Southeastern Geological Society
Field Trip Guidebook No. 67

Central Florida Phosphate District

Third Edition

Photo provided by The Mosaic Company

July 30, 2016

Edited by Marc V. Hurst

Field Trip Committee

Clint Noble
Samantha Andrews
Tom Scott
Natalie Whitcomb
Pete Karashay
Harley Means

Central Florida Phosphate District Third Edition

Southeastern Geological Society Field Trip Guidebook No. 67

July 30, 2016
Edited by Marc V. Hurst

Field Trip Committee
Clint Noble
Samantha Andrews
Tom Scott
Natalie Whitcomb
Pete Karashay
Harley Means

ACKNOWLEDGEMENTS

Much of this guidebook was originally published in the Southeastern Geological Society (SEGS) Guidebook No. 57, dated August 11, 2012. It was revised, updated, and published for the 30th Florida SME and Dreyer Conference, dated October 6, 2015. It was updated again for this edition; and new articles were added.

CONTENTS

INTRODUCTION TO FLORIDA PHOSPHATE

Marc V. Hurst
Independent Geological Services, Inc.
4432 Burlington Drive
Winter Haven, FL 33880

Jon L. Courtney
6 Hunting Ridge Lane
Leicester, NC 28748

Glen Oswald
The Mosaic Company
13830 Circa Crossing Drive
Lithia, FL 33547

Chemical, Biological, and Ecological Background

The element phosphorus was discovered in 1669 by Henning Brand, a German merchant who extracted it from urine. Its name was derived from the Greek word "phosphoros," which means light bearing, an ancient name for the planet Venus when it appeared before sunrise, and a reference to the glow emitted by some forms of native phosphorus (due to reaction with oxygen). The most reactive forms of native phosphorus catch fire spontaneously in air (Hammond, 1992).

Phosphorus, a member of the pnictogen group of elements, is the eleventh most abundant element in the Earth's crust (Shirey, 2009). In nature it is never found in its native state. With almost no exceptions, phosphorus atoms are found grouped with four oxygen atoms to form tetrahedral anionic groups, $(PO_4)^{-3}$, known as orthophosphate, or more commonly referred to as phosphate. Phosphate ions combine with cations to form a very large variety of minerals and organic compounds. Although extremely uncommon in nature, minerals containing phosphorus in more reduced states have been identified in fulgurites (Pasek and Block, 2009).

Phosphate is an essential component of living organisms. Phosphate-containing biomolecules include the nucleotides and nucleotide derivatives that are the building blocks of genetic compounds like RNA and DNA; cellular signaling compounds like cGMP and cAMP; enzymatic cofactors like coenzyme A, FAD, FMN, and NADP; the nucleoside triphosphates like ATP and GTP that serve as metabolic sources of chemical energy; and the phospholipids that are the chemical basis of all cell membranes. Phosphate functions as an essential buffering agent for maintaining acid-base homeostasis in the human body. In addition, the structural members of bones, teeth of mammals, and the exoskeletons of insects consist primarily of phosphate compounds.

All plants and animals depend upon phosphate as an essential nutrient. The availability of phosphate and/or nitrogen is the dominant limit to growth in most natural ecological systems. Biological communities typically respond to any surplus of phosphate by increasing population until it is taken up; and then growth rates of the organisms are limited to the rate at which phosphate is recycled by decomposition of plant and animal matter. This process is known as the phosphorus cycle.

Modern farmers routinely use chemical fertilizers and animal feed ingredients, derived from mineral sources of phosphate, to augment organic sources of phosphate. This practice has increased yields of crops and livestock to levels that greatly exceed natural population growth rates. Most phosphate minerals are not easily dissolved in water by natural processes; consequently mineral phosphate deposits are not part of the phosphorus cycle described by ecologists.

Early Sources of Phosphate

Phosphate soil supplements were derived exclusively from organic sources before mineral deposits of phosphate began to be exploited in the mid 1800's. Early sources included bone ash, produced by calcining bone byproducts of the livestock slaughtering industry, and “night soil” (urine collected in farmers' bedpans). These sources are part of the ecological phosphorus cycle.

Guano is the feces and urine of sea birds, bats, and seals. Guano, collected primarily from isolated islands along the coast of Peru and Chile, became an important source of fertilizer in the early 1800's. Peru began exporting guano in 1840.

The history of guano-related politics accents the economic importance of the trade. In 1856, the United States passed the Guano Act, which entitled its citizens to take possession of unclaimed lands for the expressed purpose of collecting guano for use in the United States. Spain seized the Peru's guano-rich Chincha Islands in 1864. Chile seized control of much of the guano trade after the War of the Pacific (1879-1883).

The guano trade was greatly diminished by the late 1800's. By that time the supplies of some areas, like the Chincha Islands were already exhausted. Today guano is a very minor source of phosphate. In 2010, Chile exported about 2,000 metric tons of guano (Janiski, 2011).

Mineral Deposits of Phosphate

In the late 1800's, as demand for fertilizer accelerated, mineral deposits of phosphate were developed. A major phosphate industry developed in Florida. By 1893, production had expanded to 1.25 million tons. Florida became the world's leading producer of phosphate. As world-wide demand for phosphate increased, mines were developed in other states and nations; but Florida was the world's leading producer for well over a century.

The United States was the world's leading producer of phosphate until 2006 (Janiski, 2009). China, the United States, and Morocco were the world's leading producers of phosphate in 2011, when total production reached 191 million tons (Gurr, 2012). About 28.4 million tons were produced in Florida, North Carolina, Idaho, and Utah in that year (USGS 2012 Commodity Summary). Mines in Florida and North Carolina were responsible for about 85% of the United States' production.

Phosphate mines are operated, or are under development, in Algeria, Angola, Australia, Brazil, Canada, China, Egypt, Israel, Kazakhstan, Mali, Mauritania, Morocco, Mozambique, Namibia, Peru, Russia, Saudi Arabia, Senegal, South Africa, Syria, Tunisia, Togo, Uganda, Zambia (Janiski, 2011).

Central Florida Phosphate District and the Southern Extension

Economically important deposits of phosphate occur in several regions of Florida, shown in Figure 1 (modified after Scott, 1989). Currently, phosphate is produced from the Northern, Central, and Southern Extension Districts.

The Central Florida Phosphate District occupies parts of the Lakeland Ridge and Polk Upland geomorphic provinces. In the last few years, as high-grade reserves have been exhausted, mining has progressed southward into the Southern Extension, located along the southern edge of the Polk Upland and adjoining parts of the DeSoto Plain geomorphic provinces. Figure 2 shows the locations of the major modern mines in the region.

Relatively small concentrations (2-10%) of silt to sand-sized phosphate pellets were deposited in shallow water environments over much of the Florida Plateau, in a broad range of carbonate and clastic sediments of the Hawthorn Group. Phosphate was particularly concentrated in several basins, including the area occupied by the Central Florida Phosphate District (identified as the Land-Pebble Phosphate District in older literature) and its Southern Extension. After the Middle Miocene seas withdrew from much of the area, deposition of the phosphate-rich Peace River Formation continued in the Southern Extension.

A phosphate-rich residuum, consisting of the least soluble mineral constituents (phosphate pellets, quartz sand, and clay), developed in the exposed areas as carbonate components were preferentially dissolved (Cathcart, 1989). Solution-related depressions in the ancient landscape collected the greatest accumulations. Weathered surfaces underlie some parts of the Bone Valley Member.

The Bone Valley Member of the Peace River Formation consists of cross-bedded and graded beds of phosphate-rich, pebbly and clayey sands that were deposited when seas transgressed the area again, and reworked the weathered residuum. The relatively-dense and physically-strong grains of phosphate preferentially survived the process of erosion and redeposition, while the more fine-grained and less durable materials were winnowed away. Chemical migration of phosphate ions further enriched the deposit and phosphatized underlying carbonates. The paleography of the Central Florida Phosphate district at the time of deposition of the Bone Valley Member consisted of a wide, south-facing, marine embayment, or estuary, or both. Deposition occurred in a shallow-water, near-shore and/or restricted basin environment where a complex variety of physical and chemical processes produced unusually high-grade ores of phosphate.

Following the deposition of the Bone Valley Member, the area was subjected to a period of intense lateritic weathering. Aluminum phosphate zones were formed at the land surface as

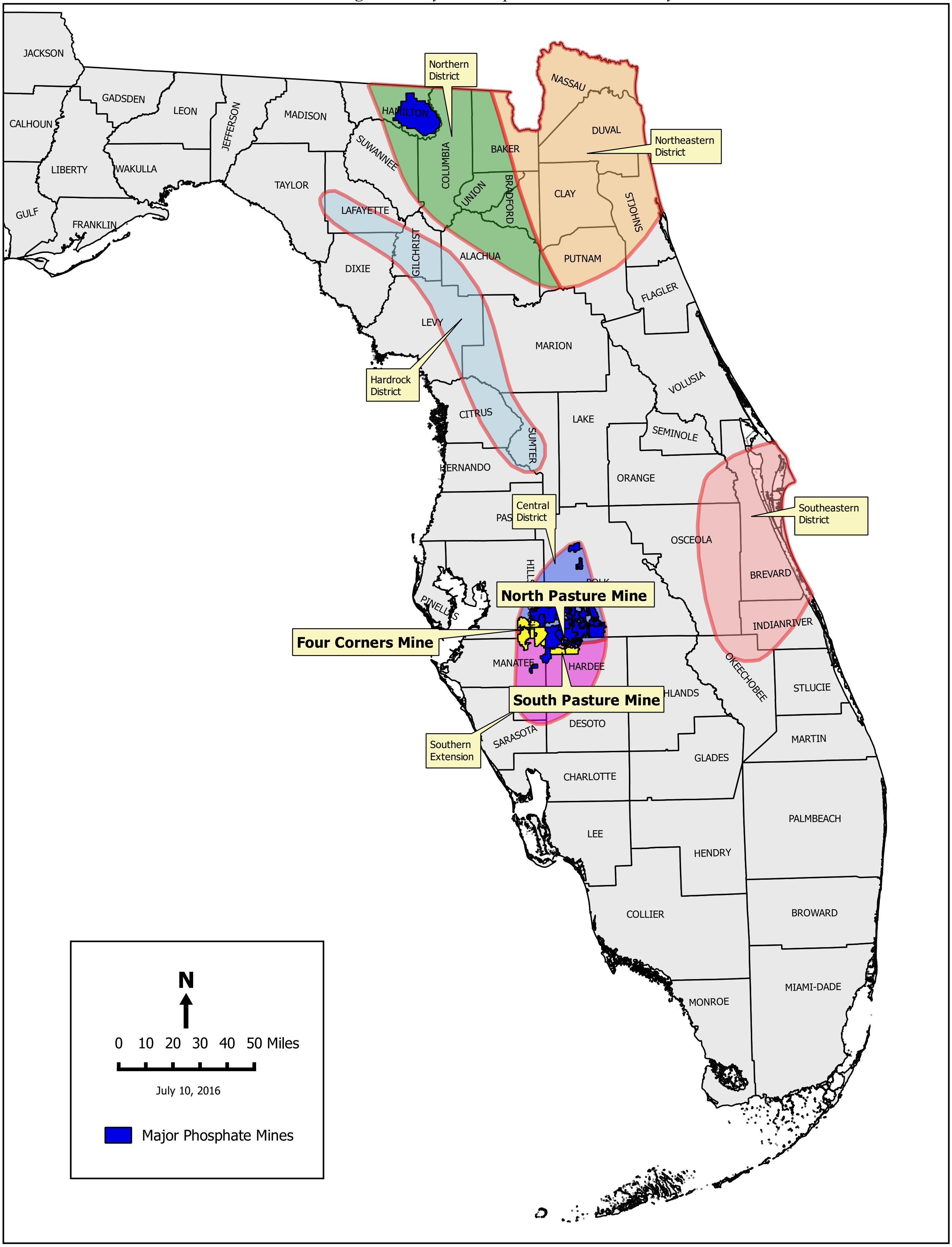


Figure 1. Florida's Phosphate Districts
(Modified after Scott, 1989)

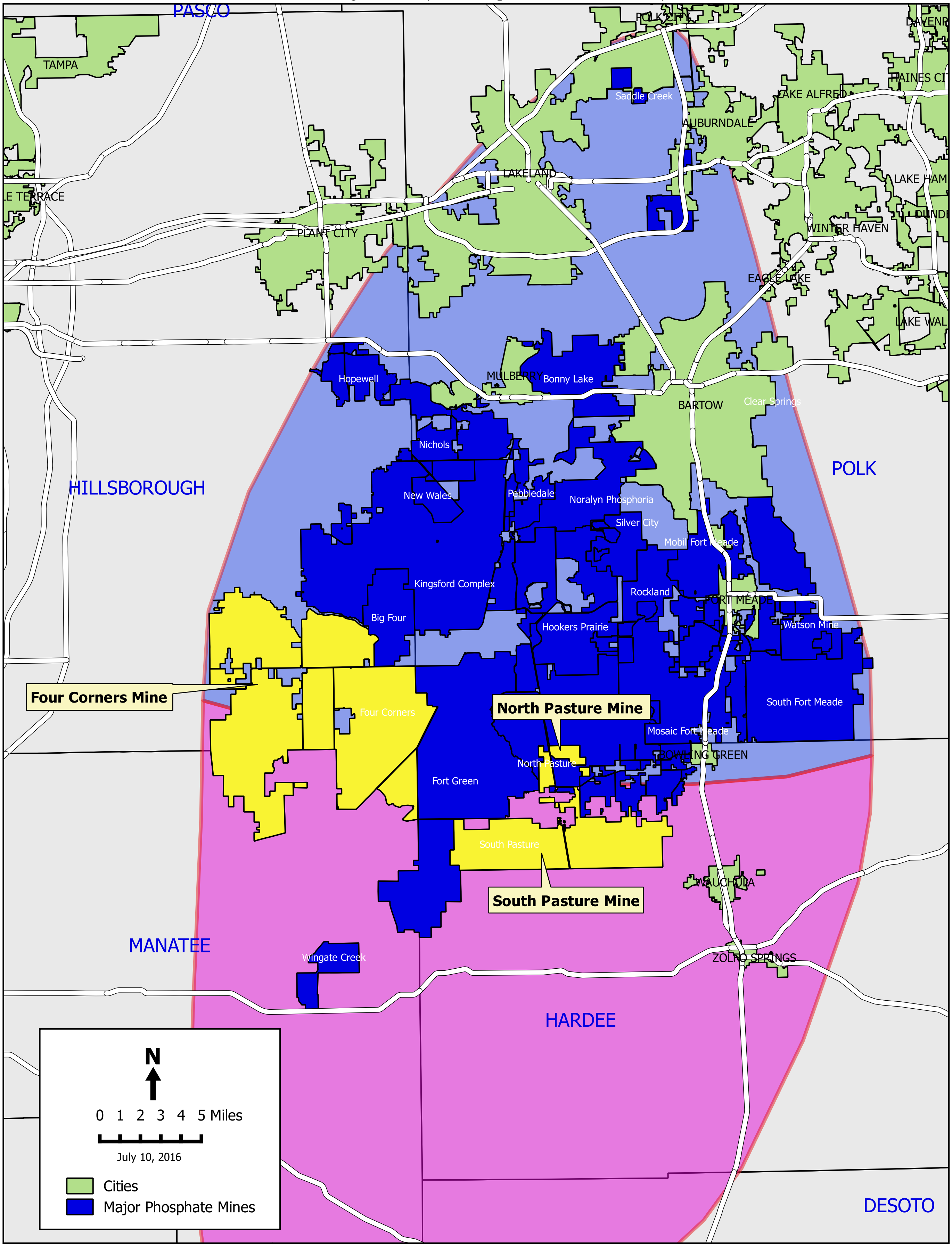


Figure 2. Mines of the Central Florida Phosphate District and Southern Extension

dissolved phosphate ions migrated downward where they further enriched deeper parts of the deposits and precipitated phosphate on underlying carbonate rocks (Cathcart, 1989).

Ketner and McGreevy (1959) identified a general sequence of lithology in Central Florida consisting, from top to bottom, of (1) quartz sand, (2) clayey quartz sand, (3) clayey quartzose phosphorite, and (4) quartzose and clayey phosphatic limestone (or dolomite). They suggested that the sequence may be the expression of a single weathering profile developed continuously or discontinuously over the region.

The phosphate deposits of the Southern Extension and the Central Florida Phosphate District are down-dip and up-dip segments of the same basin, respectively. Both districts were subjected to the same history of climatic and sealevel changes; however, a relatively small difference in base elevation resulted in significantly different depositional and geochemical responses. During the time prior to deposition of the Bone Valley Member, when the up-dip parts of the basin were sub-aerially exposed, it does not appear that the seas receded completely from the more down-dip areas where phosphate-rich sediments of the Peace River Formation continued to be deposited in the Southern Extension. While the Bone Valley Member was deposited in up-dip, submarine reworking processes were generally less active down-dip in the Southern Extension. After deposition of the Bone Valley Member, the episode of intense weathering that formed the aluminum phosphate zones in the up-dip areas does not appear to have affected the deposits of the Southern Extension nearly as extensively, possibly because they were more protected by greater thicknesses of clastic cover. Consequently, the phosphate deposits of the Southern Extension contain lower grades of phosphate and larger concentrations of carbonate impurities (Fountain, Hurst, and Brown, 1993).

Mosaic's Four Corners Mine is located near the transitional boundary with the Southern Extension; however, outliers of the Bone Valley Member found there are more characteristic of the Central Florida Phosphate District.

Matrix Lithology and Mineralogy

In Central Florida, miners refer to the phosphate-rich economic zone as “matrix.” Worthless layers of sand and clay that cover the matrix are called “overburden.” At the Four Corners Mine, about 15 to 64 feet of overburden overlie a layer of matrix ranging from about 3 to 25 feet thick.

Matrix is not confined to any specific stratigraphic unit. It is defined entirely on the basis of phosphate recovery economics, which may vary from location to location, depending upon a variety of considerations. Generally the matrix consists of select portions of the Peace River Formation, which might include parts of the Bone Valley Member. Iron, aluminum, and magnesium are avoided to the greatest possible extent because they interfere with the chemical processing of the phosphate rock. The upper parts of the Bone Valley Member might be excluded from mining due to the presence of aluminum phosphate zones, sometimes called “Leached Zones,” which typically contain excessive iron and aluminum content. Currently, the Arcadia Formation is excluded from mining due to excessive magnesium(dolomite) content.

Prospecting typically is conducted by drilling core holes on 330' centers, which results in 16 holes per forty acres, or 256 holes per square mile (Section) of land.

The lithology of the matrix varies greatly over very short vertical and horizontal distances. Abrupt transitions between almost random distributions of individual beds consisting of well-sorted gravel, sand, silt, or clay, or more poorly sorted mixtures of various grainsizes, are common.

Mineable matrix consists primarily of francolite, a carbonate-rich variety of fluorapatite, montmorillonite, attapulgite, quartz, and chert. Bernard Murowchick and Tony Gricius, long-time IMC (now Mosaic) mineralogists, identified a great variety of minerals in their lifetime study of phosphate mines. Table 1 is a list, compiled by Tony Gricius, of minerals identified by IMC in Central Florida phosphate mines, omitting clay minerals and heavy minerals. Table 2 contains lists of clay minerals and detrital heavy minerals identified by Bernard Murowchick.

Sequence of Operations

Figure 3 is a schematic representation of the complete sequence of operations required to extract phosphate, from mining to reclamation. A wide range of skill and expertise must be brought together and coordinated for successful execution of an economical, safe, and environmentally-responsible phosphate extraction operation.

Geologists identify reserves and direct day-by-day quality control at the pit. Mine planners direct the mining sequence for optimum efficiency. Hydrogeologists plan and direct dewatering. Mineralogists solve complex beneficiation problems. Process engineers design beneficiation systems. Structural engineers and civil engineers design and build plants and impoundments. Geotechnical engineers insure that foundations are prepared. Metallurgists and chemical engineers design and maintain the chemical processes. Chemists and lab technicians analyze the

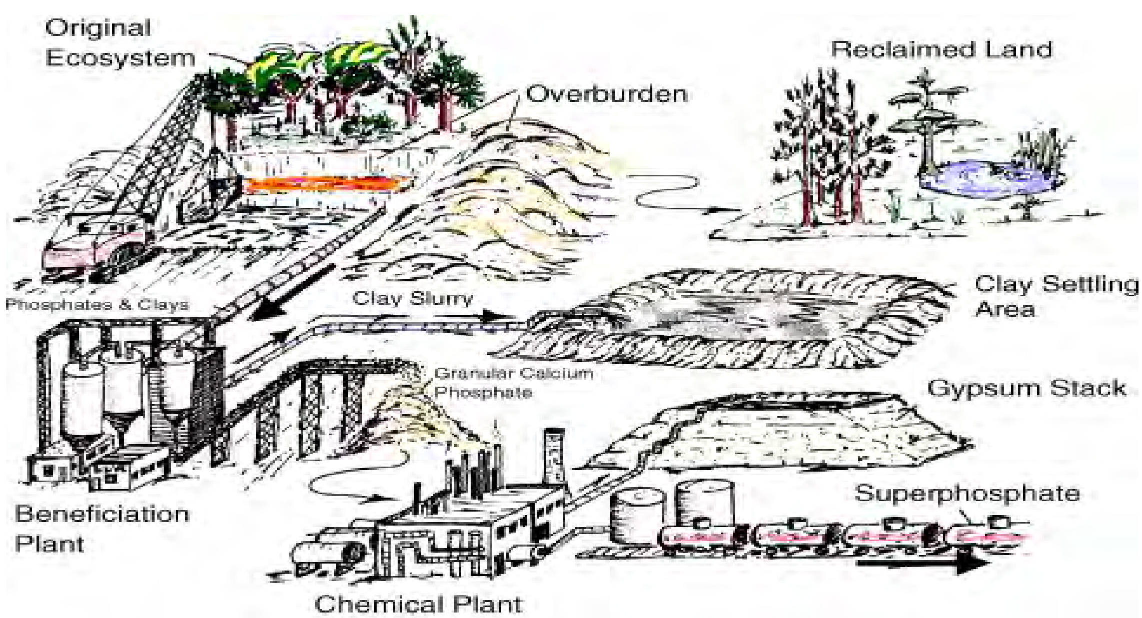


Figure 3. The typical sequence of operations in a phosphate extraction operation

	[Mine]									
	Clear Springs		Noralyn		Phosphoria		Kingsford		CF Garwood	
Mineral	**X**	**P**	**X**	**P**	**X**	**P**	**X**	**P**	**X**	**P**
Sulfides										
Marcasite	X	P								
Pyrite	X	P								
Oxides										
Hematite	X									
Gibbsite	X									
Goethite	X		X		X	P				P
Wad		P		P						
Sulfates										
Gypsum	X	P								
Jarosite	X		X							
Whewellite	X									
Phosphates										
Autunite				P						
Barbosalite										
Beraunite	X	P	X	P	X					
Cacoxenite	X	P	X	P						
Crandallite	X	P	X		X					
Cyrilovite	X									
Dufrenite										
Lipscombite			X							
Meta-autunite										
Metavivianite	X									
Millisite	X		X							
Mitridatite	X	P	X	P						
Phosphosiderite	X									
Rockbridgeite	X	P	X	P	X					P
Strengite	X	P	X							
Strunzite-ferrostrunzite	X?	P				P?				P
Variscite	X		X	P						
Vivianite	X	P								P
Wavellite	X	P	X	P			X	P		
Francolite	X	P		P	X					
Silicates										
Chalcedony	X	P								
Chert	X									
Opal-CT	X									
Opal-A	X									
Quartz	X	P						P		
Carbonates										
Calcite		P								
Dolomite	X	P				P				
Siderite	X	P								

Table 1. Tony Gricius' Central Florida Phosphate Mine Mineral List

NOTES: 1. Tabulated by Sam Upchurch from Tony Gricius' August 4, 2007 compilation.
2. X's indicate minerals found in IMC X-ray diffraction data.
3. P's mean Tony identified a photo in Dan Behnke's slides.
4. Clay minerals and heavy minerals were not compiled.

<u>Clay Minerals</u>

Attapulgite (Palygorskite)
Illite
Kaolinite
Montmorillonite
Sepiolite

<u>Detrital Heavy Minerals</u>

Andalusite
Biotite
Corundum
Epidote
Feldspar
Garnet
Hornblende
Ilmenite
Kyanite
Monazite
Muscovite
Rutile
Sillimamite
Spinel
Staurolite
Titanite
Topaz
Tourmaline
Xenotime
Zircon

Table 2. Clay Minerals and Detrital Heavy Minerals Identified in Phosphate Matrix
Identified by Bernard Murochick
From Mosaic's IMC Archives

myriads of samples that the geologists and chemical engineers collect on an ongoing basis. Mechanics fabricate the machinery and keep it running. Electricians run power to it. Miners, equipment operators, and plant workers haul the equipment around, set it up, and operate it around the clock. Salesmen find buyers for the products. Truckers and railroad crews haul the raw materials to the plants and haul the products out to customers. Environmental engineers, wildlife biologists, fisheries experts, and botanists direct reclamation. Accountants manage the finances. And a cadre of managers and middlemen direct the actions of all of the above.

Mining

Phosphate matrix is extracted from open pit excavations. Mixing of overburden with matrix materials must be minimized during mining to avoid contamination of the matrix. It is less costly to mine carefully and avoid matrix contamination than to separate the contaminants later at a beneficiation plant.

The top of matrix generally is deeper than the watertable. Phosphate is mined underwater with a dredge at Mosaic's Wingate Mine, where matrix strata are relatively continuous; however, dredging is not well suited for mining the discontinuous matrix zones that are more typical of the district. Most mining is conducted in dewatered open pits. Figure 4 is a photo of a typical dewatered excavation at a phosphate mine in Central Florida. Note the pump in the foreground. Without constant pumping all of the material exposed the 60-foot deep pit would be under water.

Figure 4. A typical dewatered open-pit phosphate mine in Central Florida.

Draglines, like the one pictured in Figure 4 are used to excavate overburden and matrix. The dragline strips overburden from a relatively small area that is within its reach and casts (dumps) the overburden into an adjacent mined out area along the previous cut line. Then the matrix is carefully dug out and dumped into a small pit-like staging area called a "slurry pit," where water jets disaggregate the matrix. When mining is complete, the dragline is moved backwards a short distance, and the mining sequence begins on the next segment along the line. Mining typically progresses along a straight line until some boundary, like a property line, is encountered. Then mining progresses in the opposite direction along the next parallel cut line, exactly as one might mow a lawn. Figure 5 looks out from the dragline into a long mine cut. The left side of the cut has not been mined (note the overburden/matrix contact). Overburden that was excavated from the current cut (center of photo) was piled to the right filling the previous mine cut. Figure 6 shows overburden being cast into the adjacent mined out cut.

Figure 5. View from dragline into mine cut.

Figure 6. Overburden is cast into a previously mined area.

Figures 7 shows matrix being placed into a slurry pit, where water jets, shown in Figure 8 are used to disaggregate and slurry it with water. The resulting slurry of matrix material and water is pumped through a pipeline to a washer plant for beneficiation.

Figure 7. Matrix is placed in a slurry pit.

Figure 8. Water jets disaggregate the matrix and produce a slurry that is sucked into the large pipe (right center) and pumped by pipeline to a beneficiation plant.

Beneficiation

Beneficiation is the process of separating ores into valuable components and waste. Phosphate beneficiation has evolved from a very simple process of washing mud from pebbles, to a more complex process that involves separating the ore into several size fractions, each of which is processed by custom-tailored methods.

The Florida phosphate ore consists of three mineral types, and each of these minerals has unique properties that can be used to facilitate separation. These physical properties are as follows:

- When the ore is removed from the ground, it is a mass of phosphate and sand particles agglomerated in a matrix of clay. Once this mass is disaggregated, it is observed that each particle consists of a single mineral. There are no locked multi-mineral particles as is common in ore bodies outside of Florida. Crushing and grinding is not necessary to "liberate" the ore, which leads to lower beneficiation costs than in other parts of the world.

- The phosphate minerals range in size from one micron to ~20 mm.

- The sand particles range in size from one micron to one mm.

- The clay particles (after disaggregation) are all smaller than 0.1 mm, averaging 10 microns in size.

Armed with this knowledge, the initial sequence of processing should be obvious; make a salable phosphate product by screening the ore at 16 mesh (1.0 mm). This processing is performed at the "washer"; the first step in beneficiation. The washer serves two purposes.

- First it must completely disaggregate the clay matrix; there should be no mud-consolidated particles remaining after scrubbing the ore. This scrubbing begins in the long pipelines transporting ore from the mine site to the beneficiation plant. High shear forces from the large centrifugal pumps and friction along the pipeline result in the clayballs breaking apart. Disaggregation is completed at the plant in the log washers.

- Second, the washer must screen at 16 mesh (1.0 mm) to produce a final product called "pebble". This sizing takes place in a series of trommels, and vibrating screens.

Trommels, shown in Figure 9, remove grossly oversized materials. Log washers, shown in Figure 10, mechanically disaggregate concretions and mudballs. Vibrating screens shown in Figure 11, separate at 16 mesh (1.0 mm). The -16 mesh material passes from the washer to the next phase of processing.

Figure 12 shows conveyors stockpiling phosphate rock after leaving the washer.

Figure 9. Trommels remove oversized material.

Figure 10. Log washers disaggregate mud balls.

Figure 11. Static and Vibrating screens separate pebble.

Figure 12. Conveyors stockpiling washed rock.

After washing, a 150 mesh (0.1 mm) separation is made using hydrocyclones (Figure 13) to remove the clay minerals. Unfortunately, some fine phosphate is rejected in this step because there is not currently an economical process to recover this material. The rejected fines are deposited in large retention ponds. The nature of these clay fines are such that they require many years to consolidate to their ultimate %solids. Much work has been performed trying to improve the clay consolidation process, but few innovations have made it to the field, mostly for economic reasons (large capital or operating costs).

Once the clays and pebble phosphate are removed, the remaining sand and phosphate particles must be separated from each other. This size fraction is called "feed" (16 mesh X 150 mesh). This is where the beneficiation process gets more costly and complex. The local industry uses a common mineral beneficiation process called "flotation" to separate these two minerals.

Flotation is a process developed well over a century ago, but was not adapted for phosphate-sand separation until 1926. The first Florida flotation plants appeared in the late 1920's, and revolutionized the business. Previously, only the +16 mesh pebble could be produced; after this innovation companies were able to double production by recovering 16 mesh X 150 mesh phosphate as well. The process is based upon the property that certain hydrocarbons tend to selectively coat the phosphate mineral, but not the sand. When properly applied, a hydrocarbon coating on the phosphate will result in the creation of a hydrophobic (water hating) surface. When this surface is exposed to water, it repels the water the same way a freshly waxed car will repel rain. Water "beads" and rolls off any waxed surface.

Figure 13. A hydrocyclone making a 150 mesh separation to remove clay minerals.

The chemical principal applied in the flotation process is that non-polar (hydrocarbon coated) surfaces will repel polar substances such as water, and will be attracted to other non-polar substances such as air (Oxygen and Nitrogen). Once a non-polar coating is placed on the phosphate particles, it and the uncoated sand are immersed in a series of water filled tanks. Fine air bubbles are injected into the tanks (called flotation cells – picture in Figure 15) which attract the coated phosphate particles. The bubbles rise due to buoyancy and carry the phosphate up to the surface leaving the sand behind. That phosphate froth is skimmed off the top of the flot cell while the sand exits out a "tailing port" at the bottom of the flotation cell.

In the early days of phosphate flotation, feed grades were almost always higher than 45 BPL. It was simple to produce an acceptable grade phosphate flot product from feed this rich. Over the years, the high grade ore was mined out. It became difficult to meet the needs of the chemical plants as the flotation feed had decreasing quantities of phosphate. Mr. Crago (the general manager of Brewster Phosphates) had his metallurgists develop a new process to address this problem. In the process named after Mr. Crago, the initial phosphate concentrate (now called "rougher" concentrate) is stripped of its hydrocarbon coating using Sulfuric acid, and then rinsed clean. The rinsed material is subjected to a second "cleaner" flotation process to remove sand.

The cleaner flot process required development of a completely new coating agent which would be selectively attracted to the sand mineral. The engineers tested many potential chemicals, but found a certain kind of amine-based reagent was best suited for this task. Under the right conditions, the amine reagent will coat sand, but not phosphate. Once the sand is coated, the (deoiled and rinsed) rougher concentrate can be subjected to the same flotation processing as the original rougher flotation feed. This time, sand rises into the froth phase and is removed. Phosphate, of high enough quality to meet the grade requirements of chemical plant customers, exits from the tailing port.

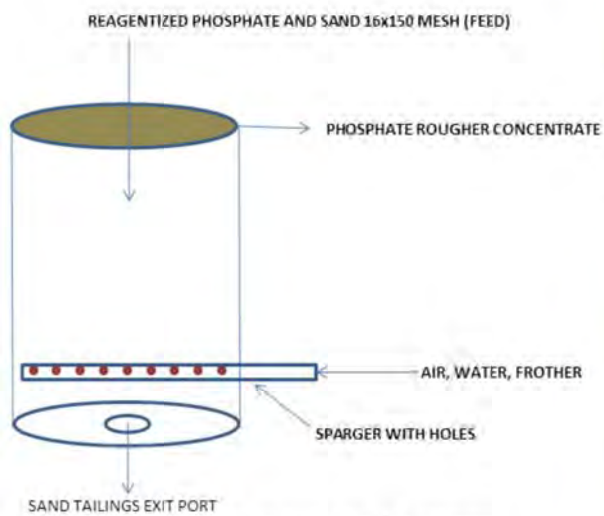


Figure 14. A schematic of a flot column.


Figure 15. A flot column in operation.

Clay Settling Ponds

Waste clays are pumped out to large impoundments, called "clay settling ponds," for disposal. Many clay settling ponds are hundreds of acres in size, with depths on the order of tens of feet. An example is shown in Figure 16. As clay-rich solids settle slowly out of suspension, clear water is decanted from the impoundments. It may take decades for some fully-filled clay settling ponds to dewater and solidify sufficiently for vehicles to drive safely across their surfaces. Experimental methods to accelerate the solidification process, including processes to pre-thicken the waste clays before discharge, have been explored, with varying degrees of success.

Solidified clay settling areas, like the one pictured in Figure 17, have been used very successfully for agriculture. The phosphatic clays are very rich in nutrients.


Figure 16. An active clay settling pond


Figure 17. Crops growing on solidified waste clays

Waste clays contain significant phosphate values, in the form of microscopically-small grains that are very difficult to extract. Although -150 mesh phosphate is currently regarded as waste, the older clay settling basins could become phosphate ore bodies of the future if beneficiation technology and economics evolve.

Reclamation

In the early days of phosphate mining, Central Florida was almost uninhabited. Land was considered to be an infinite resource with very little value other than the phosphate that it contained. Land was simply abandoned after it was mined, with no reclamation, as shown in Figure 18.

Legislation was passed in Florida requiring reclamation of phosphate lands mined after 1975, referred to as “mandatory reclamation.” The State began collecting an excise tax on the sale of phosphate rock, to finance a “non-mandatory reclamation” program for reclaiming areas that were mined before 1975. Since then the phosphate industry has become a world leader in the relatively new science of mine reclamation.

Of the 190,256 acres that were mined in Florida from July 1, 1975 through December 31, 2010, about 70% has been reclaimed (FDEP, 2011). An example is shown in Figure 19. The remainder is still used for mine-related activities.

Figure 18. Before 1975 very little reclamation was completed.

Figure 19. About 70% of the land mined since 1975 has been reclaimed.

Early Chemical Fertilizers

The first chemical fertilizers were introduced in the 1840's, when it was discovered that ground bones could be treated with sulfuric acid to produce a readily soluble fertilizer. Soon it was discovered that the same process could be applied to phosphate rock.

Treatment of phosphate (from organic or mineral sources) with sulfuric acid is an exothermic reaction that produces a somewhat plastic material consisting of a mixture of monocalcium phosphate and gypsum. After cooling and drying for several weeks, it hardens enough to be crushed into granules. The resulting product is called single superphosphate, also known as ordinary superphosphate or normal superphosphate.

Single superphosphate is easily manufactured on a small-scale; and it has the advantage that gypsum produced in the chemical reaction is incorporated directly into the product (IPNI).

Chemical Plants

The current practice of large-scale production of more concentrated forms of fertilizers at more centralized facitities was begun in the 1950's. Phosphate rock, beneficiated at washer plants associated with and located near the mines, is transported to separate chemical plant facilities where it is converted into phosphoric acid, which in turn is processed to make a variety of products.

Florida was the world's largest exporter of phosphate rock for several decades. Phosphate rock was shipped to chemical plants all over the world. However, the United States producers have not reported any exports of phosphate rock since 2004. The phosphate industry has become vertically integrated. Producers in the United States prefer to process the rock they mine (as well as additional imported rock) in their own chemical plants and export higher valued chemical products.

At chemical plants, phosphoric acid and byproduct gypsum are produced by reacting phosphate rock (fluorapatite) with sulfuric acid. Gypsum is formed as a fine-grained precipitate that must be filtered from the phosphoric acid product. Most of Florida's chemical plants produce sulfuric acid on site, from native sulfur that they import through the Port of Tampa.

Great amounts of byproduct heat are produced in the process. In the past, Florida's phosphate chemical plants were large consumers of energy. As fuel prices have risen, virtually all of the facilities have installed cogeneration facilities to generate electricity from waste heat. Now they produce more electricity than they need; and sell the excess power.

Large volumes of water are used in the production of phosphoric acid. An effluent, consisting of water with a very low pH and very high concentrations of dissolved solids, results from reaction of phosphate rock with sulfuric acid. The reaction is exothermic; so the the resulting effluent is very hot. The effluent can be reused; but it must be cooled. Typical Central Florida chemical plants circulate effluent through series of ponds and ditches to cool it by evaporation.

About seven cubic yards of byproduct gypsum are produced for every cubic yard of phosphate rock that is processed. After it is filtered out of the phosphoric acid product, it is mixed with the wastewater effluent and pumped in slurry form to the cooling ponds, where mounds of disposed gypsum, called gypsum stacks, accumulate.

Gypsum stack and cooling ponds typically begin as large shallow ponds that may cover hundreds of acres. In the old days, they were usually built in unreclaimed excavations leftover from old phosphate mines. More recent gypsum stacks and cooling ponds are constructed with underliners and carefully designed lechate collection systems to prevent contamination of groundwater.

The effluent follows a long and tortuous path through the cooling water ponds to allow sufficient time for the gypsum to settle out, and for the effluent to evaporate and cool. Cool gypsum-free effluent is drained back to the plant and reused. Excavation equipment, usually small draglines, work around the perimeter of the pond on an ongoing basis. As the pond fills, gypsum, scooped out from the edges of the pond, is used to build up the dike around the perimeter of the pond. The dike's elevation is carefully built up, as needed, to maintain an elevation just high enough to contain the effluent inside. In this way a shallow gypsum settling pond is maintained on top of a gypsum stack as it fills with gypsum and grows vertically. Slope stability criteria, determined from detailed geotechnical studies and engineering considerations, dictate the maximum safe height to which a gypsum stack can grow, which in some cases approaches 200 feet above the adjoining topography. Figure 20 is an aerial photo of a phosphate chemical plant and its associated gypsum stack and cooling water ponds. Note that the chemical plant is dwarfed by its gypsum stacks and cooling ponds. Figure 21 is a side view of a similar gypsum stack.

Figure 20. Aerial Photo of a chemical plant and its associated gypsum stacks and cooling water ponds.

Figure 21. Oblique view of a gypsum stack and cooling water ponds.

Twenty-two gypsum stacks have been built at 14 chemical plants in, and adjacent to, the Central Florida Phosphate District. Their locations are shown in Figure 22.

Most chemical plants import anhydrous ammonia and combine it with phosphoric acid to make various fertilizers and animal feed ingredients. Some phosphate chemical plants have been equipped with uranium extraction circuits to recover uranium as a byproduct.

Uses of Phosphate

About 95% of worldwide phosphate production is consumed for production of fertilizers and animal feed ingredients. Major fertilizer products include diammonium phosphate (DAP), mono ammonium phosphate (MAP), and triple super phosphate (TSP). Phosphate also is used in production of insecticides, soft drinks, vitamins, pharmaceuticals, flame retardants, and glass. The United States is the world's leading producer of processed phosphate products (Gurr, 2012).

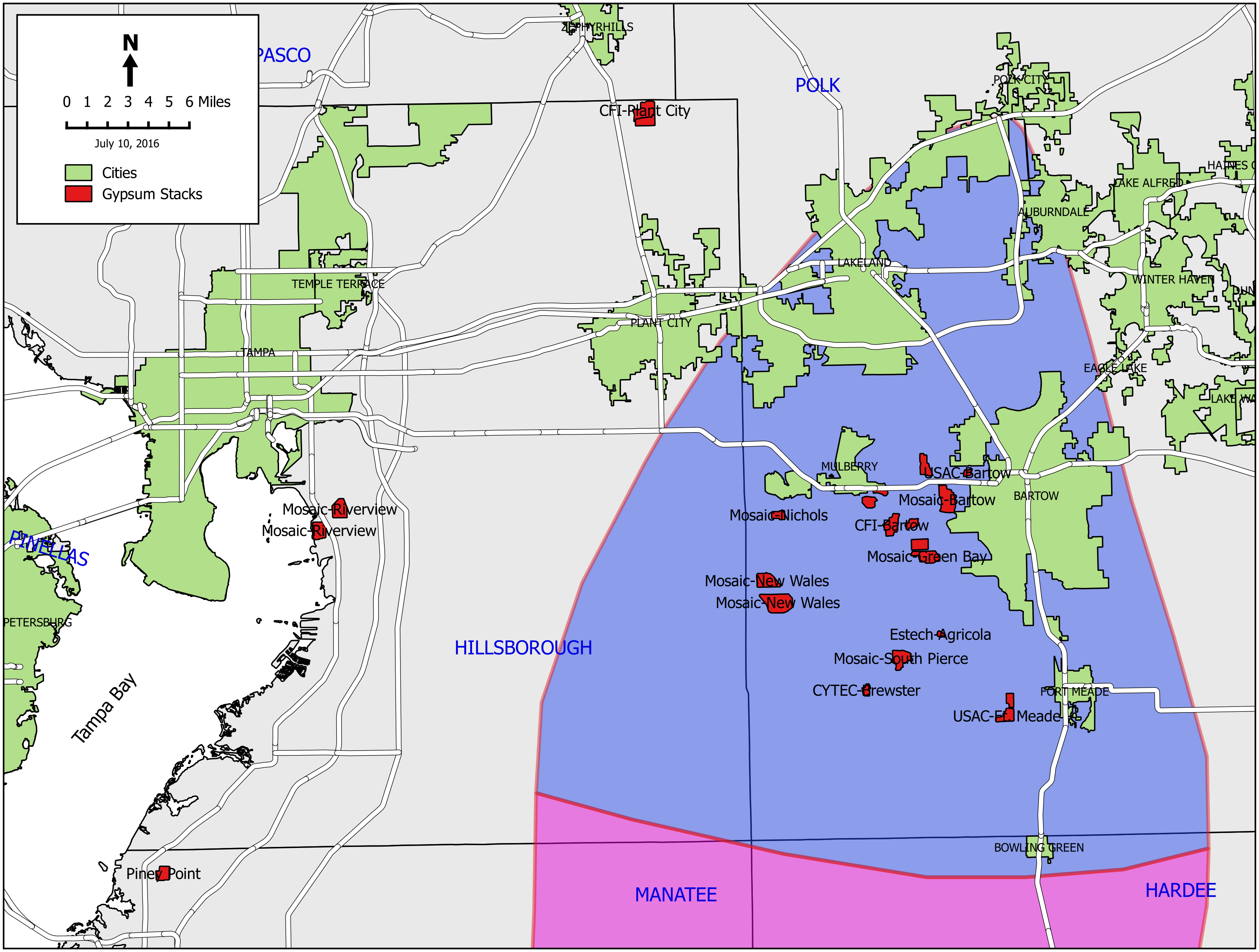


Figure 22. Locations of Gypsum Stacks in Central Florida

Bibliography

Cathcart, J.B., 1989, Economic Geology of the Land Pebble Phosphate District of Florida and Its Southern Extension, *in* Scott, T.M., and Cathcart, J.B., AGU 28th International Geological Congress, Field Trip Guidebook T178.

Florida Department of Environmental Protection (FDEP), 2011, Rate of Reclamation, July 1, 1975 Through December 31, 2010.

Fountain, Richard C.; Hurst, Marc V.; and Brown, David J.; 1993, The Geology of the Central Florida Phosphate District, A Comparison of the Bone Valley Deposits Vs. the Southern Extension, *in* Beneficiation of Phosphate: Theory and Practice, SME.

Gurr, T.M., 2012, Phosphate Rock, Mining Engineering, SME, Vol. 64, No. 6, p. 81-84.

Hammond, C.R., 1992, The Elements, *in* Lie, D.R. (ed.), CRC Handbook Handbook of Chemistry and Physics, CRC Press, p.4-24.

International Plant Nutrient Institute (IPNI), Single Superphosphate, Nutrient Source Specifics No. 21.

Janiski, S.M., 2011, 2010 Minerals Yearbook, Phosphate Rock, USGS.

Janiski, S.M., 2010, 2008 Minerals Yearbook, Phosphate Rock, USGS.

Janiski, S.M., 2012, Minerals Commodity Summaries 2012, USGS, p.118.

Ketner, K.B., and McGreevy, L.J., 1959, Stratigraphic of the area between Fernando and Harder Counties, Florida: U.S. Geological Survey Bulletin 1074-C.

Pasek, M. and Block, K., 2009, Lightning-induced reduction of phosphorus oxidation state, Nature Geo science, Vol. 2, p. 553-556.

Scott, T.M., 1989, The Geology of Central and Northern Florida with Emphasis on the Hawthorn Group, *in* Scott, T.M., and Cathcart, J.B., AGU 28th International Geological Congress, Field Trip Guidebook T178.

Shirey, S.B., 2009, Crustal Abundances, in Walker, J.D., and Cohen, H.A., The Geoscience Handbook, AGI Data Sheets, 4th Edition, Revised, AGI, p.224.

THE NORTH AND SOUTH PASTURE MINES

Kevin D. Farmer
The Mosaic Company
13830 Circa Crossing Drive
Lithia, FL 33547

Pete Karashay
The Mosaic Company
13830 Circa Crossing Drive
Lithia, FL 33547

Mosaic's North and South Pasture Mines consist of approximately 25,000 acres located in Hardee County, Florida. North Pasture comprises approximately 1,500 acres; South Pasture comprises approximately 23,500 acres. The mines were greenfield projects initialed by CF Industries, Inc. Mosaic acquired the mines from CF Industries, Inc. in March of 2014.

The phosphate deposits, called “matrix” by the miners, are Early Pliocene (3.6 Ma) to Middle Miocene (16 Ma) in age. The most desirable ores are found in the Bone Valley Member of the Peace River Formation of the Hawthorn Group. As mining in the Central Florida Phosphate District continues southward, the traditional land pebble deposits of gravel-sized phosphatic minerals taper out and transition into deposits comprised of predominantly sand-sized phosphatic minerals. Lithology and stratigraphic relationships within the phosphate deposits typically are highly variable; however, three distinct vertical zones are recognized within the current mining areas.

The uppermost parts of the deposit consist of poorly indurated, aluminum bearing, clay-to-gravel-sized phosphate, within a “matrix” of clayey sands, sandy clays and occasionally well-sorted, fine-grained, quartz sand. Occasionally manganese-rich laminar beds are found at the basal contact. The unit is often punctuated by moderately-indurated, phosphate-bearing, dolomitic limestone.

The middle parts of the deposit consist of poorly-indurated, clay- to gravel-sized, phosphate in a “matrix” of clayey sand and/or sandy clay. Sand-sized phosphate particles are predominant. The quartz sand within the “matrix” may be iron stained. In some areas the phosphate may contain elevated concentrations of iron and magnesium impurities. Sometimes beds of loose, well-sorted, phosphate-rich gravel and sand are found at the base of the middle unit.

The lowermost parts of the deposit consist of moderately-indurated, phosphatic, dolomitic marls. Although this unit contains abundant gravel-to-sand-sized phosphate ore, it is not easily separated from the carbonate cemented gangue minerals. Consequently, phosphate mined from this unit almost always contain elevated concentrations of calcium and/or magnesium impurities. Currently the lowermost parts of the deposits are not economically viable.

Draglines are used for mine excavation of overburden and phosphate-rich sediments (matrix), the overburden primarily consist of quartz sand, which is stripped to expose the matrix, which is made up of sand, clay and phosphate ore. Excavated matrix is combined with water using high powered water cannons and pumped as slurry by pipelines to on-site beneficiation facilities, where phosphate rock is separated from gangue materials consisting primarily of quartz and various clay minerals. Beneficiated phosphate rock is transported from the mine by rail to Mosaic's fertilizer manufacturing facilities in Central Florida.

The North Pasture Mine operated from 1978-1993. Two draglines were in operation at the mine. A 16 cubic yard bucket machine was used to remove the overburden and a 24 cubic yard bucket machine was used to mine the phosphate matrix. The average mining depths for overburden and matrix were 20 feet and 10 feet respectively. Annual production from the North Pasture Mine was about 1 million tons.

The South Pasture Mine started operation in 1995. Initially two draglines were in operation at the mine. The 852 dragline has a 45 cubic yard bucket and the 1370 dragline which has a 55 cubic yard bucket. A third machine was added in 2010; the 17 dragline also has a 55 cubic yard bucket. These machines are used to remove the overburden and mine the matrix. Typical mining depths for overburden and matrix are 14 feet and 21 feet, respectively. Annual production from the South Pasture Mine is about 3.5 million tons. The maximum annual tonnage produced was 3.8 million tons in 2006.

The South Pasture beneficiation plant was designed by Jacobs Engineering Group. The plant consists of two “sides”. Each side is supported by a washer, sizer and flotation cells. The washers separate the clay, larger phosphate material called pebble, and the finer sand-sized material called feed. The pebble is evaluated by overhead spectrum analyzers as it travels on the belts to the storage bins for quality. If the qualities are determined to be outside the desired parameters the pebble can be discarded. The feed material goes through a sizing process to further differentiate the feed and execrate the Intermediate Phosphate (IP) product. The finer feed is separated from the sand particles by flotation cells.

THE FOUR CORNERS MINE

Glen Oswald
The Mosaic Company
13830 Circa Crossing Drive
Lithia, FL 33547

Joe T. Alex
The Mosaic Company
13830 Circa Crossing Drive
Lithia, FL 33547

Marc V. Hurst
Independent Geological Services, Inc.
4432 Burlington Drive
Winter Haven, FL 33880

Mosaic's Four Corners Mine produces phosphate rock from phosphate-rich sediments of the Miocene-Pliocene Peace River Formation. Including the old American Cyanamid Fort Lonesome operation, the mine consists of approximately 62,000 acres located in Hillsborough, Manatee, and Polk Counties, Florida. Average annual production is about 7 million metric tons per year.

Draglines are used for mine excavation; currently 7 are in operation. Mining depths range from 40 to 80 feet. Approximately 30 feet of overburden, consisting primarily of quartz sand, are stripped to expose the phosphate-rich sediments (matrix) of the Miocene-Pliocene Peace River Formation. Excavated matrix is slurried with water and pumped by pipelines to on-site beneficiation facilities, where phosphate rock is separated from gangue materials consisting primarily of quartz and various clay minerals. Beneficiated phosphate rock is transported from the mine by rail and truck to Mosaic's fertilizer manufacturing facilities in Central Florida and Louisiana.

The Four Corners mine project was originally planned by the WR Grace Corporation (Grace). International Minerals and Chemicals (IMC) approached Grace and proposed doubling the size of the project and became a 50% partner. Grace was to be the managing partner. The engineering firm Davy McKee was hired to build the project. Plant design began in 1979, construction in 1981, and could have been complete and ready to run by 1982. Unfortunately the phosphate rock market went into a down cycle and the plant did not actually start up until January of 1985 (with 3 draglines). Market conditions were still weak, and Grace shut the plant down in February of 1986 with no near-term plans to restart, virtually all employees were released. Within a few years Grace left the industry and sold off their holdings to various companies including the 50% ownership of Four Corners to IMC. Shortly after the sale, IMC started operation on a 10/4 schedule in January of 1989, it switched to a 7 day/week schedule in January 1994 and has operated continuously (except for several short inventory reductions periods) since then. During the IMC era, Four Corners went from a 4-dragline to a 6-dragline operation, and certain areas of beneficiation underwent debottlenecking to accommodate the increased matrix tonnage. Later, during the Mosaic era, 2 more draglines were purchased for a total of 8. The maximum annual tonnage produced was 8.1 million tons in fiscal 2011/2012.

The company name changed several times along the way. In 1993 IMC and Agrico merged to form IMC-Agrico, later becoming IMC Fertilizers; and in 2004 they merged with Cargill to become Mosaic.

In April of 1991 a Heavy Media plant was started up to remove dolomite (MgO) contaminants from the coarser-grained pebble product. It operated on an as-needed basis for approximately 50 months, until 1997, when the mining strategy was changed and lower grade matrix was no longer mined. The Heavy Media plant has not operated since.

In 2007 a Central Screening station (pre-washer) was constructed in the Lonesome mining area to facilitate pumping matrix at a lower cost to the Four Corners plant. It was taken out of service in 2015 as mining in the Lonesome area began tapering down.

The Four Corners beneficiation plant consists of two nearly independent trains – a north plant, and a south plant. At each plant feed (sand-sized grains of phosphate rock) is washed, sized, and separated from gangue minerals by two fine flotation, and one coarse flotation circuits. Originally a spiral section was used to upgrade the ultra-coarse feed, but after the merger with Agrico an economic analysis showed it was better to produce a low cost screen oversize called Intermediate Phosphate (IP).

Major Grace and IMC contributors on the mine design team included Charlie Green, the project design manager, and Claire Olson, Howard Adams, Jim Lawver, George McKereghan, Mac McClintock. Operations managers of the Four Corners Mine have included Gene Armbrister (the original manager for Grace and IMC), Bob Kinsey, Steve Olson, Howie Stoughton / Gene Armbrister (co managers), Charles Morris, Don Tompkins (Mosaic), Howie Stoughton, Bruce Bodine, Karen Swager, and Alan Lulf, the current manager.

GEOLOGIC OVERVIEW OF FLORIDA

By
Thomas M. Scott
SDII Global Corporation
1579 Tallavana Trail
Havana, FL

INTRODUCTION

The Florida Platform is delimited by the 200 m (600 ft) isobath at the shelf break to the approximate location of the Paleozoic suture beneath southern Georgia and Alabama (figure 1). The Suwannee–Wiggins Suture (Thomas et al. 1989) is the proposed location where terranes with African affinities are welded to the North American Plate (Chowns and Williams 1983; McBride and Nelson 1988; Woods et al. 1991). The basement rocks of the Florida Platform are a fragment of the African Plate that remained attached to the North American Plate when rifting occurred in the Jurassic and range in age from late Precambrian-early Cambrian to mid-Jurassic (Barnett 1975). Excellent reviews of the geology of the basement are provided by Smith (1982), Arthur (1988), Smith and Lord (1997), and Heatherington and Mueller (1997). Barnett (1975) provided a structure contour map of the sub-Zuni surface. This surface equates to what is now recognized as pre-Middle Jurassic. Barnett's interpretation of the basement surface has it occurring as shallow as approximately 915 m (3000 ft) below mean sea level (msl) in central-northern peninsular Florida. The basement surface dips west and southwest toward the Gulf of Mexico basin, to the south into the South Florida basin, and to the east into the Atlantic basin. The basement surface reaches depths of more than 5180 m (17,000 ft) below msl in southern Florida (Barnett 1975).

The platform, deposited unconformably on top of the basement, is constructed of Middle Jurassic to Holocene evaporite, carbonate, and siliciclastic sediments deposited on a relatively stable, passive margin of the North American Plate. The age assignments for the Middle Jurassic to Holocene formations are, at times, tentative propositions due to limited, or lack of, paleontological evidence in some formations. The age determinations for some of the younger units, for example the Pliocene Tamiami Formation, are based on a vast amount of paleontological evidence. This, in part, is responsible for differing interpretations of when, where, and how much sediment was deposited across the platform (see and compare Salvador [1991b] and Randazzo [1997]).

STRUCTURE

The Florida Platform has been a relatively stable portion of the trailing edge of the North American Plate since the mid-Jurassic. Winston (1991) stated that the Mesozoic and Cenozoic structural movement on the Florida–Bahama Platform was entirely negative. Florida's arches, or structural highs, were not formed by uplift but as the result of subsiding more slowly than the flanking basins. However, faulting of the basement rocks created many of the structural features recognized on the pre–mid-Jurassic surface (Barnett 1975; Smith and Lord 1997). Faults

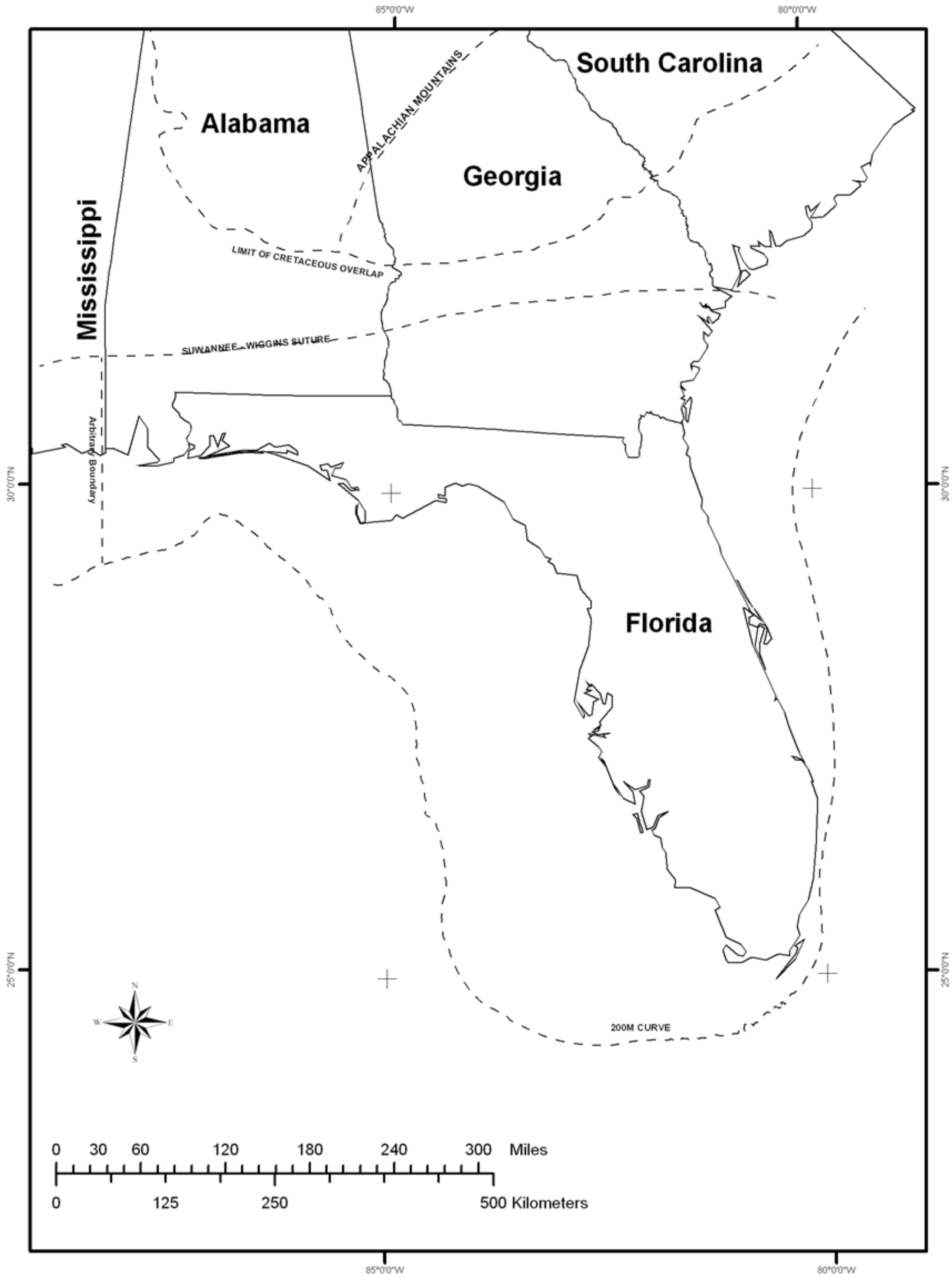


Figure 1 – Limits of the Florida Platform.

disrupting the Upper Jurassic sediments have been identified in northwestern Florida; some displacements exceed 305 m (1000 ft) (Lloyd 1989). Miller (1986) recognized a number of known or suspected Cenozoic faults that affect the Floridan Aquifer System. Duncan et al.

(1994) identified faulting in the Lower to Middle Eocene Oldsmar Formation. A number of hydrogeologic and geomorphic investigations have proposed the existence of faults (Wyrick 1960; Leve 1966; Lichtler et al. 1968; Pirkle 1970; White 1970). The faults in the Cenozoic section have very limited displacement, generally less than 30.5 m (100 ft) and are difficult to identify due to limited displacement, well control, few “marker” beds, erosional disconformities, and karstification.

Little has been said concerning folding of post–mid-Jurassic sediments on the Florida Platform. Missimer and Maliva (2004) believe that folding is more widespread on the Florida Platform than is presently recognized due to the limited amount of detailed subsurface data. They recognized folding with associated fracturing and faulting in the sediments of the Intermediate (Miocene–Pliocene sediments) and Floridan Aquifer systems (Eocene–Oligocene sediments) on the southern portion of the platform. They postulated that the interaction of the Caribbean and North American plates in the Late Miocene to Pliocene produced the folds, fractures, and faults.

The oldest features recognized as affecting deposition of post–mid-Jurassic sediments on the platform are expressed on the pre–mid-Jurassic surface (Arthur 1988). The Mesozoic structural features affecting deposition of sediments include a series of basins or embayments and arches (figure 2). Some of these features affected deposition into the mid-Cenozoic (for example, the South Florida basin; Scott 1988). Other features affected the deposition into the late Cenozoic (for example, the Apalachicola Embayment; Schmidt 1984). The Peninsular Arch affected deposition from the Jurassic through the Cretaceous and was intermittently positive during the Cenozoic (Miller 1986). The Cenozoic structural features affecting deposition are shown in figure 3.

One of the more interesting structural features of the Florida Platform is a southwest-to-northeast trending low that has affected deposition from the mid-Jurassic until at least the Middle Miocene. Some portions of the feature continued to affect deposition through the Pleistocene. This feature has an extended list of names that have been applied to all or parts of it. An excellent review of the names applied to the feature was presented by Schmidt (1984) and Huddlestun (1993). However, Georgia Channel System is the name that has been applied to the entire sequence (Huddlestun 1993) (figs. 2, 3).

The Georgia Channel System had its origin in the formation of the South Georgia Rift in the Triassic–Jurassic (?) (Huddlestun 1993). From the Late Cretaceous through the Paleocene, this area was the boundary between carbonate deposition to the south and siliciclastic deposition to the north. By the Eocene, the Appalachian Mountains had been highly eroded leaving relatively low hills and significantly reduced siliciclastic sediment transport via streams and rivers. In the Eocene and Oligocene, as the result of a greatly reduced siliciclastic supply, carbonate deposition extended across the Georgia Channel System. The channel system was then infilled by predominantly siliciclastic sediments in the Late Oligocene to the Early Miocene in response to uplift in the Appalachians (Scott 1988).

DEPOSITIONAL ENVIRONMENTS

The initial depositional environments affecting the Florida Platform were restricted environments allowing for intense evaporation and the development of evaporites in limited areas. As the Gulf continued to expand and sea levels rose, siliciclastic and carbonate depositional environments began to cover more of the platform. Continued sea-level rise through the Cretaceous eventually covered the exposed land area in northern Florida. The Florida Platform sediments were deposited in a complex interplay of siliciclastic, carbonate, and evaporite facies as a result of sea-

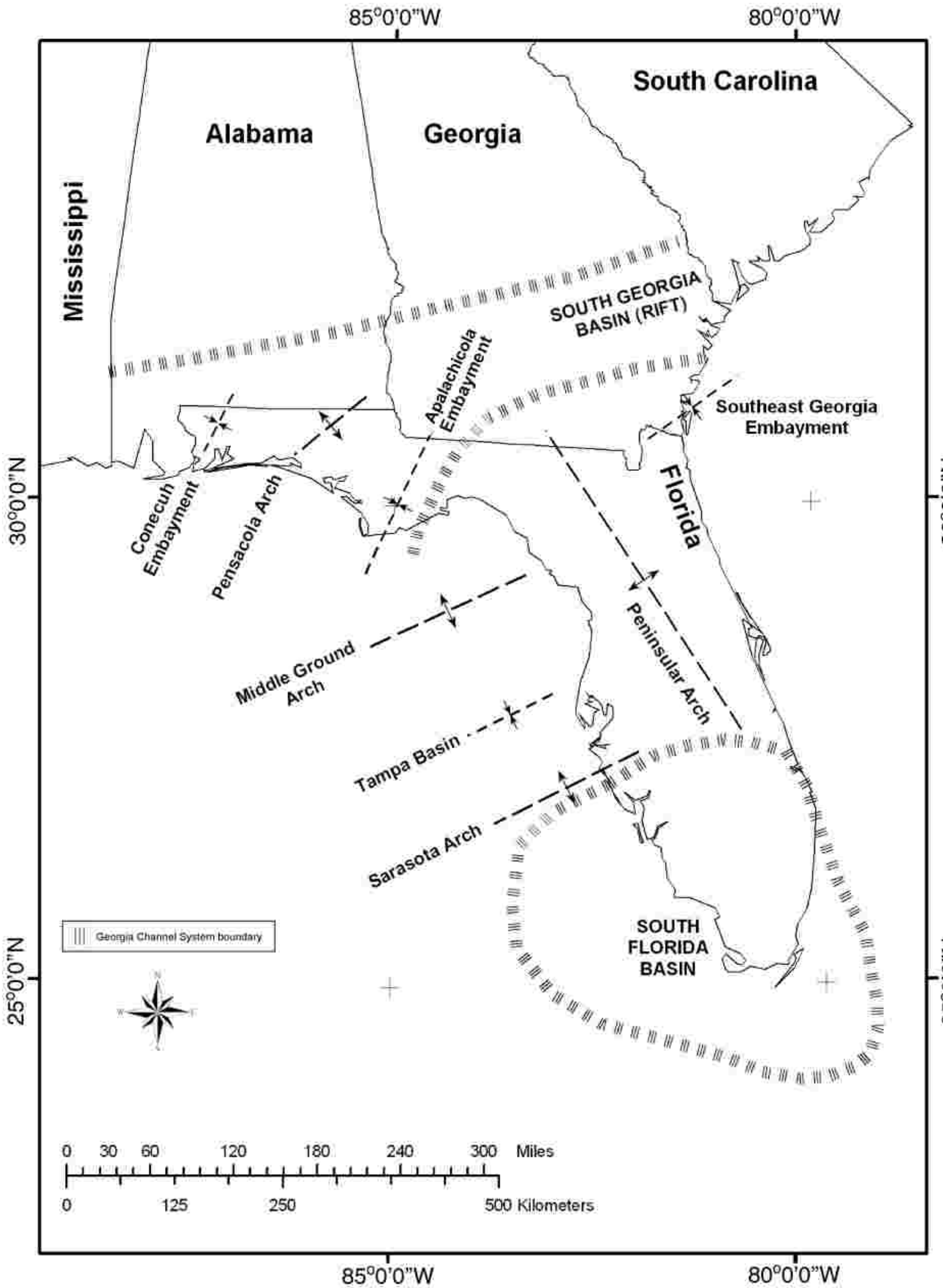


Figure 2 – Structures affecting the Mesozoic and early Cenozoic deposits (modified after Lloyd, 1997).

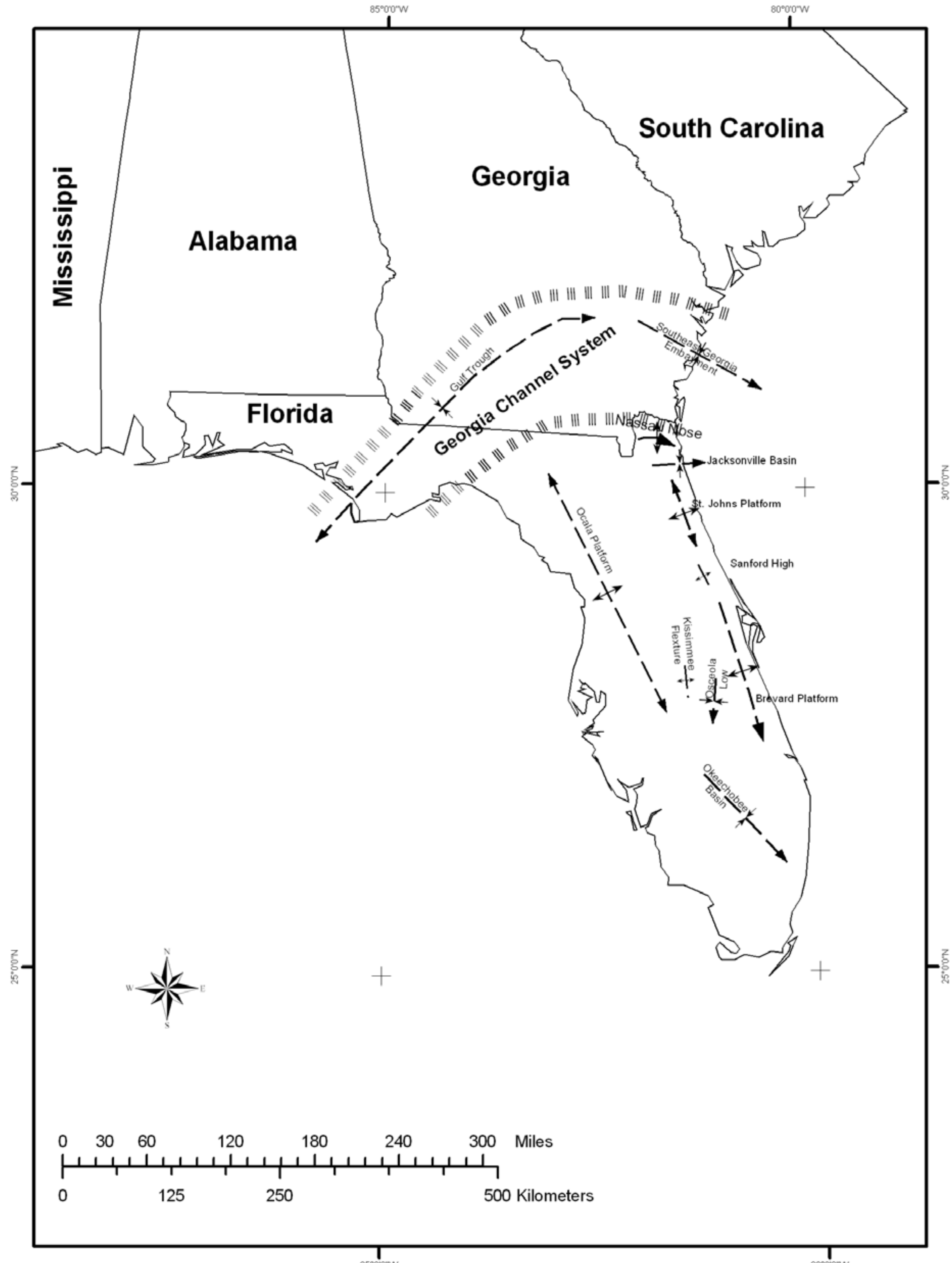


Figure 3 – Structures affecting the post-early Cenozoic deposits (modified after Scott, 1988).

level fluctuations (Randazzo 1997). Siliciclastic deposition predominated on the northern part of the platform while carbonate and evaporate sediments formed to the south (Randazzo 1997).

In the early Cenozoic (Paleogene), the siliciclastic sediment supply was limited due to the highlands of the Appalachian trend having been reduced by erosion, and carbonate deposition expanded to cover the entire Florida Platform and beyond by the Oligocene. The carbonate platform, which began as a rimmed shelf in the Jurassic, evolved to a carbonate ramp sequence by the early Cenozoic (Randazzo 1997; Winston 1991). Subsequent to the maximum development of the carbonate platform, uplift occurred in the Appalachians providing a renewed supply of siliciclastic sediments (Scott 1988; Brewster-Wingard et al. 1997). This influx of siliciclastic sediments in the Neogene replaced most carbonate deposition on the Florida Platform by the mid-Pliocene. As sea level rose in the late Pleistocene, there was a decrease in siliciclastic sedimentation and carbonate deposition increased on the southern Florida Platform. The interplay of the carbonate and siliciclastic sediments with fluctuating sea level and changing climate created complex depositional environments (Scott 1988; Missimer 2002). The interaction of the carbonates and siliciclastics on the Florida Platform has been investigated and discussed by a number of authors (Warzeski et al. 1996; Cunningham et al. 1998; Guertin 1998; Guertin et al. 2000; Missimer et al. 2000; Missimer 2001, 2002; Cunningham et al. 2003).

STRATIGRAPHY

Stratigraphically, Florida is composed of pre-Mesozoic sedimentary, igneous and metamorphic rocks overlain by Mesozoic and Cenozoic sedimentary rocks. The Mesozoic sediments consist predominantly of siliciclastics except in central and southern Florida where carbonates predominate. In the Cenozoic, the Paleogene sediments are predominantly carbonates with some mixed carbonate-siliciclastic sediments. The Neogene and Quaternary sediments are predominantly siliciclastics (Braunstien et al, 1988).

The pre-Mesozoic rocks occur nearest to the land surface in northern peninsular Florida. These rocks dip deeper in the subsurface to the south under the exposed portion of the Florida Platform, to the east under the Atlantic Ocean and west into the Gulf of Mexico (Puri and Vernon, 1964). Consequently, the Mesozoic and Cenozoic sediments thicken in these areas exceeding 13,000 feet thick in southern Florida.

Pre-Mesozoic

The pre-Mesozoic (Proterozoic and Paleozoic) framework of the Florida basement is composed of igneous, sedimentary, and metamorphic rocks (figure 4). These rocks have been penetrated by oil exploration boreholes. A number of researchers have investigated the pre-Mesozoic rocks including Smith (1982), Chowns and Williams (1983), Dallmeyer et al. (1987), Arthur (1988), and others. Refer to Smith and Lord (1997) for a summary of the research on the basement rocks. The granitic igneous rocks, which occur in east-central Florida, have been dated at approximately 530 million years old (early Paleozoic) (Dallmeyer et al. 1987; Smith and Lord 1997). Dallmeyer et al. (1987) recognized that these rocks, the Osceola Granite, were part of a complex that is also found in northwestern Africa. A metamorphic sequence, located on the southern flank of the Osceola Granite, indicates metamorphism was associated with the emplacement of the granite pluton.

Sedimentary rocks are found in two areas of the basement, a small area in the panhandle near the junction of Alabama, Florida, and Georgia, and in the northern peninsula north of a line connecting Tampa Bay in the southwest and a point between St. Augustine and Jacksonville in

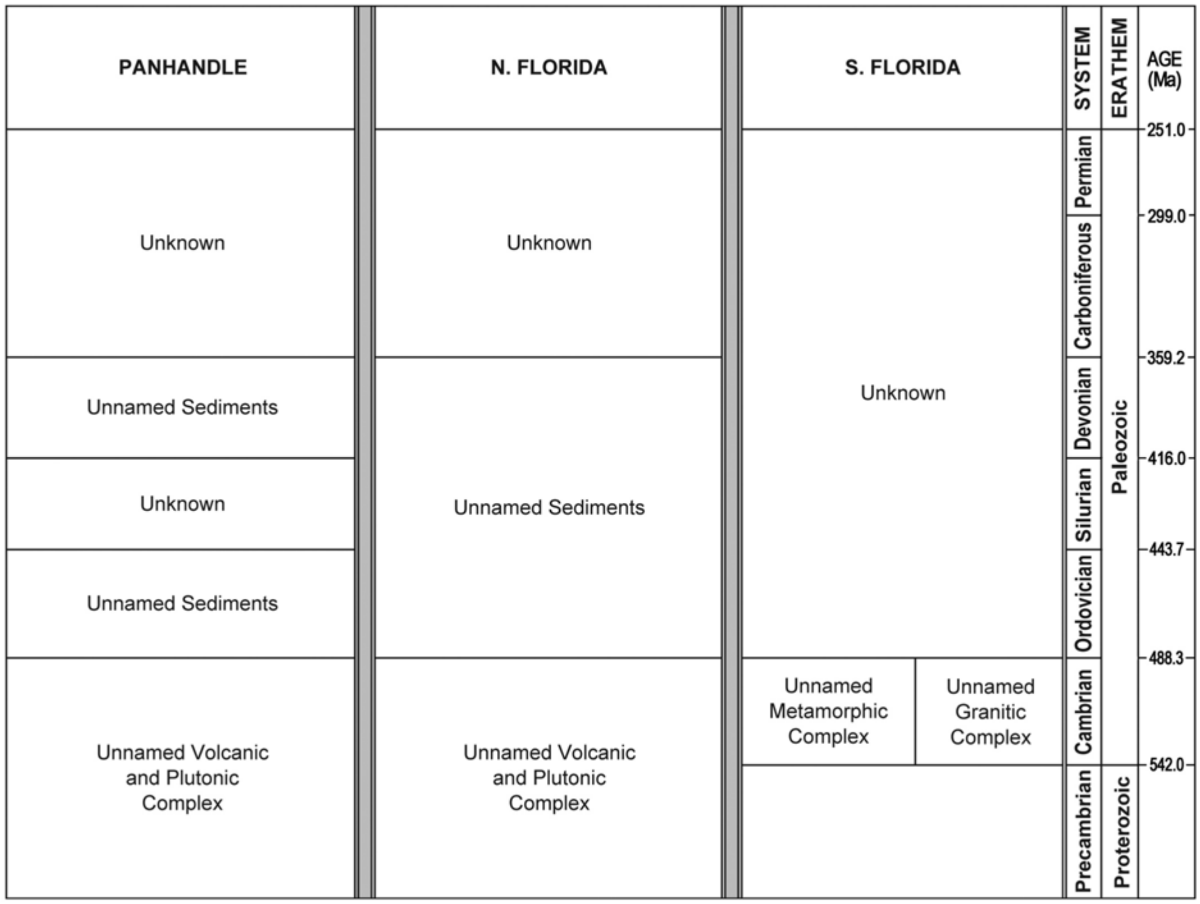


Figure 4 - Paleozoic stratigraphic columns (modified after Braunstein et al, 1988).

the northeast (Jones 1997; Smith and Lord 1997). With the exception of sediments encountered in a few wells, the sandstone, siltstone, and shale are usually sparsely fossiliferous. Ages derived from the fossil assemblages range from Early Ordovician to Middle Devonian (Jones 1997). Opdyke et al. (1987) recognized a pre-Mesozoic shale in northern Florida that exhibited low-grade metamorphism.

Mesozoic

Mesozoic sediments on the Florida Platform were deposited in response to the separation of plates beginning in the Triassic. Subsequent to the breakup of the plates, marine sedimentation began and remained the dominant depositional type for much of the geologic history of the Platform.

Triassic

Triassic rifting associated with the breakup of Pangea and the formation of the Atlantic Ocean created the South Georgia basin (Rift) (figure 2). Triassic red beds, the Newark Group, and Eagle Mills Formation (Braunstein et al. 1988) (figure 5), filled the rift system. Basalt and diabase (tholeiites), with an average age of 192 million years (Arthur 1988), have been encountered in a number of boreholes. These rocks were emplaced or occurred as flows in response to the continued separation of the plates (Arthur 1988).

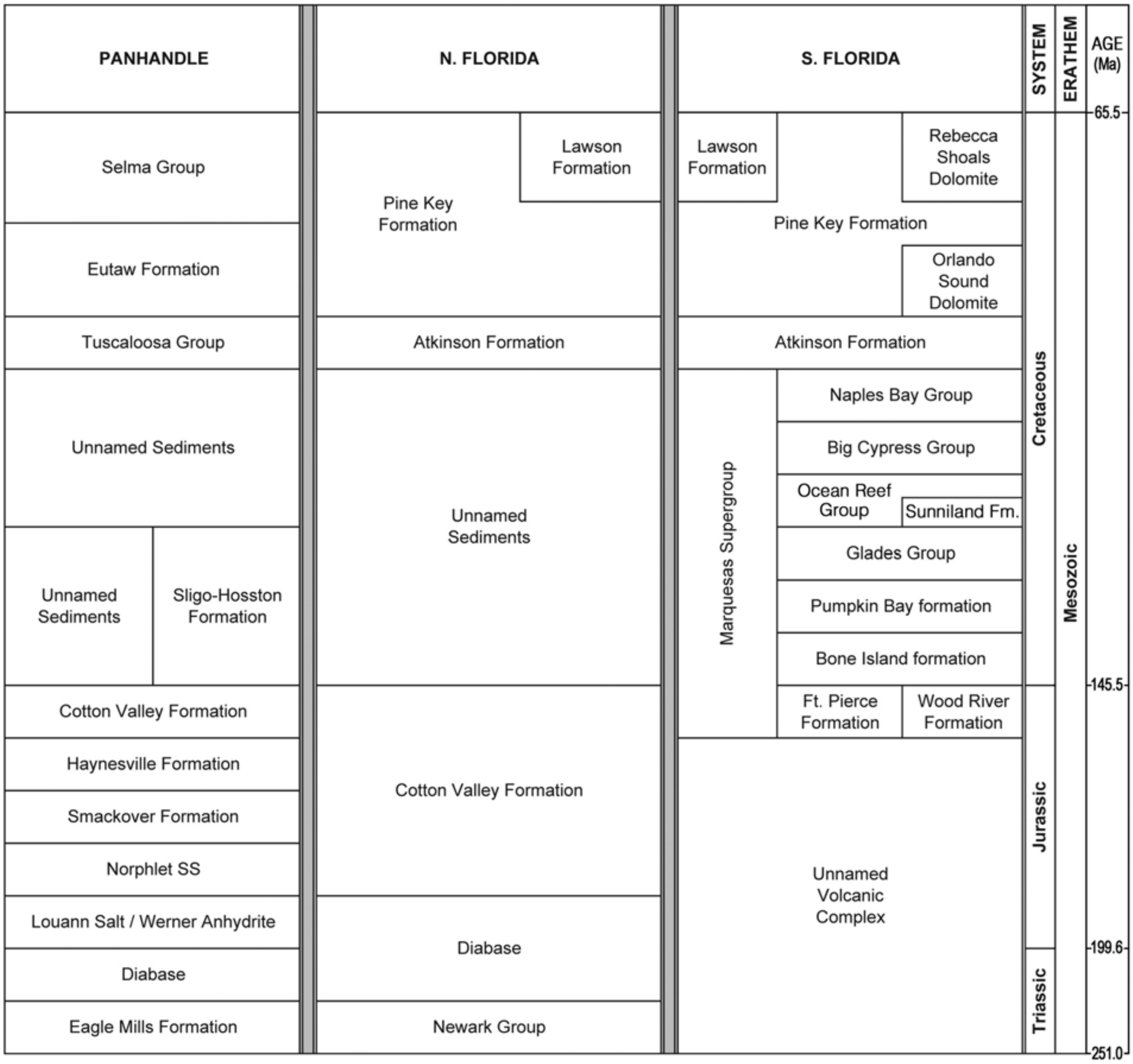


Figure 5 – Mesozoic stratigraphic columns (modified after Braunstein et al, 1988).

Jurassic

The Gulf of Mexico basin began to form in the Late Triassic as rifting began to separate the lithospheric plates (Salvador 1991a). The first post-rifting sediments deposited on the Florida Platform were upper Middle Jurassic evaporites in the Apalachicola Embayment and the Conecuh Embayment (figure 2). These were deposited in very limited portions of the northwestern Florida Platform (Salvador 1991b; Randazzo 1997). Deltaic to shallow-marine siliciclastics, carbonates, and evaporites were deposited on the northwestern Florida Platform during the Late Jurassic (Salvador 1991b). These sediments contain important petroleum-producing horizons, including the Norphlet Sandstone and the Smackover Formation (carbonates) (Braunstein et al. 1988) (figure 5) that were discovered between 1970 and 1986 (Lloyd 1997). In southern Florida, Upper Jurassic siliciclastics were followed by carbonates and evaporites deposited on an unnamed Upper Triassic to Upper Jurassic volcanic complex (Braunstein et al. 1988). These sediments occur below important petroleum producing horizons in the South Florida basin (Applegate et al. 1981). Throughout the mid-Jurassic to the beginning of the Cretaceous, sea levels rose, progressively reducing the exposed portion of the Florida Platform (Salvador 1991b; Randazzo 1997). The thickness of post–mid-Jurassic to Cretaceous sediments in northwestern Florida Platform exceeds 1000 m (3500 ft) (Randazzo 1997). In the southern part of the platform, the thickness may exceed 915 m (3000 ft) (Winston 1987).

Cretaceous

By the beginning of the Cretaceous, a limited portion of the northern Florida Peninsula remained above sea level (McFarlan and Menes 1991). As sea level rose through the Early Cretaceous, more of the platform was submerged (McFarlan and Menes 1991; Randazzo 1997). Deposition in the northwestern Florida Platform was dominated by marine and non-marine siliciclastics. Carbonates and evaporites covered the southern portion of the platform (McFarlan and Menes 1991; Winston 1987, 1991). During the Lower Cretaceous, carbonates and evaporites of the Ocean Reef Group, Sunniland Formation (figure 5) and associated units were deposited. The Sunniland sediments became the reservoir rocks for Florida's first oil discovery (1943) (Lloyd 1997). The thickness of the Lower Cretaceous sediments reaches more than 1830 m (6000 ft) on the northwestern and 2740 m (9000 feet) on the southern portions of the platform (Randazzo 1997).

In the early portion of the Late Cretaceous, sediments in the northern portion of the Florida Platform continued to be dominated by siliciclastics, while carbonates were being deposited in southern Florida (Sohl et al. 1991; Winston 1991). By the mid-Late Cretaceous, carbonates, including chalk, with limited siliciclastics were deposited over the entire Florida Platform (Sohl et al. 1991). The Upper Cretaceous sediments are more than 915 m (3000 feet) thick in northwestern and southern Florida (Randazzo 1997).

At the end of the Cretaceous, a large bolide (meteorite, asteroid, or comet) collided with Earth in the Gulf of Mexico–Caribbean region (Hildebrand et al. 1991). The bolide impacted at an oblique angle, spreading ejecta to the north and west (Schultz 1996). It is thought that 100 to 300-m (330 to nearly 1000 ft) high tsunamis (Bourgeois et al. 1988; Matsui et al. 1999) spread across the Gulf of Mexico (Kring 2000). Discussions with a number of geologists investigating the Chicxulub impact suggest that the Florida Platform should have been influenced by the event (Chicxulub planning meeting–Group on Mesozoic–Cenozoic stratigraphy and the Cretaceous–Tertiary (KT) boundary, Puerto Vallarta, Mexico, 1993). However, no evidence of the impact or tsunamis has been discovered on the Florida Platform to date. The lack of cores across the KT boundary, the limited number and wide distribution of wells penetrating the KT boundary, and the general poor quality of the cuttings from the wells hinder the search for evidence.

Cenozoic

Carbonate sedimentation dominated during the Paleogene and into the earliest Neogene on much of the Florida Platform. A significant change in sedimentation occurred in the early Neogene. Siliciclastic sediments began to replace carbonates as the dominant sediment.

Paleogene

Carbonate–evaporite deposition dominated much of the Florida Platform during the Paleocene (Miller 1986). The carbonate–evaporite sediments graded to the northwest into shallow marine fine-grained siliciclastic sediments across the Georgia Channel System. The main carbonate-producing area was interpreted to be rimmed by a reef system creating the restricted environment necessary for evaporite deposition (Winston 1991). The Paleocene sediments cover the entire Florida Platform and have a maximum thickness of more than 670 m (2200 ft). The thick anhydrite beds in the Cedar Keys Formation (figure 6) form the regionally extensive lower confining bed of the Floridan Aquifer System (Miller 1986, 1997).

The evaporite content of the Lower to Middle Eocene sediments declined in response to sea-level rise and resulted in the development of a more open, carbonate-ramp depositional system on the platform. Evaporites occur primarily as pore fill (Miller 1986). The carbonate sediments grade into siliciclastic sediments in the Georgia Channel System (Miller 1986). The Lower to Middle Eocene sediments cover the entire platform, ranging to maximum thickness of more than 945 m (3100 ft). Middle Eocene carbonates (Avon Park Formation) are the oldest sediments exposed on the platform (Scott et al. 2001). These sediments crop out on the crest of the Ocala Platform (figure 3). The Lower to Middle Eocene limestone and dolostone, in part, form the lower portion of the Floridan Aquifer System while, in some areas, these sediments are part of the lower confining bed of the aquifer system (Miller 1986, 1997).

Carbonate deposition covered virtually the entire Florida Platform in the Late Eocene. Carbonates were deposited to the north of the Georgia Channel System nearly to the Fall Line (limit of Cretaceous overlap), beyond the limits of the Florida Platform (figure 1). The carbonate ramp was well developed and evaporites have not been found in the limestone or dolostone. The carbonates grade into siliciclastics on the northwestern most part of the platform. Upper Eocene carbonates range in thickness to more than 213 m (700 ft) but, due to erosion, are absent in several areas of the platform (Miller 1986; Scott 1992, 2001). In a large area on the southern part of the platform, the Upper Eocene sediments are absent, probably due to erosion by currents similar to episodes identified in the Oligocene to Pliocene in this region (Guertin et al. 2000). On the areas of the platform where the Oligocene carbonates are absent, the Upper Eocene carbonates form the upper Floridan Aquifer System (Miller 1986, 1997).

Lower Oligocene carbonate deposition occurred as far updip as did the Upper Eocene deposition. The carbonates grade into siliciclastics on the northwestern most part of the platform. Very minor amounts of siliciclastics are incorporated in these carbonates. However, beds of fine quartz sand occur in the Lower Oligocene of southern Florida (Missimer 2002). Whether or not the carbonate deposition covered the platform is open to conjecture. The Lower Oligocene sediments range in thickness to more than 213m (700 ft) but are absent over large portions of the platform (Miller 1986; Scott 1992, 2001). These sediments are missing due to nondeposition or erosion, or both, in a large area on the eastern flank of the Ocala Platform in an area referred to as the paleo-Orange Island (Bryan 1991). Where the Lower Oligocene sediments are present, they form the upper portion of the Floridan Aquifer System (Miller 1986, 1997).

Chert (silicified limestone) occurs from the upper portion of the Middle Eocene carbonates through the Lower Oligocene carbonates. The chert formed as the result of the weathering of the overlying clay-rich Miocene sediments that covered the platform (Scott 1988). Weathering of the clays releases large amounts of silica into the groundwater and, in the appropriate geochemical environment, replaces limestone. Groundwater beneath the present-day erosional scarp near Lake City in northern Florida is supersaturated with respect to Opal-CT and slightly saturated with respect to quartz due to weathering of the clays (S. B. Upchurch, personal communication 2005). Fossils including foraminifera and corals are often preserved in the chert.

Sea-level lowering in the Late Oligocene restricted deposition to portions of southern and northwestern Florida (Missimer 2002). Although absent over much of the platform, these

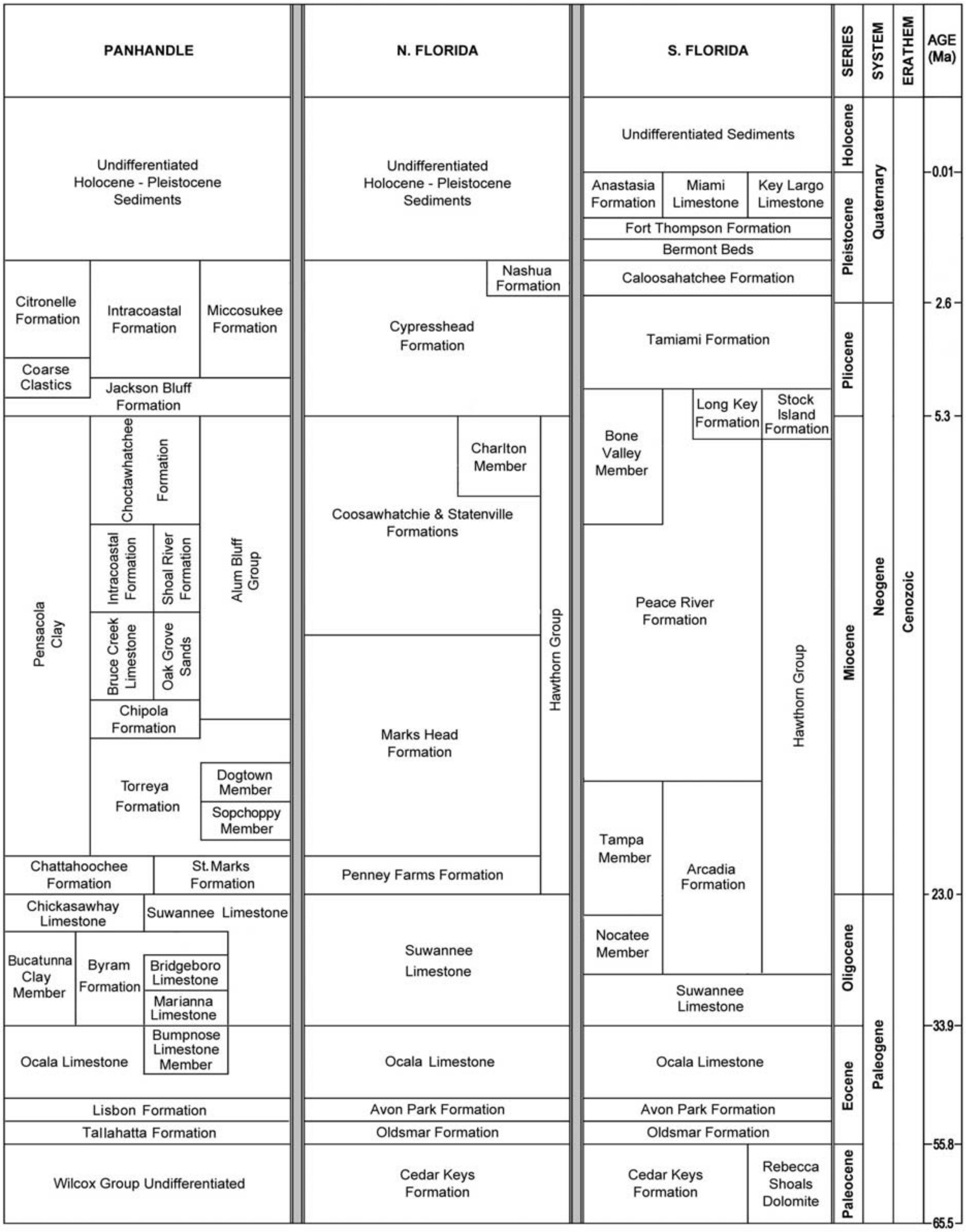


Figure 6 – Cenozoic stratigraphic columns (modified after Braunstein et al, 1988).

sediments may exceed 135 m (440 ft) in thickness (Braunstein et al. 1988). The stratigraphic section in southern Florida may represent the most complete Upper Oligocene section in the southeastern United States (Brewster-Wingard et al. 1997). In very limited areas, the Upper Oligocene carbonates may form the top of the Floridan Aquifer System (Miller 1986, 1997).

Cross sections showing the distribution of the Paleogene sediments are shown in figure 7. A generalized geologic map of Florida is shown in figure 8. The Paleogene lithostratigraphic units occurring in the surface and shallow subsurface of the panhandle, northern, and southern portions of Florida are shown in figure 9.

Neogene–Quaternary

Significant depositional changes occurred in the latest Paleogene–earliest Neogene. Several factors were responsible for the changes including epeirogeny in the Appalachians that took a highly eroded and reduced mountain range and uplifted it (Stuckey 1965; Schlee et al. 1988). The rejuvenated mountain range again became a source of sediment due to increased erosion, and the siliciclastic sediments were transported by streams and rivers; marine currents transported the sediment southward onto the Florida Platform. Sea level rose through the Middle Miocene, began significantly fluctuating until the end of the Pleistocene, and rose in the Holocene to present sea level.

Initially, in the Early Miocene, the siliciclastics were deposited interbedded and mixed with carbonates in northern Florida while carbonates continued to dominate in southern Florida (Scott 1988). By the Middle Miocene, with continued sea-level rise, siliciclastics replaced carbonate deposition (Scott 1988; Missimer 2002). Carbonate deposition continued only in the southernmost portions of the platform, and siliciclastic sediments continued to be transported further south and, ultimately, dominated the deposition system on most of the Florida Platform by the early Pliocene. Carbonates continued to be produced but on a much more limited scale and in the late Neogene, carbonate most often occurred as matrix. Siliciclastic sediments prograded onto the southernmost portion of the platform in the Pliocene, forming the foundation for the northern half of the Florida Keys (Cunningham et al. 1998). In the Quaternary, siliciclastics dominated over much of the platform. However, in the late Quaternary, with a reduction in siliciclastic supply, carbonate deposition began to occur over portions of the southernmost peninsula.

Sediments deposited in the Miocene covered the entire platform; however, subsequent erosion and redeposition created the distributional pattern seen today (Scott et al. 2001). The initial distribution of Pliocene sediments is not known but can reasonably be inferred to have been more extensive than the present occurrence (Scott et al. 2001).

Unusual depositional environments are recorded on the Florida Platform in the late Cenozoic (Neogene) as the result of sea-level fluctuations and marine upwelling bottom waters. Major phosphorite and palygorskite deposits formed as the result of these conditions (Weaver and Beck 1977; Riggs 1979; Scott 1988; Compton 1997). The age of the phosphorites indicate that the phosphogenic environment occurred in the Early and Middle Miocene (Compton 1997). The peri-marine environments in which the palygorskite deposits formed also occurred during the Miocene in northwestern Florida (Weaver and Beck 1977). Palygorskite also formed in alkaline lakes in the western-central part of the peninsula in association with sea-level fluctuations (Upchurch et al. 1982).

In the late Neogene and into the Quaternary, climate and depositional conditions allowed the development of extremely fossiliferous molluscan-bearing lithologic units. Some of the formations defined within the late Neogene and early Quaternary contain some of the most diverse faunas in the world. How these units formed has been a source of discussion (Allmon 1992; Scott and Allmon 1992). Due to the abundance and diversity of the molluscan fossils, paleontologists have been drawn to study these sediments for more than a century (Scott 1997). As sea level rose in the Pleistocene, sediments were deposited over that portion of the platform that is below 18.3–30.5 m (60–100 ft) above sea level. The Pleistocene sea level rose no higher than this level (Colquhoun et al. 1968). The rising sea level in the late Pleistocene and

Figure 7A – Cross section locations.

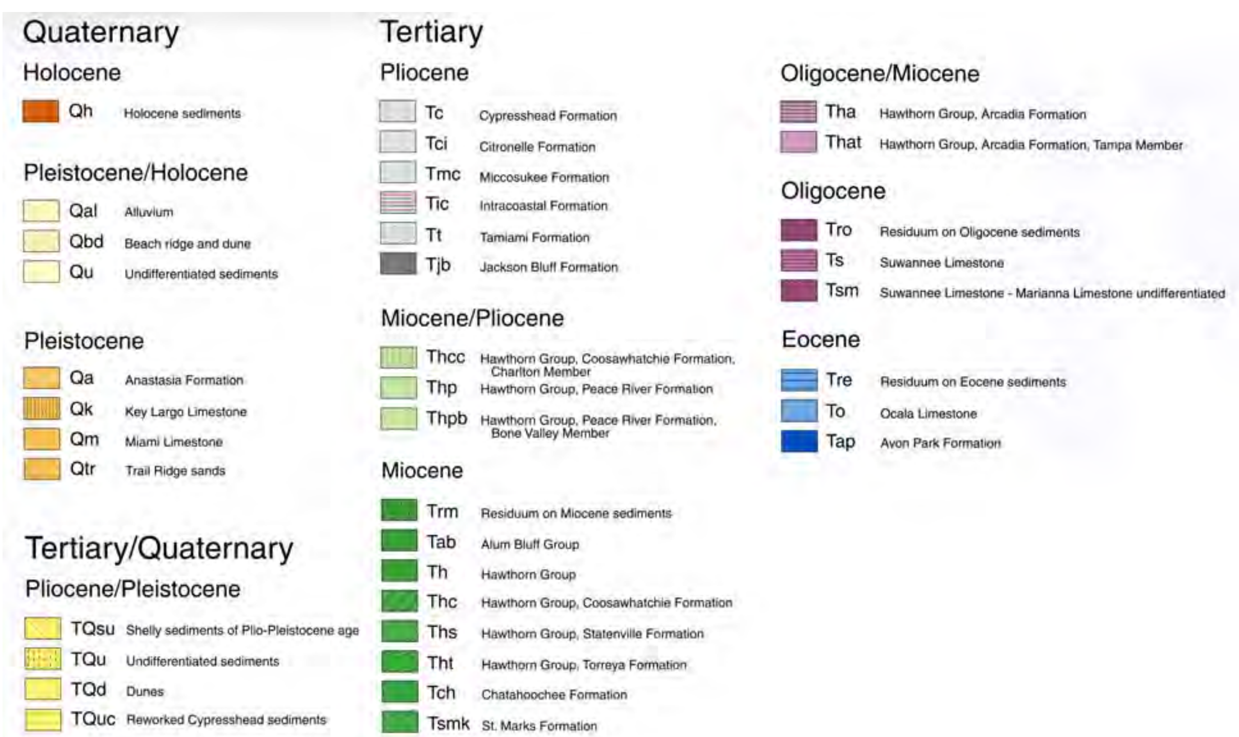


Figure 7B – legend for cross sections and geologic map.

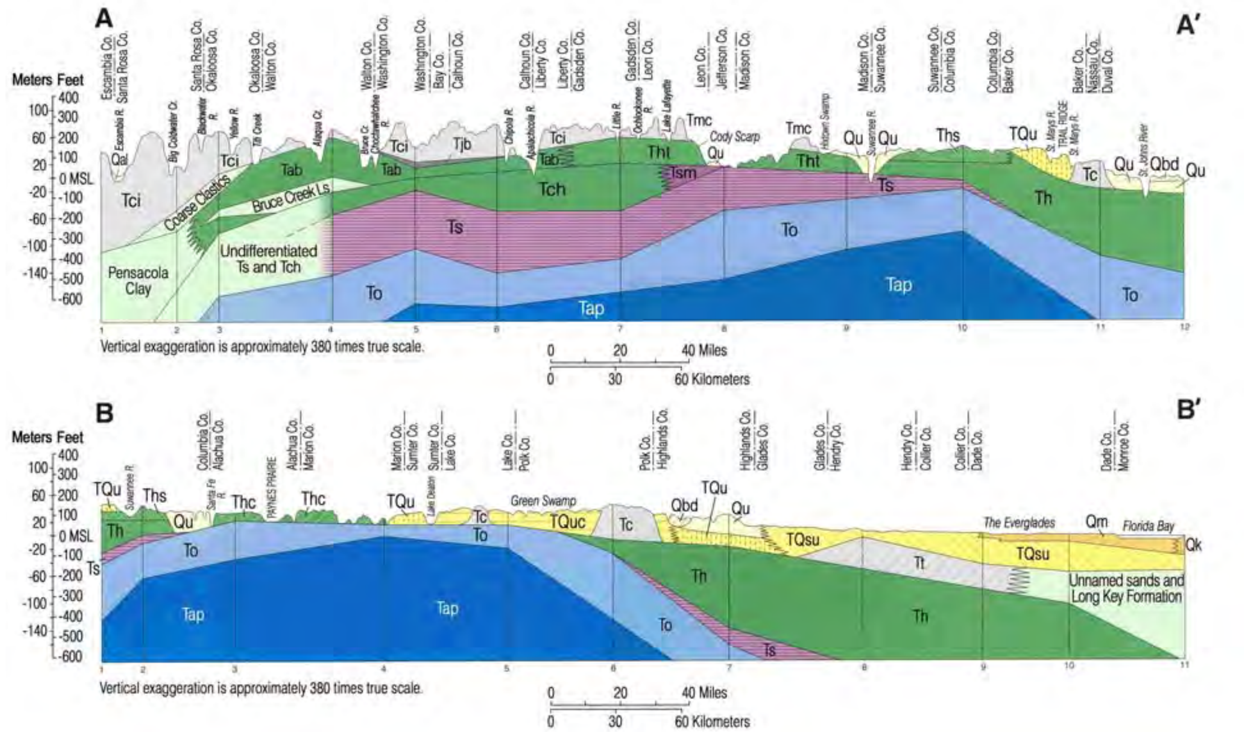


Figure 7C – Cross sections showing the shallow subsurface and surface distribution of Paleogene, Neogene and Quaternary lithostratigraphic units (Scott et al., 2001).

increased carbonate production on the southern portion of the platform allowed for the development of Miami Limestone (figure 6), a broad carbonate bank and oolite shoal complex, and Key Largo Limestone, the paleo-reef tract of Florida Keys. The Neogene–Quaternary sediments range in thickness from 0 to more than 914 m (3000 ft) (Miller 1986).

During the last glacial stage of the Pleistocene, sea level dropped approximately 122 m (400 ft) exposing vast portions of the Florida Platform that are presently beneath marine waters of the Gulf and Atlantic Ocean. Stream and river channels that can be seen on bathymetric maps provide evidence for erosion during sea-level lowstands.

Holocene sea level rose from approximately 18 m (60 ft) depth to the present level, and 8000 to 6000 years BP-archeological sites are found offshore in the Florida Big Bend (Faught and Donoghue 1997). Davis (1997) stated that the 3000 years BP-sea level was not significantly lower than the present sea level. Davis believes that much of the present-day coastline formed during the last 3000 years as the result of the relatively stable sea-level conditions. The Florida Everglades formed during this general time frame through the deposition of mangrove peat and freshwater calcitic mud covering a broad expanse of Miami Limestone.

The distribution of the Neogene and Quaternary units overlying the Paleogene sediments are shown in cross sections in figure 7. A generalized geologic map of Florida is shown in figure 8. The Neogene and Quaternary lithostratigraphic units occurring in the surface and shallow subsurface of the panhandle, northern, and southern portions of Florida are shown in figure 9.

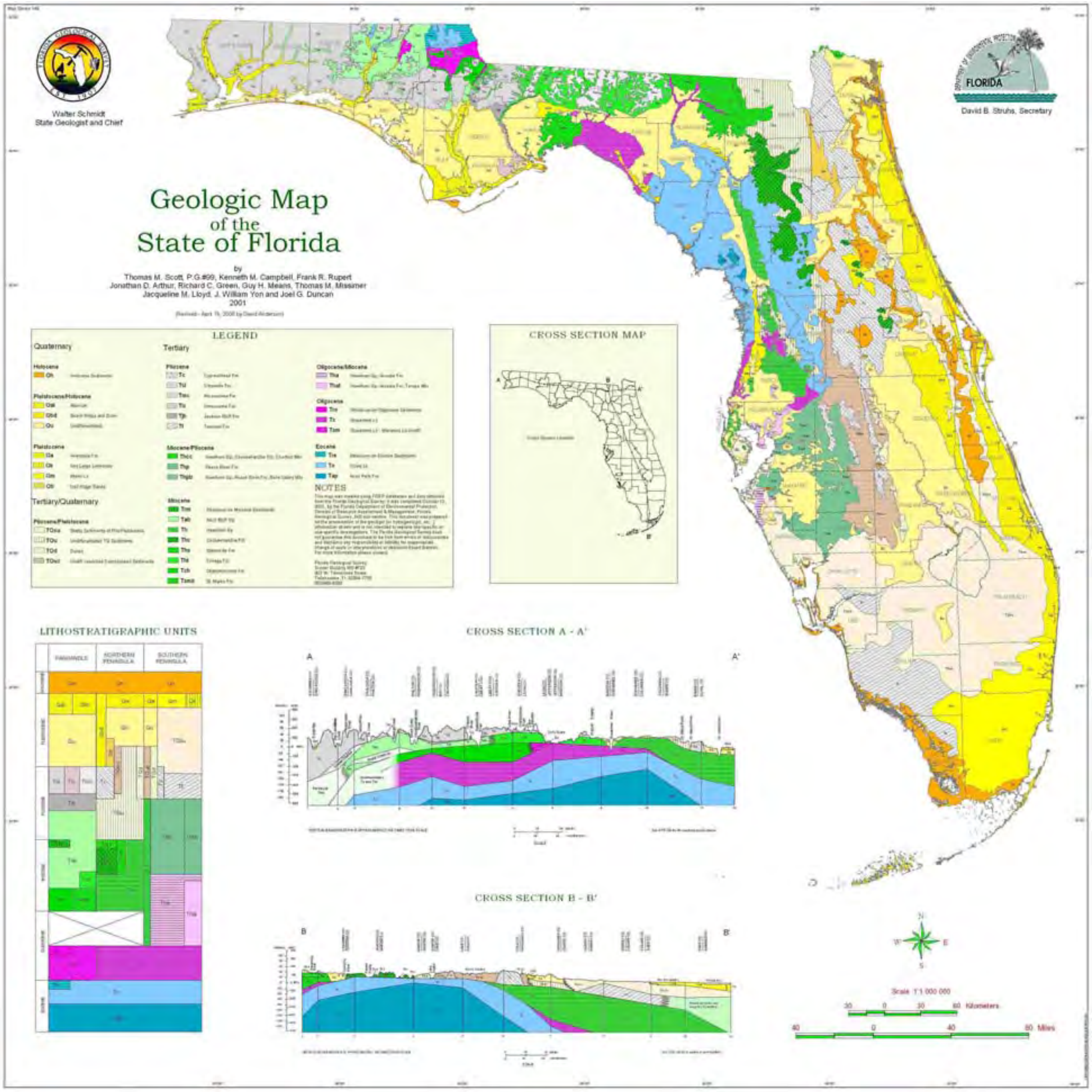


Figure 8 –Geologic map of Florida (Scott et al., 2001)

HYDROGEOLOGY

The Cenozoic sediments of Florida form a series of aquifer systems, which provide more than 90% of the drinking water for the state (Berndt et al. 1998). The aquifer systems are the Floridan, Intermediate, and Surficial (Southeastern Geological Society [SEGS] 1986; see Miller 1986 and Arthur et al. 2008 for overviews) (Figure 10).

The Floridan Aquifer System (FAS) is composed of Paleogene carbonates with highly variable permeability. This aquifer system, which is widespread in the southeastern United States, is one of the most productive aquifers in the world (Miller 1986; Berndt et al. 1998). Budd and Vacher (2004) characterize the Floridan as a multi-porosity aquifer: a fractured, porous aquifer where confined, and a karstic, fractured, porous aquifer where unconfined. The FAS

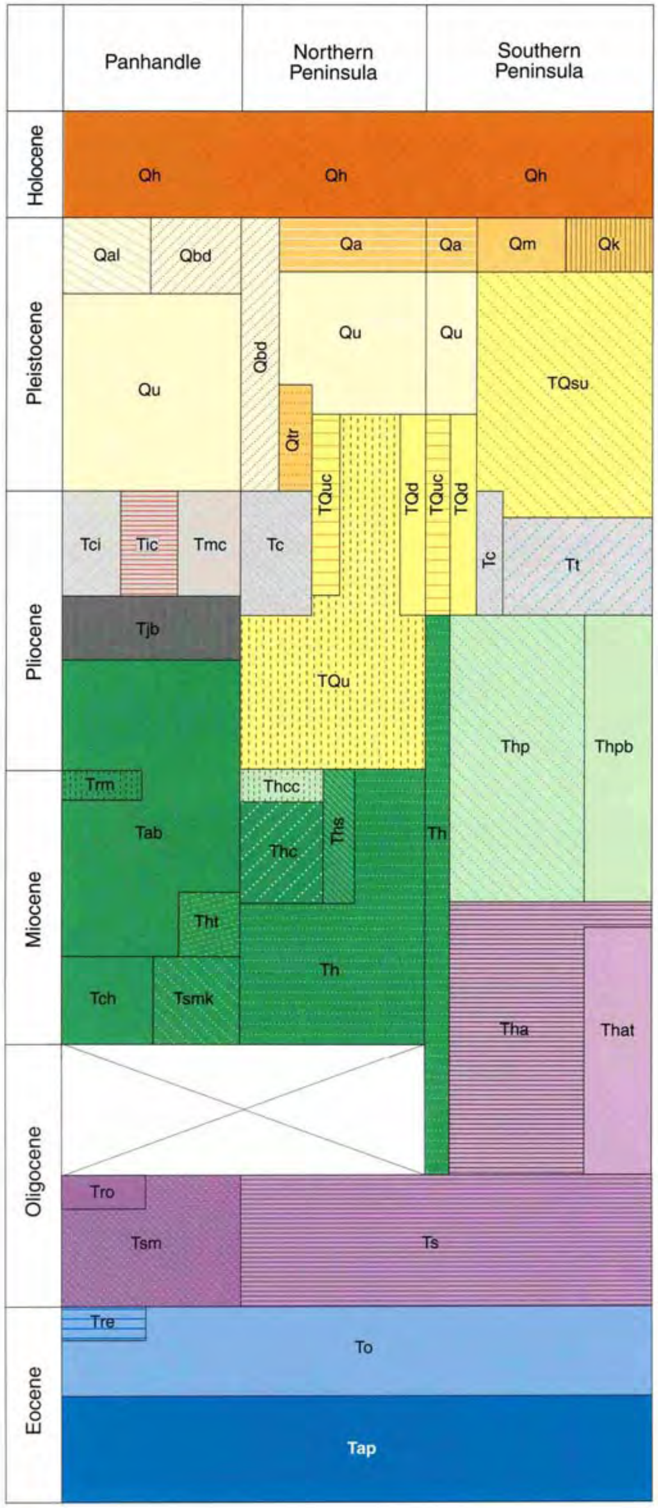


Figure 9 – Paleogene to Quaternary stratigraphic chart of Florida showing the lithostratigraphic units occurring in the shallow subsurface and at the surface (Scott et al., 2001).

occurs over the entire platform. The base of the FAS occurs in the lower Paleogene rocks where evaporites restrict the permeability (Miller 1986; SEGS 1986). The top occurs where the carbonates are overlain by impermeable sediments of the Intermediate Aquifer System or by surface sands.

The Intermediate Aquifer System (IAS) (referred to by the SEGS [1986] as the intermediate aquifer system/confining unit) is composed of permeable and impermeable

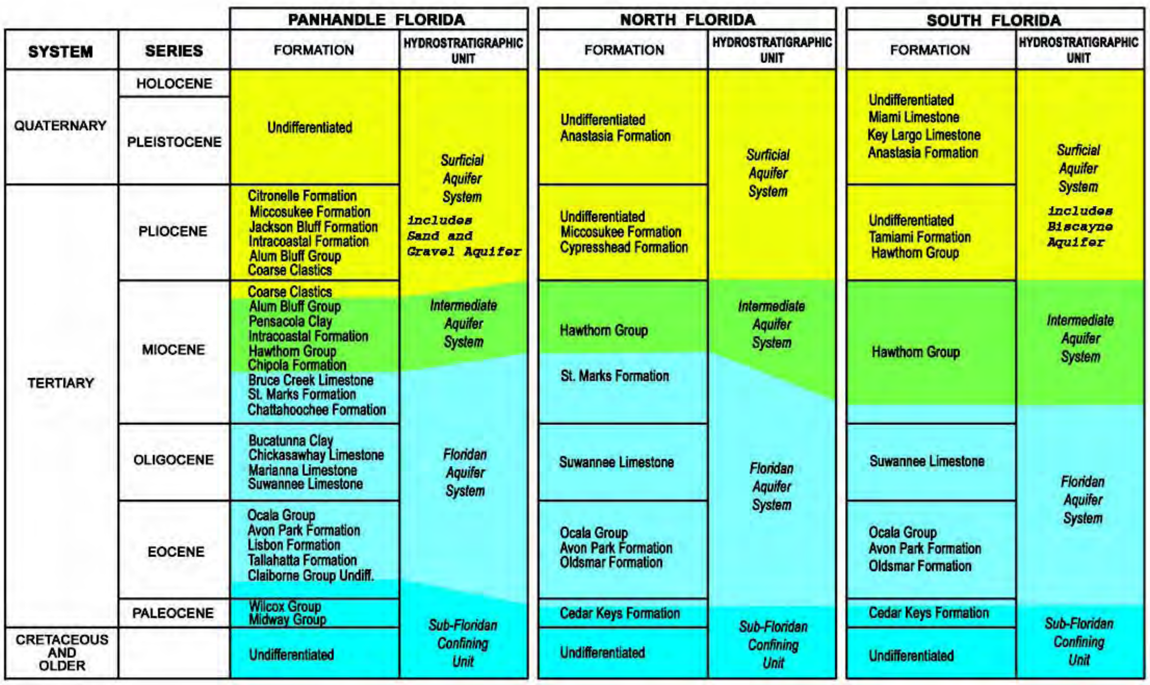


Figure 10 – Hydrostratigraphic nomenclature chart (modified from SEGS, 1986).

sediments deposited during the Neogene. The siliciclastics flooding onto the Florida Platform during the Miocene and Pliocene contained an abundance of clay. Deposition of the clayey sediments on the Paleogene carbonates created an impermeable sequence of confining beds (Miller 1986, 1997). Permeable carbonate and siliciclastic sediments are, in some areas, interbedded with the impermeable units creating regionally limited water-producing zones (Miller 1986, 1997). The base of the IAS occurs at the top of the regionally extensive, permeable carbonates of the FAS (SEGS 1986). The top of the IAS is placed at the top of the laterally extensive and vertically persistent lower permeability beds (SEGS 1986). The IAS is absent over much of the Ocala Platform.

The Surficial Aquifer System (SAS) is composed of late Pliocene through the Pleistocene–Holocene, permeable siliciclastic and carbonate sediments with some zones of more clayey, less-permeable sediments (Berndt et al. 1998). In two areas of the state, the SAS is particularly important since the FAS does not contain potable water. In these areas, the westernmost panhandle and southeastern peninsula, the SAS is the primary source of drinking water. In the western panhandle, the SAS is a thick sequence (up to 152 m [500 ft]) of siliciclastic sediments (Sand and Gravel Aquifer). In the southeastern peninsula, the SAS is made of very permeable, interbedded carbonates and siliciclastics, which underlie some of the largest metropolitan areas in Florida (Biscayne Aquifer). The base of the SAS occurs at the top of the laterally extensive and vertically persistent lower-permeability beds (SEGS 1986). The SAS is generally absent on the Ocala Platform.

GEOMORPHOLOGY

The Florida Platform extends southward from the continental United States separating the Gulf of Mexico from the Atlantic Ocean. The exposed portion of the platform, the Florida Peninsula, constitutes approximately one-half of the Florida Platform measured between the 200-m (600 ft) depth contour of the continental shelves. The axis of the platform extends northwest to southeast approximately along the present-day west coast of the peninsula. The Florida Peninsula, from the St. Mary's River to Key West, measures nearly 725 km (450 mi). From the Alabama–Florida line to the Atlantic coastline is approximately 595 km (370 mi).

Florida lies entirely within the Coastal Plain Physiographic Province as defined by Fenneman (1938) and is the only state in the United States that falls completely within the Coastal Plain. Much of the surface of Florida shows the influence of the marine processes that transported and deposited the later Tertiary, Quaternary, and Holocene sediments. Fluvial processes, although more important in the panhandle, have helped sculpt the entire state, particularly during the lowstands of sea level, redistributing the marine sediments.

Karst processes have had a dramatic effect on the Florida landscape due to the near-surface occurrence of soluble carbonate rocks. Middle Eocene to Pleistocene carbonate sediments are affected by karstification over large areas of the state. Siliciclastic sediments, ranging in thickness from a 1 m (3 ft) to more than 61 m (200 ft), overlie the karstified carbonates.

More than 700 springs are recognized in Florida with the major springs occurring within the karstic areas of the state (Scott et al. 2004). The vast majority of the springs are located in the Ocala Karst District, the Central Lake District, and the Dougherty Karst Plain District (Scott unpublished).

The general geomorphology of the Florida consists of east–west trending highlands in the northern and western portions of the state and north–south trending highlands extending approximately two-thirds the length of the peninsula. Coastal lowlands occur between the highlands and the coastline that wraps around the entire state. The highest point in the state, 105 m (345 ft) above sea level, occurs in the Western Highlands near the Alabama–Florida state line in Walton County. There are several hilltops in the Central Highlands that exceed 91 m (300 ft) msl in elevation. Florida has the distinction of having the lowest high point of any state in the United States.

White et al. (1964) and White (1958, 1970) delineated the geomorphic subdivisions that most geologists working in the state recognize (see Schmidt 1997 for a review). Scott is creating a new geomorphic map of the state (unpublished).

REFERENCES

Allmon, W. D., 1992, Whence southern Florida's Plio-Pleistocene shell beds?: *in* Scott, T. M., and Allmon, W. D., Plio-Pleistocene stratigraphy and paleontology of southern Florida: Florida Geological Survey Special Publication 36, pp.1-20.

Applegate, A. V., Winston, G. O., and Palacas, J. G., 1981, Subdivision and regional stratigraphy of the pre-Punta Gorda rocks (lowermost Cretaceous-Jurassic?) in south Florida; Gulf Coast Association of Geological Societies Transactions, Vol. 31, p447-453.

Arthur, J. A., 1988, Petrogenesis of the Early Mesozoic tholeiite in the Florida basement and an overview of Florida basement geology: Florida Geological Survey Report of Investigation No. 97, 39 p.

Arthur, J. A., Fischler, F., Kromhout, C., Clayton, J., DeWitt, D., Kelley, M., Lee, R.A., Li, L., O'Sullivan, M., Green, R., Thompson, R., and Werner, C., 2005, in preparation, Hydrogeologic Framework of the Southwest Florida Water Management District: Florida Geological Survey Bulletin 68

Barnett, R. S., 1975, Basement structure of Florida and its tectonic implications: Gulf Coast Association of Geological Societies Transactions, Vol. 25, pp. 122-142.

Berndt, M. P., Oaksford, E. T., and Mahon, G. L., 1998, Groundwater: *In* E. A. Fernald and E. D. Purdum (Eds.), Water Resources Atlas of Florida: Florida State University Tallahassee, FL, pp. 38-63.

Bourgeois, J., Hansen, T.A., Wiberg, P.L., and Kauffman, E.G., 1988, A tsunami deposit at the Cretaceous-Tertiary boundary in Texas: Science, v. 241, pp. 567–570.

Braunstein, J., Huddlestun, P., and Biel, R., 1988, Gulf Coast Region, Correlation of Stratigraphic Units of North America (COSUNA) Project: American Association of Petroleum Geologists, 1 plate.

Brewster-Wingard, G.L., Scott, T.M., Edwards, L.E., Weedman, S.D., and Simmons, K.R., 1997, Reinterpretation of the peninsular Florida Oligocene: an integrated stratigraphic approach: Sedimentary Geology, v. 108, pp.207-228.

Bryan, J. R., 1991, Stratigraphic and paleontologic studies of the Paleocene and Oligocene carbonate facies of the eastern Gulf Coastal Plain: unpublished Ph. D. dissertation, University of Tennessee, Knoxville, TN, 324 p.

Budd, D. A., and Vacher, H. L., 2004, Matrix permeability of the confined Floridan Aquifer, Florida, USA: Hydrogeology Journal Vol. 12, no. 5, pp.531-549.

Chowns, T. M., and Williams, C. T., 1983, Pre-Cretaceous rocks beneath the Georgia Coastal Plain: Regional implications: *in* Gohn, G. S., editor, Studies related to the Charleston, South Carolina, earthquake of 1886: Tectonics and seismicity: U.S. Geological Survey Professional Paper 1313l, 42 p.

Colquhoun, D. J., Herrick, S. M., and Richards, H. G., 1968, A fossil assemblage from the Wicomico Formation in Berkeley County, South Carolina: Geological Society of America Bulletin Vol. 79, pp. 1211-1220.

Compton, J. S., 1997, Origin and paleogeographic significance of Florida's phosphorite deposits: *in* Randazzo, A. F., and Jones, D. S., 1997, The geology of Florida, University Press, Gainesville, FL, pp. 195-216.

Cunningham, K., McNeill, D., Guertin, L., Ciesielski, P., Scott, T., and de Verteuil, L., 1998, New Tertiary stratigraphy for the Florida Keys and southern peninsula of Florida: Bulletin, Geological Society of America, v. 110, n. 2, pp.231-258.

Cunningham, K., Locker, S. D., Hine, A. C., Bukry, D., Barron, J. A., and Guertin, L. A., 2003, Interplay of late Cenozoic siliciclastic supply and carbonate response on the southeast Florida Platform: Journal of Sedimentary Research, Vol. 73, no. 1, pp. 31-46.

Dallmeyer, R. D., Caen-Vachette, M., and Villeneuve, M., 1987, Emplacement age of post-tectonic granites in southern Guinea (West Africa) and the peninsular Florida subsurface: Implications for the origins of southern Appalachian exotic terranes: Geological Society of America Bulletin Vol. 99, pp. 87-93.

Duncan, J. G., Evans, W. L. III, and Taylor, K. L., 1994, Geologic framework of the lower Floridan Aquifer System, Brevard County, Florida: Florida Geological Survey Bulletin 64, 90 p., 5 plates.

Fenneman, N.M., 1938, Physiography of Eastern United States: McGraw-Hill Book Company, Inc., New York, 714 p.

Guertin, L. A., 1998, A late Cenozoic mixed carbonate/siliciclastic system, south Florida: lithostratigraphy, chronostratigraphy and sea-level record: Ph. D. dissertation, University of Miami, 424 p.

Guertin, L.A., Missimer, T. M., and McNeill, D. F., 2000, Hiatal duration of correlative sequence boundaries from Oligocene-Pliocene mixed carbonate/siliciclastic sediments of the south Florida Platform: Sedimentary Geology Vol. 134, pp. 1-26.

Heatherington, A. L., and Muller, P.A., 1997, Geochemistry and origin of Florida crustal basement terranes: *in* Randazzo, A. F., and Jones, D. S., 1997, The geology of Florida, University Press, Gainesville, FL, pp. 27-37.

Hildebrand A. R., Penfield G. T., Kring D. A., Pilkington M., Camargo Z. A., Jacobsen S. B. and Boynton W. V., 1991, Chicxulub crater: a possible Cretaceous/Tertiary boundary impact crater on the Yucatan Peninsula, Mexico, Geology Vol. 19, pp. 867-871.

Huddlestun, P. F., 1993, The Oligocene: Georgia Geologic Survey Bulletin 105, 152 p., 5 plates.

Jones, D. S., 1997, The marine invertebrate fossil record of Florida: *in* Randazzo, A. F., and Jones, D. S., 1997, The geology of Florida, University Press, Gainesville, FL, pp. 89-117.

Kring, D. A., 2000, Impact events and their effect on the origin, evolution and distribution of life: GSA Today, Vol. 10, no. 8, pp. 1-7.

Leve, G. W, 1966, Ground water in Duval and Nassau Counties, Florida: Florida Geological Survey Report of Investigations no. 43, 91 p.

Lichtler, W. F., Anderson, W., and Joyner, B. F., 1968, Water resources of Orange County, Florida: Florida Geological Survey Report of Investigations no. 50, 150 p.

Lloyd, J. M., 1989, 1986 and 1987 Florida petroleum production and exploration: Florida Geological Survey Information Circular 106, 39 p.

Lloyd, J.M., 1997, 1994 and 1995 Florida petroleum production and exploration: Florida Geological Survey Information Circular 111, 62 p.

Matsui, T., Imamura, F., Tajika, E., Nakano, Y., and Fujisawa, Y., 1999, K-T impact tsunami: Houston, Texas, Lunar and Planetary Institute, Lunar and Planetary Science XXX, Abstract #1527, CD-ROM.

McBride, J. H., and Nelson, K. D., 1988, Integration of COCORP deep reflection and magnetic anomaly analysis in the southeastern United States: Implications for the origin of the Brunswick and East Coast magnetic anomalies: Geological Society of America Bulletin, Vol. 100, no. 3, pp. 436-445.

McFarlan, E., and Menes, L. S., 1991, Chapter 9 – Lower Cretaceous: *in* Salvador, A., editor, The Gulf of Mexico Basin, The Geology of North America, Volume J, Geological Society of America, pp. 181-204.

Miller, J. A., 1986, Hydrogeologic framework of the Floridan Aquifer System in Florida, and in parts of Georgia, Alabama and South Carolina: U. S. Geological Survey Professional Paper 1403-B, 91 p., 33 plates.

Miller, J.A., 1997, Hydrogeology of Florida: *in* Randazzo, A. F., and Jones, D. S., 1997, The geology of Florida, University Press, Gainesville, FL, pp. 69-88.

Missimser, T. M., 2001, Siliciclastic facies belt formation and the Late Oligocene to Middle Miocene partial drowning of the southern Florida Platform: Gulf Coast Association of Geological Societies Transactions, Vol. LI, pp. 229-238.

Missimser, T. M., 2002, Late Oligocene to Pliocene evolution of the central portion of the south Florida Platform: Mixing of siliciclastic and carbonate sediments: Florida Geological Survey Bulletin 65, 184 p., 6 plates.

Missimser, T. M., Maliva, R. G., Walker, C. W., and Owosina, E., 2000, Anatomy of a nearshore mixed siliciclastic-carbonate deposit, the Plio-Pleistocene of southern Broward County, Florida: Gulf Coast Association of Geological Societies Transactions, Vol. L, pp. 111-128.

Missimser, T. M., and Maliva, R. G., 2004, Tectonically induced fracturing, folding and groundwater flow in south Florida: Gulf Coast Association of Geological Societies Transactions, Vol. 54, pp. 443-459.

Opdyke, N. D., Jones, D. S., MacFadden, B. J.,Smith, D. L., Muller, P. A., and Schuster, R. D., 1987, Florida as an exotic terrane: Paleomagnetic and geochronologic investigation of the lower Paleozoic rocks from the subsurface of Florida: Geology, Vol. 15, pp. 900-903.

Pirkle, W. A., 1970, The offset course of the St. Johns River, Florida: Southeastern Geology Vol. 13, pp. 39-59.

Puri, H.S., and Vernon, R.O., 1964, Summary of the geology of Florida and a guidebook to the classic exposures: Florida Geological Survey Special Publication 5 (revised), 312 p.

Randazzo, A. F., 1997, The sedimentary platform of Florida: Mesozoic to Cenozoic: *in* Randazzo, A. F., and Jones, D. S., 1997, The geology of Florida, University Press, Gainesville, FL, pp. 39-56.

Riggs, S. R., 1979, Phosphorite sedimentation in Florida – a model phosphogenic system: Economic Geology, Vol. 74, pp. 285-314.

Salvador, A., 1991a, Introduction: *in* Salvador, A., editor, The Gulf of Mexico Basin, The Geology of North America, Volume J, Geological Society of America, pp. 1-12.

Salvador, A., 1991b, Chapter 8 – Triassic-Jurassic: *in* Salvador, A., editor, The Gulf of Mexico Basin, The Geology of North America, Volume J, Geological Society of America, pp. 131-180.

Schlee, J. S., Manspeizer, W., and Riggs, S. R., 1988, Paleo-environments: Offshore Atlantic U.S. margin: *in* Sheridan, R. E., and Grow, J. A., Geological Society of America, The Atlantic continental margin: The Geology of North America, Vol. I-2, pp. 365-385.

Schmidt, W., 1984, Neogene stratigraphy and geologic history of the Apalachicola Embayment, Florida: Florida Geological Survey Bulletin 58, 146 p.

Schmidt, W., 1997, Geomorphology and physiography of Florida: *in* Randazzo, A. F., and Jones, D. S., 1997, The geology of Florida, University Press, Gainesville, FL, pp. 1-12.

Schultz, P. H., 1996, Cretaceous-Tertiary (*Chicxulub*) impact angle and its consequences: Geology Boulder Vol. 24, no. 11, pp. 963-967.

Scott, T. M., 1988, the lithostratigraphy of the Hawthorn Group (Miocene) of Florida: Florida Geological Survey Bulletin 59, 148 p.

Scott, T. M., 1992, A geological overview of Florida: Florida Geological Survey Open File Report 50, 78 p.

Scott, T. M., 1997, Miocene to Holocene history of Florida: : *in* Randazzo, A. F., and Jones, D. S., 1997, The geology of Florida, University Press, Gainesville, FL, pp. 57-67.

Scott, T. M., 2001, Text to accompany the geologic map of Florida: Florida Geological Survey Open File Report 80, 29 p.

Scott, T. M., and Allmon, W. D., 1992, Plio-Pleistocene stratigraphy and paleontology of southern Florida: Florida Geological Survey Special Publication 36, pp.1-20.

Scott, T. M., Campbell, K.M., Rupert, F.R., Arthur, J.D., Green, R.C., Means, G.H., Missimer, T.M., Lloyd, J.M., Yon, J.W., and Duncan, J.D., 2001, Geologic map of the State of Florida: Florida Geological Survey Map Series 146.

Scott, T. M., Means, G.H., Meegan, R.P., Means, R.C., Upchurch, S.B., Copeland, R. E., Jones, J., Roberts, T., and Willett, A., 2004, Springs of Florida: Florida Geological Survey Bulletin 66, 377 p. plus CD

Smith, D. L., 1982, Review of the tectonic history of the Florida basement: Tectonophysics, Vol. 88, pp. 1-22.

Smith, D.L., and Lord, K. M., 1997, Tectonic evolution and geophysics of the Florida basement: *in* Randazzo, A. F., and Jones, D. S., 1997, The geology of Florida, University Press, Gainesville, FL, pp. 13-26.

Sohl, N. F., Martinez, E., Salmeron-Urena, P., and Soto-Jaramillo, F., 1991, Chapter 10 – Upper Cretaceous: : *in* Salvador, A., editor, The Gulf of Mexico Basin, The Geology of North America, Volume J, Geological Society of America, pp. 205-244.

Southeastern Geological Society, 1986, Hydrogeological units of Florida: Florida Geological Survey Special Publication 28, 8 p.

Stuckey, J. L., 1965, North Carolina: Its geology and mineral resources: North Carolina Department of Conservation and Natural Resources, 550 p.

Thomas, W. A., Chowns, T. M., Daniels, D. L., Neathery, T. L., Glover, L. III, and Gleason, R. J., 1989, The subsurface Appalachians beneath the Atlantic and Gulf Coastal Plains: *in* Hatcher, R. D., Thomas, W. A., and Viele, G. W., editors, The Appalachian-Ouachita orogen in the United States: Geological Society of America, The Geology of North America, Vol. F-2, pp. 445-458.

Upchurch, S. B., Strom, R. N., and Nuckels, M. G., 1982, Silicification of Miocene rocks from central Florida: *in* Scott, T. M., and Upchurch, S. B., Miocene of the southeastern United States: Florida Bureau of Geology Special Publication 25, pp. 251-284.

Warzeski, E. R., Cunningham, K. J., Ginsburg, R. N., Anderson, J. B., and Ding, Z. D., 1996, Neogene mixed siliciclastic and carbonate foundation for the Quaternary carbonate shelf, Florida Keys: Journal of Sedimentary Research, Vol. 66, pp. 788-800.

Weaver, C. E., and Back, K. C., 1977, Miocene of the southeastern United Sates: A model for chemical sedimentation in a peri-marine environment: Sedimentary Geology, Vol. 17, pp. 1-234.

White, W.A., 1958, Some geomorphic features of central peninsular Florida: Florida Geological Survey Bulletin 41, 92 p.

White, W.A., 1970, The geomorphology of the Florida peninsula: Florida Geological Survey Bulletin 51, 164 p.

White, W.A., Puri, H.S., and Vernon, R.O., 1964, Physiographic setting: in Puri, H.S., and Vernon, R.O., 1964, Summary of the geology of Florida and a guidebook to the classic exposures: Florida Geological Survey Special Publication 5 (revised), 312 p.

Winston, G. O., 1987, Generalized stratigraphy and geologic history of the South Florida Basin: *in* Maurrasse, F. J-M. R., Symposium on South Florida geology: Miami Geological Society Memoir 3, pp. 230-233.

Winston, G.O., 1991, Atlas of structural evolution and facies development on the Florida-Bahama Platform – Triassic through Paleocene: Miami Geological Society, 39 p.

Woods, R. D., Salvador, A., and Miles, A. E., 1991, Chapter 7 – Pre-Triassic: : *in* Salvador, A., editor, The Gulf of Mexico Basin, The Geology of North America, Volume J, Geological Society of America, pp. 109-129.

Wyrick,G. G., 1960, The ground water resources of Volusia County, Florida: Florida Geological Survey Report of Investigations 22, 65 p.

SHALLOW DEPRESSIONS IN THE FLORIDA COASTAL PLAIN: KARST AND PSEUDOKARST

Sam B. Upchurch
SDII Global Corporation
4509 George Road
Tampa, Florida 33634

Thomas M. Scott
SDII Global Corporation
4509 George Road
Tampa, Florida 33634

Michael C. Alfieri
WRA Engineering
4260 West Linebaugh Avenue
Tampa, Florida 33624

Thomas L. Dobecki
SDII Global Corporation
4509 George Road
Tampa, Florida 33634

Abstract

In Florida, shallow depressions (i.e., depressions $<$1-2 m in depth) on the land surface are often attributed to sinkhole development. However, it has become evident that there are at least seven different mechanisms through which these depressions can form in Florida's geologically young cover sediments. These mechanisms include:

1. Cover-subsidence sinkholes over shallow limestone;
2. Suffosion sinkholes over shallow limestone;
3. Cover settlement over shallow shell beds;
4. Large, aeolian deflation areas that resemble "Carolina bays";
5. Aeolian deflation depressions within dune trains;
6. Depressions that mimic landforms developed on a shallow paleosol; and
7. Depressions created by pedodiagenesis (i.e., conversion of smectite to kaolinite) in a soil-forming environment.

Of these, only the first two appear to represent traditional mechanisms for sinkhole development in eogenetic karst. Cover settlement over shell beds is poorly understood and incorrectly attributed to sinkhole-development processes. Development of this type of depression is limited by cover thickness, textural, and shell content constraints. The last three mechanisms are pseudokarst features created by aeolian and soil-forming processes. In this paper we present examples of each and discuss their constraints and evidence.

Introduction

As a result of Florida's statutory requirement for sinkhole insurance coverage, much emphasis has been placed on identification of locations where sinkholes are developing and causing property damage. One issue related to identification of existing sinkholes deals with the origins of shallow, nearly circular to amoeboid depressions in the land surface (Figure 1), which abound in Florida. These features vary from seasonal wetlands, shallow ponds, to indistinct, dry depressions. One issue that is widely debated is whether or not these shallow depressions in the land surface represent cover-subsidence sinkholes (White 1988 and Beck and Sinclair 1986) [a.k.a. solution dolines, Field 2002].

Figure 1. **Closed depressions in the Big Cypress Swamp in Collier County, southwestern Florida. Depressions are seasonal wetlands**

Over the last few decades, the authors have conducted over 10,000 sinkhole investigations using surface geophysics, standard penetration testing (SPT), and cone penetrometer test (CPT) methods, studied cross sections of depressions exposed in quarries and borrow pits, and mapped these depressions. This paper presents our observations as to the origins of these depressions. Complete descriptions and data will be presented in a textbook, which is being written by the authors.[1]

Overview

Based on our observations, it is apparent that closed depressions in Florida have a number of possible origins, some of which are karst-related while others can be considered pseudokarst (Field 2002, Halladay 2007). We have identified at least seven different mechanisms for formation of these depressions (Table 1), including

1. Cover-subsidence sinkholes over shallow limestone;
2. Suffosion sinkholes over shallow limestone;
3. Cover settlement over shallow shell beds;
4. Large, aeolian deflation areas that resemble "Carolina bays";
5. Aeolian deflation depressions within dune trains;
6. Depressions that mimic landforms developed on a covered, shallow paleosol; and
7. Depressions created by pedodiagenesis (i.e., conversion of smectite to kaolinite) in a soil-forming environment.

Visual identification of the depression is insufficient to determine its cause. Only subsurface testing combined with petrographic examination of the carbonate fractions in the sediment can truly determine if the depression was caused by dissolution of limestone or shell material.

[1] This paper is reprinted from D.H. Doctor, L. Land, and J.B. Stephenson (Eds.), Sinkholes and the Engineering and Environmental Impacts of Karst, Proceedings of the 14th Multidisciplinary Conference, Rochester, MN, pp. 231-240.

Table 1. Summary of the types and properties of surficial depressions observed on the Florida coastal plain.

Depression Type	Mode of Depression Development	Rate of Development	Probable Evidence	Predominant Scale and Shape
Cover-subsidence sinkhole [solution doline]	Soil/sediment subsidence as result of dissolution of limestone surface	Slow (thousands to hundreds of thousands of years)	1. Limestone fragments that show evidence of dissolution 2. Leached sand and/or organics in depression sediments	<100 m in diameter; relatively circular unless they intersect each other
Suffosion sinkhole	Raveling of non-cohesive sediment into pre-existing void space in limestone	Varies, may be rapid or moderately slow (decades to centuries) if void space volume limits ability of cover materials to ravel	1. Non-cohesive sediment directly overlies limestone 2. Disruption of sediment structure in void fill and slopes of depression	<10 m in diameter; more or less circular
Cover settlement over shell beds	1. Dissolution of shell 2. Minor consolidation and sediment migration into primary porosity	Slow (thousands to hundreds of thousands of years)	1. Shell fragments that show evidence of dissolution 2. Crushing of shells and traces of collapsed and dissolved shell	<100 m in diameter; more or less circular unless they intersect each other
"Carolina bays"	1. Lowering of water table, possibly as a result of sinkhole development, allows for fine sand to be eroded by wind stress. 2. Low basin forms at upwind end of depression and a parabolic dune train accumulates at the downwind end of the depression. 3. Deflation within the "bay" reveals depressions and possible relict sinkholes in the bottom of the larger, deflation-derived depression	Apparently not forming today; assumed to be formed on the scale of decades	1. Lake, pond, or wetland depression within larger depression at point of maximum deflation 2. In Florida, the deepest area within the larger depression is located on the southwest end of the northeast to southwest oriented feature 3. Parabolic dunes developed on upwind, northeastern quarter of the larger depression	Long axis of large depression is up to 1,000 m. Smaller sinkhole-like depressions within the deflation zone are typically more or less circular and up to 100 m in diameter. Depressions are ovoid with long axis oriented northeast to southwest, the apparent prevailing wind direction;
Aeolian deflation depressions	Erosion by wind stresses within dune trains	May be rapid depending on wind stresses and vegetation cover	No subsurface expression; deflation zones typically parallel dune long axes	Depressions are complex and may be elongated, oriented parallel to the long axes of the dune train; the long axes of the depressions are typically less than 100 m
Depressions over paleosol and epikarst features	1. Fine-grained, marine terrace sand deposited over, and infilling, existing depressions developed on the late Miocene to early Pliocene paleosol 2. Consolidation and minor, early compaction of the relatively thicker sand within the infilled depressions causes development of depressions in the land surface	Slow (hundreds to thousands of years)	1. Depression floored by paleosol with no evidence of deeper limestone dissolution 2. Infilling sediments down warped by compaction; wetland or stream sediments may be included within fill materials	Scale varies with circular depressions up to 200 m and streams kilometers in length. Depressions are circular to linear; infilled stream systems are often occupied by modern streams;
Pedogenetic depressions	Late Miocene to early Pliocene alteration of Miocene smectite to kaolinite, a pedogenetic process, causes volume reduction and land-surface depressions	Very slow (thousands to millions of years)	Clay flooring and bordering depression is kaolinite rich as compared to more distant, smectite-rich sediments	Scale unknown; presumed to be more or less circular

Furthermore, use of estimates of the rate of development of the depression are insufficient to determine if the cause of the depression is cover subsidence, a process wherein the rate of subsidence is governed by the rate of carbonate dissolution, which takes thousands to hundreds of thousands of years to create volume loss sufficient to cause a depression. Cover-collapse sinkholes are also common in Florida, and the rate of cover collapse can be sudden, occurring in minutes to hours, or slow if the void into which the cover collapses has limited volume or the collapsed materials undergo long-term consolidation.

Mechanisms of Depression Formation

The following sections present the authors' opinions as to origins and examples of each of these depression-forming mechanisms.

Cover-Subsidence Sinkholes

True, cover-subsidence sinkholes (Table 1) are common in those areas of Florida where limestone is within a few meters of the land surface. They form as the upper surface of the limestone is dissolved away and the cover materials (sand- and clay-rich sediments) slowly subside to replace the volume lost to dissolution. The dissolution surface is often in the vadose zone, but evidence of cover-subsidence in shallow phreatic environments has been observed. Simple SPT boring observations do not allow for determination as to whether the phreatic dissolution surfaces are currently undergoing dissolution or not. A geochemical investigation is required to make this determination.

Even if dissolution is currently underway, the rate of subsidence is governed by the rate of dissolution of the carbonate rock, not by collapse mechanisms. This is of special interest in many areas of Florida where the limestone is overlain by Mio-Pliocene clayey sediments and/or Quaternary marine sand deposits. If the limestone is in contact with clay, dissolution may be limited because of permeability and groundwater flow-path limitations.

In addition to the relative depth of the water table and lithology of the cover material, there appears to be a cover thickness issue that limits the depth to which dissolution of the upper limestone surface can create a land-surface depression. In Florida's predominantly sandy cover materials, small amounts of limestone dissolution and concomitant settlement of the sand causes dilatation and a slight increase in porosity of the sand cover. This loss of packing density and increase in porosity must be of sufficient magnitude to translate to the land surface and cause a depression to develop.

It is important to understand the difference between cover subsidence and cover collapse. This paper deals only with cover subsidence sinkholes, which form at the rate of dissolution of the underlying carbonate stratum and where the cover materials are sandy marine strata, not weathering residue. Cover-subsidence sinkholes, therefore, develop over time frames of hundreds to thousands of years.

Cover collapse occurs as a result of failure of sediments that bridge voids. The collapse may be a result of piping failure or loss of resistance to bridging forces over a void. As a result, cover-collapse sinkholes in the Florida coastal plain develop rapidly (hours to years) in cover sediments that exhibit sufficient cohesion or structural strength to bridge a void. Because of their mode of development, cover-collapse sinkholes can be quite deep.

Suffosion Sinkholes

Suffosion or simple raveling without concomitant collapse of non-cohesive sediments into pre-existing void space can also cause small-scale depressions. These are common where the limestone is geologically young, near the land surface, and covered with sand, not insoluble residues created by limestone dissolution. The most notable locations are in the Miami and Big Cypress Swamp areas of southern Florida where limestone is within a meter of the land surface and the cover is non-cohesive sand. Figure 2 illustrates solution holes in the caprock of southern Florida. These solution holes and pipes are commonly sites where sand migrates downward creating small, suffosion-related depressions.

Figure 2. Caprock, a sandy limestone formed by repeated wetting and drying of shelly sand, penetrated by solution channels through which suffosion of sand occurs. Rock has been turned vertically on edge to serve as "yard art."

Depressions Caused by Cover Settlement over Shell Beds

Whether or not depressions caused by cover settlement over shell beds represent cover-subsidence sinkholes is problematic. These depressions are common on land surfaces underlain by late Neogene and Quaternary sand and shell strata. Where they exist and appear to be related to dissolution of shell material, the shell material is observed to be at a minimum of 50 percent of the sediment volume, and within a few meters of the land surface. Observations of hundreds of these features in SPT borings and borrow pits indicate that sediments with less than at least 50 percent shell material and deeper than about 3 m do not cause depressions or subsidence at the land surface because of lack of shell dissolution and the volume constraints mentioned under cover-subsidence sinkholes above.

White (1970) discussed the origins of these features in southern Florida and attributed them to both dissolution of carbonate sediments and differential settlement after oxidation and/or compression of organic sediments. He referred to these depressions as sag features. Schmidt and Scott (1984) referred to them as "karst depressions."

Recognition of shallow subsidence features developed by dissolution of shallow shell beds requires petrographic examination of the shells immediately under these depressions in order to determine if the shells and/or shell fragments have undergone substantial dissolution. Note that a very large proportion of the shell (>>50%) must be removed in order to create sufficient volume reduction for a depression to form. Evidence of dissolution includes rounding of sharp corners, erosion of shell decorations, development of shiny surfaces as if the shells were dipped in acid, and/or development of "punky", earthy surfaces as aragonitic components are selectively removed from the shell by dissolution. In many examples, the shell has been completely removed and only the "ghosts" of collapsed shells and/or molds of shells remain (Figure 3B).

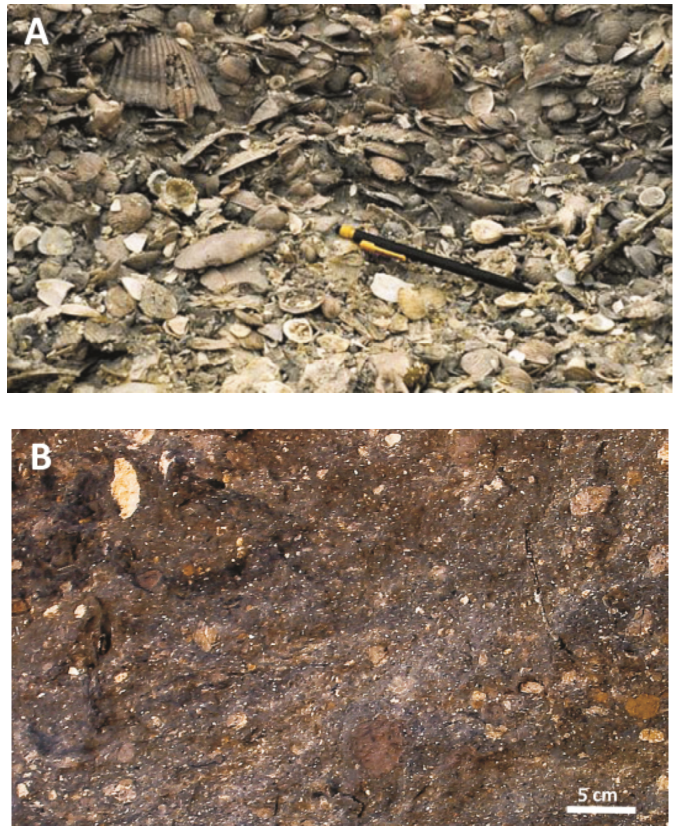


Figure 3. Examples of unweathered and undissolved shell material (A) and weathered shell material from a shallow depression (B). Note the angular and well-decorated shells in A and the rounded and highly dissolved shells in a stratum enriched in ferric hydroxide and organics in B, where collapsed shells and molds are common.

Siliciclastic sediments in soil zones where the shell has been weathered and subjected to dissolution often contain abundant ferric hydroxide, which gives the sediment/soil a reddish hue, organics, and crude Liesegang banding is often present.

Depressions That Resemble "Carolina Bays"

In west-central Florida there are at least ten large, shallow depressions that resemble "Carolina bays." Carolina bays are circular to oval wetland depressions that occur on the Atlantic Coastal Plain from New York to Florida. Swarms of the bays have a common orientation, which suggests a common origin, and they often have small, parabolic sand dunes at one end of the elliptical depressions (the presumed down-wind side). The common orientation and dunes suggest that wind, or some other unidirectional transport mechanism played a role in their formation.

The origin of the Carolina bays has been the subject of a long, and sometimes intense, debate. The origins of Carolina bays have been attributed to one, or a combination of, the following processes:

- Meteorite or comet impacts (Prouty 1935 1952; Wells and Boyce 1953);
- Substrate dissolution and sinkhole development (LeGrand 1953; May and Warne 2004; Willoughby 2007);
- Deflation as a result of eolian erosion and transport (Grant et al. 1998; Ivester et al. 2007); and
- Marine sedimentation patterns (Cooke 1954).

See also Eyton and Parkhurst (1975) for a summary of these diverse potential causes.

Carolina bays are thought to have formed sometime in the period from 10,000 to 100,000 years ago (Schalles et al. 1989; Brooks et al. 2001; Ivester et al. 2007).

There exist in Florida a number of circular depressions that bear some resemblance to Carolina bays. They are circular to elliptical in outline, occur in clusters, and the depressions show a common orientation from southwest to northeast. They have parabolic, aeolian dunes in the northeast quadrant, the apparent down-wind quadrant of the depressions. Most have small ephemeral lakes or wetlands near the center or southwest third of the depression. The interiors of the wetlands are dotted with what appear to be sinkholes, and SPT testing within the large depressions often presents evidence of sinkhole development and covered epikarst.

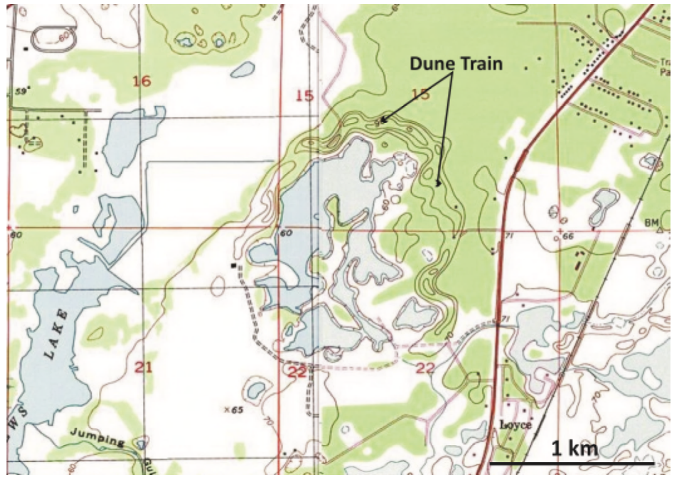


Figure 4. An example of a Carolina bay-like depression in west-central Florida. Note the parabolic dune train in the northeastern quadrant and the ephemeral lake/wetland in the center and southwestern quadrant.

We hypothesize that these depressions were formed as a result of localized dewatering of sandy sediments, most likely as a result of sinkhole development during the Pleistocene. The dry, fine sand was then entrained by prevailing winds and accumulated in down-wind locations to form the parabolic dunes.

Aeolian Deflation Depressions

Florida has extensive, Pleistocene and Holocene aeolian dune fields. These are related to the modern coasts and ancient marine terraces. As is normal, these dunes are characterized by numerous inter-dune and dune-slope depressions. They have more or less circular to linear outlines and present on topographic maps and in the field as closed depressions, often with wetlands.

Because of the closed depressions on topographic maps, they have been mistaken for sinkholes, which are commonly interspersed with the deflation depressions. Only subsurface testing can differentiate them.

Depressions over Paleosols

One of the most remarkable features of west-central Florida's Polk-Desoto Plain Physiographic Province can only be appreciated from the air. As one flies over the area, the large number of circular, wetland depressions and streams with trellis drainage patterns becomes evident (Figure 5).

Observation of these depressions in cross section in phosphate mine cuts and in SPT borings indicates that many of these features are associated with the late Miocene/early Pliocene weathering surface, which resulted in a paleosol that is locally termed the "leached zone" (Altschuler et al. 1951; Van Kauwenburgh et al. 1990).

Figure 5. **View of a portion of the Polk-DeSoto Plain Physiographic Province in Hardee County, central Florida. Many of the wetlands and streams are developed over somewhat thicker sands in pre-existing low areas developed on a late Miocene/early Pliocene paleosol.**

Pleistocene marine terrace sand is slightly thicker in depressions on the top of the paleosol, and during early sediment compaction the thickness of the sediments dictates the amount of change in thickness of the sediment overlying the paleosol. While the amount of compaction is minor and only changes the relative density of the sediments by small amount, the result is a depression. For example, if the sand body were 1 m in thickness when it was deposited and shortly after deposition it compacted under its own weight, groundwater percolation, and bioturbation by five percent, the resulting thickness would be 0.95 m, which would likely not be visible. If, however, the sediment were 10 m in thickness when deposited, the post-settlement and compaction thickness would be 9.5 m and a 0.5 m depression would be visible. With a shallow water-table aquifer, this depression would likely be seasonally wet. This process has resulted in the patterns of drainage control and shallow depressions that are so common on the Polk-DeSoto Plain Province (Figure 5).

This process was identified on the Polk-DeSoto Plain by Cathcart (1963) who noted these features and stated that

> "*The subsurface topography of the Hawthorn is similar to the present surface; ancestors of the present surface streams flowed on the surface of the Hawthorn at or close to their present positions.*" (Cathcart 1963, p.1).

In other words, the drainage and depressions on the modern land surface mimic the buried topography of the late Miocene/early Pliocene land surface. Post depositional settlement is greatest where the Plio-Pleistocene sand mantle is thickest. With settlement, new drainage systems and wetlands occupy the resulting depressions. When the drainage ways are rectilinear or trellis-like (Figure 5), they were probably developed on weak fractures or other nearly orthogonal features developed in the more cohesive and carbonate-rich sediments of the underlying Miocene Hawthorn Group.

The most comprehensive investigation of these depressions was conducted at the future site of the C.W. "Bill" Young Regional Reservoir in southeastern Hillsborough County, Florida. Numerous circular wetlands and several small streams crossed the site (Figure 6). A geophysical and stratigraphic study was used to determine the origins and risks of these features to the reservoir (Upchurch et al. 1999; Dobecki and Upchurch 2010). Every photolinear intersection, each depression, and the stream beds were tested by ground penetrating radar, seismic shear-wave analysis, and seismic reflection and refraction and then drilled using SPT techniques.

As shown in Figure 6, one problematic cover-collapse sinkhole resulted in moving the berm to avoid the risk. All of the other low areas were determined to reflect depressions in the underlying "leached zone" (the late Miocene/early Pliocene paleosol). Two of the depressions, indicated by the ERM boring designations on Figure 6, were found to be over ancient sinkhole depressions. One of the relict sinkholes was filled with Miocene smectitic clay and the other with well compacted Pliocene sand. Neither showed evidence of modern activity. The streams and all other wetland depressions were developed over depressions in the upper surface of the paleosol but had no subsurface expression in the underlying Miocene and older strata.

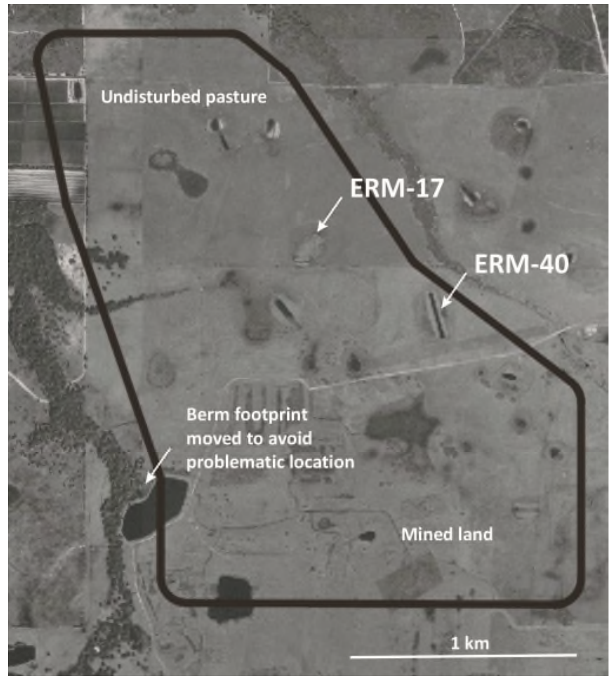


Figure 6. Aerial view of the C.W. "Bill" Young Reservoir site before construction. Dark line is the final location of the reservoir berm. Note the small stream channels and circular wetlands.

Pedogenetic Depressions

Altschuler et al. (1956 1963) and Isphording (1984) have suggested that sediment volume reductions accompanying alteration of smectite to kaolinite within the Miocene sediments of Florida have caused shallow land-surface depressions (Table 1). It is likely that these depressions were the precursors of the depressions discussed above since they would have developed during the late Miocene/early Pliocene pedogenetic event.

Karst or Pseudokarst?

The discussion above has cataloged seven different forms of shallow depressions that occur on the land surface in the Florida Coastal Plain. The discussion has purposefully omitted cover-collapse sinkholes, which are often relatively deeper and more easily identified than the shallow depressions discussed herein.

Table 2. Types of depressions representing karstic or pseudokarstic processes.

Depression Type	Karst or Pseudokarst?
Cover-subsidence sinkhole	Karst
Suffosion sinkhole	Karst
Cover settlement over shell	Both exist
Carolina bay-like depression	Pseudokarst*
Aeolian deflation area	Pseudokarst
Paleosol-related	Pseudokarst*
Pedogenetic	Pseudokarst

* May be associated with karst features such as sinkholes.

It is apparent that the many land-surface depressions in Florida have diverse origins. One cannot simply conclude that natural depressions represent karst conditions. Table 2 indicates which types of depressions are karst related and which are pseudokarst. Only detailed analysis of the sediments within and below the depression will reveal whether the depression has a karst origin or is pseudokarst.

Recommendations and Conclusions

Seven different origins of shallow depressions have been identified in Florida. The abundance of these shallow depressions in many areas of the modern Coastal Plain may be dramatic (Figure 1). Determining the origins of these depressions and the risk(s) they pose is often confusing to lay persons and professionals alike.

Based on the authors' experiences, it is inappropriate to simply observe the field appearance of the depressions and conclude that they represent sinkholes or other karst features. It is strongly suggested that:

1. Only subsurface testing can determine their origin. Visually, the depressions appear similar and depressions with different origins are often mixed in an area.

2. Detailed analysis of the sediment stratigraphy, fabric, and texture is usually required to identify the origins of the depressions.

3. Petrographic, microscopic, and/or mineralogical analyses are often required to determine if shell and limestone has been subjected to dissolution or clays have been altered. Only a geochemical analysis of the pore water can determine if the dissolution is on-going.

References

Altschuler ZS, Jaffe EB, Cuttitta F. 1956. The aluminum phosphate zone of the Bone Valley Formation, Florida, and its uranium deposits. US Geological Survey Professional Paper 300: 495-504.

Altschuler ZS, Jaffe EB, Dwornik E. 1951. The stratigraphy of the upper part of the Bone Valley Formation and its relation to the leached zone. US Geological Survey Trace Elements Memorandum Report 237.

Altschuler, ZS, Dwornik EJ, Kramer H. 1963. Transformation of montmorillonite to kaolinite during weathering. Science 141 (3576): 148-152.

Beck BF, Sinclair WC. 1986. Sinkholes in Florida: An introduction. Orlando, Florida Sinkhole Research Institute Report 85-86-4.

Brooks MJ, Taylor BE, Stone PA, Gardner LR. 2001. Pleistocene encroachment on the Wateree River sand sheet into Big Bay on the middle Coastal Plain of South Carolina. Southeastern Geology 40 (4): 241-257.

Cathcart JB. 1963. Economic geology of the Keysville Quadrangle, Florida. US Geological Survey Bulletin 1128.

Cooke CW. 1954. Carolina bays and the shapes of eddies. US Geological Survey Professional Paper 254-I: 195-206.

Dobecki TL, Upchurch SB. 2010. A multi-level approach to site characterization - C.W. Bill Young Regional Reservoir, Hillsborough County, Florida. Proceedings of the Environmental and Engineering Geophysical Society, Application of Geophysics to Engineering and Environmental Problems (SAGEEP).

Eyton JR, Parkhurst JI. 1975. A re-evaluation of the extraterrestrial origin of the Carolina bays. University of Illinois at Urbana-Champaign, Occasional Publications of the Department of Geography Paper Number 9.

Field MS, 2002. A Lexicon of Cave and Karst Terminology with Special Reference to Environmental Karst Hydrology. US Environmental Protection Agency, EPA/600/R-02/003.

Grant JA, Brooks MJ, Taylor BE. 1998. New constraints on the evolution of Carolina bays from ground-penetrating radar. Geomorphology 22: 325-345.

Halladay WR. 2007. Pseudokarst in the 21st century. Journal of Cave and Karst Studies 69 (1): 103-113.

Isphording WC. 1984. Sand craters in Gulf Coastal Plain clastic sediments: An extension of the Carolina Bays phenomenon? Geological Society of America Abstracts with Programs 16 (3): 148.

Ivester AH, Brooks MJ, Taylor BE. 2007. Sedimentology and ages of Carolina bay sand rims. Geological Society of America Abstracts with Programs 39 (2): 5.

Legrand HE. 1953. Streamlining of the Carolina bays. Journal of Geology 61 (3): 263-274.

May JH, Warne AG. 2004. Hydrogeologic and geochemical factors required for the development of Carolina bays along the Atlantic and Gulf of Mexico Coastal Plain, USA. Environmental & Engineering Geoscience 5 (3): 261-270.

Prouty WF. 1935. “Carolina bays” and elliptical lake basins. Journal of Geology 43 (2): 200-207.

Prouty WF. 1952. Carolina bays and their origin. Geological Society of America Bulletin 63 (2): 167-224.

Schalles JF, Sharitz RR, Gibbons JW, Leversee GJ, Knox JN. 1989. Carolina bays of the Savannah River Plant, Aiken, South Carolina. Aiken (SC) Savannah River Plant, National Environmental Research Park.

Schmidt W, Scott TM. 1984. Florida karst: its relationship to geologic structure and stratigraphy. In: Beck BF, editor. Sinkholes: Their Geology, Engineering and Environmental Impact. Proceedings of the First Multidisciplinary Conference on Sinkholes, Orlando, Florida, p. 11-16.

Upchurch SB, Dobecki TL, Daigle DM. 1999. Geological, hydrogeological, and geophysical investigation. In: Law Engineering Services and others, Geotechnical Site Characterization Report – Tampa Bay Regional Reservoir, Volume I, Section 3.

Van Kauwenbergh SJ, Cathcart JB, McClellan GH. 1990. Mineralogy and alteration of the phosphate deposits of Florida. US Geological Survey Bulletin 1914.

Wells BW, Boyce SG. 1953. Carolina bays: Additional data on their origin, and history. Journal of the Mitchell Society 69 (2): 119-141.

White W. 1988. Geomorphology and hydrology of karst terrains. New York (NY): Oxford University Press.

White WA. 1970. The geomorphology of the Florida peninsula. Florida Geological Survey Bulletin 51.

Willoughby RH. 2007. Carolina bays in Jordan Quadrangle, Clarendon County, central South Carolina are relict survivors from development of sinkholes due to karstic solution. Geological Society of America Abstracts with Programs 39 (2): p. 5.

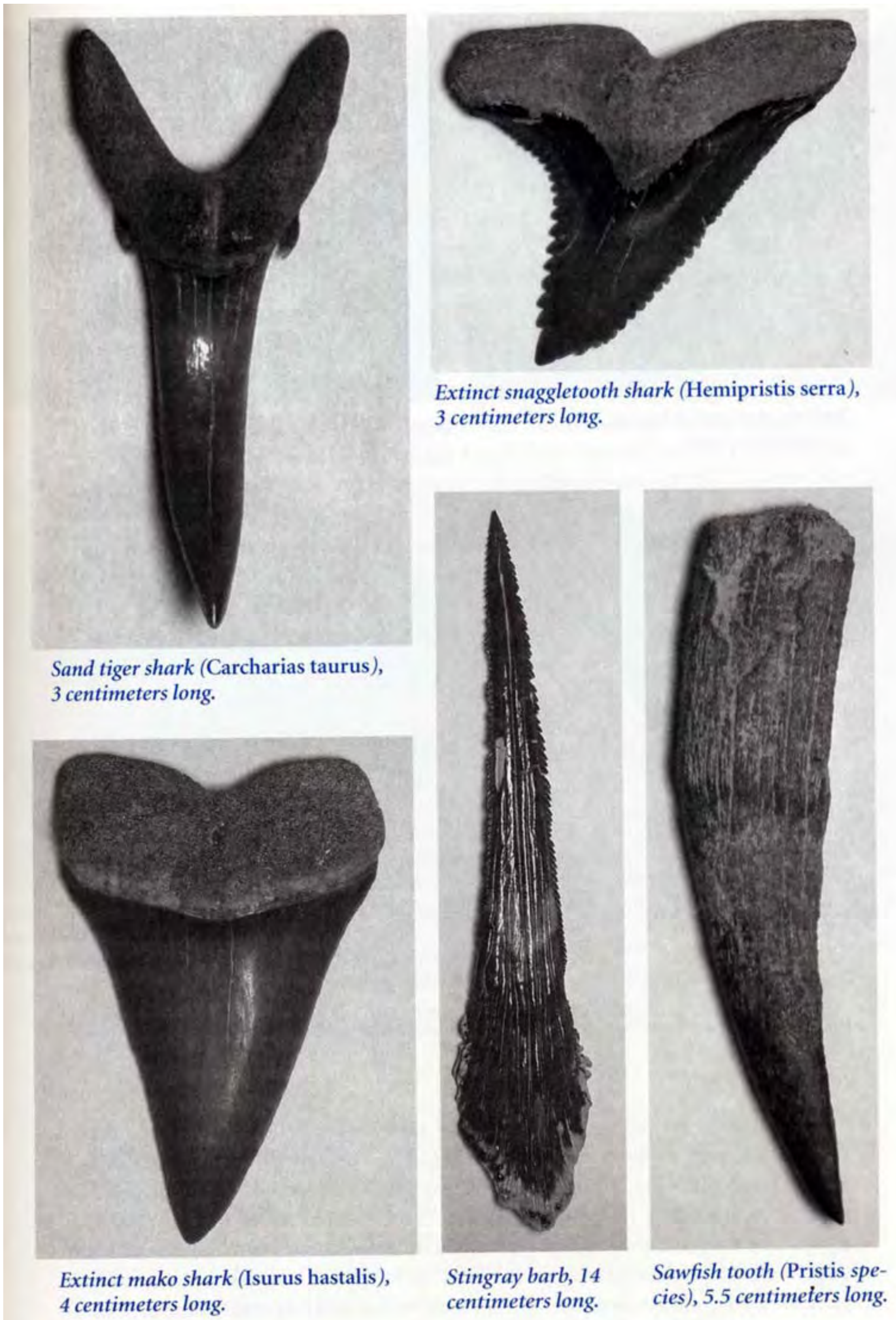
COMMON FOSSILS FROM THE PHOSPHATE DEPOSITS OF THE CENTRAL FLORIDA PHOSPHATE DISTRICT

By
Guy H. Means
Florida Geological Survey
3000 Commonwealth Boulevard, Suite 1
Tallahassee, FL 32303

The phosphate industry in Florida is well known for the production of fertilizer and other products. However, the strata that contain economic deposits of phosphate are also famous for producing some of the most spectacular fossils in Florida! The complex depositional environments and the reworking and concentrating of phosphorite was also conducive to the preservation of fossil material. The terrestrial vertebrates of the "Bone Valley" have been documented and studied since mining first uncovered fossils in the late 1800's. However, the deposits that are being mined today contain a diverse assemblage of both invertebrates and vertebrates. A few of the more commonly encountered fossils will be briefly discussed along with several newly described fossil species.

Perhaps the most well known and most highly sought after fossils from the Central Florida Phosphate District are shark teeth. During the Miocene and Pliocene the large megtooth shark *Carcharodon meglodon* patrolled the warm coastal waters of Florida. These animals are thought to have been up to 50 feet in length and probably ate marine mammals including whales. Some meglodon teeth exceed six inches in length! There are many other species of sharks that have been documented from the phosphate district. Below are some of the more commonly encountered kinds of shark teeth and some examples of other possible fossil finds.

Examples of *Carcharodon megalodon,* the extinct giant white shark.



*Sand tiger shark (*Carcharias taurus*), 3 centimeters long.*

*Extinct snaggletooth shark (*Hemipristis serra*), 3 centimeters long.*

*Extinct mako shark (*Isurus hastalis*), 4 centimeters long.*

Stingray barb, 14 centimeters long.

*Sawfish tooth (*Pristis species*), 5.5 centimeters long.*

Common fossil shark teeth and other fossils from the phosphate deposits (from Roadside Geology of Florida).

Examples of some common fossils from the Central Florida Phosphate District.

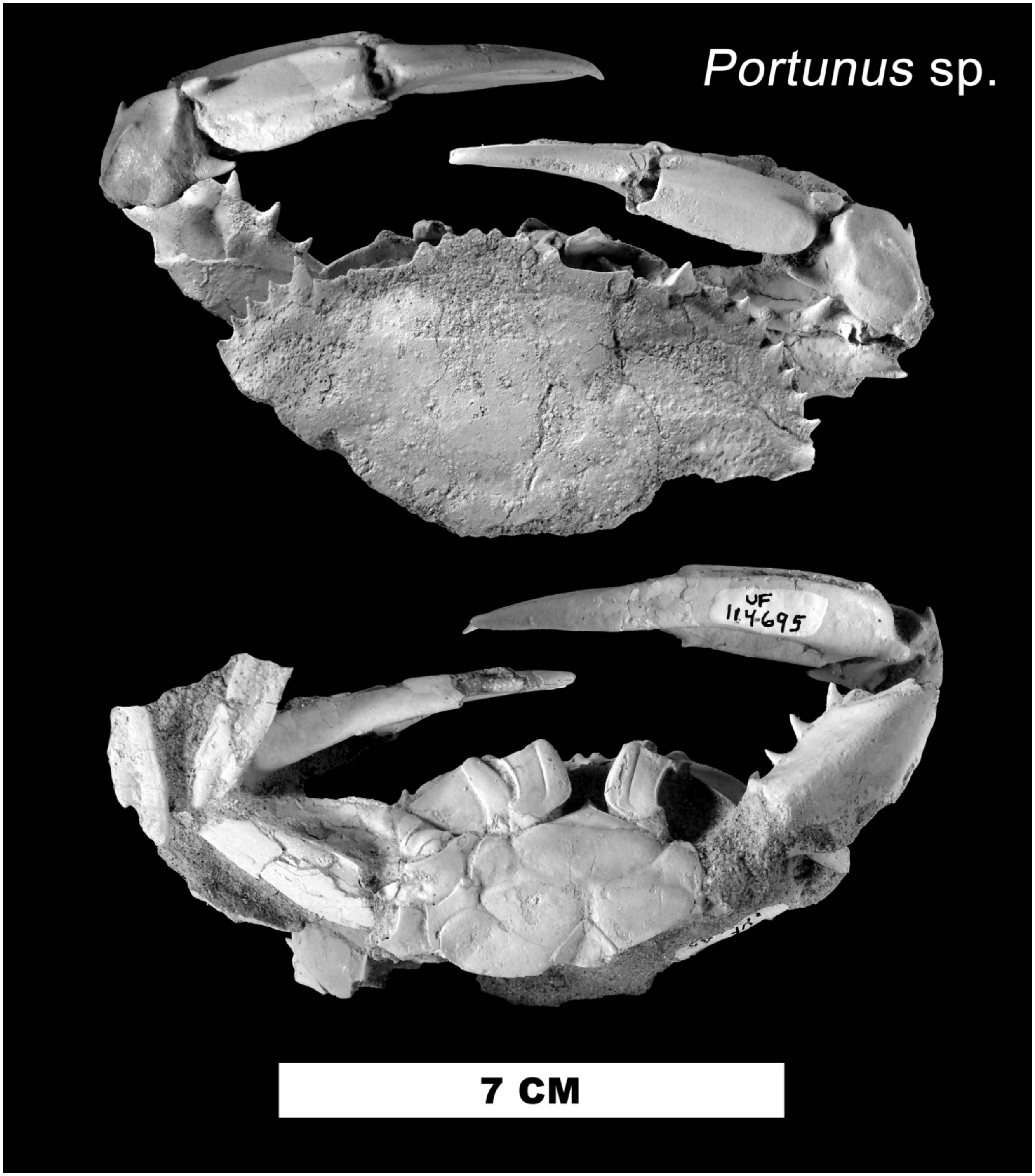
Shark teeth are commonly found throughout the Central Florida Phosphate District as are other fish bones as well as the bones of other marine vertebrates. Perhaps the most commonly found vertebrate remains in Florida are fragments of dugong ribs. Dugongs are related to manatees and belong to a group of mammals called sirenians. These large, aquatic mammals had very dense rib bones that preserved readily in Florida's marine environments. Sirenians have been in Florida since the Late Eocene and survived until the Late Miocene where their fossils are absent until the arrival of the manatee sometime in the late Pleistocene.

Dugong rib fragments.

The abundance of fossil marine organisms demonstrates that the strata in the Central Florida Phosphate District were deposited in the marine environment (See Hurst and Courtney's article in this guidebook). However, there are also abundant terrestrial vertebrate fossils. Careful investigation of the lithology and fossil assemblages within the strata of the Central Florida Phosphate District have revealed many different depositional origins. Unfortunately, climbing down into the cuts made by the draglines is dangerous and not permitted. Most of the fossil finds are made from the spoil piles where the fossils and strata are mixed. So, it is not uncommon to find, in the same general area, fossils from sharks, dugongs and terrestrial mammals! Another common fossil find in this area is horse teeth. Horses evolved in North America and their fossil record in Florida dates to some of the oldest sites that contain terrestrial vertebrates – the Late Oligocene. Horse teeth are easily recognized by their size and enamel pattern. Below is a photo of some horse teeth from different species.

Fossil horse teeth.

There are numerous other fossil vertebrate species, both marine and terrestrial, known from the Central Florida Phosphate District but most of them are not commonly found so they are not included in this brief guide. Although vertebrate fossils are common finds, and many fossil enthusiasts focus on collecting them, there are other types of fossils that occur in this area. For instance, invertebrate species including mollusks, crustaceans, and echinoids have been documented. Two recently described invertebrate species are figured below.



Portunis sp. **collected from the Mosaic Ft. Green 14 dragline in Hardee County. From Miocene or Pliocene Hawthorn Group (Courtesy of the Florida Museum of Natural History).**

The brachiopod *Glottidia inexpectans* collected at the Mosaic Ft. Green 13 dragline. From the lower Pliocene Peace River Formation (Courtesy of the Florida Museum of Natural History).

In addition to the invertebrate species mentioned above there is also a diversity of petrified wood known from these deposits. Some of the fossilized wood specimens are well preserved enough to recognize the species. Fossilized wood is uncommon but can occasionally be collected. Below is an example of petrified wood from the Central Florida Phosphate District.

Petrified wood containing the trace fossils of wood-boring organisms from the Central Florida Phosphate District.

The fossils discussed in this brief overview represent only a fraction of the species known from the Central Florida Phosphate District. We did not cover microfossils, however there are abundant foraminifera and other microfossils in the sediment in the Central Florida Phosphate District. This guide is merely a quick overview of some of the more commonly encountered fossils. There are many great publications that outline the various fossil localities and assemblages that have been uncovered by the mining operations in this area. See the reference sections of the other articles in this guidebook. Here are a few selected references as well:

Brown, R., 1988, Florida's Fossils, Guide to Location, Identification and Enjoyment, Pineapple Press, 212 p.

Bryan, J.R., Scott, T.M., and Means, G.H., 2008, The Roadside Geology of Florida, Mountain Press Publishing Company, Missoula, MT., 376 p.

Hulbert, R.C.,(Editor), 2001, The Fossil Vertebrates of Florida, University Press of Florida, Gainesville, 384 pp.

A BRIEF HISTORY OF PHOSPHATE MINING IN BONE VALLEY

By
Richard A. Fifer

The mining of phosphate has been a major Florida industry for over 100 years. Florida currently provides nearly 60% of the nation's supply of phosphate fertilizer and approximately 15% of the world's supply. However, this large industry had very humble beginnings.

Pebble phosphate was discovered in the Peace River in May 1881 by John Francis Le Baron, a civilian surveyor with an Army Corps of Engineers expedition, but mining of this "river pebble" phosphate, using suction dredges, did not begin until 1888. "Hard rock" phosphate was discovered near Dunnellon by Albertus Vogt in May 1889, with mining operations beginning the following year. Concurrently, the vast beds of "land pebble" phosphate were discovered in Polk County, and mining in "Bone Valley" (so-called because of the many fossils found during mining) began in 1890.

The land pebble phosphate in Bone Valley lay in a matrix of sand and clay, 10 to 30 feet thick. It was covered by an overburden of sand and clay that was 5 to 30 feet thick. Best of all, the phosphate matrix ran almost continuously through Bone Valley. The overburden was removed by either steam shovel or hydraulics to expose the phosphate bed. Land pebble phosphate mining was thus cheaper and easier than either river pebble or hard rock mining and soon dominated production.

In the 1890's, a phosphate mining boom ensued, centered initially around Bartow. Scores of companies were formed, only a fraction of which actually mined any phosphate. Most of these small, under-capitalized companies failed to produce a profit and quickly went bankrupt. The thickest and richest layer of pebble phosphate surrounded the small town of Mulberry, and Mulberry quickly rose to be the capital of Bone Valley phosphate mining.

By the early 1900's, the phosphate mining boom was over. Larger, well-capitalized companies were formed to mine phosphate, and they quickly acquired many of the remaining smaller enterprises. Large fertilizer companies, including the Virginia-Carolina Chemical Company and the American Agricultural Chemical Company (A.A.C.Co.), entered the mining business to control the source of their raw materials. Meat-packing companies, including Swift & Company and Armour & Company, also began phosphate mining in Bone Valley.

Central Florida was primitive at the beginning of the Twentieth Century, and amenities were few. The roads were poor, so transportation was especially difficult. As a result, each mining company built a village or town near its mining operations to house its workforce and their families. Each family lived in a company-owned house and were required to shop at the commissary --- the company-owned store. Larger villages usually had a school and church for their employees and families, as well as a company doctor to tend their medical needs. Some of these early company-owned mining towns included Agricola, Bone Valley, Brewster, Christina, Coronet, Jane Jay, Kingsford, Morris, Nichols, Pebble, Pebbledale, Pembroke, Phosphoria, Pierce, Prairie, Ridgewood, Royster, San Gully, Tancrede, and Tiger Bay.

By 1920, only fourteen companies were mining phosphate in Bone Valley. This number dwindled to seven by 1938, as only a few companies began to dominate production. These major companies and their towns were the A.A.C.Co. (Pierce), the Amalgamated Phosphate Company (Brewster), the Coronet Phosphate Company (Coronet), the International Agricultural Corporation (Prairie), the Phosphate Mining Company (Nichols), Swift & Company (Agricola), and the Southern Phosphate Corporation (Ridgewood).

An attempt to use a dragline to remove overburden was made by the Armour Fertilizer Works in 1908. It was unsuccessful due to the steam-powered dragline's low power and small bucket size. However, by the 1920's, draglines with improved capability began to be used throughout Bone Valley. By the 1940's, they were used (as they are today) to remove both the overburden and the phosphate ore. The first "mammoth" dragline, a Bucyrus-Erie 1150-B with a 24 cubic-yard bucket, was introduced in 1946.

Beneficiation of the phosphate ore initially consisted of washing and screening the ore to remove as much of the sand and clay as possible. However, as much as 50% of the phosphate, consisting primarily of small phosphate particles, was not being recovered. Introduction of the double-flotation process in 1929 solved this problem, allowing up to 90% of the phosphate to be recovered. The recovered phosphate was then carried by rail to the company's drying plant, where it was dried and stored, ready for transport to the ship terminals at Tampa and South Boca Grande.

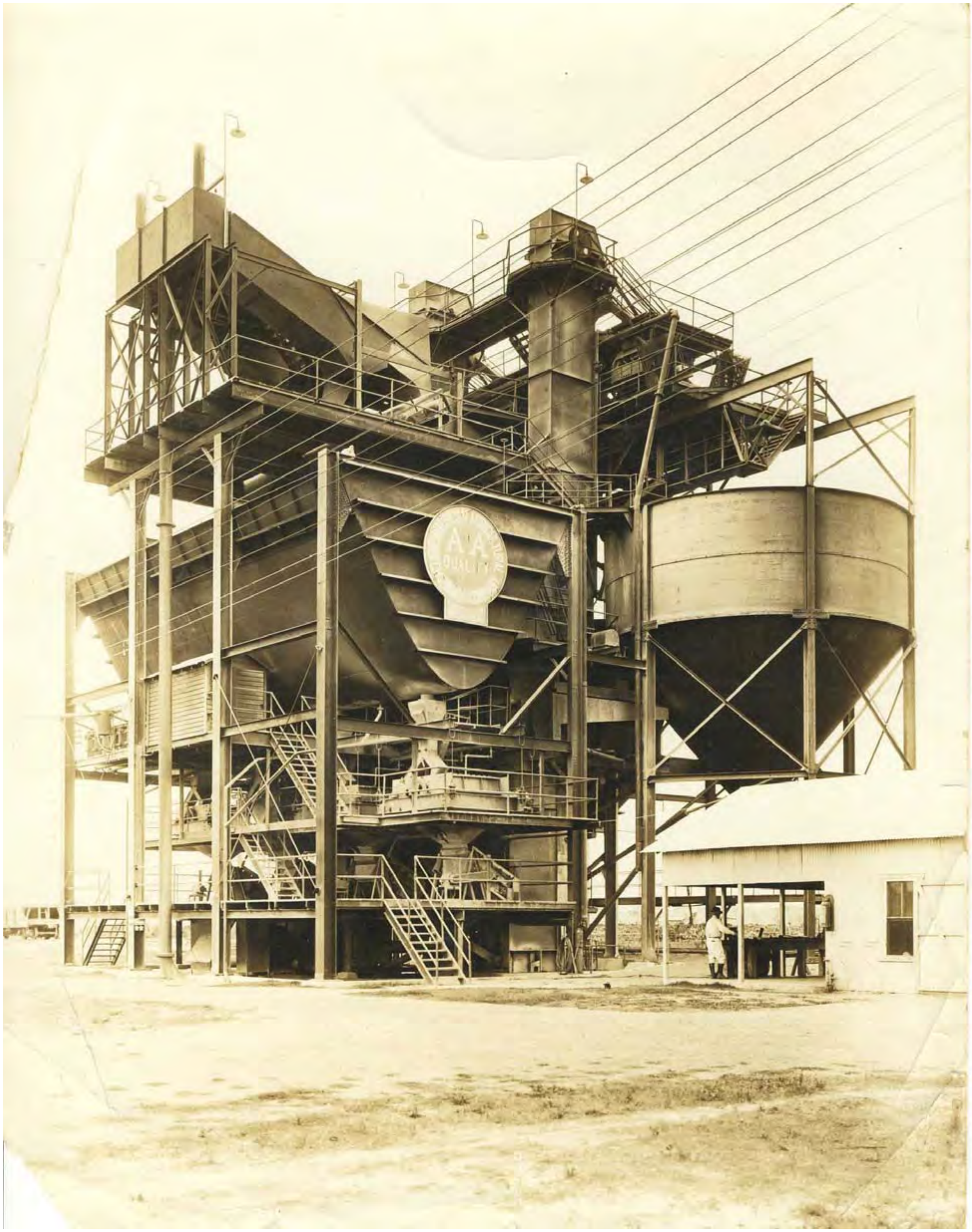
By the 1950's, the need for company-owned towns had disappeared. Employees could commute to work, and the existing company towns were too small to accommodate all of the companies' employees. One by one, the company towns were closed, and their houses sold to the employees. Brewster was the last company town to shut down, closing in 1961.

In the 1940's and 1950's, a major change took place in the Florida phosphate mining industry. Prior to this time, the recovered phosphate rock was shipped to fertilizer factories on the Eastern Seaboard of the U.S, as well as to foreign countries, to be rendered into fertilizer. However, at this time, chemical plants began to be built in Bone Valley, so that the finished fertilizer ingredient (monoammonium phosphate, diammonium phosphate, triple superphosphate, etc.) could be produced. At the present time, very little, if any, phosphate rock is shipped from Bone Valley.

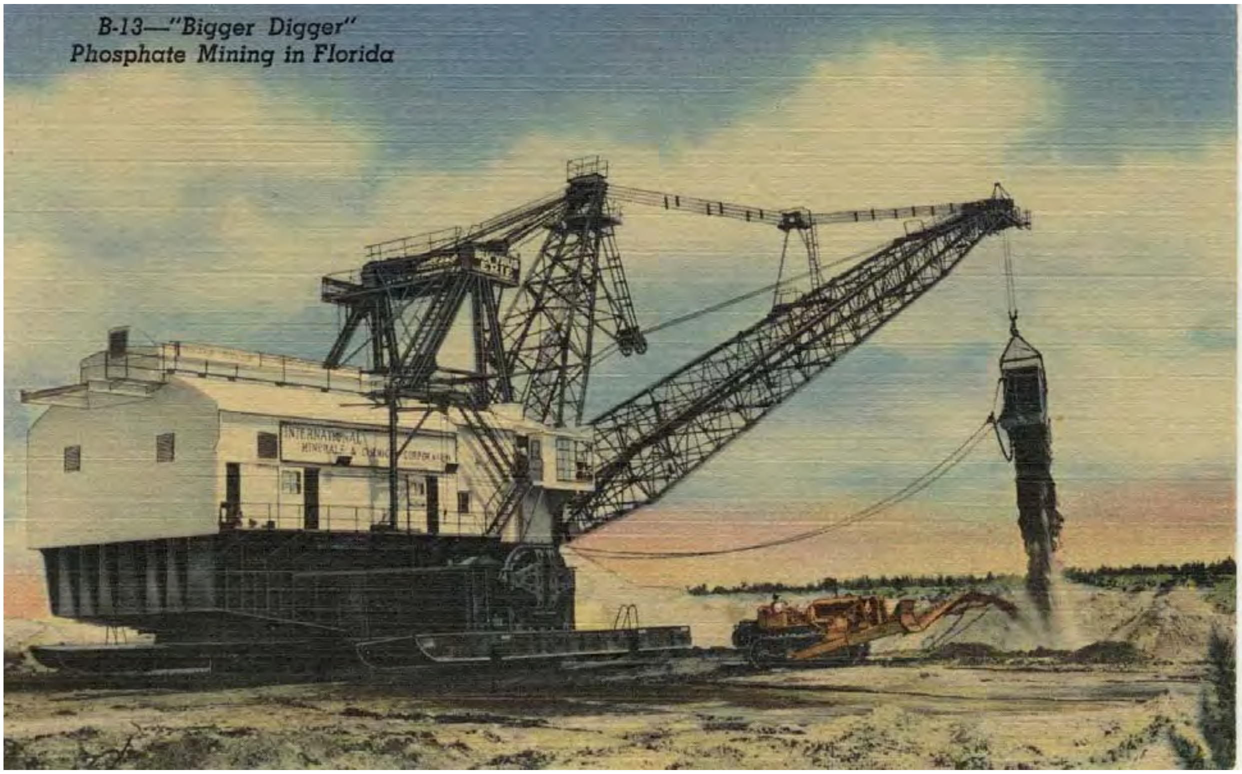
Until recently, only two companies were mining and processing phosphate in Bone Valley, the Mosaic Company and CF Industries. Through mergers and acquisitions over the years, these two companies were the direct descendants of many of the original phosphate mining companies in Bone Valley. In March 2014, the Mosaic Company acquired the phosphate business of CF Industries, leaving just one company in Bone Valley.

River Pebble Mining on the Peace River Using a Suction Dredge, ca. 1895

Hydraulic Mining of Land Pebble Phosphate, ca. 1924



A.A.C.Co. Washer at South Pierce, 1937



IMC's Bucyrus Erie 1150-B Dragline, the "Bigger Digger," 1946

Aerial View of Pierce Showing Drying Plant and Dry Storage Bins, 1938

THE WORLD PHOSPHATE ROCK POSITION AND FLORIDA PRODUCERS' POTENTIAL POSITION IN THE FUTURE

S. Van Kauwenbergh
Principal Scientist, Retired, IFDC
Phosphate Rock Geology, Mining and Processing Consultant
Sjvk1@msn.com

Introduction

This effort relies mainly on the paper, World Phosphate Rock Reserves and Resources" (Van Kauwenbergh, 2010), and the author's thirty years of experience in the world phosphate rock and product arena.

World Phosphate Rock Reserves and Resources

The results of my 2010 study indicated world reserves of phosphate rock product were 60 billion tons and 290 billion tons of resources. This reserve total was approximately four times the USGS estimate for 2010 (16 billion tons). As a result of the Van Kauwenbergh (2010) analysis, the USGS revised their estimates for several countries. The most significant change was the amount of Moroccan reserves. The current USGS estimate (2015) is 67 billion tons of world reserves with over 300 billion tons of resources.

The Current World Phosphate Rock Situation

Reserves are economically producible materials under current conditions, or within certain defined potential costs in the future. An economically viable product must be in demand at viable production levels. Consumers must be willing to pay a price for the product that allows a profit margin that will cover the costs for development and production. Phosphate rock has always been a relatively high volume bulk commodity.

We live in a world economy. The lowest cost producers and users in free market economies define one segment of the market. In the world fertilizer sector there are many government controlled producers, marketing and distribution functions. Many countries subsidize fertilizer prices and/or distribution.

Phosphate rock and fertilizer production costs change due a wide variety of factors including energy costs and raw materials costs. In so-called developed counties, a particular burden is placed upon industrial concerns with respect to health and safety, and environmental protection. Often producers do not incur these costs in so-called under developed countries.

The entire world has not been exhaustively explored for phosphate rock. Not every phosphate deposit in the world has been found.

Three periods of world phosphate exploration have occurred. In the late eighteen hundreds, islands all over the world were explored for guano or guano related deposits. In the early to mid 20th century, as higher analysis fertilizers were being developed, another period began. Since 2007-2008 a great amount of phosphate deposit reevaluation and green field development work has been performed. However, exploration has somewhat cooled off after several viable projects were identified and implemented. Additional minable phosphate rock deposits may be located in the future. Eventually, underwater deposits may become viable.

Both phosphate rock beneficiation and fertilizer production technology can change and alter ultimate fertilizer production costs and prices. The emphasis of fertilizer research in the 20th century was to make high analysis fertilizers, which could be transported more cost effectively. If energy costs go up and become prohibitive, localized production and the use of lower analysis products may be economically viable and even necessary.

Based on the current state of knowledge, Morocco has about 75% of the known world reserves of phosphate rock. The Van Kauwenbergh (2010) analysis did not include the Meskala deposit. Moroccan and Soviet interests evaluated this deposit in the 1980s; it has not produced to date. Less than half of the Khouribga and Ganntour Plateaus, the two developed production areas, have been extensively drilled. All of the currently defined reserves are suitable for phosphoric acid production. Eventual producible Moroccan reserves, including reserves and resources associated with the Bu Craa deposit, may be double the current estimate.

Current plans are to increase Moroccan production over 20 million tons per year to 50-55 million tons per year. Numerous expansions of the Moroccan phosphate firm OCP's fertilizer plants are in progress along with numerous joint ventures. A planned on-land gypsum disposal project was cancelled due to an internal study which indicated the environment effects of land disposal may be more environmentally unfavorable than sea disposal.

China is currently the leader in world phosphate rock production at about 100 million tons. This production is mostly used internally. In 2010, China was thought to have 3.7 billion tons of phosphate rock reserves. Exploration is ongoing; and over 5 billion more tons of resources have been proved since the Van Kauwenbergh (2010) estimate. For internal use, Chinese rock doesn’t have to be of high enough grade to make diammonium phosphate (DAP) at world market grade (18-46-0). There are numerous plants in China that make off-grade monoammonium phosphate (MAP) at a low grade; approximately 40%-42% P. The highest-grade, low-magnesium phosphate rock is used to make phosphoric acid for manufacturing export DAP.

Algeria has reevaluated its reserves and according to the USGS (2015) has 2.2 billion tons of reserves. Algerian phosphate rock is very similar to Tunisia rock (30 million tons of reserves.) Senegal completed a mine move about 4-5 years ago; and its resources are listed at 50 million tons. More material may be identified. There is some carbonate containing material in the new mine area. Togo is mining out the original deposit with about 30 million tons of concentrate remaining. South Africa has about 1.8 billion tons of reserves mainly in the Phalaborwa Deposit. This is a high quality igneous rock deposit.

Jordan has approximately 1.3 billion tons of reserves. The Jordanian Geological Survey indicates phosphate rock underlies over 50% of the land surface of Jordan. Saudi Arabia is listed at 211 million tons of reserves. One mine is currently working and another mine is under development in Saudi Arabia. The basin containing the reserves, shared by Jordan, Iraq (430 million tons of reserves) and Iran, contains over 3 billion tons of resources. Much of these resources contain carbonates. The methods used to beneficiate the Al Jalamid Deposit in Saudi Arabia may be amenable to these deposits. Syria has 1.8 billion tons of reserves; however, it is hard to mine, process, and ship concentrate in the middle of a civil war. Egypt has reevaluated its reserves at 715 million tons. Much of this material is marginally suitable for phosphoric acid. Kazakhstan claims 260 million tons of reserves, although their resources are not the most suitable for production of phosphoric acid.

Russia is thought to have about 211 million tons of reserves. It should be noted there are numerous carbonatite deposits containing phosphates in Russia, particularly in Siberia. Exploration for fertilizer production raw materials has not been at the forefront of Russian interests since the breakup of the Soviet Union in 1989-1990.

In the current USGS listing, Finland reserves are listed in the other countries category (300,000 million tons). Remaining reserves at the Siilinjarvi Mine are on the order of 15-20 million tons. The Sokli igneous deposit in Finland was under evaluation, but the project has been suspended. There are other phosphate resources in Europe, in Estonia for example.

Brazil is listed by the USGS at 270 million tons of reserves. Several green field projects have looked at carbonatite/alkaline complexes in southeast Brazil. Studies indicate P2O5 contents of potential ores at levels that are similar to ores being beneficiated at current Brazilian phosphate rock operations. Peru's reserves are listed at 820 million tons. The ore reserves at the original Sechura mine are well defined. Mosaic owns a substantial interest in the deposit and utilizes a substantial portion of the production. Work continues adjacent to the original concession.

In North America, Canada's reserves are listed at 76 million tons. This would be phosphate rock from the Martison Deposit and a new mine project in Quebec hosted in a gabbro deposit.

Several deposits around the world are currently being developed. Some will make it, some will not. Technical suitability of the phosphate rock, minability, sound planning, effective implementation, the market, political influences and eventually economics will dictate long-term viability of these deposits. Several of these deposits may be shelved for the future.

The United States is listed by the USGS (2015) at 1.1 billion tons of phosphate rock reserves. This includes Florida, North Carolina and the Western Phosphate deposits in Montana, Idaho and Utah. Based mainly on USGS literature, Van Kauwenbergh (2010) estimated about 8.5 billion tons of remaining phosphate rock resources in Florida.

Florida Producers Position in the Future

While China may continue to be the world's leader in phosphate rock production, based on the vast high quality reserves and established infrastructure and expertise, OCP will become the world leader in available phosphate rock and phosphate intermediates and products, that is, phosphate rock, phosphoric acid and phosphate fertilizer products for sale on the world market.

High analysis products will continue to dominate world trade. There is enough high quality phosphate rock in the world to support the production of phosphoric acid for the foreseeable future.

Prior to developing a phosphate rock and fertilizer industry over the last 20 years, China was a major fertilizer importer. Florida producers sold a lot of fertilizer to Chinese buyers. Rapidly expanding production has allowed China to export DAP fertilizer and small amounts of phosphate rock. Note that the Chinese government can and will cut exports through various methods if national fertilizer shortfalls occur. The industry is being rationalized; small inefficient and wasteful producers are being incorporated into larger companies. Environmental rationalization in China will eventually occur. Chinese farmers are simply using too much fertilizer. Water quality is generally atrocious.

Similar to China, India was, and is, a major player in the world phosphate fertilizer and raw materials markets. India has minor amounts of phosphate reserves; possibly 35 million tons. Not all of this material is suitable for production of phosphoric acid. Phosphoric acid is purchased to run several DAP plants in India. India interests hold a major share of the mine and phosphoric acid facility in Senegal and have formed a joint venture in Jordan. The India industry has been subsidized and was developed to supply internal demand. Eventually, fertilizer use will become environmentally rationalized; water quality is generally very poor across the main agricultural areas. Not all water pollution problems are from fertilizer use in developing countries. High population and non-existent waste treatment has its effects, too.

US production of phosphate rock is third in the world at 27,100 tons per year, mainly from Florida. The US phosphate industry, and in particular the Florida producers, battle the influence of environmental interests. Significant amounts of land are simply taken out of play due to various setbacks and land use issues. The only place with a more restricted, or repressive, regulatory scheme might be the European Union where phosphoric acid production is being systematically eliminated and forced offshore. As a person peripheral to the industry, I've never seen an industry strive to meet regulations and meet them with good margins only to have new more stringent regulations, often without scientific justification, literally shoved in their faces. Many people just do not seem to realize where their food is coming from. Environmental concern is not unwarranted; but irrational laws and costly legal games impeding progress are not good for anyone except regulators and attorneys.

It is no secret the Central Florida Phosphate district is mainly depleted. The so-called Southern Extension mining started in the mid-1980s. The US Army Corps of Engineers recently completed an area wide study of the remaining proposed mining limits to the south of the currently mined areas. North Florida reserves are limited. More potential reserves lie under the lands of the Ocala National Forrest, thus far not available for mining.

Remaining potential Florida reserves are difficult to access for a variety of reasons. For tax purposes, and for political reasons, land is usually classified as agricultural until it must be permitted for mining. When land is identified as mining land it becomes taxable at higher rates and is subject to political parlay by environmental activists. Although the industry knows where there is more phosphate rock in Florida, it is not willing to wave flags to environmental groups and attract attention.

Additional potential phosphate rock reserves are located under thicker overburden than a one-pass mining system, as exclusively used in the Florida Phosphate industry, will allow. Deeper phosphate resources are known to exist in several parts of the state. When rock prices are sufficiently high, a large amount of this phosphate rock can probably be mined by a multiple pass system, or borehole mining, with minimal surface environment effects.

There are previously mined areas where deeper phosphate rock beds were not taken because the magnesium (dolomite) contents were too high for the existing beneficiation plants technology and configurations to reduce the dolomite content. Some of these areas might be re-mined if future phosphate rock prices and technology allow. While there is currently not the technology to utilize them, existing clay settling areas contain vast amounts of phosphate in various forms.

The industry has numerous phosphoric acid plants that are currently running and some that are mothballed. One of the most significant liabilities of the Florida Florida fertilizer industry is stacked phosphogypsum. By buying phosphoric acid from Morocco, or sourcing it somewhere else offshore, these plants could be running without producing phosphogypsum.

Predictions and Conclusions

Back when I got into this business I worked for well-known Florida Geologist, Dr. Guerry McClellan. He taught me much of what I know about the world of phosphate rock and products, and allowed me the opportunity to discover more. When he made predictions he put on his Swami hat, made interesting gestures and announced in a loud deep voice, “Swami says!” Well, I borrowed Dr. McClellan’s Swami hat. Swami says:

-The Florida phosphate rock industry will continue to produce into the future working with rational environmental and safety regulations, and battling irrational environmental interests. Mines are planned for about 30 years.

-The Florida and US industry will continue to seek alternative sources of phosphate rock and phosphoric acid for existing fertilizer plants. The US has signed free trade agreements with Morocco. I expect additional agreements will be forthcoming.

-While the Florida industry has been very export orientated, and may continue to be if supplies of raw or intermediate materials are available and it is economically viable, the emphasis will shift to domestic production eventually. It is in the natural interest to maintain production from domestic sources.

-Florida production from the Southern Extension will systematically decrease, although the life of the current operations will be extended as long as possible. Eventually the rock will be used to supplant production of rock and acid from other sources.

-Sources of other reserves within Florida will be eventually economically evaluated on their own merits. However, the cost of doing business will include the costs of legal challenges and the time to address such challenges and permitting. It may take a countrywide rationalization of environment interests with respect to agriculture, mining and industry in general to change the current situation.

Numerous factors will affect the long-term future of the Florida phosphate industry. Reserves will certainly be limited by land availability. The main factor will be economics and the constant battle to limit and/or just stop the mining. The apparent current attitude within Federal government, particularly the EPA, may change with changes in administrations and the realization phosphorus is a strategic material. Numerous countries currently view phosphate rock as a strategic material. The Federal government treated phosphate rock as a strategic commodity practically throughout the 20th century. This is not to say the phosphate industry should be allowed to wreak unwarranted environment carnage, but rational, realistic, scientific based rules would be welcomed.

Eventually, for a variety of reasons, Florida phosphate rock reserves will run short. The existing targeted deposits cannot be produced forever. Technology may change (innovations like the Hard Process) and some Florida resources in existing areas may become reserves.

The ability of other deposits in the US to make up for Florida production is limited. The phosphate producers of the Northwest US are a long way from the west coast, and the Mississippi Valley, the breadbasket of the US. The sole North Carolina producer is limited by the same regulatory factors as the Florida producers, particularly with respect to setbacks and coastal issues.

One or more world economic crisis or political disruptions in exporting countries could influence the market. Political disruptions in exporting countries are a distinct possibility. At the present time US import dependence on phosphate rock is 18% (USGS, 2015). Import dependence will grow as Florida production is curtailed; for whatever reason.

Transportation is a distinct potential long-term issue. While the world at this moment in time is currently in an increasingly favorable situation with respect to oil availability, hydrocarbons are also a limited natural resource. If the world-shipping situation should change due to fuel costs and availability, transportation costs may increase dramatically. Security of the domestic phosphate supply is a distinct long-term concern.

The phosphate rock reserves and resources of Florida and the Florida phosphate fertilizer industry are national assets, and should be treated as such. A world of phosphate processing technology and environmental science was developed in the US and applied in Florida. Time and funding that are currently devoted to opposing rational development would be much better used to achieve common goals working with industry. With a changing situation, the industry could work much longer that projected into the future. I have many friends in the Florida phosphate industry; I wish them good luck.

References

Van Kauwenbergh, SJ, 2010, World Phosphate Rock Reserves and Resources, IFDC Technical Bulletin IFDC-T-75, IFDC, Muscle Shoals, Alabama, U.S.A., 56 pp.

United States Geological Survey (USGS), 2010-2015, Mineral Commodities Summaries, Phosphate Rock, U.S. Department of the Interior, Washington DC, U.S.A.