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**SEDIMENTARY PHOSPHATE DEPOSITS
— AN INTERIM REVIEW**

R.L. CHRISTIE





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SEDIMENTARY PHOSPHATE DEPOSITS – AN INTERIM REVIEW

Abstract

The most widely used ore in the world's phosphate industry is sedimentary phosphate rock, or phosphorite, in which the apatite mineral series is prominent. The sedimentary phosphate minerals probably form during diagenetic phosphatization of sediments in certain shallow-marine environments near loci of upwelling deep-sea water. Hypothetical models of various sedimentological-tectonic conditions that apparently occurred during phosphate deposition have been used in delineating promising areas for prospecting. In this paper, several models are drawn from descriptions of known phosphoritic regions, and a genetic scheme of classification is proposed.

Canada has a well-developed phosphate industry although no ore is mined in this country. Phosphorite is reported, however, from beds of a wide range of ages and it should be possible, using criteria derived from the models for deposition of marine apatite, to delineate favourable sites for prospecting and testing.

Résumé

Le minerai le plus fréquemment utilisé par l'industrie mondiale des phosphates est une roche sédimentaire phosphatée, appelée phosphorite, où domine la série des minéraux de la famille de l'apatite. Les minéraux sédimentaires phosphatés se forment probablement pendant la phosphatation diagénétique des sédiments dans certains milieux marins peu profonds, près de zones de remontée des eaux profondes. On a utilisé des modèles fictifs, reproduisant les diverses conditions sédimentologiques et tectoniques qui ont probablement régné pendant le dépôt des phosphates, pour délimiter les zones où la prospection pourrait s'avérer intéressante. Dans cette étude, on décrit plusieurs modèles basés sur la description de régions connues de gisements phosphoritiques, puis on propose un mode de classification génétique.

Le Canada possède une industrie des phosphates bien développée, même s'il n'exploite aucun gisement de phosphate sur son territoire. Toutefois, on a signalé la présence de gisements phosphoritiques dans diverses couches sédimentaires d'âge variable, et on doit pouvoir, en utilisant les critères fournis par les modèles de sédimentation des apatites marines, délimiter les sites à prospecter et étudier en détail.

INTRODUCTION

A study of Canadian bedded phosphates was begun recently by the Geological Survey of Canada with the objective of assembling information on identified Canadian occurrences and of evaluating the geological potential for further discoveries. This review summarizes the first phase of the project: a survey of the world phosphate industry and a preliminary attempt to classify sedimentary phosphate deposits.

The phosphate industry in Canada is well-developed, using phosphate rock imported mainly from the United States. No phosphate ore is mined in Canada; sedimentary (and other) occurrences are known across the country, but grades and mining conditions are such that none are now suitable for production.

Definitions

Phosphate is a commercial term for a rock, mineral or salt containing one or more phosphorous¹ compounds. Phosphate rock² contains one or more phosphate minerals, usually calcium phosphate (apatite), in sufficient quantity for use, either directly or after beneficiation, in the manufacture of phosphate products. The most widely used ore is sedimentary phosphate rock or phosphorite; other phosphate rocks include phosphatized limestones, sandstones, shales, and igneous rocks. Phosphate rock is graded on two bases: P₂O₅ equivalent; and "bone phosphate of lime" (Ca₃(PO₄)₂) content. The latter is commonly abbreviated to BPL or TPL (tricalcium phosphate). (1.0% BPL is equivalent to 0.458% P₂O₅.)

Phosphorites are white to dark brownish grey, mainly light coloured, shaly to sandy rocks, many of which contain rounded to ovoid structureless pellets or nodules. They are not very distinctive rocks and can be overlooked or misidentified. A bluish grey 'phosphate bloom' may be present on weathered surfaces. Phosphorites are of marine or restricted-marine origin.

Demand for Phosphorus

Phosphorus plays an essential role in plant and animal life and the heavy and continual cropping of food-growing land results in depletion of phosphorus in the soil. Agriculture in the developed nations takes the major part of mined phosphate in order to maintain high food production. In addition, however, certain phosphorous compounds improve the efficiency of industrial and domestic products: e.g. detergents, dental cements, pesticides, and metallic alloys. Phosphorus is also used in military smoke screens and incendiary bombs.

The world demand for phosphate for manufacture of fertilizers and the uneven distribution of easily mined phosphate rock have resulted in a substantial international trade. Fertilizers, however, are an industrial product and require other chemicals and energy; prices and market activity have, therefore, been tempered by increasing costs due to the recent, universal energy crisis. About 110 million metric tons of phosphate are mined annually in about thirty countries of the world. Three countries – the United States, the Soviet Union and Morocco – account for 75 per cent of the production. About 85 per cent of the mined phosphate is consumed by the developed industrial agricultural countries of Europe, North America and Asia, and by Australia.

¹ The reader is reminded here that the element is phosphorus and the adjectival form is phosphorous.

² Phosphate rock is used here in a geological sense. In the industry, 'ore' is a naturally occurring phosphate too low in grade to be converted (economically) to fertilizer in a fertilizer plant, whereas 'phosphate rock' is a higher grade phosphorous product (i.e. beneficiated ore) that can be used in a fertilizer plant or put directly on cropland. Where the natural material is of high enough grade it also is referred to as 'phosphate rock' (Wells, 1975, p. 4).

In Canada, some 13 phosphate rock acidulation plants produce about one million metric tons of P_2O_5 equivalent annually; in addition, two plants produce elemental phosphorus by electric thermal reduction. The entire output of the acid treatment plants is superphosphate and ammonium phosphate fertilizers; about half of the Canadian production is exported to the United States.

¹(Boyd, 1976; Killin, 1975, 1976; Lewis, 1970; Noyes, 1944; Spence, 1920).

Distribution of Phosphorus

Phosphorus forms 0.10 to 0.12 per cent of the earth's crust. Although widely distributed in nature, it never occurs as a free element because of its strong affinity for oxygen. The phosphorus of the earth's surface occurs primarily as orthophosphates: PO_4^{3-} . Small amounts of gaseous phosphine, PH_3 , have been found in polluted springs, lakes, and marshes under highly reducing conditions.

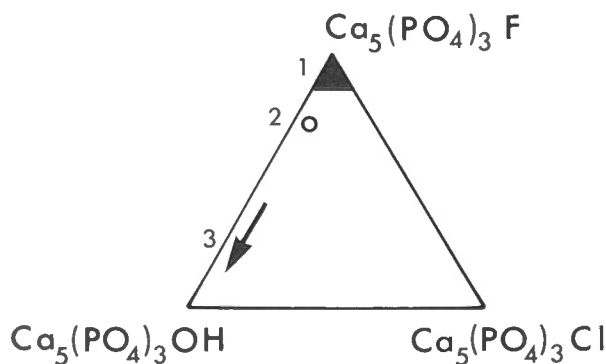
The phosphorus of the world is contained mainly in minerals, in the biosphere, and in ocean water. More than 200 minerals are known that contain up to 5 per cent phosphorus, but many of these are rare. Most mineral phosphate is the ubiquitous apatite.

Soils contain 0.022 to 0.83 per cent P; only a small fraction of this is available (or soluble) for plant and microbial use. The phosphate minerals of soils are mainly compounds of calcium, iron, and aluminum, but have not been clearly defined. Unpolluted ocean and lakewaters contain meagre amounts of P: 0.001 to 0.1 ppm in oceans, and trace amounts in rivers and lakes. The oceans, however, except for the uppermost layers, are nearly saturated with phosphate; a weighted-average phosphorus content of ocean water is about 0.07 ppm, or about 330 tons per cubic mile (73 metric tons per cubic kilometre).

Sedimentary Phosphate Minerals

Most sedimentary phosphate minerals may be placed in the series, fluorapatite-chlorapatite-hydroxyapatite (Fig. 1). Phosphate occurs on the ocean and sea floors as the carbonate fluorapatites: collophane (amorphous) and francolite (crystalline). The amorphous and colloidal phosphates occur as nodules, conodonts, coprolites, and bones in marine deposits, and as guano (usually bird excrement).

(Simpson, 1972; Fuller, 1972; Mero, 1966; Blatt, Middleton and Murray, 1972).



1. Igneous rocks, and stable phase under sedimentary conditions.
2. Authigenic phosphorite in which CO_3^{--} replaces PO_4^{--} to a few per cent.
3. Modern bones, teeth, etc.

Figure 1. The apatite mineral series.

Geochemistry

The 'phosphorus cycle' comprises many interwoven cycles, with the sun's energy a driving force within and between them. The controlling factor for the general geochemical cycling of phosphate is the biological system: that is, the events of solution of phosphate, growth and decay of organic matter, and deposition of phosphate are all entered into and their rates controlled by life processes. The slow breakdown of rocks by weathering results in soluble phosphates, colloidal particles, and fine mineral fragments. The solubility of the phosphate is enhanced by the presence of carbon dioxide (a product of biological metabolism) in the water. The phosphate ions are concentrated by biological processes from a very dilute level in the habitat of the organisms, and are released as orthophosphates upon death and decay of cells.

Apatite, the most abundant mineral phosphate, is relatively insoluble in alkaline or neutral waters, but its solubility increases with acidity and with decrease in temperature. Apatite may be concentrated as a residual deposit in early stages of weathering, but it eventually breaks down and is carried away. Such dissolved phosphate is easily redeposited: as apatite in a limestone terrane, and as wavellite and crandallite in a clay terrane.

Human activity has become an important factor in the phosphorus cycle in modern times: soil is lost through erosion resulting from destructive agricultural practices; phosphorus from fertilizers and pesticides is fixed in soils to forms unavailable to biological processes; and phosphate is lost from the land to form a 'dead end' precipitate in ocean bottoms through disposal of sewage and industrial chemicals.

(Enc. Britannica, 1974; Fuller, 1972; Cathcart and Gulbrandsen, 1973; Simpson, 1972; Mefo, 1966).

ORIGIN OF SEDIMENTARY PHOSPHATES

A widely accepted explanation of the formation of marine phosphorite is based on a theory originated by A.V. Kazakov in 1937: that upwelling of cold, phosphate-rich waters plays an important role in phosphate deposition in both present and former oceans. A biogenic origin for sedimentary phosphates was early suggested from the observed abundance of organic remains in the rock; the possibility of precipitation through bacterial activity also was considered. Kazakov, on the other hand, emphasized inorganic precipitation of apatite and reasoned that calcite should precipitate before apatite. From experimental studies by different workers (see Cook, 1976, p. 526), it was concluded, in one case, that seawater is slightly undersaturated in phosphorus, and in another, super-saturated. In either case, apatite could precipitate quite readily. But Bushinskiy (1966) called attention to an elementary point: that any phosphate precipitated in seawater would be so fine grained, as shown by experiment, that it would not settle on the sea floor if any current were active. Others (e.g. Senin, in 1970; see Cook, 1976, p. 526) elaborated, adding that a fine inorganic precipitate should be associated with fine pelitic sediments of the shelf whereas, in fact, the highest phosphate concentrations are found in the sandy sediments. Cook (op. cit.) reasoned that while organisms, especially phytoplankton, can concentrate phosphorus to a high degree, other mechanisms must operate also because simply incorporating phytoplankton in sediments would produce only slightly phosphatic, organic-rich rocks. Decay and other post-depositional modifications clearly are required to produce phosphorite.

An understanding of the depositional conditions under which phosphorite is formed should be obtainable from a study of the textures and structures of ancient deposits and by analogy with sites where phosphate deposition is now

¹ Sources are given in part in the text (e.g. McKelvey, 1967) and in part as appended lists of selected references following sections of text, as in this case.

taking place. The chief questions concern the depositional conditions and whether colophane is primary or secondary in origin.

Most phosphates evidently formed in shelf environments at water depths considerably less than 500 m — possibly between 50 and 150 m as off southwest Africa today. A reducing, anaerobic environment is suggested by the abundance of organic material in most phosphorites; also, 50 to 150 m is the depth below which modern water and bottom sediment conditions change from oxidizing to reducing. Phosphate deposition is generally considered to be controlled by pH level (a high level conducive to deposition). Cook (1976), however, from solubility measurements of interstitial fluids in modern sediments, suggested that alkalinity¹ (in part a result of abundance of organic matter) may be a primary control.

From facies distributions it appears that phosphates were deposited under near-normal salinity, but that flanking areas were commonly hypersaline. The Phosphoria Formation of the Western States region grades eastward (toward the craton) into carbonates, then into red-beds and evaporites. Modern analogs are known: for example, the Namib coastal desert forms a hinterland of saline lagoons to the phosphorites off southwest Africa.

How much of the colophane of phosphorites is primary, and how much is secondary (diagenetic and later) in origin? Some phosphatic material clearly is primary: rounded fragments of phosphatic brachiopod remains are present in Ordovician phosphorites of the Baltic region. On the other hand, previously calcareous pelmatozoan fragments are now phosphatic in the Georgina Basin of Australia. Also, the common phosphatic pellets of many phosphorites are interpreted by some authors to be faecal in origin (faecal pellets are abundant in phosphatic sediments off southwest Africa), but most faecal pellets are originally only slightly phosphatic, so the pellets of ancient phosphorites would have to have been phosphatized since deposition to impart present high phosphate concentrations (Cook, 1976).

The phosphorus-content of interstitial water of marine sediments (off southwest Africa) is ten to a hundred times greater than that of sea water. The phosphate is deposited as soft pellets and nodules of gel-like calcium phosphate that incorporate other phosphate particles. As lithification proceeds in these sediments the phosphate content of the pellets and nodules increases. Thus it appears that phosphate-rich interstitial water will phosphatize clays, oozes, calcareous sediments, and biogenic debris to form colophane just below the sediment surface (Cook, 1976, p. 527-528).

An important upgrading process at many localities, both modern and ancient, is that of mechanical reworking of the sediments. High-energy environments due to wave and storm action, with consequent reworking, are characteristic of certain sites of phosphate deposition; these aspects are discussed in a following section. Sediments may also have been reworked ('winnowed') by bottom currents. Cook (1976) suggested that wide fluctuations in sea level (e.g. during a glacial epoch) are likely to have resulted in extensive reworking of shelf sediments and so may have favoured the formation of some phosphate deposits.

Marine phosphorites thus may originate through the following steps:

1. A prolific biota develops where phosphate- (nutrient-) rich ocean water upwells and flows onto a shallow marine region with a slow rate of terrigenous deposition and a warm, arid climate.
2. Anoxic, organic-rich sediments form from dead organisms. Formation of dilutant calcium carbonate may be depressed by "phosphate ion activity" according to Gulbrandsen (1969).
3. Phosphate is leached from organic remains below the sediment surface by low-pH, high-alkaline interstitial water.
4. Diagenetic phosphatization of the sediments takes place; apatite may precipitate directly from pore water.
5. Sediments may be reworked and upgraded, the coarser patches of phosphatized sediment remaining as a lag deposit as the less phosphatic fines are winnowed out.

(Wang and McKelvey, 1976; Cook, 1976; Blatt, Middleton and Murray, 1972).

SEDIMENTARY PHOSPHATE DEPOSITS OF THE WORLD

Both descriptive and genetic schemes for classification of sedimentary phosphate deposits are complicated by the variety of processes that commonly appear to have operated. In any case, a genetic scheme is clearly the most useful one for a study of origins in spite of uncertainty in status of some terms, such as eugeosynclinal. In these notes, a three-fold scheme outlined by Cook (1976: geosynclinal, platform, and weathered or residual) will be adapted as follows.

- A. Marine
 1. Geosynclinal (Western States)²
 2. Platform and shelf-type (Pamlico Sound, North Carolina; Miocene of Florida).
- B. Secondary
 1. Residual (Tennessee brown rock)
 2. Phosphatized rock (Tennessee white rock)
 3. Reworked (Florida 'river pebble')

Hypothetical 'models' for the various marine sedimentary-tectonic circumstances in which phosphorite appears to have occurred have been used in delineating promising areas for prospecting, and may serve as aids in identifying essential processes and conditions. The models used to illustrate the following descriptions are drawn from described phosphoritic regions.

A. Marine Phosphorites

Phosphorites of marine origin are found characteristically on former continental shelf or slope areas at low- to middle paleolatitudes. The deposits are presumed to have been associated with the upwelling of phosphate-rich sea water in an environment in which sedimentation was slow or restricted.

Both geosynclinal and platformal tectonic settings evidently were conducive to phosphate deposition. The 'geosynclinal' sites can further be divided into 'eu-' and 'mio-' geosynclinal.

¹ The 'alkalinity of seawater' is a measure of the concentration of anions of weak acids that are present in the water: mainly HCO_3^- , but also CO_3^{--} , H_2BO_3^- and others, as well as OH^- . The definition of the term is: the number of milliequivalents of hydrogen ion neutralized by 1 L of seawater at 20°C. Measurement is carried out by the introduction of quantities of a strong acid (HCl) until an end point or equivalence point is reached, beyond which further addition of acid results in rapid change of pH and conductivity. The end point occurs at a pH of 4.5 (see Li and Moore, 1966). The reader is here cautioned that in the present context 'alkalinity' (of seawater) and acidity are not complementary, and high-alkalinity seawater does not necessarily mean a high pH value.

² Examples are those noted by Cook (1976), McKelvey (1967), and Cathcart and Gulbrandsen (1973).

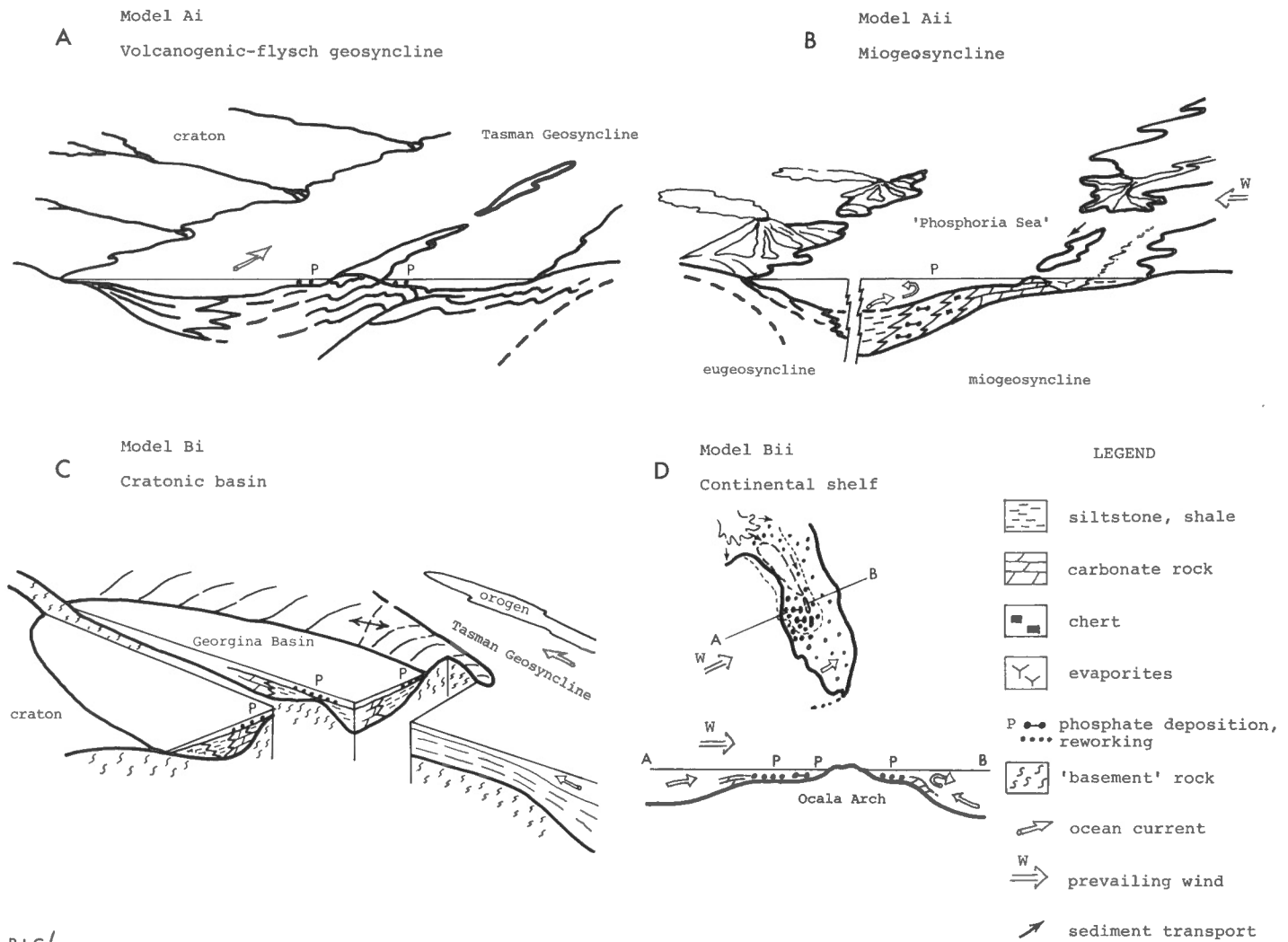


Figure 2. Sedimentological models for deposition of phosphorite.

1. Geosynclinal Deposits (Models Ai, Aii)

- i) **Eugeosynclinal:** deposits commonly associated with thick volcanogenic sequences; usually small and not economic. The only economic examples reported lie in eastern Sayan and in central Tien Shan in central Asia (Cook, 1976).

Phosphorite occurs within a mainly clastic-turbidite, lower Paleozoic geosynclinal sequence in the Tasman Geosyncline of Australia (Fig. 2A). The phosphates are associated with black shale and chert in 'belts' within the geosynclinal sequence; the belts evidently were related to former "anticlines and structural highs" (Howard, 1972). Model Ai of Figure 2A illustrates a possible sedimentary-tectonic situation within a geosyncline: a positive tectonic element presumably would result in reworking of phosphatic sediments and 'condensation' of the stratigraphic section. Nutrients may have come both from rivers on the craton and from oceanic water.

- ii) **Miogeosynclinal:** deposits characterized by association with chert, fine organic-rich argillaceous sediments, and carbonates, particularly dolomite. The phosphorites are generally pelletal and extend

over wide areas, with a high phosphate content throughout. Examples include the Western States phosphate field in the U.S. (Phosphoria Formation) and those of Karatau in south Kazak Republic of the U.S.S.R.

The Permian Phosphoria Formation occurs at a flexure zone between a stable shelf and the Cordilleran Geosyncline (Fig. 2B). Winds, latitude (hence, climate) and presumed ocean currents resulted in nutrient-rich water rising onto a shallow-water shelf region with little clastic sedimentation. Reducing conditions are suggested by a strong association of phosphorite with organic-rich beds. The 'Phosphoria Basin' was roughly elliptical, flanked by low-lying, emergent landmasses. Most sediments from the craton were trapped, presumably, in lagoons cratonward of the miogeosyncline; fine material introduced by a river system to the north, however, was carried by longshore currents into the miogeosynclinal basin and the zone of phosphorite deposition.

(McKelvey et al., 1959; Sheldon, 1963)

2. Platform Deposits (Models Bi, Bii)

Phosphorites occur as both discrete pockets and extensive sheets on or bordering cratons. Various stratigraphic and structural conditions appear to have provided for phosphate deposition so that a wide range of sedimentological features is included. Two main sites may be favoured:

- i) **Cratonic basins:** deposits discontinuous, or as thin, low-grade beds covering large areas; ore may be within the sedimentary basins, on the flanks of uplifts, or along shorelines. Phosphorite occurs as pelletal, nodular, and massive rock with either a quartzose or carbonate matrix. Limestone, dolomite, shale, glauconitic sandstone, and quartz-siltstone are associated. Shallow-water features such as crossbedding and scour structures may be present, and from certain faunal remains it has been inferred that water depths were only a few tens of metres. Winnowing due to wave action and currents along shorelines and structural-topographic highs resulted in condensation of the sections and enrichment of the phosphate deposits.

The Miocene Pamlico Sound deposit of North Carolina and the Late Cretaceous Mishash deposits of Israel are examples of relatively rich pockets of limited area; the Cambro-Ordovician deposits of central Australia (Georgina and Amadeus Basins) are thin, low-grade beds that extend over large areas. Other platform deposits include those of the Moscow Basin of the U.S.S.R. (mainly Jura-Cretaceous) and the Ordovician and Carboniferous sandstones and shales of Minnesota, Arkansas, and Tennessee.

The Moscow Basin, from an early description (Bushinskiy, 1935), fits the 'platform' model for phosphate deposition. The basin is characterized by gentle dips and thin phosphorite units (up to 0.5 m thick). The phosphorite occurs as a cement in rounded nodules of quartz-glaucinite sand. The phosphate is supposed to have grown at intervals in water of normal salinity; phosphate replaces calcite, aragonite, bones, and calcareous shells and tests.

The Georgina Basin of Australia (Fig. 2C) was, in Middle Cambrian time, an epicontinental and shelf 'arm' branching from the Tasman Geosyncline. The Georgina Basin lay within 10° latitude of the equator at that time. Phosphorite was deposited in a shallow, partly barred embayment contemporaneously with offshore carbonate rocks; phosphate deposits are distributed along the edge of the basin and over basement highs. Restricted conditions in places are indicated by dark carbonaceous siltstones and bituminous limestones but the phosphate deposits themselves are marked by oxidizing conditions as indicated by phosphatized and silicified coquinas and crystalline limestones, and by light-coloured, fine-grained phosphorite (Howard, 1972).

- ii) **Stable Shelf:** phosphatic limestone or sandstone and diatomaceous material sometimes present; generally of low grade and only economic when reworked or winnowed by currents. Ore occurs in basins or structural lows on the flanks of domes or arches that were rising at the time of deposition. Barrier islands were built to seaward by longshore currents, with sediment and possibly some nutrients supplied by large rivers. Deposits of this type formed along the eastern coasts of North and South America where wind-driven warm ocean currents and the outflow of surface waters at the mouths of large rivers resulted in countercurrents or upwellings of deeper ocean water.

The Florida deposits (Fig. 2D) provide the model for this type of deposition. The following processes appear to have taken place: uplift along the Ocala Arch in Miocene time resulted in shallow water, emergent land, and barrier islands built by longshore currents; phosphorite formed as a thin blanket in shallow bank areas behind the islands; tidal currents and storms repeatedly broke up hardened phosphorite mud to form fragments or intraclasts; the intraclasts were transported away from the arch and redeposited on the shelf. The phosphorite was concentrated or 'upgraded' in places during transport and redeposition.

Uplift and erosion of the Florida marine deposits took place in Pliocene to Recent time to form extensive "reworked" phosphorite in fluvial, estuarine, and lagoonal environments. In addition, many deposits have been enriched due to weathering and movement of ground water (Freas, 1967).

B. Secondary Phosphorite

1. Residual Phosphorite

Many sedimentary phosphate deposits — particularly those of the platform type, which may never have been deeply buried — have been subjected to weathering for prolonged periods. High-grade phosphate can result from the leaching out of more soluble components (usually calcite) to leave a residual phosphorite. The Tennessee 'brown rock' deposits are an example; these deposits were derived from several more or less phosphatic limestone formations of Ordovician age (Mansfield, 1940).

One might expect to find buried residual phosphorite (as 'subcrop') in certain basins, associated with unconformities.

2. Phosphatized Rock

Phosphates from overlying phosphate rock or guano may be carried downward by solution under tropical or subtropical conditions to precipitate as phosphatic minerals in a lower part of the weathering profile or in underlying beds. Apatite is usually formed in carbonate rocks; igneous rocks or clay may react with phosphatic solutions to form iron-aluminum phosphates: e.g. strengite, crandallite, and wavellite.

The Tennessee 'white rock' deposits are examples of ore formed by redeposition of phosphate ions; in this case, the source rock is a sandstone member of the Chattanooga shale of late Devonian or early Mississippian age and the host rock is an underlying limestone formation. Phosphate minerals formed both as fillings in openings and by phosphatization of limestone (Mansfield, 1940).

3. River Pebble (reworked) Deposits

Phosphate nodules and pellets may weather out of phosphatic beds in a humid region of low relief; reconcentration of such phosphate nodules by stream action can result in ore grade phosphate rock. Reworked deposits of this type are commonly nodular and are generally mixed with coarse, crossbedded quartzose sands. The phosphate bodies are typically lenticular and fill depressions in underlying formations. The phosphate in the Pliocene Bone Valley Formation of Florida is derived from the Miocene Hawthorne Formation.

(Cook, 1976; Cathcart and Gulbrandsen, 1973; Gulbrandsen, 1969).

EXPLORATION FOR PHOSPHORITE

Phosphorites, as noted earlier, are generally featureless rocks that are easily overlooked. The rounded, structureless pellets or nodules characteristic of some phosphorites,

however, aid in recognition. Phosphatized bone fragments, faecal pellets, and fish and sharks' teeth may be present, and glauconite is a common accessory mineral. A bluish to white 'bloom' on the surface of the rock is an additional clue at the outcrop. Organic-rich phosphorites give a bituminous odour when struck by a hammer, and high-grade phosphorite may be distinguished by a fairly high specific gravity.

Phosphates may be associated with distinctive rocks depending on the geological setting or type of deposit: in a miogeosynclinal basin, for example, phosphorite is characteristically associated with a black shale, chert, and carbonate suite of rocks; associated rocks in a platform setting include light-coloured quartz-siltstone, sandstone, and shale, and glauconite and phosphatized coquina may be present. Breccias and conglomerates can be guides to secondary phosphate deposits associated with an unconformity in a stratigraphic sequence.

Geophysical techniques using radiometric instruments can also be used in exploration for phosphates: marine apatite usually contains a small amount (0.001 to 0.065 per cent) of uranium and the gamma radiation from this 'tracer' element can be detected by scintillometer or gamma-ray spectrometer (see McKelvey and Carswell, 1967).

Exploration Programs

Undiscovered large phosphate deposits will almost certainly be marine phosphorites; a search for such rocks should begin, as outlined by Cathcart and Gulbrandsen (1973, p. 523), with identification of promising marine sedimentary basins, the most favoured basins being those similar to one or another of the 'models' for phosphate deposition. A 'formula' for prospecting and discovery using this reasoning was developed by V.E. McKelvey and R.P. Sheldon of the U.S. Geological Survey from studies of the Phosphoria Formation of the western United States. Their scheme was particularly applicable to the miogeosynclinal (or 'Phosphoria') type of phosphorite; similar programs for discovery of other types (e.g. shelf or cratonic basin) were derived during later application of the first 'formula'.

The 'Phosphoria formula' of McKelvey and Sheldon was based on the supposition that phosphorites form near strong oceanic upwellings in specific paleogeographic settings, such as that of the 'Phosphoria Basin'. A reconnaissance survey of a suitable or potentially phosphoritic sedimentary basin begins with a search of oil well logs and rock collections for gamma ray activity and phosphate content. Finally, promising formations are studied in outcrop or are sampled by drill (see McKelvey, 1963; Sheldon, 1964b).

The formula of McKelvey and Sheldon was tested and proven in Turkey (McKelvey, 1963; Sheldon, 1964b) and has been useful in the discovery of phosphorites in Peru, Saudi Arabia, Australia, India, and Columbia (Sheldon et al., 1967). In Australia, however, where many sedimentary basins were epicontinental or were shelf-type and adjacent to a geosyncline, it was found that phosphate deposition was related to former areas of shallow water deposition such as along basin margins and on syn-sedimentary basement arches. Even in the Tasman Geosyncline, with its volcanic and flysch facies, it was concluded that phosphate deposition (albeit of the black shale-chert suite) occurred in belts of "chemical sediments" associated with geanticlinal ridges within the tectonically complex geosyncline (see Howard, 1972).

A search for phosphorite in a eugeosynclinal region does not appear to be a promising venture, although economic deposits of this type are reported in central Asia. Belts of chert and black shale in the large, volcanogenic geosynclinal region of the Canadian Cordillera may be phosphatic, however, as in the Tasman Geosyncline, presumably at least if the section is 'condensed'.

The black shale-chert-carbonate suite of rocks characteristic of phosphorite can be delineated in recognized marine basins from geological maps and from oil-well cuttings. Gamma-ray logs and chemical tests can be used to identify phosphatic beds in the sedimentary succession (Sheldon, 1964b). Numerous textures are present in phosphorite of this type: pelletal, oolitic, nodular, pisolitic, bioclastic, and coquinoid. Fish remains are usually present, and phosphatic brachiopod shells and phosphatized calcareous shells may also be found. The chert beds may comprise various siliceous organisms, a product of silica-rich upwelling water. Sedimentary features often suggest shallow-water deposition and winnowing action. The phosphorite-bearing formations are generally not over 100 m thick.

The facies association of miogeosynclinal phosphorites also can be used in directing exploration. The phosphoritic rocks pass into basinal black shales in the direction of the former ocean, while phosphatic carbonates, cherts, saline deposits and red or light-coloured shale or sandstone facies may be encountered progressively 'shoreward'.

A search for phosphorites of former marine basins in cratonic regions (continental interior or stable shelves) would be directed along two lines: structural and facies. The deposits tend to occur on the flanks of structural highs with abundant evidence of shallow water and reworking of sediments: crossbedding, scour features, and shallow-water fauna. The phosphate occurs as phosphatic limestone, usually of low grade unless naturally enriched by reworking or leaching. Associated rocks include light-coloured quartz-siltstone, sandstone, and shale. Glauconite may be abundant, and phosphatized coquina may be present.

(Cathcart and Gulbrandsen, 1973; Sheldon, 1964a; Hale, 1967; Sheldon et al., 1967).

Phosphate Provinces

It has been argued that there is a cyclicity, or at least that there are worldwide maxima, in the deposition of phosphorite (Strakhov, 1969). Others, however, dispute this and suggest instead that phosphate, always present in the oceans, precipitates in response to favourable local conditions (see Cook, 1976, p. 507; Bushinskiy, 1969). In any case, data do enable phosphogenic provinces of various ages to be outlined on each continent. Some of these are:

1. a late Precambrian province in central and south-eastern Asia;
2. a Cambrian province in central and southeastern Asia, extending into northern Australia;
3. an early Paleozoic (Ordovician-Devonian) province in the eastern interior United States;
4. a Carboniferous province in the eastern United States;
5. a Permian province in western North America;
6. a Jurassic-Early Cretaceous province in eastern Europe;
7. a Late Cretaceous-Eocene Tethyan province in the Middle East and northern Africa;
8. a Cretaceous-Paleocene province in southeastern interior United States;
9. a Miocene province in southeastern North America;
10. Tertiary provinces on the western borders of North America, South America, and Africa.

Some of these provinces extend for thousands of kilometres; note, however, that the original form and extent of the older provinces may depend upon continental reconstructions.

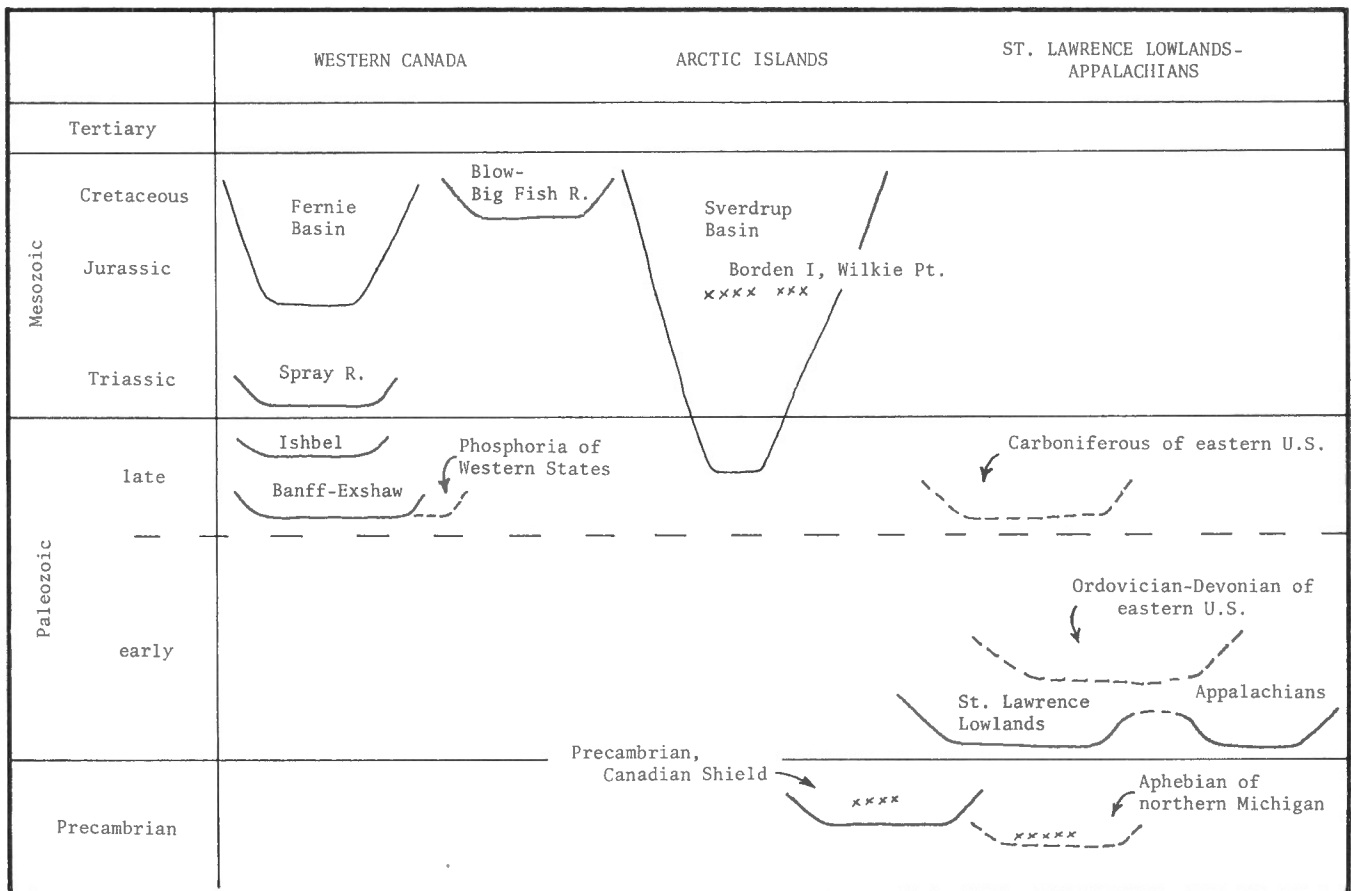


Figure 3. Some phosphogenic basins in Canada and nearby areas.

In known phosphoritic regions it is usually clear that beds of certain ages are non-phosphatic whereas beds representing other times of origin contain minor to substantial amounts of sedimentary apatite. In an early stage of exploration one would distinguish mainly between known 'presence' and 'absence' of phosphate to delineate favourable basins or favourable stratigraphic levels and sedimentary trends within basins. Such a scheme was followed in a recent exploration program in Australia (see Howard, 1972); there, it was known that phosphate was present in minor amounts in the Proterozoic and Cambrian, and in greater amounts in the Ordovician, Permian, and Cretaceous successions, whereas it was evidently absent in Silurian, Devonian, and Carboniferous beds.

The western Canada Sedimentary Basin contains phosphatic beds of Mississippian, Permian, Triassic, Jurassic, and Cretaceous ages. These beds form at least two phosphoritic provinces: a late Paleozoic province, apparently a northern extension of the 'Phosphoria' province of Idaho, Montana, and Wyoming; and a Triassic-Cretaceous province of western Alberta and eastern British Columbia. Cambro-Ordovician beds of the St. Lawrence Lowlands and Appalachian region appear to form a third phosphogenic province in Canada. Phosphatic beds are also known in Manitoba (Cretaceous), in northern Yukon (Lower Cretaceous); and in the Canadian Shield (Precambrian) (see Fig. 3).

(Cook, 1976; R.L. Kenny, pers. comm.; British Sulphur Corporation, 1971; Howard, 1972; Young, Myhr, and Yorath, 1976).

AN EXPLORATION PROGRAM FOR CANADA

The principles described for exploration for phosphate rock can be applied to Canada; the steps in an exploration program might be: a) identification of marine sedimentary basins; b) selection of favourable basins from consideration of 'model concepts' for phosphate deposition; c) survey of rock collections and well samples and logs; d) study of selected field areas.

A study of rock collections and other data can include the following activities:

- i) a study of existing aerial radiometric surveys;
- ii) examination of gamma logs of existing wells;
- iii) scanning (by scintillometer) of existing suites of rock from stratigraphic sections, well cuttings, and paleontological collections;
- iv) chemical tests on collected material.

Field surveys of suspected phosphoritic areas would include examination and testing, both by scintillometer and chemical reagent (ammonium molybdate), of selected stratigraphic sections; diamond drill cores would be logged if accessible.

The geometry of the smallest identifiable, or 'unit' basins and their place in major geological regions such as the Canadian Cordilleran Geosyncline or the Western Canada Basin is critical in evaluation of appropriate sedimentary 'models'. The presence during sedimentation of relatively positive arches or geanticlinal ridges is evidently important in 'platform' types of phosphate deposition, and such structures should be taken into account.

- Encyclopaedia Britannica
1974: 15th edition; Warren E. Preeco, gen. ed.; Helen Hemingway Benton Publ., v. 14, p. 284, 288; Microped., v. VII, p. 961.
- Freas, D.H.
1967: Exploration for Florida Phosphate Deposits; Handbook, Int. Minerals and Chemical Corp., Skokie, Illinois, U.S.A.
- Fuller, W.H.
1972: Phosphorus: element and geochemistry in Enc. of Geochemistry and Environmental Sciences, R.W. Fairbridge, ed., Van Nostrand Reinhold Co., New York, p. 942-946.
- Gulbrandsen, R.A.
1969: Physical and chemical factors in the formation of marine apatite; Econ. Geol., v. 69, p. 365-382.
- Hale, L.A.
1967: Phosphate exploration using gamma-radiation logs, Dry Valley, Idaho in Anatomy of the Western Phosphate Field, L.A. Hale, ed.; Intermountain Assoc. Geologists, 15th Field Conference, Salt Lake City, Idaho, p. 147-159.
- Howard, P.F.
1972: Exploration for phosphorite in Australia – a case history; Econ. Geol., v. 67, p. 1180-1192.
- Kenny, R.L.
1977: Phosphate exploration in southeastern British Columbia by Cominco Ltd. ms., CIM meeting, Ottawa, April 1977.
- Killin, A.F.
1975: Phosphate; no. 34 in Canadian Minerals Yearbook, 1974, Ottawa, Canada.
1976: Phosphate; Energy, Mines and Resources, Canada, Mineral Policy Series MR 160.
- Lewis, R.W.
1970: Phosphorus in Mineral Facts and Problems, 1970 edition; U.S. Bureau of Mines, Bull. 650, p. 1139-1155.
- Li, Y.H. and Moore, W.S.
1966: Alkalinity (of seawater) in The Encyclopedia of Oceanography, R.W. Fairbridge, ed., Reinhold, New York, p. 29.
- Mansfield, G.R.
1940: Phosphate deposits of the United States; Econ. Geol., v. 35, p. 405-429.
- McKelvey, V.E.
1963: Successful new techniques in prospecting for phosphate deposits: Science, Technology, and Development; U.S. papers prepared for the United Nations Conf. on the application of science and technology for the benefit of the less developed areas, v. II, p. 163-172.
1967: Phosphate deposits; U.S. Geol. Surv., Bull. 1252-D.
- McKelvey, V.E. and Carswell, L.D.
1967: Uranium in the Phosphoria Formation in Anatomy of the Western Phosphate Field, L.A. Hale, ed.; Intermountain Assoc. Geologists, Salt Lake City, Idaho, p. 119-123.
- McKelvey, V.E., Williams, J.S., Sheldon, R.P., Cressman, E.R., Cheney, T.M., and Swanson, R.W.
1959: The Phosphoria, Park City and Shedhorn Formations in the western phosphate field; U.S. Geol. Surv., Prof. Paper 313-A.
- Mero, J.L.
1966: Mineral potential of the ocean in The Encyclopedia of Oceanography; R.W. Fairbridge, ed.; Reinhold, New York, p. 517-524.
- Noyes, F.C.
1944: Phosphate rock industry of foreign countries; Mining and Metallurgy, v. 25, p. 495-506.
- Sheldon, R.P.
1963: Physical stratigraphy and mineral resources of Permian rocks in western Wyoming; U.S. Geol. Surv., Prof. Paper 313-B, p. 49-273.
1964a: Paleolatitudinal and paleogeographic distribution of phosphorite; U.S. Geol. Surv., Prof. Paper 501-C, p. C106-C113.
1964b: Exploration for phosphorite in Turkey – a case history; Econ. Geol., v. 59, p. 1159-1175.
- Sheldon, R.P., Maugham, E.K., and Cressman, E.R.
1967: Sedimentation of rocks of Leonard (Permian) age in Wyoming and adjacent states in Anatomy of the Western Phosphate Field, L.A. Hale, ed.; Intermountain Assoc. Geologists, 15th Field Conf., Salt Lake City, Idaho, p. 1-13.
- Simpson, D.R.
1972: Phosphatization in Enc. of Geochemistry and Environmental Sciences, R.W. Fairbridge, ed.; Van Nostrand Reinhold Co., p. 940-942.
- Spence, H.S.
1920: Phosphate in Canada; Dept. of Mines, Mines Branch, Publ. 396.
- Strakhov, N.M.
1969: Principles of Lithogenesis, 2; Consultants Bureau, New York, N.Y., p. 235-261.
- Wang, F.F.H. and McKelvey, V.E.
1976: Marine mineral resources in World Mineral Supplies, Assessment and Perspective, G.J.S. Govett and M.H. Govett, eds.; Elsevier, Amsterdam.
- Wells, F.J.
1975: The Long Run Availability of Phosphorus; Johns Hopkins Univ. Press.
- Young, F.G., Myhr, D.W., and Yorath, C.J.
1976: Geology of the Beaufort-Mackenzie Basin; Geol. Surv. Can., Paper 76-11.