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Paleoceanographic Model of Neogene Phosphorite Deposition, U.S. Atlantic Continental Margin

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Summary. The Neogene stratigraphic section of the southeastern U.S. continental shelf–coastal plain system is characterized by (i) a series of major regional phosphogenic episodes; (ii) a strong spatial relationship between the structural or topographic framework and phosphate deposition; and (iii) distinct cyclical and regional patterns of deposition of the terrigenous, carbonate, and phosphate lithofacies. The complex depositional patterns are explained by a paleoceanographic model based upon the interaction of glacial eustatic sea-level fluctuations, associated changes in climate, and the dynamics of the Gulf Stream in response to the bathymetric configurations of the continental margin during the past 20 million years.

Most sedimentary rocks and sea-floor sediments contain less than 0.3 percent P_2O_5. However, periodically through geologic time phosphorite sediments containing 5 percent P_2O_5 or more (*1*) have formed on the sea floor in response to specialized oceanic conditions and accumulated sufficiently to form major stratigraphic units of regional extent. This deposition has been thought to represent periods of low rates of sedimentation combined with large supplies of nutrient phosphorus derived through upwelling on shallow continental slope, plateau, and shelf environments in low to middle latitudes. Cold, nutrient-enriched upwelling currents are generally considered essential for the production of large volumes of organic matter (*2*). Phosphorus is then concentrated by bacteria at the sediment-water interface or in interstitial pore waters (*3–5*). This leads to the primary formation of phosphate grains, some of which may be transported as clastic particles within the environment of formation. During subsequent periods of time, some primary phosphate grains may be reworked into another sediment unit in response to different environmental processes (*1, 3, 6–8*).

Sheldon (*2*) pointed out that most marine phosphorites occur on western continental shelves associated with paleoceanographic trade wind belts and coastal upwelling (*9*) or on east-west seaways characterized by equatorial upwelling currents (*10*). A few major deposits occur on eastern continental shelves, where conventional upwelling hypotheses apply with great difficulty, if at all. Marine phosphorites and phosphatic sediments in the southeastern United States are in this third category and thus have usually been considered an enigma.

However, the Miocene phosphorites in the southeastern United States are part of a series of major deposits that formed in response to an oceanographic episode of global extent. Anomalous concentrations of phosphate formed contemporaneously throughout a major portion of the world's continental margins below 45° latitude. Many of these deposits occur on the emerged coastal plain and are fairly well known geologically. They extend seaward under the continental shelf, occasionally cropping out on the sea floor, where the phosphate grains may be reworked into younger sediments (*8*). However, not all Miocene shelf deposits have counterparts extending onto the emerged coastal plain. The known Miocene deposits have the following general distribution: (i) east Atlantic continental margin: Portugal; northwest Africa through South Africa; and Agulhas Bank; (ii) west Atlantic continental margin: North Carolina through Florida; Cuba; and Venezuela; (iii) east Pacific continental margin: California through Baja California, Mexico; and Peru through Chile; and (iv) east Australian shelf and Chatham Rise east of New Zealand. Their large-scale temporal and geologic relations should result from similar global paleoceanographic processes. Detailed sediment patterns in each deposit are dependent on interaction of the regional geologic setting with regional oceanographic and climatic conditions. Since the Miocene phosphorites of the southeastern U.S. coastal plain and continental shelf are part of this global system, they should record changing global paleoceanographic events through time.

Patterns of Phosphate Sedimentation

Regional structural framework. Drilling and stratigraphic work throughout the southeastern U.S. coastal plain–continental shelf system (*1, 3, 11–17*) established that the major phosphorites are primarily early to middle Miocene with smaller amounts in the Pliocene and Pleistocene. The Hawthorn and Pungo River Formations of Miocene age are contemporaneous and contiguous sediment units with abnormally high concentrations of sedimentary phosphate. Hawthorn sediments extend from southern Florida into southern South Carolina

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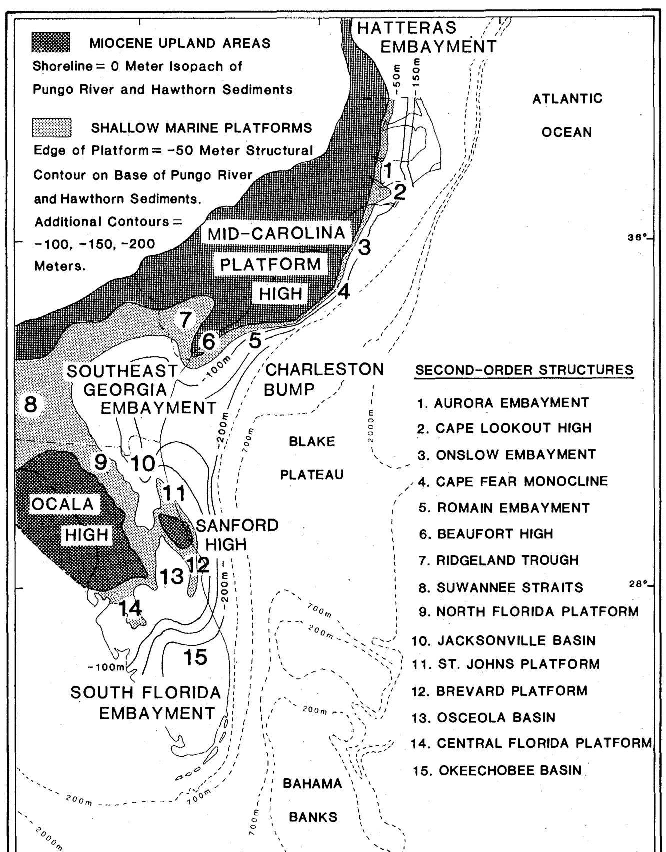
(Fig. 1). In northern South Carolina and southern North Carolina, they are displaced seaward to the outer edge of the continental shelf by the Mid-Carolina Platform High, a major pre-Tertiary structural feature. The same sediments continue northward across the North Carolina continental shelf and coastal plain, where they are called the Pungo River Formation. This group of sediments extends into Virginia with a major decrease in phosphate and increase in glauconite and diatomite concentrations.

General patterns of Neogene sedimentation throughout the southeastern U.S. continental margin were controlled and defined by the pre-Neogene structural framework and erosional topography (Fig. 1). Two scales or orders of structures and topographic features controlled the primary formation and subsequent deposition of phosphorites. First-order or large-scale features define the regional setting and determine location, size, and geometry of the phosphogenic provinces; these structural features include the Ocala and Mid-Carolina Platform Highs and adjacent South Florida, Southeast Georgia and Hatteras Embayments (Fig. 1). The greatest concentrations of phosphate formed and accumulated in shelf environments around the nose and flanks of the Ocala and Mid-Carolina Platform Highs, producing the Florida and Carolina Phosphogenic Provinces, respectively (Fig. 2). Phosphate formation decreased away from the structural highs and was minimal in adjacent first-order embayments. Two additional first-order features off the continental shelf were important areas of phosphate formation and accumulation during the Neogene: the south and southeast nose of the Florida Peninsula and the Charleston Bump off South Carolina (Figs. 1 and 2).

Superimposed on this regional pattern is a series of second-order structural or topographic highs and adjacent entrapment basins which define the various phosphate districts (Fig. 2). Geographic location of each second-order feature determines the amount and type of phosphate formed and type of associated sediment components. The size and geometry of each district are dictated by the genesis of the basin where the phosphates accumulated (structural deformation, primary depositional processes, and subaerial or submarine erosion) and its postdepositional erosional history.

Carolina phosphogenic province. The Mid-Carolina Platform High, a relatively broad structural feature extending from Cape Romain, South Carolina, to central Onslow Bay, North Carolina, controlled sedimentation throughout the Tertiary. Deposition of Miocene sediments off its east flank took place in the Aurora and Onslow Embayments separated by the second-order Cape Lookout topographic high (Figs. 1 and 2) (*18–20*). These embayments contain the Aurora Phosphate District and the newly discovered Onslow Bay Phosphate District, respectively. Miocene sediments occur in shallow subcrop around the eastern side of the Mid-Carolina Platform High (*18, 19*) and in the subsurface at the shelf edge (*21, 22*). The Pungo River phosphatic sediments dip east and southeast off the High and thicken rapidly to over 250 m.

Studies of Neogene sediments in the Aurora Phosphate District (*12, 20, 23, 24*) led to interpretation of the phosphate-rich Pungo River and Yorktown Formations as depositional sediment packages produced by two large-scale or second-order sea-level cycles (Fig. 3). The formations are bounded by three major erosional surfaces or unconformities representing measurable periods of geologic time and are characterized by (i)



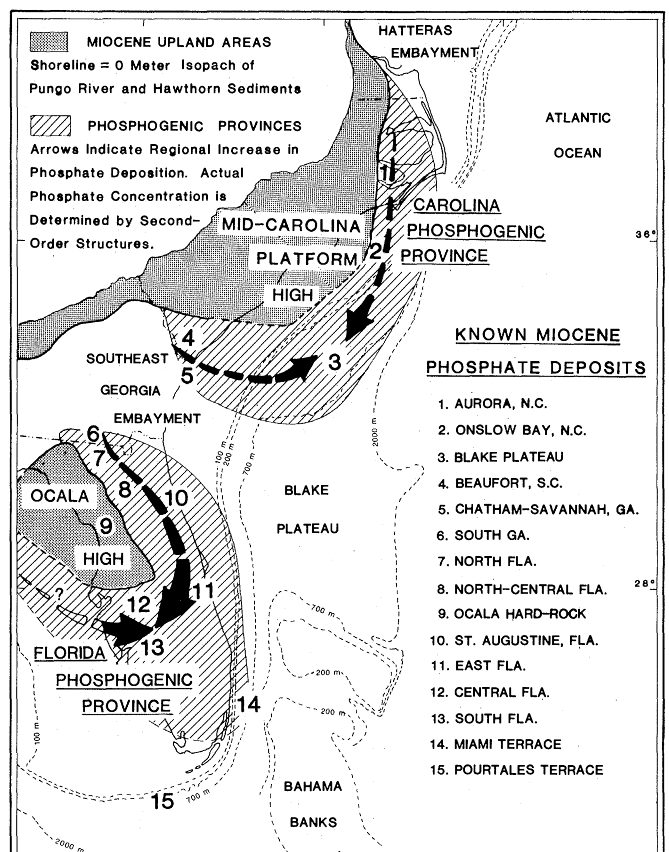


Fig. 1 (left). Map of the southeastern United States showing the general Miocene shoreline and major first- and second-order structural and topographic features which controlled Neogene phosphate sedimentation. Fig. 2 (right). Map of the southeastern United States showing the regional distribution of cumulative phosphate formed during the Miocene and the location of major phosphate deposits.

topographic relief up to 15 m; (ii) hardgrounds of moldic sandstone or limestone which supported extensive populations of hardrock boring infauna; and (iii) local pavements of laminated and burrowed phosphate mud which were subsequently indurated, bored, and locally fragmented, producing phosphate intraclast pebbles. Regional erosion has, in part, determined the final occurrence and distribution of the underlying lithofacies.

Smaller scale cyclic depositional units occur within each formation (*20*). In the Aurora District the Pungo River Formation consists of four sediment units separated by three minor unconformities, and the Yorktown consists of two units separated by one minor unconformity (Fig. 3). These minor unconformities show only regional evidence of significant erosion and they mark abrupt changes in lithologies between units. The underlying units are commonly highly burrowed, fossiliferous carbonates which were exposed as submarine surfaces during sediment bypass and nondeposition. During these brief periods, the carbonates were often indurated, shells leached producing undeformed fossil molds, and surfaces bored by hardrock boring infauna.

In the Aurora District the sediment distribution pattern of the Pungo River Formation is persistent with only minor lateral lithologic variation (*20, 24*). In each of the four sediment units distinct vertical relations between the three main sediment components (phosphate, carbonate, and terrigenous sediments) are cyclically repeated through time. The terrigenous-dominant lower clayey phosphorite quartz sands, with minimal populations of cold-water fauna, grade upward into clayey phosphorite sands, and culminate in carbonate deposition containing minor terrigenous and phosphate sediment and large populations of diverse subtropical invertebrate fauna. Thus there is (i) a strong inverse relation between the terrigenous and phosphate components, both of which are inversely related to the carbonate component; (ii) a repetition of the major pattern of deposition both through time and at different scales; and (iii) a significant change in faunal assemblages as depositional regimes change through time (*20*).

The Pliocene Yorktown Formation consists of a lower phosphorite gravelly sand unit and an upper very fossiliferous clayey sand unit without any phosphate. The phosphate in the lower unit, which is generally coarsest at the base, has been thought to be reworked from the underlying Pungo River Formation (*12*); however, similar types of coarse phosphate occur only rarely and locally within the Pungo River associated with unconformities. Instead, the lower Yorktown phosphate gravels are related to development of phosphorite pavements on carbonate hardgrounds on top of the Pungo River sediments during initial stages of the Pliocene transgression, and thus represent primary phosphorite sedimentation at that time (*20*). Preliminary petrographic and chemical analyses of the lower Yorktown suggest that all the phosphate represents such primary formation and deposition during a Pliocene phosphogenic episode.

Vibracoring and high-resolution seismic profiling of Pungo River sediments in Onslow Bay (Figs. 1 and 2) showed that the sediment units in the Aurora Phosphate District represent part of a more complex depositional regime during the Miocene (*18, 19, 22, 25, 26*). In addition, (i) four regional unconformities subdivide the Pungo River section into at least three major depositional sequences of sediment which reflect third-order sea-level cycles (Fig. 3). (ii) These three sequences are composed of at least 18 smaller scale depositional units similar to those in the Aurora area, characterized by distinct interbedded lithologies and deposited in response to fourth-order sea-level cycles (Fig. 3). (iii) Minor phosphate (< 2 percent) occurs in all Pungo River lithofacies; however, numerous depositional units represent periods of increased phosphate formation and accumulation (> 2 percent and up to 75 percent). (iv) Pungo River phosphate formation had begun at least by the late early Miocene, about 19 million years ago, and continued cyclically, but not regularly, into the late middle Miocene, about 13 million years ago (Fig. 3). (v) Local erosion occurred by Gulf Stream current processes during the periods of deposition (*22*) and during periods of nondeposition between each fourth-order depositional unit, while severe truncation of large portions of the section and channeling occurred during low sea-level stands following deposition of each of the three major sediment sequences formed during the third-order cycles.

High phosphate concentrations (2 to 75 percent) occur in Pleistocene and Holocene sediments of the Frying Pan area in southern Onslow Bay (*27*). These irregularly distributed surface sediments contain phosphate grain types which appear to represent different periods and processes of origin (*28, 29*). The stratigraphic, petrographic, paleontologic, and chemical evidence, including 26 uranium-series ages (*30*), suggests that primary phosphate grains (black and brown) formed during late Pleistocene sea-level highs and were subsequently protected by deposition of carbonate caprocks. Predominantly orange phosphate grains in Holocene sediments formed when the carbonates were eroded during subsequent glacial low stands, subjecting the primary grains to subaerial leaching. Petrographically distinct brown phosphate grains from Miocene

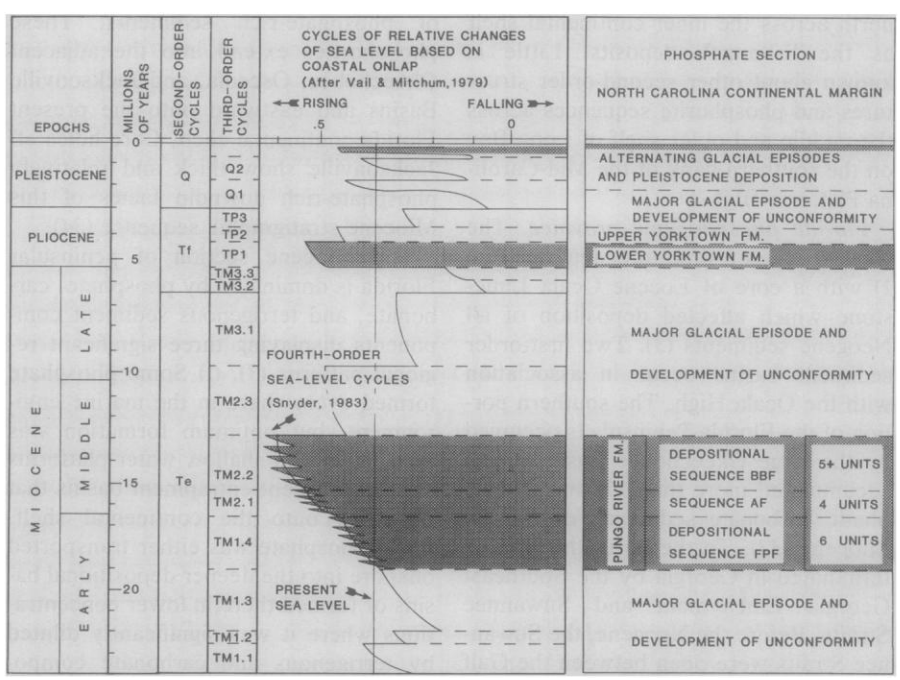


Fig. 3. Stratigraphic section of phosphorite sediments from North Carolina showing the relationship of periods of deposition and nondeposition to the second-, third-, and fourth-order cycles of global sea-level fluctuation.

sediments, which are in uranium-thorium isotopic equilibrium (*31*), were eroded from outcropping Pungo River units during low stands and weathered orange as they were incorporated into Holocene sands.

Extensive phosphorite pavements, pebbles, and pellets occur in conjunction with manganese sediments on the northern Blake Plateau (*31*) (Fig. 2). These phosphates occur on the nose and flanks of the Charleston Bump, a first-order topographic wedge of Cretaceous sediments (*32*) extending from the continental slope southeast across the Plateau (Fig. 1). Manheim *et al.* (*31*) think that primary phosphate formation began in the Oligocene and continued through middle Miocene in at least four cycles of phosphatization. They interpret younger fossils within some phosphates as the result of secondary processes (*31*). Could the latter phosphates be products of primary phosphogenesis during younger episodes?

On the southern flank of the Mid-Carolina Platform High, second-order features such as the Beaufort High and Ridgeland Trough (*16*) have controlled the distribution and character of associated phosphate sediments (Fig. 1). The Beaufort, South Carolina, deposits (Fig. 2), with generally low phosphate concentrations, occur in the Ridgeland Trough west of the Beaufort High. These sediments extend southward and increase in phosphate concentration into the Chatham, Georgia, deposits, which occur on and around the nose of the Beaufort High. Phosphorites continue east and north across the inner continental shelf as the Savannah deposits. Little is known about other second-order structures and phosphorite sequences across the middle and outer shelf of Long Bay on the southern flank of the Mid-Carolina Platform High.

Florida phosphogenic province. The Ocala High is a first-order feature (Fig. 1) with a core of Eocene Ocala Limestone which affected deposition of all Neogene sediments (*3*). Two first-order sediment basins occur in association with the Ocala High. The southern portion of the Florida Peninsula is occupied by the large Okeechobee Basin, which accumulated more than 225 m of phosphatic carbonate sediments during the Miocene (*33*). To the north the High is terminated in Georgia by the Southeast Georgia Embayment and Suwannee Straits. Before the Neogene, the Suwannee Straits were open between the Gulf of Mexico and the Southeast Georgia Embayment, preventing southward transport of terrigenous sediments to peninsular Florida. However, by the end of the Oligocene, a flood of terrigenous sediments began to move across the straits, diluting inner-shelf phosphorites of South Georgia and Florida (*3*).

Miocene phosphorites were deposited in association with second-order features around the perimeter of the Ocala High (Figs. 1 and 2). The southern end of the High forms the broad Central Florida Platform, which plunges gently into the subsurface; the crest and adjacent flanks of this structure contain the world's largest producing phosphate districts, the Central and South Florida deposits (*11*, *13*, *14*). Along the eastern side of the Ocala High is a broad, irregular, shallow continental-shelf system referred to as the North Florida Platform. The southern half of this Platform contains only a thin sequence of Miocene sediments with minor amounts of phosphate because of the shadow effect of the Sanford High on major oceanographic current systems. The northern half of the North Florida Platform contains an irregular to moderately thick section of Miocene sediments, which are up to 25 m thick with high phosphate concentrations in the second-order embayments. Seaward, off the flank of the platform, Miocene phosphatic sands and clays become more than 150 m thick in the Jacksonville Basin (*33*).

Another positive element of importance to Neogene sedimentation is the Sanford High. This smaller second-order feature has long, narrow plunging platforms off the north and south ends which contain a thick and extensive sequence of phosphate-rich sediments. These phosphorites extend into the adjacent Okeechobee, Osceola, and Jacksonville Basins and eastward onto the present Florida continental shelf. Core holes off Jacksonville show thick and relatively phosphate-rich downdip facies of this Miocene stratigraphic sequence (*34*).

The Miocene section of peninsular Florida is dominated by phosphate, carbonate, and terrigenous sediment components displaying three significant regional patterns (*3*). (i) Some phosphate formed everywhere in the marine environment, but optimum formation was associated with shallow water platforms and the adjacent entrapment basins that projected onto the continental shelf. Some phosphate was either transported offshore into the deeper depositional basins or formed there in lower concentrations where it was significantly diluted by terrigenous and carbonate components. (ii) The distribution of terrigenous sediments suggests a major source from the north across the Suwannee Straits and into shallow-coastal and inner-shelf environments around the Ocala High. Sands and clays were then transported east and southeast into the Jacksonville Basin and adjacent areas on the north side of the Sanford High with distinct pulses into southern and eastern Florida. (iii) The regional distribution of the carbonate component, predominantly dolosilt, is opposite that of the terrigenous sediments. The carbonate is an authigenic or diagenetic sediment formed in the outer- to middle-shelf marine environments in southern and eastern Florida, where it is the dominant component. Carbonate interbeds thin into the inner-shelf environments around the Ocala High and north of the Sanford High, where it is the subordinate component.

The highly interbedded lithologic character of the Hawthorn sediments (*3*) suggests alternating sequences of the three main sediment components through time. Cyclic patterns exist and appear to be similar to those in the Pungo River Formation. Both Pungo River and Hawthorn sediments display two distinct depositional patterns of the three major sediment components (*3*, *20*): (i) a strong regional pattern, with terrigenous sedimentation dominant on the landward portions of the shelf, carbonate dominant on the seaward portions, and phosphate occurring in a broad transition zone between them; and (ii) terrigenous sediment influx with a cold-water fauna decreasing and carbonate deposition with a subtropical fauna increasing vertically through a transgressive sea-level cycle, while optimum development of the phosphate component occurs in the vertical transition zone between the terrigenous and carbonate end members.

The Pliocene Bone Valley Formation contains highly variable concentrations of phosphate. In the Central Florida district and scattered localities around the Ocala High, phosphate is mostly reworked from erosion of the updip portion of Hawthorn sediments into complex fluvial, estuarine, and open bay facies (*1*, *3*). However, the Pliocene phosphate in shallow marine facies scattered through eastern and southern Florida is probably primary. Minor phosphate concentrations occur in Pleistocene surface sediments throughout much of the western Florida continental margin (*35*).

The western margin of the Ocala High occurs on the western Florida continental shelf in the Gulf of Mexico, where little is known about the Tertiary geology. However, Neogene phosphorites should exist on the shelf with similar distributions and relations to first- and second-order structures as elsewhere within the Florida and Carolina Phosphogenic Provinces (Figs. 1 and 2).

Extensive phosphate pavements and slabs have been described on the upper Miami Terrace, 200 to 375 m below present sea level, with abundant phosphate nodules on the lower Miami Terrace, 600 to 700 m below present sea level (*36*). Evidence suggests multiple episodes of phosphatization associated with the deposition of Hawthorn sediments during the lower to middle Miocene. Similar phosphorites have been described on the Pourtales Terrace (*37*). All these deposits are off the continental shelf on the southern nose of the Florida Peninsula (Figs. 1 and 2) and are similar to the Blake Plateau phosphates.

Oceanographic and Climatic Conditions

Gulf Stream dynamics. Complex patterns of Neogene sedimentation along the southeastern U.S. continental margin result from a series of interdependent oceanographic processes interacting through geologic time. The main factors are the Gulf Stream, the wind-driven, clockwise North Atlantic current gyre system which hugs the southeastern U.S. continental margin, and major fluctuations in global sea level, which cause the transgressive and regressive pulses of oceanic water onto and off the continental margin, respectively.

Atmospheric circulation is the primary driving force for the most extensive forms of upwelling, including coastal upwelling, open-ocean divergence, and channeled-flow upwelling (*38*). These types of upwelling have been thought to be essential to the formation of most major phosphate deposits. Since none of these types of upwelling are known to occur along the southeastern U.S. continental margin, East Coast phosphorites are often considered to be of a different type and origin. However, upwelling does occur along the East Coast and is primarily associated with interactions between the Gulf Stream, coastline configuration, bathymetry, and to some extent wind patterns (*39–41*). In this dynamic or topographic upwelling, strongly sheared currents flow atop the shelf break and over the bottom topography with diverging isobaths in the downstream direction, producing upwelling and onshore flow of cold bottom water if the current maximum is deflected seaward of the shelf break. (*42*).

Two different modes of dynamic upwelling are now active along the southeastern U.S. continental margin (*39–41*): First, large-scale topographically induced offshore deflection of the Gulf Stream by the Charleston Bump (Fig. 1) causes persistent upwelling over the top and north of the Bump (*43*). The Bump is a first-order bathymetric feature similar to the Mid-Carolina Platform High and is the general location of the Blake Plateau phosphorites. Second, the modern Gulf Stream interacts with second-order bathymetric features on the continental shelf, producing upwelling events that affect shelf processes. For instance, the downstream regions of the North Florida shelf, Onslow Bay, and Raleigh Bay, associated with the cape-shoal sand bodies off Cape Canaveral, Cape Fear, and Cape Lookout, respectively, are characterized by local intrusions of deeper and colder Gulf Stream waters resulting from topographically induced upwelling (*44*). This produces frontal or meander eddies on the inshore edge of the Stream; southward flowing warm filaments of near-surface Stream water occur over and around a cold core of deeper upwelled Stream water (*39–41, 45, 46*). The eddies rapidly exchange shelf waters with the upwelled waters carried shoreward as a bottom intrusion layer beneath the warm filament. Thus, both first-order features such as the Charleston Bump and second-order features such as the cape shoals interact with the Gulf Stream to produce dynamic upwelling events.

In Onslow Bay, the magnitude and extent of an upwelling event at the shelf edge depends on three critical factors (*47*): (i) The position of the current axis of the Gulf Stream. A western position supplies higher temperatures and stronger poleward currents at the shelf break, producing a more favorable upwelling situation. (ii) The seasonal density stratification of shelf waters. During summer months, the middle to inner shelf is dominated by low-density water. High-density upwelled Stream waters set up a strong density stratification and move across the shelf as a subsurface intrusion layer. (iii) The wind system. The dominant summer wind set is southerly and favorable to upwelling, whereas the winter wind set is northerly and favorable to downwelling. Wind alone has only minor effects, but in consort with the other processes it determines the magnitude and extent of upwelling. Thus, if a westward Gulf Stream meander interacts with a bathymetric high coincident with upwelling-favorable winds when the shelf water column is highly stratified, there will be a very intense upwelling event which will affect large portions of the shelf. This suggests that long-term climatic conditions could significantly affect continental shelf processes (*47*). For example, warming global climates would produce lower shelf-water densities with increased stratification and increased dominance of upwelling-favorable southerly winds; this would result in a greater influence of upwelling events on the shelf.

Many deep or semienclosed continental shelves have extensive nutrient traps which recycle upwelled nutrients to the euphotic zone through continuous vertical mixing. Along the very shallow southeastern U.S. continental margin, Gulf Stream upwellings are the major source of nutrients and dominate the nutrient flux processes (*46–49*). Continental shelf waters and warm surface Gulf Stream waters are both low in nutrients, while colder deeper Stream waters have significantly higher levels of nitrates and phosphates (*47*). However, present-day productivity is low due to the short duration of upwelling events (*46*) and lack of recycling mechanisms to trap the nutrients.

The southeastern U.S. continental shelf is "at a very crucial point with respect to Gulf Stream–derived nutrient flux" (*47*). Under present oceanographic and climatological conditions, the colder Gulf Stream waters are dominantly situated below the shelf break. Only during specialized sets of conditions do nutrient-enriched waters upwell onto the continental shelf. However, when long-term changes in global sea level and climates, which affect the Gulf Stream processes, are considered through geologic time, oceanographic conditions of the continental margin may be dramatically modified including nutrient supplies and resulting biota. The geologic record of the shelf attests to this.

The processes of the Gulf Stream, or its predecessor, have been operational since it first appeared on the Blake Plateau during the late Paleocene or early Eocene (*32, 50, 51*). Closing of the deep oceanic connection through Central America during the early Miocene caused the northward deflection of deep currents and intensification of the Gulf Stream (*52*). The Stream axis has migrated across the Blake Plateau in response to major fluctuations in global sea level and eroded major channel networks up to 100 m deep (*50, 51*). During low stands of the sea, the current flowed northeasterly as it was deflected seaward across the Blake Plateau by the Charleston Bump. During periods of high sea level, the Stream shifted landward against the Florida-Hatteras Slope, overriding the Bump with a northward current flow. Gulf Stream migration patterns have been correlated directly with sea-level curves and are thought to have controlled type and distribution of sediment facies, location and geometry of sediment depocenters, and location of major unconformities in the continental margin sediments throughout the past 50 million years, both north and south of the Bump (*50, 51*).

Sea-level and climatic fluctuations. Stratigraphic sections provide very sensitive records of global, regional, and local fluctuations in relative sea level. However, the patterns of sediment deposition resulting from these fluctuations and the causes and nature of the cyclical events have been subjects of controversy. Vail *et al.* (*53*) defined three orders of relative sea-level change. First-order or "global" cycles are records of worldwide sea-level responses to large-scale geotectonic processes with durations of 100 million to 300 million years. Second- and third-order cycles have durations of 10 million to 80 million and 1 million to 10 million years, respectively (Fig. 3). Some second-order cycles are responses to geotectonic mechanisms; however, glaciation and deglaciation are responsible for some second- and many third-order sea-level cycles, particularly in the Neogene (*53*).

Sea-level fluctuations dramatically affect sediment flux and resulting deposition and erosion patterns on the world's continental shelves (*53*). Global high stands are times when sea level is above the shelf edge in most regions and are characterized by widespread deposition of marine sediments on shelves and adjacent coastal plains. Global low stands occur when sea level is below the shelf edge and are characterized by erosion and nondeposition, producing major interregional unconformities (*53, 54*).

A vast array of oxygen isotope, sedimentologic, and paleontologic evidence supports the interpretation that all third-order and many second-order cycles during the Neogene resulted from glaciation and deglaciation (*55*). A general cooling trend at the end of the Paleogene culminated in well-documented glacial episodes and associated low stands of the sea during the late Oligocene, late Miocene and late Pliocene, and at least three intense episodes during the Pleistocene (*55*) (Fig. 3).

World climates primarily control sea level insofar as glaciation is concerned; however, sea level also plays a major role in controlling world climates due to the greater heat capacity of water than of land (*55*). Thus, during interglacials with high sea levels, more incoming radiation is absorbed, producing warmer and more humid climates with increased chemical weathering. Such climates could lead to higher nutrient supplies to world oceans (*56*) and to the development of strong density stratification, which would minimize vertical circulation and produce oceanic stability. Sheldon (*57*) believes this is when phosphorus concentrations of the deep-ocean sink could become abnormally high. Low stands of the sea, with less incoming radiation absorbed, wider temperature fluctuations over large landmasses and significant changes in evaporation and precipitation rates due to decreased oceanic area, could accelerate glacial growth and expansion of mid-latitude continental deserts (*55*). Declining oceanic water temperatures during the glacial episode would lead to gradual weakening of the density stratification of world oceans. Maximum vertical oceanic circulation would occur when density stratification was at a minimum, and this could lead to increased availability of phosphorus to continental margins during the initial sea-level transgression resulting from deglaciation.

In the marine phosphorus cycle there are four major burial sinks (*58*): phosphorus associated with organic matter (40 percent), biogenic calcium carbonate sediments (40 percent), inorganic clays and hydrothermal processes (10 percent), and phosphate sediments (10 percent). Most of the major phosphate deposits formed during limited periods of geologic time, such as 6 million years for the Miocene of the southeastern United States. These deposits contain far more phosphorus than that dissolved in the present ocean, which has a residence time of 10^5 years (*58*). Thus, during such phosphogenic episodes there must have been either some form of "sink-switching," which allowed the phosphorite sediment sink to increase relative to other sinks (*58*), or enhanced phosphorus input from increased chemical weathering and fluvial input, low-temperature seawater-basalt exchange, or hydrothermal solutions associated with increased tectonism. Thus, the phosphorus cycle in the ocean must be episodic, as suggested by the geologic record (*10, 57*).

In the southeastern United States, there are two known Neogene episodes of phosphogenesis and possibly minor and local phosphogenesis during the Pleistocene. Extremely large volumes of phosphate sediment formed here, as well as in many other parts of the world, during Miocene time. The Pliocene and Pleistocene were characterized by sequentially and dramatically decreased volumes of phosphate sedimentation. Figure 3 shows that the phosphogenic episodes occurred between periods of glaciation and were associated with rising sea levels in conjunction with second-order sea-level high stands (*54*). Sheldon (*57*) attributed the major Mio-

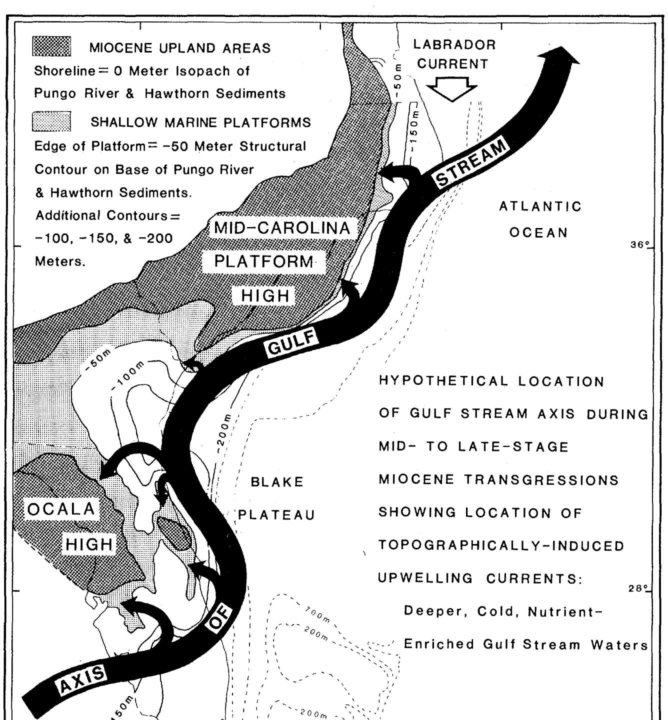


Fig. 4. Map of the southeastern United States showing the relationship of first- and second-order structures (Fig. 1) and major Miocene phosphate deposits (Fig. 2) to the hypothetical location of the Gulf Stream and the resulting topographically induced meanders and upwellings during a mid- to late-stage Miocene transgression.

cene episode of phosphorus withdrawal from the deep-ocean sink to a time of transition from the warm, highly stratified, stable, and high sea-level oceans of the Paleogene to rapid vertical mixing resulting from colder, poorly stratified, less stable, and lower sea-level oceans associated with Neogene glacial episodes. Phosphogenesis may be initiated during glacial events but only produce deeper water phosphate deposits such as those on the Blake Plateau and Miami and Pourtales Terraces. Since most of the continental shelf and coastal plain of the southeastern United States would have been above sea level during the glacial periods, these phosphate deposits must have been formed under conditions of higher sea level. Stratigraphic evidence suggests that shelf deposition of the Pungo River–Hawthorn phosphorites took place on the transgressive cycle of sea-level high stands.

Several factors may be responsible for the decline in phosphogenesis since the Miocene. First is the duration of phosphogenic episodes. The Miocene episode lasted 6 million years, whereas the Pliocene was about 1 million years and the Pleistocene sea-level high stands were only tens of thousands of years in duration. Second is a possible change in phosphorus concentrations in the deep-ocean sink (*57*). High levels of phosphorus could have accumulated during the 20 million to 30 million years of warm climates and high sea levels since the major world Eocene phosphogenic episode (*10*). The global Miocene phosphogenic episode could have severely depleted the deep-ocean phosphorus reservoir. Third is a lack of a significant renewal of phosphorus in the deep-ocean sink due to the increased frequencies of global cooling and associated glaciations and lowered sea levels that occurred through the Neogene and Pleistocene. Consequently, the potential phosphogenic episode associated with each sea-level transgression through the Neogene and Pleistocene could have found decreasing volumes of phosphorus available and inadequate time for production and accumulation of significant volumes of phosphate in the sediment sink.

Conclusions

The data and relations summarized in this article allow the following interpretations and conclusions to be made.

1) Neogene sediments are characterized by (i) cyclical depositional patterns which represent at least three different time scales and (ii) distinctive regional and vertical distribution patterns of major lithologic components which reflect changing environmental conditions. These patterns of deposition were direct responses to fluctuations in eustatic sea level resulting from multiple glaciation and deglaciation events.

2) Fluctuating sea levels caused the major oceanographic currents to interact differentially with the bathymetric configuration of the continental margin, producing dramatically different oceanographic conditions and processes which affected depositional and erosional patterns on the continental shelf.

3) Changing climatic conditions associated with glaciation and deglaciation caused major changes in vegetation, erosion, and sediment and nutrient supplies to the continental margin, and affected density stratification of continental shelf and oceanic waters.

4) Changing paleoceanographic conditions during the past 24 million years interacted with extensive platform environments of first-order structural highs projecting seaward across the continental margin and delineating the adjacent regional embayments. The outer nose and adjacent flanks of the first-order structures became sites of major phosphorite sedimentation when the conditions were right to produce a phosphogenic episode: shoaling and large-scale dynamic upwelling of nutrient-enriched waters in response to major deflection of the Gulf Stream in conjunction with a slowly transgressing sea level (Figs. 4 and 5). Phosphorite sedimentation gener-

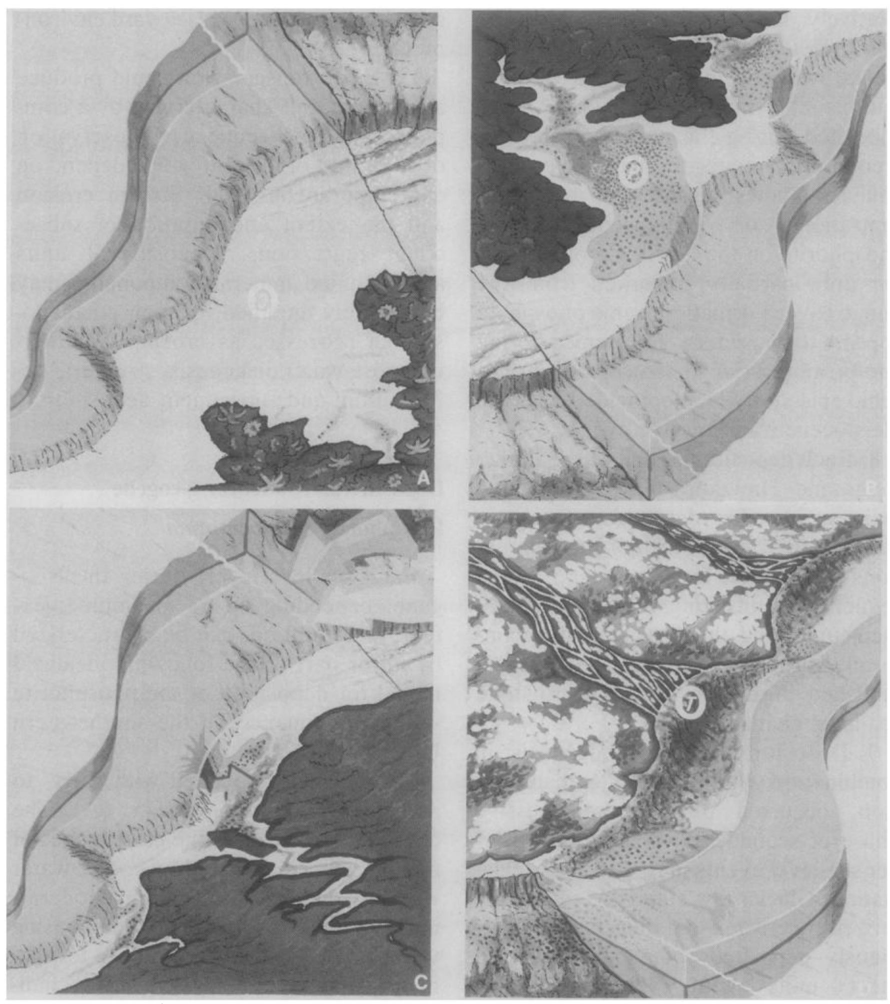


Fig. 5. Block diagrams depict an idealized cycle of Neogene sedimentation on the U.S. Atlantic continental margin; deposition is a direct response to fluctuations in (i) sea levels, (ii) climates, and (iii) continental shelf water masses. The first three stages reflect warming climates through a sea-level transgression associated with deglaciation and increased interaction of the Gulf Stream with the configuration of the continental margin; the accentuated Gulf Stream meanders produce dynamic upwelling of deeper, nutrient-rich waters and phosphate deposition. Stage 4 reflects cold climates and sea-level lowstands of glacial maximums. *P*, phosphate deposition; *C*, carbonate deposition; *T*, terrigenous deposition. (A) Early- to mid-stage transgression, temperate climate, and phosphate deposition beginning on outer shelf. (B) Mid- to late-stage transgression, temperate climate; phosphate deposition optimum on mid and inner shelf. (C) Sea-level maximum (interglacials), warm climatic; shelf dominated by subtropical carbonate deposition. (D) Regressing sea level (glacial maximums), cold climate, no Gulf Stream influence on the shelf; shelf dominated by terrigenous sedimentation with the possibility of phosphate formation on the deeper plateaus. [Paintings by Whiting M. Toler, Washington, North Carolina]

ally decreased into regional first-order embayments as shelf environments became more remote from the oceanic system (Fig. 2).

5) Away from the nose of first-order structures, second-order structural or topographic highs became more important in controlling the location of phosphate deposition. These highs diverted upwelled waters into adjacent second-order embayments with phosphate forming along mid-slope environments (Figs. 4 and 5).

6) During transgression, phosphate depocenters migrated farther onto the inner shelf of first-order embayments as the oceanic current system increasingly impinged on the shelf system.

7) Pungo River and Hawthorn sediments represent a major phosphogenic episode which was coincident with the relatively long second-order Miocene transgression (Fig. 3). Pliocene sediments, with considerably lower concentrations of primary phosphorite, were deposited during the next, but shorter, second-order transgressive cycle. Preliminary studies suggest that local concentrations of Pleistocene/Holocene phosphorite on the North Carolina shelf are only partially reworked from the Pungo River Formation; some phosphate appears to be primary and formed during one or more brief Pleistocene phosphogenic episodes which coincided with the Pleistocene transgressive cycles.

8) Each depositional unit in the Pungo River and Hawthorn Formations, and their associated hardground surfaces, reflect small-scale, fourth-order fluctuations of sea level. The larger depositional sequences, consisting of multiple sediment units and their associated unconformity surfaces, are correlated with established third-order cycles of eustatic sea-level change (Fig. 3).

9) Deposition and phosphogenesis, in combination with local Gulf Stream erosion, occurred on the transgressive phase of second-, third-, and fourth-order sea-level events in response to deglaciation. Glacial low stands were characterized by erosion and diagenesis of previously deposited sediments and sediment units with development of hardgrounds and unconformity surfaces.

10) Duration of sea-level high stands with associated warm climates may have been important to the development of a stratified ocean and a significant deep-ocean phosphorus reservoir resulting from increased chemical weathering and nutrient supply to the oceans.

11) Major global cooling associated with glaciation may have brought about a breakdown of oceanic stratification and increasing oceanic overturn by the end of each glacial episode. If the preceding high stand was of adequate duration, this oceanic overturn could have supplied abundant phosphorus for continental margin deposition during the subsequent transgression.

12) Transgressive cycles of adequate duration allowed a significant volume of phosphate to form and accumulate within the sediment unit. If phosphogenesis occurred, it was optimum (i) during the middle stages of transgression and (ii) the transition zone between dominantly terrigenous and dominantly carbonate sedimentation, both laterally and vertically. Terrigenous sedimentation was dominant during early stages of transgression and in shallower, landward environments; carbonate sedimentation was dominant during late stages of transgression and in deeper, seaward environments.

13) Each transgression could produce a sediment unit characterized by a complete lithologic sequence; preservation of all or part of the unit would depend on contemporaneous Gulf Stream erosion and the extent and duration of subsequent regressions. Depositional units and included mineral components may be severely modified by such postdepositional processes as erosion, weathering, pore-water diagenesis, structural deformation, and subsequent deposition.

Depositional Model for Neogene Phosphorite Sedimentation

Each sea-level cycle during the Neogene, depending on its magnitude, extent, and duration, can be characterized by all or part of the following idealized model for deposition of the phosphorite sediment sequence on the southeastern U.S. continental margin.

1) Sea level associated with early- to mid-stage transgression (Fig. 5A). The continental shelf is in the early stages of flooding; it is dominated by cooler water with low-density stratification. Moderating climatic conditions cause increasing vegetative cover and decreasing terrigenous sediment input. Active fluvial channels and estuaries are backfilled with fine-grained terrigenous sediment. The Gulf Stream migrates west against the Florida-Hatteras Slope, where structural characteristics of the slope and shelf begin to affect the dynamics of the impinging current system. Topographically induced upwellings and associated frontal eddies are initiated; deeper, colder, nutrient-enriched Gulf Stream waters lead to deposition of primary phosphate sediments around the nose of first-order shelf features. Carbonate sediment begins to form on the outer shelf under the alternating influence of warm surface-water incursions of the Gulf Stream and is deposited as interbeds with the phosphate. Fine-grained terrigenous sands with a large mud component and a cool-water fauna are dominant on the inside of the embayed shelf system.

2) Sea level associated with mid- to late-stage transgression (Fig. 5B). With continued transgression, there is an increase in Gulf Stream deflections and frontal eddies in response to shelf bathymetry. Moderating climate warms surface shelf waters, producing a high-density stratification on the shelf. The resulting increase in associated upwellings causes phosphate sedimentation to increase and migrate farther onto the embayed shelf system, with depocenters associated with second-order structural or topographic features. The influence of terrigenous sedimentation continues to decrease in the inner and middle shelf environments at the expense of expanding phosphate deposition. Carbonate sedimentation is limited to the outer shelf, where it interacts with phosphate sedimentation.

3) Sea-level maximum associated with major interglacials (Fig. 5C). Warm climatic conditions produce a heavy vegetative cover, which decreases terrigenous sedimentation to a minimum. The upper portion of the warm-water Gulf Stream encroaches far onto the shelf, resulting in development of a carbonate depositional system containing a rich subtropical molluscan fauna. The decrease in deposition of phosphates around the first-order structures at this time probably results from the occurrence on the shelf of Gulf Stream currents, which erode and channel some of the previously deposited facies on the outer shelf and locally produce phosphate pavements and bypass surfaces on topographic and structural highs. This stage is the culminating depositional event for each unit associated with a sea-level cycle.

4) Regressing sea associated with development of glacial maximums (Fig. 5D). Each regression erodes, truncates, and channels all or portions of previously deposited sediment facies, producing complex stratigraphic patterns and unconformity surfaces. Gulf Stream waters and their influence are completely removed from the shelf as the Stream axis is forced eastward by the increasing influence of the bathymetry of the Florida-Hatteras Slope and Blake Plateau. Waters that remain on the shelf are cold and

increasingly dominated by the cold-water Labrador Current, which flows farther south along the western side of the Gulf Stream. Colder and more arid climatic conditions produce a decreased vegetative cover in the Appalachians and northern portion of the southeastern United States, leading to increased fluvial channeling and renewal of terrigenous sedimentation across the shelf. Subaerial or submarine nondepositional exposure on the shelf often indurates or diagenetically alters the carbonates and leaches away the shells, producing moldic sediments or rocks with heavily bored and corroded sediment surfaces. With the beginning of oceanic overturn, increasing amounts of phosphorus are supplied to surface waters of the oceans. Under these sea-level conditions, first-order structural features and terraces on the continental slope and Blake Plateau begin to respond similarly to the continental shelf during higher sea-level conditions. Nutrient-enriched currents and upwellings produce extensive, thick phosphorite pavements. With the onset of the subsequent transgression, bored and corroded sediment bypass surfaces develop thin phosphorite pavements, which are alternately torn up to produce phosphate intraclast pebbles; both the pavements and pebbles are characteristic of unconformity-type phosphorites and dominate the lower and inner shelf facies of each cycle.

Considering global cycles of relative change of sea level (*53, 54*), the present Holocene transgression is approximately at a mid-shelf stage with the shoreline about 50 m above the shelf break in Onslow Bay. This is the minimum water depth required on a shallow shelf to initiate active upwelling and maintain strong bottom-water intrusion layers across the shelf (*38*). Present sea-level position recently placed the axis of the Gulf Stream against the Florida-Hatteras Slope and at the shelf edge, approximately the position occupied by the Gulf Stream during each Cenozoic high stand (*50, 51*). Thus, sea level is now high enough to cause the Gulf Stream to begin to interact with the bathymetric configuration of the shelf and produce the modern topographically induced upwelling. Assuming that the present transgression continues, along with the warming climate, it is logical to conclude that Gulf Stream waters and associated oceanographic processes should increasingly influence productivity and sedimentation patterns on the continental margin. This, in combination with decreased terrigenous sediment influx, could lead with time to an increased dominance of authigenic sediment deposition on the shelf, including phosphates, if adequate concentration of phosphorus occur in the ocean waters (Fig. 5, A and B) and carbonates (Fig. 5C).

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