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AUTHIGENIC PHOSPHORITE CONCRETIONS IN THE TERTIARY OF THE SOUTHERN NORTH SEA BASIN: AN EVENT STRATIGRAPHY

by

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Sedimentary phosphatic deposits (phosphorites) are found at a number of horizons within the Tertiary succession of the southern North Sea Basin. The majority occur as reworked gravelly lag deposits formed by the winnowing of formations containing *in situ* (authigenic) phosphorite material. The authigenic phosphorite consists mostly of scattered horizons of sparse concretions, often within glauconitic sediments, and represents phosphogenic episodes occurring in the southern North Sea area. Four episodes occurred during the Palaeogene, in the Early Eocene, Middle-Eocene, Early Oligocene and early Late Oligocene, and two in the Neogene, in the Middle Miocene and latest Miocene/ Early Pliocene. Despite the sparse and apparently localised nature of this phosphorite material the Neogene episodes in particular appear to correlate well with the two major Neogene phosphogenic events which occurred in the south-eastern United States and with major phosphogenic events worldwide.

Traditional models of phosphogenesis related to upwelling ocean waters are difficult to apply in the southern North Sea and it is believed that during favourable times for phosphorite deposition, authigenic phosphorite concretions formed at shallow depths within the sediment in shelf seas remote from sites of upwelling.

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SAMENVATTING

Authigene fosforietconcreties in het Tertiair van het zuidelijke Noordzeebekken: een "event"-stratigrafie.

Sedimentaire fosfaathoudende afzettingen (fosforieten) worden aangetroffen in een aantal horizons van de tertiaire opeenvolging in het zuidelijke Noordzeebekken. Het merendeel ervan komt voor als verspoelde basisgrindafzettingen, ontstaan door de erosie van afzettingen die in situ (authigene) fosforieten bevatten. Authigene fosforieten komen meestal voor in een beperkt aantal lagen met verspreide concreties, dikwijls in glauconiethoudende sedimenten. In het zuidelijke Noordzeegebied vertegenwoordigen dergelijke niveaus perioden waarin fosforietvorming plaats vond. Vier van dergelijke perioden kwamen voor tijdens het Paleogeen (Vroeg Eoceen, Midden Eoceen, Vroeg Oligoceen en vroeg Laat Oligoceen), en twee tijdens het Neogeen (Midden Mioceen en Laat Mioceen/Vroeg Plioceen). Ondanks het verspreide en kennelijk lokale karakter van dit fosforietmateriaal blijken vooral de Neogene fosforietvoorkomens goed gecorreleerd te kunnen worden met twee belangrijke Neogene perioden van fosforietvorming die bekend zijn uit de oostelijke Verenigde Staten, alsmede met belangrijke wereldwijde perioden van fosforietvorming.

De traditionele hypothese, waarin fosforietvorming wordt gerelateerd aan opwellend oceaanwater, is in de zuidelijke Noordzee moeilijk toepasbaar. Het wordt dan ook verondersteld dat tijdens gunstige perioden afzetting van authigene fosforietconcreties plaats vond op geringe diepte in het sediment in ondiepe zeeën van het continentale plat, verwijderd van plaatsen waar opwelling plaats vond.

INTRODUCTION

Most sedimentary rocks and sea-floor sediments contain less than 0.3% P_2O_5. However, at certain periods through geologic time marine sediments containing more than 5% P_2O_5 (phosphorites) have formed on the sea floor in response to specialised conditions (Riggs, 1984).

Despite extensive and voluminous research over many years there is still no general agreement as to the conditions or set of conditions which result in the precipitation of phosphorite sediments (see summaries in e.g. Bentor, 1980; Sheldon, 1981; Cook, 1984). It is clear that there is no single model which explains the origin of all phosphorites, rather there are several models which have varied in importance both temporally and geographically. This paper will summarise some of the general characteristics and models for phosphorite deposition which are then compared to the features observed in the southern North Sea Basin.

In Tertiary sediments of the southern North Sea Basin, phosphorite concretions of carbonate fluorapatite containing approximately 30% P_2O_5 occur *in situ* within several marine formations. The aim of this paper is to show that authigenic phosphorite concretions were formed only during certain specific time intervals, and that these phosphogenic "episodes" occur during basin-wide transgressive events. The southern North Sea phosphogenic episodes can be correlated with other, volumetrically more significant phosphorite deposits elsewhere in the world. Most of the data on the stratigraphic distribution of phosphorites for this paper has come from exposures and boreholes on land areas around the present southern North Sea and relatively little information is available from the offshore region. The data is still very incomplete and there are problems of interpretation of records in the literature. Phosphorite concretions have attracted relatively little interest and may therefore go unrecorded or conversely may be erroneously recorded, as concretions of other authigenic minerals are often superficially similar in appearance. Wherever possible the authigenic concretions mentioned in the text have been analysed by the author to confirm their mineralogy.

GENERAL CHARACTERISTICS OF PHOSPHORITE SEDIMENTS

Phosphorite sediments occur in many physical forms but have one characteristic in common: they generally contain a significant proportion of sedimentary apatite, a carbonate fluorapatite called francolite. This paper will consider only those forms of phosphorite which form penecontemporaneously with sedimentation and are therefore primary precipitates. Biogenic primary precipitates, e.g. vertebrate teeth and bones and certain invertebrate skeletons such as inarticulate brachiopod shells will not be considered. The rôle of these and other biogenic precipitates is summarised in Riggs (1979) and Sheldon (1981). There are 4 main types of non-biogenic primary precipitate of sedimentary apatite:

— Microcrystalline phosphorite (microsphorite) may be precipitated at the sediment/water interface where phosphorus is concentrated by bacteria to form layers which may eventually be preserved as distinct beds or bands.

— This microsphorite may be aggregated by biological activity into pellets to ultimately become a pelletal phosphorite.

— Microsphorite may also be precipitated from interstitial pore waters to form concretions (often associated with an organic nucleus) that probably developed within a few centimetres of the sediment surface.

— Sedimentary apatite may also replace pre-existing rocks, particularly carbonates, or biogenic material. Molluscan shells are apparently less readily replaced than limestones, possibly due to their larger crystallite size. Vertebrate skeletal materials such as bones or teeth are also readily replaced. Occasionally wood and other materials may be replaced.

There may be a degree of overlap between the third and the fourth type, i.e. some replacement of sediment grains may be involved in concretion development.

Each of these types of authigenic (i.e. formed *in situ*) phosphorite may be reworked and the resultant selective concentration of phosphatic material may lead to the formation of an economic deposit.

PHOSPHORITE CONCRETIONS IN THE TERTIARY OF THE SOUTHERN NORTH SEA BASIN

Occurrence

In the southern North Sea area the authigenic sedimentary phosphorite consists entirely of lithified concretions formed within the sediment which are often reworked during sedimentary breaks or transgressions to form thin lag or remanié deposits of pebble-sized phosphatic nodules. Some deposits of this latter type have formerly proved economic e.g. beneath the Pliocene Crags in eastern England (Reid, 1890) and in the Oligocene of the eastern Netherlands and West Germany (Dietz, 1960).

Such lag deposits tend to occur in areas presently, or once, underlain by formations bearing authigenic phosphorite concretions. Nodules of apatite (SG $\approx$ 3.0) are not easily transported but will be readily concentrated by winnowing of the unlithified enclosing sediments leaving behind phosphatic lag gravel deposits more or less geographically at their place of origin. These deposits were then incorporated, possibly with further erosion, into the transgressive basal gravels of later deposits (see Balson, 1987).

From the available evidence it is apparent that phosphorite concretions formed most abundantly and are geographically most widespread during two periods, the Early-Middle Eocene and the Miocene, although they also occur in the Oligocene of the Netherlands and West Germany (for details see Balson, 1987). There may be other occurrences of phosphorite concretions, for instance within ? Late Eocene sediments of West Germany (Gramann et al., 1975) but the age of the concretions remains to be confirmed.

Characteristics

The phosphorite concretions in the southern North Sea Tertiary occur in a variety of marine sediments. The Eocene concretions are dominantly found within muds, whereas younger concretions are mostly within sandy muds or muddy sands which are usually very glauconitic. The sediments represent a range of depositional environment from nearshore to shelf depths in excess of 100 m.

The concretions commonly appear to have formed around organic-rich nuclei which include vertebrate remains such as bone or teeth, crustacean carapaces, molluscs or burrows. Bones and teeth are primary biogenic precipitates of apatite so the concretion has the same mineralogical nature as the nucleus. Crustaceans are invertebrates with a relatively high phosphate content (Clarke & Wheeler, 1922), although the phosphate is not in the mineral form of apatite. Mollusc and burrow nuclei represent sites of organic concentration. There appears to be no strong correlation between mineralogical composition of the nucleus and preference for concretion growth, but almost all nuclei represent sites of organic matter concentration. The mudstone concretions particularly, usually have dark organic-rich centres on sectioning. Organic matter is of prime importance in concentrating phosphorus from seawater. Organic matter represents an enrichment by a factor of 140,000 over seawater. However further enrichment by a factor of 10-15 is required to form a phosphorite concretion with a P_2O_5 content of 30-35%, in itself an enrichment of two-million fold over seawater (Bentor, 1980).

From this it is clear that the nucleus does not in itself contain sufficient P_2O_5 to form the concretions; an external source is necessary. Phosphorites are generally associated with high productivity which allows large amounts of organic matter to be trapped in the sediments. This organic matter supplies the P_2O_5 within interstitial pores, which can then concentrate around suitable nuclei.

The rate of sediment deposition may have rôle in phosphorite concretion growth. If the rate is too high organic matter may be rapidly trapped beneath the sulphate reduction zone where phosphorite concretions are believed to form, leading to the formation of other authigenic minerals such as siderite. If the rate is too low organic material may not be buried at all. Recent phosphorite concretions on the Peru/Chile shelf form under conditions of rapid sediment accumulation (0.5 to 1.6 mm/yr) (Burnett, 1980), whilst concretions off South-West Africa are forming in an area with only slightly slower rates (0.15-1.14 mm/yr) (Baturin, 1982). Both are areas of anoxic or O_2 deficient seabeds. In such areas deposition rate will be less important (Jones, 1983) as organic material can remain unoxidised on the sea bed until it is buried. In such cases apatite may also be precipitated at the sediment/water interface.

By contrast in the southern North Sea the concretions are associated with rich benthic faunas and bioturbated sediments indicating an oxic seabed. Concretions are found within the upper part of the Middle Eocene Lillebaelt Clay where sedimentation rates are believed to have been very low (Thiede et al., 1980), whereas in the London Clay sedimentation rates were clearly more rapid (cf. King, 1984).

Thus in order to form phosphorite concretions there must be an adequate supply of phosphorus, usually from organic matter entrapped in the sediment, associated with high productivity in the overlying water and probably a moderate rate of deposition.

Correlation with transgressive events

The early Eocene (Ypresian) transgression is represented in eastern England by the London Clay Formation. The earliest sediments of this transgression (the Harwich Member, Fig. 1) are of latest Palaeocene age and record extensive volcanic activity with many layers of argillised volcanic ash. At a certain stage in the transgression a more open connection with the Atlantic Ocean to the West is indicated by an influx of planktonic Foraminifera into the sediments, the so-called "planktonic datum" (see Fig. 1). Water depth reached a maximum of more than 100 m in division B and lower part of division C (King, 1984) followed by a gradual regression terminating with shallow, tidally influenced sediments (the Claygate Member).

Phosphorite concretions in the London Clay Formation are found to occur exclusively after the "planktonic datum" and before deposition of the shallowest sediments, i.e. during the peak of the transgression only. Elsewhere, e.g. in the stratigraphically equivalent Ieper Clay of Belgium, a similar distribution is seen, although rare concretions have been found just below the planktonic datum (Balson, 1987).

Phosphorite concretions occur at approximately the same stratigraphic levels in other parts of the southern North Sea Basin e.g. in Belgium, West Germany and a BGS borehole (81/46A) off the NE England coast (Fig. 2).

In Denmark deposits stratigraphically equivalent to the London Clay (the Rosnaes Clay) form a condensed sequence due to very slow depositional rates. The sediments are oxidised, and lacking in the organic content (Heilmann-Clausen et al., 1985) usually associated with phosphorite precipitation.

The evidence from the Early Eocene indicates that the phosphorite concretions formed most abundantly during the maximum extent of the transgression.

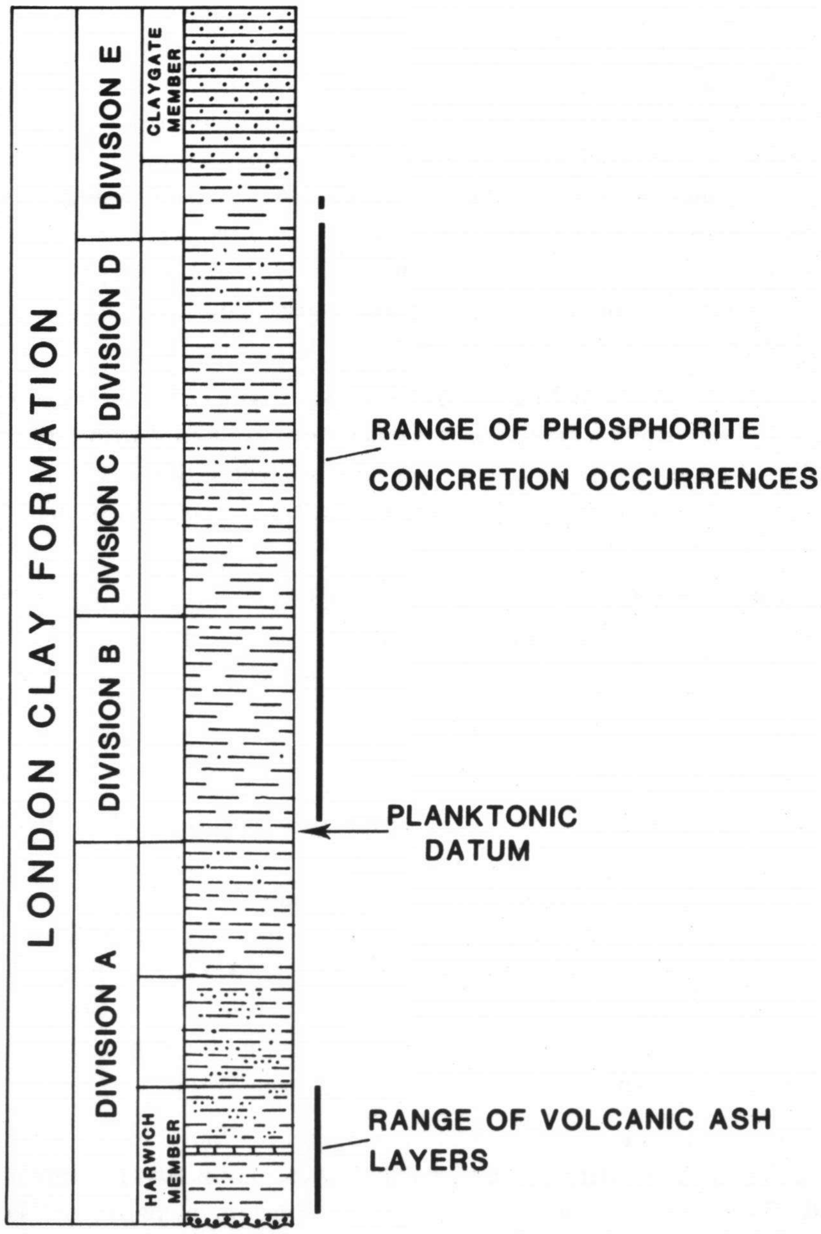


Fig. 1. Composite stratigraphy of the London Clay Formation in eastern England (modified after King, 1981) showing range of occurrence of phosphorite concretions. Thickness represented approximately 134 m.

The phosphogenic episode represented by the concretion-bearing parts of the Middle Miocene sequence of the Netherlands (Miste Bed) and Belgium (Antwerp Sands) also correlates with faunas which indicate an open connection with the Atlantic Ocean (van den Bosch et al., 1975, p. 77).

When the known occurrences of authigenic phosphorite concretions are plotted against global sea level (Fig. 3) there is a strong correlation with the peaks of major eustatic transgressions as indicated by the "Vail" curve of coastal onlap (after Vail & Hardenbol, 1979). However the eustatic cycles represented by this figure may differ in detail from the actual rise and fall of sea level in tec-

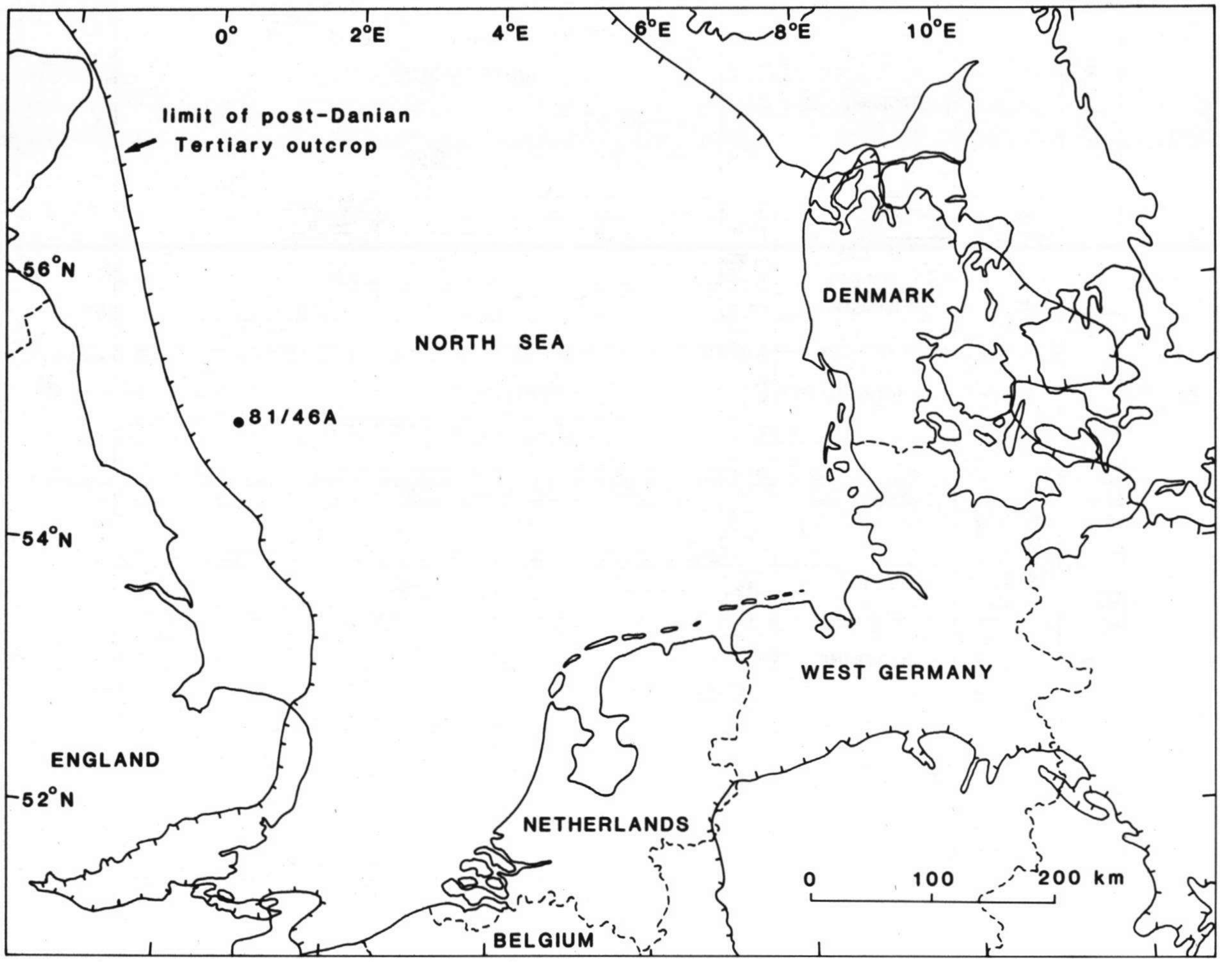
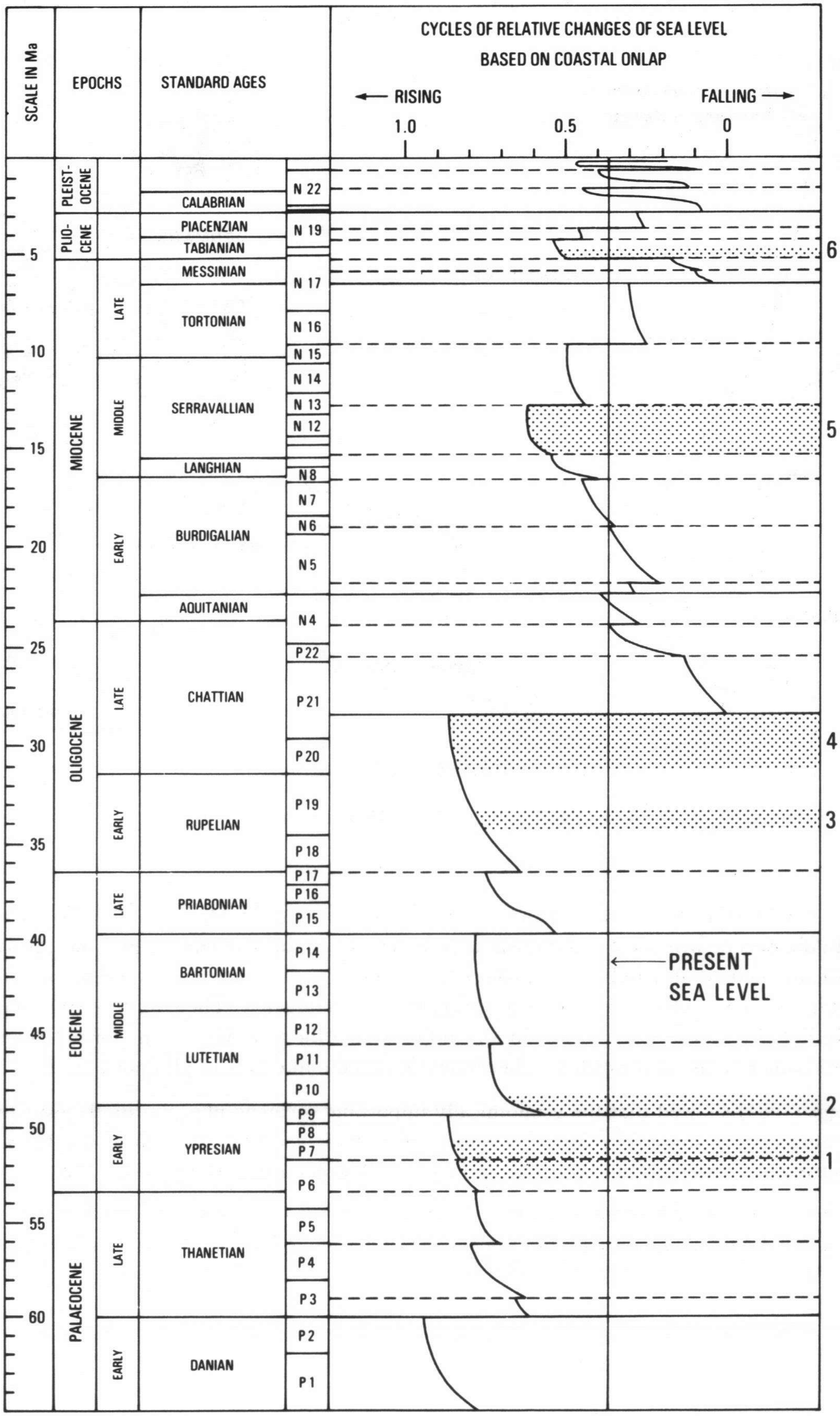


Fig. 2. Southern North Sea Basin showing limit of post Danian Tertiary outcrop.

tonically active basins such as the North Sea (see discussion in Summerhayes, 1986). For instance the early Middle Eocene Brussels Sands appear to lie at a point on the Vail curve which indicates a period of eustatic regression, although inaccuracies will inevitably occur due to problems of absolute dating of the transgressive cycles and of the concretion-bearing sediments. The lengths of the "episodes" shown in Fig. 3 are necessarily approximate and represent the time span of the formations in which authigenic concretions are recorded rather than the specific intervals of phosphogenesis.

Riggs (1984) showed that the economically important Neogene phosphorite deposits of the SE United States, were similarly related to changes in eustatic sea level with phosphogenesis concentrated during the Early-Middle Miocene and earliest Pliocene transgressions (see Fig. 4).

Although the phosphogenic episodes recorded in the SE United States are of longer duration there is an obvious correlation with the Neogene episodes identified in the southern North Sea Basin (cf. Fig. 3).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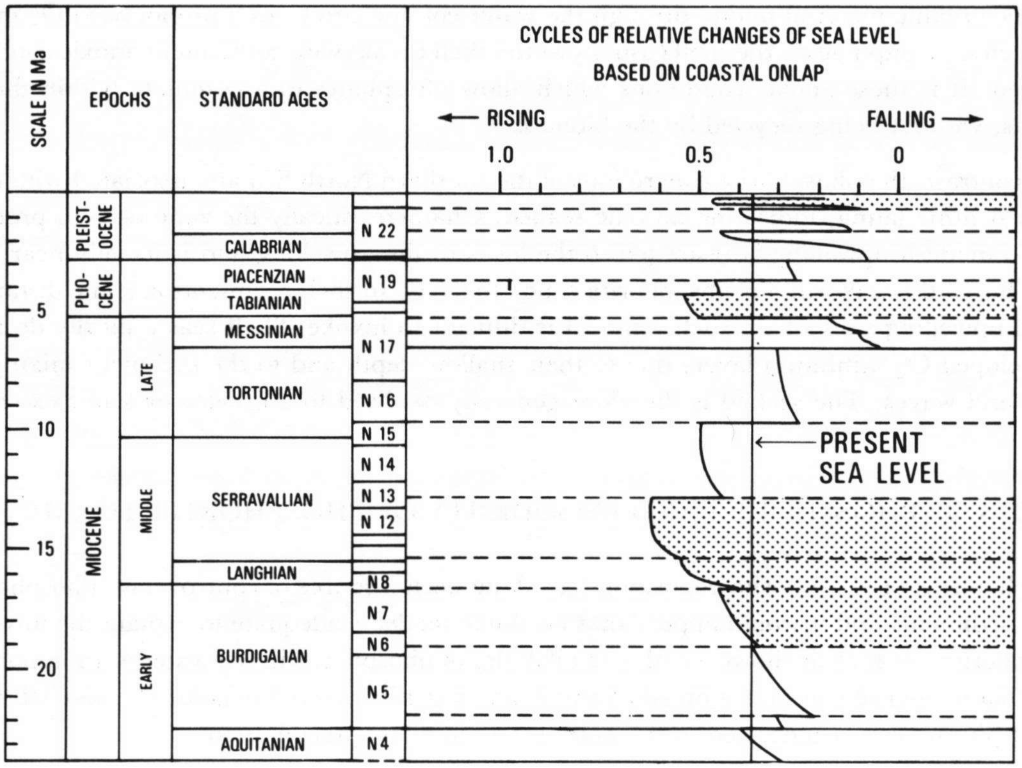

Fig. 4. Phosphogenic episodes in the SE United States Neogene plotted against "eustatic sea level" (after Riggs, 1984).

THE ROLE OF UPWELLING IN PHOSPHOGENESIS

Many models of phosphogenesis rely on the presence of oceanic upwelling to create the necessary environment for phosphorite precipitation (see discussion in Sheldon, 1981; Cook, 1984). Upwelling is a process by which nutrient-rich oceanic waters rise into the surface productive layers. Dynamic, or topographic, upwelling is induced where strong currents near the shelf break flow over large-scale bathymetric features but the most commonly quoted form of upwelling with respect to the formation of Recent phosphorites is coastal upwelling caused by longshore trade winds.

As a result of surface wind stress nutrient-rich (phosphate-rich) water from the deep ocean rises onto the continental shelf resulting in enhanced productivity within the shelf waters. The oxidation of

Fig. 3. Phosphogenic episodes in the southern North Sea Tertiary plotted against "eustatic sea level" adapted from Vail & Hardenbol (1979). Approximate time intervals in which phosphorite concretions occur are stippled.

1. London Clay (UK), Ieper Clay (B), "Tarras" (D)
2. Brussels Sand (NL), Lillebaelt Clay (DK)
3. "Berg Sands" (B)
4. Chattien (NL, D)
5. Miste Bed (NL), Antwerp Sands (B, NL)
6. Delden Member (NL), ? "Trimley Sands" (UK)

planktonic organic material falling through the water column produces a pronounced O_2 minimum layer which may impinge on the shelf (usually at the shelf break) with consequent anoxic conditions at the seabed. It is these anoxic conditions which allow phosphates to accumulate within the seabed sediments, without being recycled by the biomass.

By contrast, the phosphorite concretions of the southern North Sea are associated with evidence of a rich benthic fauna, indicating an oxic seabed. Characteristically the zone of high productivity related to modern upwelling is restricted to the locus of the upwelling and is usually near the shelf break. The southern North Sea phosphorite concretions are in shelf sediments at some distance from potential upwelling sites where such a model is difficult to invoke. Shelf seas typically do not have well developed O_2 minimum layers due to their shallow depth and to the turbulent mixing caused by tides and waves. The seabed is therefore generally oxidised to a greater or lesser extent.

SOURCES OF PHOSPHORUS AND EPISODICITY OF PHOSPHORITE FORMATION

The mechanisms of phosphorite deposition have long been a source of controversy. Phosphorites are complex sediments and it would appear that no single model is adequate to explain the formation of all phosphorites. It is clear, however, that availability of phosphorus in sea water is an important factor and that biological concentration is required. The organic material must be effectively buried and sufficient phosphorus regenerated in the pore waters to allow precipitation.

Phosphorus is supplied to the oceans at the present time from two major sources:

— Continental weathering. At the present time 1.7×10^6 tonnes of phosphorus are input into the world's oceans by rivers (Arthur & Jenkyns, 1981). This input will have been enhanced during times of warm humid climatic conditions.

— Volcanic emanations. Present day volcanoes input 0.07×10^6 tonnes of phosphorus into the world's oceans (Arthur & Jenkyns, 1981). A correlation of phosphorite concretion occurrence with volcanic activity in the southern North Sea area was proposed by Paproth & Zimmerle (1980). In this area the Late Palaeocene was a time of extensive volcanic activity depositing thin ash bands, such as those within the Harwich Member of the London Clay Formation in eastern England and the Ølst Formation in Denmark. These ash-bearing sediments appear, however, to predate the earliest occurrence of phosphorite concretions, although according to Wirtz (1937) they have been found occasionally within stratigraphically equivalent ash-bearing sediments in West Germany. Later volcanic activity in the North Sea Basin was confined to the Rhine Graben area and no direct correlation with phosphogenic episodes is apparent. In any case the Late Palaeocene example apears to confirm that periods of extensive volcanicity in the North Sea Basin were not times of significant phosphogenesis.

Seafloor hydrothermal vents have been thought by some authors (e.g. Riggs, 1979) to have been important, but it has been shown that the contribution to ocean water from this source is negligible (Froelich et al., 1982).

Episodicity of phosphorite development has been noted by many previous authors (e.g. Cook & McElhinny, 1979; Sheldon, 1980). However it should be noted that much of the data used in such compilations arises from *economic* phosphorite deposits. Data from uneconomic or small deposits or deposits which presently lie in offshore regions may not be included. Some of the economic deposits have been reworked from older formations and therefore their age will not reflect the age of phosphogenesis. In the Tertiary worldwide the Early Eocene and Miocene are particularly noted for their abundance of phosphorite deposits (Cook & McElhinny, 1979), and it is clear that the volume of these and other ancient deposits far exceeds that of deposits forming at the present time. For instance the Permian Phosphoria Formation of the western U.S.A. contains about 7 × 10^{11} tonnes of phosphorus. Under present conditions more than the total annual P-influx into the ocean would have to be precipitated continuously for 10 m.y. within one localised area to form a deposit of this size (Bentor, 1980).

Two conclusions would appear to be inescapable:

— There were periods in the past more favourable for phosphorite formation than the present.

— The mechanisms of apatite precipitation acting at the present time might also have been operative periodically in the past, but additional mechanisms were necessary to create very large deposits.

Fischer & Arthur (1977) discussed the episodicity of processes in the world's oceans. They defined two alternating oceanic states:

— *Oligotaxic*. Oligotaxic periods are characteristically times of:
- lowered diversity of pelagic communities,
- marine regression,
- cool seas with sharp latitudinal and vertical temperature gradients,
- vigorous oceanic circulation with strong upwelling,
- reduced continental weathering, and
- phosphorite formation of limited extent.

— *Polytaxic*. Polytaxic periods are times of:
- diverse pelagic communities,
- marine transgression,
- warm seas with weak latitudinal and vertical temperature gradients,
- less vigorous circulation,
- increased continental weathering, and
- extensive phosphorite development.

During polytaxic periods continental weathering (source of P) is increased and residence time in the ocean lengthened so that apatite saturation may develop. Upwelling during these times is inhibited and may not play an important rôle in phosphogenesis. Phosphorites form over a wide range of palaeolatitudes c. 45° to the North and South of the equator (Sheldon, 1981). Using the methods outlined in Cook & McElhinny (1979) the palaeolatitude of the southern North Sea Basin during Early Eocene times was c. 40° N and in the Middle Miocene c. 46° N. It would appear therefore that during the Tertiary the North Sea Basin was near the assumed northern limits of potential phosphogenesis, although it should be understood that the theoretical latitudinal limits of phosphogenesis cannot be defined with accuracy. It is likely that the latitudinal range would have been greater than during oligotaxic periods. According to data from oxygen isotope ratios the Early-Middle Eocene and Middle Miocene were times of relatively warm climates in the southern North Sea Basin, whilst the Middle and Late Oligocene were relatively cool (Buchardt, 1978). However the faunas of the Middle Oligocene Brinkheurne Formation in the eastern Netherlands indicate tropical to subtropical conditions at this time (van den Bosch et al., 1975). There appears therefore to be a good correlation of phosphorite concretion occurrence with warm climates in the southern North Sea area. The commonly observed correlation of phosphorite concretions and smectite-rich clay sediments (e.g. see Paproth & Zimmerle, 1980; Heilmann-Clausen, 1985) may reflect increased weathering during warm, humid periods rather than indicating a causal relationship between volcanicity and phosphorite precipitation.

During oligotaxic periods such as the present day, upwelling may be the essential factor resulting in sufficient concentration of phosphorus in the sediments for phosphorite precipitation. The latitudinal limits of phosphogenesis would be expected to be more limited to low latitude positions during oligotaxic periods as suggested by the location of modern phosphorites e.g. off SW Africa (18-24° S) and off Peru-Chile (5-21° S) (Baturin, 1982).

PHOSPHORITE-GLAUCONITE ASSOCIATIONS

Many authors have noted the association between phosphorite and glauconitic sediments (e.g. Odin & Letolle, 1980; Burnett, 1980). The formation of glauconite also appears to be favoured by transgressions and increased humid continental weathering with the implied increased input of iron. Glauconite formation has a wider latitudinal range than phosphogenesis (Odin & Letolle, 1980). Given favourable conditions near the limits of potential phosphogenesis, glauconite may be expected to be the dominant authigenic sedimentary mineral. Almost all of the southern North Sea phosphorite concretions, with the possible exception of the London and Ieper Clay examples, are associated with glauconite which is occasionally the dominant component of the enclosing sediments. In the Early Eocene of BGS borehole 81/46A the phosphorite concretions are associated with increased glauconite abundance although the grains are sparse when compared with the Oligocene or Neogene occurrences. This may be due to higher sedimentation rates in the Early Eocene as glauconite formation requires relatively slow deposition rates.

PHOSPHOGENIC EPISODES AND TERTIARY CORRELATION IN THE SOUTHERN NORTH SEA BASIN

From the foregoing discussion it appears that phosphogenesis in the southern North Sea occurred only during stratigraphically short periods of time, associated with the peaks of certain basin-wide transgressive episodes. It is likely to a first approximation that phosphogenesis occurred contemporaneously at geographically separate localities within the basin wherever suitable marine sedimentary facies existed. It is therefore not unreasonable to suggest that approximate stratigraphic correlation may be possible when other supporting evidence from faunas is available.

The Early Eocene phosphogenic episode (Episode 1 of Fig. 3) is represented by concretions in the London Clay Formation of eastern England, Ieper Clay of Belgium and Early Eocene "Tarras" of West Germany. Concretions also occur in the Early Eocene of BGS borehole 81/46A, which is over 400 km from the southernmost occurrences (see Fig. 1).

The Middle Eocene episode (Episode 2 of Fig. 3) is represented by concretions in the Brussels Sand of the Netherlands and Lillebaelt Clay of Denmark.

The two Oligocene phosphogenic episodes are the most poorly known with evidence coming from the Rupelian sands beneath the Boom Clay of northern Belgium (Episode 3) and derived Chattian material in the eastern Netherlands (Episode 4) (see Balson, 1987 for details).

The Middle Miocene phosphogenic episode (Episode 5) is represented by phosphorite concretions within the Miste Bed of the eastern Netherlands and within part of the Antwerp Sands of the SW Netherlands and northern Belgium (see Balson, 1987 for details). Correlation of this relatively short-lived phosphogenic episode is thus possible on available evidence over a distance of over 200 km.

The second Neogene episode (Episode 6) is represented by a phosphorite development within the Delden Member of the eastern Netherlands. The Delden Member has been correlated with other formations of latest Miocene or earliest Pliocene age (Janssen, 1984). So far no other phosphorite sediments unequivocally of the same age as the Delden Member have been identified in the southern North Sea Basin although the Early Pliocene Kattendijk Sands with which this formation has been correlated in part (van den Bosch et al., 1975) are notably glauconitic.

Within the conglomeratic reworked phosphorite deposit at the base of the Pliocene crags of eastern England are found large cobbles of an apatite cemented sandstone which contain a fauna of indeterminate Neogene age. These cobbles, or "Suffolk box-stones" of the literature, originated as phosphorite concretions in a now destroyed formation of muddy sands informally termed the "Trimley Sands" by Balson (1987). In the past the fauna was correlated with the Middle Miocene "Black Crag" (Antwerp Sands) of Belgium (Lankester, 1868), an interpretation subsequently followed by Balson (1980). However, recent work by the author suggests that this correlation is in error and a more recent age is indicated, possibly contemporaneous with the Delden Member of the eastern Netherlands.

Beyond the North Sea Basin correlation appears possible with other Tertiary sequences. On a global scale the two major Tertiary phosphogenic episodes with mean ages of 14 and 54 Ma identified by Cook & McElhinny (1979) correlate well with the two most extensive episodes in the North Sea Basin (see Fig. 3).

In the Neogene of the SE United States authigenic precipitation of phosphorite occurs in the Middle Miocene and earliest Pliocene (Riggs, 1984). In this area some limited phosphorite precipitation may also have occurred in the Holocene although this episode is not represented in the North Sea Basin where conditions were clearly unfavourable for phosphogenesis.

If the cyclicity of phosphorite formation on a global scale is the same as that seen within the southern North Sea Basin then it follows that features on a local sedimentary or basin-wide scale must be of minor importance in determining whether phosphogenesis occurs, except that they may provide a suitable milieu for precipitation to occur. The occurrence of phosphorite concretions in the southern North Sea Tertiary may thus form an event stratigraphy which reflects global rather than local events.

CONCLUSIONS

1. In the southern North Sea Basin scattered authigenic phosphorite concretions occur within a variety of marine sediments deposited over a range of shelf depths during the Tertiary. There is often an association between occurrence of concretions and glauconite-rich sedimentation. The concretions commonly have an organic-rich nucleus although the mineralogical composition of this nucleus appears unimportant.

2. The concretions occur during six distinct "phosphogenic episodes". Four in the Palaeogene: Early Eocene, Middle Eocene, Early Oligocene and early Late Oligocene, and two in the Neogene: Middle Miocene and ? earliest Pliocene. Concretion-bearing horizons can be correlated over distances of 10's to 100's of kilometres.

3. The phosphogenic episodes were periods of high organic productivity as evidenced by the rich benthic faunas. The apparent contradiction of phosphate-rich sediments without O_2 deficient bottom waters may be due to organic material entering the sediment because of high productivity of benthic and infaunal organisms rather than plankton.

4. These episodes correlate with global events of high eustatic sea-level and warm climates within the southern North Sea area. Thus, sea level would appear to be a first order control—controlling both phosphate supply and potential sites. Local supply of phosphate into the North Sea Basin was not apparently important.

5. Recent phosphorite precipitation is occurring during oceanic conditions unfavourable for widespread phosphogenesis and only then where intense nutrient upwelling and warm climates allow. During more favourable ocean conditions giant phosphorite deposits could form at low latitudes and even at higher latitudes near the theoretical limits of phosphogenesis and in nutrient-rich shelf areas unconnected with upwelling small amounts of deposition in the form of francolite concretions (associated with glauconite) was possible.

6. The occurrence of authigenic phosphorite concretions in the southern North Sea Tertiary is cyclical. The cyclicity is similar to that seen on a global scale, so local sedimentary and basin-wide factors such as volcanic activity must be of minor importance in controlling phosphogenesis in the southern North Sea.

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