Central Florida Phosphate District

Photo provided by The Mosaic Company

August 11, 2012
Edited by Marc V. Hurst

Field Trip Committee
Jon Courtney
John Herbert
Clint Noble
Central Florida Phosphate District
Southeastern Geological Society
Field Trip Guidebook No. 57

August 11, 2012
Edited by Marc V. Hurst

Field Trip Committee
Jon Courtney
John Herbert
Clint Noble
CONTENTS

INTRODUCTION TO FLORIDA PHOSPHATE
by: Marc V. Hurst and Jon L. Courtney ................................................................. 1

GEOLOGIC OVERVIEW OF FLORIDA
by: Thomas M. Scott .............................................................................................. 21

COMMON FOSSILS FROM THE PHOSPHATE DEPOSITS
OF THE CENTRAL FLORIDA PHOSPHATE DISTRICT
by: Guy H. Means .................................................................................................... 45

A BRIEF HISTORY OF PHOSPHATE MINING IN BONE VALLEY
by: Richard A. Fifer ................................................................................................. 53
INTRODUCTION TO FLORIDA PHOSPHATE

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

Jon L. Courtney
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)
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 subaerially 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 South Fort Meade Mine is located near the transitional boundary with the Southern Extension; however, the 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 South Fort Meade Mine, about 20 to 45 feet of overburden overlie a layer of matrix ranging from about 5 to 30 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 grain sizes, 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**
<table>
<thead>
<tr>
<th>Mineral</th>
<th>Clear Springs</th>
<th>Norlyn</th>
<th>Phosphoria</th>
<th>Kingsford</th>
<th>CF Garwood</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sulfides</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marcasite</td>
<td>X</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyrite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Oxides</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gibbsite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goethite</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Wad</td>
<td></td>
<td>P</td>
<td></td>
<td>P</td>
<td></td>
</tr>
<tr>
<td><strong>Sulfates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gypsum</td>
<td>X</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jarosite</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whewellite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Phosphates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autunite</td>
<td></td>
<td></td>
<td></td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Barbosalite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beranite</td>
<td>X</td>
<td>P</td>
<td>X</td>
<td>P</td>
<td>X</td>
</tr>
<tr>
<td>Cacoxenite</td>
<td>X</td>
<td>P</td>
<td>X</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Crandallite</td>
<td>X</td>
<td>P</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Cyrilovite</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dufrenite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lipscombite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Meta-autunite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metavivianite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Millisite</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitridatite</td>
<td>X</td>
<td>P</td>
<td>X</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Phosphosiderite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rockbridgeite</td>
<td></td>
<td></td>
<td>X</td>
<td>P</td>
<td>X</td>
</tr>
<tr>
<td>Strengite</td>
<td>X</td>
<td>P</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strunzite-ferrostrunzite</td>
<td>X?</td>
<td>P</td>
<td>P?</td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Variscite</td>
<td>X</td>
<td></td>
<td>X</td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Vivianite</td>
<td>X</td>
<td>P</td>
<td></td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Wavellite</td>
<td>X</td>
<td>P</td>
<td>X</td>
<td>P</td>
<td>X</td>
</tr>
<tr>
<td>Francolite</td>
<td>X</td>
<td>P</td>
<td>P</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td><strong>Silicates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chalcedony</td>
<td>X</td>
<td>P</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chert</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opal-CT</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opal-A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>X</td>
<td>P</td>
<td></td>
<td></td>
<td>P</td>
</tr>
<tr>
<td><strong>Carbonates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcite</td>
<td></td>
<td></td>
<td></td>
<td>P</td>
<td></td>
</tr>
<tr>
<td>Dolomite</td>
<td>X</td>
<td>P</td>
<td></td>
<td></td>
<td>P</td>
</tr>
<tr>
<td>Siderite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.
Clay Minerals
Attapulgite
Illite
Kaolinite
Montmorillonite
Sepiolite

Detrital Heavy Minerals
Andalusite
Biotite
Corundum
Epidote
Feldspar
Garnet
Hornblende
Ilmenite
Kyanite
Monazite
Muscovite
Rutile
Sillimanite
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.

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.
**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 an extremely complex process that involves separating the ore into several size fractions, each of which is processed by custom-tailored methods.

Phosphate matrix consists of a mixture of granules, pebbles, cobbles, and boulders of phosphate and phosphatized limestone; quartz sand referred to as “tailings”; and clay referred to as “slime.” At the mine, matrix is partially disaggregated with water jets, and pumped in slurry form through pipelines, sometimes for miles, to central washer plant.

At the washer, the matrix slurry is processed through a series of trommels, log washers, 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 the particles into different fractions by size.

The coarsest fraction is referred to as “pebble.” In the early days, the beneficiation process was very simple. Only high-grade pebble products were saved; and all of the other components of the matrix were discarded as waste. Simple washing and screening, to remove sands and clays, was sufficient to beneficiate the highest grade ores.

More efficient methods of phosphate beneficiation were developed as demand for phosphate increased and high-grade ores became more scarce. Product yields were greatly improved by recovering more of the fine-grained materials that had once been considered waste. Washers were redesigned to recover finer sizes of pebble materials; and, eventually, they were designed to recover sand-sized particles of phosphate, referred to as “concentrate.” Modern washers recover several different sizes of pebble and concentrate. Figure 12 shown conveyors stockpiling washed and sized phosphate rock. The clay sized fractions, appropriately called “slimes,” and some low-grade pebble fractions are discarded as waste.
Clay Settling Ponds

Slimes 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 13. As clay-rich solids settle slowly out of the slimes, 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, including processes to pre-thicken the slimes before discharge, and mixing sand tailing with slimes, have been successful in accelerating the solidification process.

Solidified clay settling areas, like the one pictured in Figure 14, have been used very successfully for agriculture. The phosphatic clays are very rich in nutrients.
Slimes contain significant phosphate values, in the form of microscopically-small grains that are very difficult to extract. Although slimes currently are discarded as waste, much research is directed toward finding economical ways to beneficiate them.

**Froth Flotation**

The sand-sized concentrate fractions contain appreciable quartz sand impurities. Washing and sizing processes alone cannot separate the particles of quartz sand from similarly-sized particles of phosphate. Additional processing is required to beneficiate the sand-size concentrate.

In the early days of phosphate beneficiation, it was not practical to separate quartz sand impurities from phosphate concentrates. The sand-sized fraction of the phosphate matrix, in some cases containing half of the phosphate that was mined, was routinely discarded as waste. In 1927 a new beneficiation technique was introduced to the phosphate industry. Froth flotation virtually doubled phosphate production by allowing quartz sand to be economically removed from sand-sized phosphate. It was one of the industry's most important advances.

Froth flotation exploits a surface chemical property called hydrophobicity. Hydrophobic molecules are repelled by water. Molecules that are attracted to water are called hydrophilic. If air is introduced to a slurry of water containing particles with hydrophobic surfaces and particles with hydrophilic surfaces, the hydrophobic particles will preferentially adhere to bubbles of air and float to the surface of the slurry. The hydrophilic particles will remain in suspension with the water in the slurry, or sink to the bottom of the tank.

The hydrophobicity of particles' surfaces can be altered by changing the pH of the water and/or by applying certain chemicals, referred to as conditioners. Typically a slurry is prepared for flotation by adjusting its pH and mixing in an appropriate conditioner until all of the surfaces of the particles are sufficiently coated. In addition, a soap-like chemical called a frothing agent is mixed into the conditioned slurry to encourage the formation of stronger and more long-lasting bubbles. Then the conditioned slurry is pumped into specially designed tanks, referred to as flot cells, for flotation.

A flot cell consists of a tank with a blender-like impeller designed to inject air and thoroughly mix the resulting bubbles into a slurry. The level of the top of the slurry is maintained very close to the level of the lip of the tank, so that the froth of bubbles that rises to the top of the tank will dool over the edge of the tank into a trough placed outside the tank to collect the froth. Frequently, moving paddles are installed above flot cells to scrape the froth from the surface of the slurry and push it into the adjacent collection trough. A schematic of a flot cell is shown in Figure 15.

The throughput of a single flot cell as relatively small; so typical industrial-scale flot circuits consists of many flot cells are arranged in rows, as shown in the photo in Figure 16.
A two-stage flotation process, called the Crago Process after the name of the inventor who patented it in 1942, typically is used to separate quartz sand from phosphate concentrates. In the first stage, the washed and sized concentrate slurry is treated with a conditioner that makes the surfaces of phosphate particles very hydrophobic. When air is applied, quartz particles remain in suspension in the flot cells until they are pumped out for disposal; however, the phosphate particles stick to air bubbles and float with the froth to the surface where they are scraped off and collected. The resulting froth, called a rougher concentrate, contains much less quartz.

A second stage of flotation is required to remove the remaining quartz impurities from the rougher concentrate. After washing, to remove the first conditioner, the rougher concentrate slurry is treated with a different conditioner that makes the surfaces of quartz particles very hydrophobic. In the second flot circuit, quartz particles adhere to air bubbles and float to the surface where they are scraped off and disposed of. The particles that remain in suspension after the second stage of flotation consist almost exclusively of phosphate.

**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 17.

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 18. The remainder is still used for mine-related activities.

![Figure 17. Before 1975 very little reclamation was completed.](image1)

![Figure 18. About 70% of the land mined since 1975 has been reclaimed.](image2)

### 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 facilities 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 leachate 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 19 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 20 is a side view of a similar gypsum stack.
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 21.

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 21. Locations of Gypsum Stacks in Central Florida
Bibliography


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.


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


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).
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 (?) (Huddleston 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
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 northwesternmost 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 forms 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.
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.
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 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

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


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


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 over 75% of the nation’s supply of phosphate fertilizer and approximately 25% 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,

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.

At the present time only two companies mine phosphate in Bone Valley, the Mosiac Company and C. F. Industries. Through mergers and acquisitions over the years, these two companies are the direct descendents of many of the original phosphate mining companies 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