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AN APPROACH TO THE SEARCH FOR SEDIMENTARY PHOSPHATE

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FOREWORD[*]

The Australian demand for phosphate as a fertilizer has increased so much in recent years that it has surpassed the output from Nauru, Ocean, and Christmas Island, and phosphate has had to be imported from other sources. The search for indigenous phosphate deposits has therefore acquired a new impetus, and the Commonwealth Government is encouraging both private companies and public organizations to intensify it.

For a number of reasons, the sedimentary basins hold the most promise of potential sources of phosphate on the continent and it is therefore logical that an Australia-wide search should first concentrate on this type of occurrence.

The mechanics of the search for and identification of phosphate deposits in the field, using methods such as examination of outcrop, chemical testing of specimens, bore cores, and cuttings, and the measurement of radioactivity from the air, on the surface, or in bore holes, are fairly well-known. These play a vital part in any successful search for phosphate, but need to be applied to carefully selected areas.

This record deals with concepts and methods by which critical areas and rock sequences may be selected rather than with complementary field procedures appropriate to the detailed examination of favourable terrain. Discussion of these fundamental aspects will be closely followed, in a later Record, by an analysis of an Australian sedimentary basin as a suggested prototype for basin studies. In this way, it is hoped to encourage a fundamental approach to phosphate search as a sound basis for a developing programme.

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[*] The above "Foreword" is by L.C. Noakes of the Bureau of Mineral Resources, Canberra, A.C.T.

AN APPROACH TO THE SEARCH FOR SEDIMENTARY PHOSPHATE

by

J.A. Kaulback

Phosphorite, for the purposes of this discussion, is defined as a sedimentary phosphatic rock.

Phosphate is relatively common in sedimentary rocks; but most occurrences are of too low grade to be of economic value, and, moreover, their presence is no indication that higher-grade deposits are likely to be found in the vicinity. So the indiscriminate testing of phosphate-bearing rocks is not a good basis for exploration. Only if environments and rock sequences are considered in the light of genesis of phosphate can criteria be applied to guide field investigations. This record, therefore, discusses the origin of phosphate in rocks and the favourable milieu and rock sequences in which it would accumulate, and develops a method by which field data may be analysed and favourable areas delineated.

A sedimentary phosphorite is a product of the interaction of two normally exclusive environments, each governing its own set of special processes - the ocean and the continent.

A. Phosphate in the Ocean

Phosphorus in the oceans takes part in the cyclic exchange of chemical elements between sea-water and organic matter: inorganic phosphate in solution is synthesised by plants - phytoplankton - which support zooplankton and other animals. The phosphate is regenerated through the decomposition of organic material or dissolved organic matter, which can originate as a metabolic product or from excreta. Bacteria are known to play a role in the phosphate cycle, but the nature of this role is unknown.

In present-day oceans phosphate is most concentrated in cold, deep, stable bodies of water (e.g. deep waters of Antarctic, North Pacific and the Timor Trough), which have a slow circulation and little exchange of water with water-bodies from other areas. This is principally because in shallow regions, and particularly in the euphotic zone, the available nutrient elements are used up by biota, which then take part in the general downward movement of particulate matter, living or dead, away from the surface layer to the ocean deeps, where a phosphate reserve is formed.

However, the store of nutrient elements, including phosphate, in the euphotic zone is continuously replenished from deeper water by processes of vertical diffusion, convection overturn, and upwelling. In regions where these processes are active, large biological populations can be supported: such regions occur in the open oceans at the Equator and at the northern boundary of the Equatorial Countercurrent, and along continental coasts where the prevailing winds are such that upwelling is induced (Morocco, Southwest Africa, California, Peru, and possibly the north coast of Australia). There are regions, on the other hand, where surface water-bodies, depleted of their nutrient elements by biota, converge and are drawn downwards; here waters low in nutrients may extend for a considerable distance below the euphotic layer.

Rivers contribute a certain amount of phosphate to the sea surface, and may have been its original source, but their contribution at the present time is negligible in comparison with that of these processes.

In basins, the distribution of nutrient elements is generally different from that characteristic of open oceans. In well-aerated basins, where there is inflow at the surface (such as the Mediterranean), the nutrient content is usually low. In restricted basins of low oxygen content (such as the Red Sea), the nitrate and phosphate contents are relatively high. In stagnant Norwegian fjords, where hydrogen sulphide is present in the water, phosphate content is extremely high (10 mg atoms/L).

B. Phosphate of the Continent

Erosion produces three broad types of sedimentary deposit:

(a) Biochemical - where the humic and organic components are predominant, and chemical solutions are carried into the basin.

(b) Residual - where residual particles are carried into the basin.

(c) Detrital - where the coarser debris of the source rocks is carried into the basin.

Only biochemical deposits (dolomites, limestones, argillites, cherts,) seem likely to be capable of providing a regular supply of phosphate for the basin (in phosphatic solutions), apart from the exceptional cases of direct erosion of phosphate-rich rocks. However, the proportion of phosphate in biochemical deposits is very small compared to the other biochemical materials brought to the basin in solution, and it is difficult to imagine how phosphate can become a major constituent of a resulting sediment in the presence of this relative abundance of other material; in fact, the study of deposits resulting from biochemical erosion and transport shows that most of them, such as the large magnesian argillaceous and cherty sequences, contain little or no phosphate, inferring that biochemical erosion has been contributing phosphate to the phosphate reserve of the oceans. (At the end of a long period of biochemical sedimentation this contribution, if confined to the basin, can become important.)

The phosphate reserve of the oceans thus appears to be the most likely source from which important deposits of phosphate can be accumulated. Water in present-day ocean deeps contains up to 20 times more soluble phosphate than surface waters; Kazakov (1937) suggested the formation of phosphate deposits by phosphate-rich marine currents ascending from ocean deeps where phosphate would be more soluble.

This idea accentuates the anomalous relationship which in nature often exists between a phosphatic zone and its surrounding, normally phosphate-barren sediments. The latter are directly derived from the continent; the former from solutions which have previously accumulated in the oceans over long periods of time.

LINES OF REASONING GUIDING THE SEARCH FOR PHOSPHATES

The search for workable phosphate deposits is fundamentally concerned with this antithesis between phosphate-rich and phosphate-barren rocks. Since these two types of deposits have a radically different genesis, one related to solution in oceanic reserves, the other to materials derived directly from the continent, a basin where both exist may be deduced to be supplied in both ways at the same time. Other things being equal, barren sedimentation, because of its abundance and its possible inhibiting properties, has a strong chance of predominating. Thus, for the formation of a phosphate deposit, the following must have existed in the area of deposition at the same time:

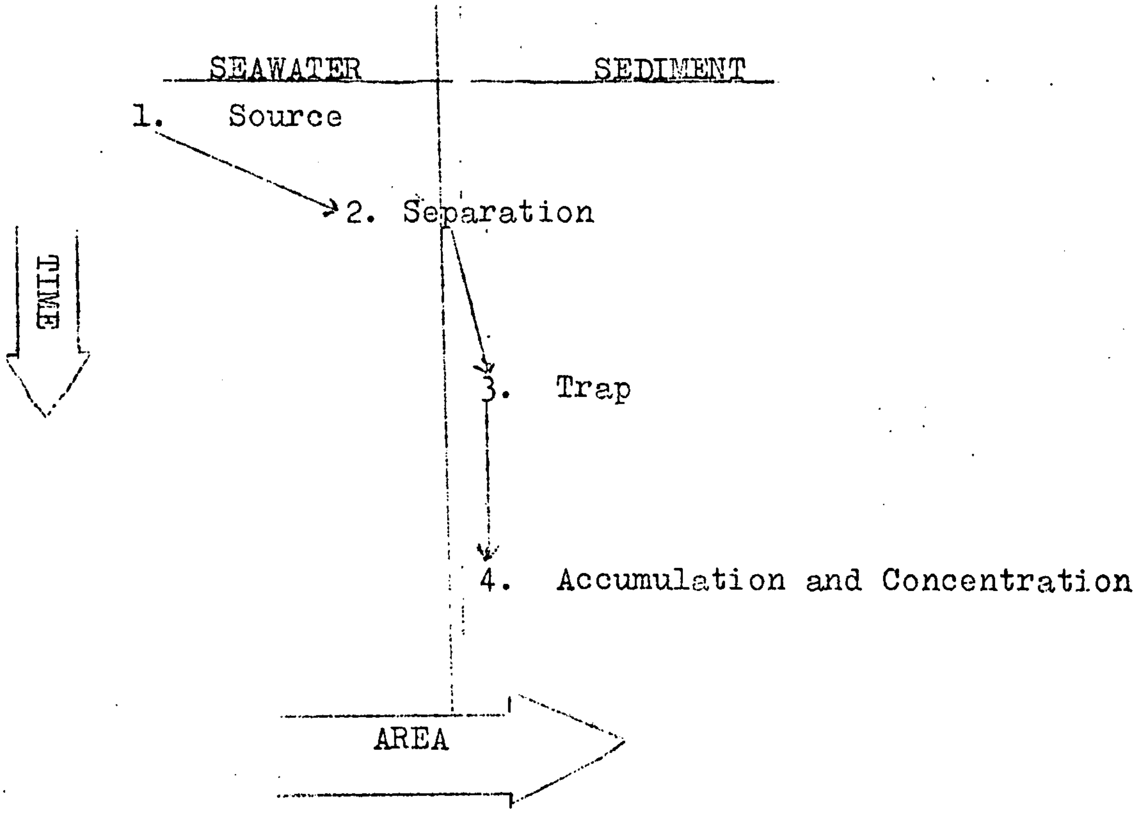
(1) A source of phosphate
(2) A mechanism for separating phosphate from its source
(3) A mechanism for trapping phosphate into sediment
(4) A means of accumulation and concentration of phosphate (implying, also, a time and place unfavourable for abundant barren sedimentation).

In the search for oil, a universal formula has been adopted for convenience, which contains the three factors necessary for the existence of an economic oil field; source rock, reservoir rock and trap. Under these three headings can be combined a variety of circumstances, lithologies and origins. All three may not be discovered, but they must all exist if there is to be an economic accumulation of oil.

In the same way it is possible to formulate the primary factors necessary for the existence of an economic deposit of sedimentary phosphate in such a way that they can be universally applied to sedimentary phosphate deposits with different genesis and mode of accumulation. This has the advantage of enabling the prospector to programme the search for phosphate regardless of the vagaries of current theories about origin. These factors can be formulated thus:

(1) Phosphate SOURCE
(2) Phosphate SEPARATION MECHANISM (from Source)
(3) Phosphate TRAP (into sediment)
(4) Phosphate ACCUMULATION AND CONCENTRATION (within sediment into an economic form).

DIAGRAMMATICALLY:



(1) SOURCE

A basin must have access, at the time of sedimentation, to the phosphate reserves of the ocean deeps. This is a palaeo-oceanographic and also a sedimentological problem, in which faunal ecology plays a role.

(a) Palaeo-oceanographic criteria: it is difficult or impossible to determine directly the times when currents brought phosphate-rich solutions to areas of deposition from the ocean deeps. But indirect evidence is commonly helpful - the age of known phosphate indications in the local stratigraphical succession or in neighbouring basins, or the study of fossil microplankton and other fauna, which are directly dependent on water-borne nutrients.

(b) Sedimentological criteria: as the phosphate reservoir of the ocean is permanent, phosphatogenic currents can have their effect at any point in the sedimentary cycle. However, it has been noted from many places (Togo, West Africa, North Africa, Columbia) that important phosphatic deposits occur at the end of a cycle of chemical sedimentation which itself is poor in phosphate but appears (page 4) to have contributed phosphate to the marine reserve. Workable phosphate deposits are therefore probably not related simply to the phosphate reserve in ocean deeps, but more specifically to the proximity of the ocean reserve from the inception of and during the period of phosphate-barren biochemical sedimentation.

It seems therefore that a long period of phosphate-barren chemical sedimentation, particularly towards the end of a sedimentary cycle, can be an indicator of specially favourable conditions for phosphate genesis.

Practically, proximity of a source can be deduced from the lithology itself from (a) evidence of chemical supersaturation, precipitation or aggregation: nodules, concretions, pellets, ooliths etc., and (b) microplankton swarms, or related fauna, which are dependent on nutrient-rich water.

(2) SEPARATION MECHANISM

Phosphate must be separated from its source in order to be trapped and accumulated in sediment. For this, many mechanisms have been invoked. All of them dependent on physico-chemical changes which would liberate phosphate from solution. In the case of phosphate-rich water flowing from ocean deeps, for instance, phosphate loss from solution to suspension may be due to the fall in hydrostatic pressure of the rising water body, to temperature differences, or variations in pH. Such changes in physico-chemical conditions would be caused if bodies of deep water were forced upwards by marginal slopes or elevated submarine offshore regions, by divergent oceanic circulation, by normal upward basinal circulation, or by nutrient- rich waters entering restricted and stagnant basins.

Moving water-bodies, or currents, are directly interpreted from current-bedding, ripple-marks etc., and indirectly by concentrations of microplankton and other fauna, and organic chert. There are numerous lithological criteria by which marginal slopes, offshore regions and stagnant or restricted basins can be detected.

A restriction in the area where the phosphate-rich water-body is subjected to physico-chemical changes would induce more concentrated precipitation. Channels, gulfs or embayments would have such a restricting effect.

(3) TRAP

The phosphate released from its source by the Separation Mechanism must be trapped into or fixed as sediment lest it becomes re-circulated, dispersed or redistributed. With upwelling, for example, phosphate precipitated from solution to suspension through fall in hydrostatic pressure would probably be finer and therefore lighter than the sediment suspended in the water, and could be widely dispersed unless some mechanism were present to trap it into the sediment. Suspended phosphate could be trapped into sediment by adsorption by fine sediment particles (Jitts, 1959), or it could accrete into pellets in suspension, which would sink to the sea floor. Over carbonate provinces, phosphate may be abstracted by organic processes (shells) or mechanical and chemical processes (ooliths). In regions of fast currents, precipitated phosphate may be driven mechanically on to rock or pebble surfaces, to form successive layers (D. Freas, pers.comm.). Sediments capable of absorbing or localising phosphate in the sea would be: siltstone, mudstone, oolite and shelly sediments.

(4) ACCUMULATION AND CONCENTRATION

Sediment containing phosphate is likely to be economic only where dilution by barren material is low: ideally a time and place with no concurrent deposition of phosphate-barren sediments is required. Economic deposits are also commonly concentrated into pelletal or nodular form.

(a) Time unfavourable to barren deposition

Certain periods of the depositional cycle are favourable to barren deposition. At times of pronounced continental relief, erosion is lively, and detrital deposits are abundant. As the continental relief is gradually diminished, erosion is less energetic, detritus decreases in grain-size and volume, and, if the climate is favourable, vegetation increases the obstacles to direct erosion of soils or source rocks. At this stage basin sedimentation is transformed, and the detrital influx is slowed down and begins to alternate with solutions of the biochemical phase. It should be noted that at this point in the cycle are found the phosphate deposits of Senegal and Dahomey (Slansky, 1962).

Towards the end of the cycle chemical sedimentation becomes dominant but is generally less abundant than the detrital sedimentation and, as it is much more dependent on the physico-chemical condition of the basin, with many periods of extremely slow sedimentation.

After a long period under conditions of biochemical sedimentation, if a new cycle is not initiated by diastrophism, biochemical sedimentation gradually diminishes, either through the slowing down of chemical attack on the rocks by the depth of soils, or because of climatic change; in this case the detrital contribution remains small because of the abundance of vegetation which still persists, and because of the low relief. In either case, the most favourable time for the maximum inhibition of barren sediments in the area of deposition is at the end of a long period of biochemical sedimentation.

(b) Place unfavourable to barren deposition

Sediments are normally more abundant in the troughs or subsiding zones of the depositional areas; they are least abundant at the basinal margin, at the border of the continental talus, and above all on elevated offshore regions.

The determination in detail of zones with reduced sediment is a palaeogeographic problem which needs for its resolution precise stratigraphic, sedimentological and structural data. Isopach maps and facies variations are in this case particularly valuable.

A lack of sediment can be due to non-deposition or to post-depositional current and winnowing action. Both conditions are found in the regions listed above and in back-reefs, and direct evidence of them can be found in the sediments: condensed sections; current bedding, sandstone and pebble lenses in silt and other evidence indicating winnowing, and current activity; disconformities, etc. Both conditions are favourable for phosphorite formation.

(c) Time for phosphorite accumulation and concentration

The longer the processes of phosphate deposition and accumulation last, the richer the deposit is likely to be. The time elapsed between the separation of phosphate from source and the trapping of phosphate as or into the sediment is important in controlling the location, grade and extent of a sedimentary phosphate deposit: if the phosphate passes quickly from source to sediment, it is likely to be deposited in localised areas which may be relatively easy to predict; if, however, the mechanisms involved in trapping phosphate in sediment are slow or absent, the phosphate will either be dispersed over a larger area or localised later by accidents of currents, circulation or bathymetry.

In addition, time may be necessary for concentration within the sediments.*

CONCLUSION

This short note does not treat the whole problem of phosphate search. It simply indicates an approach to phosphate exploration which involves the systematic study of the sediments according to the broad principles of a universal, genetic formula. This formula summarises the principal factors in the formation of phosphorite as 1. Source, 2. Separation, 3. Trap, 4. Accumulation and Concentration.

A study of this kind is an essential preliminary to exploration in the field. It can result in the elimination of extensive non-productive areas, and in the selection of areas and formations with relatively high phosphate potential, suitable for further investigation; it gives the exploration-programmer a basis for estimating

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* There is very little knowledge or evidence of an absolute rate for the formation of sedimentary phosphorite. The Phosphoria Formation took about 15 million years (or less) to accumulate, during which time between 15 x 10^{12} and 68 x 10^{12} tons of P_2O_5 would have been brought to the sea, at an esitmated rate of between 1 and 4.5 million tons annually. (Clarke, 1924; Conway, 1942; Kazakov, 1950). The Phosphoria Formation itself contains about 1.7 x 10^{12} metric tons of P_2O_5 (McKelvey et.al., 1952).

an area's potential and for deploying his resources. *

Analysis of an area under exploration can be conveniently divided into two parts:

(1) A Preliminary Analysis, which seeks, in a broad way, to eliminate non-productive areas and sections of the stratigraphic column, such as non-marine rocks and thick detrital sequences, as well as to delineate formations, lithofacies and areas favourable for phosphorite occurrence in terms of the four principal factors;

(2) Detailed analysis, which selects particular lithological zones within these chosen areas, in which phosphorite is most likely to occur.

Phosphorite is the product of positive marine influence in the form of precipitation, on the one hand, and of negative continental influence, in the form of sparseness of barren sedimentation, on the other. Evidence of both influences should be sought in the lithological column.

For example:

First: select marine sediments which show evidence of access to source during deposition.

Second: pay particular attention to sediments which were deposited at the end of long periods of biochemical sedimentation.

Third: from these areas eliminate thick detrital sediments.

Fourth: isolate areas where sedimentation was probably sparse (such as basin-marginal areas and highs on the sea-floor contemporaneous with sedimentation).

These analyses are only as reliable as the geological information available, and the possibility of phosphorite occurrence can only be proved or disproved by fieldwork.

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* Analysis of sedimentary basins along these lines is designed as a guide to potential primary deposits. Indications of secondary deposits, in which phosphate has been chemically or mechanically concentrated from lower grade sediments, are commonly far less well defined; but at least areas which have been delineated as favourable to primary mineralisation are also the best, although not the only, locale for secondary accumulations.

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