is close to the southern boundary of the land-pebble district, and hole 5 is at the north end of the southern extension. Both of these drill holes penetrated substantial thicknesses of phosphate of the Bone Valley and also penetrated thick, possibly minable, sections of undifferentiated Peace River. Hole 4 penetrated a thick section of the Arcadia, but hole 5 bottomed at the top of the Arcadia. Hole 6 is well south of the boundary of the land-pebble and the southern extension. The Bone Valley is not present at this drill hole; the Peace River is overlain by the Tamiami Formation. At hole 6 all of the potentially minable material is within the Peace River Formation.

The southern extension is within the northern part of the South Florida Embayment, but the land-pebble district is on the Central Florida Platform, at the northern edge or outside of the embayment.

Regional geologic structure has had a profound effect on the distribution and physical characteristics of the phosphate deposits. The coarse phosphate of the land-pebble district was deposited in a restricted shallow basin at the shoreward edge of the sea during Miocene and Pliocene time. Carbonate rock was phosphatized during regressions of the sea and near shore wave action during transgressions broke up the phosphatized rock to form the coarse conglomerate beds so characteristic of the

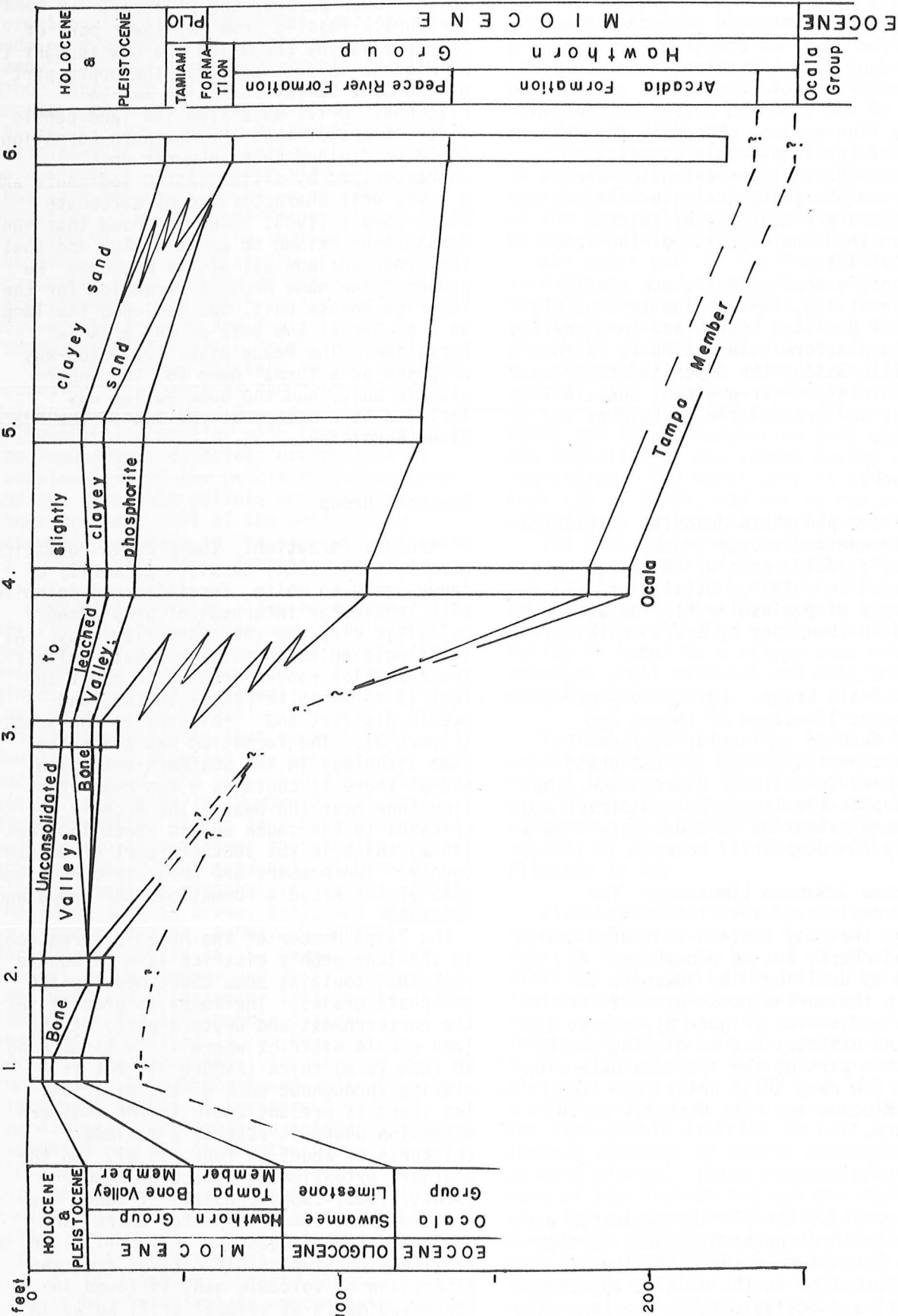


Figure 3. Diagrammatic cross section, land pebble district and southern extension. Location of section shown on Figure 1.

land-pebble district. Finer grained phosphate and quartz sand were deposited further from shore in deeper water, along with abundant clay. Examination of samples from a few drill holes indicates that the deposits of the southern extension contain more very fine-grained phosphate than the deposits of the land-pebble district. Deposits in the southern extension are thicker, the phosphate grains are less abundant, and are overlain by thicker overburden than the deposits of the land-pebble district.

Relations in north Florida are similar (Patterson et al., 1984). The land-pebble deposits of Hamilton County are in a shallow basin on a platform. To the east, in the Jacksonville Basin, the deposits of the same age are thicker, finer-grained, contain less phosphate, and are covered by thicker overburden.

Stratigraphy

All of the phosphate deposits in Florida are in Miocene and younger rocks. Consequently, only rocks of these ages will be discussed in detail. Details of the stratigraphy of peninsular Florida are presented in the paper by Scott in this volume.

Eocene-Ocala Group. White, very pure, fossiliferous limestone of Eocene age underlies much of peninsular Florida. Because prospect drilling for phosphate stops in hard dolomite of Miocene age, the Ocala Group in the land-pebble district and its southern extension is known only from a relatively few deep drill holes.

Oligocene Suwannee Limestone. The Suwannee consists of fossiliferous limestone, that may contain scattered quartz grains and chert, but no phosphate. As indicated by drilling, the Suwannee is present in the northernmost part of the land-pebble district (Figure 3), and to the west of the district but is missing in the northeastern part of the southern extension where the few deep drill holes show that rocks of Miocene age rest directly on the Ocala Group.

Miocene rocks

The Miocene of the Florida Peninsula was divided into three parts by Cooke, (1945): the Tampa Formation at the base, the Hawthorn Formation in the middle, and the Duplin Marl and equivalents at the top. The overlying Bone Valley Formation was placed

in the lower part of the Pliocene. Vertebrate fossils from the lower part of the Bone Valley Formation are now thought to be Miocene in age, and only the upper part of the Bone Valley Formation may be Pliocene. Drill data from the land-pebble district showed that the Hawthorn Formation could be divided into an upper unit characterized by siliciclastic sediments and a lower unit characterized by carbonate rock. Scott (1985; 1988) proposed that the Hawthorn be raised to group status and that the group include all of the Miocene. He proposed the name Arcadia Formation for the lower carbonate unit, and included the Tampa as a member at the base of the Arcadia Formation. The Peace River Formation was proposed as a formal name for the upper clastic unit, and the Bone Valley was included as a member at the top of the Peace River Formation.

Hawthorn Group

Arcadia Formation. The Arcadia Formation (Scott, 1985; 1988) consists primarily of sandy, gray to white, fossiliferous dolomite with lenticular interbeds of gray-green dolomitic clay and sandy or silty clay. All lithologic units contain phosphate pellets. The formation ranges from 10 to about 100 feet (3-30 m) in thickness in the land-pebble district and thickens to the south (Figure 3). The formation has about the same lithology in the southern extension except there it contains a few beds of limestone near the base. The Arcadia thickens to the south and is about 150 feet (45 m) thick in the southern part of DeSoto County. Two members are recognized near the base of the Arcadia Formation, the Tampa and Nocatee.

The Tampa Member of the Arcadia Formation in the land-pebble district is a carbonate rock that contains some chert nodules and phosphate grains. The Tampa is present in the northernmost and western parts of the land-pebble district where it is as much as 20 feet (6 m) thick (Figure 3), but is missing throughout much of the district. The Tampa is present again in the southern extension where it reaches a maximum thickness of about 50 feet (15 m). In the southern extension, the Nocatee Member (Scott, 1985; 1988) consists of sandy clay that contains some phosphate, chert, and carbonate rock fragments. Clinoptilolite, a zeolite mineral possibly derived from the alteration of volcanic ash, is found in these sediments at several drill holes in Hardee, Manatee, and DeSoto Counties.

Peace River Formation. The Peace River Formation (Scott, 1985; 1988) consists of beds of gray-green dolomitic clayey sand to sandy clay that contain abundant pellets and minor fine pebble size phosphate. In the northern part of the land-pebble district, the Peace River is thin or absent and siliciclastic rock (so-called "bedclay") may be residual from the underlying carbonate, thus this material may be in the Arcadia Formation. The Peace River is as much as 60 feet (18 m) thick in the southern part of the land-pebble district and contains thin lenticular beds of hard dolomite that are more abundant with depth making the contact between the Arcadia and Peace River Formations difficult to locate precisely.

The Peace River thickens in the southern extension to as much as 150 feet (45 m) in DeSoto County (Figure 3) and is lithologically similar with the formation in the land-pebble district, except that it contains less of the pebble-size phosphate, and the phosphate pellets are somewhat finer-grained. All of the potentially economic phosphate in the southern extension is in the Peace River Formation.

Bone Valley Member. The name Bone Valley was first used by Matson and Clapp (1909) who used the term "Bone Valley Gravel" to describe the phosphate deposit then being mined. Cooke (1945) formally applied the term Bone Valley Formation to the phosphorite deposits that overlie the Hawthorn Formation and are overlain by unconsolidated sand of probable Pleistocene age. The Bone Valley Member of the Peace River Formation of the land-pebble district was divided into a lower phosphorite unit and an upper clayey sand unit with only minor amounts of phosphate (Cathcart, 1963). The lower unit is brown, gray, and white and is a sandy, clayey, pebbly phosphorite. Vertebrate fossils in the member are now thought to be Miocene and early Pliocene in age (Webb and Crissinger, 1963; Scott, 1985; 1988). In the land-pebble district, phosphate deposited in the Peace River Formation was reworked, concentrated and enriched in Late Miocene and Early Pliocene times by a series of transgressions and regressions. During these episodes, exposed carbonate rock of the Hawthorn Group was phosphatized, and large cobbles and boulders were reworked into conglomerate beds in the Bone Valley Member. The base of the Bone Valley is commonly a phosphate conglomerate with boulders that are as much as 1.5 feet (50 cm) in diameter. Coarse phosphate rock (the pebble fraction) is concentrated on the Bartow Ridge in the central part of the

land-pebble district, while fine-grained (concentrate size) phosphate was deposited on the flanks of the ridge and on the flat lands adjacent to the ridge. The phosphorite unit of the Bone Valley is as much as 50 feet (15 m) thick and is thickest as sinkhole fillings.

Pebble-size phosphate is not as abundant in the southern extension and the very coarse boulders of phosphate characteristic of the Bone Valley Member do not appear to be present in the southern extension.

The upper unit of the Bone Valley Member is a clayey sand that contains only minor amounts of phosphate. The unit is leached and is characterized by aluminum and iron phosphate minerals (wavelite, crandallite, and vivianite). The upper clayey sand extends as a transgressive unit to the north of the land-pebble district (Figure 3), where the lower phosphorite unit either was not deposited or was eroded during a regression. The upper unit is as much as 30 feet (10 m) thick, and may be the only part of the Bone Valley that is Pliocene in age.

The Bone Valley is irregularly present in the northern part of the southern extension, but is not present throughout much of the southern part. At a drill hole in DeSoto County (Figure 3) the position of the Bone Valley is taken by a clayey sand with abundant shell material and only trace amounts of phosphate.

Tamiami Formation. The Tamiami Formation overlies the Peace River Formation at drill hole 6 (Figure 3). The Tamiami is a green-gray clayey sand that contains abundant calcareous shell material and only minor amounts of phosphate. The Tamiami is Late Pliocene in age.

Pleistocene and Holocene sediments. Rocks of Pleistocene and Holocene age overlie the Bone Valley in the land-pebble district and overlie the Peace River or Tamiami in the southern extension. The cross section (Figure 3) shows the thickening of Pleistocene sediments to the south, from 10 feet (3 m) in the land-pebble district to as much as 70 feet (20 m) in the southern extension. Pleistocene rocks in the land-pebble district include lenticular channel deposits of coarse phosphate pebble at many places. These deposits are at the base of the Pleistocene and may rest directly on phosphorite of the Bone Valley. Vertebrate fossils in the channel deposits have been identified as Pleistocene in age. Swamp muck and wind blown sand at the surface are thought to be Holocene in age. These deposits range from 2 to 6 feet (1-2m)

in thickness in both the land-pebble and the southern extension.

THE PHOSPHATE DEPOSITS

The phosphate deposits of the land-pebble district differ markedly from the deposits of the southern extension, primarily reflecting variations in the geologic history of the area.

Origin of the deposits

Factors that are common to phosphorite deposits include: (1) Periodicity-economic phosphate deposits are confined to rocks of late Precambrian-early Cambrian, Permian, late Cretaceous-early Eocene, and Miocene ages; (2) they are located only in areas where clastic sedimentation was at a minimum; (3) they are very large, so they formed over relatively long periods of time, in tectonically stable areas; (4) they are marine, so they had to be open to oceanic circulation; (5) they are in part structurally controlled; (6) Ocean water is saturated with respect to P_2O_5 , but cool water contains more P_2O_5 than warmer water, so warming of the cool water will promote precipitation of phosphate.

All of these factors can be demonstrated to have been operative during the deposition of phosphate in Florida. (1) Although some phosphate grains are present in all rocks of the Atlantic Coastal Plain, deposits are present only in rocks of Miocene age. (2) The deposits are a very long distance from the primary source of clastic material in the Appalachian, the clastic material is fine grained, and the Miocene rocks are thin, that is, they were deposited in an area where clastic sedimentation was minimal. (3) The area of deposition, the Florida Plateau, has been tectonically stable from Late Cretaceous to the present. (4) The Miocene rocks are marine and the area was open to oceanic circulation throughout the Miocene. (5) Deposits are in basins on the flanks of topographic or structural highs that were present during phosphate deposition. (6) Cool coastal currents from the north were diverted by the structures into the warmer water of the Gulf Stream. Some deeper cool water also was moved into the warm surficial water by upwelling.

The phosphate in the Hawthorn Group was deposited in shallow water with fine-sand, silt, clay, and carbonate rock over much of the Florida Plateau, but was concentrated in basins at several places, including the one that became the land-pebble district. The

Early Miocene seas withdrew, leaving carbonate rock that contained abundant phosphate in the land-pebble area. Clastic material of the Peace River Formation continued to be deposited to the south (in the southern extension).

Acid weathering removed carbonate rock forming a residuum enriched in phosphate pellets, quartz sand, and clay. When the sea readvanced in Bone Valley time, the residuum was reworked, the phosphate was concentrated by virtue of its high specific gravity; unweathered or partly weathered carbonate rock was phosphatized, and the coarsest phosphate was concentrated by submarine winnowing on the ridges of the sea bottom. Phosphate particles were enriched by phosphatization of carbonate rock and by replacement of CO_3 by PO_4 in the apatite structure. The Bone Valley Member was deposited in a restricted basin, and it is only in this basin that the high P_2O_5 content pebble and concentrate are found.

In the southern extension, clastic material covered the carbonate rock and the sea probably never withdrew from the area, so that coarse phosphatized carbonate was not formed, and reworking and concentration were not effective. Thus the phosphate particles contain dolomite grains and the apatite is high in CO_3 , and therefore, lower in P_2O_5 .

A period of intense lateritic weathering followed the deposition of the Bone Valley Member. The acid water attacked and dissolved the phosphate particles forming the aluminum phosphate zone. Some P_2O_5 moved down in solution and further enriched the phosphate particles in the lower part of the Bone Valley and formed phosphate precipitates on the underlying carbonate rocks.

The deposits, in the land-pebble district, then are complex. They are partly depositional, partly residual, partly reworked, altered, enriched, and concentrated. The deposits in the southern extension were not subjected to subaerial weathering, they are single cycle deposits.

Land-pebble (Central Florida) Phosphate district

Most of the phosphate mined in the district, in the past, was from the Bone Valley Member. The Bone Valley Formation was informally divided into a lower phosphorite unit and an upper clayey sand unit by Cathcart (1963). The lower unit is a gray-green to gray-brown clayey sand that is characterized by graded bedding and crossbedding, and by an abundance of coarse phosphate nodules. Although individual beds

within the lower unit may be nearly pure clay, sand or phosphate grains, the average composition of the unit, as mined, is about one-third recoverable phosphate, one-third quartz sand, and one-third slime ($<0.1m$). The slime fraction contains quartz, clay, and fine phosphate grains. The recoverable phosphate grains range in size from 0.1mm to as much as 30 cm in diameter, and a coarse (>1 mm) phosphate product is made by washing and screening. The minus 1 mm fraction is separated by screening and froth flotation into a phosphate product (concentrate), a quartz sand (tailing), and a slime fraction.

The ratio of the amount of the pebble product to the amount of the concentrate produce can theoretically range from infinity, where the concentrate fraction is absent, to zero where the pebble fraction is absent, but in practice, the ratio ranges from about 0.1 (very low percentages of pebble) to about 5 or 6 (very high percentage of pebble). Ratios greater than one indicate a predominance of pebble; ratios less than one indicate a predominance of concentrate.

Within the land-pebble district, ratios greater than 1 are characteristic of the deposits that are on the Lakeland Ridge, while ratios of less than 1 are characteristic of the flatwoods areas adjacent to the Peace and Alafia Rivers (Altschuler et al., 1964).

Tonnages of phosphate in Florida are computed only for the potentially recoverable phosphate particles, that is, the pebble and the concentrate fractions, and are reported as tons of product per acre. Tonnages in the land-pebble district range from 3,000 to about 15,000 tons per acre except in a few areas where the Bone Valley Member is over-thickened in sinkholes and where tonnages of as much as 50,000 tons per acre have been recorded. Thicknesses on the cross section are from single drill holes at the location shown. Tonnages of recoverable phosphate in the Bone Valley decreases from north to south. At hole 3, which is on the flank of the Lakeland Ridge, almost all of the tonnage is in the pebble fraction, and at hole 5, the concentrate fraction is much more abundant than the pebble fraction. Holes 4 and 5 are located in the flatwoods areas, close to the modern streams.

Southern Extension

All of the potentially economic phosphate in the southern extension is in the Peace River Formation, and is predominantly in the concentrate fraction. The pebble fraction

contains so many dolomite fragments, quartz grains, and calcitic shell material that without upgrading, it is not economic. The Bone Valley Member is not present. From a visual inspection of the core at locality 6 (Figure 3), it is estimated that the Tamiami Formation contains only 2 to 3 percent phosphate pellets, about one-tenth the amount in the Bone Valley Member. The 20-foot bed at hole 6 contains an estimated 500 tons per acre, far below the minimum tonnage needed for an economic deposit.

The Peace River Formation of the Hawthorn Group is gray-green to dark olive green clay, silt, fine sand, and minor dolomite. All of these lithologies contain some phosphate grains, mostly in the concentrate fraction. The black and brown phosphate pellets are highly polished and rounded. There are many disc shaped pellets and the finest sizes tend to be spherical. Some of the pellets have outer rims of contrasting color, and many contain dark organic grains that may be concentrated as centers or as outer rims, but only a small percentage of pellets are oolitic. The pebble fraction is minor in amount and is low in P_2O_5 content and high in MgO content (Table 1).

The concentrate fraction is abundant and is high enough in P_2O_5 content to be economic. Contents of MgO are slightly high, averaging about 1.0 percent, but other deleterious elements (Fe and Al) are not above economic limits. The material, therefore, is potentially economic.

The overburden in the southern extension is thicker than in the land-pebble district. For example, it is 63 ft thick at hole 6 (Figure 3). At this hole the potential ore zone is about 72 ft thick and it is estimated that there may be about 20,000 tons per acre of concentrate size phosphate pellets. At holes 4 and 5 (Figure 3), the Peace River Formation of the Hawthorn Group although about the same thickness as at hole 5, contains only about half as much recoverable phosphate.

Chemistry

Chemical analyses of the pebble (+1 mm) and concentrate (minus 1 mm to 0.1 mm) fractions of samples from the land-pebble district and the southern extension are shown in Table 1. Chemical data for the pebble fraction show that the fraction in the land-pebble district is relatively high in P_2O_5 , low in MgO (average less than 0.3 percent) and the amount of CaO is within the limits for the apatite mineral. In contrast, the pebble fraction from the southern extension is low in P_2O_5 , high in

Table 1. Chemical analyses, in percent, of phosphate samples, land-pebble district and its Southern Extension (Range of several samples for each category)

[Analyses by G. T. Burrow, J. P. Cahill, S. J. Fennelly, I. C. Forst, J. Gardner, H. H. Lipp, V. Merritt, W. Mountjoy, D. R. Norton, R. L. Rahill, G. D. Shipley, and T. L. Yager, U.S. Geological Survey]

	Pebble Fraction		Concentrate Fraction	
	Central District	Southern Extension	Central District	Southern Extension
P ₂ O ₅	30.7-36.1	13.9-30.0	32.2-37.4	22.0-31.9
CaO	40.8-49.0	34.2-47.0	46.5-48.5	40.0-47.6
F	3.63-4.01	1.24-3.61	4.04-4.16	2.28-3.82
SiO ₂	6.33-10.4	8.6-14.4	2.81-4.23	4.91-23.4
Al ₂ O ₃	.57-3.77	1.29-1.90	1.27-1.77	1.21-1.67
Fe ₂ O ₃	.55-1.38	.82-1.76	.57-.89	.91-1.12
MgO	.14-.35	.63-7.3	.15-.45	.60-1.20
Na ₂ O	.11-.57	.58-.78	.18-.53	.56-.79
K ₂ O	.07-.11	.11-.25	.10-.17	.22-.60
TiO ₂	.04-.06	.04-.06	.10-.16	.05-.10
MnO	.01-.03	.01-.04	.03-.05	.02-.04
S	.10-.52	.40-2.09	.21-.39	.48-.53
CO ₂	1.8-3.8	3.7-12.7	1.81-3.09	2.86-5.48
LOI ¹	3.7-8.8	3.9-14.8	3.9-6.3	6.7-7.8
Al ²	5.7-9.9	6.9-12.8	3.3-3.8	3.5-22.7
U(ppm)	120-175	100-160	100-130	80-100
Ratios (average)				
CaO/P ₂ O ₅	1.40	1.61	1.35	1.70
F/P ₂ O ₅	0.113	0.121	0.113	0.119

- 1 Loss on ignition
2 Acid insoluble

MgO, and the CaO to P₂O₅ ratios are in excess of the ratios for apatite. Fluorine in the pebble fraction of the land-pebble district is high, whereas in the southern extension, the pebble fraction is deficient in fluorine. Iron and alumina (Fe₂O₃ + Al₂O₃) contents of the pebble fraction are low in both the land-pebble district and the southern extension, and acid insoluble contents are moderate in both areas.

The chemical data show that the pebble fraction of the land-pebble district consists primarily of moderately substituted francolite with quartz as the principal gangue mineral. On the other hand, the pebble fraction of the southern extension consists of a rather highly substituted, fluorine deficient apatite with abundant quartz and dolomite. Consequently, the pebble fraction of the southern extension is not an economic source of phosphate.

Chemical data for the concentrate fractions show that the P₂O₅ content of the concentrate from the land-pebble district is very high; MgO content is low (average about 0.3 percent); iron and alumina and acid

insoluble contents are low, and the ratios of CaO to P₂O₅ are well within the limits of apatite. The concentrate from the southern extension is considerably lower in P₂O₅ than the concentrate from the land-pebble district, but the contrast is not as great as that in the pebble fraction. Iron and alumina and acid insoluble contents are moderate. Fluorine contents of the concentrate are within the limits of the apatite mineral, but ratios of F to P₂O₅ are somewhat higher in the concentrate from the southern extension. The contents of MgO in these samples is high, averaging about 0.9 percent.

The data indicate that the apatite in all of the concentrate samples is francolite, moderately substituted in the land-pebble district, and more highly substituted in the southern extension. There is little excess carbonate in the samples, none in the land-pebble and minor amounts in the southern extension. The chemical data indicate that apatite is the major mineral in the concentrate fraction, quartz is the principal gangue mineral, and the samples

from the southern extension contain small amounts of dolomite. The lower P₂O₅ content of the samples from the southern extension is due to the more highly substituted apatite.

MINERALOGY

Apatite

The apatite of all of the phosphate deposits of Florida is francolite (carbonate fluorapatite). Detailed work on the mineralogy of francolite (Lehr et al., 1967; McClellan and Lehr, 1969; McClellan, 1980; Van Kauwenburgh and McClellan, 1985) has shown that carbonate substitutes for phosphate in a 1:1 ratio and that the maximum amount of substitution is slightly less than 6 percent, by weight, (expressed as CO₂); that replacement of Ca²⁺ by Na⁺ and Mg²⁺ is limited but systematic, and that charge imbalances are compensated by both cation and anion substitution. These substitutions can be represented by a series with end member formulas and idealized chemical analyses as shown on Table 2.

Because of the CO₂ substitution, the P₂O₅ content of the francolite end member is only about four-fifths of that of the fluorapatite end member-34.8 percent in francolite and 42.2 percent in fluorapatite (Table 2). Both magnesium (MgO) and sodium (Na₂O) are present in the francolite structure; the maximum MgO in the most highly substituted francolite is almost 0.6 percent, while Na₂O may be as much as 1.1 percent (Table 2).

The changes in composition of the apatite are very important economically. The magnesium in the apatite structure cannot be removed by beneficiation. Furthermore, the greatest theoretical amount of 0.57 percent MgO is approximately the maximum amount of magnesium that can be present in a commercial concentrate. Similarly, the P₂O₅ content of the most highly substituted apatite (34.8 percent) is probably the maximum phosphate content that might be expected.

The CO₂ content of the apatite of a commercial concentrate is difficult to measure because of the admixed particles of calcite and dolomite in the concentrate. Gulbrandsen (1970) demonstrated that the measurement of an x-ray diffractogram, of the difference in degrees 2θ, of the 410 and 004 peaks of francolite could be used to estimate the CO₂ content of francolite, and therefore, the approximate degree of substitution. A scatter diagram (Figure 4)

shows the relationship of CO₂ content and the 2θ. For example, fluorapatite that contains about 5 percent CO₂ has a 2θ of only about 1.2.

Plots of samples from the Bone Valley Member are clearly separated from the plots of samples from the undifferentiated Peace River (Figure 4). The samples are from drill holes and mine faces in Polk and Hillsborough Counties. All of the samples from the undifferentiated Peace River are more highly substituted than are the samples from the Bone Valley Member. Deep samples from near the base of the Peace River are from a drill hole in DeSoto County. No CO₂ analyses are available for these samples, but they all fall between 1.17 and 1.30 2θ and are therefore highly substituted. The CO₂ contents of these samples probably ranges between 3.5 and 5.0 percent. Because the apatite in the deposits of the southern extension is highly substituted, it will be high in MgO content (0.3 to 0.4 percent) and low in P₂O₅ content (29 to 31 percent).

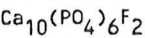
Table 2. Idealized compositions and chemical formulas for fluorapatite and francolite.

IDEALIZED COMPOSITIONS - APATITE END MEMBERS

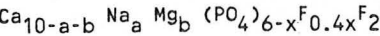
	Fluorapatite	Francolite
CaO	55.60	55.20
P ₂ O ₅	42.22	34.85
CO ₂	0	5.72
F	3.77	4.92
Na ₂ O	0	1.13
MgO	0	0.57

	Ratios	
CaO/P ₂ O ₅	1.318	1.583
F/P ₂ O ₅	.089	.141

EMPIRICAL END-MEMBER FORMULAS
FLUORAPATITE



FRANCOLITE (Carbonate fluorapatite)



EXPLANATION

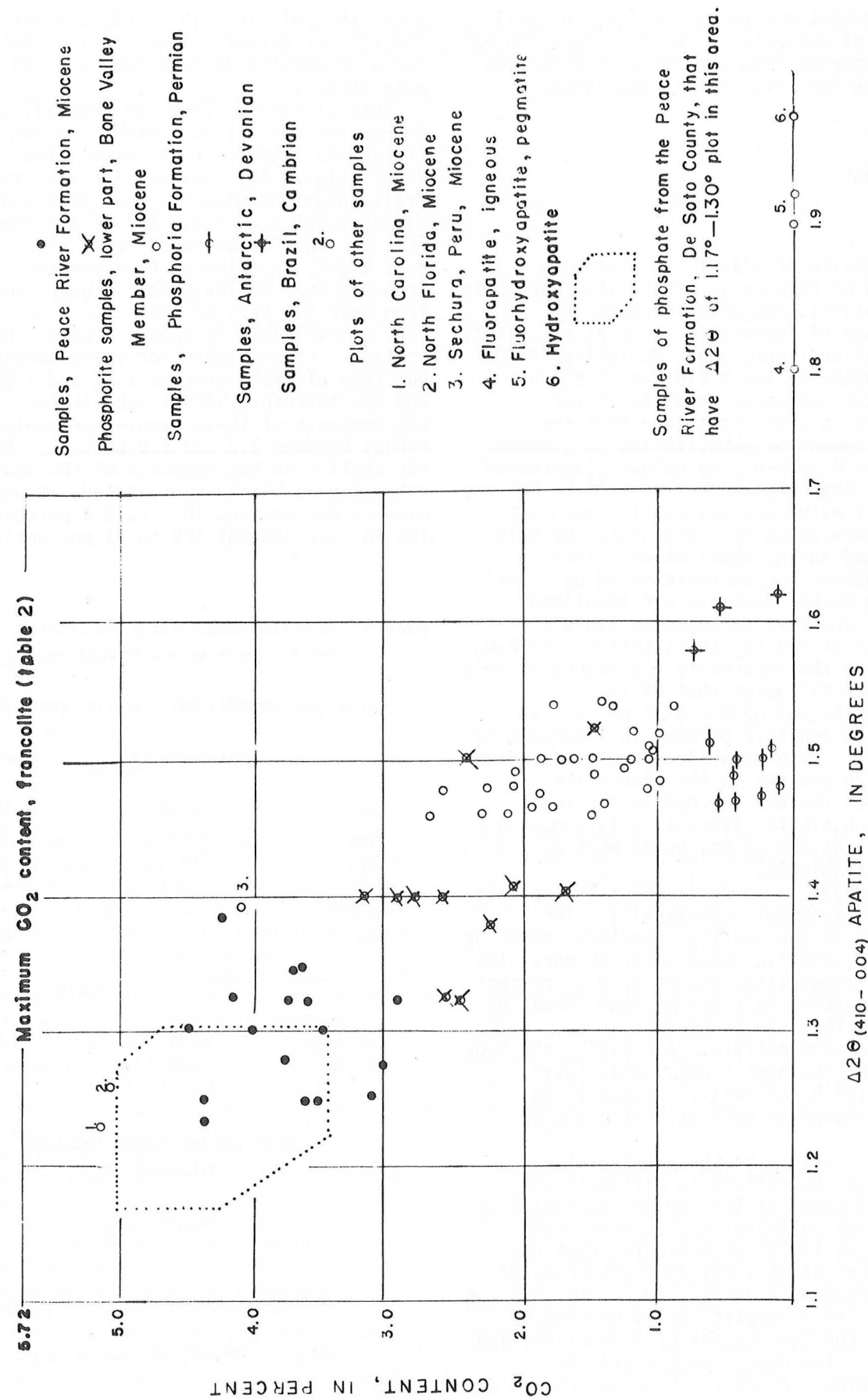


Figure 4. Scatter diagram of relations of percent CO₂ and 2θ (410004) of apatites.

Clay minerals

The clay minerals in the phosphate deposits of Florida are a mixture of the common clay minerals kaolinite and smectite (montmorillonite) and the less common clay minerals palygorskite (attapulgite) and sepiolite. Trace amounts of illite or mixed layer illite-smectite are present in some samples.

Kaolinite $(Al_4Si_4O_{10}(OH)_8)$ is the dominant, and in some cases, the only clay mineral in the surficial sediments of the land-pebble district where it formed as an alteration of smectite during acid weathering (Altschuler, Dwornik, and Kramer, 1963). Kaolinite is present in the top five samples from the drill hole in Hardee County (Figure 5), where it is inversely correlated with smectite. In a drill hole in DeSoto County, however, where kaolinite is mixed with dolomite as well as smectite, the kaolinite is thought to be detrital.

Smectite $[1/2 (Ca, Na)_{0.7}(Al, Mg, Fe)_4(Si, Al)_8]_{20}nH_2O$ is the principal clay mineral of the matrix of the Bone Valley Member and is present throughout in varying amounts. The smectite of the land-pebble and the southern extension is probably beidellite although montmorillonite is also present.

Palygorskite (attapulgite) $[Si_8Mg_5O_{20}(OH)_4H_2O]$ and sepiolite $[H_6Mg_8Si_{12}O_{30}(OH)_{10}H_2O]$ are clay minerals with crystalline structures consisting of long double silicate chains which are parallel to the length of the mineral fibers (Carroll, 1970). Between the double chains are channels that are filled with water. In general, palygorskite occurs in samples at the bottom of mine pits in the land-pebble district, in the Arcadia and Peace River Formations, and is abundant only in that part of the stratigraphic section that contains carbonate minerals. Sepiolite is not present or is very rare in samples from mine pits; it is abundant only in stratigraphically lower parts of the Arcadia and may be the only clay mineral in the basal part of the Hawthorn Group, in clay beds of the Tampa or Nocatee Member. Palygorskite and sepiolite in the phosphate deposits of Florida may have formed in a

perimarine environment (Weaver and Beck, 1977), in ephemeral lakes (Strom and Upchurch, 1985), or some may have formed from alteration of smectite (Altschuler, Jaffee, and Cuttitta, 1956, p. 496).

Carbonate minerals

Dolomite is the principal carbonate mineral in the phosphate deposits of the land-pebble district and in the potentially economic deposits of the southern extension. Calcite is present as shell material in the Tamiami (Table 1), as "rice-grain" crystals in stratigraphically lower parts of the Peace River Formation and as a major constituent of the lower parts of the Arcadia Formation (Scott, 1988). Further down dip and deeper below the surface, calcite may be the principal carbonate mineral (Berman, 1953).

The origin of the dolomite of the phosphate deposits is not precisely known, but replacement of calcite has been proposed by Altschuler, Cathcart, and Young (1964), who postulated that the source of the magnesium is from the alteration of smectite to kaolinite and the alteration of the original francolite.

Other minerals

Heavy minerals, present in very minor amounts throughout the deposits, include ilmenite, tourmaline, rutile, zircon, kyanite, sillimanite, epidote, garnet, and possibly monazite (Cathcart, Patterson and Crandall, 1983). The content of heavy minerals has been measured for a few samples and averages about 0.5 weight percent of the total rock. The heavy mineral content is too low to be recovered as a by-product. All of the heavies are resistant minerals that remain after strong acid leaching.

Aluminum and iron phosphate minerals, present in the upper beds of the land-pebble district, formed during lateritic weathering. Aluminum phosphate minerals have not been found in the southern extension which has undergone less severe weathering.

Mineral distribution

Vertical (stratigraphic) distribution of minerals in the minus 200 mesh (slime) fraction of samples from a drill hole in Hardee County are shown on Figure 5. Data are from x-ray diffractograms, and the slime fraction data are shown because the clay and aluminum phosphate minerals are concentrated in this fraction, and the relative amounts of the other minerals reflects their percentage in the total rock. The minerals are plotted in two groups, the clay minerals in one group, and all other minerals in the other. Amounts of minerals in each group were recalculated to 100 percent to better indicate distribution. Kaolinite is the only clay mineral in the overburden and the upper, leached part of the Bone Valley. As leaching becomes less intense downward, kaolinite decreases and smectite increases. Palygorskite is the more abundant clay mineral in the upper samples from the Peace River Formation, where it is inversely correlated with smectite. In the Arcadia Formation and in the lower part of the Peace River Formation, palygorskite is sparse and the abundant clay minerals are sepiolite and smectite. In the bottom samples, however, smectite is the only clay mineral.

Aluminum phosphate minerals are present only in the top samples, at the same levels where kaolinite is the only clay mineral. Apatite is most abundant in the middle part of the Bone Valley Member but is also abundant elsewhere in the Peace River Formation and in present in minor amounts in the Arcadia Formation and Tampa Member. The carbonate minerals, largely dolomite, are distributed throughout the Arcadia and Peace River Formations and are the most abundant minerals in the hard dolomite beds in both formations. The zeolite mineral clinoptilolite is present only in the Tampa Member at the base of the Hawthorn Group, where smectite is the only clay mineral.

By-products

Fluorine. The carbonate fluorapatite of the phosphate deposits contains from 3 to 4 percent fluorine. In the manufacture of phosphoric acid, about one-third of the total fluorine stays in the phosphogypsum as a water insoluble precipitate, the rest remains in the acid or is volatilized. That part which is volatilized, either initially, or as the acid is concentrated by evaporation, may be recovered as fluosilicic acid. Two plants are recovering fluorine from several of the wet process acid plants in the district. All of the fluorine

recovered is being converted to artificial cryolite for use in the manufacture of aluminum metal.

Uranium. Uranium substitutes for calcium in the apatite mineral and is present in amounts ranging from 30 to about 200 ppm. Uranium is recovered as a by-product of the manufacture of phosphoric acid at several plants in the district and at least in one plant in Louisiana. In a recent report (Anonymous, 1984), it was noted that the Freeport's uranium recovery company "...produced 1.1 million pounds of yellowcake in 1983." Phosphate rock mined in Florida is shipped to their plant in Louisiana where uranium is recovered from phosphoric acid. The company has been producing uranium for at least 10 years. The amounts of uranium produced by other companies in the district are not known.

Resources

During the past century, about 1 billion tons of phosphate rock has been produced from the land-pebble district, primarily from the Bone Valley Member. In the last 20 years, however, an increasing amount of the material mined has come from the undifferentiated Peace River Formation. Average P_2O_5 contents of material mined from the undifferentiated Peace River Formation are lower, and amounts of deleterious material are higher.

Most of the remaining resources of the land-pebble district are thought to be in the Peace River Formation although some material will continue to be mined from the Bone Valley Member. Total resources remaining in the land-pebble district are thought to be about 800 million metric tons (Cathcart et al., 1984); but some additional resources, particularly in the deeper parts of the Hawthorn Group, have not been evaluated and will increase the resources by a moderate amount.

The total resource in the southern extension is not well known, but Bernardi and Hall (1980) point out that vast potential reserves of low-grade phosphates exist in the southern extension, and "Mining . . . will continue for many decades even though these mines will be significantly higher cost producers." Identified and hypothetical resources in the southern extension were estimated to be about 3 billion metric tons by Cathcart et al., (1984), and there are additional resources that have not been evaluated.

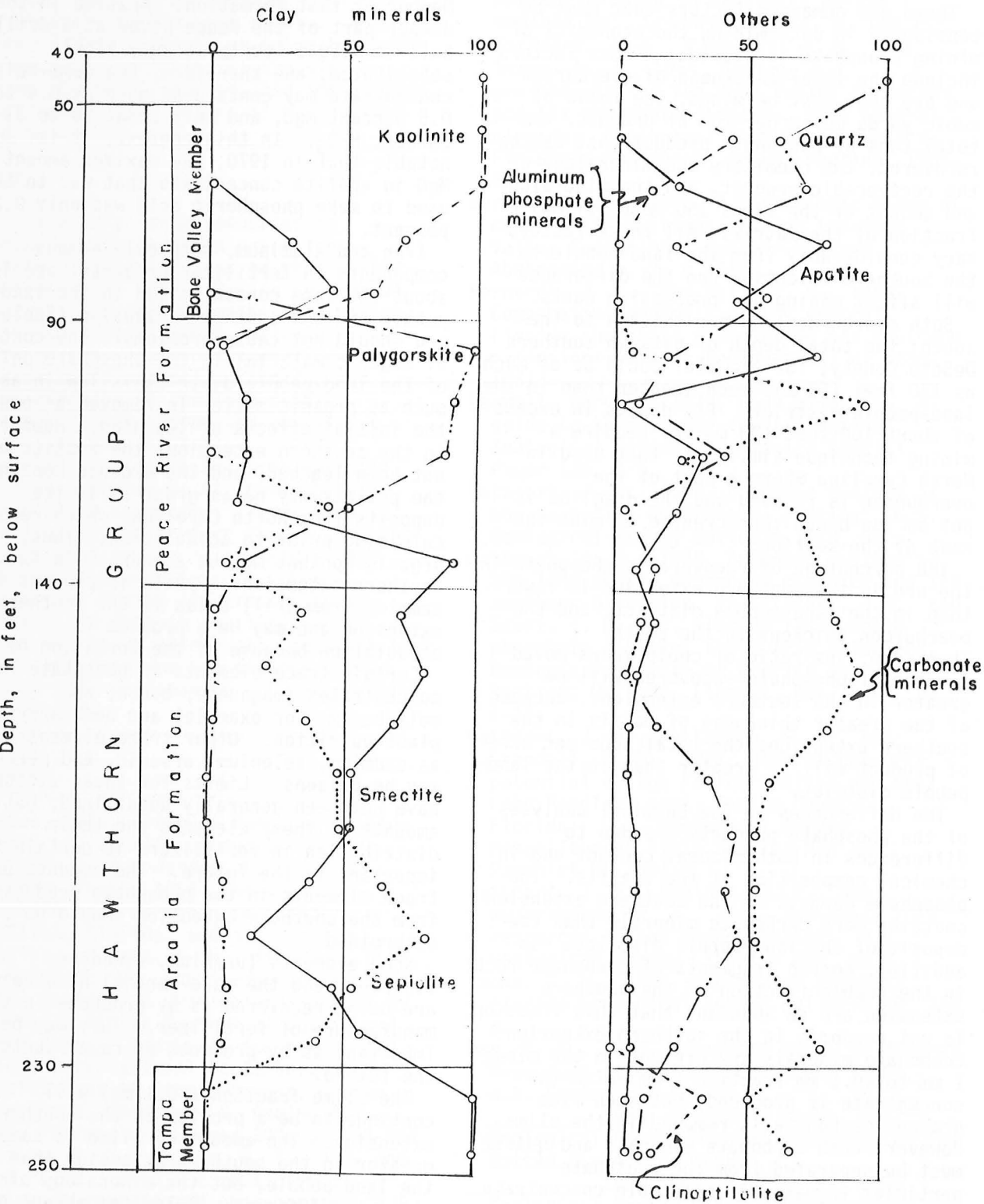


Figure 5. Mineral distribution in a drill hole in Hardee County, Florida. Location of drill site shown on Figure 1. Amounts, recalculated to 100 percent, estimated from X-ray diffractograms.

Discussion

There are numerous factors that must be considered in determining the economics of mining phosphate in Florida. These factors include the total thickness of overburden and ore that must be mined, the ratio of cubic yards moved per ton of product, the total tons of phosphate product that can be recovered, the chemistry and mineralogy of the recoverable product, and the mineralogy and amount of the minus 150 mesh (slime) fraction of the matrix. All these factors vary considerably from the land-pebble to the southern extension and the difference will affect mining and processing costs.

Both overburden and ore thicken to the south; the total depth of pits in southern DeSoto County, for example, could be as much as 170 feet (52 m), much greater than in the land-pebble district. Pit depths in excess of about 100 feet (30 m) may require a mining technique similar to that used in North Carolina where a part of the overburden is removed and the dragline is put on the bench thus created to mine the rest of the section.

The percentage of recoverable phosphate in the ore in the southern extension is lower than in the land-pebble district, and the overburden thickens to the south. Therefore, the ratio of cubic yards moved per ton of phosphate recovered will be greater in the southern extension. Because of the greater thickness of matrix in the southern extension, the total tons per acre of product will be greater than in the land-pebble district.

The differences in the chemical analyses of the phosphate products are due to differences in both mineral content and in chemical composition of the apatite. The phosphate deposit of the southern extension contains more carbonate minerals than the deposit of the land-pebble district. In addition, coarse fragments of carbonate rock in the pebble fraction of the southern extension are so abundant that this fraction is not economic in the southern extension. Carbonate minerals are present in the minus 1 mm to +0.1 mm fraction from which the concentrate is produced, but much fine-grained carbonate is removed in the slime. However, both carbonate minerals and quartz must be separated from the phosphate particles to make an acceptable concentrate.

The apatite in the southern extension is more highly substituted and less weathered than the apatite in the land-pebble district and therefore, contains more MgO and less P_2O_5 . This is also true with the deeper and less weathered apatite of the Peace River

Formation in the land-pebble district, as compared with the apatite of the Bone Valley Member of that formation. Apatite in the deeper part of the Peace River at a drill hole in DeSoto County is very highly substituted, and therefore, the commercial concentrate may contain as much as 0.4 to 0.5 percent MgO, and only about 30 to 31 percent P_2O_5 . In this context, it is notable that in 1970, the maximum amount of MgO in apatite concentrate that was to be used to make phosphoric acid was only 0.25 percent.

Iron and aluminum, both deleterious components in fertilizer products, are in about the same concentration in the land-pebble and the southern extension (Table 1) and should not cause problems. The content of organic material in the phosphate pellets of the land-pebble district is low in as much as organic matter is removed as one of the initial effects of leaching. However, in the southern extension, the apatite has not been leached, and the organic content of the pellets may be as great as in the deposits from North Carolina, which require calcining prior to acidulation. Thus, organic content may be a problem in the southern extension. Pyrite is present in samples from drill holes in the southern extension and may be a problem in acidulation because of the formation of H_2S .

Certain trace elements in phosphate concentrates (manganese, boron, and molybdenum, for example) are necessary for plant nutrition. Other trace elements such as cadmium, selenium, arsenic, and mercury may be poisons. Limits for these elements have not been generally determined, but the amounts of these elements and their distribution in fertilizers is certain to be important in the future. The amounts of trace elements in the phosphate products from the southern extension should be determined.

Some elements (uranium, vanadium, fluorine, and the rare earths) have been or are being recovered as by-products in the manufacture of fertilizer. They may be important as by-products or co-products in the future.

The slime fraction (>0.1 mm) will continue to be a problem in the southern extension. The amount of slime is somewhat greater in the southern extension than in the land-pebble, but the mineralogy of the slime is different. Dolomite, absent or in minor amounts in the slime fraction of the land-pebble district, is a major constituent of the slime in the southern extension. The major clay minerals of the slime fraction in the land-pebble district are smectite and

kaolinite, whereas the slime of the southern extension contains abundant palygorskite and sepiolite. Because of their morphology, these minerals settle very slowly. The effects of large amounts of dolomite on the settling characteristics of the slime fraction should be studied, and the average mineral composition of the slime fraction should be determined.

Outlook

There are very large resources of phosphate in the southern extension, certainly billions of tons of recoverable concentrate, and future mining in central Florida will be in the southern extension. The data presented herein indicates that mining and processing costs will be higher in the southern extension than for the premium deposits of the land-pebble district, but the mining and processing problems are not insoluble.

Important environmental problems will have to be overcome or mitigated before mining will be permitted. Industry must work diligently to protect the environment from permanent damage by the mining and processing of phosphate rock. Legal restraints on mining and processing are being complied with in the land-pebble district and it is absolutely necessary that the industry convince the general public that they will continue to act responsibly in the future.

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HYDROLOGY AND CHEMISTRY OF GROUND WATERS IN THE CENTRAL FLORIDA PHOSPHATE DISTRICT

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ABSTRACT

Ground-water quality in the central Florida phosphate district is remarkably good. The only major concerns involve radiation and localized contamination around agricultural plants.

There are three hydrostratigraphic horizons in the district. The water chemistry of each reflects the composition of the host rock. The surficial aquifer system is predominantly quartz sand. Water in this system is unconfined and usually slightly acid-, iron- and organic-rich. The surficial aquifer system is separated from an uppermost artesian aquifer, a component of the intermediate aquifer system, by clay-rich sediments of the phosphatic Hawthorn Group. The uppermost aquifer (artesian) is a highly localized series of permeable, sandy strata within the upper Hawthorn Group. Water quality is highly variable and concentrations of phosphorus, fluorides and radionuclides are of concern. Clays and

silts in the lower Hawthorn Group comprise the intermediate confining unit which separates the secondary artesian aquifer or upper Floridan aquifer system from the uppermost artesian aquifer. The upper Floridan aquifer system consists of limestones and dolostones of the Arcadia Formation, especially the Tampa Member. The Floridan aquifer system often lies below a regionally persistent clay horizon in the Tampa Member and consists of the lower Tampa Member of the Arcadia Formation, Suwannee Limestone, Ocala Group and Avon Park Formation. Floridan aquifer system horizons are karstic and water quality is typical of carbonate aquifers.

Radiation in ground water is a result of weathering of uranium-bearing phosphorites. The radionuclides of concern are radium-226, radon-222, and polonium-210. Other uranium and thorium daughters are present, but are not considered hazardous. Gross-alpha and

radium activities exceed state and federal standards in scattered wells. In general, these high radiation activities are not considered to be a result of phosphate mining. They are a result of natural releases from mineralized strata. Mining activities do, however, redistribute the radioactive materials.

Chemical processing of the phosphate ore involves dissolution of fluorapatite with sulfuric acid. This process results in large accumulations of slightly radioactive waste-gypsum and highly acidic waste process water. Both are contained at plant sites and pose little threat to regional ground water; however, concern remains and examples of ground-water contamination have been documented.

INTRODUCTION

Ground-water quality in the Central Florida Phosphate District is remarkably good in spite of the widespread mining and development activities. Due to laws that rank among the nation's most rigorous, ground-water quality is thoroughly monitored and the industry takes an active initiative in preventative and corrective measures to insure protection of potable water supplies. Nevertheless, public concern about the effects of mining on water quality remains high.

Two activities associated with mining and chemical processing of phosphate contribute to this concern. First, naturally-occurring radiation is redistributed by mining and may pose a threat to industry personnel or the public (there is minimal evidence of this). Second, chemical processing of the ore results in acidic and slightly radioactive gypsum wastes.

This paper summarizes the natural quality of ground waters in the central Florida phosphate mining district and discusses some of the concerns of the public with respect to ground-water pollution.

REGIONAL HYDROGEOLOGY AND HYDROCHEMISTRY

According to Stewart (1966), there are four hydrostratigraphic horizons in the central Florida phosphate district. These are: (1) the surficial, unconfined aquifer, (2) the uppermost artesian aquifer, (3) the secondary artesian aquifer, and (4) the Floridan aquifer. These have recently been placed into a statewide nomenclature. The currently accepted hydrogeologic units, defined by the Southeastern Geological

Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition (1986), include: the surficial aquifer system, the intermediate aquifer system and confining unit, and the Floridan aquifer system, which combines (3) and (4) of Stewart's (1966) breakdown.

Regional Flow Systems

The potentiometric surfaces of the three aquifer systems in the Central Florida Phosphate District are such that downward flow from the surficial and intermediate aquifers and recharge of the Floridan aquifer is predicted. The Floridan aquifer system is unconfined just north of the district, in the Green Swamp. The aquifer has a potentiometric high in the Green Swamp; therefore, it is believed that the aquifer is recharged there and that flow is radial, with minimal recharge, to the coasts. In the phosphate district, the Floridan aquifer system is confined; however, local recharge continues through open and sediment-filled sinkholes, fractures, and leakage through the confining system.

The phosphate mining industry utilized considerable Floridan aquifer system water in beneficiation and chemical processing during the late 1960's and early 1970's. This use, combined with several relatively dry years, lead to a reduction in the Floridan aquifer system potentiometric surface. Fear of induced up-coning of deep, sulfate-rich water, loss of aquifer storage, and depletion of water resources caused the industry to come under considerable criticism. Industry-generated, water-conservation techniques, such as water re-use and artificial enhancement of local recharge by means of interaquifer connector wells, have minimized industry withdrawals from the Floridan. Today, a similar decline in the potentiometric surface is taking place in agricultural regions just south of the phosphate district.

Surficial Aquifer System

Consumption and Thickness. The surficial, unconfined aquifer consists of clean quartz sand to clayey sand of eolian and marine origins. The age of the horizon varies from Plio-Pleistocene to Recent. Organic and ferruginous handpans locally present. Near the base of the aquifer, phosphate grains and clays may be reworked from the underlying Peace River Formation (Hawthorn Group). The surficial aquifer system ranges from 0 to over 100 feet in

thickness.

The sand is not cohesive and tends to slump when water-saturated. Because of the impact of slumping on mine-cut stability and because of excess water transmitted by the surficial aquifer system to the mine cut, de-watering the surficial aquifer system prior to mining is preferred. This is one of the primary motivations for use of interaquifer connector wells.

Natural Ground-Water Quality. Upchurch et al. (1979a, 1988) collected water samples from wells in the surficial aquifer system. These data are used to illustrate water quality in this system because they are closely controlled by a hydrostratigraphic horizon. Table 1 lists the mean chemical properties of the surficial aquifer system and the Floridan aquifer system. Figure 1 compares the major element chemistry of the surficial aquifer system to that of the Floridan aquifer system. Note that, in general, surficial aquifer system waters are acidic and higher in dissolved ions and radionuclides than the Floridan aquifer system. The composition of the water is basically a sodium-sulfate solution. Sodium is concentrated from maritime rainfall and weathered from sodium silicate, while sulfate comes from oxidation of pyrite and possibly organics. The water is often stained by organics and has the odor of sulfides, which indicates reducing conditions.

Intermediate Aquifer System

The uppermost artesian aquifer of Stewart (1966) has received little attention because it is localized and not a major source of potable water. The aquifer consists of beds of phosphatic sand and gravel within the Peace River Formation (Hawthorn Group). These beds include the "matrix", or ore-bearing beds, targeted for mining by the industry. Individual beds range from less than 3 to 15 feet in thickness. The aquifer horizons are confined by adjacent clay- and silt-rich strata. Lateral continuity of individual beds can be demonstrated over distances on the order of kilometers (the scale of mine cuts), but horizontal continuity at larger scales and vertical connectivity is usually minimal.

Thus, each individual horizon is confined to some degree. The potentiometric surfaces of each horizon may coincide or differ, depending on connectivity. The potentiometric surface of the aquifer is usually below the water table, but flowing wells do exist.

Composition and Thickness. The secondary artesian aquifer of Stewart (1966) has been often termed the upper Floridan aquifer (Wilson, 1977). The upper Floridan is a component of the intermediate aquifer system and is confined by overlying clay- and silt-rich beds of the Peace River and Arcadia Formations of the Hawthorn Group. The intermediate aquifer system is separated from the Floridan aquifer system by a laterally-persistent clay zone in the Miocene Tampa Member of the Arcadia Formation. The intermediate aquifer system is composed of karstic, slightly-phosphatic dolostone and limestone. In the northern part of the district the aquifer is thin (less than 3 feet) and it thickens to the south, where thicknesses in excess of 100 feet are known.

Floridan Aquifer System

The lower Floridan aquifer of Wilson (1977), the Floridan aquifer system, consists of over 1000 feet of limestone. It is karstic and lost circulation zones are commonly encountered upon well drilling. The aquifer includes the lower Miocene, lower Tampa Member, Oligocene Suwannee Limestone, Eocene Ocala Group and Avon Park Formation. The unit is confined above by the Tampa Member clay-rich horizon and below by evaporite-rich dolostones and limestones.

Natural Water Quality. Table 1 gives an average composition of the Floridan and Figure 1 compares the composition with the surficial aquifer system. In general, the water is somewhat hard and slightly alkaline. The water is a calcium-magnesium-bicarbonate solution. Sulfate does not appear to be a problem in the upper Floridan.

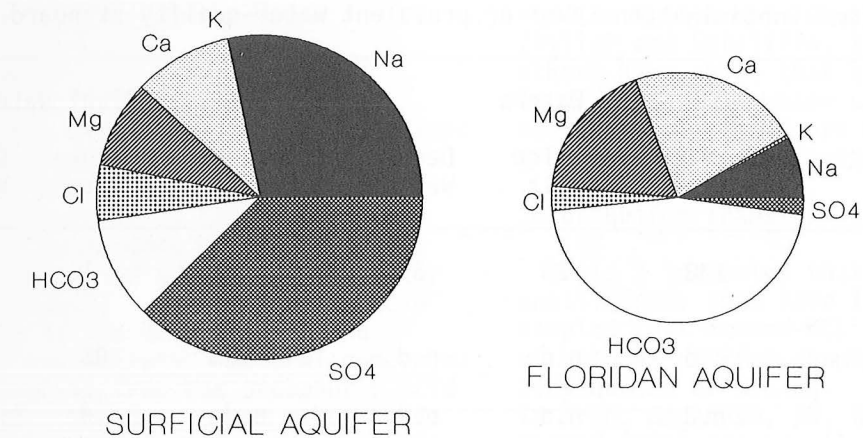
The Floridan contains potable water throughout the district. However, sulfate is a problem in several areas. In the central part of the district, sulfate concentrations increase with depth, but water-quality standards are seldom exceeded. Along the Peace River lineament, there is upconing of sulfate-rich water along the southern edge of the southern extension of the district. In these areas of Hardee and DeSoto Counties, sulfate limits use of the water for certain agricultural purposes when standards for public-water supplies are exceeded. Radium and gross-alpha radiation standards may also be exceeded in these areas. The high sulfate total dissolved solids (TDS) and radionuclide activities are a result of chemical maturation along deep

Table 1 - Means and Standard Deviations (Std. Dev.) of raw data from monitor wells. From Upchurch et al. (1988).

Variable	Surficial aquifer		Floridan aquifer	
	Means	Std. Dev.	Means	Std. Dev.
Temp. (°C)	24.2	0.7	24.4	1.2
Cond. (umhos cm ⁻¹)	731.2	264.7	388.3	109.4
pH	5.3	0.8	7.3	0.2
Eh (mv)	-96.6	83.9	-139.1	64.1
D.O. (mg/l)	1.2	0.3	1.5	0.3
Alk. (mg/l)	68.7	69.9	183.6	13.0
Cl (mg/l)	26.7	14.8	8.9	1.6
F (mg/l)	0.1	0.1	0.7	0.1
HCO ₃ (mg/l)	83.7	85.2	223.9	15.8
PO ₄ (mg/l)	0.3	0.2	0.1	0.1
SO ₄ (mg/l)	243.2	177.0	8.3	15.0
SiO ₂ (mg/l)	4.0	1.7	36.6	6.4
TOC (mg/l)	8.3	2.1	4.4	0.5
TDS (mg/l)	496.0	188.6	288.9	96.8
VDS (mg/l)	90.6	83.9	79.1	51.7
Al (mg/l)	71.5	81.7	0.0	0.0
Ca (mg/l)	26.3	23.8	35.2	3.8
Fe (mg/l)	5,414.0	3,218.5	12.6	16.5
K (mg/l)	0.4	0.1	1.2	1.1
Mg (mg/l)	14.2	7.7	17.6	4.3
Mn (mg/l)	10.7	4.8	0.7	0.2
Na (mg/l)	87.4	71.4	14.6	1.4
Pb (mg/l)	5.7	2.3	5.2	1.8
Sr (mg/l)	36.8	30.2	45.9	23.4
Pb-210 (pCi/l)	1.0	1.7	0.2	0.2
Po-210 (pCi/l)	18.8	21.2	0.8	0.9
Ra-226 (pCi/l)	1.6	1.1	1.0	1.0
U-234 (pCi/l)	0.3	0.1	0.1	0.2
U-238 (pCi/l)	0.1	0.0	0.1	0.1
Gross Alpha (pCi/l)	38.3	40.5	5.8	2.6

MAJOR ELEMENT COMPOSITIONS

Size of circle is proportional to total concentration. Averages in meq/L.



Averages from paired monitor wells, n = 9 samples from each horizon

Figure 1. Comparison of major-element compositions, in milliequivalents per liter, of the Surficial and Floridan aquifers in the Central Florida Phosphate District. Data from Table 1.

flow paths (Back and Handshaw, 1970), and of contact with evaporites at the base of the aquifer.

POLLUTION AND OTHER WATER-QUALITY PROBLEMS

There is much concern about water quality in the mining district. The industry is thought by many to be responsible for numerous water quality problems; however, heavy monitoring of water quality by the industry and close scrutiny by regulatory agencies limits most actual damage. An interesting example of this "blame placing" took place in the mid-1970's. At that time, there was a popular impression that coastal Floridan ground water came from the Green Swamp potentiometric high north of the phosphate district and low-quality coastal waters must have been polluted by contact with phosphate mining. Because of public concern and pressure by the press, President Ford ordered that the Environmental Protection Agency undertake an areawide environmental impact study before new mining ventures could be permitted. That study (Texas Instruments, Inc., 1978a, b, c, d, e) indicated several negative environmental impacts, but the low-quality ground water

near the coast was not found to be due to industry activity. In fact, it was found that industry activities have a minimal impact on regional water quality, although local quality may be degraded.

In recent years, concern about pollution of ground water has focused on three areas: organic pollutants around beneficiation plants; radiation in mined area; and radiation, acid, and other contaminants around agricultural plants.

Organic Pollutants

Both state and federal regulatory agencies are presently concerned about contamination of surface and ground waters by trace organics. There are several on-going studies to determine if the so-called "priority pollutants" are present. The data are incomplete and it is too early to make a definitive statement, but it appears that there is little or no problem.

Gordon Palm and Associates (1983) conducted a reconnaissance survey of water quality in surface and ground waters for the Phosphate Council and Florida Department of Environmental Regulation. That study found remarkably few cases in which the Maximum Contaminant Levels (MCL's) were exceeded (Table 2). Organic chemicals, such as

Table 2 - Percent of samples that exceed MCL's in the Florida phosphate industry. Data are from Gordon Palm and Associates (1983).
MCL = Maximum Contamination Level or prevalent water-quality standard.

Constituent	Mine Waters			Chemical Plant Waters		
	Surface Waters	Shallow Wells	Deep Wells	Surface Waters	Shallow Wells	Deep Wells
Number of samples	128	25	31	14	1	20
Heavy metals	n.d	n.d	n.d	7-93%	0%	0%
Pesticides	n.d	n.d	n.d	n.d	n.d	n.d
Trihalomethanes	n.d	n.d	n.d	n.d	n.d	n.d
Fluoride	6%	8%	0%	100%	0%	0%
Turbidity	20%	36%	10%	79%	100%	35%
Colifom bacteria	45%	16%	10%	0%	0%	20%
Chlorides	0%	16%	13%	0%	0%	0%
Surfactants	0%	0%	0%	0%	0%	0%
Color	38%	16%	13%	100%	0%	10%
Iron	7%	20%	10%	93%	100%	50%
Manganese	25%	8%	10%	100%	0%	5%
pH	5%	4%	3%	100%	0%	0%
Sulfate	5%	0%	6%	100%	0%	0%
TDS	5%	0%	6%	100%	0%	10%
Langelier Index	79%	80%	55%	100%	0%	80%
Odor	2%	0%	13%	43%	0%	20%

n.d. = not detected

pesticides, trihalomethanes, and surfactants, are not a problem in mining areas. More recent, unpublished industry studies have revealed a few, isolated occurrences, but the results of the Palm study hold.

Chemical Plants

Contamination of ground and surface waters around argichemical plants is well documented (Table 2). In these plants, phosphate concentrate is treated with sulfuric acid to produce phosphoric acid, which is the basis of fertilizer and other phosphorus-products. The phosphoric acid contains much of the uranium from the original ore concentrate. Several companies strip this uranium from the phosphoric acid and market it. Radium, on the other hand, remains in the process waste products.

The biggest waste problem facing the agrichemical industry is the production of a gypsum. Gypsum is produced by the reaction of carbonate fluorapatite with sulfuric acid. It cannot be marketed because it includes radium and other materials. This gypsum is stored on plant sites in huge piles, locally called "gypstacks".

Agrichemical plants serve as water-contamination sites in two ways. First, some of the phosphoric and sulfuric acid is lost as waste and is circulated to the gypstack for disposal of the solids by settling. Thus, acid may leach through the gypstack and water-circulation is usually restricted to a zone with a radius of 300 meters or less around the gypstack. Second, waste heat is dissipated through cooling ponds, which may also serve as sources of pollution. With central Florida's heavy, short-term precipitation during hurricanes, the coaling and gypstack ponds have to be carefully controlled to compensate for added rainfall. Otherwise, overflow and accidental contamination of nearby surface and ground waters is likely. The companies avoid these problems by construction of surge ponds and emergency systems that can introduce overflow into closed circulation systems within nearby mines. Present waste-water disposal practices include treatment, such as liming, and release to area waters; containment and reuse; and deep-well injection. Older surface-water impoundments are unlined, more recent ones are lined or under-drained. Recent state and federal laws require the plants to develop extensive ground-water monitoring plans, which are now being implemented.

The data in Table 2 for surface waters at chemical plants include coaling ponds and

gypstacks. These surface-water impoundments contain untreated or partly treated process water. Thus, a majority of samples fall above standards with respect to pH, sulfates, turbidity, and so on. Recent studies by the U.S. Geological Survey (Miller and Sutcliffe, 1982; 1984) and others have shown that gypstacks can cause localized ground-water contamination. Thus, agrichemical plants are more prone to ground-water contamination than are mines.

Interaquifer Transfer of Chemical Pollutants

Table 2 indicates that many of the constituents that have large numbers of samples that exceed MCL's are high because of natural aquifer chemistry, rather than a consequence of mining. For example, changes in iron, manganese, pH, TDS, and sulfate in ground water are usually a product of aquifer water-rock interactions and soil microbiological activity. Upchurch et al. (1988) have provided detailed chemical models to explain these aquifer-water interactions. While the data in Table 2 do not give the industry a "clean bill of health", they do clearly show that mining is not of itself a major cause of pollution. Mining, however, does not have the impact of moving natural waters that fail water-quality standards from one area to another. In some cases (e.g., interaquifer connector wells or "recharge wells") these waters are transferred into other hydrostratigraphic horizons where contamination may result.

Interaquifer connector wells, or recharge wells, are advantageous to the phosphate industry because they allow dewatering of surficial sediments and mitigate withdrawals from the Floridan aquifer system (Figure 2). Recharge wells operate by gravity (Figure 3). Surficial aquifer system water flows into the well through screens placed above the base of the aquifer so as to avoid contamination by lower-quality waters of the intermediate aquifer system located in the Peace River Formation. The water cascades downward to the Floridan aquifer system potentiometric surface. This drop may be as much as 30 meters, although it is usually much less. Flow in the recharge wells ranges from 0 to over 2,800 l/min. The recharging water is received by the Floridan aquifer system through karst conduits. The actual horizon that receives the recharging water varies. Most wells have open hole through the upper Floridan and much of the lower Floridan. In some wells there is no preferential receiving zone and flow enters the Floridan in many zones. In many wells there is a karst zone at the base of the

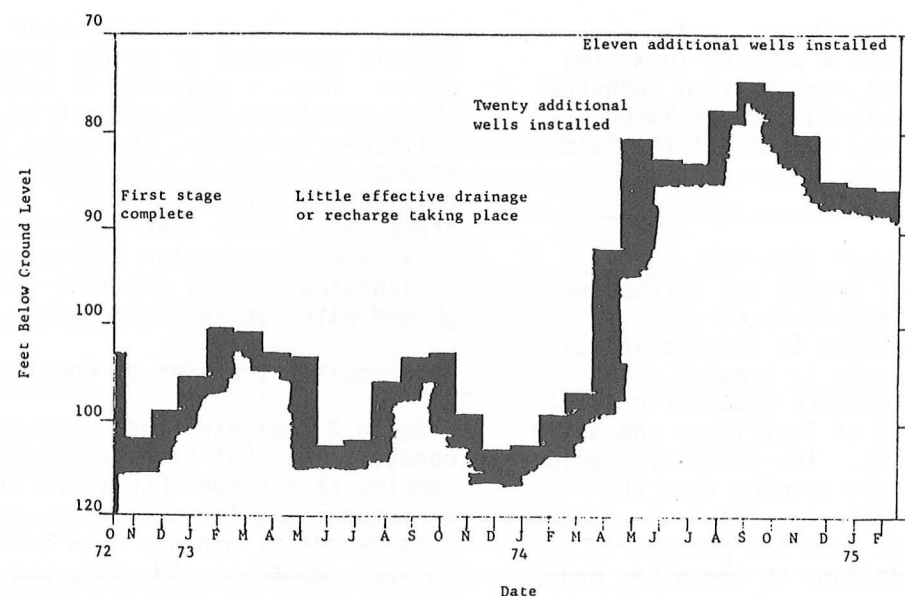


Figure 2. Increase in the Floridan aquifer potentiometric surface as a result of use of interaquifer connector (recharge) wells. From Cawley (1979).

Hawthorn Group which takes all of the flow.

Recharge wells have been the target of several studies. Upchurch et al. (1979 a,b) looked for evidence of contamination of the Floridan by recharge well operation at the Kingsford Mine. They found no evidence for contamination and, in fact, some evidence that naturally-high sulfate concentrations in the Floridan might be diluted by the recharged waters. Regional monitoring programs have not found evidence of contamination directly attributable to recharge well operation either. Direct monitoring of recharge wells has found evidence of radiological contamination and violations of turbidity and other minor constituents. Kimrey and Fayard (1984) examined samples from 12 recharge wells in the district for a diversity of pollutants, including trace metals and organics. They found that turbidity exceeded MCL in 9 wells, iron exceeded standards in 11 wells, and 6 wells exceeded the gross-alpha radioactivity standard. Otherwise, the wells were not found to contaminate the Floridan aquifer system.

There are two major problems with recharge wells. The first, screen plugging, deals with efficiency of operation, rather than potential ground-water contamination. Ferric oxyhydroxide and iron- and sulfur-

dependent microbial mats that form on the well screen are a chronic problem. Thus, the wells require maintenance to keep them operating. The second problem, radiation, is not so simple to resolve.

Upchurch et al. (1988) have characterized the chemistry of recharge wells. They also developed criteria for siting recharge wells to minimize radioactivity problems and developed chemical models for explaining mobilization of radium-226, lead-210, and polonium-210 in the aquifer environment.

A scenario of water-chemical changes in the vicinity of a recharge well can be constructed (Upchurch, et al., 1988). Prior to contact with the recharge well, surficial aquifer water system is reducing, acid, iron rich, low in radium activity and relatively high in gross-alpha activity. The gross-alpha activity is largely polonium-210 and short-lived radon daughters (Figure 4). Upon entering the well, the water falls to the potentiometric surface of the Floridan aquifer system. During the fall, minor oxidation and mixing occur. The pH and Eh increase, temperature changes, and mixing alters the bulk chemistry. In this environment ferric hydroxide precipitates and microbial populations flourish. Once the water enters the Floridan aquifer system, many of these reactions are

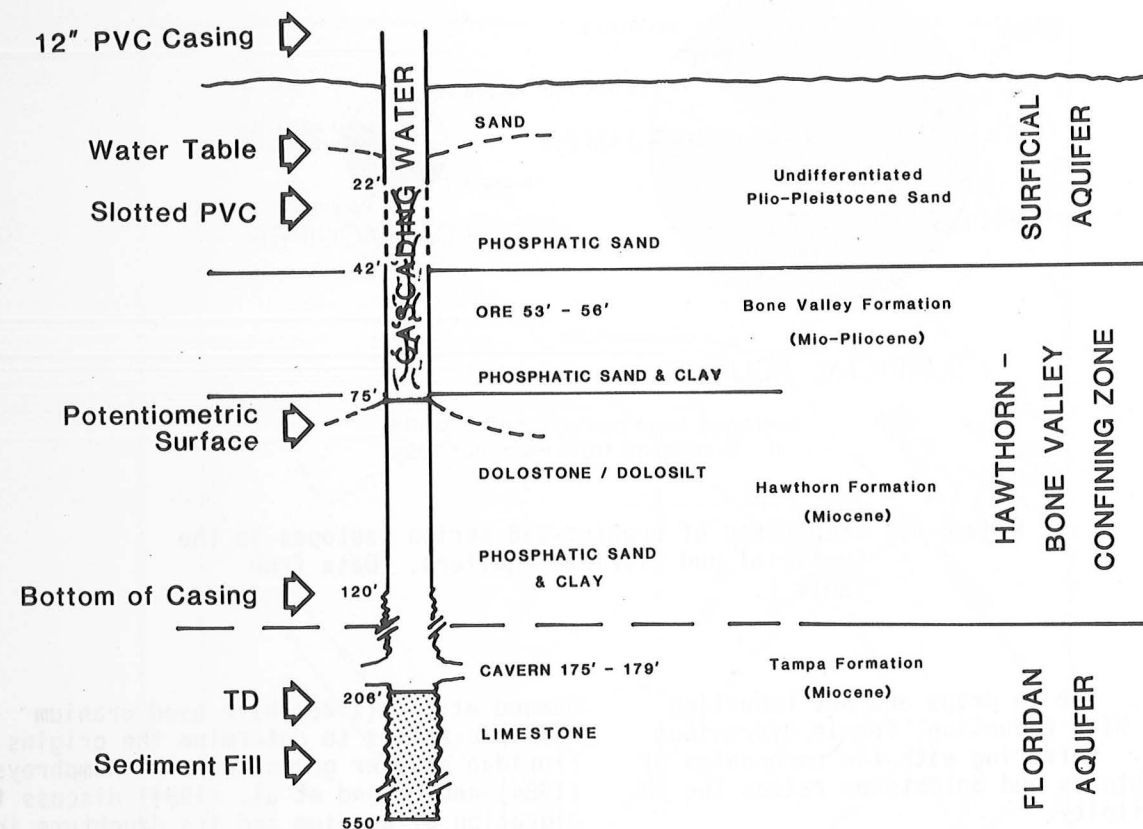


Figure 3. Diagram showing the design and hydrostratigraphy of a typical recharge well.

URANIUM-SERIES ACTIVITIES

Size of circle is proportional to total activity. Average activities in pCi/L.

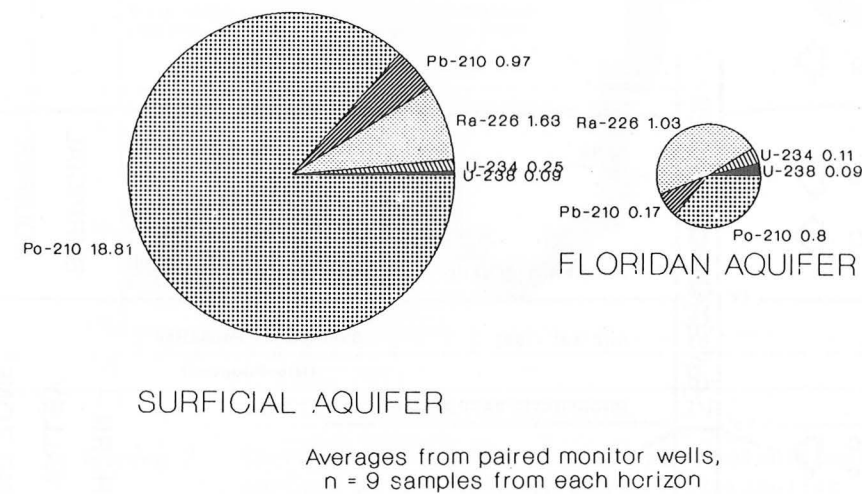


Figure 4. Comparison of uranium-238 series isotopes in the Surficial and Floridan aquifers. Data from Table 1.

reversed. The Eh drops and net reduction occurs. With reduction, ferric hydroxides dissolve. Buffering with the carbonates of the limestones and dolostones raises the pH and alkalinity.

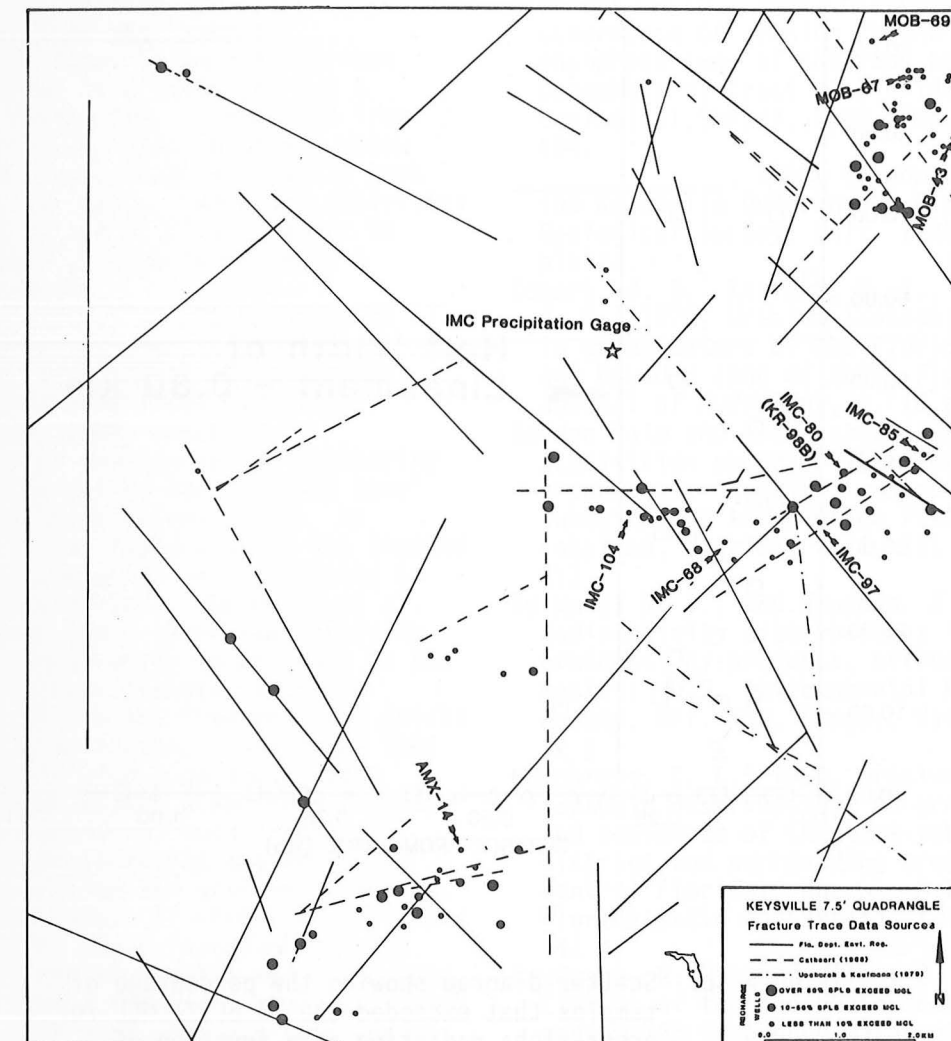
Radioactivity

Ground-water radiation is of greatest concern in recharge wells. Uranium-238, the progenitor of radium-226, radon-222, and polonium-210, constitutes 99.3% (by mass) of the uranium present in the phosphate district (Guimond and Windham, 1975). The remaining 0.7% is uranium-235. Thorium-232, the ancestor of radium-228, has an activity that is nearly two orders of magnitude less than that of uranium in the host rock. Thus, one can assume that, on the average, uranium-238 and its daughters constitute the primary sources of radiation in the District.

There have been several important studies that determined how uranium and its daughters behave in ground-water systems. Kaufmann and Bliss (1977) compared radium in ground water in coastal areas of Florida with the mining district. They concluded that high radium in coastal areas is not due to mining, but is natural. Osmond and Cowart (1977), Cowart et al. (1978) and

Osmond et al. (1983) have used uranium isotopic ratios to determine the origins of Floridan aquifer ground water. Humphreys (1984) and Osmond et al. (1984) discuss the migration of uranium and its daughters in the phosphate district, including recharge wells. Upchurch et al. (1981) studied the distribution of radium-226 in surface waters and biota in unmineralized, mineralized, mined, and reclaimed lands.

There have been several radiation studies that dealt with recharge wells in particular. Upchurch et al. (1979a) undertook one of the first studies that allows evaluation of the effects of recharge wells on ground-water chemistry. They studied water from the surface, surficial aquifer system, "Hawthorn-Bone Valley aquifer", and Floridan aquifer system at the International Minerals and Chemical Corporation's (IMCC) Kingsford Mine. They concluded that water in the recharge wells chemically reflects the surficial aquifer system and that radium-226 in the recharge wells was within standards. They found no indication of contamination of the Floridan aquifer system by radium-226 as a result of the recharge wells. In subsequent studies, Oural et al. (1986) and Upchurch et al. (1988) studied the distribution of gross-alpha radiation in recharge wells. They



LOCATIONS OF LINEAMENTS AND INTERAQUIFER CONNECTOR WELLS
- KEYSVILLE QUADRANGLE, FLORIDA

Figure 5a. Fracture-trace map of the Keysville Quadrangle showing locations of recharge wells and the precipitation gage at the New Wales chemical plant. Size of well-location dots reflects the percentage of the samples that exceeded the 15 pCi/l MCL for gross-alpha radiation. From Upchurch et al. (1988).

RELATIONSHIP OF WELLS EXCEEDING 15pCi/l GROSS ALPHA MCL TO LINEAMENTS

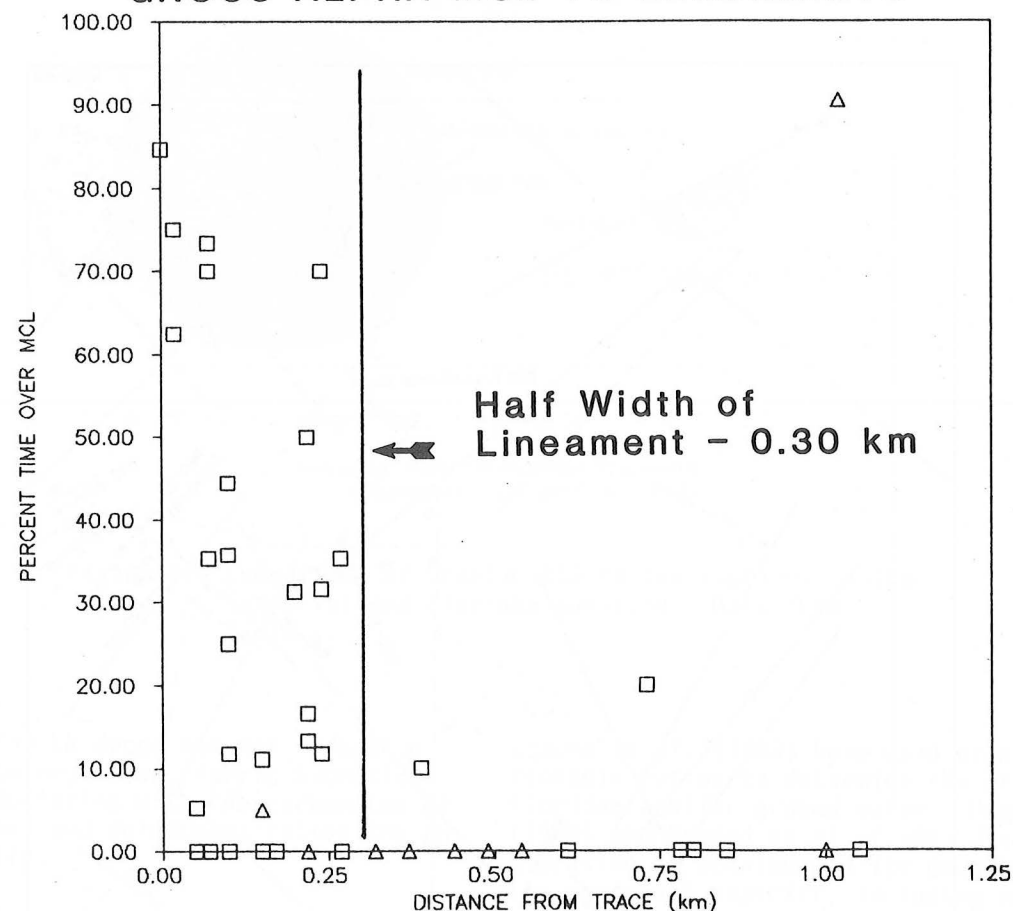


Figure 5b. Scatter diagram showing the percentage of samples that exceeded the 15 pCi/l MCL for gross-alpha radiation as a function of distance from the nearest fracture trace. From Upchurch et al. (1988).

found that polonium-210 is the major alpha-producing radionuclide in the surficial aquifer system and recharge wells (Figure 4) and that polonium is mobilized or fixed depending on the chemistry of the aquifer system. Polonium is mobilized in highly acid environments and fixed as radiocolloidal polonium-hydroxide complexes in near-neutral pH environments.

Polonium was found to be high because radon-222, which is a noble gas and a daughter of radium-226, is expelled from minerals and accumulates in ground water. Subsequently, radon daughters partly sorb onto mineral surfaces. Radon gas activities in excess of 20,000 pCi/l are common in Florida waters, so high polonium is a natural phenomenon.

One of the results of the Upchurch et al. (1988) study is an understanding that radioactivity problems in the phosphate district result from local hydrology. Cathcart (1956, 1963) described accumulations of uranium in the weathering mantle, locally called the "leached zone", at the top of the Hawthorn Group. He illustrated linear regions where the leached zone is thick and which he interpreted to coincide with fractures. Upchurch et al. (1988) compared gross-alpha radioactivity data from recharge wells to distance to the nearest photolinear feature, which is presumed to reflect the fractures and joints in the underlying strata. They found that all of the wells with high gross-alpha activities occur within 0.3 km of a fracture (Figure 5). Therefore, local recharge through alluvial sinkholes and fractures concentrates uranium and uranium daughters, in the leached zone. If chemical conditions are appropriate, these radionuclides are mobilized. If recharge wells are sited more than 0.3 km from a fracture, there is a high probability that they will not fail the water-quality standards for radioactivity. Upchurch et al. (1988) also determined that chemical conditions are such that iron, color, and radioactivity are reduced in the Floridan, so recharge-well use should be a viable water-management practice.

Because of adverse water-quality data, the Florida Department of Environmental Regulation was caused to order owners of cited wells to file for permits to operate those wells as Class V wells (Tschinkel, 1983), and most companies began to shut the wells down. Pressure to abandon the wells has recently decreased, and some of the companies are again applying for permits to install new wells from the local water management district (Southwest Florida Water Management District).

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