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# SEDIMENTARY PHOSPHATE DEPOSITS AND THE WORLD PHOSPHATE INDUSTRY - AN INTERIM REVIEW

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# I. INTRODUCTION

Phosphate is a term used for a rock, mineral, or salt containing phosphate compounds--that is, oxides of the semi-metal, phosphorus.

A study of phosphates maybe divided into two domaines: theoretical and practical. The theoretical aspect concerns the geochemistry of phosphorus, the origin of phosphate deposits, and the devolvement of a geological model to explain and predict phosphate deposition. The practical phase is that concerning the technology of phosphates: uses, classification of ores, tonnages and reserves, empirical methods of exploration, and the salvaging and recycling of phosphates. These two aspects will be covered separately in the chapters that follow.

Phosphate deposits of the world are found in beds of a wide range of ages and in more than one tectonic setting; it appears highly probable that favourable conditions and sites for deposition have existed in the geological past in the large and geologically diverse area of Canada.

## II. GEOCHEMISTRY OF PHOSPHORUS

### Introduction: The Importance of Phosphorus

Elemental phosphorus was named from the Greek: phòsphoros, which means "light-bearing". Appropriate as this name is, it might well have been named "lift-giving", for phosphorus is one of the most important mineral constituents for the support of cell activity, both in plant and animal life. That calcium phosphate is the principal inorganic constituent of teeth and bones is general knowledge; it is less widely known that the DNA molecules that make up genes all contain phosphorus, and that cells store the energy obtained from nutrients in molecules of ATP, or adenosine triphosphate. Phosphorus was first prepared (by a German alchemist, Hennig Brand, in 1669) from the residue of evaporated urine (!).

Given the essential rôle of phosphorus in plant and animal life and the heavy and continual cropping of much of the world's food-growing land, it is little wonder that the agricultural industry takes the major part of the mined phosphate minerals. 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 uncivilized activity: military smoke screens and incendiary bombs. The spectrum of uses is given in more detail in a later section of this report.

Many products containing phosphorous compounds, such as phosphatic detergents, were first described as 'wonder products' from their marvelous convenience or effectiveness, and great advantages seemed to accrue for industrial societies for many years. The other side of the coin eventually

was discovered: the vast increase in and indiscriminate use of soluble phosphate chemicals resulted in severe ecological imbalances, for example algal 'blooms' on formerly clear bodies of water, and destruction of inland fisheries through resultant deoxygenation of water.

Knowledge of the geochemistry of phosphorous compounds has increased considerably in the course of ecological studies and this knowledge is essential to the proper management of the world environment.

## Distribution of Phosphorus

Phosphorus is present in abundance in the upper lithosphere of the earth, in meteorites, and in the solar atmosphere and is thus believed to be one of the original elements present during the formation of the earth. Phosphorus forms about 0.10 to 0.12 percent of the earth's surface; it is about 11th in abundance of elements in igneous rocks. Although widely distributed in nature, it is never found as a free element because of its strong affinity for oxygen.

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

Phosphorus on 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. Phosphate is present in the atmosphere only as dust, organic debris, and microbial matter. Water-soluble orthophosphate occurs in relatively small amounts because calcium, iron, aluminum, and clay-minerals units readily with phosphorus to form insoluble compounds. Soils contain 0.022 to 0.83

percent P; as just noted, only a small fraction of this is available (or soluble) for plant and microbial use. Phosphate minerals in soils have not been clearly defined.

Ocean and lake waters contain meagre amounts of P: 0.001 to 0.1 ppm in oceans, and trace amounts in rivers and lakes. "Polluted" waters, however, contain considerably more. The oceans, 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).

(Fuller, 1972)[1]

## Phosphate Minerals

Phosphorus is present in both common and rare minerals, and phosphorus-bearing minerals occur both as rich, mineable deposits and as widespread but minor or accessory minerals. Most mineable phosphate is of the apatite series (fluor-apatite to chlor-apatite). Some phosphates are gemstones: turquoise, apatite, variscite. Certain phosphate minerals are also sources of thorium (monazite), uranium (torbernite, autunite), or rare earths (monazite, xenotime). Amorphous and colloidal phosphates occur as nodules in marine environments, as conodonts, bones and coprolites, and as guano. Some secondary minerals include pyromorphite, vivianite , wienschenkite, wavellite and turquoise.

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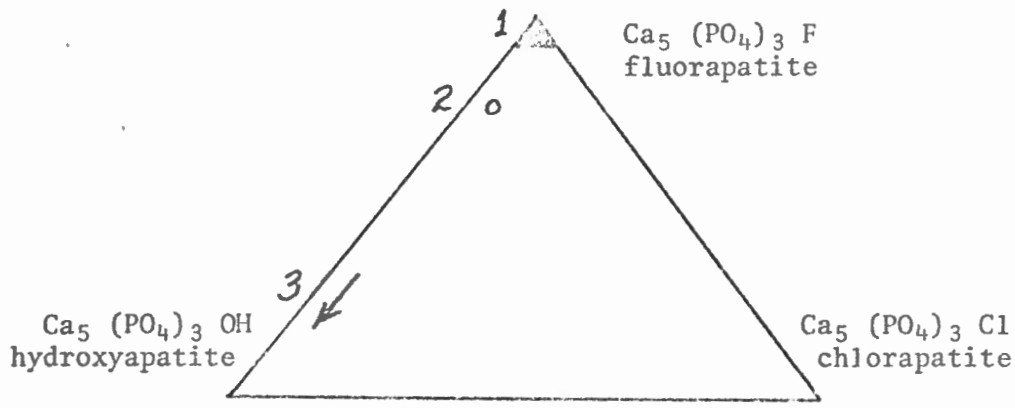
[1] References are given in this report in two formats: a) in the text, and b) following the text. The first form gives the source of a specific fact or concept; the second (as above), the sources for a general discussion or synthesis.

Phosphate in the form of collophane and francolite (carbonate fluorapatites) is present on the ocean and sea floors.

Most sedimentary phosphate minerals may be placed in a series, as shown below:




Notes:

1. igneous rocks, and stable phase under sedimentary conditions.
2. authigenic phosphorite in which $CO_3^{--}$ replaces $PO_4^{---}$ up to a few per cent.
3. modern bones, teeth etc.

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

## Geochemistry of Phosphorus

Phosphorus presumably was present at the formation of the earth's surface primarily as apatite in igneous rock. Weathering of this rock liberated phosphate ions that eventually were distributed among plant and animal systems, deposited in seas, and precipitated as stable compounds in the soil. Soluble phosphorus carried to the oceans by rivers

supported abundant growth of marine life, especially plankton. Precipitation of phosphate from decaying marine life and from the nearly phosphate-saturated ocean water formed phosphorite deposits on the ocean floors; deposits of marine sedimentary phosphate formed from mid-Precambrian to recent time represent the majority of phosphate ores now being mined.

Phosphorus thus is an important component of the lithosphere, the hydrosphere, and the biosphere. The overall '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 cyclical 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 processes 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 that are taken up by living organisms form both diverse organic compounds and an inorganic component of cell fluids; phosphorus is thus concentrated in living matter from a very dilute level in the organism's habitat. Phosphorus is released in the form of orthophosphates upon death and decay of the cells.

The phosphate cycle in soils involves the biological and other cycles: microbial organisms help extract the phosphorus from soils; the 'available' phosphate content of soils directly affects the level of plant growth; and the amount of organic matter returned to soils affects the phosphate level. Mineral interplays, particularly those involving calcium, also take place in soils.

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 may be redeposited: as apatite in a limestone terrane, and as wavellite and crandallite in a clay terrane.

The 'homosphere' has become a significant part of the biosphere in modern times as a result of an explosive increase in human population, destructive agricultural practices, and the extensive mining and distribution of phosphate as agricultural and domestic products. Some processes that result from human activities include: loss of phosphate-rich (humic) soil due to erosion; fixing of phosphates from fertilizers and pesticides in soils to forms unavailable to biological processes; and loss of phosphate from the land and 'dead-end' precipitation in ocean bottoms through disposal of sewage and industrial chemicals.

(Fuller, 1972; Cathcart and Gulbrandsen, 1973)

# III. PHOSPHATE TECHNOLOGY

## Introduction

Phosphates are used for a wide variety of industrial and agricultural purposes, but the principal application is as a raw material in the manufacture of fertilizer. In the United States, fertilizers account for about 76 per cent of the consumption; in less industralized countries the proportion ranges to 100 per cent.

The natural phosphorus in agricultural croplands has, in many regions, become depleted through prolonged crop production and transport of the produce. Productivity can be regained, it was early found, by the application of mineral phosphate to the land. Later, it was discovered that treatment of phosphate minerals with acid produces a soluble phosphate compound, 'superphosphate', that makes the phosphorus more readily accessible to plants. Those agricultural countries of the world in which farming is more organized and productive than on a peasant or 'subsistence' level have come to depend upon a continuous supply of inorganic fertilizers, of which phosphates are a principle component. This dependence was illustrated by the events of World War II, when the international movement of phosphates was disrupted: the fields of Europe were described as 'starved for phosphate' (Noyes, 1944). The demand for some form of phosphate additive for soils will increase as more countries organize their food production to gain revenue or to feed increasing populations.

About 3.5 billion acres (1.4 billion hectares) of land under cultivation throughout the world in 1968 did not provide enough food for all of the people. It has been estimated that by the year 2000 not more

Canada imported about 3.6 million short tons (3.3 million metric tons) of phosphate rock in 1975, mainly from the United States. From available data, it appears that about 90 per cent of the material was used in the manufacture of fertilizers and of stock and poultry feed, and about 10 per cent in the manufacture of chemicals, refractories, medicines and drugs, and in food processing. In Canada, the phosphate fertilizers are normally produced by decomposing phosphate rock with sulphuric acid. Elemental phosphorus, mainly used in the manufacture of industrial compounds, is produced by thermal reduction using coke and siliceous flux in electric furnaces.

Ordinary superphosphate is the simplest fertilizer to make and has been the most widely used. During the 1960s, however, attention changed to higher-analysis products. The more complex triple superphosphate and other derivatives of phosphoric acid, such as ammonium phosphate, now dominate in agriculture, their higher costs offset by savings in transportation costs.

The proportions of the total phosphate consumption that are used for various purposes in the United States, an agricultural-industrial country with a high standard of living, were as follows (in 1970): Fertilizers, 76%; detergents, cleaning compounds, 7%; plating, polishing, and surface treatment of metals, 3%; feed supplement for animals and fowl, 3%; 'other', 11%. 'Other' consists of a myriad of uses:

| | | |
|---|---|---|
| rat poisons | soft drinks | matches |
| fire retardants | toothpaste | dental cement |
| plastics | shaving cream | gasoline additive |
| baking powder | bone china | water softeners |
| dyes for textiles | photographic film and chemicals | glass |

than 4 billion acres (1.6 billion hectares) of cultivated land will be available. The population by that time will be such that widespread famine is virtually unavoidable; the cultivated land will supply enough food only if the productivity of the land is vastly increased as by the application of fertilizer. Most of such additives will be mineral, phosphatic fertilizer.

Technology

Phosphate is a commercial term for a rock, mineral or salt containing one or more phosphorous compounds. Phosphate rock[1] contains one or more phosphate minerals, usually calcium phosphate (apatite), in sufficient quantity for use, either directly or after benefication, 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: $P_2O_5$ equivalent, and "bone phosphate of lime" ($Ca_3(PO_4)_2$) content. The latter is commonly abbreviated to BPL or TPL (tricalcium phosphate). Comparative: 0.458 $P_2O_5$ equals 1.0 BPL.

As noted earlier, most of the world's phosphate production is used for agricultural fertilizers. The most popular of the fertilizers in the U.S., triple superphosphate, contains 20.5 per cent (mean) phosphorus (P). Other superphosphates include 'normal' superphosphate (8.7 per cent P); 'enriched' superphosphate (9.5 to 17.5 per cent P); and 'anhydrous' superphosphate or 'high-analysis' triple superphosphate (23.5 per cent P).

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[1] '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, while 'phosphate rock' is a higher-grade phosphorus 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).

| | | |
|---|---|---|
| insecticides | | pharmaceuticals |
| oil refining | sugar processing | military uses |
| | silk fabrics | |

(Boyd, 1976; Lewis, 1970).

History of Mining

The earliest recorded mining of phosphate rock is 1847, when a few tons of nodules (coprolites) were produced from Pliocene beds near Suffolk in England. Igneous apatite was mined as early as 1851 in Norway. The search for phosphate rock intensified after the discovery that agricultural crops could be increased by the application of bones or phosphate rock that had been treated with sulphuric acid.

The mining of phosphate rock in North America began in the period 1863-70 with the recovery of pegmatitic apatite in the township of North Burgess, Lanark County, Ontario. The ore was shipped to Brockville and to Great Britain for conversion to superphosphate fertilizer. Other deposits in Ontario and Quebec had been noted by 'The Survey' and were soon opened up. The first production in the U.S. began in 1867, when a few tons of South Carolina sedimentary phosphate were mined. Annual production in the U.S. had reached 65,000 tons (59,000 metric tons) by 1870. By 1875, mining of the Precambrian apatite deposits in Canada had virtually ceased because of high land prices and shipping costs. However, a short-lived "phosphate boom" took place between 1875 and 1880 when shipping costs declined and easily mined, high-grade apatite deposits were found in the townships of Wakefield, Templeton, and Hull, Québec. Production began

from the vastly more easily mined Florida deposits in 1888, and by 1890 the price of phosphate rock dropped drastically, ending Canadian phosphate mining. The last activity in Ontario and Quebec took place in 1894; thereafter, phosphate rock was imported from the U.S., except for small amounts of apatite that continued to be derived from mica mines.

Mining began in the 'Western States' (Idaho, Montana, Utah and Wyoming) - the last major deposits to be developed in the U.S. - in 1906. Total production of phosphate rock in the U.S. has about doubled each decade since 1870, except for depression and war years, and by 1970 had reached 38 million tons. World production at that time was about 94 million tons; of this, the U.S. production formed about 40 per cent, that from the U.S.S.R. and Europe, 32 per cent, North Africa, 18 per cent, Asia, 5 per cent Oceania, 3 per cent.

(Spence, 1920; Cathcart and Gulbrandsen, 1973; McKelvey, 1967)

Patterns of Supply and Consumption

The uneven distribution of easily mined phosphate rock and the heavy, world-wide demand for fertilizer to improve food production result in a substantial international trade in phosphate. Phosphate fertilizers, however, require reagents and energy, as do other industrial products, so that the world demand for phosphates has been tempered markedly by increasing costs due to the recent, universal energy crisis.

About 110 million metric tons of phosphate rock are mined annually in about 30 countries of the world, and of this production about 75 per cent is supplied by only three countries: The United States, the U.S.S.R., and Morocco. Quantities in the order of 1,000 to 4,000 metric tons annually are produced from certain islands in the Pacific Ocean, North Viet Nam, and some countries of northern Africa. World prices are set usually by Moroccan producers.

Phosphate rock is consumed mainly by the developed industrial-agricultural countries of Europe, North America, the U.S.S.R., Japan, China and Australia; these countries consume about 85 per cent of the mined phosphate. The United States and the U.S.S.R. together take about 42 per cent of the world's production (both are net exporters, unlike most of the developed nations). The 'developing' nations, on the other hand, consume less than 10 per cent of the world's phosphate.

The commercial history of phosphate rock has been one of steady growth with periods of shortage or surplus. The demand for phosphate rock for the manufacture of fertilizer is continually increasing due to present and predicted world-wide shortage of food. Future production, consumption, and prices, however, are difficult to predict because of such factors as the high capital costs of expanding phosphate rock and fertilizer production and the uncertainty that developing countries can pay for high-priced fertilizer.

The world's resource (reserves and 'potential reserves') of phosphate rock and apatite is considerable: some estimes provide for 1000 years at present production rates. However, other figures--48

billion tons reserves[1] and over 100 million tons annual production[2]--allow only 500 years[3], with no account taken of the evident exponential increase in demand and production of phosphate.

A 1970 review of world demand and reserves of phosphate estimated that the world supply is more than ample to satisfy any demand to the year 2,000.

(Killin, 1976; Lewis, 1970)

Types of Deposits; Mining and Beneficiation

Most phosphate rock is mined by open pit methods. Some underground mining takes place in the Western States region of U.S.A. where top slicing, sublevel stoping, and open stoping methods are used to recover high-grade ore.

Nearly all ore from the residual phosphate deposits of eastern United States must be beneficiated to produce material suited to industrial processing. This is usually accomplished by washing and sizing, with the fines discarded. Phosphate is recovered in a few places by flotation.

A large part of the phosphorite produced in the western mines is of suitable grade as mined; certain ores, however, are beneficiated by flotation or washing.

Phosphate rock has been finely ground and applied directly to the soil in Belgium, Estonia, Poland, and Indo-China. In general, the direct application of phosphate rock is practical in tropical or subtropical

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1 Enc. Brit. (source: U.S. Dept. of the Int., Mineral Facts and Problems, 1965).

2 Killin, 1975, Table 3.

3 But note that the 1974 figure for production used here is about 10 years more recent than the estimate of world reserves.

regions, where acid soil conditions obtain. In Curacao, finely ground phosphate has been mixed with cattle feed.

(Noyes, 1944)

Byproducts

The principal byproducts of the phosphate processing industry are calcium sulphate, calcium silicate slag, and ferrophosphorus. Other materials, such as fluorine, vanadium, and uranium[1], can be separated but at present are recovered either in small quantities or are lost with the waste products.

Impure calcium sulphate is produced in large quantities in the wet process production, using sulphuric acid, of phosphoric acid. The calcium sulphate is left in the mixture in the production of 'single' or 'standard' superphosphate, but is filtered out in the production of phosphoric acid, which in further stages is used to make other fertilizers. For every ton of $P_2O_5$ equivalent, about 4.5 tons of calcium sulphate are generated. In the U.S. in 1968, not more than 0.5 per cent of some 12 million tons of calcium sulphate byproduct was sold as a soil conditioner.

The co-products ferrophosphorus and calcium-silicate slag result from the thermal reduction of phosphate rock in the production of elemental phosphorus. Some of the ferrophosphorus can be used as a ferroalloy in the steel industry. Also, vanadium is extracted (in the U.S.) from ferrophosphorus, where it and other metals are concentrated during smelting. The calcium-silicate slag is normally a waste product, but some is crushed and used as a

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[1] A fertilizer plant in Calgary, Alberta, is being adapted to produce uranium from Montana 'phosphate rock'; the uranium is intended for shipment to the U.S.

concrete aggregate, as ballast in highway and railroad construction, or is foamed to form lightweight aggregate or slag wool.

(Boyd, 1976; Lewis 1970)

Problems

The phosphate mining industry in populated areas shares the problems of any such mining activity: the cost of valuable land, conflict in land use, and the cost of reclamation. In addition, much phosphate ore must be beneficiated before shipping, and the demand for water and disposal space for slimes poses formidable problems. A third set of problems arises during processing or manufacturing stages with the production of more solid wastes and of noxious gases.

Finally, retention of phosphate compounds in waste products in both the beneficiation and manufacturing phases of the industry raises questions of mineral conservation.

The economic and environmental problems of exploitation are most acute in the mining of the Florida land-pebble deposits. The slimes tailings occupy 50 per cent more volume than the original ore matrix and take many years to settle. The industry in Florida has taken major steps toward land reclamation, the prevention of air pollution and the avoidance of pollution of waterways through failure of settling pond dams. Some phosphate resources have become unavailable as a result of competition for land, but the loss has been small.

The country with the most critical land use problem is probably Nauru, a tiny (8 square miles) nation of 3,700 people in Micronesia. About 2.2 million tons of calcium phosphate is mined annually from open pits. It appears possible to mine much of the island to sea level!

Almost all of the ore from southeastern United States, or nearly 90 per cent of U.S. production, must be beneficiated by washing to be usable in industrial processes. The ore is passed through sizing screens, washers, various types of classifiers, and mills to disintegrate clay balls. The tailings are fine slimes, usually minus 200 mesh, with a solids content from 4 to 6 per cent. The slimes are settled in mined-out pits and in large ponds retained by earth dams. A substantial quantity of re-usable water is obtained during settling, yet after 2 years of settling the slimes contain only 25 per cent solids. Hugh areas are occupied by old ponds, and land for new ponds must be purchased at high cost.

The problem of settling of slimes appears to be much less severe in the Western States, where modest settling ponds are adequate for the relatively small production. In addition, advances have been made recently in techniques for settling slimes (R. Kimball, pers. com. 1977).

The demand for land and the pollution of air and water have resulted in adverse public opinion and the passing of restrictive regulations in some regions. On the other hand, considerable effort is now being put into planning (for multiple use of land), land reclamation, and pollution control.

Virtually all sedimentary phosphate ores, raw or beneficiated, contain about 3 per cent fluorine. The conversion of ores by either electric reduction or the wet process releases fluorine as hydrofluoric acid or as silicon tetrafluoride, both of which are noxious gases that must be prevented from contaminating the atmosphere. The fluorine is being controlled, but only a small amount is converted to marketable products, so the removal is a cost to the industry.

The production of large amounts of calcium sulphate in the wet process manufacture of phosphoric acid was noted earlier. The disposal of such quantities of solid waste (12 million tons in 1968 in the United States) presented a space problem and the loss of a mineral resource.

The principle of conservation of mineral resources, applied to the phosphate industry, poses some knotty problems: on the one hand, reserves of phosphate rock appear enormous and a primary requirement for the major use of the material (fertilizer production) is low costs of production and processing; on the other hand, the resource is a finite one, the annual rate of extraction is high and increasing, and the recovery rate for phosphate ($P_2O_5$) is conspicuously low. In addition, the substantial quantities of solid calcium sulphate and a wide variety of minor elements - fluorine, vanadium, uranium, scandium, and rare earth - are lost as waste products, although recovery is possible and for some elements is carried out on a limited scale.

The slimes produced in the beneficiation of Florida phosphate rock contain 5.5 to 7 per cent P - nearly the same values as the original ore; this represents about a 33 per cent loss of the phosphorus resource. Phosphorus is retained, also, in the ferrophosphorus produced in thermal reducation furnaces. To the extent that not all of this byproduct is used, a further loss of resource is represented.

Research in the United States toward improved recovery of phosphorus and the minor elements has resulted in some improvements, for example; the flotation separation of calcite and phosphate (about 1968), and the economical recovery of vanadium. A major improvement in phosphate recovery could add about one-third to the world's proven phosphate reserves.

(Lewis, 1970; Cathcart and Gulbrandsen, 1973; Sweeney, 1972)

# IV. PHOSPHATE DEPOSITS OF THE WORLD

## Introduction

Phosphate ore is mined from three main sources (in decreasing importance): marine sedimentary phosphate; igneous apatite; and guano-derived deposits.

The guano deposits, such as those of Nauru and Christmas Islands, are tiny compared to the world reserves or production. These high grade deposits result from penecontemporaneous alteration of the excrement of birds, bats, and other animals, or from the phosphatization of coral and other material by phosphate-rich waters derived from the organic matter. Guano deposits occur on islands in low latitudes, and along certain continental margins near nutrient-rich, upwelling ocean currents. Guano deposits are late Tertiary or modern in age; no ancient examples are known. Igneous apatite deposits occur in nepheline syenite, in pegmatitic and basic intrusions, and associated with carbonatite. The larger igneous deposits of the world are in the Kola Peninsula of the U.S.S.R., eastern Uganda and Palabora (eastern Transvaal) in Africa, and Araxa and Jacupiranga in Brazil. In the early 1970's about 17 per cent of the world's production of phosphate was from igneous apatite, mostly from the Kola Peninsula and Palabora (Cathcart and Gulbrandsen, 1973; Spence, 1920).

By far the greatest production of phosphate (more than 80 per cent) is from bedded, sedimentary rocks. These deposits have been found on every continent except Antarctica, and range in age from Precambrian to Recent. Most of the sedimentary phosphorites are of marine origin, or result from weathering of marine deposits.

The following notes on the origin of phosphate rocks are concerned only with the sedimentary deposits.

## Classification of Sedimentary Phosphates

Sedimentary phosphate deposits have been classified by several descriptive and genetic schemes. All schemes, however, are complicated by the variety of processes that commonly appear to have operated. The most useful scheme for a study on origins clearly is a genetic one, in spite of uncertainty in status of terms such as eugeosynclinal. The most widely used classification, according to P.J. Cook (1976), is three-fold: A. Geosyncinal type (e.g. Western States field of the United States); B. Platform type (e.g. The North Carolina deposits); and C. Weathered or residual type (e.g. the brown rock deposits of Tennessee). In the present report, Cook's scheme will be adapted and expanded as follows:

A. Marine

1. Geosynclinal (Western States)
2. Platform and shelf (Pamlico Sound, North Carolina; Miocene of Florida)

B. Derived

1. Residual (Tennessee brown rock)
2. Phosphatized rock (Tennessee white rock)
3. Reworked (Florida 'river pebble')

## A. Marine Phosphorites

Phosphorites of marine origin are found characteristically on former continental shelf or slope areas at low to middle (paleo-) latitudes. The deposits are presumed, from younger analogs, to be associated with ancient upwelling of cold, phosphate-rich sea water.

The sedimentary environment is one in which sedimentation was slow or restricted; the phosphate occurs as flat-bottomed, smooth nodules. Associated sediments include black carbonaceous shale, chert or diatomite, sandstone, and minor limestone. Although the phosphate clearly derives from the upwelling seawater, the mechanics of precipitation and accumulation are as yet not entirely clear. Most marine phosphate beds are of Tertiary age or older; few are forming today (Wang and McKelvey, 1976).

Marine phosphorites evidently formed in both geosynclinal and platform tectonic settings. The 'geosynclinal' deposits can be further divided into 'eu- and 'mio-' geosynclinal. Despite differences noted below, however, it must be added that some deposits share attributes of more than one category and are not easily classified, or are intermediate or 'border' in type.

1. Geosynclinal Deposits

i. Eu-geosynclinal: these deposits are commonly associated with thick volcanogenic sequences; they tend to be small and uneconomic. Economic examples lie in eastern Sayan and in central Tien-Shan in central Asia (Cook, 1976).

ii. Mio-geosynclinal: deposits characterized by association with chert, fine organic-rich argillaceous sediments, and carbonates, particularly dolomite. The phosphorites are generally pelletal and commonly extend over large areas, with a high phosphate content through-out. The deposits are commonly folded and faulted. Examples include the Western States phosphate field of the U.S. and those of Karatau in south Kazak Republic of U.S.S.R.

## 2. Platform Deposits

Phosphorites occur as both discrete pockets and extensive sheets on or bordering former cratons. A wide variety of paleogeographic conditions, and hence lithological and structural features, may obtain on stable platforms and shelves; the deposits formed may, however, be classified in two groups:

i) Cratonic basins: deposits discontinuous (as "pockets") or as thin, low-grade beds covering large areas; ore may be within the sedimenatary basins or on the flanks of uplifts. Phosphorite occurs as pelletal, nodular, and massive rock with either a quartzose or carbonate matrix. Associated rocks include limestone, dolomite, shale, glauconitic sandstone, and quartz-siltstone. Water depths are inferred from faunal remains to have been only a few tens of metres and shallow-water features such as crossbedding and scour structures may be present. Examples of such deposits include: Pamlico Sound deposit, North Carolina and the Mishash deposits of Israel (in both cases relatively rich pockets of limited area); Mesozoic of the Moscow Basin of U.S.S.R.; the Ordovician deposits of central Australia (thin, low-grade beds of large areas); and Ordovician and Carboniferous sandstones and shales of Minnesota, Arkansas, and Tennessee.

(Cook, 1976; Cathcart and Gulbrandsen, 1973; Sheldon, 1964a)

ii) Stable shelf, Bahamas Bank type; phosphatic limestone or sandstone and diatomaceous material sometimes present; generally of low grade and only economic when reworked or winnowed by submarine currents. Ore occurs in basins or structural lows on the flanks of domes that were

rising at the time of deposition. Probably barrier islands were built seaward by longshore currents, with sediment and possibly some nutrients supplied by large rivers. Examples are the deposits along the east coast of the United States, from Florida to North Carolina, and phosphate of the Upper Cretaceous Gramame Formation near Recife, Brazil. These deposits were formed along the eastern coasts of continents where wind-driven warm ocean currents and the outflow of surface waters at the mouths of large rivers resulted in countercurrents or upwellings of cold sea water.

## B. Derived 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. Such deposits should also be associated with unconformities and be found as 'subcrop'.

### 2. Phosphatized Rock

Phosphates from overlying phosphate rock or guano may be carried downward by solution under tropical or subtropical climatic conditions to react with and precipitate in a lower part of the weathering profile or in underlying limestone. Apatite is usually formed. Similarly, 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.

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 Bone Valley Formation of Florida is derived from the Miocene Hawthorne Formation.

(Cook, 1976; Cathcart and Gulbrandsen, 1973; Spence, 1920; Gulbrandsen, 1969)

Origin of Marine Phosphorites

The generally 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 rôle in phosphate deposition in both present and former oceans. Other explanations, such as volcanogenic and estuarine origin, have been put forward but shown to be inadequate in one respect or another.

The history of the development of ideas on oceanic upwelling and biogenic origin of sedimentary phosphorites is about as follows. Biogenic origin and precipitation of phosphates was suggested in 1891 by J. Murray and A.F. Renard and in 1918 by G.R Mansfield because of the observed abundance of organic remains in phosphorites. The possibility that bacteria might be agents of precipitation was suggested by D.L. Breger in 1911.

Kazakov, in 1937, proposed the upwelling of the deeper, phosphorus-rich oceanic waters as the source of phosphorus, but emphasized inorganic precipitation of apatite, and concluded that calcite should precipitate before apatite. Experimental work published by A.I. Smirnov and others in 1962 indicated that sea water is slightly undersaturated in phosphorus, but that removal of $CO_2$ would result in precipitation of apatite. C.E. Roberson, writing on experimental work in 1966, concluded that sea water in general is supersaturated in phosphorus and that apatite should precipitate quite readily. But Bushinski, in 1966, made an elementary and important point: than any phosphate precipitated in sea water would be so fine-grained, as shown by experiment, that it would not settle on the sea floor where there is any current activity. Others (e.g. Senin, in 1970) agreed, 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 (1976) reasoned that organic life - especially phytoplankton - can concentrate phosphorus to a high degree, but that 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.

Thus we arrive at the question of the depositional conditions under which phosphorites are formed, and the question of whether collophane is primary or secondary in origin. The textures and structures of ancient phosphorites and the conditions under which phosphate deposition is now taking place should provide sufficient evidence to enable construction of a model or models to account for older deposits.

A complicating factor, however, is the apparent rarity of active deposition of submarine phosphate in modern oceans or seas.

Most phosphates probably 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 about the depth below which the 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 alkalinity[1] (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.

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[1]The 'alkalinity of seawater' is a specialized concept and 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 litre 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 & Moore, 1966).

Petrographic and chemical studies have shown with reasonable certainty that *phosphatization* normally takes place to enrich already phosphatic sediments. Mechanical process (e.g. winnowing) also have served to upgrade phosphatic rocks in many deposits.

How much of the collophane of phosphorites is primary, and how much is of secondary (diagenetic and later) origin? Some phosphatic material clearly is primary: rounded fragments of originally 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 usually considered faecal in origin, but faecal pellets in modern sediments off southwest Africa are only slightly phosphorus-rich, so the pellets of phosphorites appear to have been phosphatized since deposition.

According to Cook (1976), most pelletal phosphorites are not oolites: the pellets are ovular, with no indication of calcite precursors. Diagenetic changes, including phosphatization, calcitization, and silicification are known to occur readily in newly deposited sediment, probably in response to changes in pH. Phosphatization, therefore, probably can take place at or below the sediment surface whether or not calcite is present.

From recent measurements it is known that 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 incorporates other phosphate particles. As lithification procedes in these sediments there is an increase in the phosphate content of the pellets and nodules. Thus it appears that phosphate-rich interstitial

water will phosphatize clays, oozes, calcareous sediments, and biogenic debris to form collophane just below the sediment surface. Further: pseudomorphs of collophane after dolomite have been observed, so that similar chemical or biochemical processes may operate to form both pelletal- and structureless-collophane phosphorites.

An important upgrading process at many localities, both modern and ancient, is that of mechanical reworking of the sediments: changes in ocean currents due perhaps to rise or fall of sea level result in removal of low-phosphate fines. Reworking of sediment is, of course, a common feature of platform sedimentation.

Marine phosphorites thus may originate through the following steps:

1. A prolific biota develops where phosphate- (nutrient-) rich ocean water upwells to 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 as a consequence of low pH and high alkalinity[1] in the sediments.

4. Diagenetic phosphatization of the sediments takes place; perhaps in some instances apatite precipitates directly from pore water.

5. Sediments may be reworked and upgraded. The coarser patches of phosphatized sediment remaining as a lag deposit while the less phosphatic fines are winnowed out.

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

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[1]See earlier footnote.

## V. GEOLOGICAL MODELS FOR PHOSPHATE DEPOSITION

Reconstruction of the paleogeographic and tectonic conditions for some known phosphate deposits suggests that phosphorite can be deposited under widely varying circumstances. Hypothetical "models" may serve as aids in identifying essential processes and conditions; in any case, such models have been used in evaluating known phosphogenic provinces and in delineating promising areas for prospecting.

Some sedimentary models are discussed below in the order followed by the 'geosynclinal' and 'platform' classification used in this report.

### A. Models for Geosynclinal Phosphorite

Ai, Eugeosynclinal: Tasman Geosyncline; a volcanic-flysch trough with intra-geosynclinal tectonic highs (Fig. 1). The occurrence of phosphorite within a mainly clastic-turbidite geosynclinal sequence was described by Howard (1972). The phosphates are associated with black shale and chert, which occur as 'belts' within the thick clastic sequence, related to "anticlines and other structural highs". The model of Figure 1 is constructed to illustrate a possible sedimentary-tectonic situation within the Tasman Geosyncline. The tectonic high presumably would result in reworking of phosphatic sediments and some 'condensation' of the section. Nutrients may have come both from rivers on the craton and from oceanic water via breaks in the orthotectonic orogenic chain.

Aii, Miogeosynclinal: Phosphoria Formation; a flexure zone between a stable shelf and the Cordilleran Geosyncline (Fig. 2). The winds, latitude (and climate), and ocean currents resulted in nutrient-rich water rising onto a shallow-water shelf region with little clastic sedimentation.

A strong association of organic-rich beds and phosphorite suggests dominantly reducing conditions. Both transgressive and regressive phases are indicated by the stratigraphic record, but the changes in depth probably were small and the stratigraphic sections are thin, measured in a few tens of metres. Although the sedimentary trends conform broadly to the north-trending Cordilleran Geosyncline, the Phosphoria basin was roughly elliptical, flanked by low-lying, emergent land masses. Most sediments from the craton were trapped, presumably, in the lagoons east of the miogeosyncline; fine material introduced by a river system to the north, however, was carried by long-shore currents into the miogeosynclinal basin and the zone of phosphorite deposition.

(Sheldon, 1964a; McKelvey *et al.*, 1959)

B. Models for Platform and Shelf Phosphorite.

Bi, Cratonic basin: shallow, transgressive seas with access to open ocean (Fig. 3, 4). Nutrient presumably supplied by upwelling ocean currents and phosphorite formed in shallow water along shorelines and structural-topographic highs. Winnowing due to wave action and currents at these sites resulted in condensation of sections and enrichment of the phosphate deposits.

The Moscow Basin contains phosphatic beds of Jura-Cretaceous age, and from an early description (Bushinsky, 1935) fits the 'platform' model for phosphate deposition (Fig. 3). 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-glauconite sand.

The shallow basins are thought to have contained water of normal ocean salinity and the phosphate is supposed to have grown in intervals, some of which were periods of erosion. The phosphate replaces calcite, aragonite, bones, and calcareous shells and tests.

The Georgina Basin of Australia (Fig. 4) 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 limestone, and by light-coloured, fine-grained phosphorite (Howard, 1972).

(Bushinsky, 1935; British Sulphur Corporation, 1971; Howard, 1972)

Bii, Shelf, or Bahamas Bank type: carbonate rocks deposited on a broad, shallow shelf, with phosphate deposition taking place along positive tectonic elements.

The Florida deposits (Fig. 5) 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 marine phosphatic sediments took place in Pliocene time to form extensive "reworked" phosphorite in fluvial, estuarine, and lagoonal environments. These processes have continued into the Recent so that reworked phosphate deposits of various ages are found. In addition, the grade of many deposits has been raised by weathering during emergent periods and by enrichment by ground water.

(Freas, 1967)

## VI. EXPLORATION FOR PHOSPHATES

Phosphorites are indistinctive white to dark brownish-grey, mainly light-coloured rocks, many of which contain rounded to ovoid structureless pellets or nodules. Phosphatized bone fragments, fecal pellets, and fish and sharks' teeth are frequently found, and glauconite is a common accessory mineral. A bluish to white 'bloom' on the surface and a bituminous odour on the rock being struck by a hammer are additional clues at the outcrop.

Phosphorite is easily overlooked or misidentified; aids to exploration are the more important, therefore, in finding the large deposits that are needed to satisfy the requirements of today's phosphate industry.

Undiscovered large phosphate deposits will almost certainly be marine phosphorites. A 'formula' for prospecting and discovery of at least the miogeosynclinal type of phosphorite 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 States. Similar programs for discovery of other types (e.g. shelf or cratonic basin) of phosphorite were derived during the application of the early 'formula'.

The 'Phosphoria formula' is based on the theory that phosphorites form near strong oceanic upwellings in specific paleogeographic settings: where it appears that upwelling should have occurred, - e.g. in a setting similar to that of the 'Phosphoria basin' - then oil well logs and rock collections are surveyed for gamma ray activity and phosphate content and promising formations are studied in outcrop.

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, Colombia (Sheldon, *et al.*, 1967). In Australia, however, where many sedimentary basins were epicontinental or were shelf-type 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.

In any case, a search for marine phosphorites will begin, as outlined by Cathcart and Gulbrandsen (1973, p. 523), with identification of promising marine sedimentary basins, the most favoured basins being those most similar to one or another of the 'models' for phosphate deposition (*see* preceding chapter, this report). The lithological associations and facies relationships characteristic of the various phosphate deposits provide means for directing the search to favourable parts of the basin or stratigraphic section.

Eugeosynclinal deposits

Phosphate associated with thick volcanic sequences is reported as 'economic' in central Asia, but no literature has been obtained on these deposits.

This type of phosphorite does not appear to be a promising one for prospecting, but the possibility of deposits being present in the large volcanogenic geosynclinal region of the Canadian Cordillera should not

be overlooked. As in the Tasman Geosyncline (Howard, 1972), belts of chert and black shale within the geosyncline may be phosphatic, presumably at least if the section is a 'condensed' one.

Miogeosynclinal deposits

The miogeosynclinal, or Western States type phosphorite deposit has, through relatively thorough study, almost become the 'type' economic phosphate deposit. The black shale-chert-carbonate suite of rocks characteristic of these deposits can be delineated in recognized marine sedimentary basins from geological maps and from oil well cuttings; gamma-ray logs and chemical tests then are used to identify phosphatic beds in the sedimentary succession (Sheldon, 1964b).

The rock suite, black shale - chert - carbonate rocks - and phosphorite presumedly represents slow deposition in areas of upwelling ocean water. Numerous textures are present in phosphorite of this type: pelletal, oolitic, nodular, pisolitic, bioclastic, and coquinoid. Many fish remains are usually present, as may be phosphatic brachiopod shells and phosphatized calcareous shells. The chert beds may comprise various siliceous organisms, a product of silica-rich upwelling water. Sedimentary features often suggest shallow-water deposition and more or less winnowing action. The phosphorite-bearing formations are generally not over a hundred metres thick, but represent, nevertheless, a substantial time interval and may be described as 'condensed sections'.

Prospecting for miogeosynclinal phosphorites is aided by the resistance of the associated chert beds and by the consistent presence in marine apatite of uranium in greater or lesser amounts. The chert is easily identified in outcrop or in drill cuttings and logs, and gamma-

ray logs of oil-well tests allow great thicknesses of rock to be scanned rapidly for phosphorite. Even aerial radiometric data can aid in a phosphate search, which thus can coincide with exploration for uranium.

The facies association of miogeosynclinal phosphorites also can be used in directing exploration. The phosphatic 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'.

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

Platform deposits

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 domes 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. Breccias and conglomerates and other evidence of unconformity in a stratigraphic sequence may be guides to buried, 'derived' phosphate deposits.

Another step usually is required following delineation of a phosphoritic facies in a former platform or shelf region: that is, discovery

of enriched rock, the phosphate content increased through leaching to form either a residual or a phosphatized deposit. For this step, knowledge is required of former or recent erosion surfaces and climatic conditions.

Geophysical Methods

The use of radiometric intruments to detect uranium associated with marine apatite, both in aerial surveys and by means of sensors in drill holes, has already been noted. Lithological and paleontological collections can be scanned by means of a scintillometer, and a portable scintillometer can be carried in the field during study of stratigraphic sections.

Gamma ray logs have been used as aids in regional mapping and in interpretation and evaluation of phosphate prospects. Some uraniferous beds are non-phosphatic, however, so that assay control is necessary in relating $P_2O_5$ grade to radiation intensity (Hale, 1967).

Other geophysical techniques, such as electrical well logging, seismic refraction, and gravity, are used to a limited extend in development work on phosphate prospects. Seismic data have been used to obtain depth and degree of weathering (and hence, grade and ore type under appropriate conditions), and gravity to predict thickness of Tertiary and Quaternary overburden.

## Phosphate Provinces and Phosphates in Geological Time

It has been argued that there is a worldwide cyclicity in deposition of phosphorite, but others dispute this and suggest instead that

phosphate, always present in the oceans, precipitates in response to favourable local conditions. In any case, data enable phosphogenic provinces to be outlined on each continent. Some of these are:

1. a late Precambrian province in central and southeast Asia;
2. a Cambrian province in central and southeast Asia, extending into northern Australia;
3. a lower 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-Lower Cretaceous province in eastern Europe
7. an Upper 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; the original form and extent of the Paleozoic and older provinces depends upon continental reconstructions.

Phosphate rocks are evidently absent from beds of certain ages in given regions, while beds of other ages may be known to contain variously minor or substantial amounts. In an early stage of exploration, however, one would distinguish only between know 'presence' and 'absence'. Such a scheme was followed in a recent exploration program in

Australia, where phosphatic beds were known in five stratigraphic 'levels' between Proterozoic and Cretaceous and were 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 phosphogenic provinces: a late Paleozoic province, apparently a northern extension of the 'Phosphoria' province of Idaho, Montana, and Wyoming; and a Jurassic-Cretaceous, 'Fernie Basin' province of southeastern 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), in the Canadian Shield[1] (Helikian and Aphebian), and beneath the Fernie Basin, in Triassic rocks, in southwestern Alberta.

(Cook, 1976; R.L. Kenny, pers. comm; British Sulphur Corporation, 1971; Howard, 1972; Young *et al.*, 1976)

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[1]Occurrences confidential.

# VII. THE CANADIAN PHOSPHATE INDUSTRY AND AN EXPLORATION PROGRAM FOR CANADA

## Introduction

Canada produces no phosphate ore but has, nevertheless, a well-developed phosphate industry using phosphate rock imported mainly from the United States. (Some ore is obtained from South Africa and from the Netherlands Antilles). Some 13 phosphate rock acidulation plants produce over 1 million short tons (about 1 million metric tons) annually of $P_2O_5$ equivalent; in addition, 2 plants produce elemental phosphorus by electric thermal reduction. The entire production of the acid treatment plants is as superphosphate and ammonium phosphate fertilizer, about half of which is exported to the United States.

An important aspect of the phosphate manufacturing industry is the supply of sulphuric acid, of which an amount (tonnage) about equal to phosphate rock is needed; relatively low-cost and abundant supplies of acid (or sulphur) have been key factors in the expansion of Canadian production capacity for phosphate fertilizer.

The discovery and development of domestic phosphate deposits has been stated as a prime goal in a 'Canadian mineral policy'. A step toward this goal would be the designing of an exploration program for marine phosphorite in Canada; an outline of such a scheme follows.

## An Exploration Program for Canada

As already described, exploration programs for marine phosphorite based on numerous data have been tested on several continents. Concepts and models have been refined so that substantial direction can be given to a modern exploration program.

A search for 'ancient' marine phosphate deposits should consist of three phases: a) identification of marine sedimentary basins and delineation of known phosphogenic provinces; b) consideration of 'model concepts' for phosphate deposition and selection of favourable basins for exploration; c) survey of data and rock collections already on hand and of selected field areas.

## A. Identification of Basins and Provinces

Phosphorites were deposited in marine sedimentary basins; the phosphate content of such sedimentary rocks is presumably retained even where the rocks have undergone considerable metamorphism and disturbance. The uranium in apatite is expelled during recrystallization, however, so that gamma-ray detection may not serve as a useful prospecting aid in altered terrane. Mining practices and costs will be affected by severe folding and faulting. The apatite may be mobilized at higher grades of metamorphism, in which case the mineral will approach a 'hardrock' character and completely different approaches to exploration will become appropriate.

A search for phosphorite might attempt to narrow the limits of the area or volume of rock to be prospected by determining the most favourable sedimentary basins and most favourable intervals of geological time:

i) the various, former marine basins of deposition of Canada can be identified as a first step in estimation of their paleogeographic relationships with oceans and cratons. Knowledge of the geometry of the smallest identifiable, or 'unit' basin and its place in a major geological region such as the Cordilleran Geosyncline or the Western Canada Sedimentary Basin is critical in evaluation of appropriate

sedimentary 'models'. The presence during sedimentation of arches or geanticlinal ridges is evidently critical in 'platform' types of phosphate deposition, and such structures, where known or suspected, should be plotted with other paleogeographical features. Paleogeographic charts for older basins must, of course, take into account former continental configuration. An example of a preliminary, small-scale chart for certain Mesozoic basins in Canada may by seen in Fig. 6.

ii) it cannot yet be assumed that phosphate deposition in Canada was limited to certain geological periods, except in the context of specific phosphogenic provinces. Phosphorite is reported from beds of nearly every age in North America (*see* Fig. 7) although certain intervals, such as Cambrian, Carboniferous, Permian and Jura-Cretaceous appear from present data to be favoured.

B. Application of Concepts, or 'Models'.

The geological features of known phosphorites have been assembled into several sedimentological 'models', described in an earlier section. Canadian marine sedimentary basins for which former latitudes, wind and current directions, and paleogeography can be determined can be 'tested' against the seidmentary models to determine probably favourability for the presence of phosphorite. Such a 'test' might be carried out by means of a series of paleogeographical maps, each map representing an interval of sedimentation or geological time.

A published, small-scale paleogeographical and sedimentological map for Middle Cambrian time in western Canada (*see* Douglas, *et al.*, 1970, p. 377) can serve to demonstrate how Canadian basins might be tested

against the hypothetical models for phosphate deposition. One can compare a diagram or 'cartoon' (Fig. 8) constructed from this map with the models and suggest, for example, that sedimentary-tectonic conditions in the Alberta Trough may have conformed to Model Aii (Fig. 2). Phosphates may have formed, oceanic and climatological conditions allowing, near the hinge line in the eastern part of the trough. Other possible sites for phosphate deposition, such as near the former shoreline on the craton or on the flanks of the Peace River Arch, might also be considered (i.e., conforming to Model Bi, Fig. 3, 4). In the north, the presence of tectonic highs and an evaporite basin (Mackenzie Arch and Trough) may be taken as features that conform favourably to Model Bi (Fig. 4) so that phosphorite could be expected on the highs and near shorelines. Some essential characters of the models (e.g. the chert-shale association of Model Aii) are evidently missing, however, so that suggested probabilities for ore-grade phosphorite at certain sites can be lowered. On the other hand, the presence of glauconite in many of the sediments of the Lloydminister Embayment (Douglas *et al.*, p. 384) is a favourable sign for circumstances following Model Bi.

## C. Surveys

A search for phosphorite will include a wide range of physical tests for phosphate on material from basins judged to be most favourable. In a thorough search, material from all basins will be tested.

Data leading to identification of phosphatic beds can be obtained by the following means:

i) aerial radiometric surveys, both existing and new;

ii) survey of gamma logs of existing wells;

iii) surveys (scanning by scintillometer) of existing suites of rock from stratigraphic sections, well cuttings, and paleontological collections;

iv) chemical tests on collected material;

v) field surveys: examination, collection, and testing of selected exposed section. If cores are available for which no logs exist, these can be tested and logged.

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Model Ai

VOLCANOGENIC - FLYSCH GEOSYNCLINE
WITH "CHEMICAL SEDIMENTS" ASSOCIATED WITH
STRUCTURAL HIGHS: TASMAN GEOSYNCLINE

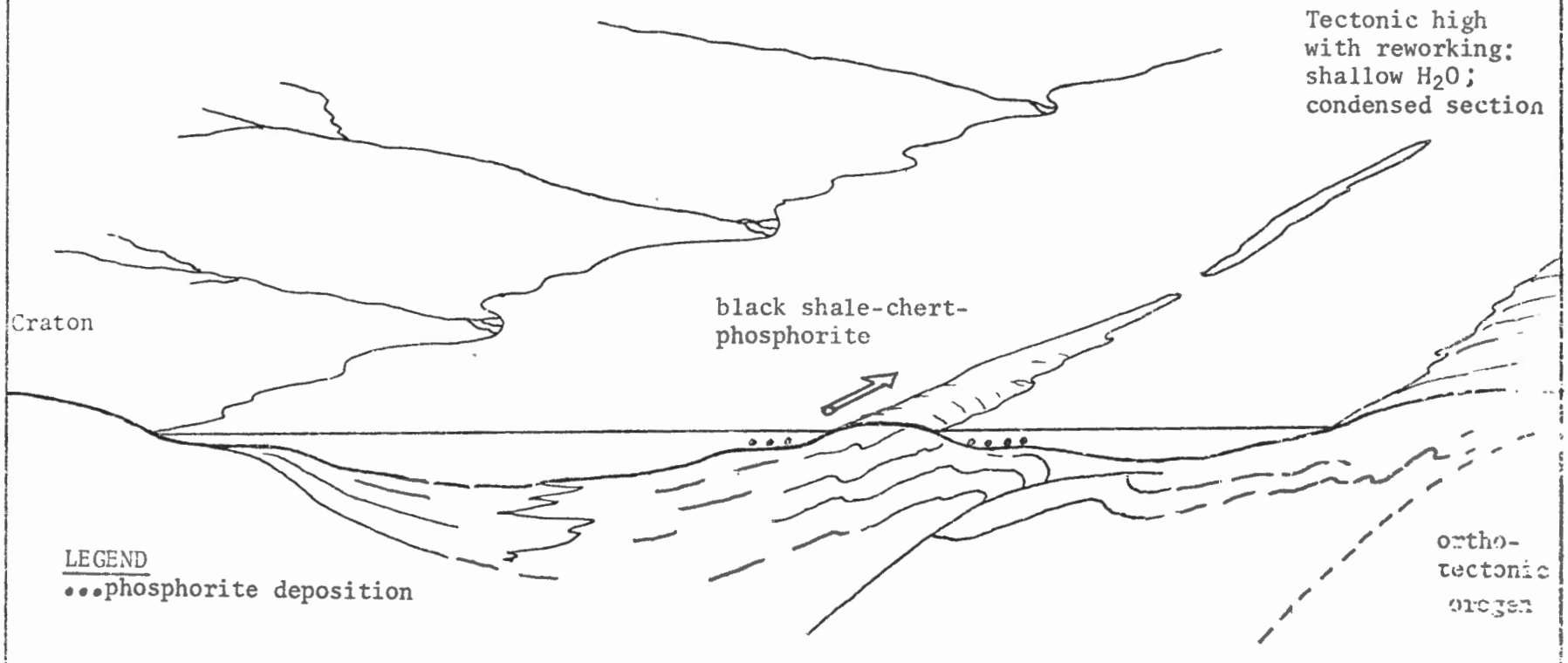



Fig. 1 Sedimentological model for deposition of phosphorite in a eugeosynclinal basin. (ref: Howard, 1972, p. 1185).

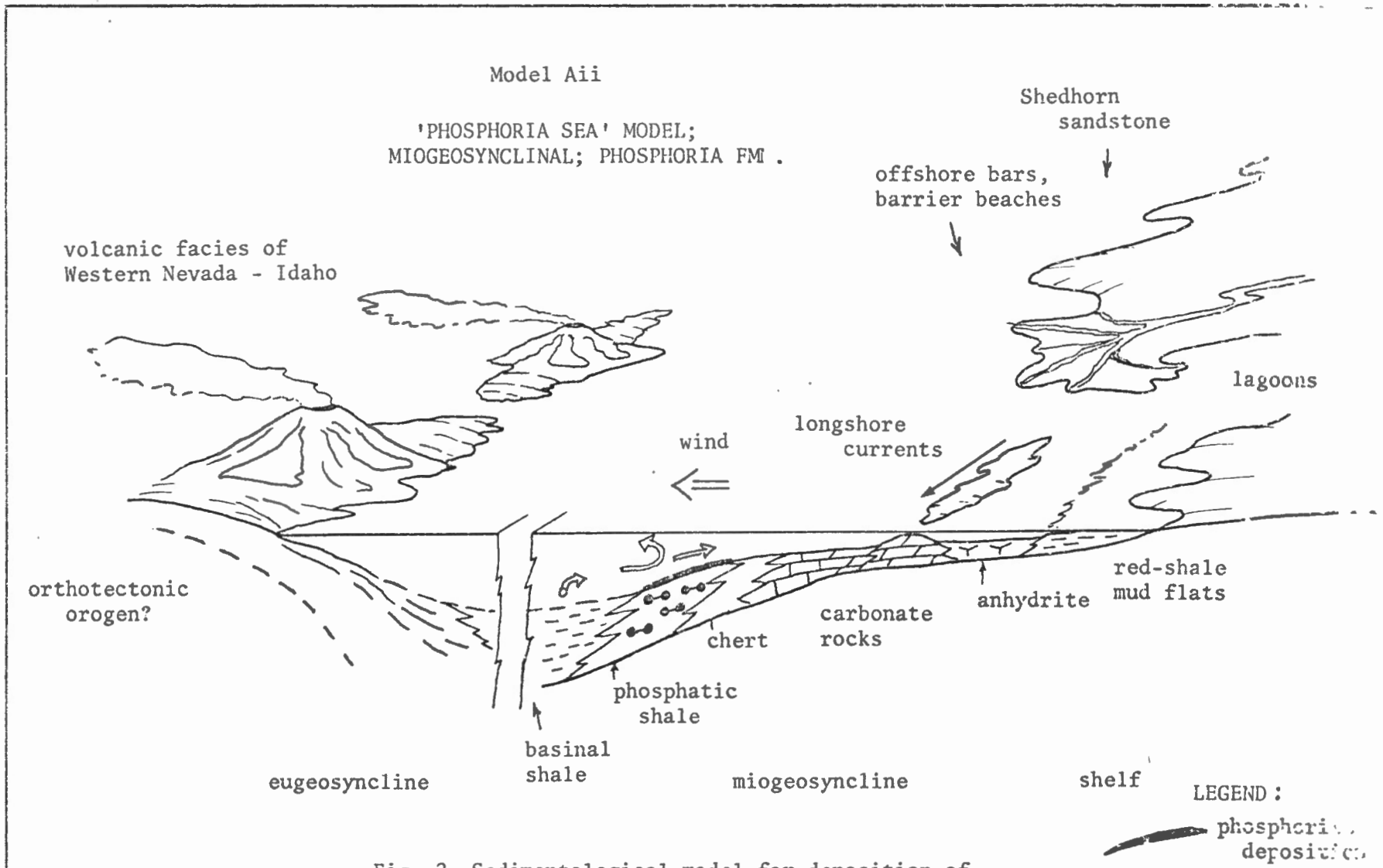



Fig. 2 Sedimentological model for deposition of phosphorite in a miogeosynclinal basin (After Cook, 1976, p. 525, from Sheldon, 1963)

ELC
Sept.

Model Bi

MOSCOW BASIN MODEL: PLATFORM OR
CRATONIC BASIN ("SHALLOW TRANSGRESSIVE SEA")
WITH ACCESS TO SEA, NORMAL SALINITY

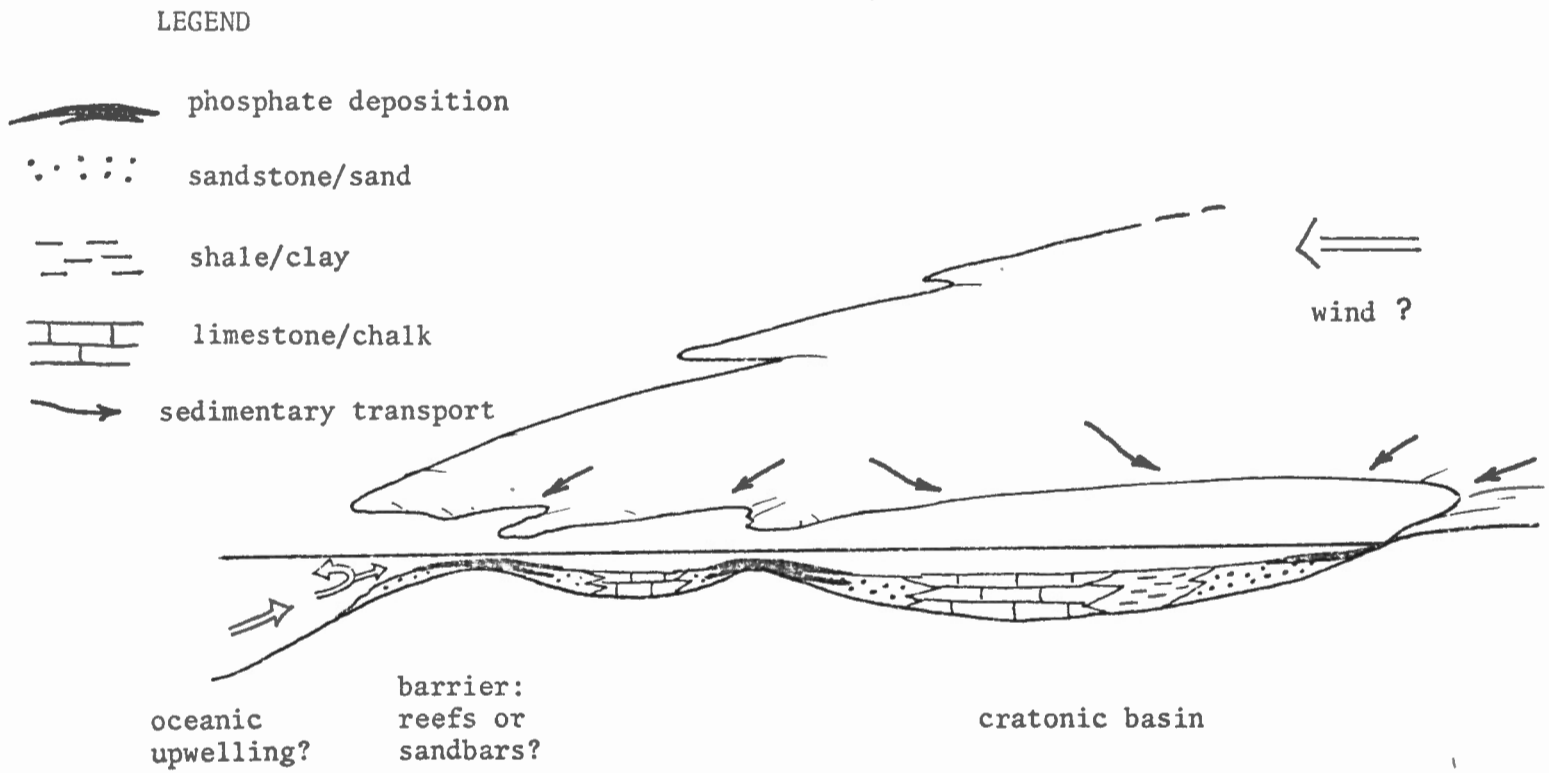
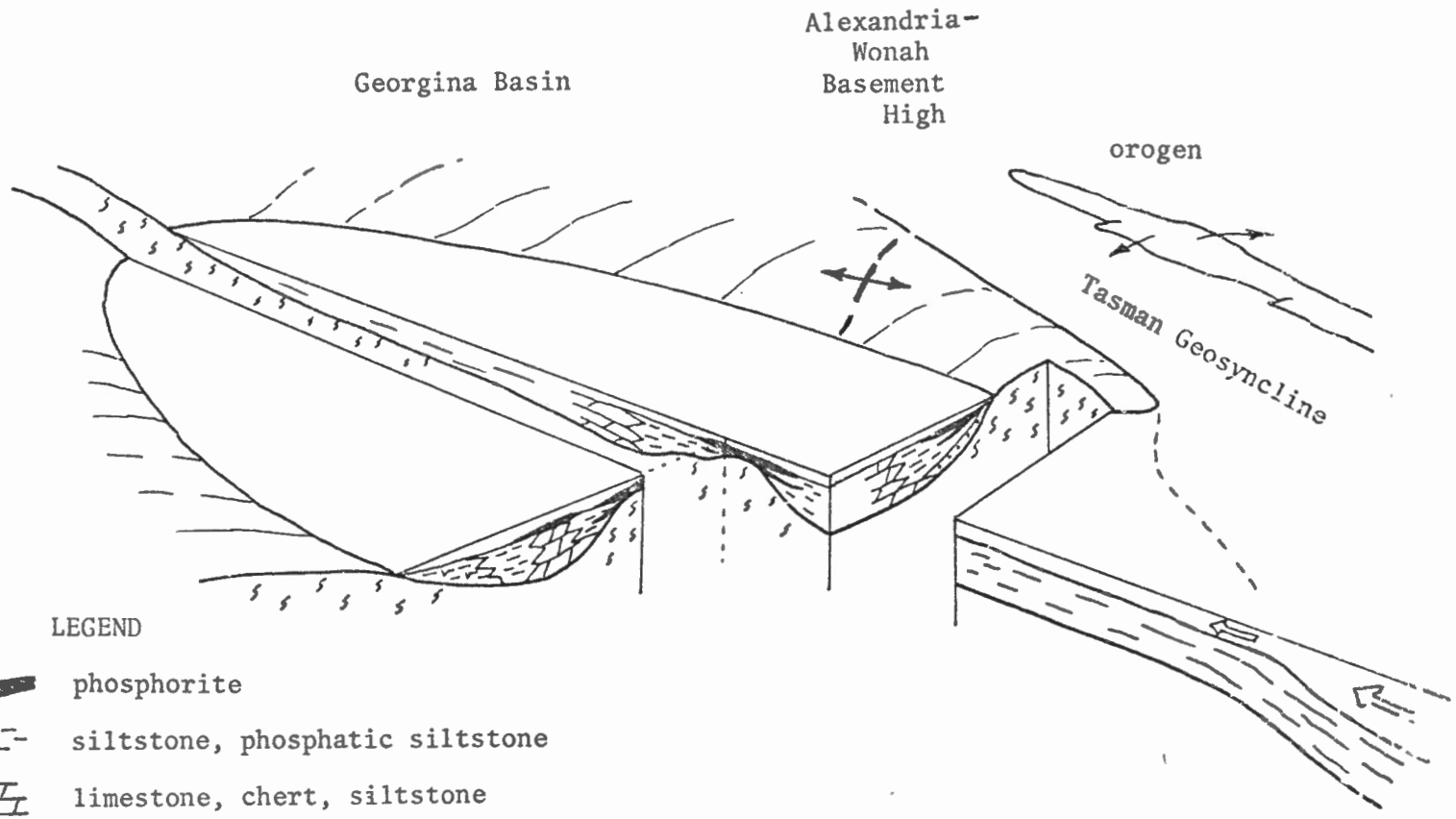



Fig. 3 Sedimentological model for deposition of phosphorite in a cratonic basin.

RLC
Aug/7.

MODEL Bi

GEORGINA BASIN MODEL: EPICONTINENTAL SEA & SHELF
WITH CROSS - TRENDING BASEMENT ARCHES




LEGEND

- phosphorite
- siltstone, phosphatic siltstone
- limestone, chert, siltstone
- red beds: siltstone, sandstone, limestone, anhydrite
- conglomerate, sandstone
- Precambrian basement
- ocean currents

Fig. 4 Sedimentological Model for deposition of phosphorite in a cratonic basin.
(See Howard, 1972)

Model Bii

FLORIDA, OR BAHAMAS BANK MODEL

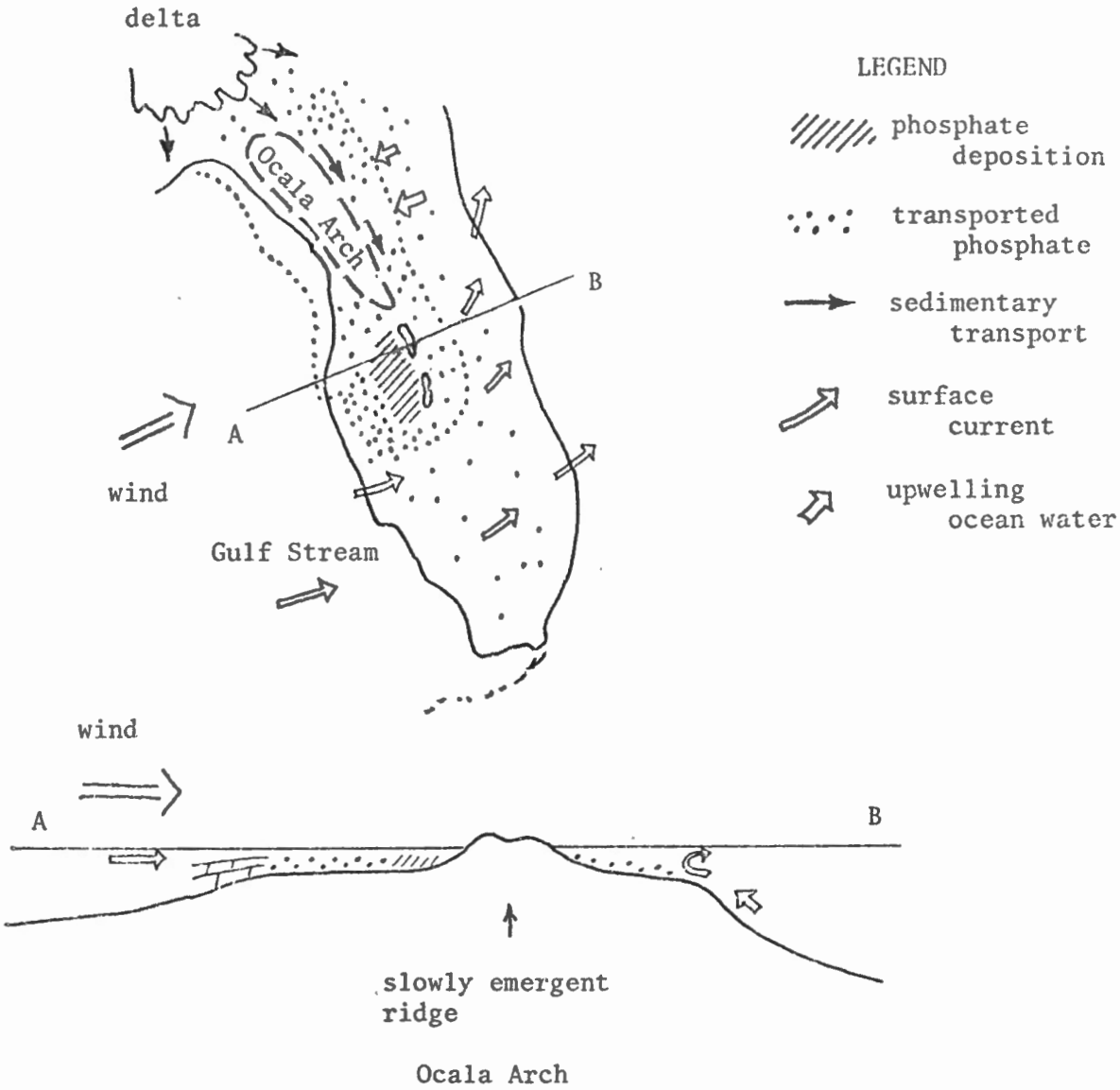



Fig. 5 Sedimentological model for deposition of phosphorite on a continental shelf.

(Freas, 1967)

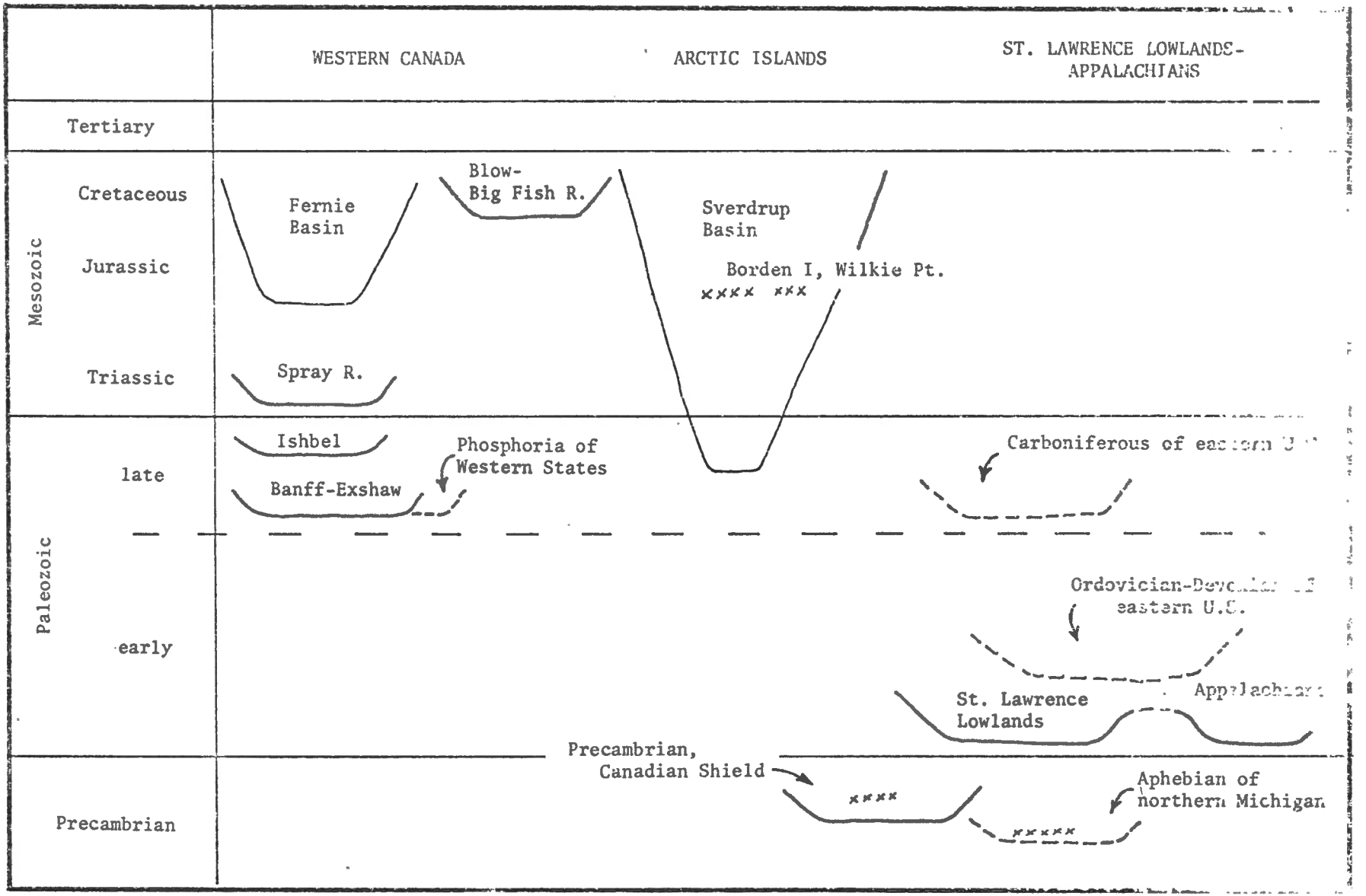



Figure 7: Some phosphogenic basins in Canada and nearby areas

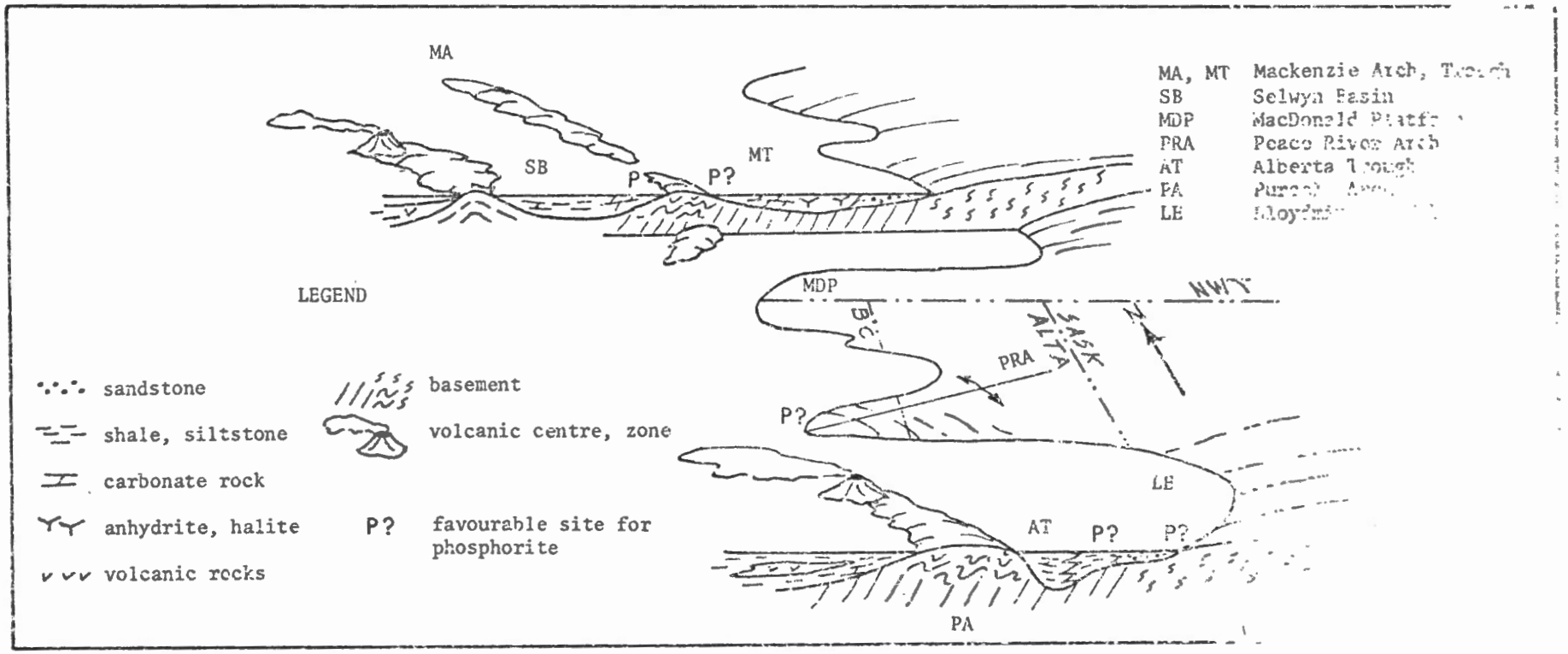



Figure 8: Paleogeographical and sedimentological diagram for Middle Cambrian time in Western Canada (based on figure, Douglas *et al*, 1970, p. 377).