NEOGENE PHOSPHOGENESIS ALONG THE EASTERN MARGIN OF THE PACIFIC OCEAN

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ABSTRACT

Neogene phosphatic rocks along the eastern margin of the Pacific occur associated with pelagic and hemipelagic sediments in three main forms. *F-phosphates* are friable, light colored peloids, lenses, and laminae of authigenic carbonate fluorapatite (CFA) which formed during early diagenesis in organic-rich host sediments and experienced no subsequent reworking. *P-phosphates* consist of phosphatic peloid sand or sandstone beds, many of which show basal scour surfaces, graded bedding, and other evidence of reworking and concentration by bottom currents. D-phosphates are dark, dense hardgrounds, nodules, and conglomerates of CFA. Facies associations and correlations with the sea level curves of Haq *et al.* suggest F-phosphates formed most commonly in low-energy, low-oxygen environments during sea level highstands, whereas D-phosphates typically occur at hiatuses or in condensed sections in shelf, upper slope, and isolated banktop settings, and most P-phosphates were deposited in shelfal environments subject to periodic changes in sea level. Evidence presented herein indicates tha phosphogenesis has occurred locally more or less continuously since the late Oligocene, suggesting the existence of eastern boundary currents and associated upwelling zones at least since late Oligocene time. Economically important Neogene phosphorite deposits occur in Perú, Baja California, and Alta California. These formed on board shelves adjacent to upwelling regions at times of generally high but sharply and rapidly fluctuating sea levels, and this combination of elements might serve as a model in the exploration for undiscovered economic phosphates.

Key words: *Phsophates, Neogene, Upwelling, Phosphogenesis, Eastern Pacific.*

RESUMEN

LA FOSFOGENESIS NEOGENA A LO LARGO DEL MARGEN ORIENTAL DEL OCEANO PACIFICO. Rocas fosfáticas del Neógeno a lo largo del margen oriental del Pacífico ocurren asociadas con sedimentos pelágicos y hemipelágicos y se encuentran en tres formas principales. Los *fosfatos tipo F* son peloides de color claro que se desmenuzan fácilmente y lentes o láminas de carbonato fluorapatita (CFA) autogénico, formados durante las primeras etapas de la diagénesis en sedimentos orgánicos y que no fueron retrabajados después de su formación. Los *Fosfatos tipo P* consisten en arenas de peloides fosfáticos o capas de areniscas, muchas de las cuales contienen superficies basales erosionales, gradación positiva y otras huellas que sugieren retrabajo y concentraciones por corrientes profundas. Los *fosfatos tipo D* consisten en superficies duras, oscuras y densas con nódulos y conglomerados de CFA. Asociaciones de las diferentes facies y correlaciones con las curvas del nivel del mar de Haq *et al.* sugieren que los fosfatos tipo F pudieron haberse originado en un ambiente de baja energía y bajo oxígeno durante etapas de transgresión. Los fosfatos tipo D suelen ocurrir durante hiatos en la sedimentación o en secciones condensadas de ambientes de plataforma, talud superior y aislados montes submarinos. El ambiente más común para la formación del fosfato tipo F parece haber sido la plataforma donde fueron directamente afectados por cambios periódicos del nivel del mar. Evidencias presentadas en este trabajo indican que la fosfogénesis se desarrolló localmente en forma continua desde el Oligoceno, sugiriendo que las corrientes orientales y zonas de ascendencia de aguas profundas o 'upwelling' han existido al menos desde el Oligoceno. Depósitos fosfáticos neógenos de importancia económica existen en Perú, Baja California y Alta California, habiéndose formado en plataformas anchas adyacentes a regiones de 'upwelling' durante tiempos de transgresión marcados por cambios bruscos y rápidos en el nivel del mar. Esta combinación de elementos puede servir como modelo en la exploración de fosfatos económicos aún no descubiertos.

Palabras claves: Fosfatos, Neógeno, Surgencia, Fosfogénesis, Pacífico oriental.

INTRODUCTION

Phosphate-enriched rocks include phosphorites, which are sedimentary rocks with >20% P_2O_5, and phosphatic rocks, which are less concentrated phosphate-bearing mudrocks, cherts, carbonates and others. Many sedimentary geologists have speculated on linkages between the presence of these kinds of deposits and unusual paleoceanographic conditions. Among the latter, intense and prolonged coastal upwelling is perhaps the most commonly postulated condition thought to have caused widespread phosphogenic episodes in the past (*e.g.* Sheldon, 1980; Baturin, 1971), though some workers have cautioned that simple and direct linkages are not always evident (Bentor, 1980; Heggie *et al.*, 1987).

At intermediate latitudes, the eastern margin of the Pacific is at present dominated by two large boundary currents, the California Current to the north and the Perú-Chile Current to the south (text Fig. 1). Coastal upwelling associated with these systems has been linked with the occurrences of phosphorites off western South America (Burnett, 1977; 1980) and Baja California (D'Anglejan, 1967). In this article, the record of Neogene phosphogenesis in continental margin sequences at selected localities in the eastern Pacific is discussed (text-Fig. 1), discriminating between different types of phosphatic deposits, and examining possible correlations between these deposits and known paleoceanographic events.

TYPES OF PHOSPHATE OCCURRENCES

Sedimentary phosphate occur in several different forms, and these appear to record different conditions of phosphogenesis and sedimentation. Hence it is important to discriminate among different varieties of phosphates in speculating on their possible paleoceanographic significance. The classification of sedimentary phosphates followed here is one previously proposed for phosphates recovered from the Perú shelf (Garrison and Kastner, 1990). It is based on petrology, sedimentary structures, and associated lithologies, and it includes three categories discussed below.

F-PHOSPHATES

These are **friable**, typically light-colored laminae and small nodule lenses composed of authigenic carbonate fluorapatite (CFA) (Plate 2, Fig. 1). Most F-phosphates show no signs of reworking. They occur in laminated muds and mudstones, marls, diatomites, or porcelanites deposited in low-energy and low-oxygen environments. They appear to represent *in situ* phosphates which were formed during early diagenesis in organic-rich host sediments through interstitial precipitation of CFA as well as through replacement of host sediment particles (*e.g.* forаmininferal and diatom tests) by CFA. In the Miocene of Alta California, Reimers *et al.* (1990) showed a common association between F-phosphates and phosphate-enriched bacterial mats, leading to speculations that decomposition of these mats during the early stages of burial supplied phosphorus for CFA precipitation. Evidence discussed below sugests that F-phosphates formed preferentially during Quaternary sea level highstand and expanded low oxygen conditions on the Peruvian shelf. F-phosphates are difficult to recognize in weathered outcrops; consequently many examples have probably been overlooked by field geologists, and both their abundance and importance have doubtless been underestimated.

P-PHOSPHATES

These are phosphatic sands in which phosphate **peloids** are commonly the dominant component (Plate 2, Figs. 2,3). Other grain types present include coated phosphate grains, fish and other vertebrate remains (bones, teeth), and phosphatic intraclasts. Sand of this type commonly contain an admixture of siliciclastic grains (quartz, feldspar and others) whose average grain size is smaller than the co-occurring phosphate grains (cf. Plate 1, Figs. 2, 3). Some P-phosphate sands also contain glauconite peloids in

Fig. 1. Occurrences of Neogene phosphatic sediments and rocks along the eastern margin of the Pacific, with major ocean current systems.

amounts ranging from rare to abundant. The coated grains are complex entities some of which superficially resemble ooids; the coatings in most, however, are irregular and discontinuos, and scanning electron microscopy shows the presence of phosphatized cyanobacterial structures (Plate 2, Fig. 4) indicating algal growth around varied nuclei followed by phosphatization of the algal coatings. The textures of P-phosphate sands range from well sorted, matrix-free to poorly-sorted, matrix-rich.

These sands occur in beds which range from a few centimeters to several meters thick, and which occur interlayered with fine-grained biogenic diatom muds, mudrocks, and porcelanites (text-Figs. 2, 3); there is thus a juxtaposition of sediments deposited in relatively high energy and low energy conditions. The most common sedimentary structure in the sand beds is graded bedding, and the basal portions of many such beds contain rip-up clasts of the underlying lithology. Most of these phosphatic sand beds are thoroughly burrowed, hence current structures such as cross stratification, if they existed, have been destroyed; bioturbation may have commonly also introduced fine-grained material into sandy beds, accounting for the relatively poor sorting of many P-phosphate sands. P-phosphate beds are most common in shelf sequences, but also occur as turbidite layers in deep basinal settings (Garrison *et al.*, 1987). Though many resemble 'event beds' resulting from storms, seismicity, or other episodic processes (Seilacher, 1982), these beds may be complex entities that record longer term processes such as sea level lowstands; this question is addressed more fully in a following section.

D-PHOSPHATES

D-phosphates are typically **dense** and **dark**, finely crystalline aggregations of CFA in the form of nodules, gravels, and hardgrounds (Plate 1, Fig. 1; Plate 2, Fig. 5). Because of their hardness and durability, they are the most common type of phosphate recovered in dredge hauls from continental margin areas in the eastern Pacific (*e.g.* off Perú, Burnett, 1977). Most D-phosphates are compound entities comprising several distinct generations of phosphatizations (Plate 1, Figs. 2, 3); many D-phosphates from the modern Perú margin, for example, show evidence for multiple cycles of phosphatization-exhumation-reburial-

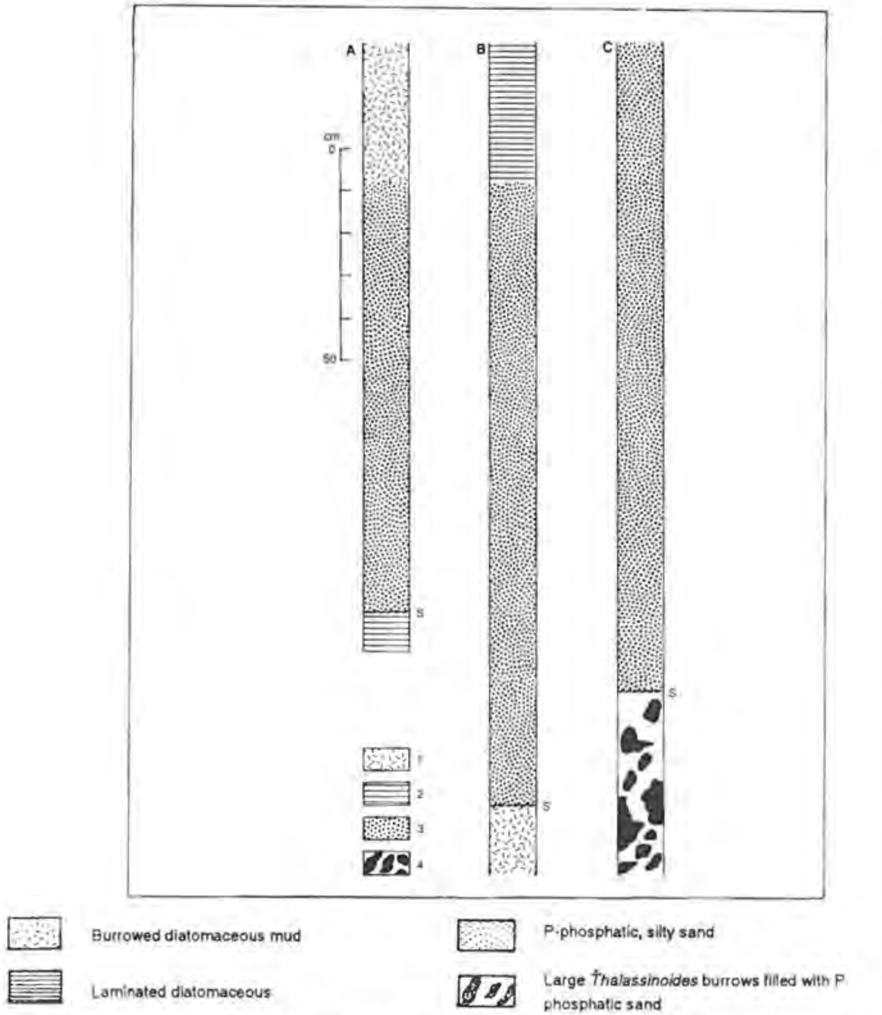

Fig. 2. Examples of graded P-phosphate sand beds associated with unconformable surfaces beneath the Perú shelf. The drawings were made from photographs of cores recovered during Leg 112 of the Ocean Drilling Program (ODO). Symbols are: S=scoured erosional surfaces. **A.** Graded P-phosphatic sand below diatomaceous mud and above laminated diatomaceous mud (Quaternary, ODP Site 684). **B.** Thick graded P-phosphatic sand bed lies above burrowed diatomaceous mud and below laminated diatomaceous mud. This sand layer occurs at an unconformity between Pliocene and upper Quaternary diatom muds (ODP Site 684). **C.** The scoured basal contact of the thick, glauconite-bearing -phosphate sand layer occurs above an unconformity that separates low energy diatom muds of Miocene age from higher energy and coarser Pliocene P-phosphate sands above. Note the penetration of *Thalassinoides* burrows across the unconformity (ODP Site 684). From Garrison and Kastner (1990).

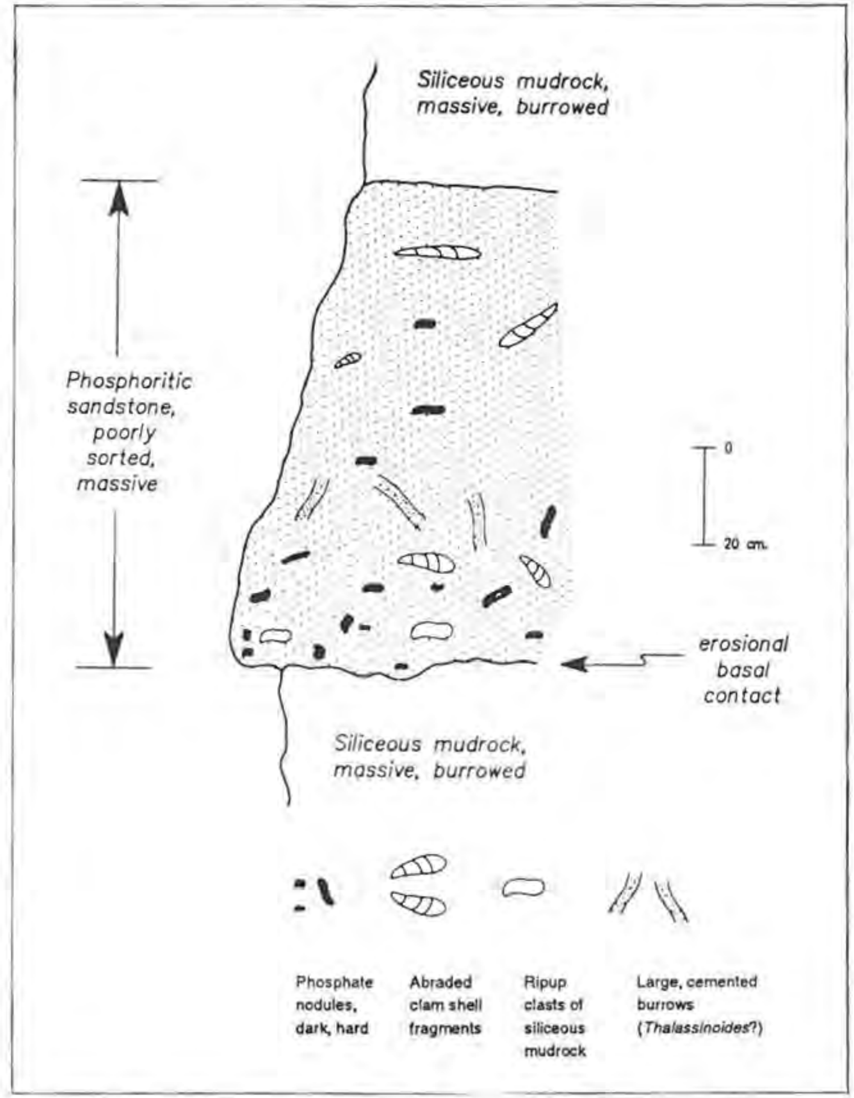

Fig. 3. P-phosphate sandstone bed in the upper Miocene part of the Santa Margarita Formation, Cuyama Basin, Alta California, USA. Note the crude graded bedding, bioturbation, and the presence of scattered, reworked D-phosphate nodules. From Garrison *et al.* (1990).

rephosphatization (Garrison and Kastner, 1990). Commonly, P-phosphate sands have become cemented by finely crystalline CFA to form D-phosphate pavements, hardgrounds, and nodules (Plate 1, Figs. 2, 3). A few D-phosphate conglomerates formed through exhumation of F-phosphate nodules and winnowing of their host mud by botton currents. D-phosphates occur preferentially at unconformities; as discussed below, we believe they form as a consequence of extended periods of non-sedimentation in the marine environment.

RELATIONSHIPS AMONG VARIETIES OF PHOSPHATES

Though each of the phosphate varieties is petrologically distinctive, several observations suggest linkages between them. For example, as noted above, some D-phosphates form as a consequence of lithification by CFA cements. And erosion and reworking of F-phosphate nodules and peloids may lead to the formation of D- or P-phosphates. Text-figure 4 portrays hypothetical relationships among the phosphate types in a time-energy spectrum, based on observations from the Perú margin (Garrison and Kastner, 1990).

DISTRIBUTION OF PHOSPATHIC DESPOSITS ALONG THE EASTERN MARGIN OF THE PACIFIC

ALTA CALIFORNIA

Phosphates of Neogene age are widespread in both onshore and offshore regions of California. The dominant tectonic setting is one of transform-dominated, pull-appart basins marked by submarine topographic differentiation into narrow shelves, steep slopes, small basin floors, and offshore banks. Most of the phosphate dredged from the offshore borderland areas of southern California, originally thought to be modern (Emery, 1960), were shown by uranium series dating to be pre-Quaternary (Kolodny and Kaplan, 1970); most are probably relict Miocene D-phosphates.

Miocene phosphates occur in the Miocene Monterey Formation and associated units in all of the onshore Neogene basins (Dickert, 1966, 1971; Garrison *et al.*, 1987). Garrison *et al.*, (1987)

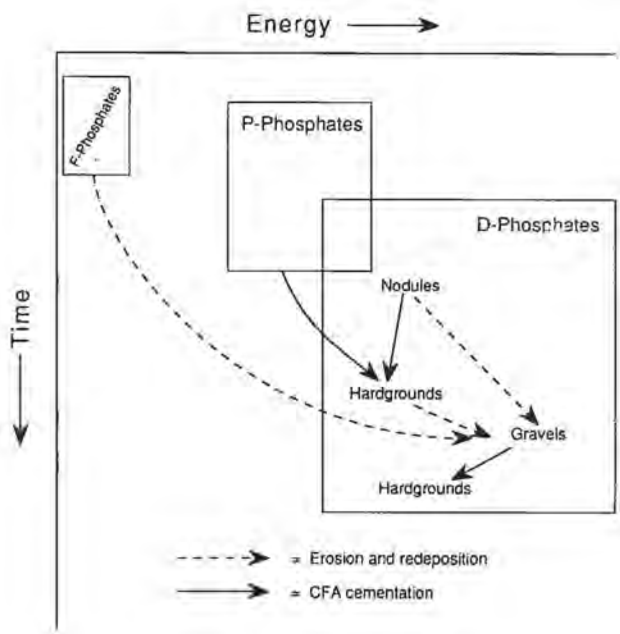

Fig. 4. Schematic diagram showing the time and energy relationships of the different kinds of phosphates in Perú margin upwelling sediments. Note the transitions among the three kinds of phosphates resulting from reworking and cementation on or near the seafloor (from Garrison and Kastner, 1990).

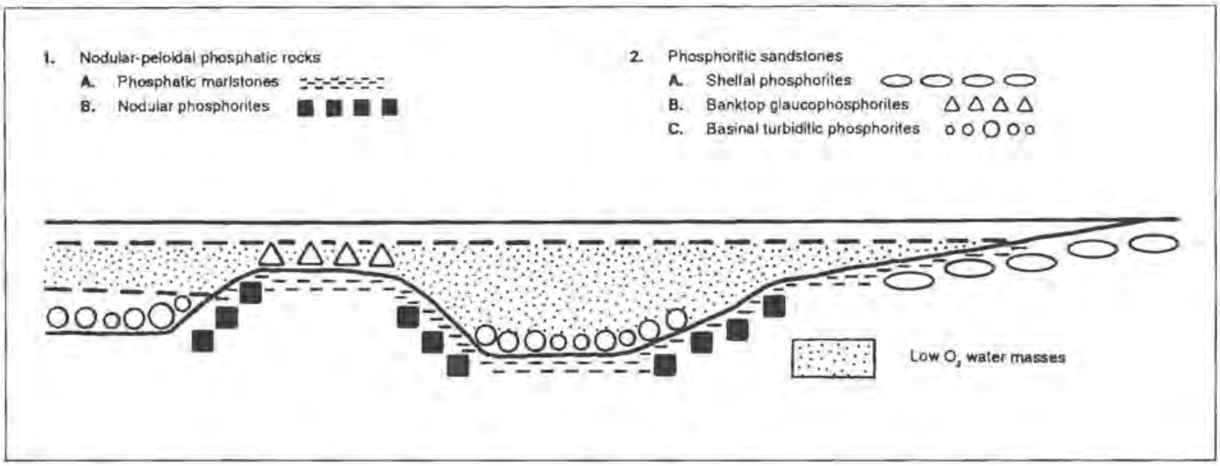

Fig. 5. Schematic cross-section showing hypothesized depositional settings for different phosphatic facies in Miocene borderland basin of Alta California, USA. Phosphatic marlstones (facies 1A) correspond to F-phosphates described in this paper. Nodular phosphorites (facies 1B) are D-phosphates, and phosphoritic sandstones (facies 2) are P-phosphates. From Garrison *et al.* (1987).

recognized F-, P-, and D-phosphates and demonstrated a linkage between the depositional setting and the dominant type of phosphate present (text-Fig. 5). F-phosphates (Plate 2, Fig. 1), for example, formed mainly in low oxygen basin floor, slope, and outer shelf environments, whereas most P-phosphates accumulated in middle to inner shelf environments or on current-agitated submarine banktops. There is also a temporal variation in the distribution of phosphate types (Garrison *et al.*, 1990). D-phosphates occur throughout the Monterey Formation and are most prominent in condensed sequences or at unconformities; they occur, for example, within middle Miocene condensed intervals in the Santa Barbara and Pismo basins, and they mark a prominent Messinian-age (~6.0 Ma) unconformity between the Monterey and Sisquoc formations in the Santa María Basin (Plate 2, Fig. 5; Arends and Blake, 1986; Khan *et al.*, 1989; Föllmi *et al.*, 1991; Föllmi and Garrison, 1991). F-phosphates occur mainly in the interval between about 12 and 16 Ma (text-Fig. 6); they thus coincided with the general sea level highstand of the middle Miocene (Haq *et al.*, 1987), and their associated host rocks are typically organic-rich (up to 30% TOC), commonly contain remains of bacterial mats (Reimers *et al.*, 1990), and in many cases are calcareous. P-phosphates, in contrast, occur as beds up to 2 m thick which are interbedded with diatomaceous mudrocks (or diagenetically modified porcelanites; text-Fig. 3); they are most common in the time interval between about 8 and 14 Ma (text Fig. 6), a period of generally high but fluctuating sea levels and a period which includes a marked sea level lowstand centering at around 10 Ma (Haq *et al.*, 1987). The most extensive and the only potentially mineable phosphate deposits in Alta California are the P-phosphate layers in the Cuyama basin (Roberts and Vercoutere, 1985; Robert, 1989); here, they occur in graded, burrowed sandy beds which are interbedded with siliceous mudrocks and have prominent erosional basal contacts (text-Fig. 3). The precise origin or origins of these beds requires further study. My preliminary interpretation is that they are event beds formed by repeated episodes of reworking on a shelfal region during sea level lowstands or during intervals of rapid sea level changes, as discussed below.

BAJA CALIFORNIA

Offshore and coastal regions. D'Anglejan (1967) reported P-phosphatic sands from shelfal areas west of the Baja California peninsula, but most of these were shown by Kolodny and Kaplan (1970) to be pre-

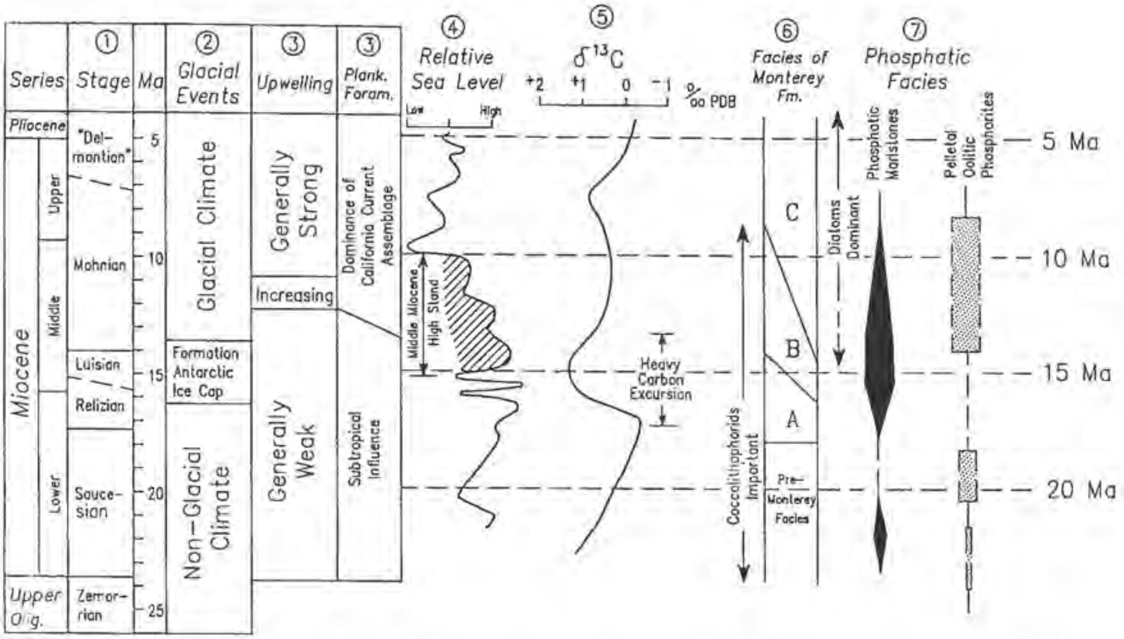

Fig. 6. Age distribution of Miocene phosphatic facies in Alta California , USA, and correlation of these facies with Miocene paleoceanographic events and trends. Column 1 portrays the California Miocene stages of Kleinpell (1938, 1980) as calibrated by Barron (1986a, 1986b). Column 2 shows Antarctic glacial history as reconstructed by Woodruff *et al.* (1981). Column 3 is a reconstruction of the upwelling history of the northeastern Pacific by Barron and Keller (1983). Column 4 is the short-term eustatic sea level curve of Haq *et al.* (1987). Column 5 is a synthesis of carbon isotopic measurements of benthic foraminfers from deep ocean cores, from Savin *et al.* (1981). Column 6 shows the generalized facies of the Monterey Formation in Alta California (Pisciotto and Garrison, 1981); Facies A is a calcareous or calcareous-siliceous facies, Facies B is a phosphatic facies, and facies C is a siliceous (diatomaceous) facies. In column 7, 'Phosphatic Marstones' are equivalent to the F-phosphates described in this paper, whereas «Pelletal Oolitic Phosphorites» correspond to the P-phosphates described in this paper. Diagram from Garrison *et al.* (1990).

Quaternary relict sands. Microfossil age dating reported in Normark *et al.* (1987) indicates that some P-phospates dredged from Baja California margin have a middle Miocene age. But Jahnke *et al.* (1983) demonstrated a Holocene age for some of these deposits, indicating that phosphogenesis has occurred since at least the middle Miocene to the present in this region, perhaps locally and sporadically. Studies of pore water profiles in the Holocene phosphatic sediments (Schuffert *et al.*, 1987) suggest two possible sources of phosphorus to form CFA: either an iron redox cycle phosphate pump or molecular diffusion of dissolved phosphorus from seawater. Both mechanisms would be optimally effective during periods of low or no net sediment accumulation.

P-phosphate grains mixed with dominantly siliciclastic sand grains occur in Holocene coastal dune sands in the low grade Santo Domingo phosphorite deposit of the Isla Magdalena area of Baja California Sur (Salas, 1978). A large proportion of both the phosphatic and siliciclastic grains appear to have been reworked from offshore shelfal regions, hence the exact age of the phosphogenesis is unknown. It appears likely that much of the reworking may have been by eolian processes which acted on shelfal sands subaerially during Pleistocene lowstands of sea level.

Bahía Tortugas. Lying on the western side of the Vizcaíno Peninsula, this is the onshore portion of the mostly offshore Tortugas Basin. The Miocene Tortugas Formation in this area is largely a diatom-bearing siliceous unit which contains scattered, thin beds of P-phosphatic sands (Hellenes, 1980). These layers are most common in the basal portion of the Tortugas Formation in areas marginal to the basin, perhaps parts of narrow shelves; foraminiferal and diatom dating suggest this portion of the unit is around 16 Ma (Hellenes, 1980; Normark *et al.*, 1987). Turbiditic P-phosphate beds also occur interbedded with siliceous rocks in younger parts of the unit.

Santa Rita area, Baja California Sur. Nodules and gravels of D-phosphates occur in small amounts in the lower part of the Salada Formation along Arroyo del Salado in a remote portion of southern Baja California Sur (Salas, 1978; Quintus-Bosz, 1980). The Salada Formation has been assigned a general Pliocene age, but more precise age assignments are not yet available.

Oligocene-lower Miocene Phosphorites of Baja California Sur. These deposits occur in a unit variously called the Monterey Formation (Alatorre, 1988), the El Cien Formation (Applegate, 1986), or the San Gregorio Formation (Hausback, 1984; Kim and Barron, 1986; Galli-Olivier *et al.*, 1990). The latter formation name is used here. The main lithology in the San Gregorio Formation is opal-CT siliceous mudrock, the burial diagenetic product of a diatomaceous mud. This lithologic similarity to the Miocene Monterey Formation of Alta California led earlier workers to call this unit the Monterey Formation. However, a combination of isotopic dating of associated volcanic rocks and diatom biostratigraphy clearly establishes a late Oligocene to earliest Miocene age (*ca.* 23-28.5 Ma) for the San Gregorio Formation (Hausback, 1984; Kim and Barron, 1986). The unit occurs in the part of Baja California Sur between La Paz on the south and San Gregorio on the north, *i.e.* between about latitudes 26.5° and 24.0°N.

The formation appears to represent high fertility deposition beneath an upwelling zone in a forearc basin setting; environments appear to have ranged from shallow inner shelf to deeper water outer shelf to slope (Ojeda, 1979; Hausback, 1984; Alatorre, 1988; Galli-Olivier *et al.*, 1990). It thus resembles very closely the modern forearc basins along the Peruvian margin (see below). Interbedded with the siliceous mudrocks are layers of rhyolitic tuff beds, siliciclastic sandstones, cross-bedded coquinoid limestones, and P-phosphates sandstones. The latter range from a few centimeters to nearly 3 m thick (the thicker beds may be amalgamated), are commonly graded, contain ripup clasts, and have erosional basal contacts. They thus are similar to the Miocene P-phosphate beds of the Cuyama Basin in Alta California (see above) and probably have a similar origin, *i.e.* they are event beds recording periodic high energy events/conditions in normally low energy environments. But like the Cuyama deposits, the origin or origins of the P-phosphate beds in the San Gregorio Formation are not yet completely understood. The presence of phosphatized microbial coatings on some grains (Plate 2, Fig. 4) suggests multiple episodes of phosphogenesis at the sea floor during periods of non-deposition. Also suggesting periodic non deposition is the local presence (*e.g.* in the section at San Hilario) of thin hardground horizons at tops of P-phosphorite layers; these surfaces are coated with laminated phosphatic films (phospatized microbial mats?) and penetrated by pholad clam borings. In some of the deeper water sections, Föllmi and Grimm (1990), noting a common association of P-phosphates layers and large burrows (*Thalassinoides, Gyrolithes*), postulated transport of shallow-water burrowing organism along with gravity flows of P-phosphate sands into deep-water and low oxygen environments where the allocthonous organism temporarily colonized and burrowed the sea floor.

Analysis of the diatom floras led Kim and Barron (1986) to recognize a mixture of low and high latitude species, suggesting to them that the San Gregorio Formation was influenced by both cool and tropical water masses. They compared this environment to the present distal end of the California current. Also suggesting a low latitude setting (as well as shallow-water environments) is the presence of interbeds of cross-stratified coquinoid limestones. These types of beds are very rare in the Cuyama Basin but relatively common in Neogene, phosphate-bearing siliceous sequences of the low latitude Peruvian margin (see below).

P-phosphate beds form the economically important deposits at San Juan de la Costa north of La Paz, one of the largest phosphorite occurrences in Latin America (Salas, 1978; Ojeda, 1979; Alatorre, 1988, Galli-Olivier *et al.*, 1990). In addition, siliceous mudrocks of The San Gregorio Formation also contain scattered F-phosphate nodules and peloids, particularly in the deeper water sections (K. Grimm, personal communication, 1991). The greatest abundance of P-phosphate beds occur in the lower, presumably late Oligocene part of the San Gregorio Formation, although this age interpretation has not yet been confirmed in all sections. The tentative interpretation, therefore, is that major episode of phosphogenesis occurred in this area between about 24 and 28.5 Ma.

PERU

Offshore Perú margin. The Perú margin consists of a number of forearc basins, some now uplifted, others occupying the modern shelfal regions, and a few located on the upper continental slope (Thornburg and Kulm, 1981; Thornburg, 1985). Phosphatic sediments of Quaternary age have been recovered in abundance during dredging and coring on the Peruvian shelf and upper continental slope for the past three decades (Baturin, 1971; Baturin *et al.*, 1972; Burnett, 1977; 1980, 1990; Burnett *et al.*, 1980, 1982, 1988; Glenn and Arthur, 1988; Veeh *et al.*, 1973). The major types recovered by these sampling methods were D- and P-phosphates, with only minor amounts of F-phosphates reported; this, however, may be an artifact of the main sampling method, coring, which preferentially recovers D-phosphate nodules and hardground slabs as well as P-phosphate sands. Uranium-series disequilibrium dating has shown that nearly all of these phosphates formed during late Quaternary time (Baturin *et al.*, 1972; Burnett, 1977), and geochemical studies indicate that the CFA precipitation occurs either at the sediment-water interface or just below (Burnett *et al.*, 1982; Froelich *et al.*, 1988; Burnett *et al.*, (1980) pointed out that D- and P-phophates are concentrated near the boundaries of the present oxygen minimun zone (OMZ), whereas F-phosphates (called 'collophane mudstones' by Burnett, 1980) occur in sediments deposited in the OMZ. Uranium-series dating reported by Burnett (1977) suggests late Quaternary phosphogenesis occurred preferentially during interglacial highstands of sea level. Uranium series and Carbon-14 dating of D-phosphate nodules indicate that they grow more slowly than the sedimentation rates of the enclosing sediments, hence should be quickly buried beneath the zone of active CFA precipitation near the sea floor unless they are maintained in this zone by burrowing organisms of current reworking (Burnett, 1980; Burnett *et al.*, 1982). D-phosphates therefore appear to be connected with low net sedimentation rates. P-phosphate grains, in contrast, may form very rapidly, in as little as 10 years (Burnett *et al.*, 1988).

In 1986, Leg 112 of the Ocean Drilling Program recovered Neogene phosphates at six coring sites in the shelf and upper slope west of Perú (text-Fig. 7; Garrison and Kastner, 1990); an additional middle slope site (Site 688, present water depth=3,826 m) contains small amounts of phosphates which were probably displaced from shallower water. All three types of phosphates occur in Quaternary through middle Miocene diatomaceous muds, but they are most abundant in the Quaternary and Pliocene (Table 1). The shelfal phosphate-bearing sites fall into two categories (Table 1): **1.** Shallow shelf sites with present water depths between about 150 and 300 m, near the upper boundary of the present OMZ (Sites 680, 681, 687); **2.** Outer shelf-upper slope sites lying in the present oxygen at depths of 425 to 450 m (Sites 679, 684, 686).

D-phosphates are present in all Quaternary and most Pliocene sections at all six sites, whereas F-phosphates are most common in the deeper water outer shelf/upper slope sites perhaps because these localities were more persistently within the OMZ during the Neogene. D-and P-phosphates are most abundant in the shallow shelf sites probably because these experienced more frequent episodes of current reworking. F-phosphates tend to occur in laminated, unburrowed diatomaceous muds which were deposited within the OMZ (text-Fig. 8), whereas D- and P-phosphates typically occur in burrowed sequences (text-Figs. 2, 8). Many of the D-phosphates bear evidence of multiple generations of CFA precipitation, indicating long and complex sedimentologic/diagenetic histories (Plate 1, Fig. 3; text-Fig. 4); these multistage rocks probably mark hiatuses of varying durations. Some of the D- and P-phosphates contain phosphatized microbial structures (Garrison and Kastner, 1990).

Alternations of laminated and massive, burrowed intervals characterize the Quaternary and Pliocene section at the shelf sites (text-Fig. 8). According to Wefer *et al.* (1990), the laminated diatomaceous muds accumulated mainly during warm, interglacial highstands, thick intervals (5-10 m) of burrowed sands and silty muds mainly during interglacial lowstands. Schrader and Sorknes (1990) interpreted the diatom assemblages in the laminated intervals as upwelling floras, suggesting that upwelling and the

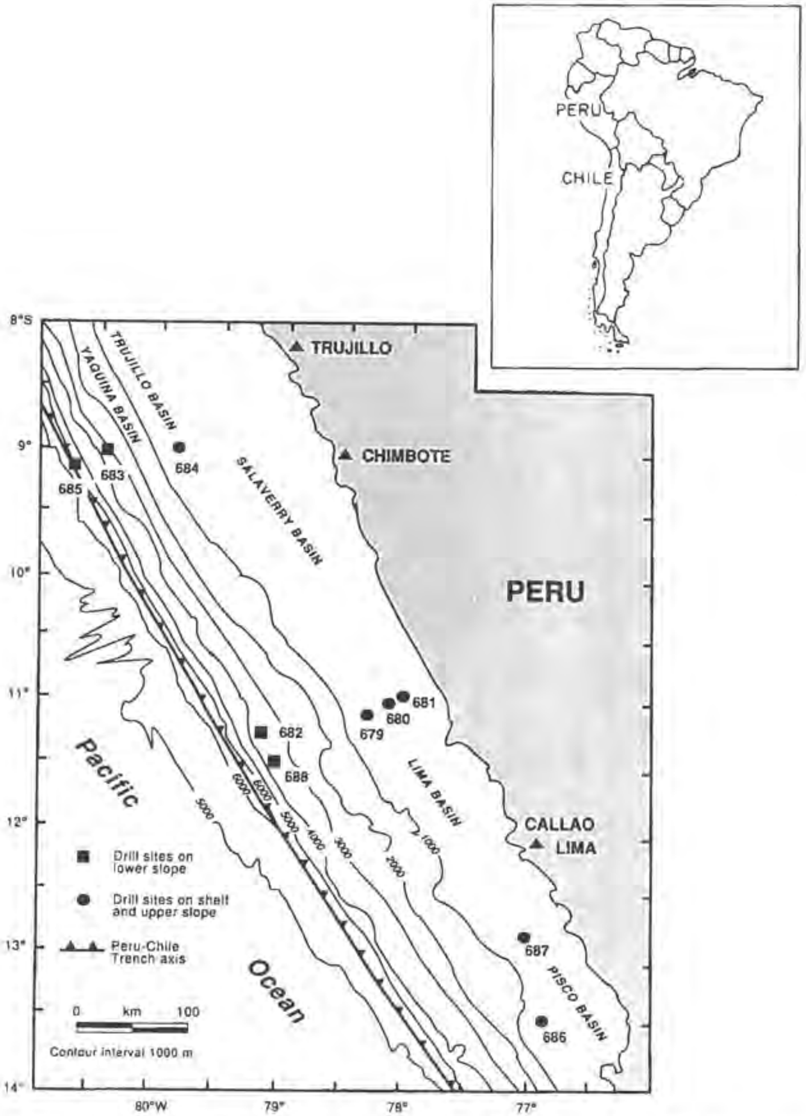

Fig. 7. Location of drilling sites cored during Leg 112 of the Ocean Drilling Program. Phosphatic sediments were recovered at forearc shelf sites 679, 680, 681, 684, 686, and 687 (see Table 1).

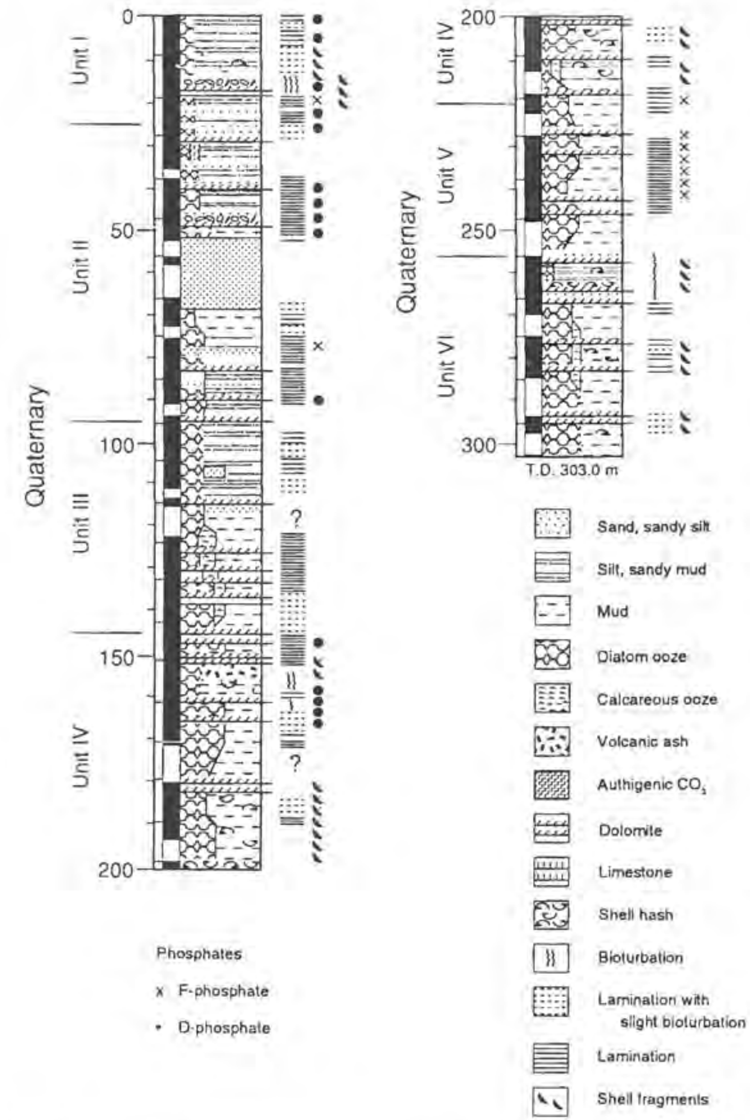

Fig. 8. Distribution of F- and D-phosphates in Quaternary sediments recovered at ODP site 686 (Hole 686B) on the Perú shelf. Note alternations of laminated and massive (structureless) to burrowed diatom muds. Note also the association of phosphates, particularly F-phosphates, in the laminated intervals. From Garrison and Kastner (1990).

TABLE 1. AGE DISTRIBUTION OF DIFFERENT VARIETIES OF PHOSPHATES RECOVERED FORM THE PERU MARGIN DURING ODP LEG 112

SITE	MODERN WATER DEPTH (MBSF)	QUATERNARY	PLIOCENE	MIOCENE
679	450	F, D	F,D	F,D
680	252	D,F,P	F,P,D	Not sampled
681	150	D, P	D	Not sampled
	minor F			
684	426	D,P	P,F,D	Minor D and F
	minor F			
686	447	F,D	Not sampled	Not sampled
687	307	D, minor F	Minor D	Not sampled
688	3826	None	None	*Minor D and F

NOTE: *Probably transported from shelf depths by slumping and redeposition.
F= F-phosphates, P=peloidal phosphatic sands, D=D-phosphates (see text for definitions); these are listed in order of abundance.

OMZ were most intense during interglacial stages of the Quaternary. Burrowed sands containing transported and abraded molluscan shells (text-Fig. 8) appear to be products of high energy conditions on the shelf during sea level lowstands and downward shifts in the position of the OMZ (Schneider and Wefer, 1990). D- and P-phosphate layers may record similar conditions, but with lower or even negative net sedimentation rates (Garrison and Kastner, 1990).

The evidence to date suggests the following origins for the Quaternary phosphates on the Perú shelf. F-phosphates formed during early diagenesis through *in situ* precipitation of CFA within organic-rich muds deposited in low energy environments within the OMZ; expansion and intensifications of the OMZ along with increased upwelling and higher productivity during interglacial highstands promoted widespread formation of F-phosphates during these stages. D-and P-phosphates, in contrast, record higher energy conditions and net sedimentation rates which were low or even negative. D-phosphates in particular appear to occur at unconformities where non-sedimentation and winnowing were prominent. Rates of CFA precipitation in P-phosphate grains appear to have been higher than in the D-variety (Burnett *et al.*, 1988) perhaps due to phosphorus-enriched bottom and pore waters during the times of their genesis. D- and P-phosphates thus seem to have formed during times of more vigorous bottom currents; some of these periods may have been relatively short-lived (*e.g.* storm-wave currents on the shelf), others may have been linked to glacial sea level lowstands, heightened circulation on the shelves, and more persistent and long-lived high energy conditions. Confirmation of this sequence of events, however, must await more precise age dating of the Quaternary portions of Leg 112 cores.

Sechura Basin. Neogene mudstones, diatomaceous mudstones, and diatomites in this onshore forearc basin in northern Perú are assigned to the Mio-Pliocene Zapallal Formation (Caldas *et al.*, 1980; McClellan, 1989; Dunbar *et al.*, 1990). According to Marty (1989) and Dunbar *et al.* (1990), the base of this formation is about 13-15 Ma, the top around 4-5 Ma. Well sorted P-phosphatic sandstone beds up to 2 m thick occur interbedded with shelfal diatomites just below an unconformity within the Zapallal (Cheney *et al.*, 1979). Judging by the stratigraphic data in Marty (1989) and Dunbar *et al.* (1990), these economically important P-phosphorites range in age from 8.5 to 4.5 Ma and are most abundant in the age interval between about 8.5 and 7.0 Ma.

East Pisco Basin. This mosly onshore forearc basin contains hemipelagic muddy, silty, and biosiliceous (diatomaceous) sediments of Eocene, Oligo-Miocene, and Mio-Pliocene ages (Dunbar *et al.*, 1990). Sparse D-phosphate nodules are reported to occur in laminated siltstones of the late Oligocene-early middle Miocene (*ca.* 25-26 to 15-16.4 Ma) Chilcatay Formation (Dunbar *et al.*, 1990). The most abundant phosphates are in the late middle Miocene-Pliocene (*ca.* 11-12 to 2-3 Ma) diatomaceous Pisco Formation (Dunbar *et al.*, 1990); they are, however, still not very abundant, constituting less than 1% of the Neogene section (Allen and Dunbar, 1988). Allen and Dunbar (1988) reported that all three of phosphates are present as thin, non-economic layers in the Pisco Formation. P-phosphate sands occur in very thin (millimeters to a few centimeters) beds and contain mainly pelletal and concentrically coated phosphates grains along with some shark's teeth and fish debris. D-phosphates occur as conglomerates and pavements or crusts which may have been hardgrounds. Some D-phosphate nodules are spherical to subspherical, concentrically laminated, and occur in current-deposited channel lag and cross-stratified layers which indicate considerable reworking (Allen and Dunbar, 1988). Scattered small F-phosphate nodules occur in diatomaceous mudstones of the Pisco Formation.

Dunbar *et al.* (1990) indicated an age range of about 4-5 to 10-12 Ma for phosphate-bearing rocks in the northern Pisco Basin and about 6-8 Ma for the central part. In a section at Quebrada Huarcangana in the southern part of the basin, they reported the occurrence of 23 thin D-phosphate conglomerates within a 300 m thick predominantly tuffaceous and diatomaceous section. They assigned an age interval of 5.5-6.4 Ma to this section and interpreted the conglomerates as shelfal lag deposits resulting from cyclical current or wave-induced winnowing events, possibly related to high frequency sea level lowerings during the latest Miocene (Messinian) lowstand.

CHILE

P-and D-phosphate layers are reported to occur within Neogene diatomaceous sediments of the Mejillones Basin, a forearc basin in northern Chile (E. Valdebenito, personal com., 1988). On the Península de Mejillones north of Antofagasta, Valdebenito (1989) described lenses and beds of P-phosphate sandstones in the upper part of the Caleta Herradura Formation, but no detailed descriptions of these rocks have been published.

SIGNIFICANCE OF NEOGENE PHOSPHATIC DEPOSIT IN THE EASTERN PACIFIC

ENVIRONMENTAL SIGNIFICANCE OF DIFFERENT TYPES OF PHOSPHATES

From the discussion above, it may be surmised that the different types of Neogene phosphatic sediments formed under different conditions (cf. Föllmi *et al.*, 1991; Föllmi and Garrison, 1991) F-phosphates, for example represent *in situ* precipitation of CFA in typically low-energy, low-oxygen environments (*e.g.* where the OMZ intersects the seafloor). Judging from the Miocene record in Alta California, the specific environments in which they formed included outer shelf, slope, basin floor, and isolated banktop (text-Fig. 5; Garrison *et al.*, 1987). Moreover, the temporal distribution of F-phosphates in the Miocene of Alta California and Quaternary of the Perú shelf suggests they formed preferentially during sea level higstands, especially those accompanied by expansion of the oxygen minimum zone.

D-phosphates occur most prominently at hiatuses or in highly condensed sections, in shelfal, upper slope, and isolated banktop settings (text-Fig. 5). In some cases, they may be displaced into the lower slope or basin floor environments by slumping.

The general environmental setting of P-phosphates is fairly clear, but their exact origin is not. Most P-phosphates, and particularly the larger economic phosphorite deposits, accumulated on shelves although a few formed on isolated banktops and some were displaced from these environments into deeper water settings by turbidity currents (text-Fig. 5). The extent of P-phosphates appears to be related to the size of shelfal area. For example, P-phosphates are relatively rare in the Neogene of Alta California where the shelves of most transform-dominated basins were very narrow. They are more common and of greater extent in the broader shelfal regions above the forearc basins in Baja California Sur and along the Perú margin (text-Fig. 7).

Individual P-phosphate beds are typically phosphoritic sandstones and occur in graded beds interlayered with finer grained, low energy deposits (*e.g.* mudstones, diatomites; text-Figs. 2, 3). They thus appear to represent periodic imposition of higher energy conditions on low energy shelfal environments; whether these impositions were typically short term (*e.g.* storm wave currents) or longer term (*e.g.* sea level lowstands) events is an unresolved question, and one which requires more precise age dating of phosphate-bearing sequences as well as closer study of sedimentary structures in P-phosphate beds. Unfortunately, the bioturbation of most such beds has disruputed any traction current structures that may have been present (*e.g.* cross-stratification, hummocky cross-stratification).

Another unresolved question concerns the origin or origins of the pelletal and coated phosphatic grains in P-phosphates. Soudry and Nathan (1980) showed that so-called phosphate pellets may have multiple origins (*e.g.* phosphatized fecal pellets, intraclasts and others), and Soudry's work has demonstrated that many concentric coatings on coated grains consist of phosphatized cyanobacterial sheaths (see Plate 2, Fig. 4; Soudry and Champetier, 1983; Soudry and Levy, 1988). It may be that cyanobacteria encrust sand-size nuclei on the seafloor during times of nonsedimentation and sediment stabilization, then become phosphatized during shallow burial. The occurrence of hardgrounds at the tops of some P-phosphate layers (*e.g.* in some beds in Baja California) lends credence to this stabilization scenario, but the entire sequence of events is doubtless much more complicated. And until we more fully understand the origins and histories of the individual P-phosphate grains as well as of P-phosphate beds, we cannot fully evaluate their significance.

TEMPORAL DISTRIBUTION AND PALEOCEANOGRAPHIC SIGNIFICANCE OF NEOGENE PHOSPHATE FACIES

Table 2 summarizes the temporal distribution of Neogene phosphatic facies that were previously discussed. What emerges is that phosphogenesis has occurred at least locally, along the eastern margin of the Pacific more or less continuously since late Oligocene time. This probably reflects the generally high fertility conditions associated with eastern boundary currents and upwelling, both of which must have existed to one degree or another since at least the late Oligocene.

The accumulation of phosphatic sediments is precluded by high influxes of siliciclastic sediments, thus tectonism locally affects the temporal patterns shown in Table 2. For example, most Pliocene sequences in Alta California have few phosphates and are detrital-rich due to tectonism which uplifted basin margins at that time, creating source areas which shed terrigenous sediments into basin depocenters. Thus the temporal and spatial distribution of phosphates in basins along tectonically active margins cannot be viewed as a perfect reflection of paleoceanographic conditions.

Several authors have pointed out a general correlation between phosphatic facies and highstands of sea level (Sheldon, 1980; Arthur and Jenkyns, 1981), and this trend is evident in the data of Table 2. F-phosphates in Alta California, for example, are most abundant in two age intervals: 12-16 and 20.5-23.5 Ma. corresponding to the middle and early Miocene intervals of highest sea levels (text-Fig. 6; Haq *et al.*, 1987). High sea levels may promote phosphogenesis in several ways (Arthur and Jenkyns, 1981). For example, by shifting siliciclastic depocenters landward, they reduce sedimentation rates in distal environments which both promotes phosphogenesis and prevents clastic influx from diluting any phosphates formed. The warmer climates generally associated with highstands also might be expected to favor preservation of phosphorus-bearing organic matter into the burial stage where diagenetic degradation releases phosphorus into pore waters and promotes CFA precipitation. In addition, the data of Wefer *et al.* (1990) and Schrader and Sorknes (1990) suggest that upwelling and higher productivity were greater on the Perú shelf during Pleistocene highstands, hence higher fluxes of phosphorus-bearing organic matter to the seafloor occurred during those stages.

Occurrences in Alta California and on the Perú shelf indicate that some D-phosphates are lag deposits formed during sea level lowstands when increased episodic bottom current activity may have promoted repetitive cycles of phosphatization, winnowing and exhumation, reburial, and rephosphatization. Dunbar *et al.* (1990) proposed a similar scenario for numerous thin D-phosphate conglomerate beds within latest Miocene diatomites of the East Pisco Basin; if they are correct, a high frequency of sea level changes is indicated. However, other D-phospate layers (*e.g.* in middle Miocene condensed sections in Alta California) occur during generally highstand intervals and may be products of sediment starvation rather than winnowing. These differences require further investigation.

TABLE 2. AGE DISTRIBUTION OF NEOGENE PHOSPHATIC FACIES ALONG THE EASTERN MARGIN OF THE PACIFIC

	F-PHOSPHATES		D-PHOSPHATES		P-PHOSPHATES	
LOCATION	**A**	**B**	**A**	**B**	**A**	**B**
1. Alta California, U.S.A.	9-24	two peaks: 1. 12-16 2. 20.5-23.5	3-18	5-6	7-23	two peaks: 1. 8-14 2. 18.5-21
2. Baja California, México						
a. Offshore					Quaternary	
b. Tortugas Basin					minor, *ca.* 16 Ma	
c. Baja California Sur	Age range of phosphate-bearing San Gregorio Formation is *ca.* 23 to 28.5 Ma. P-phosphates are the most abundant type and are concentrated in the time interval 24-28.5 Ma; F- and D-phosphates are less common.					
3. Perú						
a Perú Shelf	0- *ca.* 15	0-4	0- *ca.* 15-	0-4	0- *ca.* 4	0-2.0
b. Sechura Basin	not described	not described	4.5-8.5	7-8.5		
c. Pisco Basin	*ca.* 4-12	?	*ca.* 4-25	5.5-6.4	*ca.* 4-12	?

NOTE: A = time range of the phosphate facies; . B = time range of the maximum abundance of the facies (ages in Ma are approximations).

The three largest concentrations of Tertiary P-phosphates on the east Pacific margin are the late Oligocene deposits of Baja California Sur (*ca.* 24-28 M), the middle to late Miocene deposits in the Cuyama Basin of Alta California (*ca.* 8-14 Ma), and the late Miocene deposits in the Sechura Basin of northern Perú (*ca.* 7-8.5 Ma.). All encompass time intervals of generally high but sharply and relatively rapidly fluctuating sea levels, according to the compilations of Haq *et al.* (1987). The linkage here may be that short-term fluctuations between highstands and lowstands allow alternations between times of phosphogenesis (*i.e.* enhanced deposition of organic matter and CFA precipitation during highstands) and times of reworking and concentration of P-phosphate grains by currents during lowstands. This combination of processes would be most effective on broad, gently sloping shelves adjacent to upwelling regions, the suggested environment for the three examples cited above (cf. Riggs, 1984). If this model is correct, it might be useful as a guide in the exploration for other, as yet undiscovered and potentially mineable P-phosphate deposits along the eastern rim of the Pacific.

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PLATE 1

Figures

1 Quaternary D-phosphate hardground from the Perú shelf, ODP Site 686. The mottled appearance of the phosphate results from different generations of phosphatization, each of wich produced somewhat different colors and textures.

2 Thin-section photomicrograph through the edge of a D-phosphate nodule from the conglomerate shown in Plate 2, Fig. 5. The outer edge of the nodule is toward the top. Note evidence for incremental growth of the nodule, with different generations of cemented phosphatic sediment bounded by dark bands of finely crystalline CFA; these bands may be phosphatized microbial mats which coated the external surface of the nodule during pauses in its growth. The successive generations of phosphatic sediments consist of phosphatic peloids (dark) and angular siliciclastic grains (light) which are cemented in finely crystalline CFA. Scale bar is 1 mm.

3 Thin-section photomicrograph of Miocene or lower Pliocene D-phosphate nodule from the Perú shelf, Site 679 of the Ocean Drilling Program. This nodule contains at least three generations of sediment cemented by finely crystalline CFA. Generation 1 is a P-phosphate sandstone with a siliciclastic admixture. Generation 2 is finely crystalline CFA, probable a phosphatized diatom mud. An organic boaring (possibly a mollusc boring) penetrates through generation 2 and into generation 1. The boring is lined with a thin laminated crust of CFA, possibly a phosphatized microbial mat which encrusted the nodule at one stage in its growth. The boring is filled with generation 3, a P-phosphate sandstone which is similar to generation 1. Scale bar is 1 mm.

PLATE 1


1
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prop. of ODP
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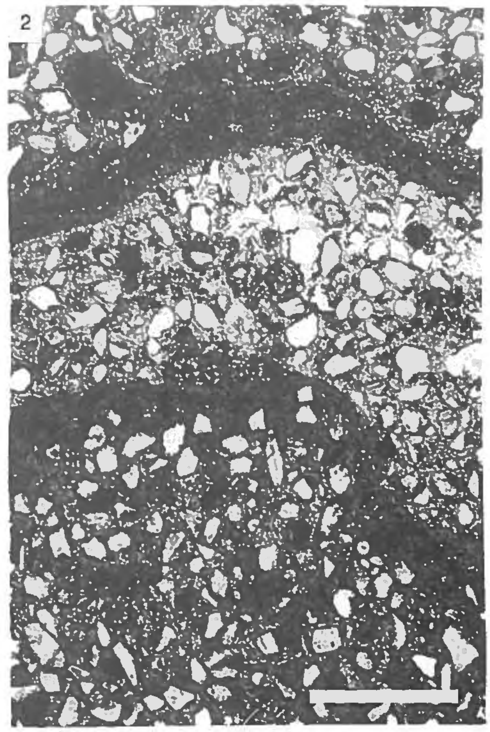
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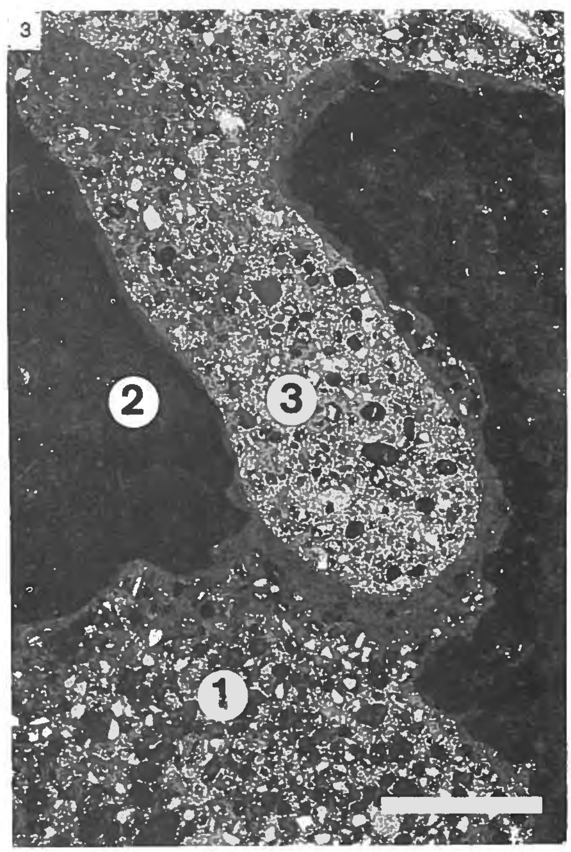
3
2
3
1

PLATE 2

Figures

1 Light-colored F-phosphate nodules and lenses within organic-rich marlstone. The ligth-colored phosphate consists of very finely cristalline authigenic carbonate fluoroapatite (CFA). This outcrop is in the Monterey Formation, middle Miocene, Santa Barbara Basin, Alta California, USA. Coin at upper right has a diameter of 1.9 cm.

2 Thin-section photomicrograph of a Pliocene P-phosphate sand from ODP Site 680 on the Perú shelf. Note the range in types of phosphate grains, from structureless peloids (A) to coated grains (B). The grain marked (C) is a coated grain with a fish bone nucleus. Sample 112-680B-11H-1, 106-108 cm, from Leg 112 of the Ocean Drilling Program (ODP). Intergranular material is epoxide mounting medium. Scale bar is 1 mm.

3 Thin-sections photomicrograph of an upper Oligocene P-phosphate sandstone from the San Gregorio Formation, La Purísima section, Baja California Sur, México. The main types of grains present are structureless peloids and coated grains (e.g. grain A at right center showing faint concentric phosphate laminations). Scale bar is 1 mm (photograph courtesy of María Ledesma).

4 Scanning electron micrograph of a lamina in a coated phosphate grain from the Oligo-Miocene San Gregorio Formation, La Purísima section, Baja California Sur, México. The lamina extending from upper left toward the lower right consists of phosphatized sheath or tubule structures formed by cyanobacterial algae. This indicates that the grain nucleus (lower part of photo) became coated by algal layers which subsequently were phosphatized.

5 D-phosphate conglomerate in vertically dipping Miocene diatomaceous rocks, Santa María Basin, Alta California, USA. Stratigraphic top is toward the left. This conglomerate, dated as about 6 Ma, occurs at the unconformable contact between the Monterey and Sisquoc formations. Note how the densely packed D-phosphate nodules extend stratigraphically downward along large burrows into laminated diatomites of the Monterey Formation on the right.

PLATE 2