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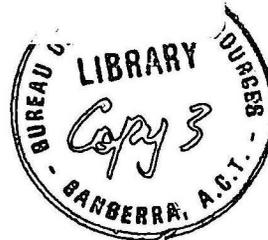
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SEDIMENTARY PHOSPHATE DEPOSIT

by

Peter J. Cook

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ABSTRACT

Sedimentary phosphate deposits are widespread and range in age from Precambrian to Recent. Deposits may be classified into geosynclinal (west coast type), platform (east coast type), and weathered or residual; however, such a classification scheme can be somewhat misleading as many deposits show characteristics of more than one class. Sedimentary phosphate ores (phosphorites) are nodular, pelletal (granular), or fine grained (non-pelletal), and are composed primarily of collophane (cryptocrystalline carbonate-fluorapatite), with minor inclusions of biogenic and terrigenous material. Evidence from both modern and ancient phosphorites indicates that many deposits are associated with oceanic upwelling, but the original Kazakov hypothesis of inorganic precipitation is not valid. A biochemical concentration of phosphate takes place in the tests of organisms which on death are incorporated into anoxic bottom sediments. High concentrations of phosphate in pore waters induce phosphatization and phosphate (collophane) precipitation below the sediment/water interface. Subsequent mechanical reworking, particularly winnowing, of the sediments results in upgrading to a phosphorite. Some shallow-water non-pelletal phosphorites are believed to have been subjected to supergene processes during their formation, although phosphate-rich interstitial waters are also believed to be a major feature in their formation.

INTRODUCTION

Phosphate ore comes from three main sources: igneous apatite accumulations such as those associated with the nephelene syenites and carbonatites of southern Africa and the Kola Peninsula (Fiveg, 1937; Deans, 1966, 1968), guano-derived deposits such as those of Nauru and Christmas Island (White and Warin, 1964), and marine sedimentary phosphate deposits. Only the sedimentary deposits will be considered here. They are known to occur on every continent except Antarctica (Fig. 1), and range in age from Precambrian to Recent.

Because of their economic importance (they contribute more than 80 percent of the world's production of phosphate rock) they have been the subject of numerous studies, and an extensive literature has developed on them. In this brief review article only the more important aspects of the geology of marine sedimentary phosphate deposits are mentioned and the major references cited. Outstanding publications to which the readers' attention is particularly directed include that on the Asian deposits by Bushinski (1969a), the papers on phosphate ores in the United Nations volume 'Mineral Resources Development Series No. 32', the series of United States Geological Survey Professional Papers (313A-F) on the Western Phosphate Field, and the world survey of phosphate deposits by the British Sulphur Corporation (1971).

The general term 'phosphate' is used to describe phosphate-rich sedimentary rocks. Most phosphorites are of marine origin or result from the weathering of marine deposits. A few deposits such as those of the Green River Formation of the Western United States (Love, 1964) are of lacustrine origin. Such non-marine occurrences are not however of economic interest, and consequently this discussion

will be directly primarily towards marine phosphorites.

The phosphate content of a rock is generally expressed as percentage P_2O_5 and this practice is followed exclusively in this paper. Alternative units which are commonly used by mining companies are BPL (bone phosphate of lime or tricalcium phosphate) where $BPL = 2.185 \times \% P_2O_5$, and elemental phosphorus where $P = 0.436 \times P_2O_5$. The grade of phosphate rock which may be economically mined depends on mining, transportation, and beneficiation costs. In some areas such as the Western Phosphate Field, it is possible to selectively mine beds with a P_2O_5 content in excess of 30 percent. Elsewhere, such as at the Lee Creek mine of North Carolina, the ore averages less than 15 percent P_2O_5 . The thickness of minable units is also highly variable depending on location and the mining methods used. In some deposits it is necessary to selectively mine units a metre or less thick; in others the minable unit is 10 metres or more thick.

Stratigraphic columns through some of the world's major phosphate deposits are given in Figure 2, and from this a wide range of ore thicknesses is evident. Some of the phosphatic beds are lenticular over distances of a few metres; others are extremely uniform in lithology and thickness over hundreds of square kilometres.

The phosphate ore is generally pelletal or nodular, though in a few deposits the ore is clay-size material. Individual deposits may range in area from a few to hundreds of square kilometres. Reserves similarly vary from small deposits containing a few million tonnes of ore which are worked, sometimes by fairly primitive methods, for local consumption, to others which contain reserves of several billion tonnes.

The 'diluent' (non-phosphatic matrix and thin interbeds) and associated sediments are also rather variable. They include mudstone and shale (e.g. southeast Idaho), chert (e.g. northeast Utah; Karatau), limestone and dolomite (e.g. northwest Queensland), and sand and sandstone (e.g. central Florida). The occurrence of some of these sediments is illustrated in Figure 2. Regional stratigraphic studies have revealed that the phosphatic sequences grade into synchronous non-phosphatic sediments. The phosphorites of northwest Queensland grade into limestone and massive dolomite. The phosphorites of the Western Phosphate Field grade into carbonates then redbeds and evaporites (Fig. 3). The Karatau deposits grade into massive chert sequences.

It is clear from this brief introduction that phosphorites are a highly variable group of sediments which are difficult to deal with adequately in a short paper. In the subsequent discussion I shall consider the distribution of phosphate deposits (in space and time, the types of deposits, their petrology and geochemistry, and the various theories for their origin.

DISTRIBUTION OF PHOSPHATE DEPOSITS

Attempts have been made to show that there is a worldwide cyclicity in the deposition of phosphate. Strakhov (1969) has suggested that worldwide phosphate maxima occur in the Late Cretaceous-Early Tertiary, the Permian, and the early Cambrian. Maxima have also been suggested for the Sinian (Riphean) and the Proterozoic. However the Sinian and the Proterozoic are each periods of about 1000 m.y. - considerably in excess of the Phanerozoic. Consequently to assert that there is a phosphate maximum in the Sinian and then to compare that to a maximum in the Permian (a period of about 40 million years) is rather misleading. Bushinski (1969b) disputes that there are any worldwide maxima; he suggests that phosphate accumulates in response to localized phenomena.

Although there is considerable doubt about the existence of worldwide peaks in phosphate deposition there is no doubt that phosphorites have been deposited in extensive phosphogenic provinces at particular times. Some of these provinces are evident from Figure 1. They include: 1) The Late Precambrian province of central and southeast Asia. 2) The Cambrian province of central and southeast Asia, extending into northern Australia. 3) The Permian province of North America. 4) The Jurassic-Lower Cretaceous eastern European province. 5) The Upper Cretaceous-Eocene Tethyan province of the Middle East and North Africa, extending into West Africa and the northern part of South America. 6) The Miocene province of southeastern North America.

These provinces extend for several thousand kilometres; their original extent is uncertain owing to the questionable nature of some (particularly Palaeozoic and older) continental reconstructions. There

are also commonly several different types of phosphorite deposits within a single province. Consequently although the common factor of abundant phosphate may be present throughout, the genetic processes that concentrated the phosphate in the sediments varies from one deposit to the next.

Phosphate-rich sediments are present on modern continental shelves (Fig. 1) off southwest Africa (Summerhayes et al., 1973), northwest Africa (Tooms and Summerhayes, 1968; Summerhayes et al., 1972) the southeastern United States (Pevear and Pilkey, 1966), southern California (Dietz, Emery and Shepard, 1942; d'Anglejan, 1967; Pasho, 1972), northern South America (Veeh, Burnett and Souter, 1973), eastern Australia (von der Borch, 1970; Marshall, 1971), and eastern New Zealand (Reed and Hornibrook, 1952). Most contain Tertiary fossils; initially these were considered to be reworked from older units but uranium series dating by Kolodny (1969) and Kolodny and Kaplan (1970) indicated that none of these deposits were less than one million years old. However, Baturin, Merkulova and Chalov (1972) and Veeh, Burnett and Soutar (1973) have shown that two phosphorites are forming at the present day on the southwest African and Peruvian Shelves. Both these localities will be discussed in detail later, but it is important to note at this stage that these two occurrences are on the shelf or the upper slope adjacent to arid regions and in areas with a high organic productivity.

TYPES OF PHOSPHATE DEPOSITS

No two phosphate deposits are precisely the same, but nevertheless a number of common features may be used as the basis for a classification scheme. Bates (1960) has suggested a descriptive phosphorite classification into (i) dark compact and fine grained; interbedded with mudstone or limestone (ii) light coloured nodular beds in a sandy matrix (iii) residual. However, the most widely used 3-fold classification is:

1. Geosynclinal or West Coast type (e.g. The Western Phosphate Field of the United States)
2. Platform or East Coast type (e.g. the North Carolina deposits)
3. Weathered or residual type (e.g. the brown rock deposits of Tennessee)

An additional category of 'foredeep' has also been suggested (Delegation of the Soviet Union, 1968); the Sayan deposit of central Asia is regarded as an example of this type. However, the foredeep type would seem to be merely a particular type of geosynclinal deposit.

The difficulty with this classification is that deposits commonly have characteristics of more than one type. In addition there are genetic implications in the terms, which are undesirable in many instances. For this reason, perhaps the non-generic terms 'West Coast' and 'East Coast' are preferable if they are taken to mean 'Phosphoria-type' and 'North Carolina-type' deposits. The palaeogeographic use of west and east is, however, totally untenable. In addition the use of terms such as engeosyncline and miogeosyncline have somewhat uncertain status (see Wyllie, 1973) in view of our new understanding of global tectonics. However, as these terms are in general used in the classification of phosphate deposits they will be used here. The characteristics of the three major types of deposits will now be considered briefly:

'Geosynclinal' phosphorites

Two types of geosynclinal deposits are distinguished - eugeosynclinal and miogeosynclinal. The eugeosynclinal deposits tend to be relatively small and are commonly associated with thick volcanogenic sequences. They are generally uneconomic although those of eastern Sayan and central Tien-Shan in central Asia contain up to 200 million tonnes of medium-grade ore.

The miogeosynclinal deposits are of much greater importance economically, with ore reserves in the order of billions of tonnes. Deposits such as those of Karatau in the U.S.S.R. and the Western Phosphate Field of the U.S.A. are important examples of this type of deposits. These deposits are characterized by a common association with chert, fine organic-rich argillaceous sediments, and carbonates (particularly dolomite). The phosphorites tend to be pelletal and commonly extend over hundreds to thousands of square kilometres, with a high P_2O_5 content throughout. Severe folding and faulting of the deposits is common.

'Platform' phosphorites

As implied by the name, these phosphorites are generally on, or bordering, cratons. Deposits commonly occur as rich discrete pockets covering tens to hundreds of square kilometres, and several metres thick, such as the Pamlico Sound deposit of North Carolina or the Mishash deposits of Israel. Alternatively they occur as thin low-grade nodular deposits covering many thousands of square kilometres as in the Mesozoic deposits of the Moscow Basin of U.S.S.R. or the Ordovician deposits of central Australia. Both types of platform deposits are commonly associated with terrigenous sediments such as quartz siltstone and sandstone or

with carbonates. Glauconite is abundant in some deposits; phosphatized coquinas are common in others (e.g. the Baltic deposits) shallow-water features such as cross-bedding and scour structures are present in some. The main differences between the geosynclinal and platform-type phosphorites are summarized in Table 1. Despite all these differences, it is perhaps necessary to stress again the difficulty in placing some deposits into one or other of these categories. The Cambrian phosphate deposits of northern Australia have attributes of both, such as an abundance of chert interbeds, but also, features such as coquinas and cross-bedding are common.

Weathered and residual phosphorites

Post-depositional modification of phosphate-bearing sediments is a feature of many deposits. This is particularly the case with platform (eastcoast) deposits which commonly have never been buried by more than a few hundred metres of sediment, and in many instances have been subjected to weathering for prolonged periods. Concentration of phosphate can occur as a result of chemical or mechanical weathering. Chemical weathering may produce a high-grade phosphorite by the leaching-out of a more soluble (generally calcareous) non-phosphatic matrix to leave a residual phosphorite such as the Tennessee brown rock deposits. Alternatively the phosphate goes into solution and is then reprecipitated within the weathering profile; the Tennessee white rock deposits are an example of this type (Collette, 1968). In some cases the phosphate-rich solutions phosphatize pre-existing carbonate rocks. The processes of solution, redeposition, and replacement commonly occur in the same deposit.

Mechanical reworking of phosphorite commonly follows chemical leaching which either removes the matrix completely or alternatively makes it softer and thus more readily reworked. Probably the best known

example of a reworked deposit is the Pliocene Bone Valley Formation of Florida in which the phosphatic material is derived from the Miocene Hawthorn Formation. Reworked deposits of this type are commonly pebbly and nodular and are generally mixed with coarse cross-bedded quartzose sands. They are typically lenticular and infill depressions in the underlying unit. Where the phosphorite has been derived from a calcareous unit the erosion surface at the top of the carbonate may be karst-like.

PETROLOGY OF PHOSPHORITES

Most phosphorites are composed of collophane, a cryptocrystalline carbonate-fluorapatite. Some phosphorites are made up predominantly of pellets of crandallite (an aluminium phosphate) but this is believed to be a secondary weathering product after collophane. The form of the collophane making up phosphorites is highly varied and several authors have discussed their morphology in detail (Bushinski, 1935; Weaver, 1955; Emigh, 1958; Gulbrandsen, 1960; Weaver, 1955; Mabie and Hess, 1964; Trueman, 1971; Cook, 1972). Many classification schemes have been suggested, but marine phosphorites have three basic forms:

(a) phosphatic nodules (Fig. 4) (b) phosphatic grains and pellets (Fig. 5)
(c) fine-grained non-pelletal (predominantly clay-size) structureless phosphorite (Figs. 6 & 7).

Although this is a grain-size classification scheme there are believed to be significant differences in the genesis of these three types. The boundary between a phosphatic pellet and a phosphatic nodule may conveniently be taken as 2 mm, which corresponds to the sand/gravel boundary.

Phosphatic nodules

Phosphate nodules range up to several centimetres in diameter; they have a characteristically irregular external surface with many re-entrant faces (Fig. 4). Some of the larger nodules are flat; others grade into pavement-like and encrusting forms. Iron-rich or manganese-rich coatings are common, and a glazed, polished appearance is typical of many of the nodular phosphorites described from the present-day continental shelves (Murray and Reynard, 1891; Dietz, Emery and Shepard, 1942; von der Borch, 1970; Pasho, 1972).

The internal structure of nodules is rather variable. Some are comparatively homogeneous and are composed predominantly of structureless collophane or alternatively silt and clay-size terrigenous material in a collophane matrix. Others are layered, and some concentrically banded which has been ascribed to accretion or post-depositional weathering. Many nodules are composed of smaller nodules or angular fragments, and have a conglomeratic or brecciated texture. Phosphatic grains and pellets are common in many nodules; Pasho (1972) found that nodules from off southern California contain, on average, 12 percent pellets. Sharks' teeth and other fossil fragments are present in some nodules, and some exhibit infaunal burrowing.

Nodular phosphorites are most abundant in platform-type deposits such as those of the Moscow Basin, and in residual deposits such as those of the Bone Valley Formation of Florida. Phosphatic nodules are also a relict feature of many disconformity and unconformity surfaces.

Phosphatic grains and pellets

Phosphatic pellets are generally well rounded, with a spherical

to ellipsoidal form. Where the phosphatic material is angular, as is the case with some phosphatized fossil fragments, then the term grain is perhaps preferable to pellet. Inclusions in phosphate pellets may include silt-size detrital grains, clay minerals, fossils and fossil fragments, glauconite, pyrite, and organic matter. The abundant organic matter commonly imparts a black or dark brown color to unweathered pellets. Pelletal phosphorites are abundant in both geosynclinal and platform deposits (Fig. 5). The most comprehensive classification of pelletal phosphorites is by Mabie and Hess (1964) who describe more than 30 different textures in phosphate ores of the Western Phosphate Field. A modified version of their classification is used here.

Ovule

This is the commonest type of pellet in most phosphorites; more than 70 percent of all the phosphatic material in the Meade Peak Member of the Phosphoria Formation is ovular. Pellets of this type have a round or subround outline and generally show no internal structure (Fig. 8). In some instances, weathering may produce a pseudo-oolitic appearance due to the marginal leaching of dark organic material (Fig. 9). The pellets of the Phosphoria Formation range in size from .10 to 50 and have a mean diameter of about 10.

Nucleated pellet

This pellet type consists of a nucleus of a single fossil fragment or detrital grain, around which precipitation of phosphatic material has taken place (Fig. 10). This appears to be a comparatively rare pellet type in most deposits. In some nucleated pellets 'ghosts' of fossil fragments may represent nucleus material which has been phosphatized.

Polynucleated pellet

As implied by the name, the nucleus of this pellet type consists of two or more detrital grains or fossil fragments. Many of these pellets form in much the same way as the nucleated pellets except that the pellet formed around a multiple nucleus. Others are believed to be of intraclastic origin as there are abundant detrital grains scattered throughout the pellet. They probably formed when a lamina cemented by the interstitial precipitation of phosphate became torn up and rounded to give a pelletal form.

Compound pellet

This pellet is composed of two or more pellets or fragments of pellets. An intraclastic origin is indicated where pellets are broken.

Commonly the pellets appear to have been cemented together; further accretion then occurred in the form of an outer skin around the multiple pellet. (Fig. 11). This type of pellet can perhaps be compared with grapestone in calcareous sediment. In the Permian phosphorites of the Western United States this type of pellet forms less than two percent of the total phosphatic components.

Oolith

Oolitic pellets are concentrically banded throughout; elongate included particles such as sponge spicules or mica flakes are concentrically aligned. (Fig. 12) Ooliths are rarer in phosphorites than is commonly realized; in the Phosphoria phosphorites, ooliths represent only three percent of the total phosphate fraction. Ooliths may form by a 'snowball' effect: gentle agitation of pellets resulting in rolling and the incorporation of phosphatic and other material in the outer skin of the pellet.

Phosphatic fossil fragments

Phosphatized fossil fragments (or in some cases, fragments of originally phosphatic shells) form a significant proportion of some deposits. The Ordovician platform phosphorites of the Baltic region, for instance, are composed primarily of a phosphatic granular coquina mainly of phosphatic brachiopod shells (Delegation of the Soviet Union, 1968). Some of the phosphorite layers in the Cambrian deposits of north-eastern Australia are composed of pellets of rounded phosphatized fragments of pelmatozoans (de Keyser and Cook, 1972). Some units such as the Fish Scale Marker Bed of the Permian Meade Peak Member comprise a fossil hash in which there is little or no rounding of the phosphatic bone and shell fragments.

Non-pelletal phosphate

This rock consists essentially of dense light-coloured structureless collophane; some forms are bedded (Fig. 6), others are encrusting on siliceous or calcareous sediments. Features such as veins and encrustations of iron and manganese oxides are common in some forms (Fig. 6). A variety of terms have been coined to describe this type of occurrence; Freas (1964); and Freas and Riggs (1968) suggested the term 'microsporite'; Trueman (1971) used the term 'collophane mudstone'. The writer (Cook, 1972) has suggested the term phospholutite (analogous to calcilutite) to describe primary deposits of this type and the term 'phoscrete' (analogous to calcrete) for secondary phosphatic deposits of supergene origin. An excellent petrological description of non-pelletal phosphorites is given by Trueman (1971) who makes the observation that this variety of phosphorite is relatively more abundant in Precambrian than in Phanerozoic deposits. In the Phanerozoic, it is more abundant in the platform than the geosynclinal-type deposits.

There are at least two major types of non-pelletal phosphorites, the primary and the secondary deposits. The primary deposits are laminate to thinly bedded, and contain included silt and clay-size terrigenous material and rare phosphate pellets. In places they are interbedded with pelletal phosphorites. Riggs (1967) discusses phosphorites of this type (microsphorite) from the Noralyn Mine of central Florida and describes abundant evidence of burrowing by organisms and the development of penecontemporaneous breccias. He found most deposits were on ancient topographic mounds, and considers that the depositional environment was intertidal. Howard and Cooney (1974) have also described primary non-pelletal phosphorite (collophane mudstone) from the Cambrian D-Tree deposit of the Georgina Basin. These phosphorites are also laminate to thin bedded and contain terrigenous non-phosphatic material; interbeds of coquinite are present and some botryoidal surfaces may be of algal origin. In thin section there is little or no internal structure, but examination of material from the Lady Annie deposits by scanning electron microscopy has shown that the phosphatic material occurs as fine acicular crystals, radially arranged in places, with no evidence of abrasion of any of the apatite crystallites.

The non-pelletal phosphorites of secondary origin are similar to (and in some instances indistinguishable from) those of primary origin. Staining by iron and manganese, the highly irregular nature of the laminations, and the presence of solution features such as stylolites and geodes, are common. De Keyser and Cook (1972) used the term 'phoscrete' for this phosphorite in the Georgina Basin and considered that the majority of such deposits were the result of supergene enrichment and replacement, much of it of Cainozoic age. More recent work by Howard and Cooney (1974) has shown that most of these deposits are of Cambrian age and they suggest

the term 'hardrock phosphorite'. Thin sections commonly show no distinguishing features whatsoever, but in some places a replacement origin is indicated by pseudomorphs after dolomite or replaced algal remains. Such evidence is lacking in some units and the rock is composed primarily of coarse hexagonal apatite crystals with no replacement textures. This type of phosphorite may be a supergene precipitate or in some instances an early precipitate, interstitial precipitation having taken place below the sediment/water interface.

GEOCHEMISTRY OF PHOSPHORITES

Most phosphorites are composed of cryptocrystalline carbonate-fluorapatite, which may be represented by the formula $\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{CO}_3)$. In common with other members of the apatite group of minerals many substitutions are possible in carbonate-fluorapatite. This topic has been the subject of a large number of publications; excellent reviews are given by Jaffe (1951) and McConnell (1973). Gulbrandsen (1966), Smith and Lehr (1966), and Tooms, Summerhayes and Crohnan (1969) discuss the geochemistry of phosphorites in particular.

Substitutions of both the simple and the coupled type are possible for Ca, P (or PO_4), and F. As phosphorites are seldom (if ever) composed of pure carbonate fluorapatite, some of the suggested substitutions are difficult to prove or disprove. Some of these substitutions are potentially of economic interest; because many trace elements are present in higher than normal concentrations in phosphates (Table 2) eventually uranium and rare earths and perhaps other trace elements may be extracted on a commercial scale from phosphorite. Substitution for Ca^{2+} in the apatite lattice is particularly common; rare earths (RE^{3+}) are known to readily

substitute for Ca^{2+} . The ionic radius of Na^+ is also similar to that of Ca^{2+} and consequently it too is readily admitted into the lattice. Both Gulbrandsen (1966) and Smirnov (1958) have found high sodium values in phosphorites. Other substitutions which have been suggested for calcium include Sr^{2+} , K^{1+} , Mg^{2+} , Ba^{2+} , Al^{3+} , Fe^{2+} and Mn^{2+} .

Substitution of uranium in the apatite lattice has been studied in some detail by Altschuler, Clarke and Young (1958) and Sheldon (1959) because of the potential that phosphorites have as a source of uranium (Tooms et al. (1969) record an average content of 190 ppm of uranium in phosphorite). The actual location of the uranium ion is somewhat uncertain; some capture of U^{4+} (radius of 0.97 Å) by Ca^{2+} (radius of 0.99 Å) may reasonably be expected. However McConnell (1973) points out that both U^{4+} and U^{6+} are present in phosphorites and suggests that substitution of UO_4^{2-} may take place, comparable with the substitution of AlO_4^{5-} in apatite. Other substitutions in the phosphate ion which have been suggested include ionic forms of vanadium, arsenic, silicon (either as a coupled Si-S substitution for P, or alternatively as coupled Si-P and Na-Ca substitutions), manganese, and chromium. McConnell and Foreman (1966) have also suggested that in some circumstances the H_4O_4 group (tetrahedral hydroxyls) will substitute for the $(\text{PO}_4)^{3-}$ ion.

Substitution for fluorine is an important feature of sedimentary apatites. Deer, Howie and Zussman (1962) assert 'Fluorine, chlorine and hydroxyl ions can mutually replace each other to form the almost pure end members fluorapatite, chlorapatite and hydroxylapatite and it appears probable that there is a complete isomorphous series in natural apatites'.

In fact, the hydroxylapatite unit cell is slightly larger (and less stable) than fluorapatite; a natural primary precipitate of hydroxylapatite (such as bone) is rapidly converted to fluorapatite in an open system. Despite the fact that the marine environment in which phosphorites normally form has a considerable excess of Cl^- ions over F^- ions (the ratio is in the order of 8000:1), chlorapatite is seldom, if ever, formed in the marine environment. This may be because of the structural difficulty in substituting Cl^- with a radius of 1.81 Å into the comparatively restricted position in the hexagonal channel normally occupied by F^- , with an ionic radius of 1.36 Å.

The location of carbonate in the apatite lattice has been the subject of much discussion. Hendricks (1952) and Carlstrom (1955) claimed that the carbonate is present outside the apatite lattice, as adsorbed cryptocrystalline or amorphous calcite. However, more recent work by Ames (1959), McConnell (1960), and Kolodny and Kaplan (1970) clearly indicates that the carbonate is within the lattice. The nature of this lattice substitution has still not been finally settled, but the most plausible suggestion is perhaps that made by Gulbrandsen et al. (1966), of a CO_3 -F substitution for PO_4 . This would seem to be a reasonable way of achieving substitution of a trigonal for a tetragonal complex.

In addition to substitution of elements directly into the apatite structure a further mode of occurrence is either by adsorption or the formation of metallic complexes with the abundant organic material which is commonly associated with phosphorites. Tooms et al. (1969, p. 65) conclude 'The ability of organisms to concentrate minor elements

from seawater is not particularly effective in causing major differences to arise between elemental abundances in phosphorites and those in seawater'. They do not, however, offer any compelling evidence in support of this statement. Conversely there is a considerable amount of data (Krauskopf, 1955; Trudinger, this volume) indicating that organisms are indeed able to concentrate some trace-elements to a very high degree. Gulbrandsen (1966) concludes from his work on the Phosphoria phosphorites that several elements such as arsenic and antimony are associated with the organic material in phosphorite. Thus although phosphorites undoubtedly show some marked elemental concentrations, the location of many of these elements is still uncertain.

A geochemical question remaining is the nature of the organic matter in the phosphorites. This is important not only because of the influence it may have on the trace element composition of the phosphorites but also because phosphorites constitute potential source rocks for petroleum. Both McKelvey (1959) and Barbat (1967) have suggested that some of the world's major oil fields have phosphatic source rocks. Work by Powell, Cook and McKirdy (1974) has shown that although phosphorites commonly do not have an excessively high concentration of organic matter, a very considerable proportion of this organic matter is in the form of readily extractable hydrocarbons, and consequently phosphorites do constitute potentially important petroleum source rocks.

THE GENESIS OF PHOSPHORITES

Four fundamental questions may be asked about all sedimentary phosphate deposits:

(1) What was the source of the phosphate? (2) Was the collophane an organic or an inorganic precipitate? (3) Was the collophane a primary deposit or was it formed by post-depositional phosphatization of pre-existing sediments? (4) What were the depositional conditions under which phosphorites formed? Some of these questions are of course inter-related.

In the marine environment, above-average concentrations of phosphate can occur in association with volcanic exhalations, estuarine waters, cold surface currents, and upwelling currents. Although biological production might be regarded as an additional source of phosphate it is not considered as such here; high biological production is merely a result of a pre-existing abundance of phosphate (and other nutrients) and as such is the result rather than the cause of high phosphorous concentrations in seawater.

A volcanogenic origin has been suggested for a number of deposits. Mansfield (1940) considered that fluorine played a vital role in the precipitation of phosphate and suggested that there is a correlation between times of volcanism (when fluorine-rich gases are common) and phosphate deposition. Bidaut (1953) also attributes the Dinantian phosphorites of the Pyrenees to the action of submarine fumeroles rich in fluorine. However, as pointed out by Kazakov (1950) there is in fact no fluorine problem, for the amount of fluorine in seawater is very much greater (in proportion to PO_4) than is needed for carbonate fluorapatite. Rooney and Kerr (1967) found that the zeolite clinoptilolite is ubiquitous in the phosphorites of North Carolina. They conclude from this that volcanism played a major role in the formation of these deposits and suggest that 'Ash falls of long duration killed large numbers of marine organism whose subsequent decay contributed phosphate'.

However, as pointed out by Cathcart (1968) clinoptilolite is a comparatively minor component, forming only 0-5 percent of the total sediment. Consequently there is no compelling evidence to indicate a significant volcanic association in any of the major sedimentary phosphate deposits.

Rivers are known to carry abundant phosphate in solution and consequently are capable of directly supplying much of the phosphate present in phosphorites. Pevear (1966) has suggested that the Cainozoic phosphorites of the eastern United States are of estuarine origin. Bushinski (1964, 1969b) considers that one large river was capable of supplying all the phosphate present in the Phosphoria Formation. Such a river would build up a large delta and Bushinsk suggests that the Shedhorn Sandstone (Fig. 3) is a fluvatile sand. The Shedhorn Sandstone is, however, a blanket-type body of clean well-sorted sandstone which appears to have few affinities with most deltaic sediments; it is considered by Sheldon, Maughan, and Cressman (1967) to be the result of the build-up of offshore bars and barrier islands. Recent investigations by Cook and Mayo (1974) into the distribution of phosphorus in the water and sediments of a tropical estuary have shown that the phosphate concentration in estuarine waters is not necessarily the most important factor. A greater degree of phosphatization of sediments occurs in areas of very low phosphate concentration in the surface water but a slow rate of sedimentation, than in areas of very high phosphate concentration but rapid sedimentation. This points out the major difficulty in postulating an estuarine source for the phosphate in phosphorites, namely, that there is generally a high rate of sedimentation in estuaries and that this will in most cases produce nothing more than a very slightly phosphatic mud or sand. The organic geochemistry of several phosphorites of wide geographic distribution

and ranging in age from Precambrian to Cenozoic was examined by Powell et al. (1974). They found evidence (from the odd-even distribution of the n-alkanes) of land - plant material being the dominant organic component in only the North Carolina deposit. They conclude from this, that there was little to support an estuarine origin for most of the phosphorites they examined. An estuarine source is conceivable only in circumstances where the great bulk of the river sediment is prevented from reaching the estuary. It is unlikely that these conditions operated throughout an extensive phosphogenic province such as the Tethyan Late Cretaceous-Eocene province.

Gold oceanic currents on the other hand affect the phosphate abundance of oceanic zones over considerable distances at the present time. Presumably they occurred in the past though perhaps to a greater or lesser degree, depending on the size of the polar ice caps and ocean/continent configuration. In many areas the distribution and productivity of cold currents cannot be divorced from the presence of upwelling areas. Sheldon (1964) has shown that virtually all important phosphorites were deposited within 40 degrees north or south of the palaeoequator and within this longitudinal range most cold currents are associated with coastal upwelling. Coastal upwelling may occur in response to seaward-moving surface water (divergent upwelling) or the movement of a current over a topographic high (dynamic upwelling) Freas and Eckstrom (1968) have summarized the conditions conducive to upwelling as follows:

1. In situations where ocean currents flow parallel or offshore and are enhanced by strong prevailing winds blowing in the same direction.
2. In situations where ocean currents flow up onto a positive submarine topographic feature.

3. In the belts of trade winds at low latitudes between 0° and 25° .
4. Along the north and west coasts in the northern hemisphere, and the south and west coasts in the southern hemisphere at latitudes between 0° and 25° .
5. Along coasts of land masses with dry climates.
6. Along the coasts in the belt of westerlies approximately between 20° and 40° .
7. In large ocean basins with unrestricted circulations and open connection to polar seas.

As a result of one or more of these conditions cold deep water, rich in phosphate and other nutrients, is brought to the surface. There is strong evidence particularly from the sedimentary facies distribution pattern to suggest that phosphorites of the west coast type such as those of the Phosphoria Formation (Fig. 13) and the Lesser Karatau are associated with large-scale divergent upwelling. Other deposits such as those of Florida and some of the Middle East deposits are clearly associated with topographic highs which are likely to have produced dynamic upwelling. McKelvey et al. (1959) have shown that the mechanism of upwelling is more than adequate to produce the very considerable amount of phosphate in phosphorites. Thus, there are reasonable grounds for regarding upwelling as being the major source of phosphate for many deposits. The greatest difficulty in applying the upwelling hypothesis is for deposits which are obviously of very shallow water origin with a maximum water depth of a few tens of metres. Some such deposits may owe their origin primarily to a fluvial or estuarine source, but these deposits are likely to be of comparatively small areal extent. Small-scale, dynamic upwelling can occur in very shallow depths provided the current is sufficiently strong,

though it is likely to be a very much less potent source of nutrients than deep upwelling currents. Entrainment of bottom waters by seaward-flowing surface waters in estuaries can induce localized upwelling and this mechanism could possibly also act as a further source of phosphate in very shallow water phosphate-rich water upwelling on the edge of the shelf and then being swept across that shelf may be an additional process by which nutrient-abundant conditions can prevail in shallow water.

The question of whether phosphate is incorporated by chemical or biochemical precipitation has not been considered so far. Early workers such as Murray and Reynard (1891), and Mansfield (1918) concluded from the abundance of organic remains in many phosphorites that they were biogenic precipitates. This was disputed by Kazakov (1937) who proposed a model for inorganic precipitation. He suggested that phosphate precipitation will occur in areas of cold upwelling currents; as these currents ascend, the temperature increases, the partial pressure of CO_2 decreases, and there is a commensurate drop in pH. As phosphate solubility varies inversely with pH, this decrease of pH and CO_2 results first in the precipitation of calcite and then apatite. He considered that the precipitation occurs at depths of 50 to 200 metres and that it would not take place within the photosynthetic zone, where any available phosphate would be taken up by phytoplankton. This hypothesis has been widely accepted and successfully applied to explain sedimentary associations in many phosphate deposits. McKelvey, Swanson and Sheldon (1953) used a modified version of Kazakov's hypothesis to explain the juxtaposition of various sedimentary units in the Phosphoria Formation (Fig. 13); they suggested however that calcite is not precipitated before apatite, as

suggested by Kazakov, but after.

Experimental work by Roberson (1966) indicates that seawater in general is supersaturated with phosphate and consequently precipitation should occur quite readily. Smirnov et al. (1962), on the other hand, considered from their experimental work that seawater is slightly undersaturated, but still concluded that removal of CO_2 will precipitate apatite. In recent years, however, increasing doubts have been expressed as to the relevance of these essentially inorganic reactions to a natural system in which there is a prolific biota. For instance, apatitic precipitates analogous to a calcareous 'whiting', have not been proved in areas of upwelling. Gulbrandsen and Roberson (1973), describe a milky white turbidity in the area of high productivity around the Andaman Islands, but no mineralogical identification of this suspension was made. Smirnov et al. (1962) also concluded from their work that the diffusion of CO_2 from upwelling seawater is too slow to produce a significant amount of apatite as an inorganic precipitate. In addition, Bushinski (1966) makes the elementary but important point that any phosphate precipitate would be so fine-grained (as shown by experimental studies) that there would be little possibility of it settling onto the sea floor in areas in which there is any current activity. This view is echoed by Senin (1970) who also notes that if the phosphate was a fine inorganic precipitate it would be associated with the fine pelitic sediments of the shelf, whereas he found the highest phosphate concentrations in the sandy sediments. Senin concludes that the Recent phosphorites off southwest Africa are of biochemical origin because of 'The high biological productivity of this region, the extraordinarily high concentrations [of organic carbon] for bottom sediments.... the significant coprolite content, the high concentrations of P in certain biogene sediments'. Clearly, in upwelling

arews, phytoplankton are likely to be an important biochemical agent. However, Breger (1911) considered the possibility of bacteria as the agent and McConnell (1965) has suggested that enzymes may play an important role. The role of micro-organisms as concentrators of phosphate is discussed in some detail by Trudinger (this volume) and also by Gulbrandsen, (1969). There is no doubt that phytoplankton can concentrate phosphate to a very high degree, but incorporation of phytoplankton in sediments would produce nothing more than a slightly phosphatic organic-rich sediment, and therefore decay and other forms of post-depositional modification are required before a phosphorite can result.

This then brings us to the question of whether the colophane is in fact primary or secondary in origin. Some phosphatic material in phosphorites is obviously of primary origin, such as the rounded fragments of inarticulate brachiopods which make up much of the Ordovician phosphorites of the Baltic region. Other fragments though now phosphatic were originally calcareous; phosphatized pelmatozoan fragments are a common component of some of the Georgina Basin phosphorites. If the inorganic hypothesis of Kazakov is accepted, then pellets and nodules may have formed by accretion of apatite particles as the pellet was rolled by bottom currents. Pellets are also commonly considered to be of faecal origin. Senin (1970) reports that faecal pellets are abundant in phosphatic sediments off southwest Africa, and it is probable that they are equally abundant in many ancient deposits. However, most faecal pellets are originally only slightly phosphatic and would have to undergo further phosphatization after deposition, to give the high phosphate concentrations found in them now.

Because of the similarity between phosphatic and calcitic or aragonitic oolites, Emigh (1958, 1967) suggests that the Phosphoria and

many other pelletal phosphorites had calcareous precursors. Most phosphorites are not, however, oolitic; they are ovular, and the pellets show no indication of calcitic parent material. Cook (1970) has shown that diagenetic phosphatization, calcitization, and silicification will occur readily, probably in response to changes of pH. It follows then that phosphatization can take place at or below the sediment/water interface irrespective of whether the sediment is calcareous or siliceous. Jitts (1959) has shown that bottom muds are capable of absorbing considerable quantities of phosphate. Poncet (1964) has evidence to indicate that phosphatic pellets and nodules in Ordovician sediments in western France are the product of phosphatization of clay pellets. Bushinski (1964) also considers that the phosphatization of mud-size material is important, but he suggests that this phosphatization occurs in situ in the muds and that subsequently the material not cemented by collophane is winnowed out. Cook (1967, 1972) similarly found that winnowing was an important process for upgrading Ordovician sediments in the Amadeus Basin from a slightly phosphatic mud or sand to a phosphorite. Relict bedding is present in some of these Ordovician pellets; such pellets presumably formed by the breaking-up of phosphatic beds, and subsequent abrasion of the clasts to form pellets. The writer has also found that poorly-phosphatic mudstones adjacent to rich phosphorites in the Phosphoria Formation commonly contain small patches of collophane which have not been abraded. Thus, there is evidence from ancient sediments that some of the phosphate pellets are the result of diagenetic processes; conversely, there is little evidence of direct precipitation.

Important information on the origin of phosphorites has been obtained as a result of investigations into the Recent phosphorites off

southwest Africa by Baturin (1969, 1971), Senin (1970), and Romankevich and Baturin (1972). They have shown that precipitation of (and probably replacement by) apatite is taking place at the present day, below the sediment/water interface. Initially the apatite is in form of soft pellets and nodules of gel-like calcium phosphate incorporating phosphatic particles. As lithification proceeds there is a further increase in the phosphate content of the pellets and nodules. Further upgrading occurs as a result of mechanical reworking of these sediments. Baturin (1969) considers that the phosphate concentration in seawater off southwest Africa is insufficient for there to be any significant inorganic precipitation of apatite. In the interstitial waters, on the other hand, phosphate concentrations are ten to a hundred times greater than those in seawater. The writer (Cook, 1974) obtained similar results for sediments in the Timor Trough where P_2O_5 values of up to 26 ppm are present in interstitial waters. In this case, one of the primary controls of phosphate solubility appears to be alkalinity (Fig. 14) rather than pH. This in turn is in part the result of the abundance of organic matter, but other factors may also be important in controlling interstitial alkalinity. Thus, there is now considerable evidence to indicate that collophane may be precipitated below the sediment/water interface, where phosphorus-rich interstitial fluids will phosphatize siliceous oozes, terrigenous clays, fossil fragments, copralites, and calcareous sediments.

So far most of the discussion has been concerned with nodular and pelletal phosphorites, but many of the same chemical or biochemical processes operate in the formation of non-pelletal phosphorites. Pseudomorphs of fine collophane after dolomite have been observed by Trueman (1971) and Cook (1972) and it is evident in such cases that the phosphorite is a

replacement product. Observations on the Georgina Basin phosphorites using scanning electron microscopy indicate that the apatite crystallites are morphologically different in the non-pelletal and pelletal forms. There are also indications that subaerial supergene processes may have been important in the precipitation of some non-pelletal collophane. Whether precipitation is from very shallow surface waters, or from interstitial waters, is uncertain although interstitial precipitation is considered more probable.

It is known that phosphorites are formed predominantly under marine conditions, but their location on the sea-floor, the water depth, and the physico-chemical conditions of their depositional environment are somewhat uncertain. Kazakov (1937) considered that phosphorites form at water depths of 50 to 200 metres. McKelvey et al. (1953) subsequently suggested that phosphorites form at water depths of 200-1000 metres. Krumbein and Garrels (1952) consider that the pH of the environment is of major importance, precipitation of apatite occurring within the pH range of 7.1 to 7.8; Eh on the other hand is regarded as being of little or no significance. Despite this, the abundance of organic material in most pelletal phosphorite suggests a reducing environment. This may, however, only indicate a negative Eh below or just at the sediment/water interface; the overlying waters could conceivably have still been quite strongly oxidizing. In general, phosphorites are believed to have been deposited under conditions of near-normal marine salinity. Areas flanking the region of phosphate deposition, however, were commonly hypersaline. The phosphorites of the Phosphoria Formation grade laterally into carbonates of the Park City Formation, then redbeds and evaporites of the Chugwater Formation (Figs. 3, 13).

The modern phosphorites off southwest Africa are being deposited on the inner shelf in water depths of 50 to 150 metres, which is within the euphotic zone. Senin (op. cit.) found that this depth corresponds closely to the change in the water column (and the bottom sediments) from oxidizing to reducing. Romankevich and Baturin (1972) record redox conditions down to -233 millivolts in the sediments; therefore anaerobic conditions obviously predominate there. Flanking these phosphorites is the arid hinterland of the Namib coastal desert where saline coastal lagoons are common, a situation apparently analogous to, for instance, the landward equivalents of the Phosphoria Formation. Similarly, the phosphorites of the Peruvian shelf have an arid hinterland (the Sechura Desert). Baturin (1971) notes that several sea-level changes have occurred during the Quaternary and that considerable reworking of shelf sediments has taken place. As a consequence of the removal of fine material the phosphorites have been upgraded on both the Peruvian and southwest African shelves. Little information is available on the Peruvian phosphorites to date although again they are situated in an area characterized by strong upwelling and extremely high organic productivity. Veeh et al. (1973) note that the phosphorites occur at water depths ranging from 100 to 400 metres. They also point out that the phosphorites are confined to two narrow bands corresponding to the upper and lower boundaries of an oxygen minimum layer. Sediments of this portion of the shelf are strongly anoxic.

Many of the features of the depositional environment evident in modern phosphorites may be found in ancient deposits. Most phosphorites probably formed in shelf environments at water depth considerably less than 500 m. Conditions within the water column were conducive to the

development of a prolific biota, but were strongly reducing at or just below the sediment/water interface. Subsequent mechanical reworking of sediments was a most important feature in the upgrading of phosphatic sediments to phosphorites. Such reworking may have occurred in response to the influx of bottom currents or to relative change in sea level.

Eustatic changes of sea level result from the growth or contraction of icecaps such as have occurred during the Quaternary glacial period. Bushinski (1969a) discusses the possibility of an association between phosphatic sequences and tillites. He concludes that few of the 'tillites' are in fact of glacial origin. Even some of the undoubted glacial deposits (e.g. those of northwest Queensland described by de Keyser, 1972) which underlie phosphatic sequences are in fact separated by extensive time breaks so that the association is more apparent than real. Nevertheless glacial epochs are likely to have been times with wide fluctuations of sea level resulting in extensive reworking of shelf sediments. In addition, upwelling is likely to have been more intense. Consequently, it is possible that glacial epochs may have been a preferred time for the formation of some phosphate deposits.

No extensive non-pelletal phosphorites are known to be forming at the present day; consequently their depositional environment is less certain. The Cambrian non-pelletal deposits of the Georgina Basin have many features which indicated very shallow water and even subaerial conditions. (Cook, 1972; Howard and Cooney, 1974; Howard and Perrino, 1974). The closest comparison which may be drawn with this type of environment in the Cainozoic is the formation of phoscretes as a result of lateritic weathering, and the formation of phosphorites by the phosphatization of coral and other material by phosphate-rich groundwaters

derived from guano deposits. Thus, the comparison of ancient with modern phosphorite is not entirely satisfactory as it seems that some ancient phosphorites have formed in much shallower water than that presently prevailing in modern phosphogenic environments. It is unlikely, however, that any major phosphate deposits have formed in waters much deeper than those off southwest Africa and Peru, i.e. approximately 500 metres.

CONCLUSIONS

1. Phosphorites range in age from Precambrian to Recent and are widespread. No two occurrences are precisely the same but nevertheless a number of common features are evident which may be used as the basis for a three-fold lithogenetic classification into 'geosynclinal', 'platform', and weathered or residual deposits.
2. Phosphorites have a varied petrography comprising phosphate nodules, grains, pellets, and non-pelletal (clay size) material. Oolites are not nearly so abundant as is commonly supposed. Most pellets are ovular. Some pellets are believed to be of intraclastic origin and it is evident that winnowing and reworking are a common feature of many ancient phosphorites. Nodules are common in platform deposits. Non-pelletal phosphorites (microphosphorite etc) are common in the platform and residual deposits.
3. Most phosphorites are composed of collophane - cryptocrystalline carbonate-fluorapatite. Lattice substitution of many trace elements in the apatite is common, but, the nature of some substitutions is uncertain.
4. Association with areas of oceanic upwelling is believed to be an important feature of ancient and modern phosphorites, but extensive revision to the original upwelling hypothesis of Kazakov is necessary as there is no evidence of inorganic precipitation of apatite during upwelling.

5. The genesis of non-pelletal phosphorites (phospholutite, collophane mudstone, microspherite, and phoscrete) is only poorly understood. Some may be comparative deep subaqueous replacement deposits which have never undergone reworking. Most are believed to be the product of very shallow-water or subaerial environments, and are either replacement deposits (particularly replacement of dolomite) or interstitial supergene collophane precipitates.
6. Knowledge of modern and ancient phosphorites indicates the following six-stage genetic scheme to account for the formation of nodular and pelletal phosphorites:
 - (a) Influx of nutrient-rich water, generally by upwelling, into a shallow marine region (maximum water depth 500 m, but commonly considerably less) with a slow rate of terrigenous deposition, and often a warm arid climate.
 - (b) Development of a prolific biota.
 - (c) Formation of anoxic organic-rich bottom sediments; loss of C, N, and H from dead organisms occurs either before or immediately after burial.
 - (d) Interstitial waters rich in phosphorus form below the sediment/water interface by leaching of phosphate from organic remains as a consequence of low pH and high alkalinity in the sediments.
 - (e) Localized patches of apatite develop by phosphatization of sediments in the presence of phosphate-rich pore waters or in some instances by direct precipitation of apatite from the pore waters. Diagenetic phosphatization will take place whether the sediments are clayey, siliceous, or calcareous. Phosphatized faecal pellets are a common feature of some deposits.

- (f) Reworking of sediments occurs in response to changes of current pattern or relative sea level. The coarser patches of phosphatized sediment remain as a lag deposit and the finer matrix is winnowed out, resulting in extensive upgrading of the phosphatic sediments into a high-grade phosphorite.

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TABLE 1

COMPARISON OF PHOSPHATE DEPOSITS

<u>FEATURE</u>	<u>GEOSYNCLINAL OR WEST-COAST TYPE</u>	<u>PLATFORM OR EAST COAST TYPE</u>
1. Phosphorite type	generally pelletal; minor oolitic	pelletal, nodular, and non-pelletal
2. Matrix to pellets	argillaceous or siliceous	quartzose (sandy) or calcareous
3. Grade of the phosphorite	high grade	low grade
4. Nature of the deposit	thick extensive continuous beds	discontinuous beds
5. Fauna	pelagic	shallow water
6. Inferred water depth	hundreds of metres	tens of metres
7. Sediment association	black shale-chert	carbonates-sands
8. Influence of syn-sedimentary structures	generally lacking	deposits commonly in synclines or the flanks of anticlines
9. Tectonics	strongly folded	gently folded

TABLE 2

Trace element concentrations in phosphorites

	(1)	(2)	(3)
Ag	3		4
As	40	21	
B		16	
Ba	100		210
Co		3	6
Cr	1000	285	140
Cu	100	22	48
I		24	
La	300		100
Li			6
Mn	30	428	479
Mo	30	19	4
Ni	100	13	27
Pb			39
Rb			8
Sb	7		
Sc	10		
Se	10	3	
Sn			2
Sr	1000	1900	354
Ti		476	243
U	90	190	78
V	300	167	116
Y	300		610
Zn	300	90	144
Zr	30		

(1) - Phosphoria Formation averages (Gulbrandsen, 1966, tabel 3).

(2) - Worldwide phosphorite averages after Tooms et al. (1969, table 1).

(3) - Georgina Basin averages for pelletal phosphorites (after Cook, 1972, table 3).

FIGURE CAPTIONS

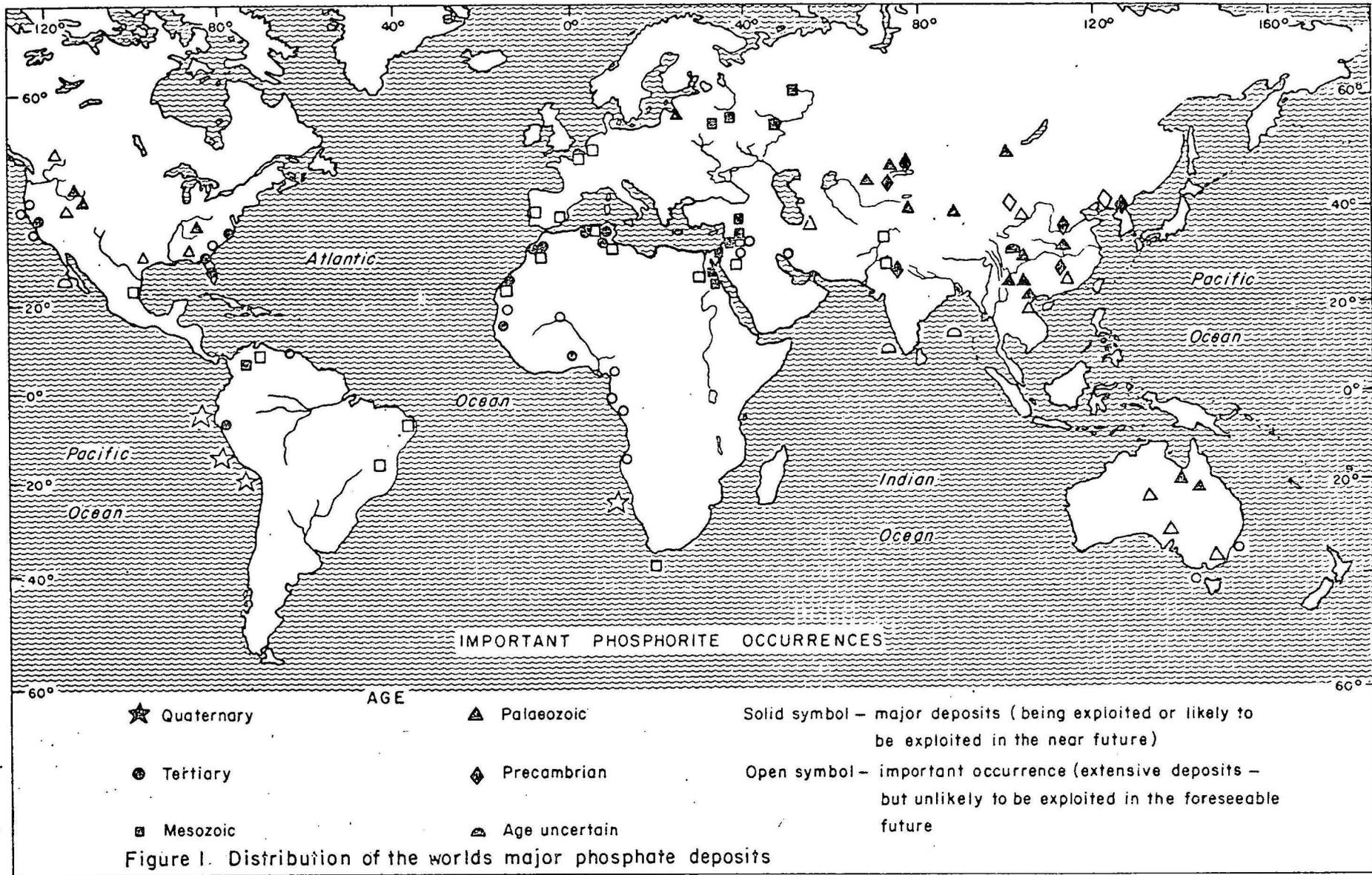
- Figure 1: Distribution of major sedimentary phosphate deposits.
- Figure 2: Stratigraphic columns for some major phosphate deposits.
- Figure 3: Distribution of main sediment types and major rock units in the Western Phosphate Field (after Sheldon, 1963).
- Figure 4: Nodular phosphorite from the Ordovician Stairway Sandstone of central Australia. Scale at the base of the sample is marked in one-inch (2.54 cm) intervals.
- Figure 5: Pelletal phosphorite from the Cambrian Beetle Creek Formation, northwest Queensland. The darker bands are chert; note the micro-troughs infilled with fine pelletal collophane.
- Figure 6: Finely bedded non-pelletal phosphorite from the Late Precambrian Areyonga Formation of central Australia. The darker patches are rounded clasts of chert.
- Figure 7: Structureless collophane (poscrete) from Georgina Basin of northwest Queensland. The dark patch near the margin of the sample is due to manganiferous and ferruginous staining.
- Figure 8: Phosphatic ovule (dark) in a light coloured silty matrix. Sample from the Ordovician Stairway Sandstone of central Australia.
- Figure 9: Pseudo-oolitic ovule with a rim of light coloured collophane from where organic carbon has been removed by oxidation.
- Figure 10: Nucleated pellet with a radiolarian test forming the nucleus. Sample from the Cretaceous deposits of Khourigba, Morocco.

Figure 11: Compound pellet from the Permian Meade Peak Member of the Phosphoria Formation.

Figure 12: Oolith from the Meade Peak Member of the Phosphoria Formation, showing well developed concentric banding.

Figure 13: Schematic representation of the sedimentation pattern in the Permian Phosphoria sea (diagram after Sheldon, 1963).

Figure 14: Plot to show the positive correlation of P_2O_5 content of interstitial waters with alkalinity in Deep Sea Drilling Project Site 262, Timor Trough.



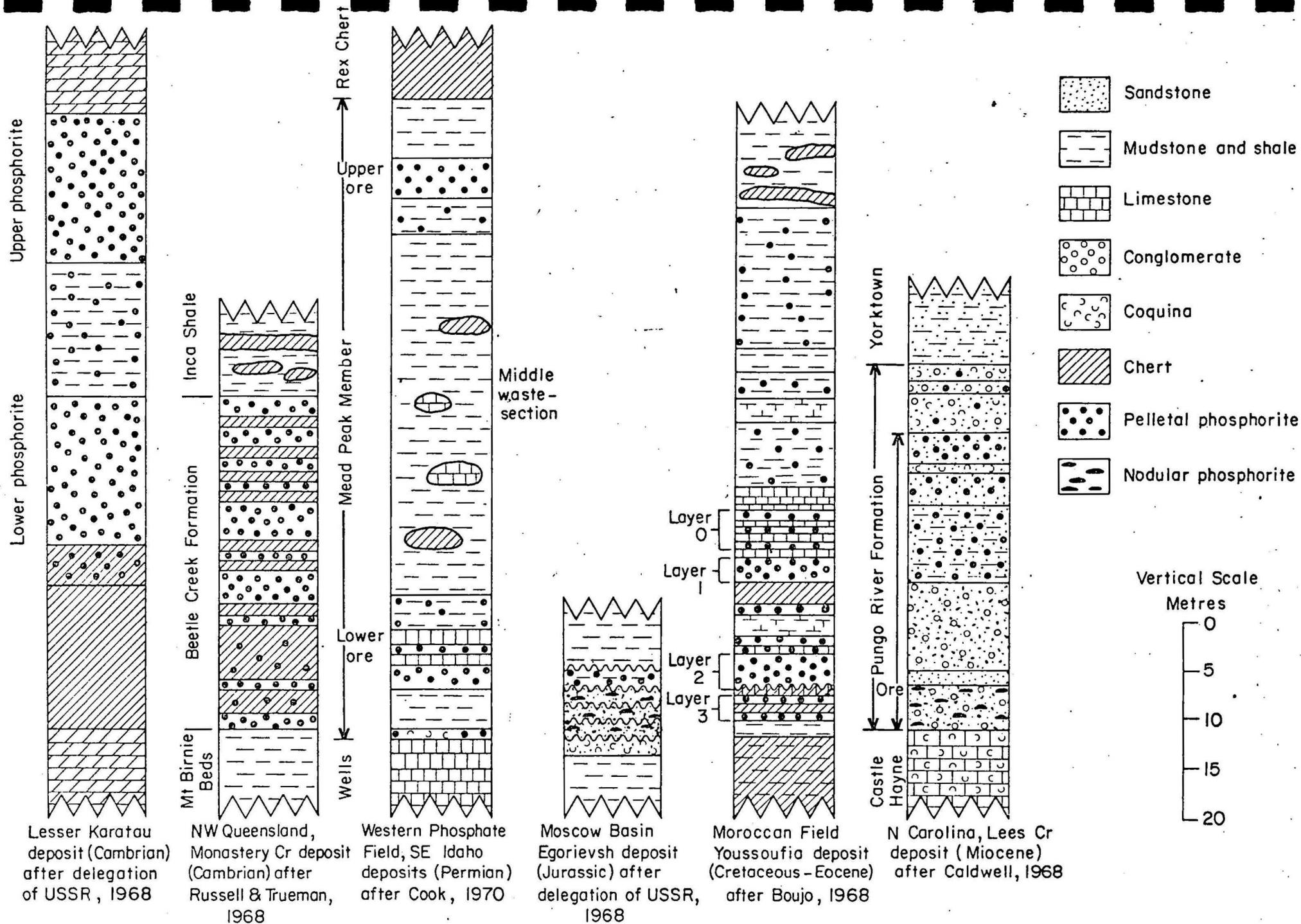
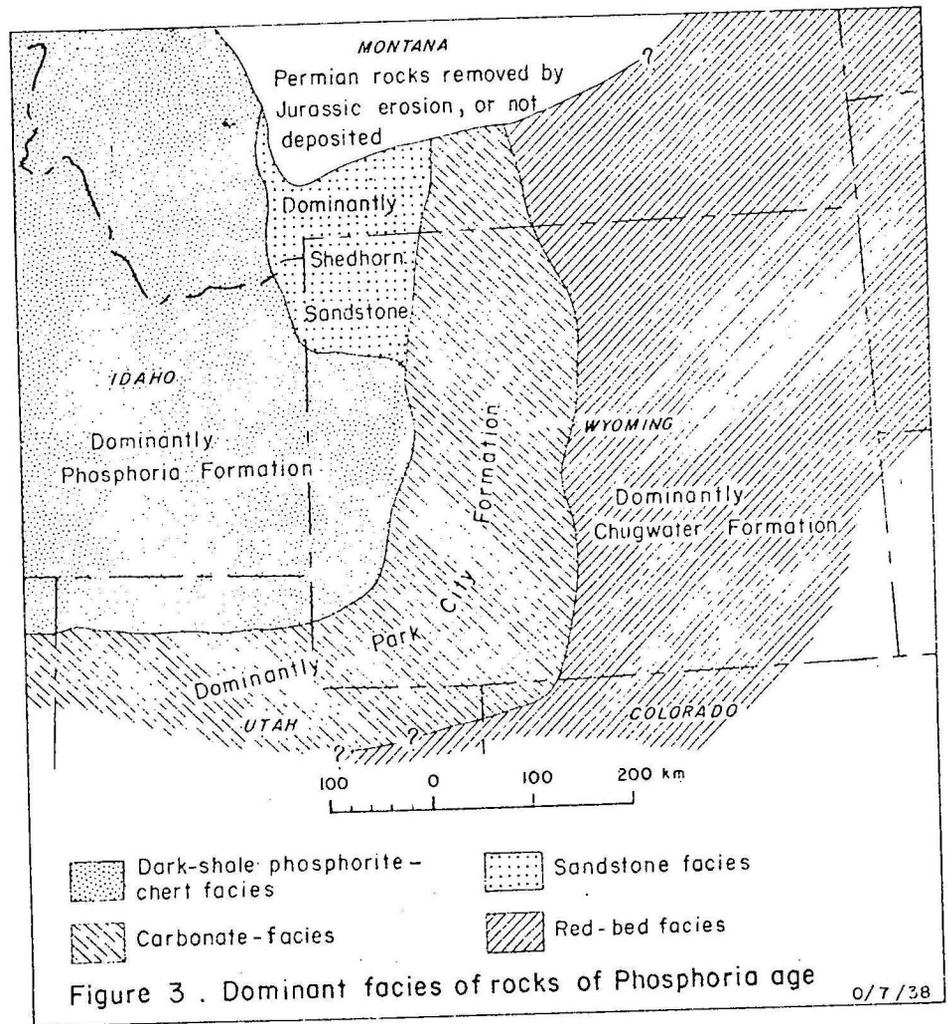
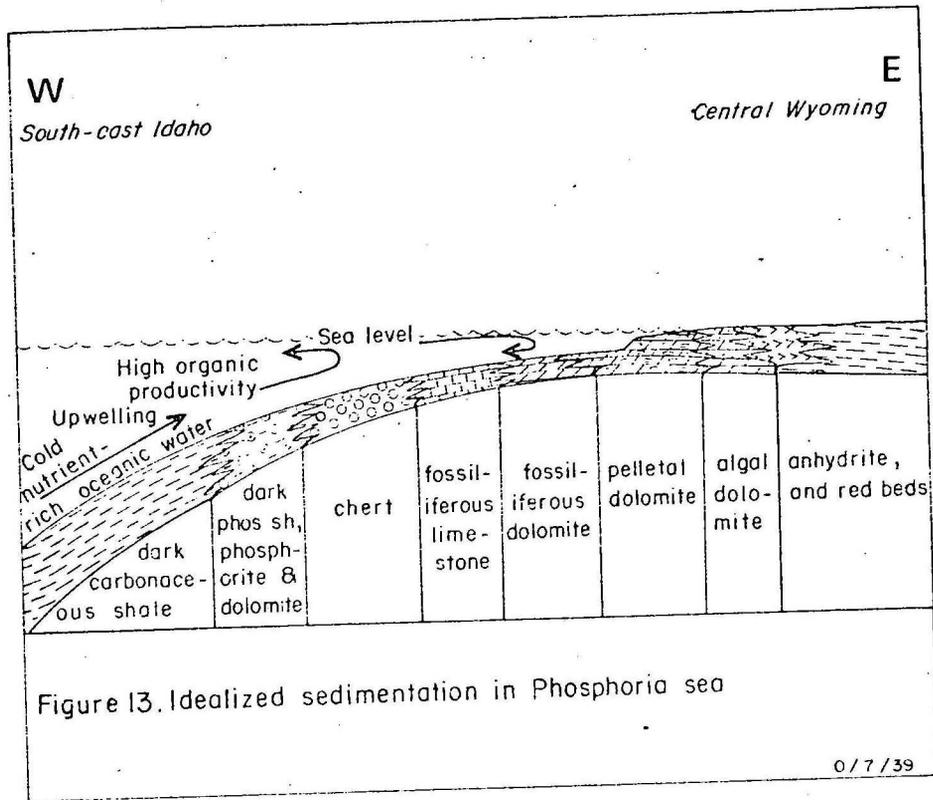


Figure 2. Stratigraphic columns for some major phosphate deposits.



To accompany record 1974/18

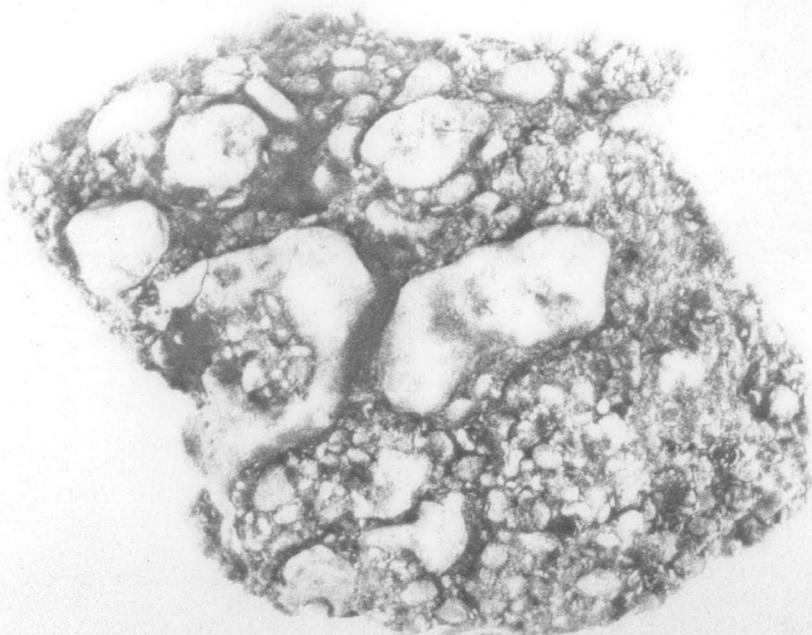


Figure 4: Nodular phosphorite from the Ordovician Stairway Sandstone of central Australia. Scale at the base of the sample is marked in one inch (2.54 cm) intervals.

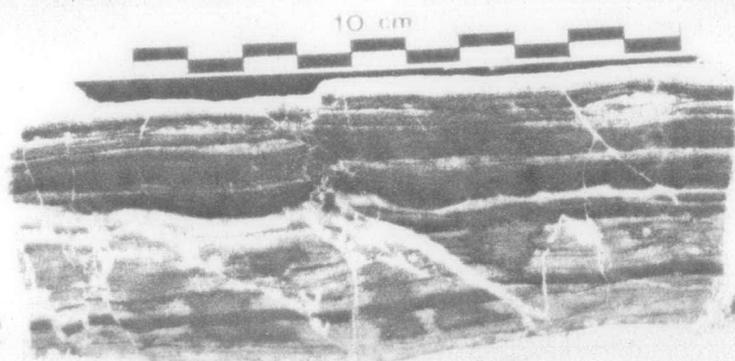


Figure 5: Pelletal phosphorite from the Cambrian Beetle Creek Formation, northwest Queensland. The darker bands are chert; note the micro-troughs infilled with fine pelletal collophane.

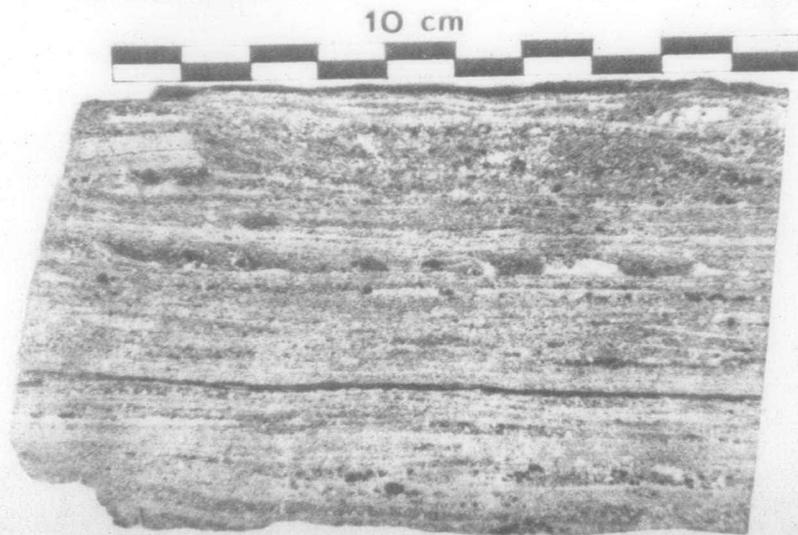


Figure 6: Finely bedded non-pelletal phosphorite from the Late Precambrian Areyonga Formation of central Australia. The darker patches are rounded clasts of chert.

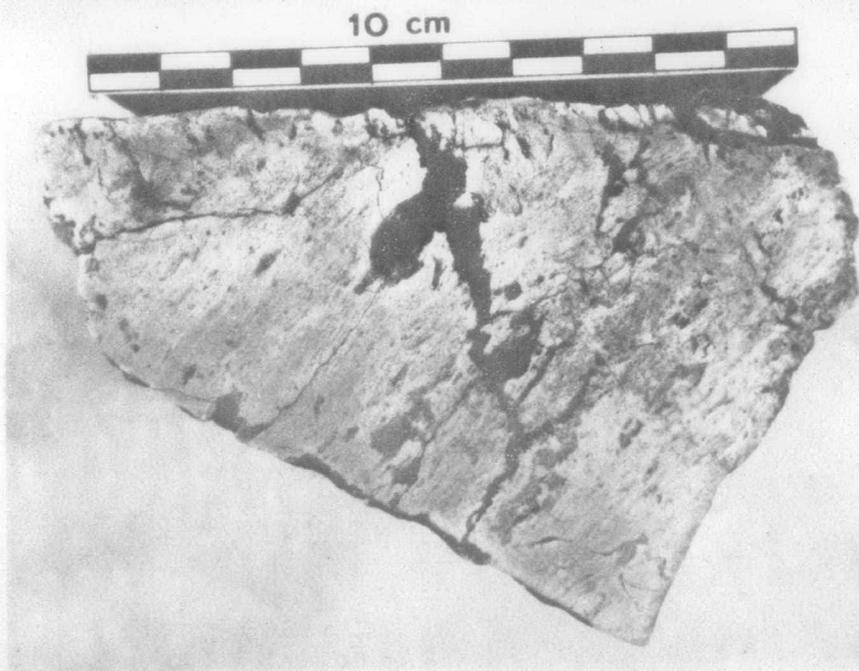


Figure 7: Structureless collophane (phoscrete) from Georgina Basin of northwest Queensland. The dark patch near the margin of the sample is due to manganese and ferruginous staining.

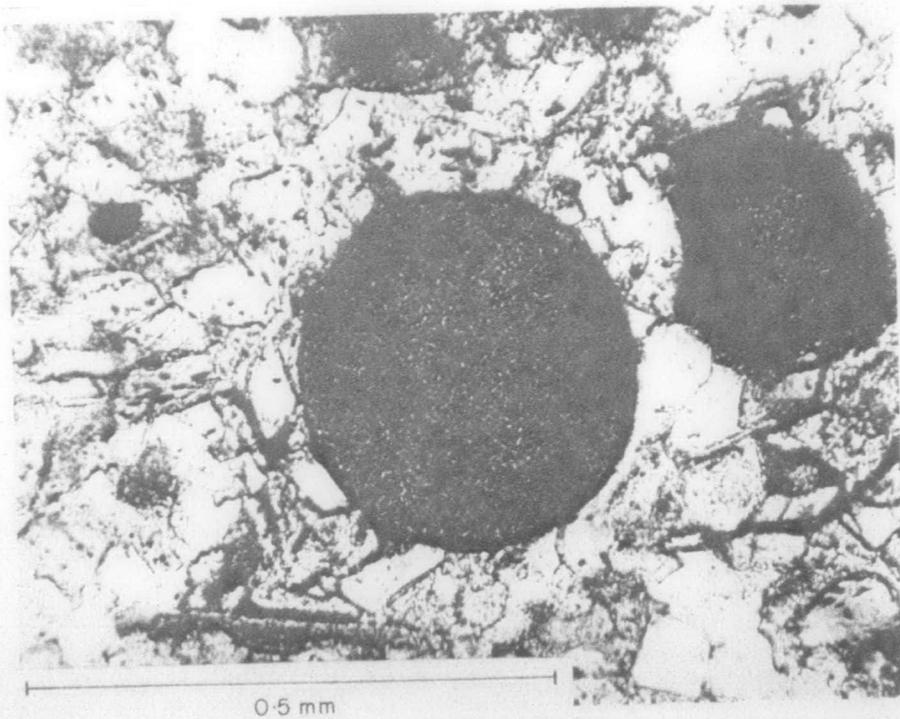


Figure 8: Phosphatic ovule (dark) in a light coloured silty matrix. Sample from the Ordovician Stairway Sandstone of central Australia.

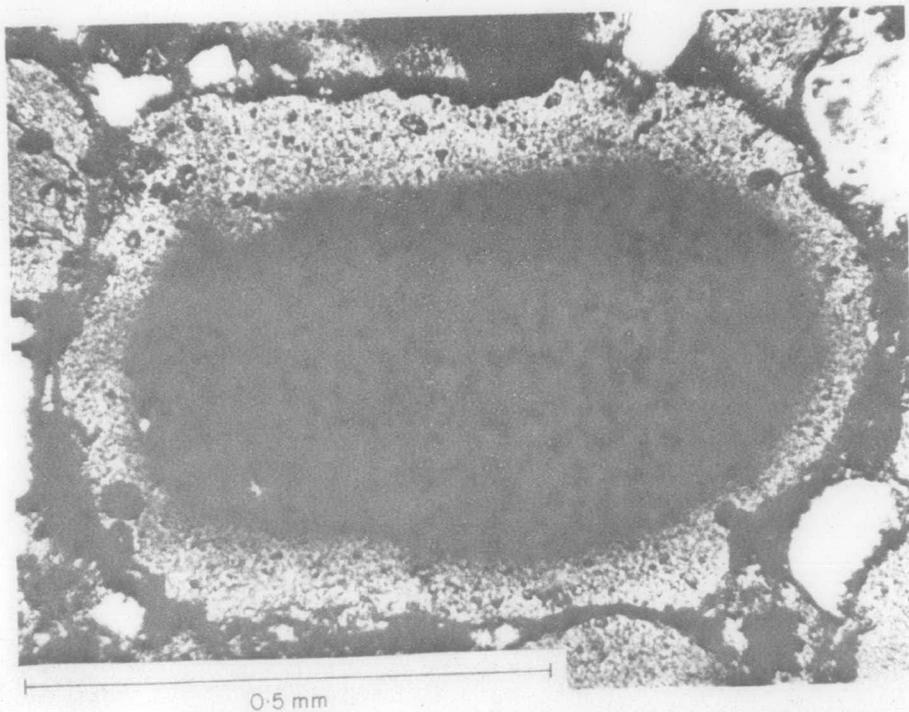


Figure 9: Pseudo-oolitic ovule with a rim of light coloured collophane from where organic carbon has been removed by oxidation.

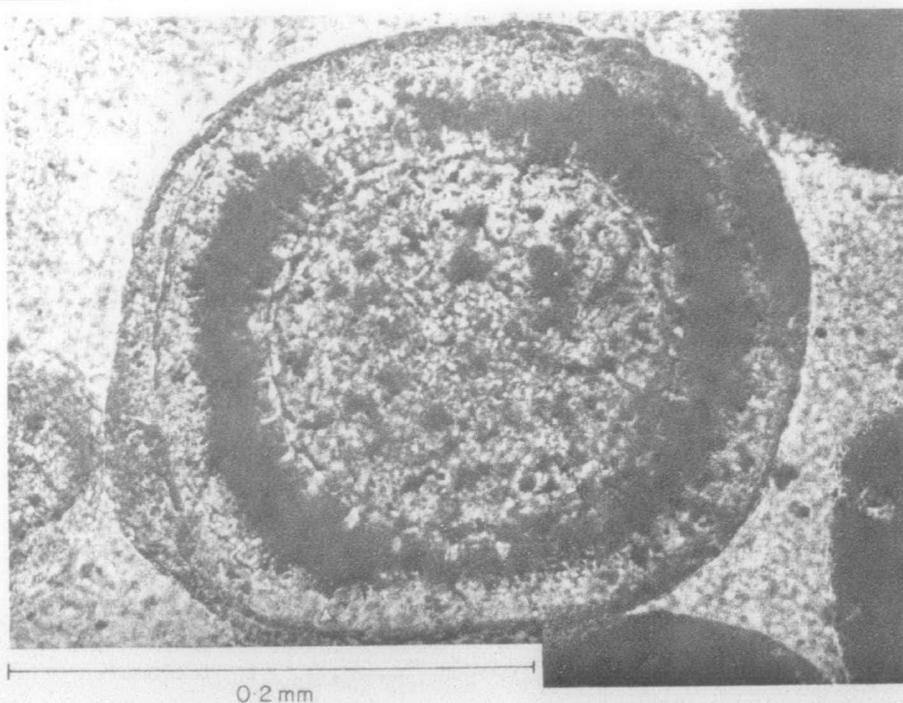


Figure 10: Nucleated pellet with a radiolarian test forming the nucleus. Sample from the Cretaceous deposits of Khourigba, Morocco.

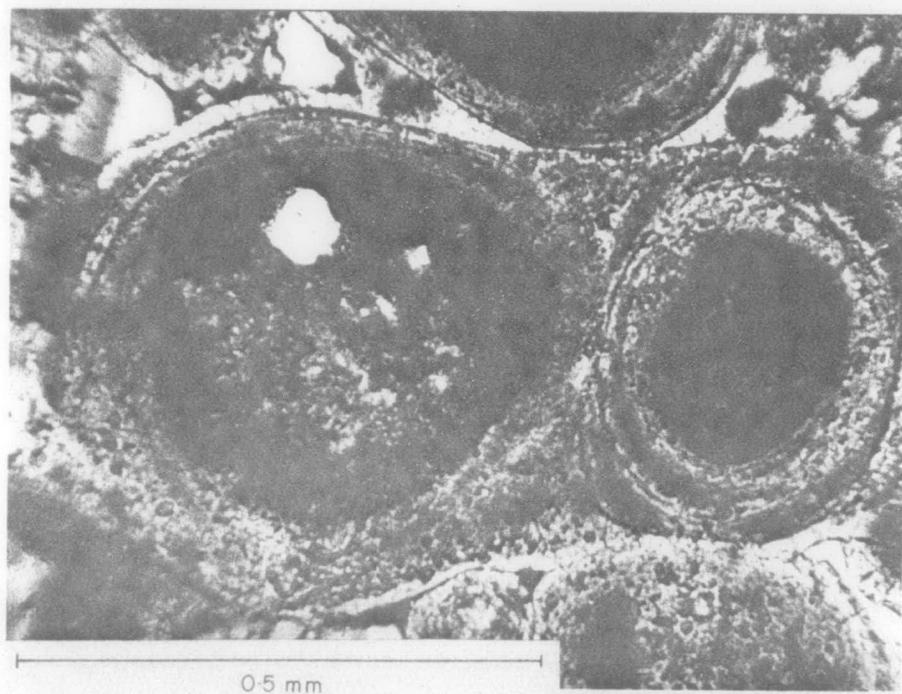


Figure 11: Compound pellet from the Permian Meade Peak Member of the Phosphoria Formation.

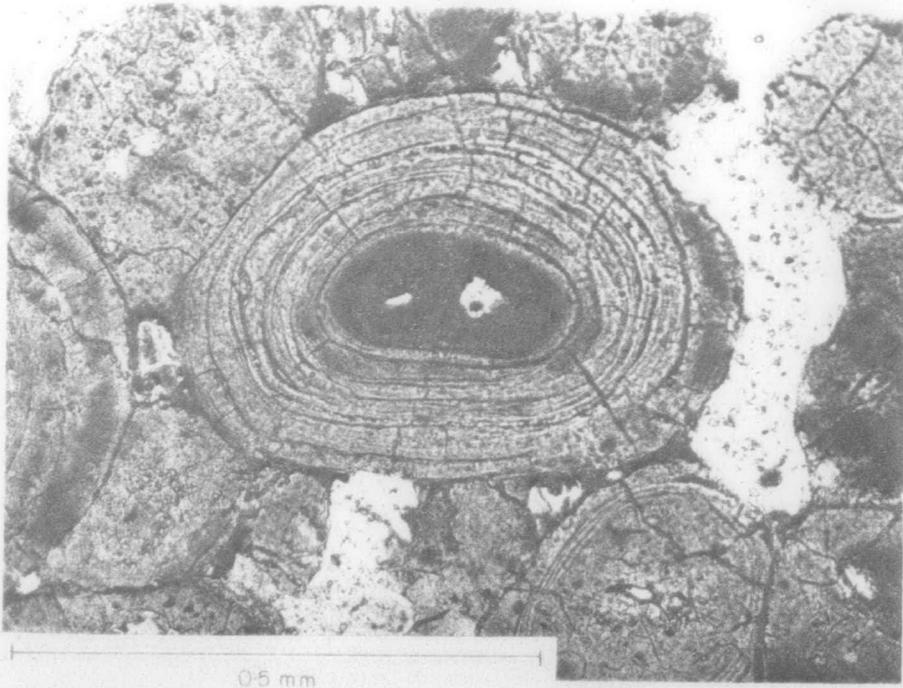


Figure 12: Oolite from the Meade Peak Member of the Phosphoria Formation, showing well developed concentric banding.

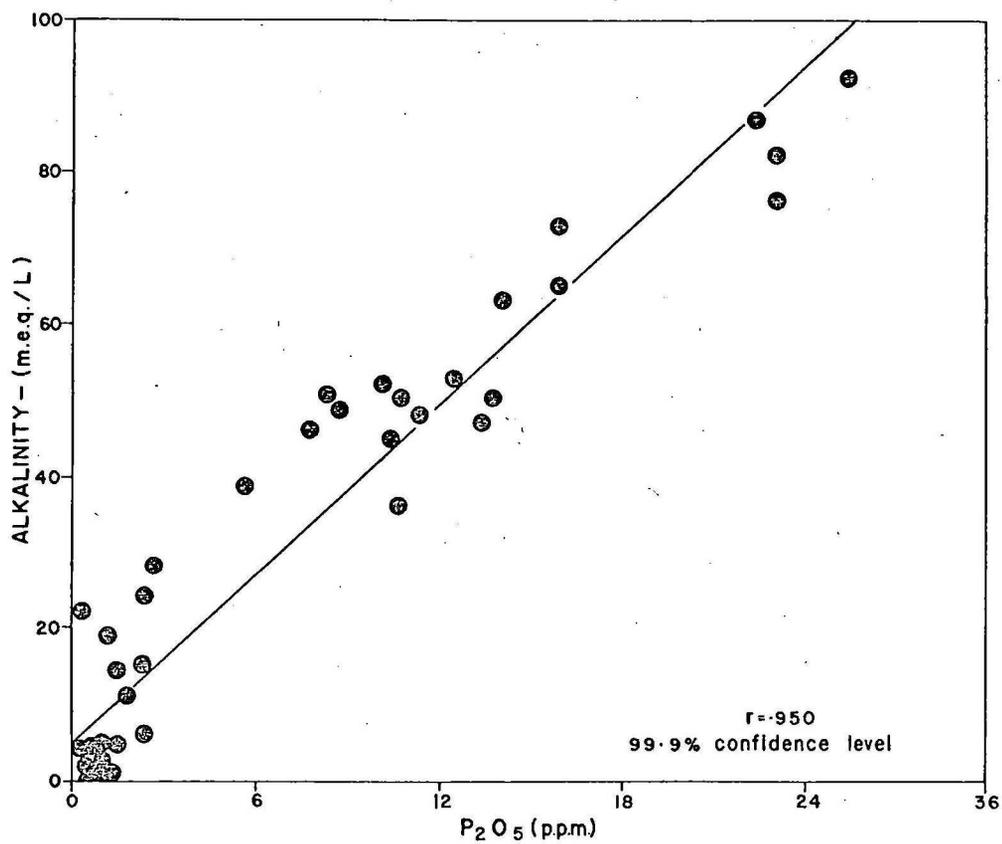


Figure 14. Alkalinity P₂O₅ correlation in interstitial waters DSDP Site 262 Timor Trough

0/2/6