

AREA  
FL  
PSFPhosphorite Sedimentation in Florida—A Model  
Phosphogenic System

STANLEY R. RIGGS

## Abstract

Some phosphatic sediments occur in many places in the geologic column and form in many environments on the sea floor in response to "normal" conditions and processes of sedimentation. However, that portion of the Miocene which contains the extensive phosphorites and associated anomalous mineralogies of the Hawthorn Group represents a very "abnormal" period of sedimentation. This phosphogenic system was characterized by a specific tectonic setting, structural framework, and an abnormal set of environmental conditions; the consequences represent one of the most extensive and important phosphate deposits in the world.

The structural framework which controlled the formation and deposition of the phosphorites of the Florida Miocene was a series of arches or topographic highs associated with the major Ocala Upland and Sanford High. Extensive coastal, shallow nearshore shelf, and platform environments occurred around the highs and were the sites of major phosphorite sedimentation—the phosphate machines and associated entrapment basins. The perimeter phosphogenic belt is situated around the Ocala Upland and was dominated by microspherite-intraclast sedimentation. The outer phosphogenic belt occurs downdip from the Ocala and in the offshore areas around the Sanford High; this area was characterized by pelletal phosphorite sedimentation. Phosphorite precipitation took place as the cold, chemically supercharged and somewhat toxic upwellings moved across the shallow platforms and into the coastal environments. The biologically stressed shallow-water environments received the bacterially precipitated microcrystalline phosphorite mud, or microspherite, as well as the other biologically produced phosphate grains. This orthochemical microspherite mud, along with all of the included microorganism hash, dolomite mud, and fine terrigenous sediment, then responded to the local environmental energy conditions and biological processes. The muds, populated by a benthic community characterized by high environmental tolerances and a low diversity index, ingested and excreted the muds as fecal pellets. Under low-energy conditions the muds settled out, became indurated, and were subsequently broken up by biological and physical processes producing intraclasts. Very locally, under high-energy conditions, some of the mud was aggregated to produce pseudo-oolites. The resulting phosphorite allochems (phosphorite gravel, sand, and clay) were then transported as clastic particles along and off the shoals by periodic high-energy conditions. They were diluted by the associated terrigenous and carbonate sediment systems and were deposited and accumulated in the adjacent entrapment basins and on the flanks of the structural highs. Thus, wherever the phosphorus sources were adequate, the physical current and the geochemical systems were appropriate, and the shallow marine environments had the proper geometry, then the "phosphate machine" produced and supplied clastic phosphorites to the associated "entrapment basins." The ultimate magnitude of phosphorite deposition was then dependent upon the size and extent of the structural system, the duration of the phosphogenic system through geologic time, and the volume and rate of terrigenous or carbonate diluent sedimentation. Subsequent fluvial erosion and subaerial weathering severely modified the most updip portions of the Hawthorn phosphorites following emergence.

## Introduction

THE literature on phosphates is voluminous and most of it represents good solid geology. However, much of it deals only with bits and pieces of an extremely complex system, and all too often the studies are totally out of context of the stratigraphic section and/or the associated sediment system. I have found

evidence to support most of the major ideas as to the genesis of phosphorite sediments. Many of these ideas at first seem to be quite diverse and even conflicting. However, in almost every case they represent only small pieces of the total puzzle. The disagreements as to the origin of phosphorite sediments by most workers is simply one of scale. Phosphate

does replace carbonate, but this is only one of numerous processes of formation in a complex system of authigenic sediments and is not *the* origin of phosphorite sediments. Likewise, mollusk kidney stones and replaced foraminifera may occur within the phosphorite, but they are not *the* origin of the bulk of the phosphorite macrograins. Upwellings are an important process, but they are not *the* sole mechanism necessary to produce a major phosphate deposit.

I find a great similarity from one phosphate deposit to the next even though superficially they may appear quite different—one is indurated and one is unconsolidated, one is black and one is cream colored, one is unweathered and one is weathered, one is Paleozoic and one is Tertiary. The only way to prevent being overwhelmed by the superficial differences in such a complex system and to be able to sort out the commonalities is to become intimately familiar with the system. Since the phosphorites are first and foremost a sedimentary deposit which occurs within a stratigraphic context with a multitude of vertical and lateral environmental facies, any study must start from this point. Interpretations based upon detailed chemical and geochemical studies, mineralogy, paleontology, petrology, etc. can only be beneficial in helping to understand this system when their detailed stratigraphic context is first known.

My search for the modern sediment analog has convinced me that many of the existing ideas are incomplete and *not* the answers in themselves. My interest is not to summarize the literature or history of phosphorite geology for the umpteenth time but rather to pull together some of the loose ends and tie them into the sedimentological-stratigraphic framework of the Florida phosphorite system. I would like to underscore two facts: (1) this model does not resolve all of the answers in this extremely complex and variable sediment system and (2) the model is still very active and evolving.

The model only considers the marine phosphorites associated with a major phosphogenic system. Such a system is characterized by a specific tectonic setting and unique or "abnormal" set of environmental conditions. The consequences are a constructional unit in which deposition is significant enough to produce a major stratigraphic horizon containing an extensive accumulation of phosphorite sediments which are potentially of economic importance. This model does not consider the "normal" marine sediments which universally contain small and disseminated concentrations of phosphorus and phosphatic material. Nor does it consider the ubiquitous occurrence of phosphorites associated with unconformities or surfaces of sediment bypass and nondeposition. These phosphate occurrences are extremely common

in the geologic record and on the ocean floor and often represent destructional units.

This paper will deal primarily with the definition of the phosphogenic system, the conditions prerequisite for the formation of phosphorites, the mechanisms of deposition, and the processes of accumulation of a major phosphorite unit. The proper geologic setting during some period of geologic time is the first and foremost prerequisite which dictates the potential of any given region to contain a phosphate deposit which may ultimately be of economic interest. If the phosphate deposit is formed, then additional factors determine the specific economics of the deposit. They include the subsequent history of sedimentation and burial, the structural deformation and erosion of the total sediment system, and the weathering and diagenetic history of the deposits. Only when enough basic geologic information has been obtained to demonstrate the potential occurrence and distribution of a phosphorite facies for a given region and a specific portion of the stratigraphic column do the factors dealing with the subsequent geologic history become important in delineating a possible economic deposit.

#### The Phosphogenic System—An Abnormal Sediment Regime

Some phosphatic sediments form and occur almost anywhere on the sea floor and in the sediment system in response to normal processes and conditions of sedimentation. Phosphorus and its various organic and inorganic components is an element which has a very small but ubiquitous concentration throughout the rocks of the earth's crust and waters of the world's oceans and is absolutely essential to the development of all forms of life. As pointed out by McKelvey (1973) phosphorus is the eleventh most abundant element in the earth's crust. It forms 0.1 percent of the rocks that make up the bulk of the crust; it occurs in about 200 minerals that contain 1 percent or more  $P_2O_5$  in igneous, metamorphic, and sedimentary rocks; and it is an essential component of every living cell and life's existence is contingent upon its availability. He goes on to point out that the major sedimentary rocks (sandstone, shale, and carbonates) contain an average of about 0.10, 0.17, and 0.07 percent  $P_2O_5$ , respectively, while deep-sea carbonates and clays have a  $P_2O_5$  composition of 0.10 and 0.30 percent respectively.

Thus, phosphorus and phosphatic materials occur in minor concentrations in most types of marine sediments ranging from the terrigenous sands and clays to the authigenic carbonates, glauconites, diatomites, clays, and even the sedimentary iron ores. The point is that the presence of some phosphate in the sediments on the sea floor, whether it be as a

replac  
or as  
not n  
phosp  
the o  
syster  
tion,  
tion c  
tion—  
thorn  
Form  
Th  
phosp  
strati  
econd  
envir  
logic  
and e  
be a  
of s  
occu  
geolo  
geolo  
acter

1.  
tinct  
mal  
2.  
whic  
nitur  
for t  
and  
3.  
fron  
to n  
basi  
unit  
tion  
mer  
bed  
foot  
and  
4.  
two  
occ  
and  
con  
in a  
5.  
soc  
mit  
rich  
clim  
6.  
of  
are

replaced foraminifera, as a discrete phosphate pellet, or as a phosphatic encrusting sediment surface does not necessarily constitute the occurrence of a major phosphogenic system. Nor does the definition of the origin of that particular occurrence define the system, the mechanisms or processes of sedimentation, or the environments of formation and accumulation of a major phosphogenic system of sedimentation—a system which is capable of producing a Hawthorn, Pungo River, Monterrey, or a Phosphoria Formation.

The formation and subsequent accumulation of phosphorite sediments sufficient to comprise a major stratigraphic unit with the potential of becoming an economic deposit requires a highly specialized set of environmental conditions in a very specialized geologic setting. Only if all of a complex set of tectonic and environmental variables are just right will there be a significant precipitation and major accumulation of sedimentary phosphorites. Such stratigraphic occurrences represent sediment systems which are geologically quite abnormal. Such systems in the geologic column commonly have the following characteristics.

1. They occur within a relatively brief and distinctive geologic time period during which the abnormal conditions existed.

2. They occur in long narrow belts or zones in which the length of the system is an order of magnitude greater than the width. It is not uncommon for these systems to extend over 1,000 miles in length and to be about 100 to 200 miles in width.

3. The phosphatic section may range in thickness from thin feather edges along the coastal margins up to many hundreds of feet in the deepest depositional basins. However, phosphorite dominated sediment units are usually in the minority in the thicker sections and are interbedded with nonphosphatic sediments. The thickness of the phosphorite-dominated beds generally ranges from something less than a foot up to 10 to 20 feet, occasionally up to 50 feet, and rarely up to and in excess of 100 feet.

4. Such phosphorite beds generally contain between 10 to 30 percent phosphate grains by volume, occasionally the content will increase to 50 percent, and in rare instances the phosphate particles may constitute up to 80 to 90 percent of the total sediment in a given bed.

5. The phosphorite has a common and intimate association with a suite of other anomalous authigenic mineralogies which include dolomite, a magnesium-rich clay mineral assemblage, diatomites and cherts, clinoptolite, and glauconite.

6. Specific beds composed of high concentrations of the abnormal sediments, including the phosphorite, are often extensively interbedded with a more normal

sequence of sediments. This would suggest that major pulses occur which are capable of bringing about dramatic changes within the environments of deposition.

The sedimentation patterns for the Florida peninsula were dominated by normal marine shelf limestone sedimentation during most of the pre-Miocene Tertiary. The post-Miocene has been characterized by terrigenous sedimentation which graded southward into normal marine shelf limestones. The Miocene itself, or some major portion thereof, represented a transition period of mixed sedimentation. But more important, the Miocene represented a fundamental change into a system of sedimentation which was dramatically different from the normal for the entire Atlantic Coastal Plain Tertiary. The anomalous mineral components which characterize the abnormal portion of the Miocene are not regionally ubiquitous throughout the Atlantic Coastal Plain but rather show the following distribution patterns.

1. Terrigenous sediments were derived from the Appalachians; they are dominant throughout the coastal plain north of Florida.

2. Dolomite increases southward and becomes a dominant component in Florida.

3. Of the magnesium-rich clay minerals, montmorillonite is dominant throughout the system. Palygorskite-sepiolite are abundant components of the southern half of the coastal plain (Weaver and Beck, 1977).

4. The zeolite mineral, clinoptolite, is a common component in the northern half of the coastal plain (Rooney and Kerr, 1967).

5. Diatoms and sponge spicules increase northward until diatomites are developed in the Virginia Coastal Plain.

6. Glauconite increases northward until it becomes a major component north of the Albemarle Sound in North Carolina.

7. The phosphate mineral, carbonate fluorapatite, is a major component in the intermediate areas between the northern glauconite-diatomite system and the southernmost dolomite system; optimum development of the phosphorite on the Atlantic Coastal Plain occurs between North Carolina and the northern portion of South Florida.

Obviously, a geologic system which is capable of producing an uncommon, but a well-defined, stratigraphic unit in both time and space with an abnormal sediment suite bounded by thick sections of more normal limestone and terrigenous sediments is not the product of day to day or normal sedimentation. Rather, it has to be the product of a very specialized phosphogenic system; a system which cannot be rare, however, since such systems are characteristic of the major phosphorite sequences in many regions of the

world and throughout most periods of geologic time. What then are the very specialized conditions of the phosphogenic system which cause the phosphorus and associated minerals to be concentrated into the sediment sink in such massive accumulations? To resolve the origin of phosphorite is to resolve the origin of this total complex and abnormal system of sediments.

#### *Tectonic setting*

The degree of regional tectonic activity within an area is critical with respect to the potential for the development of phosphorite sedimentation. On one extreme are areas of severe or high rates of tectonic activity. Such areas cannot be conducive to the accumulation of any authigenic sediments for three reasons. First, the flood of terrigenous sediments, including volcanic detritus, is far too great to allow for the significant concentration of any authigenic sediment. Second, the relief is too severe to supply the necessary extensive shallow-water environments for the formation and accumulation of extensive phosphorite sediments. Thirdly, whatever might be deposited is usually quite ephemeral and is commonly lost from the record with continued tectonism. On the other extreme are areas of stable platforms and low tectonism. Such areas are characterized by normal sequences of sedimentation of either or both authigenic and fine-grained terrigenous sediments. Generally, the phosphorite system does not represent sedimentation in either of these extremes. The optimum conditions leading to the potential development of the phosphogenic system with the appropriate physical and chemical setting lies with intermediate but changing tectonism, somewhere between total quiescence with its carbonate banks and extreme mountain building with its deluge of terrigenous and volcanic sediments.

Sheldon (1964) reconstructed the continental positions at the time of formation of major phosphorites. He demonstrated that the origin of phosphorite had definite paleolatitude controls; they formed between 5° and 42° paleolatitude with a mean latitude of 23°. Thus, the positions of the continents themselves determine the resulting size and shape of the ocean basin, the geographical or latitudinal position, and the climatic patterns at the time of formation. Freas and Eckstrom (1968) tested this control with good results by reconstructing the continents from the Permian through the Neogene with respect to the occurrence and distribution of known phosphate deposits. In the process, they also defined important areas of potential phosphate deposits where phosphorites were previously unknown.

Little question exists that latitude dictates the climatic conditions of the land areas, as well as the

basic oceanic circulation and the general chemical system of the water mass. A look at the major phosphogenic zones in the geologic column suggests that the area of maximum development of phosphorite occurs dominantly in the temperate latitudes, slightly poleward of the more tropical carbonate system and slightly equatorward of the more boreal glauconite and silica systems. This is dramatically demonstrated in the phosphogenic system of the Atlantic Coastal Plain of the southeastern United States. This major phosphogenic system extends from the Okeechobee area of South Florida north to the Albemarle Sound area of North Carolina (Fig. 1). Southward the equivalent portion of the Miocene sediments are phosphatic carbonates, whereas northward the equivalent units are phosphatic glauconites and diatomites. Each of these systems has a broad gradational zone which is characterized by both mixed sedimentation and interbedded sequences of the pure authigenic end members. This results from the lateral migration of pulses of the different chemical systems as they oscillate through time. Other Tertiary phosphogenic systems such as the west coast of southern Africa and the southwest coast of North America have similar regional relationships.

On the continental shelf, the phosphatic sediments extend from Pourtales Terrace, south of the Florida Keys, northward at least to the Scotian Shelf (Emery and Uchupi, 1972). They believe that locally the Miocene strata under the shelf contains appreciable concentration of phosphorite. However, all of the surficial deposits on the shelf appear to be reworked from Miocene phosphatic limestone and shale that underlie the continental shelf off Florida, Georgia, and the Carolinas. This entire system of authigenic sediments continues eastward onto the Blake Plateau where the phosphorite grades into a rather large extensive area of manganese oxide sedimentation. The older phosphorite, which is apparently mixed with the manganese, has been reportedly coated by and partially replaced by the manganese (Emery and Uchupi, 1972).

#### *Structural framework*

The detailed stratigraphic work on the phosphorites of the Atlantic Coastal Plain has demonstrated that one of the most important variables of the phosphogenic system is the structural framework. This is what determines the basic sediment environments and largely dictates the resulting geometries, the basic sediment processes, and the associated sedimentation system. The structural controls of the depositional system can be considered at three different scales or orders of magnitude.

Of prime importance for a significant formation

and accumulation of phosphorite is the appropriate regional setting; this defines the limits of the basic phosphogenic system. An example would be the southeast Atlantic Coastal Plain-continental shelf which contains the Miocene Hawthorn-Pungo River phosphogenic sequence of sediments (Fig. 1). The location and geometry of this structural system must be such that it is partially subaerially exposed during the time of primary phosphorite sedimentation in order to supply the essential shallow-water coastal environments.

Second, within the regional setting, there must be a series of structural arches or highs with the associated shoaling environments and adjacent basins or embayments. The production, deposition, and accumulation of primary phosphorite is directly related to these structural highs. Figure 1 shows the relationship of the known phosphate districts to the second-order structures in the Atlantic Coastal Plain. Each major structural high has the possibility, assuming all other variables are right, of containing one or more phosphate districts depending upon its geometry, size, and subsequent history.

Third, the structural highs must have an appropriate topography to both produce the phosphorite and to allow for its accumulation. It must contain an extensive shoaling submarine nose or platform off the end of the structure; this is the site of the "phosphate machine" where the greatest volume of phosphorite sediments are produced. In addition, the platform has to contain significant topographic lows or "entrapment basins" and/or must have a broad gentle sediment plain extending downslope from the platforms, where the resulting phosphorite sediments may accumulate. The origin of the topography becomes of great significance when exploring within a specific phosphate district. This topography may be a product of any or all of the following: regional structural deformation or faulting, primary constructional or depositional processes during the previous period of sedimentation, subaerial stream erosion, submarine erosion and scour processes, or groundwater solution and collapse. Each mechanism would produce a different type of topographic basin with distinctive sizes, geometries, and orientations. Individual mines or groups of mines work at this level of the structural setting.

#### *Phosphorus and upwelling currents*

Phosphorus is a basic nutrient element whose concentrations in sea water are not constant with respect to the major conservative constituents such as sodium and chlorine. The concentration of phosphorus in sea water averages 2.3 mg atoms P/1 (0.071 ppm) (Redfield, 1958). The concentration ranges from essentially none in some surface waters to 12 mg

atoms P/1 (0.372 ppm) in the region of the Andaman Islands in The Bay of Bengal (Gulbrandsen and Roberson, 1973). In most areas, the warm surface waters of the ocean contain only 0.0033 ppm phosphorus or less, whereas deep cold waters contain nearly 0.1 ppm (McKelvey, 1973). This is mainly as inorganic orthophosphate ions, the dominant mode of occurrence in sea water. Gulbrandsen and Roberson (1973) show that the lowest concentrations of phosphorus are at the surface and rapidly increase to a maximum that occurs at a depth of about 1,000 m with only a small and variable decrease with continued increasing depth. They explain this distribution as follows: "The thin surface layer is where photosynthesis takes place and is the zone of phosphorus consumption. Below this zone is the zone of rapid phosphorus regeneration where the phosphorus maximum is attained; it is where phosphorus is returned to solution upon the dissolution and oxidation of organic excrement and dead organisms. The deep zone receives regenerated phosphorus from the organic matter that passes through the zone of phosphorus maximum and constitutes a large reservoir of phosphorus that is brought to the surface for reuse in the life cycle by the major mixing processes of the oceans."

Oceanic upwellings are thought to be one of the major mechanisms for recycling the deep supply of phosphorus back to the surface. Such upwellings result from major ocean current divergences and represent areas of high primary organic productivity. Chow and Mantyla (1965) in Gulbrandsen and Roberson (1973) report that the phosphorus content of the upwelling off the Peruvian coast at 2 mg atoms P/1 (0.062 ppm) and Armstrong (1965) reports surface concentrations up to 2.5 mg atoms P/1 (0.077 ppm) in upwelling around Antarctica.

Kazakov (1937), McKelvey et al. (1953), Sheldon (1964) and many others have described upwellings and their doubtless association with recent phosphatic sediment. The world's classic oceanic upwelling systems are generally found in the trade-wind belts where surface waters are blown offshore and the offshore current is augmented by the Coriolis force. Such upwellings generally occur on the western continental coasts, as well as on north coasts in the northern hemisphere and the south coasts in the southern hemisphere (Sheldon, 1964).

The observed association between marine phosphorites on the sea floor and known oceanic upwelling systems have led to the conclusion of a cause-effect relationship (McKelvey, 1967). This, however, does not appear to be totally the case. Numerous studies have demonstrated that many of the shelf deposits are actually Tertiary phosphorites that have been reworked into the modern sediments. This has

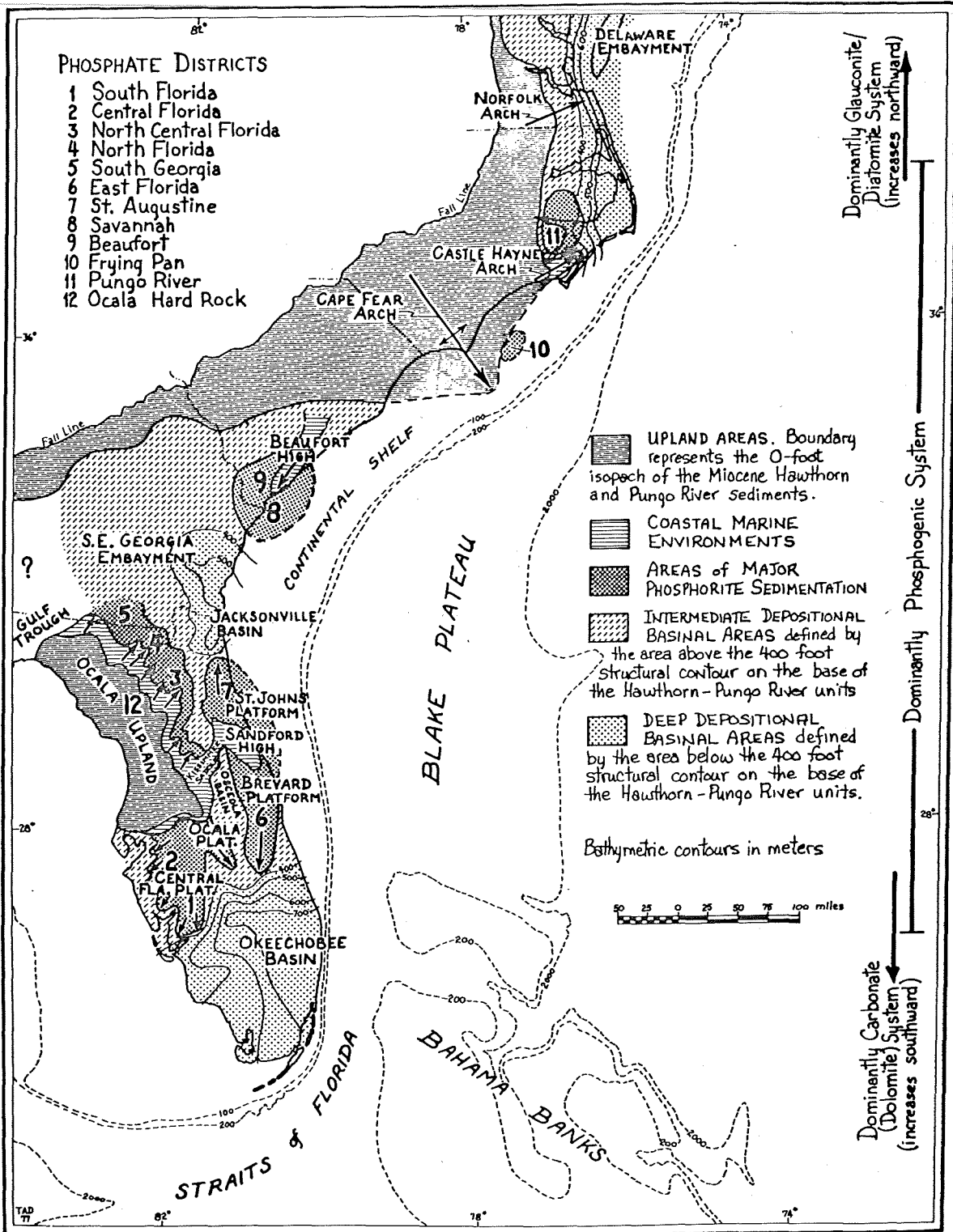


FIG. 1. Map showing the relationship between the major Miocene phosphorite deposits and the structural framework of the southeast Atlantic Coastal Plain-continental shelf system.

been supported by the radiometric dating of Kolodny (1969) and Kolodny and Kaplan (1970) where they found that the ocean-floor phosphorites are generally not forming today. Rather, they concluded that the phosphorite is a relict dating from times when the conditions were more favorable. However, Burnett and Veeh (1977) believe that the Kolodny and Kaplan work was incomplete since they did not include the two areas "where coastal upwelling, and hence organic productivity, is most intense: the areas off Peru-Chile and off Southwest Africa." Baturin et al. (1972) and Veeh et al. (1973, 1974) have subsequently demonstrated that both of the latter areas contain late Quaternary, if not Recent, phosphorite formation. In addition, Baurin et al. (1972) reported soft phosphatic nodules found in the surface sediment layer of diatom oozes on the southwest African and Peru-Chile shelves. They concluded that the occurrences of nodules in varying degrees of lithification in the same ooze samples indicates that their formation proceeds relatively fast in a highly reducing environment. According to them, this "convincing one that the origin of phosphorites is in fact connected with upwelling waters according to Kasakov's (1937) view." A little closer look at the Peruvian system suggests that phosphate is not all that abundant. Manheim et al. (1975) state that "the only high phosphate content we found on the shelf was far out on the crest of a hillock at 144 m depth. This apparently fossiliferous pavement had a concentration of 1.10%  $P_2O_5$ ." One sample with 23.7 percent  $P_2O_5$  was collected at 1,000 m depth which was described as "shale and phosphorite pebbles." The sample immediately above this at 510 m had 1.91 percent  $P_2O_5$  whereas all of them below and laterally adjacent had  $P_2O_5$  contents typical for normal marine sediments. Phosphate is probably forming today off the Peruvian coast; but does this represent a major phosphogenic system or is it an example of phosphorite sedimentation associated with a more normal sediment system?

Parker and Siesser (1972) and Parker (1975) describe the widespread in situ phosphorite deposits which occur on the Agulhas Bank off of South Africa. Parker and Siesser first placed an age of upper middle Miocene on these "phosphatized limestones." Parker subsequently concluded that phosphatization took place during late Tertiary or early Quaternary age. Kolodny and Kaplan have dated the phosphorites using uranium isotopes as older than 800,000 years. Yet Dietz et al. (1942) and Summerhayes (1970) have suggested that the Agulhas Bank is an area of nutrient rich and biologically productive upwelling waters.

In the past, the lack of modern phosphorite sediments along the western margins of ocean basins has

commonly been attributed to the general lack of upwelling (McKelvey and Chase, 1966; Tooms et al., 1969). However, in recent studies by Milliman et al. (1975) and by Summerhayes et al. (1976) of the upwelling current systems and associated bottom sediments along the continental margins of Brazil, they found well-developed upwelling currents at numerous places along the coast between Cabo Frio and Royal Charlotte Bank. In fact, Summerhayes et al. found that the "concentrations of biogenic suspensates mostly result from topographically induced, and coastal upwelling, and reach levels comparable with those reported for northwest Africa, another center of upwelling." However, "phosphate contents of local bottom sediments are usually less than 0.1 percent  $P_2O_5$ , and never greater than 0.2% suggesting a lack of phosphate mineral formation. Glauconite, a mineral commonly associated with phosphorite, is also absent." Milliman et al. (1975) concluded "that phosphorite and organically enriched sediment are absent whether upwelling is present or not."

Thus, the correlation of the distribution of known occurrences of sea-floor phosphatic sediments with known upwellings appears to be somewhat fortuitous. Some upwellings are associated with no apparent phosphatic sediments, some have minor concentrations of modern phosphate disseminated through the sediments, while many occur in conjunction with major concentrations of lithochemical phosphorites (i.e., reworked from older preexisting phosphorite sediments which either crop out on the submarine shelf or occur on the adjacent land). Consequently, I have to accept the conclusion that it may not be a direct cause-effect relationship and that the mechanism of phosphorite formation is probably much more complicated than the simple chemical precipitation of calcium phosphate from a nutrient-rich upwelling current system. The role of upwelling as a source of phosphorus-enriched waters and as a mechanism for moving these waters into continental-shelf environments is unquestionable, whereas, the role they play in the complex system of phosphorite sedimentation is not quite so clear. Normal upwelling systems are common and may be able to account for the presence of the minor amounts of phosphate which occurs in normal marine sediments. However, I believe that the major phosphate deposits of the world and their associated assemblages of abnormal authigenic sediments are a consequence of additional conditions and ingredients which comprise the abnormal phosphogenic system. When these conditions are right, then upwellings become an essential process; upwellings alone do not appear to represent the origin of major phosphorites.

### *The chemical associations*

To understand the origin of phosphorites fully, the entire assemblage of associated authigenic minerals must also be considered. One of the important anomalies of the Miocene phosphorite section of Florida is the almost ubiquitous association with dolomite and a magnesium-rich clay assemblage. In the past the dolomite component has either been totally ignored or used as evidence of an arid climate with hypersaline conditions. Hathaway et al. (1970) described small euhedral dolomite rhombs as the dominant carbonate mineral associated with the phosphatic horizons in the Miocene section of the JOIDES core holes J-1 and J-2 on the continental shelf off Florida. They interpreted the origin of the dolomite as a result of seepage refluxion associated with shallow-water evaporites in a lagoonal environment. It is interesting to note that they also described minor amounts of dolomite in the uppermost Miocene sample from J-3 at about 1,000 meters on the outer edge of the Blake Plateau.

No question exists that dolomite forms in shallow evaporite basins and in the intertidal zones of carbonate environments. This is well documented and I see no reason to include a discussion here. However, in the phosphogenic portion of the Florida Miocene, the dolomite does not seem to be related to the coastal environments. Rather, the dolomite generally increases in abundance seaward and southward into the more open platforms and depositional basins, where it was apparently forming (see section on the Florida phosphogenic system). The shallow-water equivalent facies are characterized by the magnesium-rich clay mineral assemblage including montmorillonite, palygorskite, and sepiolite. Dolomite is associated with the Arcadia Formation in the lower part of the Hawthorn Group around the perimeter belt of the Ocala Upland. However, this dolomite appears to be the downslope equivalent formed during a maximum transgression which may have temporarily covered much of the Ocala Upland depositing such isolated remnants as the Ocala Hard Rock district (Fig. 1). Portions of the Florida peninsula did have a semienclosed or restricted geometry during phosphorite sedimentation but these do not appear to be the major areas of phosphorite nor dolomite sedimentation. Thus, the Hawthorn dolomite does not appear to be directly related to the intertidal environment; rather, it appears that both the phosphate and dolomite are related to the areas of open circulation (see section on sediment facies).

It has been argued by some that the magnesium ion might be the primary inorganic constituent in sea water which could inhibit the precipitation of apatite (Martens and Harriss, 1970). However, Burnett

(1977) found on the Peru-Chile shelf that only those sediments which contained dolomite, chlorite, or sepiolite also contained detectable apatite. He believes that the diagenetic reactions that take up  $Mg^{+2}$  ions would be favorable for the precipitation of apatite. Charm et al. (1969) also found that dolomite was associated with the phosphate horizons in the JOIDES core holes on the Florida continental shelf.

The magnesium-rich clay minerals including montmorillonite, palygorskite, and sepiolite are also important components of the phosphorite sediments of the Florida Miocene (Weaver and Beck, 1977). Hathaway et al. (1970) as well as many others believe that this mineral assemblage, along with the zeolite clinoptilolite, is a result of the alteration of volcanic ash. They believe that 90 feet of a 300-foot-thick Miocene section on the continental shelf off Florida represents material of volcanic origin.

A volcanic association with phosphorites is not a new idea. Mansfield (1940) suggested a time and space association between volcanism and phosphorite deposition in the southeast Atlantic Coastal Plain using the extensive deposits of bentonites and Fuller's earth as evidence. Miller (1964) proposed a volcanic source for the anomalous fluorine and phosphorous in phosphate deposits as well as the volcanic shards which occur in some deposits. He believed that the location of phosphorite deposition is primarily determined by the location of volcanic arcs and the ocean currents. Rooney and Kerr (1967) also proposed a volcanic source for the glass shards which were subsequently altered to the clinoptilolite and montmorillonite assemblage in the Miocene Pungo River phosphorites of North Carolina. They explained the associated dolomites as a product of seepage refluxion of limestones by heavy magnesium-rich brines in the depositional lagoon. They attributed the source of phosphorus to widespread ashfalls of long duration which killed large numbers of marine organisms whose subsequent decay provided the phosphorus.

Carbonate fluorapatite is the major mineral in marine phosphorites. Fluorine is a minor element which constitutes between 2.63 to 4.45 percent by weight on the basis of 82 analyses of worldwide phosphorites (Lehr et al., 1968). Gulbrandsen (1977) gives the average fluorine grade for the phosphorites in the Meade Peak Member of the Phosphoria Formation in southeastern Idaho as 2.4 percent or 38 times the crustal abundance and 18,460 times normal sea water (1.3 ppm F, Turekian, 1968). A high fluorine content is usually considered to be toxic to many organisms. Fluorosis sets in with concentrations of 5,000 ppm in bovine bones (Largent, 1961). However, some organisms have developed special



tolerances for and are able to fix the fluorine; the inarticulate brachiopod *Lingula* produces a shell composed of carbonate fluorapatite with 1.6 percent F (McConnell, 1963).

Marine phosphorites also contain anomalously high concentrations of numerous trace elements. Kolodny and Kaplan (1970) state that "phosphorite typically contains between 50 and 200 ppm uranium, which is 15 to 90 times greater than the normal crustal abundance of uranium." According to Altschuler (1973) uranium ranges up to 2,000 ppm in marine apatites. This concentration is high enough that efforts are presently being made in Florida to recover the uranium from the phosphorites, as well as the anomalously high concentrations of the rare earths, yttrium, scandium, and vanadium. Vanadium averages 800 ppm in the phosphorites of the Phosphoria Formation and has been recovered as a by-product since 1941 (Gulbrandsen, 1977). He goes on to list an additional 17 elements plus the rare earths which are enriched enough to be considered by-product resources of the phosphate mining. Gulbrandsen (1977) states that the phosphorite from the Phosphoria is enriched in selenium, cadmium, silver, uranium, antimony, molybdenum, arsenic, rhenium, chromium, zinc, thallium, mercury, vanadium, rare earths, and tin. These rare elements are enriched in decreasing order from 600 times for selenium down to 5 times the abundance of tin in the continental crust. Altschuler (1973) also lists Ag, I, La, Mo, Sb, Se, Sn, Sr, U, and Y as being enriched in world phosphorites (from Tooms et al., 1969) by a factor of more than 2 over crustal abundances. Stow (1976) found trace amounts of metallic copper which occurred as flattened, elongated, and hackly wires along with pyrite, marcasite, and goethite as included material within the phosphorite pebbles of the Central Florida phosphate district.

It is not known how much of the enriched trace elements occur within the carbonate fluorapatite structure. In fact, much of it probably is not, but may be associated with the organic matter, clays, bacteria-like rods, or other included detrital material within the phosphate macrograins. The important point is that it is in the sediment, much of which is authigenic material formed basically at the same time and generally within the same broad environments of deposition as the phosphorite. Thus, the phosphorites contain an anomalously high concentration of many trace elements over and above the average abundance in the continental crust and the normal composition of sea water. This could readily be explained as enrichment resulting from organic activity, and in fact, much of it probably is.

Many of the rare elements concentrated within the phosphorites are essential micronutrients for plants

TABLE 1. Heavy Metal Concentrations

Metal	Concentration in phosphorites (Range in ppm)	Concentration in sea water (Avg. in ppb)	California waste-water discharge (ppm)
Mercury	10-1,000	0.15	0.001
Zinc	4-345	11.00	0.3
Copper	0.6-394	23.00	0.2
Lead	0-100	0.03	0.1
Arsenic	0.4-188	2.60	0.01
Cadmium	1-10	0.11	0.02
Chromium	7-1,600	0.20	0.005
Titanium	100-3,000	1.00	—

and animals at specific concentrations. But slight increases in the concentrations of many of the heavy metals above some critical level can act as major growth inhibitors and cause massive kill-offs. Most organisms have very definite tolerance limits for some of the elements which have extremely low concentrations in normal sea water. Bernhard and Zattera (1975) found, on the basis of the compilation of hundreds of laboratory studies, that mercury, zinc, and copper were the most important biological heavy metal toxins followed to a lesser, but quite variable, degree by lead, arsenic, cadmium, chromium, and titanium. The effect upon the organisms is considerably greater when the metals are taken in through the food chain than when they are just dissolved in sea water. The degree of impact is also dependent upon the physicochemical state of the elements, the abundance of the other metals, enzymes, chelating agents, etc. Table 1 shows the highly enriched concentrations of these heavy metals in phosphorites of the world (Tooms et al., 1969) over normal sea-water concentrations (Turekian, 1968). The table also includes the minimum criteria for minimum biological impact resulting from California waste-water discharge into the ocean for 50 percent of the time (Bernhard and Zattera, 1975). The latter numbers are manyfold lower than the concentrations of similar metals in known magmatic and hydrothermal solutions and brines on the sea floor.

For the trace element data to be meaningful, the contents of the respective elements in sea water during the Miocene need to be known. There is no direct way of knowing this; however, the indirect evidence may provide some clues. The ability of organisms to concentrate trace and heavy metals when they occur in abnormal concentrations is a well-established fact. For example, Doyle et al. (1978) found that several species of modern mollusks form phosphate concretions as kidney stones under conditions of stress. They believe that under polluted water conditions, the kidney stones become sinks for the concentration of many of the otherwise toxic trace metals.

Concentrations of 5.9% Zn, 0.4% Cu, 0.32% Sr along with 96 ppm Pb, 75 ppm Ba, 50 to 70 ppm Ni, 30 to 50 ppm Hg, 20 ppm Cr, and 11 ppm Cd were measured in some of the phosphate concretions from a polluted coastal bay. The fact that phosphorites are characterized by anomalous concentrations of many heavy metals and rare elements over and above both normal crustal abundance and the concentration in present sea water might suggest the character of the bottom waters at the time of phosphorite formation in the Miocene.

Preliminary fossil studies of the phosphorites of the Florida Miocene suggest that when the phosphorite was forming there was: (1) a high population of organisms with a low species diversity of mobile macrobenthic forms, some were burrowers and some were vagrant, and most were without skeletal parts; (2) a very high population of microorganisms, particularly bacteria, in the phosphorite muds; (3) a prolific nektonic assemblage of small almost depauperate vertebrate forms with only the larger and most mobile nekton being normal; and (4) a fairly rich assemblage of microscopic plankton. Interbedded units of terrigenous or carbonate sediments which formed in the absence of phosphorites are often quite fossiliferous and contain a more normal species diversity of marine fauna and flora. Thus, on the basis of the fossil assemblages of the major phosphorite beds, the abnormal mineralogical character of the Miocene phosphorite sequence, and the anomalous trace metal content of the phosphorites, it appears that the bottom waters were not normal during the Miocene. In fact, the indirect evidence suggests that the waters were a highly stressed chemical system and possibly even somewhat toxic at the time the phosphate was forming.

#### *Alternative chemical source*

Bushinski (1964) states that rich concentrations of dissolved phosphates, in addition to upwellings of the sea water and fluvial supply from the land, may be derived from submarine hydrothermal sources or volcanic exhalations. The possibilities of hydrothermal and/or magmatic solutions from some igneous source

containing anomalous concentrations of phosphorus, magnesium, fluorine, and a multitude of trace elements, heavy metals, and rare earths merits further consideration. During periods of increased tectonic activity, such a source might act as a "supercharger" supplying enough new materials to the chemical system to bring about a totally abnormal period of sedimentation, abnormal in terms of the chemical and biological environment and the resulting sediment system. Such magmatic and/or hydrothermal solutions exhausted from a major oceanic fracture system or crustal boundary could represent such a supercharger if it occurred adjacent to or through a shallow-water continental-shelf system.

Some form of the phosphorus mineral apatite occurs disseminated in all igneous rocks. The average  $P_2O_5$  content in igneous rocks ranges from 0.1 up to 1.68 percent in ultraalkalic rocks (McKelvey, 1973). He goes on to state that most of the igneous apatite deposits occur in ringlike intrusive structures associated with carbonatites, nepheline syenites, ultraalkaline rocks such as ijolite and urtite, and alkaline ultramafics such as alkali pyroxenite. These igneous apatites occur in shield areas and many are associated with rift-valley structures. They supply about 15 percent of the world's phosphate production including the world's largest Khibina deposit of the Kola peninsula, USSR, a nepheline syenite massif which averages 27 percent  $P_2O_5$  (McKelvey, 1973), as well as other major deposits in South Africa, Uganda, Brazil, and Canada. McKelvey summarized the average phosphorus content of various types of more common rocks based upon the analyses of many individual workers (Table 2). On the basis of these figures the amount of phosphorus in the average igneous rock or magma is several times greater than the average concentration in sediments and is many thousands to tens of thousands times greater than that of sea water and upwelling currents. The importance is that all igneous rocks have relatively high contents of phosphorus, while some less common varieties have extremely high phosphorus concentrations.

Bostrom et al. (1968) report that the pelagic sediments on active ridges are enriched in numerous elements including phosphorus as compared to other pelagic sediments. They believe that element enrichment is probably due to carbonatitic volcanism associated with the degassing of the mantle, which could also explain the occurrence of hydrothermal dolomite in the ridge sediments. Berner (1973) found  $P_2O_5$  contents which ranged between 0.18 and 3.39 percent in the predominantly montmorillonite clays on the East Pacific Rise. These numbers are considerably higher than those for the normal marine sediments. He states that the magnesium-rich mont-

TABLE 2. Phosphorus Content of Various Rock Types (from McKelvey, 1973)

Average rock	$P_2O_5$ (%)	P (ppm)
Igneous	0.22	961
Upper continental crust	0.22-0.28	961-1,222
Alkali basalt, oceanic crust	0.48	2,095
Tholeiitic basalt, oceanic crust	0.13	567
Carbonate	0.07	306
Sandstone	0.10	437
Shale	0.17	742

morillonite clay forms from the submarine weathering of volcanic glass and is responsible for the absorptive removal of phosphate from sea water.

Recent sea-floor drilling has demonstrated that fine-grained euhedral dolomite rhombs are a fairly common constituent of deep-sea sediments (Davies and Supko, 1973). Bonatti (1966) believes that dolomite on the sea floor is a result of local magnesium enrichment associated with igneous activity. He found calcite crystals and dolomite rhombs in the deep-sea sediments from the East Pacific Rise and concluded that these crystalline minerals had precipitated directly from hydrothermal volcanic solutions ejected nearby on the sea floor. Davies and Supko (1973) state that the "association between dolomite and basalt or volcanic debris has been demonstrated at many sites drilled by the GLOMAR CHALLENGER." They also describe the association of dolomite with sepiolite-palygorskite as a common couplet in the ocean sediments, all of which are major components of the Miocene phosphorite sediments.

Consequently, magmatic and/or hydrothermal solutions associated with any major tectonic fracturing have the potential of containing anomalous concentrations of phosphorus, magnesium, fluorine, heavy metals, etc. In addition, consideration should be given to the potential chemical exhalations, including phosphorus, which might be derived from the baking of organic-rich seafloor sediments by intrusive or extrusive igneous activity associated with fracturing. Such hydrothermal solutions exhausted onto the sea floor could act as a supercharger to the marine environment. If such a fracture system were located proximal to or intersected a shallow continental-shelf system, it could have a major influence upon the bottom chemistry of the shelf system. The oceanic current systems and associated upwellings become very important mechanisms at this point. They mix and move the supercharged waters up into the shallow-water shelf environments. The somewhat enriched toxic waters could modify the chemical and environmental conditions, stressing the organic populations and producing abnormal authigenic sediment systems. The type and degree of development of authigenic sediments formed (dolomite, glauconite, phosphorite, etc.) depend upon the composition of the enriched solutions and their duration and volume, as well as the physical dynamics of the entire upwelling system.

The evidence for such a submarine supercharger, at this point in time, is all indirect, but it is an important hypothesis which demands further work. Continued work on the deep sea floor is providing a wealth of new information which is increasing the apparent importance of hydrothermal and/or mag-

matic solutions in basic chemical and sediment processes. Major fracture and rift systems exist in great abundance on the sea floor and brine solutions have already been recognized in conjunction with some of these.

The real testing grounds for some of these ideas may be the phosphorites of Baja California where I have done some recent work with the Consejo de Recursos Minerales of Mexico. This work is beginning to shed some interesting light on the fairly extensive Tertiary deposits of mixed authigenic, terrigenous, and volcanic sediments. The interesting relationship is that the Gulf of California is known to be an active rift valley which first opened about 20 to 25 million years ago during the early Miocene (Suppe, 1970; Ingle and Moore in Elders and Biehler, 1975). Thus, the Tertiary stratigraphic section in Baja should be a rather sensitive tape recorder of the episodic events associated with the rifting and opening of the Gulf of California. The changing patterns of authigenic, terrigenous, and volcanic sediments and associated faunal characteristics should be a direct response to type, intensity, and duration of each tectonic event and the resulting chemical systems and sediment pulses (see the sections in this paper on the abnormal sediment regime and the tectonic setting).

In his description of the phosphate deposits of Baja California, Salas (1978) suggests that the lower middle Miocene Monterrey Formation, with its abundant phosphorites, was deposited unconformably on the Paleocene and Eocene nonphosphatic sandstones of the Tepetates Formation. Salas describes the contact as a fossiliferous, volcanic conglomerate in a phosphatic sand matrix. The remaining 110 m of the Monterrey is characterized by alternating beds of diatomite, silicified shales, calcareous sediments, and phosphorite siltstones and sandstones which range from 1 to 27 percent  $P_2O_5$ . The middle Miocene San Isidro Formation is similar to the Monterrey in the lower portion with  $P_2O_5$  contents varying from 3 to 9 percent and locally to 24 percent plus high concentrations of glauconite. This formation grades upward into a volcanic sediment sequence of interbedded tuffaceous sandstones and bentonitic clays with beds of great concentrations of *Turritella*. By this time all authigenic sediments were totally overwhelmed by the volcanic input as 2,000 m of tuffaceous sandstones and volcanic conglomerates of the upper Miocene to lower Pliocene Comondu Formation were dumped into the sediment system. As volcanism subsided into the Plio-Pleistocene, phosphorite sediments (up to 10%  $P_2O_5$ ) began to accumulate again within the sandstones in the lower part of the Salada Formation. Salas believes these phosphorites may be of equal or even

greater importance than those in the Miocene. The phosphatic sandstones grade vertically to a normal nonphosphatic limestone sequence in the upper portion of the Salada Formation. Detailed sedimentological studies of the Tertiary section should demonstrate whether there is a direct relationship between the phosphorites and the tectonic events. Can similar relationships be developed for the Monterey Formation in California and the Sechura deposits in Peru?

Preliminary sedimentologic and petrographic studies of the Baja phosphorites suggest to me that they are very similar to the phosphorites of Florida and the southeast Atlantic Coastal Plain. If these associations are real, then maybe the abnormal sediments in the Tertiary stratigraphic section represent the record of major tectonic events along the southeast Atlantic coast. Several possible structural elements could be associated with major tectonic fracture systems which should be considered further. The extensive Blake Plateau (Fig. 1) is a 228,000 km<sup>2</sup> platform which has an average depth of 850 m (Pratt and Heezen, 1964). The entire Blake Plateau is composed of thick sections of shallow-water carbonate sediments formed during the Cretaceous behind an extensive series of algal banks which flourished along the eastern margin (Uchupi, 1967). Uchupi believes that sometime after the banks died during Late Cretaceous, the plateau began to submerge. The basement structure of the Atlantic continental margin is interpreted by Sheridan (1974) to be a block-faulted series of marginal basins with accumulations of great thicknesses of shallow-water sediments. The drastic subsidence, carrying the shallow-water sediments to as much as 8 to 12 km under the continental shelf, Blake Plateau, and Bahamas, is in response to the spreading of the Atlantic Ocean, which began in the Triassic. Dillon et al. (1976) believe that the subsidence of the Blake Plateau resulted from the reactivation of a major crustal boundary near the end of the Cretaceous or beginning of the Tertiary.

The stratigraphic record of the southeastern Atlantic Coastal Plain may very well carry the evidence marking the time(s) of foundering of the Blake Plateau and the discharge of extensive hydrothermal and/or magmatic solutions to the continental margin. The uppermost part of the Upper Cretaceous, as well as the Paleocene sediments of the central coastal plain, which are poorly known, consist predominantly of authigenic glauconite with some dolomitic and phosphatic sediments. Could this represent the initial foundering of the Blake Plateau? The Eocene and Oligocene throughout the southeastern coastal plain are characterized by normal limestone and mixed limestone-terrigenous sedimentation. Could

the anomalous Miocene represent a reactivation of the fault blocks and another period of foundering and further submergence of the Blake Plateau? The chemical system which produced the phosphogenic portion of the Miocene sediments throughout the southeast Atlantic Coastal Plain is truly abnormal compared to the rest of the Tertiary section and reflects some major changes within this time period. Sheridan et al. (1974) found early late Miocene turbidites in their piston cores from the Blake-Bahama Basin. These were overlain by nearly 1,000 m of hemipelagic sediments of late Miocene through Holocene age (Sheridan, 1974). He concludes that the late Miocene marks an important change in the oceanic current regime. Could these turbidites be a product of an earlier Miocene foundering? The relationship of the Tertiary section to other structural components such as the Caribbean lithospheric plate, the Straits of Florida, and the Bahama Platform should also be pursued.

#### *Role of organisms*

Phosphorus plays an essential role in the realm of the living organism. As such, organisms cannot help but play a multiple and unquestioned role in the distribution and the multitude of processes effecting inorganic phosphorus in the marine environment. Hence, organisms must also play a major role in the formation of sedimentary phosphorites, some obvious, most not so obvious. Ongoing research is attempting to establish more clearly some of the organic functions in the formation of phosphorite sediments.

The role of the vertebrates is fairly obvious since almost their entire skeletal structure is composed of biological apatite, carbonate hydroxyapatite (McConnell, 1973). The nektonic marine forms, upon death, may contribute up to 15 percent of the phosphorite grains as teeth, bones and bone fragments, and fish scales. These organisms have concentrated the phosphorus manyfold from the minute concentrations in normal sea water; thus, they represent a very efficient phosphate machine in themselves, but rarely is it of direct importance volumetrically.

The role of the invertebrates is much more diverse and not quite so obvious. Invertebrates are directly involved in the following aspects of phosphorite sedimentation.

1. A few living inarticulate brachiopods such as *Lingula*, (McConnell, 1963), *Glottidia*, and *Disciniscia* (Clarke and Wheeler, 1922), build their shells out of carbonate fluorapatite. Many of the fine-grained shell fragments, which in the past have been described as replaced calcite shells, have been identified as actual phosphatic brachiopod shells.

2. Crustaceans generally have a carapace with a very high phosphorus content. Clarke and Wheeler

(1922) gave analyses of crabs and shrimp which ranged from 15 to 50 percent  $\text{Ca}_3\text{P}_2\text{O}_8$ . Thus, the chitinous carapaces are almost entirely calcium phosphate, however, they are generally not preserved.

3. McConnell and Ward (1978) found that phosphatic hydrogels formed solid silt- and fine sand-sized uroliths which were excreted from the urinary tracts of the cephalopod *Nautilus*. Doyle et al. (1978) found that several modern mollusks including *Argopecten* and *Mercenaria* form concentric phosphate concretions of varying size in the kidneys which can subsequently be excreted as solid sediment particles. Glenister et al. (1976; 1978) have described similar fossils which are translucent, honey-colored, dimpled sand-sized phosphate spherules. They believe these phosphate "pearls" were secreted by the conodont-bearing animal as a response to an organic or particulate irritant. They go on to report that Martinsson (1964) described many organisms which eliminate metabolic waste as laminated phosphate and Eisenack (1964) described concentrically banded phosphatic concretions which form in association with the degradation of organic tissue. Thus, it appears that many invertebrates have this capability of forming silt- and sand-sized phosphate concretions in their kidneys and urinary tracts, particularly under conditions of chemical stress, which may play an important role in the production of the pelletal phosphorites.

4. Lowenstam (1963) has found that some tectibranch gastropods have phosphatic hydrogel gizzard plates which contain up to 12 percent  $\text{P}_2\text{O}_5$ .

5. The churned and burrowed sediment structures characteristic of most phosphorite sections suggest an obvious presence and an important indirect contribution of invertebrates. The low species diversity and high populations of crustaceans, polychaete worms, and other vagrant and benthic infauna play an integral part of the pelletal phosphate machine (described in a subsequent section).

6. Any empty invertebrate shells constituting part of the sediment are infilled with the phosphorite mud, producing the very abundant internal and external molds which occur as intraclasts.

7. Some calcareous shell material of invertebrates and foraminifera is replaced by phosphate when the surrounding chemical conditions are appropriate. This was not an important process in the major phosphogenic system operating in the Miocene in Florida, the southeast Atlantic Coastal Plain, most of the major phosphate deposits of the world, nor in some of the phosphorites of the continental margins. Burnett (1977) found that most of the phosphorites on the Peru-Chile shelf grew as euhedral crystals of apatite on the surfaces of biogenic fragments without any replacement. Thus, he concluded that apatite

formed authigenically by precipitation rather than by replacement. Also, Parker and Siesser (1972) found that all of the invertebrate shell material occurring within the phosphorite matrix of the South African continental margin phosphorites was unreplaced calcium carbonate.

The role of the microscopic plankton and bacteria is probably even more important, but it is also more elusive. The relationship of bacteria-like cells preserved in the marine phosphorites has been fairly well established by Riggs and others (Riggs, 1979). Also, the direct relationship of bacteria to the precipitation of carbonate hydroxyapatite (the same mineral vertebrate bones and teeth are composed of) as oral calculus and in many forms of pathological depositions in vertebrates has been well demonstrated (McConnell, 1973). Rizzo et al. (1962) and Ennever (1963) found that bacterial cells will readily mineralize with carbonate hydroxyapatite under the proper biological conditions.

Since organic phosphorus and insoluble phosphates cannot be utilized directly by plants, the actions of bacteria, fungi, and actinomycetes play a vital role in making the bound phosphorus available (Hodson, 1973). Lear (1966) found that marine bacteria can regenerate inorganic phosphate from organophosphorus compounds in zooplankton, phytoplankton, and fish meal. Hodson concludes that microorganisms are responsible for the following critical transformations of phosphorus: altering the solubility of inorganic compounds of phosphorus; mineralizing organic compounds with the release of orthophosphates; converting the inorganic available anion into cell protoplasm, an immobilization process analogous to nitrogen fixation; and bringing about an oxidation or reduction of inorganic phosphorus compounds. Particularly important to the phosphorus cycle in nature are the microbial mineralization and immobilization reactions. Since bacteria-like rods have been found to be major fossil components of many varieties of phosphate grains, not only in the Florida deposits but also within most of the worldwide deposits (Riggs, 1979), it is logical to assume that they have played some role in the formation of the phosphorite sediments. The specific cause and effect relationships are presently under investigation.

McConnell (1965) believes that "organisms of various kinds are quite important in the precipitation of carbonate fluorapatite from sea water, particularly in view of the fact that certain bacteria appear to be capable of initiating similar types of precipitation." He found that a common enzyme (carbonic anhydrase) plays an important role in the precipitation of carbonate hydroxyapatite in the oral cavity; he also reported that this same enzyme has a high activity in

the mantle tissue of the phosphatic brachiopod *Lingula*.

In a similar nature to authigenic phosphorites, Dugolinsky et al. (1977) found that bacteria were associated with manganese nodules and that they might play a significant role in the concentration of trace metals in the nodules. Also, Burns and Brown (1972) found that the postdeath dissolution and diagenesis of the microorganism tests acted as important nucleating surfaces for the precipitation of manganese and iron. Dugolinsky et al. (1977) found all stages of epitaxial growth of manganese oxide crystals on and around diatom tests until the entire test was completely encrusted. This is associated with partial to complete solution of the silica leaving layers of fine manganese oxide crystals. A comparable process might explain the unique discoid phosphate grains described by Riggs (1979). Burnett (1977) found that opaline diatom frustules were commonly covered with apatite. However, he considered it conceivable, but unlikely, that the frustules and other "small undetected fragments of calcite served as 'seeds' for epitaxial growth of apatite."

The role of plants in the phosphogenic system is totally unknown at present. McConnell (1973) states that there are no known true plants that form inorganic phosphates analogous to the carbonates and silica tests of calcareous algae and diatoms. However, Azad and Borchardt (1970) have found that the permanent storage of inorganic phosphorus by algae is a normal characteristic in environments where there is an excess over and above what is necessary for continuing metabolic needs. This "luxury uptake of phosphorus" reached levels of 10 percent  $PO_4$  dry weight in several species of green algae. Under circumstances which started with phosphorus starvation, followed by a rich slug of phosphates, they found that the algae took up to 20 percent  $PO_4$  dry weight. This is in comparison to the critical concentration of phosphorus established to be about 3 percent  $PO_4$  dry weight. The role that algae might play in the processes of concentration and precipitation of inorganic phosphorus in the sediments is not known. Information about the mineral and structural form in which the inorganic phosphorus is stored and the fate of the phosphorus upon the death of the plant might contribute to a better understanding of phosphate deposition. Is it possible that some algae might be capable of concentrating even higher levels of phosphorus or of phosphatizing in a manner similar to the calcareous algae under the influence of anomalous and stressed chemical systems?

One further, and possibly important, role of organisms is their process of supplying and concentrating phosphorus in the muds, whether it be above, at, or

below the sediment interface. Stumm and Leckie (1970) believe that anoxic pore waters obtain phosphate from the decomposition of organic materials such as diatoms, which are known to contain large quantities of organic phosphorus. Also, they believe that the reduction of hydrous ferric oxides that bind phosphate to their surfaces under oxidizing conditions supplies significant phosphorus to the sediments. Sholkovitz (1973) has demonstrated that the dissolved phosphate content of pore waters in anoxic areas reaches a maximum at 15 cm below the sediment interface and is higher than under normal oceanic conditions. Gulbrandsen (1969) felt that organic matter represented a special steady-state supply of phosphate to the sediments of the shallow oxygenated waters adjacent to the continents from which large amounts of apatite could form. Bushinski (1946) also believed that the phosphate was concentrated in the muds of the shallow-water zones from which the phosphorite was formed.

Organic enrichment of phosphorus in the bottom sediments as demonstrated by Stumm and Leckie (1970) and Sholkovitz (1973) is a well-documented fact. However, the phosphate particles themselves demonstrate that the initial processes must have taken place at or immediately above the sediment interface prior to burial (Riggs, 1979). Many of these processes directly involve organisms and will be expanded upon in the next section. Petrographic and sedimentological studies of phosphate particles suggest that organisms do play a very major role in the formation of sedimentary phosphorites. Organisms are an important biological phosphate machine which directly concentrates phosphorus and modifies its distribution and its chemistry within the depositional environment.

### Florida Phosphogenic System

#### *Phosphate stratigraphy*

A basic stratigraphic pattern of phosphorite sedimentation characterizes the Florida peninsula. Detailed stratigraphic and petrographic analyses of many mines, thousands of drill cores and gamma-ray logs, and hundreds of water-well cuttings have proven that: (1) definite lithologic sequences occur within the phosphorite section of each district, (2) specific sediment facies are readily and easily correlatable from hole to hole and mine to mine within any given district of Florida, and (3) similar patterns are recognizable throughout the entire phosphatic portion of the Florida peninsula with very distinctive lateral and vertical variations on a theme.

The phosphorite stratigraphy as used herein is an evolutionary modification of that presented by Riggs (1967) and Freas and Riggs (1968) for the Central

Florida phosphate district. The terminology, presented in Table 3, represents lithostratigraphic units defined and delineated on the basis of the sedimentological characteristics.

Whereas phosphate is a minor mineralogical component of most of the sedimentary rocks of the world, its presence in concentrations of more than 1 percent is uncommon and yet very important because it reflects highly specialized depositional conditions. Thus, its presence defines an important primary lithostratigraphic unit. Because of the significance of a sequence of phosphatic and phosphorite rocks and sediments, the rocks in peninsular Florida which have this lithologic feature in common are defined as the Hawthorn Group. The Hawthorn Group is subdivided into the Arcadia, Noralyn, and the Bone Valley Formations. Table 3 describes the basic characteristics of each of these stratigraphic units.

The Hawthorn Group is an extensive unit which covers all peninsular Florida except the Ocala Upland and the Sanford High (Puri and Vernon, 1964). However, scattered phosphatic sediments do occur on the Eocene and Oligocene limestones of the Ocala Upland area and include the hard-rock phosphate deposits (Fig. 1). I believe that these phosphates were deposited on the limestones during a maximum transgression which took place at the beginning of the phosphogenic portion of the Miocene. These deposits have been severely altered and modified by subsequent weathering and occur as isolated and scattered remnants today. The main portion of the Hawthorn is wedge shaped and ranges from a feather edge on the flanks of the two structures to more than 700 feet in the Okeechobee Basin. The geologic age of the former "Hawthorn Formation" has generally been considered to be middle or middle and upper Miocene (Puri and Vernon, 1964). By raising this name to group rank, the reworked phosphorites of Pliocene age are included with the Miocene units.

Riggs and Freas (1965) resurrected the name Arcadia to include that portion of the Miocene section which is dominated by dolomite. The Arcadia often contains thinner interbedded units dominated by terrigenous sands and/or clays. Around the Ocala Upland, the Arcadia constitutes the lower portion of the Hawthorn section, decreasing in importance into North Florida. East and south off the Ocala Upland and down the depositional slope, the Arcadia Formation increases in thickness and importance. The Arcadia Formation is the dominant unit of the Hawthorn in the East and South Florida districts and contains a vast resource of low-grade pelletal phosphorite.

In a broad 50-mile-wide zone around the east and south perimeter of the Ocala Upland, the upper por-

tion of the Hawthorn Group is dramatically different from the Arcadia Formation. This upper portion of dominantly terrigenous sediments with distinctive kinds of phosphate constitutes the major stratigraphic units which have been and are presently being mined throughout Central and North Florida. This section is characterized by two distinctly different units, both of which have been recognized in the past, though inconsistently through time, and geographically, and have been loosely called the Bone Valley Formation (Riggs, 1967). Since each of the units has quite a different age, origin, and history, and consequently has different effects on the mining economics, differentiating between the two units is both geologically and economically useful and essential. Thus, each unit has been defined as a separate formation within the Hawthorn Group. The name Noralyn Formation was proposed for the intermediate stratigraphic unit by Riggs and Freas (1965) and defined in detail by Riggs (1967). The name was derived from the Noralyn mine of International Minerals and Chemical Corporation at Bartow, Florida, one of the largest and most important phosphate mines in the world. The name Bone Valley Formation is an established name which has many unnatural, confusing, and inconsistent usages; however, the name is retained because it is so well ingrained. It is herein used only for the uppermost portion of the section for which it best fits. Riggs (1967) outlined the history of the stratigraphic nomenclature and presented detailed descriptions of each of these units.

The Miocene Noralyn Formation is a shallow-water coastal and nearshore shelf deposit which formed around the east and south sides of the Ocala Upland. It pinches out onto the Ocala Upland, reaches a maximum thickness of 50 feet, and has been locally modified or eliminated by weathering or erosion. Thus, the thickness of the formation varies according to pre-Noralyn topography and the amount of post-Noralyn erosion. Down the depositional slope into East and South Florida, the Noralyn Formation grades laterally and vertically into the Arcadia; however, in the north and northeast, the Noralyn Formation lithology thickens and continues down the depositional slope.

The Bone Valley Formation is predominantly a terrigenous sand and clay with varying amounts of lithochemical phosphorite. It occurs as a complex set of fluvial channel deposits in the upslope areas adjacent to the Ocala Upland. In the Central Florida district, these reworked fluvial units constitute only about 10 percent of the mined phosphorite. The unit does not occur everywhere, but where it does occur it may constitute up to 100 percent of the phosphorite section in a given mine. The unit is best developed in the structural lows in the top of the

TABLE 3. Phosphate Stratigraphy of the Florida Peninsula

Age	Group	Formation	Environments of deposition	Sediment structures	Nonphosphate lithology	Phosphate lithology	Fossil assemblage	Stratigraphic relationships
Pliocene	Hawthorn	Bone Valley	Complex fluvial facies (upslope)	Linear geometries, abundant cut and fill channels, well-bedded and often cross-bedded	Rapidly changing terrigenous clays and sands, common quartz and chert granules and pebbles	Lithochemical sands and gravels, often black-stained, low-grade, and local deposits	Mixed assemblages of (1) reworked marine vertebrates and (2) articulated and disarticulated terrestrial vertebrates	Unconformably cut into the Noralyn Fm., unconformably overlain by various nonphosphatic Pliocene and Pleistocene units, grades downslope into the estuarine facies
			Estuarine and open-bay facies (downslope)	Blanket geometry, well-bedded to highly burrowed and homogenous	Interbedded to homogenous terrigenous sands and clays, minor quartz and chert granules	Lithochemical sands and minor gravels, black-stained, and very low grade	As above with increasing abundance of calcite invertebrate shell material	Unconformably overlies the Arcadia or Noralyn Fm., unconformably overlain by various nonphosphatic Pliocene and Pleistocene units
Miocene	Noralyn	Noralyn	Complex coastal marine facies grading downslope to uniform nearshore shelf facies	Well-bedded and cross-bedded coastal facies grading to poorly bedded and highly burrowed nearshore shelf facies	Dominantly intermixed terrigenous sands and clays with minor dolomite	Dominantly orthochemical microspherite and allochemical intraclasts of gravels and coarse sands in coastal facies grading to sands and fine gravels in the nearshore shelf facies	Limited marine vertebrates consisting of scattered nekton teeth and bones with an occasional articulated sirenian and cetacean, invertebrates very limited with some molds in microspherite beds, abundant trace fossils	Conformably overlies and grades downslope and southward into the Arcadia Fm., in the upslope portion it unconformably overlies either the Oligocene Suwannee Limestone or the Eocene Ocala Limestone Group
			Arcadia	Uniform marine continental shelf facies	Poorly bedded to mottled and homogenous, highly burrowed	Dominantly a dolosilt with subordinant amounts of terrigenous quartz sand and clay, interbedded with facies of the reverse lithologies	Dominantly allochemical fine sand pellets with subordinant amounts of sand intraclasts and fossil skeletal material	Locally fossiliferous with abundant invertebrate molds, limited marine vertebrates consisting of scattered teeth and bones of various nekton, abundant trace fossils



Arcadia Formation and the areas proximal to the modern-day drainages. Thus, the modern drainage tends to reflect the underlying structures and to some extent represents an inherited drainage pattern.

Down the depositional slope of the Ocala Upland, the reworked fluvial phosphorite sediments give way to an assorted complex of reworked phosphorites which were deposited in estuarine, open-bay, or shallow marine environments. The reworked lithochemical phosphorite in the Bone Valley is usually a mixed bag of textures and grain types which commonly has a black surficial stain. Since the entire process of reworking is one of dilution, the reworked estuarine and shallow marine deposits are usually very low grade and rarely of economic value in Florida.

The Bone Valley Formation is generally Pliocene in age and contains three suites of fossils. One is a suite of broken and rounded fragments of marine vertebrates and invertebrates which were eroded from the subjacent Noralyn Formation. The second suite consists of land vertebrates which were indigenous to the environment of deposition and which are unabraded and commonly articulated. Downslope, the estuarine and open-bay beds contain an abundant suite of calcareous invertebrate fauna. The upslope beds are the very prolific vertebrate fossil beds which led to the appropriate name, the "Bone Valley Formation," and for which the unit is so famous. Also, being geographically and genetically associated with the rivers, they were the first beds mined in the early mining days. Consequently, the name is now being restricted to its original usage.

#### *Structural framework*

The basic structural framework which dictated Miocene sedimentation in Florida is presented in Figure 2. The two most important structural units controlling phosphate sedimentation were the Ocala Upland and the Sanford High. The Ocala is a gentle flexure composed primarily of the Eocene Ocala Limestone. It is about 230 miles long by 70 miles wide with a northwest-southeast-trending crest (Puri and Vernon, 1964). This feature became active after the Eocene, affecting the deposition of all subsequent sediment units. A strong northeast-southwest-topographic component developed along the east side of the subaerially exposed Ocala Upland. This resulted in a broad and irregular coastal zone and shallow-water nearshore shelf platform called the North Florida Platform (Fig. 2). The irregular platform was instrumental in controlling the formation and regional accumulation of the Miocene phosphorite in this region. The topographic features are products of various origins such as constructional carbonate banks, erosional ridges and valleys resulting from

solution or fluvial processes, and structural deformation. Similar topographic features occur in association with the Sanford High (H. S. Johnson and J. Maddry, pers. commun., 1977). The Miocene rocks were deposited unconformably on top of the distinctive and fossiliferous Eocene and Oligocene limestones.

The Ocala structural high continues southward in the subsurface as a major broad structural platform with several prominent noses. The broad Central Florida Platform plunges gently southward through the center of the Central Florida phosphate district into South Florida (Fig. 2). Whereas, the smaller Ocala Platform plunges more steeply to the southeast (H. S. Johnson and J. Maddry, pers. commun. 1977). The Central Florida Platform has been the primary control in the location, the character, and the concentration of the Miocene phosphorite sediments throughout this major and important phosphate district. Northward, the Ocala Upland is terminated by the Gulf Trough which separated the continental landmass and its terrigenous sediments from the Eocene-Oligocene limestone banks (Patterson and Herrick, 1971). By the Miocene, the trough must have been almost ineffective in separating the Ocala Upland from the terrigenous sediments moving off the Appalachians and along the mainland coast. These sediments filled the trough, moved through the coastal system of the Florida peninsula, and diluted the Miocene authigenic sediments.

The Sanford High was the other positive element of extreme importance. The Miocene sediments rest unconformably on the Ocala Limestone around the perimeter of the high with very little Miocene sediment across the crest. The Sanford High was probably not a major land mass during the deposition of the Miocene. Rather, it was either just barely a positive element, or more probably it was a very shallow water shoal system. It is relatively narrow and trends northwest-southeast with major shallow platforms extending off both ends. To the north is the St. Johns Platform; to the south is the long and narrow Brevard Platform (Fig. 2). It is presently unknown what happens to these structures eastward onto the continental shelf. I suspect that much of the phosphorite described in core hole J-1 of the JOIDES drilling program off Jacksonville, Florida (Charm et al., 1969; Hathaway et al., 1970) is related to the St. Johns Platform-Jacksonville Basin structures and/or a similar structural high described by Emery and Zarudski (1967) as occurring about halfway across the continental shelf.

During the Miocene two major structural basins dominated the depositional patterns. The southern one-third of the Florida peninsula dropped off along the southwest-northeast hinge line (Fig. 2) into a

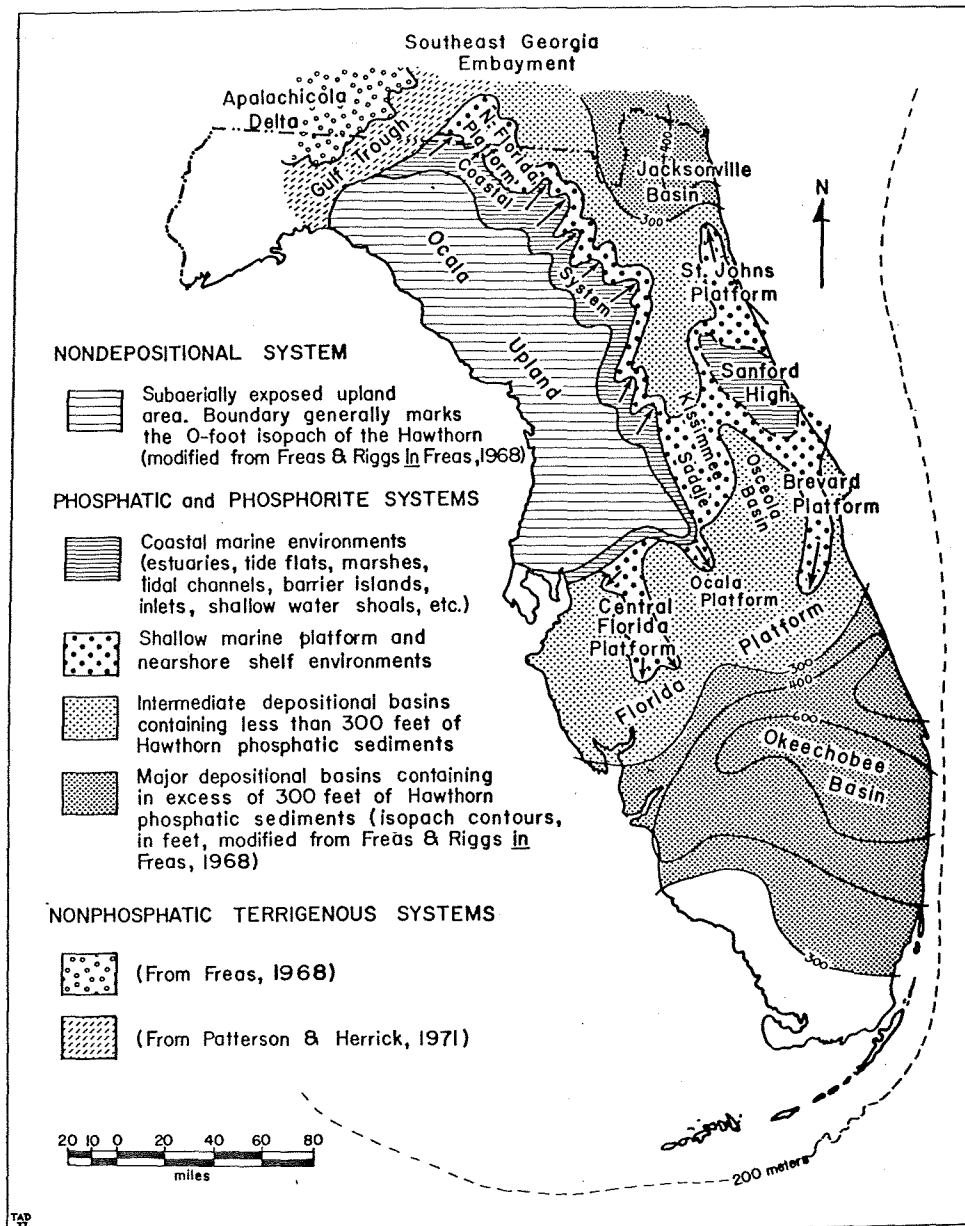


FIG. 2. The structural framework and the resulting depositional environments for the phosphogenic portion of the Miocene of Florida.

fairly deep and well-defined Okeechobee Basin. This basin accumulated over 700 feet of Miocene Hawthorn phosphatic carbonate sediments (Freas, 1968). To the north of the Florida peninsula is another major basin called the Southeast Georgia Embayment. This extensive basin, which is located primarily in Georgia, opens to the southeast and includes the northeast corner of Florida. The well-defined subbasin, the Jacksonville Basin (Fig. 2), contains up to 500 feet of the Miocene sediments which are dominated by phosphatic sands and clays (Freas, 1968).

Several other smaller basins occur west of the Sanford High and have to some extent separated this area of sedimentation from the area adjacent to the Ocala Upland. Off the southwestern side of the Sanford High is the fairly deep but small Osceola Basin. This basin drops abruptly off the Sanford High and Brevard Platform and is filled with over 350 feet of Miocene sediments (Puri and Vernon, 1964). Immediately northwest of, and terminating the Osceola Basin, is the Kissimmee Saddle (Fig. 2). This is an area of thin erratic Miocene sediments on top of a pre-Miocene structural high which Puri and

Vernon (1964) interpreted to be part of a fault-block complex in which they included both the Osceola Basin and the Sanford High. Northward, the Ocala and Sanford highs are separated by a minor trough-shaped basin which opens and deepens northward into the Jacksonville Basin.

The remainder of the area of the Florida peninsula was located in intermediate areas between the Miocene highs with their associated coastal areas and shallow-water nearshore platforms and the deeper basins. These intermediate areas generally had gentle slopes characterized by moderate accumulations of mixed Miocene sediments.

Thus, the environments of Miocene phosphorite sedimentation become obvious when the basic structural framework is considered. The topographic highs occur partly as subaerially exposed uplands which plunge gently into the marine environment producing a normal sequence of coastal systems including estuaries, tidal flats, beaches, open bays, and an extensive shallow nearshore shelf or marine platform (Fig. 3). Riggs (1967) described in detail the sediments, sediment structures, fossil assemblages, and lateral and vertical facies relationships, etc., of the phosphorites in the coastal system around the nose of the Ocala Upland in the Central Florida phosphate district. Down the nose and off the flanks of the topographic highs are the major sediment

basins associated with the structural lows. These open marine shelf environments are dominantly areas of sediment deposition and accumulation (Fig. 3).

In Florida the environments which have the maximum development of the phosphorite sediments are the shallow-water coastal and nearshore shelf platforms associated with the structural highs (Fig. 3). Other major Cenozoic phosphorite deposits with which I have worked are characterized by similar environments of deposition. A. J. Tankard (pers. commun., 1977) has found that the pelletal phosphorites of the South African Tertiary coastal plain have sediment structures, fossils, and geometries which are characteristic of tide-dominated shoreface and estuarine environments. I have come to similar conclusions with the South African phosphate as well as the Miocene phosphates of the Baja California Monterrey Formation and the Cretaceous phosphorites of the Recife-Natal coastal plain of Brazil. Freas (pers. commun., 1967) reported similar environmental interpretations for many of the other West and North African deposits, with which he had worked. Bushinski (1964) and Gulbrandsen (1969) also found that most of the major marine phosphorite deposits of the world were of a shallow-water origin.

#### *Sediment facies*

To understand the relationship of the basic sediment facies to the structural framework, it is extremely important to recognize each of the major sediment components and understand its regional distribution. The Miocene of Florida contains three basic components, each of which occurs throughout the phosphogenic portion of the Miocene sediments. However, there are some significant regional patterns. The sources and general directions of sediment movement and deposition are shown in Figure 4.

*The terrigenous component:* Prior to the Miocene, the Florida peninsula was an isolated carbonate bank which received basically little or no terrigenous sand or clay input. With the Miocene came a significant source of quartz and feldspar sands, silts, and clay minerals. Apparently there was a major climatic and environmental change (Alt, 1974) which led to increased terrigenous sedimentation and the development of major deltas associated with the rivers draining the Appalachian Mountains. This ultimately filled the Gulf Trough, spilling a flood of terrigenous sediments into the Florida peninsula. This appears to be the major source of terrigenous sediments for the Miocene. The entire phosphatic portion of the Miocene section contains some terrigenous material; however, the distribution is not uniform. The sediments around the perimeter of the Ocala Upland are dominantly terrigenous. These sediments moved south through the coastal system and onto the Cen-

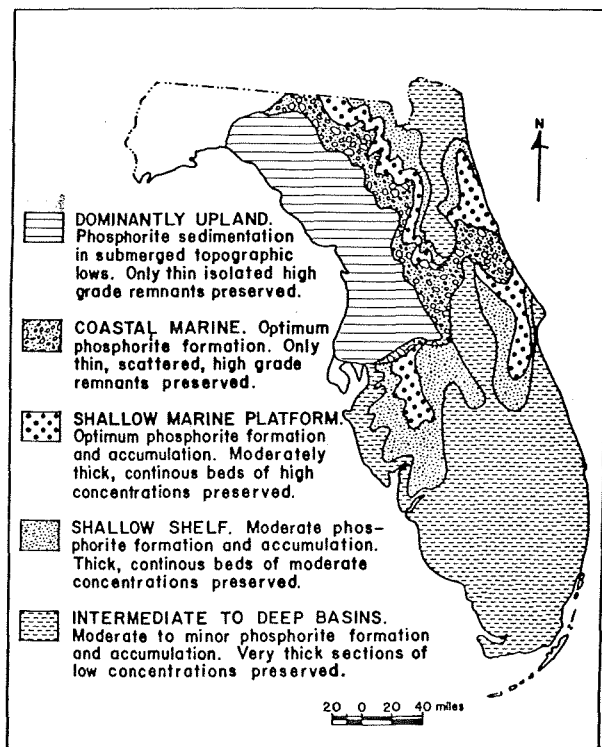


FIG. 3. The environments of phosphorite sedimentation for the phosphogenic portion of the Miocene of Florida.

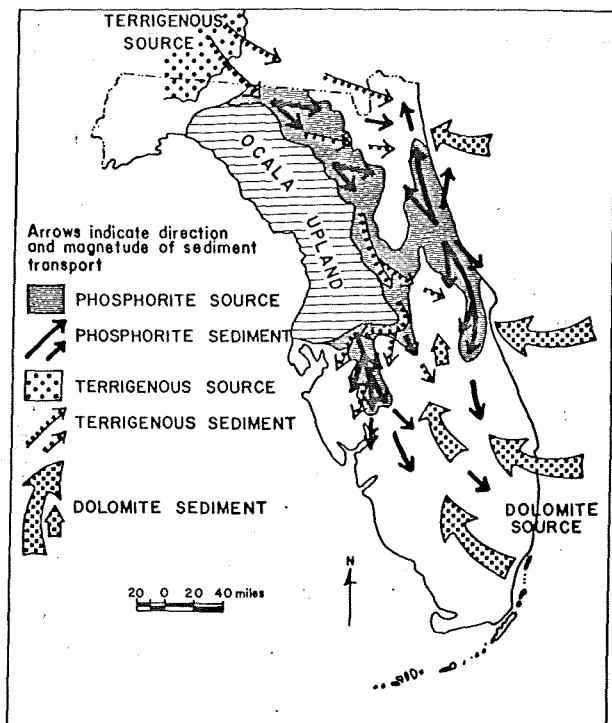


FIG. 4. The major sediment sources and the general patterns of sediment transport for the phosphogenic portion of the Florida Miocene.

tral Florida Platform (Fig. 4). The amount of terrigenous material moving off the Central Florida Platform into the South Florida phosphate district decreases rapidly where it becomes a subordinate component. Also, the terrigenous sediment formed a clastic wedge which moved east and southeast into the Jacksonville Basin and adjacent areas on the north side of the Sanford High. Only minor amounts of terrigenous sediments were able to move across the Kissimmee Saddle and along the Sanford High into the Okeechobee Basin.

*The dolomite component:* This is the second major component of the Florida Miocene. Considering the regional patterns of the major dolosilt component, it obviously has an opposite relationship to the terrigenous sediments. It is an authigenic sediment which was derived from the marine component to the east and the southeast (Fig. 4). Consequently, the sediments south of and off the two major upland areas are dominated by the dolosilt component. The dolomite rapidly decreases in importance onto the Ocala Upland shoals and north of the Sanford High where it becomes a subordinate component.

*The phosphorite component:* Detailed stratigraphic and petrographic studies of the authigenic phosphorites (Riggs, 1979) have demonstrated that the coastal environments and shallow-water structural platforms, as outlined in Figure 4, were

areas of optimum phosphorite formation. From these areas, the phosphorite allochems moved across and along the structural platforms as clastic particles and were subsequently deposited and accumulated on and adjacent to the platforms. Some of the phosphate was transported into the major depositional basins where it was significantly diluted by the terrigenous and dolomite components, forming the ubiquitous phosphatic sediments of the Florida Miocene.

With the understanding of the major sediment components, their sources, and patterns of movement, the regional facies patterns fall into place. Figure 5 is a generalized sediment facies map for the phosphogenic portion of the Miocene of Florida. This interpretive map is based upon the dominant mineralogical components for the entire phosphogenic portion of the section. It must be remembered that at any location the section generally contains beds of each of the facies; these represent lateral migrations and/or pulses of sedimentation which affected the sediment patterns throughout the entire state. All contacts are approximate and gradational in that the facies are highly interbedded.

The dominantly subaerial Ocala Upland was a broad area of low relief with an irregular topography. The resulting low areas were occasionally submerged

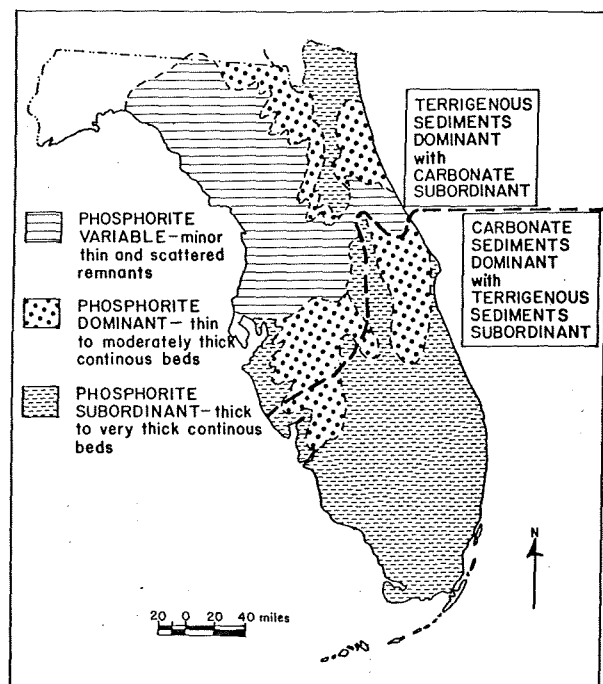


FIG. 5. The sediment facies map for the phosphogenic portion of the Miocene section of Florida. Contacts are based on the dominant mineralogies of the total Miocene section and are all approximate and gradational (modified from Freas and Riggs, in Freas, 1968). Any one stratigraphic unit within a section may vary dramatically from the dominant.

during maximum transgressions and received thin isolated deposits of phosphatic sediments. The phosphorites of the Ocala Hard Rock phosphate district were probably deposited on top of the Ocala Upland and represented these remnants. All of these scattered Miocene units were severely modified by subsequent fluvial erosion and subaerial weathering.

The remainder of the Florida peninsula was submerged during the phosphogenic portion of the Miocene and, consequently, received coastal and marine sediments. The zones immediately adjacent to the Ocala Upland, the Kissimmee Saddle and the Sanford High, were dominated by coastal or shallow-shoaling marine environments. Thin complex facies of phosphorite and terrigenous sediments were deposited. However, these sediments in the pinchout areas were severely modified by the coastal processes themselves, as well as subsequent fluvial erosion and subaerial weathering.

The nearshore shelf and shallow marine platforms lie adjacent to and downdip from the coastal environments. The sediments in these environments are dominantly phosphorites in mixed terrigenous, dolomite, and calcite lithologies. The section is moderately thick with regular and continuous stratigraphic units which have only been partially modified by subsequent erosional and weathering processes in the updip portions. The phosphate content for the entire sequence will generally average well over 10 percent with major portions of the section containing specific beds averaging between 20 and 50 percent phosphorite.

The remaining portions of the Florida peninsula are the deeper basinal marine environments. The Miocene section becomes very thick, exceeding 700 feet in the Okeechobee Basin and 500 feet in the Jacksonville Basin. The major stratigraphic facies are very regular and continuous over large areas. There has been little subsequent modification of the unit other than minor ground-water, sink-hole, or structural deformation. In the greatest portion of the thick section, the phosphate will be quite dilute and rarely exceed 10 percent of the sediment. However, specific beds do commonly contain phosphorite concentrations of 20 to 50 percent. North of the Kissimmee Saddle and the Sanford High and south around the Ocala Upland (Fig. 5), the phosphatic sediments are diluted dominantly by terrigenous sediments with subordinant amounts of dolomite and calcite. East and south of this into the Osceola Basin, the Florida Platform, and the Okeechobee Basin, the phosphatic sediments are diluted dominantly by dolomite with subordinant amounts of terrigenous and calcite sediment (Fig. 5).

In addition to the general regional sediment patterns, the Miocene of Florida also shows some in-

teresting vertical changes through time. The vertical component has been considerably more difficult to work. However, there are several obvious conclusions. Any stratigraphic section through the Miocene is always characterized by major changes from sediment units dominated by terrigenous components to those dominated by dolomite sediments. First, the quantitative importance of each component is directly dependent upon the regional location with respect to the major structural elements and sediment sources. Then the relative changes of the two diluting components within a section represent very distinctive pulses of sedimentation. Major pulses of terrigenous sedimentation and/or declines in the carbonate sedimentation lead to a situation where the dolomite sediments are either overwhelmed or actually regress southeastward. Major periods of carbonate sedimentation and/or declines in the terrigenous input lead to a unit in which the dolomite becomes dominant or actually transgresses northwestward. Both the carbonate and terrigenous systems have pulsed at least several times, but I have not yet been able to establish the detailed pattern. Thus, it appears that the regional pulses of terrigenous-carbonate sedimentation represent part of a more extensive transition which characterizes the entire Miocene section (i.e., from pure limestones in the pre-Miocene to a dominantly terrigenous system in the post-Miocene).

#### *The phosphate machine-entrapment basin concept*

During the Miocene, when marine conditions were favorable for the phosphogenic system to become active, some phosphorite sediments were forming everywhere in the submarine environments of the Florida peninsula. However, phosphorite was *not* produced uniformly everywhere in all depositional environments or uniformly through time.

In any given area the phosphatic portion of the geologic section is composed of a stratigraphic sequence of variable lithologies. Recent work suggests that phosphorite concentrations are independent of the type of diluting sediment. Whether the diluting sediment is terrigenous and/or carbonate is a direct function of the geographic location and the relative intensity of sedimentation of each of these components at any moment in time. Since similar vertical lithologic changes in phosphorite content take place in both the north and south of Florida and since there are definite directional sources for both the terrigenous and carbonate diluents, it appears safe to conclude that in Florida the phosphorite concentration in any stratigraphic unit is primarily a product of its own pulsing rates of sedimentation and secondarily upon the rate of diluent sedimentation. Consequently,

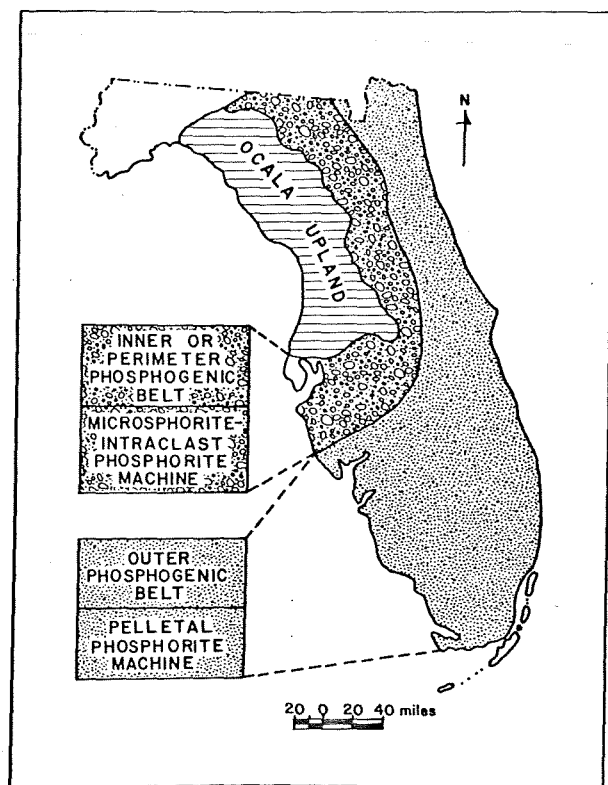


FIG. 6. The major belts and the dominant mechanism of phosphorite sedimentation for the phosphogenic portion of the Miocene section of Florida.

the supply and/or the process producing phosphorite sediments varied through time.

Even though phosphorite sediments can form in any marine environment, detailed studies of the vertical and regional distribution of the phosphate grain sizes and types in the North, Central, East, and South Florida districts point to well-defined environments which are most conducive to the formation of phosphorite. These nucleus environments are up the depositional slope in the coastal and shallow near-shore shelf areas. The shallow-shelf or platform environments on any of the second-order structural arches or highs, which are open to the supercharged upwelling currents, can be thought of as the main "phosphate machines." This is the environment of optimum development of the orthochemical and allochemical phosphorite sediments.

The allochemical phosphorites are then moved along and across the platform as clastic sediments being deposited in any topographic low or "entrapment basin" on the platform. These topographic entrapment basins are the third-order features associated with the major arches or highs and may be structural, depositional, or erosional in origin. The resulting deposits are generally the richest phosphorite sediments in any district. Some of the clastic

phosphorite is also moved off the platform enriching the phosphatic sediments on the adjacent flanks.

The structural setting of the "machine" determines, in part, the regional extent of the resulting phosphorite sediments. If the position of the platform is situated in front of an upland area such as the North Florida Platform, then major phosphorite accumulation is limited to the entrapment basins on the platform. There is some sediment transport seaward down the flanks of the platform supplementing the lower concentrations of phosphorite which are forming there. This results in a downslope zone of intermediate concentrations of phosphorite. On the other hand, if the platform is on the nose of a major structural arch or high such as the Central Florida, St. Johns, or the Brevard Platforms, then both flanks of the platform become important areas of sediment accumulation. The front flank receives some phosphorite sediment as described above. However, the back flank is supplemented by high concentrations of phosphorite which are transported down and off the platform. The areas of optimum phosphorite accumulations are still the entrapment basins on top of the platform. The size, shape, and slope of the platform obviously determine the total volume and regional extent of the resulting phosphorite deposits. For example, the Central Florida Platform is long and broad, the Brevard Platform is long and narrow, and the Ocala Platform is very short and steep.

The phosphorite sediments which are transported off the platform to the flanking basins do supplement whatever phosphate is forming there. However, the net phosphorite content is generally of intermediate concentrations. This is due to the considerably lower production levels of phosphate away from the machines and the fact that the phosphate which is transported into the adjacent environments of deposition is increasingly diluted by terrigenous and carbonate sediments. In addition, the general grain size of the phosphate decreases outward from the area of the phosphate machine. This is particularly true in the areas of microsporite-intraclast sedimentation. Consequently, the average character of the phosphate grains becomes increasingly finer grained, more dilute, and disseminated in thicker sequences of sediments down onto the depositional flanks of the platform and into the adjacent depositional basins. The general characteristics of phosphorite sedimentation in Florida resulting from the phosphate machine concept are summarized in Table 4.

Florida can be divided into two major phosphogenic belts or zones (Fig. 6). The first area includes the coastal and platform environments along the inner perimeter of the Ocala Upland: the narrow North Florida Platform along the northeast flank of

TABLE 4. The General Characteristics of Miocene Phosphorite Section of Florida

Marine environments of phosphorite sedimentation	Average thickness of phosphorite section	Average thickness of postphosphorite section	Regularity and uniformity of deposit	Dominant phosphate grain size	Dominant type of phosphate	Average percent phosphorite	Average P <sub>2</sub> O <sub>5</sub> content of phosphate grains	Development of metachemical phosphate zone	Present status and relative reserve situation	Examples of deposits
Coastal	Very thin (<5 ft)	None to thin (<20 ft)	Erratic and scattered remnants	Gravel and sand	Microsporite, intraclasts	Very high (>50%)	Very high	Very high	Mined locally in early days, not mined today (minor reserves)	Around the perimeter of the Ocala Upland
Shallow platform	Thin, thickens seaward (5-10 ft)	None to moderate (<30 ft)	Irregular and discontinuous	Gravel and sand	Microsporite, intraclasts and/or pellets	Very high (>50%)	Very high	Very high	Presently being mined (low to moderate reserves for present and short-term future)	High-grade mines in northern portion of Central Florida district and Hamilton Co. in the North Florida district
Shallow entrapment basins (upslope)	Moderate (10-25 ft)	Thin to moderate (20-40 ft)	Regular and uniform	Sand and fine gravel	Intraclasts and/or pellets	High (30-50%)	High	High to moderate	Presently being mined (moderate reserves for present and short-term future)	The bulk of the mines in the Bartow-Mulberry area of the Central Florida district
Shallow entrapment basins (downslope)	Thick (25-50 ft)	Moderate to thick (40-100 ft)	Very regular and uniform	Sand	Intraclasts and/or pellets	Moderate (20-40%)	Moderate	Moderate to none	Presently being explored for and mined (high reserves for present to long-term future)	Western and southern Polk Co., east Hillsborough Co., and Hardee Co. in Central Florida district. Brevard Platform in East Florida district
Nearshore shelf	Thick (50-100 ft)	Thick (60-100 ft)	Very regular and uniform	Fine sand	Pellets	Moderate (15-30%)	Low	None	Presently being explored for (vast long-term reserves)	South Florida, St. Augustine and much of the East Florida districts
Intermediate to deep basins	Very thick (>100 ft)	Very thick (>100 ft)	Very regular and uniform	Very fine sand	Pellets	Low (<20%)	Low	None	Presently being explored for (unlimited long-term potential reserves)	Osceola, Jacksonville, and Okeechobee Basins

the upland which extends south to the Kissimmee Saddle, the small Ocala Platform, and the broad and extensive Central Florida Platform off the southern end of the upland (Fig. 2). Only minor phosphate formation took place on the southern end of the North Florida Platform and on the Kissimmee Saddle; this is probably because of its protected location behind the Sanford High. The second zone or outer phosphogenic belt includes the coastal environments and the long and narrow platforms at both the north and south ends of the Sanford High. To the south, the outer belt swings westward to include much of the South Florida phosphate district. The phosphorite sediments within each of these belts is quite different in texture and structure reflecting two different processes of formation or phosphate machines. Each one operates in a different way and results in distinctively different phosphate products. The phosphorites which formed around and associated with the Ocala Upland are dominated by the "microsphorite-intraclast machine" while those in the outer phosphogenic belt associated with the Sanford High and the deeper basins are dominated by the "pelletal machine" (Fig. 6).

#### *The microspherite-intraclast machine*

The perimeter belt of phosphorite sedimentation includes the North, North Central, and Central and grades southward into the South Florida phosphate districts (Fig. 6). This belt of phosphorite sediments is associated with the coastal and shallow near-shore shelf environments occurring around the northeast, east, and south sides of the Ocala Upland. The associated sediments are dominantly terrigenous materials moving south from the Appalachians through the coastal environments around the Ocala Upland. The phosphorite sediments in this system are dominantly a product of the microspherite-intraclast machine with subordinant amounts of intermixed pelletal phosphorite.

Orthochemical phosphorite mud, called microspherite (Riggs and Freas, 1965) is a contraction of "microcrystalline phosphorite" which is analogous to "micrite" in carbonates (see Riggs, 1979). Microspherite occurs widely throughout the updip portion of the perimeter belt and has been described in detail by Riggs (1967). Microspherite is an in situ precipitate of microcrystalline carbonate fluorapatite mud formed as laminae, beds, disseminated mud, and as organic structures in discrete and conformable stratigraphic units. The microspherite beds formed at the sediment interface and accumulated as a soft phosphate mud flocculant in relatively low energy semiprotected coastal environments. It is not certain yet whether the mud is a chemical precipitate or whether it is produced biochemically by bacteria

and other organisms. A limited variety of invertebrate fauna of churning and burrowing forms lived in the soft mud. The mud buried and filled any shells which were in the environment, it was molded to the burrow walls and was injected and excreted as pellets which were included in the muds. Terrigenous sediments, dolomite rhombs, and planktonic shell hash settled out and became incorporated in the mud. The microspherite muds were semiindurated and indurated, possibly by periodic intertidal exposure. During brief periods of increased turbulence, the bypassed clastic sediments abraded and polished the indurated microspherite surface and truncated the protruding quartz and phosphate inclusions. A small infauna of boring organisms was established on the surface, additional muds were accreted, and the calcareous shells were leached. This sequence was repeated numerous times within the deposition of a single microspherite unit which very commonly developed from a few inches up to 1 foot thick and occasionally up to 3 to 4 feet thick.

Allochemical phosphorite, which constitutes the bulk of the phosphorite of the perimeter belt, is composed of 80 to 90 percent intraclasts. The intraclasts contain the same structures that are present in the microspherite—the laminations and textural zonations, the sediment surfaces, the burrows and borings, the accretionary and infilling structures, the fossil molds, and the inclusions. All of these structures are indiscriminately cut by the intraclast grain boundaries and have been subsequently abraded. Most of the intraclasts are somewhat irregular to angular, especially in the coarse sand and gravel fractions. The inclusions protrude from and have been abraded to the grain surfaces and have effected the resulting shape of the abraded intraclast. External fossil molds of invertebrates occur as individual intraclastic grains. The same microscopic components occur in both the orthochemical microspherite and the intraclastic grains; they are present in about the same abundance and have the same structural relationships. This textural and structural evidence supports the concept that a great proportion of the allochemical grains are intraclasts.

All of the structures and textures mentioned above are extremely obvious in the pebble-size phosphate grains for which these mines are famous. However, recognition of the diagnostic structures and textures of the intraclasts becomes increasingly difficult with decreasing grain size. The intraclasts are fragments of penecontemporaneous microspherite sediment that have been torn up from adjoining depositional areas, transported and modified as clastic grains, and re-deposited within the depositional environment. The continual process of deposition and fragmentation of the microspherite probably occurred in or very near



to the intertidal zone during and following induration. Thus, the microspherite forms the source for intraclastic phosphorite sediments deposited elsewhere in the area. However, it must be remembered that the production of intraclasts destroys the microspherite beds. Consequently, the preservation of microspherite in the geologic section is limited to extremely low energy environments or to those areas of rapid burial.

After phosphorite intraclasts were produced through the fragmentation of beds of microspherite, they were transported into the main entrapment basins or onto the flanks of the structure with the terrigenous sediments. The intraclasts were progressively diluted by the terrigenous sediments as the clastic phosphorite moved away from the area of microspherite formation.

The size and abundance of the phosphate pebble intraclasts is directly dependent upon the degree of development of the microspherite—the thicker and the more extensive the microspherite development, the coarser and more abundant the pebble intraclasts—and the proximity to the area of major microspherite formation—the closer to the area, the coarser and more abundant the pebble intraclasts. The general grain size of the phosphate intraclasts within any specific stratigraphic unit is coarsest with the poorest sorting in the coastal environments around the Ocala Upland. The phosphate generally becomes finer grained and better sorted with a complete loss of pebble down the depositional slope and off the shoals. The importance of intraclasts is easily documented in the phosphorite grains well into the fine sand sizes. Below fine sand, there is little question that intraclasts are still present, but they decrease in importance and become subordinate to the pelletal phosphorites which will be described in the following section. The pellets constitute between 5 and 10 percent of the allochemical phosphate in the perimeter belt.

Another variety of intraclast in the perimeter belt includes the sucrosic grains of phosphate pseudomorphs after dolomite. They formed by replacement of dolomite in contact with the phosphorite mud at the sedimentary interface and constitute between 5 and 10 percent of the allochemicals. Technically they are intraclasts because of their derivation by fragmentation from penecontemporaneous beds within the area of deposition.

Fossil skeletal material constitutes another variety of allochemical grain in the perimeter belt. They comprise about 2 to 3 percent of the allochemicals and consist mostly of vertebrate teeth, small bone fragments, and brachiopod shell fragments. Oolites, or nucleated grains, are not common in the perimeter belt.

### *The pelletal machine*

The outer phosphogenic belt of phosphorite sedimentation (Fig. 6) includes the St. Augustine East and southern portion of the South Florida phosphate districts. This belt of phosphorite sediments occurs in the shallow shoaling and shelf environments associated with the offshore Sanford High and the deeper basinal environments of the Florida peninsula (Fig. 2). The northern and western portions of this belt are still under the dominant influence of terrigenous sedimentation from the north. However, south of the Kissimmee Saddle and the Sanford High and into the Okeechobee Basin and around to South Florida, dolomite becomes the dominant associated sediment (Figs. 4 and 5). The phosphorite sediments associated with this system are dominantly a product of the pelletal machine. Locally, and within specific stratigraphic horizons, there were minor developments of the microspherite-intraclast machine.

In the pelletal system, orthochemical phosphorite generally does not settle out and accumulate as discrete beds of bottom mud or matrix material. This is apparently due to the higher energy, more open marine system and the lack of semiprotected coastal environments in the outer belt. Consequently, the orthochemical phosphorite mud floats in suspension above the sediment interface as loose colloidal aggregates. These loose suspensions trap and incorporate all of the very fine "garbage" in the system including planktonic shell hash, rhombic dolomite muds, and fine-grained terrigenous silts and clays. Due to the presence of the planktonic hash and other organic material, this colloidal suspension of phosphate mud is rich in bacteria and thus is a nutritious broth or soup. It is not known at present whether this orthochemical phosphorite mud is a direct biochemical product of the bacterial action or whether it forms inorganically in response to the chemical system. Nevertheless, the overlying waters appear to contain a fairly rich population of planktonic and larger nektonic forms, whereas the nearbottom and benthic environments appear to be somewhat stressed and possibly even somewhat toxic. The fossil record of the major phosphorite beds and the sedimentary structures suggest that, during the time of major phosphate formation, the benthic environment had a fairly low species diversity but had high populations of a few invertebrate forms without calcareous exoskeletons. These benthic forms were probably varieties of polychaetes or arthropods, or both, which actively churned the bottom sediments producing the characteristic and dominant bioturbation structures. The fauna were largely detritus and filter feeders which aggregated the suspended broth, fed on the

bacteria, and excreted the pellets of soft compacted phosphate mud. These excreted pellets, composed of all of the garbage that existed within the loose flocculant material, now occurred as denser silt- and fine sand-sized clastic particles. The pellets were transported and deposited as discrete clastic particles with slight deformation and modification since they were still soft sediment. Induration appears to have taken place with time after deposition. The resulting pelletal phosphorites accumulated on the platforms if there were adequate entrapment basins, or they were transported to deeper depositional sites off the flanks where they were diluted.

The pellets generally constitute over 80 percent of the phosphate grains in the outer belt. The pellets are relatively uniform in size and shape, are extremely well sorted, and relatively fine grained. The size of the pellets ranges between 2.5 phi (0.177 mm) and 4 phi (0.0625 mm), which is fine to very fine sand, with the mode generally occurring in the very fine sand fraction. There is only minor phosphate occurring in the silt and clay fractions and only a few percent in the fine pebble to medium sand fractions. All of the latter are allochemical intraclasts, most of which are obviously broken and angular fragments of internal fossil molds. An occasional stratigraphic horizon will be dominated by the intraclasts, but this constitutes local and minor parts of the total section.

Skeletal material may constitute up to 10 to 15 percent of the phosphorite grains in the outer phosphogenic belt. The majority of this material is actual fragments of bones and teeth, mostly an assemblage of extremely small and almost depauperate fish bone fragments. Extremely uniform and regular discoid grains constitute a large portion of the fossil material. These abundant grains are between 0.25 mm and 0.125 mm in size and may constitute up to 50 percent of the phosphate grains in this size fraction. They are, in part, formed externally from material in the environment. The distinctive discoid-shaped grains are composed of a circular diatomlike valve as a nucleus with the phosphate flocculant and its included garbage accreted to and around the nucleus. Some phosphatic fossil grains are inarticulate brachiopod fragments while a very small portion appear to be actually replaced invertebrate shell material including rare foraminifera and ostracods.

Usually less than 5 percent of the phosphate grains are nucleated grains or pseudo-oolites. These are grains with a single relatively large nuclei consisting of a grain of quartz, feldspar, dolomite, etc., which has accreted the phosphate mud with its included garbage. The accreted material is not regularly laminated or concentric and thus, the term pseudo-oolites.

#### *The modification processes*

An extremely important aspect of the Miocene sedimentation in Florida is the subsequent post-Miocene erosional history. Generally, the topographic and structural features which controlled Miocene sedimentation persisted through the Miocene. Consequently, post-Miocene erosional patterns were, to a large extent, inherited from the pre-Miocene structures. These subsequent processes of erosion and weathering, which are still going on today, have in places severely modified the original distribution of Miocene sediments. This is especially true in the perimeter zone around the Ocala Upland.

Following the maximum transgression of the Miocene sea and the culmination of phosphorite formation, the sea regressed and large areas of the topographically highest portions of phosphorite sedimentation became emergent land areas. These phosphorite sediments were eroded largely by Pliocene fluvial processes and redeposited as fluvial sands, gravels, and clays forming sinuous channel deposits. Locally, the streams completely removed and replaced the subjacent marine deposits in the uppermost portions. Down the depositional slope, the reworked Pliocene fluvial sediments grade into estuarine and open marine deposits with decreasing amounts of phosphate. These downdip environments are broader depositional systems in which the new sediments buried and, consequently, protected the primary Miocene phosphorites from subsequent modification. The reworked phosphates constitute the lithochemical sediments—lithified phosphate fragments which have been eroded from older sediments, or rocks, of an emergent land area, transported, and redeposited. The lithochemical phosphorites are differentiated primarily on a stratigraphic basis since petrographically they are similar to the orthochemical and allochemical phosphorites. The lithochemicals usually consist of complex mixtures of varieties, colors, and varying degrees of altered material. They commonly contain secondary black surficial stain. Nonphosphatic clays, sands, and gravels were deposited along with the phosphorite channel and estuarine deposits and interfinger with the phosphorite units. The drainage system which developed in the stratigraphic lows after regression often persists today. Rivers such as the Peace and Alafia continue to erode and deposit lithochemical phosphorite sediments.

Weathering and supergene alteration of the Miocene phosphorites became a prominent process following emergence in the updip emergent areas. It modified the mineralogy and chemistry of the sediments, destroying the primary stratigraphic characteristics, and producing the metachemical phosphorite. The

effects of alteration migrate downward as a series of wave fronts crossing the primary stratigraphic units. Eventually, alteration completely destroys the primary stratigraphic unit through the alteration of the clay, phosphate, and carbonate components of the sediments. In the downdip areas which have been buried beneath the subsequent estuarine and marine sediments, the Miocene phosphorites are rarely modified by supergene weathering; consequently, these units have not been chemically upgraded.

### Conclusions

Phosphorite constitutes a geologically significant and anomalous component of the Tertiary section of the Atlantic Coastal Plain-continental shelf of the United States. This paper has described the conceptual framework for the formation, deposition, and subsequent modification of the Florida phosphorite system. This evolving model is based upon the work of numerous geologists working in many mines and with many thousands of drill holes throughout the Atlantic Coastal Plain; the basic concepts are equally applicable throughout the southeast. The test of the value of any model is not only how well it explains the data but whether it can predict and project into the areas of no data; this model has evolved out of and been tested on numerous exploration projects, and with considerable success.

The formation and subsequent accumulation of the phosphorite sediments sufficient to form a major stratigraphic unit with the potential of becoming an economic deposit requires a highly specialized set of conditions in a very specific geologic setting. The essential prerequisites for such phosphorite sedimentation define the phosphogenic system which is largely controlled by two major variables. First and foremost is the tectonic setting. Since sediments are the direct products of the regional tectonic framework and history, the stratigraphic patterns represent the tape recorder of the type, magnitude, duration, and spatial location of regional tectonic events or lack of such events. In addition, the tectonic framework largely determines the geographical latitude, the physical current system, and the chemical compositions of the associated water masses. The optimum conditions leading to the potential development of the phosphogenic system with the appropriate physical and chemical setting lies in the low to intermediate latitudes with intermediate tectonism. Maximum phosphorite formation occurs intermediately between total quiescence with its carbonate banks and extreme mountain building with its deluge of terrigenous and volcanic sediments. But more important, the formation of phosphate appears to occur during periods of changing tectonism which apparently modifies the regional chemical system of the bottom waters. The

phosphogenic system occurs simultaneously with and adjacent to other anomalous chemical sediments with which the phosphates commonly mix and become interbedded with as the chemical systems pulse with the tectonism and oscillate laterally. The iron- and silica-rich sediments (glauconite, diatomite, chert, etc.) dominantly occur on the polar side of the phosphates while the magnesium-rich sediments (dolomite and various clay minerals) dominantly occur on the equator side.

The second variable controlling phosphorite formation and deposition is the regional structural framework. This is what determines the basic sediment environments and largely dictates the resulting geometries and the basic sediment processes. Critical to the Florida-type phosphorite is a structural system which provides the essential shallow-water coastal and shelf marine environments. Within this setting there must be one or more structural arches or topographic highs which are the sites of optimum phosphate formation—the phosphate machines. Associated with these shallow-shoaling environments there must be topographic lows or adjacent basins in which major concentrations of phosphorite can accumulate—entrapment basins.

When all of the conditions are right, phosphate precipitates as the cold, chemically supercharged and somewhat toxic upwelling bottom currents move onto the shallow shelf environments and across the structural highs. The phosphate is thought to precipitate as a loose colloidal microcrystalline mud suspension, microspherite, as well as other biologically produced phosphate material such as teeth and bones, shells, kidney stones, etc. The orthochemical microspherite mud, along with all of the included microorganism hash, dolomite mud, fine terrigenous sediments, and any other material within the system, then responds to the local energy conditions and biological processes within the environment. The muds, populated by a benthic community characterized by high environmental tolerances and a low diversity index, ingest and excrete the mud and associated garbage as fecal pellets. Under low-energy conditions the muds settle out, are indurated, and subsequently broken up by biological and physical processes producing intraclasts. Very locally, under high-energy conditions, some of the mud is physically aggregated producing oolites or pseudo-oolites. The resulting phosphorite gravels, sands, and clays are then transported as clastic allochemical particles along and off the shoals by periodic high-energy conditions. They are diluted by the associated terrigenous and chemical sediment systems and are deposited and accumulate in the adjacent entrapment basins and on the flanks of the structural highs.

The net volume of phosphorite sediment which ac-

cumulates within the entrapment basins and adjacent basinal deposits is a direct function of (1) the intensity, duration, and stability of the current systems which constitute the basic phosphorus source and control the geochemical environment; (2) the basic size and definition of the sediment system including both the shoaling environments of microsporite precipitation (the phosphate machine) and the adjacent environments of deposition and accumulation (the entrapment basin); and (3) the amount and rate of phosphorite sediment dilution resulting from simultaneous terrigenous and other authigenic sedimentation. Thus, if the phosphorus sources are adequate, the physical current and the geochemical systems are appropriate, and the shallow marine environments have the proper geometry, then the phosphate machine will produce and supply clastic phosphorites to the associated entrapment basins. If the phosphorite deposit is formed, then additional secondary factors determine the specific economics of the deposit. These secondary factors include the subsequent history of sedimentation and burial, the structural deformation and erosion of the total sediment systems, and the weathering and diagenetic history of the deposits. Only when enough basic geologic information has been obtained to demonstrate the potential occurrence and distribution of a phosphorite facies for a given region and a specific portion of the stratigraphic column, do the factors dealing with the subsequent geological history become important in delineating a possible economic deposit.

The conditions necessary for the formation of phosphate have occurred many times during the geologic past as evidenced by the many major occurrences within the geologic column. But does the phosphogenic system operate anywhere in the world today? Several convincing accounts of soft unconsolidated semiliquid, gel-like masses of phosphorite have been recently described in the modern sediment system. Baturin (1971) described the formation of "modern" phosphorite on the inner shelf off South West Africa. He feels it formed by biogenic-diagenetic processes in fine-grained sediments (largely a diatom ooze) enriched in organic matter. He described gradual transitions in the material to completely lithified concretions and microconcretions. These were similar to the phosphate grains in the sediments of the outer shelf area where locally the phosphorite reaches concentrations of 75 percent. Veeh et al. (1974) reported phosphorite occurring as thin unconsolidated laminae within Recent diatomaceous sediments off Walvis Bay, South West Africa. Burnett (1977) also described the occurrence of semiconsolidated to indurated phosphorite pellets from cores off the Peru-Chile coast.

Little question remains that modern phosphate is forming today; however, several important ques-

tions must be considered further: Do these modern occurrences represent normal day-to-day phosphorite sedimentation or do they represent an abnormal sediment system which is capable of producing a Hawthorn Formation? Are the modern pellets forming on the inner shelf of South West Africa being mixed with older Tertiary phosphorites being reworked as lithochemical phosphorite on the outer shelf? The answers to these questions are extremely important in our understanding of the phosphorite system. If either, or both, of these areas are the modern analogs, then a massive investigation of the total system not only including the sediment-stratigraphic components, but the chemistry, the biological constituents, and the tectonic framework, needs to be mounted. On the other hand, if either, or both, of these occurrences turn out to be a product of the normal day-to-day processes rather than the abnormal phosphogenic system, then not enough of the right pieces of the complex puzzle have been put together to define the totality of the phosphogenic system. I believe that someplace the tectonic framework is appropriate with the necessary environmental conditions, that the phosphate machine is working and producing a modern sediment system analogous to the Hawthorn, Pungo River, Monterrey, or Phosphoria deposits.

Even though phosphogenic sediment systems represent abnormal conditions, they occurred often enough in the geologic past that these limited deposits are not uncommon on a worldwide basis. The future economics of developing and recovering adequate supplies of phosphorus for the necessary fertilizers to feed the world is not going to be a function of whether it exists or not, but rather of its availability with respect to international political situations and of its minability, etc. The world as a whole, the southeast Atlantic Coastal Plain, and Florida have plenty of major phosphate deposits; it will be a long time before this critical commodity runs out. However, many of the developing third and fourth world nations are desperately in need of fertilizer raw materials but cannot afford them on the open international market. Thus, it becomes increasingly imperative to refine and improve our understanding and basic model for the origin and occurrence of phosphorite. This can only result in an increased probability of discovering "new" phosphate deposits in those portions of the developing world where internal sources are essential.

#### Acknowledgments

This paper is the product of the work of many individuals and a long-term program carried out over the past 17 years under the leadership of Dr. Donald L. Everhart, former Vice-President of Exploration for International Minerals and Chemical Corporation.

Numerous people have supplied various types of basic input into this work; a few individuals should be recognized for major contributions. The initial work on the Florida phosphorites was done by Donald H. Freas and myself, parts of which have been presented in the following publications: Riggs and Freas (1965), Riggs (1967), Freas and Riggs (1964, 1968), and Freas (1968). As chief geologist, Peter O. Sandvik both supported our work and contributed to our present understanding. More recently, Henry S. Johnson and John Maddry have contributed extensively to the regional understanding of the Florida phosphate system. I wish to specifically thank Dr. Don Winston, University of Montana, for instilling in me a fundamental appreciation of the total natural system; Dr. Everhart, who has persistently encouraged and supported the application of new geological knowledge and techniques to exploration; and The International Minerals and Chemical Corporation for permission to publish this paper.

GEOLOGY DEPARTMENT  
EAST CAROLINA UNIVERSITY  
GREENVILLE, NORTH CAROLINA 27834  
September 29, 1978

## REFERENCES

- Alt, D., 1974, Arid climatic control of Miocene sedimentation and origin of modern drainage, southeastern United States, in Oaks, R. O., and DuBar, J. R., eds., Post-Miocene stratigraphy, central and southern Atlantic Coastal Plain: Logan, Utah State Univ. Press, p. 21-29.
- Altschuler, Z. S., 1973, The weathering of phosphate deposits—geochemical and environmental aspects, in Griffith, E. J., Beeton, A., Spencer, J. M., and Mitchell, D. T., eds., Environmental phosphorus handbook: New York, John Wiley and Sons, p. 33-96.
- Armstrong, F. A. J., 1965, Phosphorus, in Riley, J. P., and Skirrow, G., eds., Chemical oceanography, v. 1: New York, Academic Press, p. 323-364.
- Azad, H. S., and Borchardt, J. A., 1970, Variations in phosphorus uptake by algae: Environmental Sci. Technology, v. 4, p. 737-743.
- Baturin, G. N., 1971, The stages of phosphorite formation on the ocean floor: Nature, Phys. Sci., v. 232, p. 61-62.
- Baturin, G. N., Merkulova, K. I., and Chalov, P. I., 1972, Radiometric evidence for recent formation of phosphatic nodules in marine shelf sediments: Marine Geology, v. 13, p. 37-41.
- Berner, R. A., 1973, Phosphate removal from sea water by absorption on volcanogenic ferric oxides: Earth Planet. Sci. Letters, v. 18, p. 77-86.
- Bernhard, M., and Zattera, A., 1975, Major pollutants in the marine environment, in Pearson, E. A., and Defraja Frangipane, E., eds., Marine pollution and marine waste disposal, 2nd Internat. Cong., San Remo 1973, Proc.: New York, Pergamon Press, p. 195-300.
- Bonatti, E., 1966, Deep-sea authigenic calcite and dolomite: Science, v. 153, p. 534-537.
- Bostrom, K., Tallbacka, L., and Joensuu, O., 1968, Evidence for carbonatitic volcanism on active oceanic ridges [abs.]: Am. Geophys. Union Trans., v. 49, p. 364.
- Burnett, W. C., 1977, Geochemistry and origin of phosphorite deposits from off Peru and Chile: Geol. Soc. America Bull., v. 88, p. 813-823.
- Burnett, W. C., and Veeh, H. H., 1977, Uranium-series disequilibrium studies in phosphorite nodules from the west coast of South America: Geochim. et Cosmochim. Acta, v. 41, p. 755-764.
- Burns, R. G., and Brown, B. A., 1972, Nucleation and mineralogical controls on the composition of manganese nodules, in Horn, D. R., ed., Ferromanganese deposits on the ocean floor: Harrison, New York, Arden House, p. 51-62.
- Bushinski, G. I., 1964, Shallow water origin of phosphorite sediments, in van Straaten, L. M. J. V., ed., Deltaic and shallow marine deposits: Amsterdam, Elsevier, p. 62-70.
- Charm, W. B., Nesteroff, W. D. and Valdes, S., 1969, Detailed stratigraphic description of the JOIDES cores on the continental margin off Florida: U. S. Geol. Survey Prof. Paper 581-D, 13 p.
- Chow, T. J., and Mantyla, A. W., 1965, Inorganic nutrient anions in deep ocean waters: Nature, v. 206, p. 383-385.
- Clarke, F. W., and Wheeler, W. C., 1922, The inorganic constituents of marine invertebrates: U. S. Geol. Survey Prof. Paper 124, 62 p.
- Davies, T. A., and Supko, P. R., 1973, Oceanic sediments and their diagenesis: some examples from deep-sea drilling: Jour. Sed. Petrology, v. 43, p. 381-390.
- Dietz, R. S., Emery, K. O., and Shepard, F. P., 1942, Phosphorite deposits on the sea floor off southern California: Geol. Soc. America Bull., v. 53, p. 815-848.
- Dillon, W. P., Sheridan, R. E., and Fail, J. P., 1976, Structure of the western Blake-Bahama basin as shown by 24-channel CDP profiling: Geology, v. 4, p. 459-462.
- Doyle, L. J., Blake, N. J., Woo, C. C., and Yevich, P., 1978, Recent biogenic phosphorite: concretions in mollusk kidneys: Science, v. 199, p. 1431-1433.
- Dugolinsky, B. K., Margolis, S. V., and Dudley, W. C., 1977, Biogenic influence on growth of manganese nodules: Jour. Sed. Petrology, v. 47, p. 428-445.
- Eisenack, A., 1964, Mikrofossilien aus dem Silur Gotlands; phosphatische Reste: Paläont. Zeitschr., v. 38, p. 170-178.
- Elders, W. A., and Biehler, S., 1975, Gulf of California rift system and its implications for the tectonics of western North America: Geology, v. 3, p. 85-87.
- Emery, K. O., and Uchupi, E., 1972, Western North Atlantic Ocean: Topography, rocks, structure, water, life, and sediments: Am. Assoc. Petroleum Geologists Mem. 17, 532 p.
- Emery, K. O., and Zarudzki, E. F. K., 1967, Seismic reflection profiles along the drill holes on the continental margin off Florida: U. S. Geol. Survey Prof. Paper 581-A, 8 p.
- Ennever, J., 1963, Microbiologic calcification: New York Acad. Sci. Annals, v. 109, p. 4-13.
- Freas, D. H., 1968, Exploration for Florida phosphate deposits, in Proceedings of the seminar on sources of mineral raw materials for the fertilizer industry in Asia and the Far East: Economic Commission for Asia and the Far East, Bangkok, Thailand, Mineral Resources Devel. Ser. 32, New York, United Nations, p. 187-200.
- Freas, D. H., and Eckstrom, C. L., 1968, Areas of potential upwelling and phosphorite deposition during Tertiary, Mesozoic, and Late Paleozoic time in Proceedings of the seminar on sources of mineral raw materials for the fertilizer industry in Asia and the Far East: Economic Commission for Asia and the Far East, Bangkok, Thailand, Mineral Resources Devel. Ser. 32, New York, United Nations, 28 p.
- Freas, D. H., and Riggs, S. R., 1964, Stratigraphy and sedimentation of phosphorite in the Central Florida Phosphate District [abs.]: Econ. Geol., v. 59, p. 1619.
- 1968, Environments of phosphorite deposition in the Central Florida Phosphate District, in Brown, L. F., ed., Fourth forum on geology of industrial minerals: Austin, Univ. Texas Bureau Econ. Geol., p. 117-128.
- Glenister, B. F., Klapper, G., and Chauff, K. M., 1976, Conodont pearls?: Science, v. 193, p. 571-573.
- 1978, Nautiloid uroliths composed of phosphatic hydrogel-response: Science, v. 199, p. 209.
- Gulbrandsen, R. A., 1969, Physical and chemical factors in the formation of marine apatite: Econ. Geol., v. 64, p. 365-382.
- 1977, Byproduct resources in phosphate ore of southeastern Idaho: Geol. Soc. America Abstracts with Programs, v. 9, p. 728.
- Gulbrandsen, R. A., and Roberson, C. E., 1973, Inorganic phosphorus in sea water, in Griffith, E. J., Beeton, A., Spencer, J. M., and Mitchell, D. T., eds., Environmental phosphorus handbook: New York, John Wiley and Sons, p. 117-140.

- Hathaway, J. C., McFarlan, P. F., and Ross, D. A., 1970, Mineralogy and origin of sediments from drill holes on the continental margin off Florida: U. S. Geol. Survey Prof. Paper 581-E, 26 p.
- Hodson, P. H., 1973, The role of phosphorus in bacteria and viruses, in Griffith, E. J., Beeton, A., Spencer, J. M., and Mitchell, D. T., eds., Environmental phosphorus handbook: New York, John Wiley and Sons, p. 451-474.
- Kazakov, A. V., 1937, The phosphorite facies and the genesis of phosphorites, in Geological investigations of agricultural ores: USSR Sci. Inst. Fertilizers and Insectofungicides Trans. 142, p. 93-113.
- Kolodny, Y., 1969, Are marine phosphorites forming today?: Nature, v. 224, p. 1017-1019.
- Kolodny, Y., and Kaplan, I. R., 1970, Uranium isotopes in seafloor phosphorites: Geochim. et Cosmochim. Acta, v. 34, p. 3-24.
- Largent, E. J., 1961, Fluorosis, the health aspects of fluorine compounds: Columbus, Ohio State Univ. Press, 140 p.
- Lear, D. W., 1966, Bacterial participation in phosphate regeneration in marine ecosystems [abs.]: Dissert. Abstracts, v. 27, p. 357-B.
- Lehr, J. R., McClellan, G. H., Smith, J. P., and Frazier, A. W., 1967, Characterization of apatites in commercial phosphate rocks, in Colloque Internat. Phosphates Mineraux Solides, Toulouse 1967: Paris, Masson, p. 29-44.
- Lowenstam, H. A., 1963, Biologic problems relating to the composition and diagenesis of sediments, in Donnelly, T. W., ed., The earth sciences—problems and progress in current research: Chicago, Univ. Chicago Press, p. 137-195.
- Manheim, F., Rowe, G. T., and Jipa, D., 1975, Marine phosphorite formation off Peru: Jour. Sed. Petrology, v. 45, p. 243-251.
- Mansfield, G. R., 1940, The role of fluorine in phosphate deposition: Am. Jour. Sci., v. 238, p. 863-879.
- Martens, C. S., and Harriss, R. C., 1970, Inhibition of apatite precipitation in the marine environment by magnesium ions: Geochim. et Cosmochim. Acta, v. 34, p. 621-625.
- Martinsson, A., 1964, Phosphatic linings in bryozoan zoecia: Geol. fören. Stockholm, Förh., v. 86, part 4, p. 404-408.
- McConnell, D., 1963, Inorganic constituents in the shell of the living brachiopod *Lingula*: Geol. Soc. America Bull., v. 74, p. 363-364.
- 1965, Precipitation of phosphates in sea water: ECON. GEOL., v. 60, p. 1059-1062.
- 1973, Apatite: New York, Springer-Verlag, 111 p.
- McConnell, D., and Ward, P., 1978, Nautiloid uroliths composed of phosphatic hydrogel: Science, v. 199, p. 208-209.
- McKelvey, V. E., 1967, Phosphate deposits: U. S. Geol. Survey Bull. 1252-D, p. 1-21.
- 1973, Abundance and distribution of phosphorus in the lithosphere, in Griffith, E. J., Beeton, A., Spencer, J. M., and Mitchell, D. T., eds., Environmental phosphorus handbook: New York, John Wiley and Sons, p. 13-31.
- McKelvey, V. E., and Chase, L., 1966, Selecting areas favorable for subsea prospecting: Exploiting the oceans, 2nd Ann. Marine Technology Soc. Conf., Trans., p. 44-60.
- McKelvey, V. E., Swanson, K. W., and Sheldon, R. P., 1953, The Permian phosphorite deposits of western United States: Internat. Geol. Cong., 19th, Algiers 1952, Comptes rendus, sec. 11, pt. 11, p. 45-64.
- Miller, L. J., 1964, The origin of sedimentary phosphate [abs.]: ECON. GEOL., v. 59, p. 1619.
- Milliman, J. D., Summerhayes, C. P., and Barrette, H. T., 1975, Oceanography and suspended sediment off the Amazon River: February-March, 1973: Jour. Sed. Petrology, v. 45, p. 189-206.
- Parker, R. J., 1975, The petrology and origin of some glauconitic and glauco-conglomeratic phosphorites from the South African continental margin: Jour. Sed. Petrology, v. 45, p. 230-242.
- Parker, R. J., and Siesser, W. G., 1972, Petrology and origin of some phosphorites from the South African continental margin: Jour. Sed. Petrology, v. 42, p. 434-440.
- Patterson, S. H., and Herrick, S. M., 1971, Chattahoochee Anticline, Apalachicola Embayment, Gulf Trough and related structural features, southwestern Georgia, fact or fiction: Georgia Geol. Survey Inf. Circ. 41, 16 p.
- Pratt, R. M., and Heezen, B. C., 1964, Topography of Blake Plateau: Deep-Sea Research, v. 11, p. 721-728.
- Puri, H. S., and Vernon, R. O., 1964, Summary of the geology of Florida and a guidebook to classic exposures: Florida Geol. Survey Spec. Pub. 5, 312 p.
- Redfield, A. C., 1958, The biological control of chemical factors in the environment: Am. Scientist, v. 46, p. 205-221.
- Riggs, S. R., 1967, Phosphorite stratigraphy, sedimentation, and petrology of the Noralyn Mine, Central Florida Phosphate District: Ph.D. dissert., Univ. Montana, Missoula, 268 p., Univ. Microfilm no. 67-13, 473, Ann Arbor, Mich.
- Riggs, S. R., 1979, Petrology of the Tertiary phosphorite system of Florida: ECON. GEOL., v. 74, p. 195-220.
- Riggs, S. R., and Freas, D. H., 1965, Stratigraphy and sedimentation of phosphorite in the Central Florida Phosphate District: AIME Preprint 65-H-84, 13 p.
- Rizzo, A. A., Marlin, G. R., Scott, D. B., and Mergenhausen, S. E., 1962, Mineralization of bacteria: Science, v. 135, p. 439-441.
- Rooney, T. P., and Kerr, P. F., 1967, Mineralogic nature and origin of phosphorite, Beaufort Co., North Carolina: Geol. Soc. America Bull., v. 78, p. 731-748.
- Salas, G. P., 1978, Sedimentary phosphate deposits in Baja California, Mexico: AIME Preprint 78-H-75, 21 p.
- Sheldon, R. P., 1964, Paleolatitudinal and paleogeographic distribution of phosphorite, in Geological survey research: U. S. Geol. Survey Prof. Paper 501-C, p. 106-113.
- Sheridan, R. E., 1974, Atlantic continental margin, in Burke, C. A., and Drake, C. L., eds., The geology of continental margins: New York, Springer-Verlag, p. 391-408.
- Sheridan, R. E., Golovchenko, X., and Ewing, J. I., 1974, Late Miocene turbidite horizon in the Blake-Bahama basin: Am. Assoc. Petroleum Geologists Bull., v. 58, p. 1797-1805.
- Sholkovitz, E., 1973, Interstitial water chemistry of the Santa Barbara Basin sediments: Geochim. et Cosmochim. Acta, v. 37, p. 2043-2073.
- Stow, S. H., 1976, Effects of weathering on the chemical and heavy mineral composition and physical properties of phosphate pebbles from the Bone Valley Formation of Florida: Southeastern Geology, v. 18, p. 83-98.
- Stumm, W., and Leckie, J. O., 1970, Phosphate exchange with sediments; its role in the productivity of surface water, in Advances in water pollution research, v. 2: New York, Pergamon Press, p. III 26/1-26/16.
- Summerhayes, C. P., 1970, Phosphatic deposits on the northwest Africa continental shelf and slope: Ph.D. dissert., Univ. of London, 282 p.
- Summerhayes, C. P., de Melo, V., and Barretto, H. T., 1976, The influence of upwelling on suspended matter and shelf sediments off southeastern Brazil: Jour. Sed. Petrology, v. 46, p. 819-828.
- Suppe, J., 1970, Offset of Late Mesozoic basement terrains by the San Andreas fault system: Geol. Soc. America Bull., v. 81, p. 3253-3258.
- Tooms, J. S., Summerhayes, C. P., and Cronan, D. S., 1969, Geochemistry of marine phosphate and manganese deposits, in Barnes, H., ed., Oceanography Marine Biology Ann. Rev., v. 7: Millport, Scotland, Hafner Pub. Co., p. 49-100.
- Turekian, K. K., 1968, Oceans: Englewood Cliffs, New Jersey, Prentice Hall, Inc., 120 p.
- Uchupi, E., 1967, The continental margin south of Cape Hatteras, North Carolina: shallow structure: Southeastern Geology, v. 8, p. 155-177.
- Veeh, H. W., Burnett, W. C., and Soutar, A., 1973, Contemporary phosphorites on the continental margin of Peru: Science, v. 181, p. 844-845.
- Veeh, H. W., Calvert, S. E., and Price, N. B., 1974, Accumulation of uranium in sediments and phosphorites on the South West African shelf: Marine Chemistry, v. 2, p. 189-202.
- Weaver, C. E., and Beck, K. C., 1977, Miocene of the S. E. United States: a model for chemical sedimentation in a peri-marine environment, in Developments in sedimentology, v. 22: Amsterdam, Elsevier Pub. Co., 234 p.