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PRELIMINARY APPRAISAL OF THE AUSTRALIAN CONTINENT FOR SEDIMENTARY PHOSPHATE DEPOSITS

by

RICHARD P. SHELDON

* United States Geological Survey.
Assigned by arrangement with
Director U.S.G.S.

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SUMMARY

Exploration for phosphorite can be efficiently carried out by using modern knowledge of the geology of phosphorite. This hypothesis essentially consists of looking for sedimentary, tectonic, and paleogeographic environments that are known from observations of modern phosphorite on the ocean floor and studies of ancient phosphorite to be favorable for phosphorite deposition. This type of phosphorite is deposited by divergent upwelling ocean currents. Despite the success of this hypothesis, in other parts of the world, if it is used to the exclusion of all other approaches, some phosphate deposits of other origins could be overlooked.

The lower Paleozoic of eastern Australia appears to be a potential phosphogenic province, based on the occurrence of the suite of rocks found in areas of divergent upwelling ocean currents, favorable paleolatitudes, and paleotectonics. Phosphate rock occurs at many localities scattered through central and western Australia and in rocks from Ordovician to Cretaceous in age. Despite these indications, for several reasons this area does not seem as highly favorable for the occurrence of large phosphate deposits as the lower Paleozoic of eastern Australia. The area was tectonically stable so that deep seaways were probably absent, and if so, this would preclude major upwelling ocean currents and the chance of major deposits of phosphate. During much of this time the latitudes were probably too high for significant phosphorite deposition. Finally, tectonism in these areas in general has been too weak to bring any potentially phosphatic basinal facies to the surface.

INTRODUCTION

I was asked by the Bureau of Mineral Resources to assist them in their role in the exploration for rock phosphate in Australia. In view of the large amount of current exploration for phosphate by private industry in the country, a major part of the assignment has consisted of visiting the company geologists in the field and in the office to get a concept of the problems facing them. In addition field reconnaissance of most of the basins where phosphate may occur was carried out to see a representative stratigraphic section in each basin and get an idea of the basin tectonics and sedimentation. Finally, most of the important known phosphate localities were visited.

I spent a little over 4 months in Australia from September 1965 to January 1966. After two weeks of conferences and reading in Canberra on arrival, I visited the Darwin area for a week to see the Rum Jungle phosphate deposits, the Lee's Point phosphate nodule locality, and a small outcrop of Ordovician rocks in the Daly River Basin. This was followed by a trip from Derby to Perth by land rover where L.C. Noakes, S. Marchant, D.J. Guppy, and I visited the various phosphate localities and stratigraphic sections in the Fitzroy Trough and Canning, Carnarvon, and Perth Basins of Western Australia. Noakes and I then visited Christmas Island for 6 days to get a concept of these deposits. This was followed by field trips to the Amadeus Basin, in the Northern Territory, the Cambrian and Ordovician rocks of central Victoria, the Tertiary rocks of the Otway Basin in Victoria, the Adelaide Geosyncline in South Australia, the Bowen Basin and the lower Paleozoic rocks near Rockhampton in Queensland, and the Cambrian rocks of the Undilla Basin in north west Queensland.

During the course of the trip I had conferences with the following companies involved in phosphate exploration: IMC Development Corp, Oro Grande, Mines Exploration, British Phosphate Commission, Cyanamid, Electrolytic Zinc, Planet Oil Co, Phosphate Exploration, Continental Oil Co., and Esso Oil Co. Very profitable conferences were spent with the Geological Surveys of Western Australia, South Australia, Tasmania, Victoria, New South Wales, and Queensland. I gave lectures on the geology of phosphorite to the local divisions of the Geological Society of Australia in Perth, Melbourne, Adelaide, Brisbane, and Sydney, to the A.I.M.M. in Canberra, to the geological staff of the Mt. Isa Mines Co. in Mt. Isa, and to the Geological Survey of Tasmania in Hobart. Most of these lectures were given at the local universities so that I had the opportunity of conferring with their faculties. The last month of the project was spent in Canberra writing reports and studying the literature on the geology of Australia.

To acknowledge the geologists who helped in this program would be to acknowledge a good portion of the geologists of Australia. Their generous support made the project possible. In particular the geologists of the Bureau of Mineral Resources and the geologists of the phosphate mining companies were helpful. L.C. Noakes of the BMR was almost wholly responsible for setting up the program and was indispensable for its success.

Although the field trips were not designed as an exploration program, two specific areas of interest were turned up. Nodules of medium grade phosphate were found in the Langey Siltstone of Jurassic age by the Fitzroy River near Derby. The extent and value of the deposit is at present unknown. In the Undilla Basin, Queensland, the Inca Formation of

Cambrian age consists of a chert and shale assemblage, which is known to be associated with phosphorite in other parts of the world. Although no phosphate was found in outcrop, cuttings of a bore show anomalous P_2O_5 values, one 10-foot interval reaching about 4 percent P_2O_5.

This report deals with the rock phosphate potential of Australia. It is impossible to assess adequately a country the size of Australia for any mineral in so short a time. However, if the geology of a mineral is fairly well known, it is not too difficult to delineate the more promising areas. This is the case for rock phosphate, although much is yet to be learned of its geology. In this report, the geology of phosphorite is discussed and then is applied in a general way to the rocks of Australia in an attempt to point out the areas that hold the best prospects for phosphate deposits. Some of the difficulties of application are also pointed out. A suggested program for the BMR is presented in another report.

Exploration hypothesis

The exploration hypothesis that is working well throughout the world at the present has been put forward in several papers by V.E. McKelvey and R.P. Sheldon. This hypothesis in its present form is based largely on research done by the U.S. Geological Survey on the Permian rocks of the Rocky Mountains in the U.S. See papers by McKelvey, Sheldon, J.M. Cheney, E.R. Cressman, R.W. Swanson, and R.A. Gulbrandsen, from the period 1953 to the present. Of course, many other geologists have worked on various aspects of phosphorites and their work is carefully credited in the above work. In particular, the studies of A.V. Kazakov and Brongersma Sanders are basic. The above references are listed by Sheldon (1964).

This hypothesis essentially consists of looking for sedimentary, tectonic, and paleogeographic environments that are known to be favorable for phosphorite deposition. These environments have been identified through observations on modern phosphorite on the ocean floor and studies of ancient phosphorite.

All known large deposits of Recent marine sedimentary apatite occur in areas of divergent upwelling marine water on the west coasts of continents in latitudes lower than about 40°. Where the geologic history allows, late Tertiary marine phosphorite is usually found adjacent to these areas of modern divergent upwelling. This rather unique marine environment produces a rather unique suite of marine sediments, which include sediments rich in organic matter, biogenic silica, remains of fish and other pelagic fauna, and pelletal and nodular phosphorite. The sedimentation is extremely slow. The apatite contains minute but important quantities of uranium bound up in the apatite lattice.

Ancient phosphorite-bearing formations containing the same suite of rocks are found in condensed stratigraphic sections. The reason for this is that if other sedimentation, either clastic or chemical, was rapid, only slightly phosphatic rocks could be found due to the slow rate of deposition of the phosphorite. Because clastic sedimentation must be slow, only certain tectonic environments favor phosphorite accumulation and these mainly include the cratonic margins of miogeosynclines. In the Permian Phosphoria Formation, much more phosphate was deposited than there is in the entire ocean now. Assuming that the ocean in Permian time contained about the same concentration of phosphate, it obviously takes a major circulation of ocean currents acting over a long period of time to deposit such vast quantities of phosphate. The same must be true of the Tethys Cretaceous-Eocene rocks of North Africa and the Middle East. The point is then, that at a starved basin stage in the evolution of the miogeosyncline, the basin is usually connected to the open ocean so it can support major ocean currents, and also clastic sedimentation is slow because of the long distance from an orogenic provenance. This is the cause of the empirical relationship between the large high grade phosphate deposits and starved basin development on miogeosynclinal shelf areas.

The paleogeography of phosphorite sedimentation is also distinctive, as pointed out above. When the distribution of late Tertiary and older phosphorite is studied, it is found that they have a much wider latitudinal distribution than the young phosphorite, and occur at latitudes as high as 72°. When replotted according to their paleolatitudes, based on paleomagnetic measurements, they show the same distribution as the young phosphorite, i.e. less than 40°, and most of the larger deposits are less than 20°. The reason for this narrow latitudinal distribution of phosphorite is that the phosphorite is climatically controlled due to the partial dependence of its precipitation from sea water on temperature. Thus the validity of this concept can be checked by the association of phosphorite with other warm arid climate indicators. By and large this works quite well as a common distant facies of phosphorite is eolian sandstone and evaporite. Also in vertical sections it is common to find other warm arid climate indicators associated with phosphorite, although their conditions of sedimentation are different and large paleogeographic changes in time are implied. On the other hand, rocks that contain cold or temperate climate indicators such as high latitude coal and glacial deposits are generally not associated with phosphorite.

Exploration for phosphorite based on these principles has been very successful. Phosphorite deposits have been found in Miocene and Jurassic rocks in Peru, Cretaceous rocks in Turkey, Paleocene-Eocene rocks in Saudi Arabia, and in Mesozoic(?) rocks in Colombia. Although these results may be impressive, it is important to understand the limitations of the hypothesis.

Perspective on exploration hypothesis

One important limitation of the hypothesis is that even though one can locate deposits of divergent upwelling origin, one would tend to overlook marine phosphorite of a dynamic upwelling origin. This type of phosphorite is typified by the Florida and North Carolina deposits of Miocene age, which were probably deposited by the forcible upwelling of the ancient Florida current over the ancestral Ocala uplift and Cape Fear arch respectively, and helped by the coriolis force and the westerly winds. The deposits are found around the flanks of these structures and are not associated with siliceous sediments or sediments particularly rich in organic matter. They are not very widespread, at least not as widespread as the divergent upwelling phosphorites. They seem to be deposited in shallower water than the other type of phosphorite. The points in common between the two types of phosphorite are their occurrence in condensed sections and paleogeographically in a low latitude swept by major ocean currents. The dynamic upwelling phosphorites have not been studied sufficiently, I believe, to formulate a really workable exploration hypothesis. By workable, I mean that one knows where to look for such deposits with a fair chance of finding one, and not spending an inordinate amount of time and money looking at barren rock. This is particularly true when one is exploring by drilling.

The success of the divergent upwelling exploration hypothesis depends directly on the amount of accumulated geologic knowledge about an area. One needs regional syntheses of tectonics and sedimentation, and well described stratigraphic sections. Thus, exploration in large areas that are little known geologically, for any reason, cannot be expected to be very successful. Of course the lack of knowledge may be due to insufficient study as in the Ngalia trough in the Northern Territory. On the other hand, the lack of knowledge is commonly due to lack of outcrop or intensive weathering.

Other Approaches

Other techniques than the one outlined here have been used for phosphate exploration. Some of these are discussed below.

Much thought has been given to the relation between phosphate deposits and structures. Yaakov Bentor (1953) perhaps discussed most completely the genetic relation between sedimentation and bottom topography controlled by tectonics. It would seem that in areas of divergent upwelling submarine highs would locally increase the upwelling and cause local thick deposits of phosphorite. This apparently is the case in Israel, where phosphorite is deposited on the flanks of anticlines and in the trough of synclines but not on the crests of anticlines. Sedimentation of clastics would be less on the crests and flanks of high areas so that the grade of phosphatic chemical sediments if deposited would be greater. The relation between tectonic highs and phosphorite in the Florida and North Carolina deposits has been mentioned above. Thus, this interrelationship can be used as an exploration tool, particularly as a supplement to other approaches.

The occurrence of minor amounts of apatite nodules in rocks has been used as an indicator of phosphate deposits. To m~~a~~y knowledge this approach has never been successful. For one thing, apatite is a common sediment and can be found in minor amounts in rocks deposited in many environments, for example iron rich sediments and coaly sediments. Such occurrences would probably indicate slow sedimentation and supersaturation of the waters with respect to apatite. However, unless there is a large supply of phosphate, large deposits cannot be formed. The only such source that has been identified is upwelling marine ocean water.

Several of the mining companies have initiated a program ma of qualitatively testing bore cuttings for phosphate. In areas where outcrops are rare or non-existent, study of cuttings is indispensable. However, many problems arise in this sort of a program. First, contamination of cuttings from cavings can be serious. Also, contamination by phosphatic drilling muds can be misleading. Phosphorite is generally a soft rock and can be lost with the fines when washing the samples. Because the sample is representative of an interval, generally a 10-foot interval, a thin bed of phosphorite interbedded with rock barren of phosphate is poorly represented in the cuttings. Rough-necks are responsible for collecting samples on the drill rigs, and quite frequently their techniques of sampling leave a great deal to be desired. For these reasons, cuttings only poorly represent the rock drilled, and if too much reliance is placed on them, phosphatic beds could be overlooked. The problem is mainly one of condemning a section of rocks when in fact it is phosphatic. Also, one should be skeptical of positive tests. Such chemical testing should be guided by geologic reasoning in order to reduce the amount of effort spent on obviously barren rock, and the results should be carefully analyzed by experienced geologists. Frankly I am skeptical of the shotgun approach to exploration, that is setting up a program based on systematic sampling either randomized or comprehensive. There is no substitute for an imaginative well-aimed program based on sound scientific principles. I would think that chemical examination of cuttings should be used as a technique of checking ideas evolved from geological reasoning, and then only as a part of a petrographic examination of the cuttings. It is argued that a low-salaried technician can do the work without loss of time for a highly trained geologist. It is my understanding that three or four man years would be required to run all the cuttings available in Australia. This would seem a large waste of the technician's time when probably about 95% of the cuttings can be ruled out as prospective on geological grounds, and the technician can be used in much more productive pursuits.

Glauconite also has been used as an indicator of phosphate deposits. Although the two are sometimes found together, they are just as commonly found separately. Except that both indicate slow sedimentation, there is no genetic link between them. The aluminium and iron and probably the silica in the glauconite is derived from terrigenous or volcanic material and the potassium is derived, or can be derived, from sea water. The physical-chemical conditions of the formation of glauconite are not well known because of the complexity of the mineral, but the presence of ferrous iron would indicate mildly reducing to mildly oxidizing conditions. One can see reasons for the association then between near-shore phosphorite and glauconite, but it is not a genetic link. The finding of glauconite in a stratigraphic unit probably would suggest slow sedimentation, but would not suggest necessarily that a phosphatic facies exists some place else.

Igneous apatite is mined in Russia and South Africa for use as fertilizer. Such sources of apatite should not be overlooked in Australia, and of course exploration would follow entirely different lines. The alkalic igneous rocks are the main ones that can be rich in apatite.

GENERAL APPRAISAL OF AUSTRALIA FOR PHOSPHATE ROCK

Tectonism

A first step in appraising Australia for phosphate rock can be made with a tectonic approach. The basins of central and western Australia can be characterized as intra-cratonic in the sense that that part of the continent was relatively stable throughout most of Phanerozoic time, but some areas were mildly negative and others mildly positive. If phosphate rock were to occur in large amounts in these basins, it would necessitate some period of deeper water with a major connection with the ocean. Such conditions in general do not occur in cratonic areas with scattered basins. It is common, however, to find minor amounts of phosphorite in such tectonic environments. One such deposit occurs in Devonian and Mississippian rocks of North America. At the base of the Chattanooga shale in the central and eastern U.S. and equivalent shale formations elsewhere in western U.S. and Canada, phosphorite is quite commonly found. In some places it occurs in beds up to several feet thick, and near Nashville, Tennessee it is being mined in a very small operation. These deposits were

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laid down during a very widespread transgression at a time of extreme tectonic stability. Large periods of time are represented by a few tens of feet of rock and in many of the basinal areas reducing and relatively low pH conditions of sedimentation obtained. The sedimentation environment was suitable for phosphate deposition, but the paleogeographic environment was not. These basins of deposition were not supplied by sufficient phosphorus-rich ocean water to allow deposition of large amounts of phosphate rock. However, at the same time in the Cordilleran miogeosyncline in northern Utah, a major seaway bordered the craton allowing the circulation of major oceanic currents and sizeable phosphate deposits of the Mississippian Brazer Formation were laid down. It would seem that the cratonic area of Australia would not be particularly prospective for these reasons, although small deposits of phosphate rock, such as those of the Stairway Sandstone of the Amadeus Basin, are to be expected. It is possible that somewhere such deposits might be economic, but it does not seem likely to me.

Another feature that goes with the stability of the Australian craton is the lack of tectonism sufficient to bring basinal facies to the surface. If phosphate rock were deposited in some of the intracratonic basins, it would likely be in the deeper water facies which commonly are restricted to the basins. Again, by analogy with the Devonian-Mississippian rocks of North America, in the Williston Basin of North Dakota and surrounding states and provinces, phosphate rock is known in the deeply buried central parts of the basin but the shallow water marginal facies are much less phosphatic. Thus the rocks of central and western Australia that are most likely to contain phosphate rock are also the most likely to be deeply buried. The search for phosphate in these cratonic areas then should be directed to exceptions to the above generalizations; that is, if an area is found where the basinal facies are brought to the surface, they should be carefully examined for phosphate rock.

The geology of eastern Australia is entirely different from central and western Australia. Although much of the area is covered by the transgressive Cretaceous rocks, in Paleozoic and early Mesozoic time an extensive and complex geosynclinal zone developed. There is no question that major oceanic currents could have been active in the area, as shown by the extensive black graptolitic shales of lower Paleozoic age, particularly in Victoria and New South Wales. A large part of this area was eugeosynclinal, that is, was the site of deposition of large amounts of volcanic debris, and the rate of deposition of this and other material was rapid. Also much of the area was intensely deformed when the geosyncline broke up. Thus much of the area or stratigraphic section can be ruled out as prospective for phosphate rock on these counts. Much still remains, however as prospective. On the western side of the geosynclinal complex, where it joins the craton,the tectonic setting would seem to be suitable for the slow sedimentation required for the deposition of high grade phosphate rock. Also the presence of local synsedimentational highs in the southeastern part of the complex gives suitable tectonic conditions for slow sedimentation, in that sediment traps could be formed causing sediment "shadows" away from the provenance, and the highs themselves would be sites of slower sedimentation. The paleogeographic position of this is, of course, wrong for west coast upwelling. However, local highs and geanticlines could provide suitable paleogeography for divergent upwelling on their western flanks. The presence of chert, carbonaceous shale, and minor phosphorite in this area, as discussed below, gives credence to these ideas and shows the area has some potential for phosphate deposits. Furthermore, tectonic break up of the geosyncline has brought the basinal facies to the surface.

History of Sedimentation. In the cratonic areas of central and western Australia, one cannot help but be impressed by the thicknesses and continuity of shallow water sediments, particularly sandstone. Although there were transgressions and regressions with resulting disconformities, there is little evidence other than the Stairway Sandstone of widespread deeper seas at any time over the craton causing the formation of extensive low Eh-pH sedimentary environments. It is this sort of sediment that commonly contains phosphorite. Thus the history of relatively continuous shallow water sedimentation does not seem particularly favorable for phosphorite deposition in these areas.

In eastern Australia sedimentation was much more varied. It is difficult to make generalizations concerning the whole area because it is so complex, but a very crude pattern of sedimentational history may be inferred. Early in the development of the geosyncline, widespread shales rich in organic matter were deposited. Their thickness was not excessive when compared to the coarser clastics and volcanics deposited later, and associated with them from place to place are biogenic cherts and thin beds of phosphorite. These seem to represent a relatively starved basin stage in the development of the geosyncline, which was followed by rapid filling due to an increasingly orogenic provenance. Phosphorite in other parts of the world is commonly found at the starved basin stage in the development of the geosyncline, and Australia seems to be no exception. Pettijohn in the second edition of his book, Sedimentary Rocks, (p. 636-644) discusses the concepts of evolution of geosynclines.

Paleolatitudes - The paleoclimates of Australia have been the subject of a large amount of research so that quite a bit is known about them. Also Dr. E. Irving (1964) has done much work on the paleomagnetism of Australian rocks. From this set of data, an evaluation of the areas and times of warm climates can be made. From this point of view, the lower Paleozoic (from Cambrian to lower Carboniferous) and the upper Tertiary rocks are the warmest climate sediments and would most likely contain phosphate deposits insofar as the climate is concerned. On the other hand, upper Carboniferous to lower Tertiary rocks were by and large deposited in colder climates at higher latitudes and would be much less likely to contain phosphate deposits.

Summary - Several factors point to the lower Paleozoic of eastern Australia as a potential phosphogenic province. First, the chert-black shale-phosphorite suite of rocks is known to occur locally. Second, tectonically it seems likely that major seaways existed in the area in the past and in some areas sedimentation was slow. Third, tectonism has brought deeper water facies to the surface. Fourth, rock of this age probably were deposited in warm climates at low latitudes. Central and western Australia appear to be less prospective because the rocks there were mostly deposited in intracratonic basins which tend to exclude deep seaways. Also tectonism in general has not brought basinal facies to the surface.

In the following parts of the report several specific areas are discussed in more detail and some remarks are made on the effects of weathering on apatite.

PHOSPHATE POTENTIAL OF SPECIFIC AREAS

In the limited time I was in Australia, it was impossible to digest all the geology of the various areas in terms of phosphate potential. This is a major job that would take at least several weeks and probably longer for each sedimentary basin. However, the field reconnaissance included most of the known phosphate localities, and general comments on some of them are in order.

Lower Paleozoic of Eastern Australia

Phosphate rock of Cambrian age has long been known in Victoria (Howitt, 1904; Howitt, 1923; Harris and Thomas, 1954). To date, of course none of these deposits has been commercial, but they are highly significant geologically. The suite of rocks found there, particularly at Mansfield, consists of chert, black shale, and phosphorite. There seems to be little question that they represent a divergent upwelling suite and they give hope that other larger deposits exist in the region. Several features of the Mansfield deposit may help in exploring for phosphate in the area. First, the black shale and chert association is important. Turquoise is present as a secondary weathering product, and because it is so obvious a mineral, reports of turquoise in other areas may be a clue to apatite deposits. Variscite also is a weathering product of apatite and can have a greenish color and be confused with turquoise, but would have equal value as an indicator mineral for apatite. The rocks are slightly radioactive, undoubtedly due to a small uranium content, so traverses with a scintillometer may be used as a prospecting technique.

Chert of lower Paleozoic age has been reported in several places in Victoria, New South Wales, and Queensland. Black shale occurs at many of the chert localities, and black shale without chert is known in Tasmania. Also turquoise has been reported in many places in this region.

The Undilla Basin has a particularly interesting section of Cambrian rocks. The Inca Formation comprises spicular chert and mudstone that probably is dark and carbonaceous in the subsurface but weathers light-colored in outcrop. No phosphate rock was found in outcrop in a brief examination, but in the Morstone No. 1 bore just to the west of the outcrop cuttings from one 10-foot interval analyzed about 4 percent P_2O_5 and 80 feet of rock analyzed about 0.5 percent P_2O_5. In the Adelaide geosyncline, Cambrian rocks contain small quantities of phosphate, in part apatite and in part the weathering product crandallite and other aluminium iron phosphates. On Sellick Hill south of Adelaide a dark shale unit contains scattered apatite nodules up to 3/4 inch in diameter. No chert is associated with these rocks. Many of the localities are so intensely deformed and in part slightly metamorphosed as well as highly weathered, that it is difficult to reconstruct the original stratigraphic section or in fact to identify the original rock types. However, the fact that the phosphate rock is widespread and of Cambrian age shows that the phosphogenic province of eastern Australia extends into the area.

In the southern Georgina Basin phosphatic sandstone of Ordovician age similar to that in the Stairway Sandstone in the Amadeus Basin is found. In the Daly River Basin a glauconitic sandstone of Ordovician age crops out near the structural center of the basin and contains rare scattered apatite brachiopod shell fragments. Thus it would appear that the phosphogenic province of eastern Australia extends stratigraphically into the Ordovician.

Mesozoic of Western Australia and Northern Territory

Phosphatic nodules have been reported from quite a few horizons and from quite a few areas in Western Australia and Northern Territory. A summary of these occurrences prepared by L.C. Noakes is given in Table 1. The Cretaceous localities are the most numerous and by and large are associated with iron minerals, mainly glauconite, but in part siderite and chamosite. Aside from the fact that the resulting high iron and aluminium content spoils the rock as an ore, all of these localities show only thin lenticular beds of phosphate rock with medium to low P_2O_5 content, although individual nodules contain higher quantities of phosphate. Thus, in themselves they do not represent minable phosphate rock. The question arises whether they represent a facies of minable phosphate rock elsewhere. This can only be resolved by extensive prospecting and drilling, but several comments seem appropriate at this time.

It was originally hoped that the modern upwelling off the coast of western Australia was operative in the past and that young marine rocks cropping out on the coast would be phosphatic. The reported occurrence of phosphate in the Cretaceous rocks helped support these hopes. However, the upwelling is quite minor as reported by CSIRO, and the phosphate rock of the Cretaceous does not appear to be of divergent upwelling origin.

The phosphorite in general is not associated with dark shale and diatomaceous chert, as in the case of Cretaceous phosphorites of divergent upwelling origin in the rest of the world. There apparently is no pelagic fauna found in the phosphate-bearing formations. The petrography of the phosphorite is quite different from that of open marine origin. Instead of a pelletal-oolitic texture, the phosphorite occurs usually as a matrix to the rock, although phosphatized wood and scattered nodules occur. The apatite associated with siderite and chamosite definitely is not normal marine, as these iron minerals do not occur in that environment, but in restricted lagoonal or estuarine environment. Most of the apatite occurrences are associated with glauconite, however, and their environment of deposition is much harder to assess. The glauconite indicates marine waters, but whether the environment is restricted or open marine is open to question. In addition according to Irving's data, the paleolatitudes of Western Australia were 45 to 60 degrees in the Cretaceous and 40 to 60 degrees in the lower Tertiary. This would indicate colder climates than those in which phosphorites of marine upwelling origin are commonly found. This is supported somewhat by the lack of the warm arid climate indicators commonly found as facies of marine phosphorites, such as evaporites and eolian sandstones.

It would seem possible that the phosphorites of Western Australia are restricted environment deposits originating largely from rivers rich in phosphate flowing into the shallow marine waters. The association of chamosite and siderite with some of the phosphate would indicate this, as this association is not uncommon in iron rich deposits in other parts of the world. If this were true, one would probably find the better phosphorite farther to the west where it would be deeply buried, and possibly to the north or south where it could crop out. So either way, the westward facies

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Table 1. Description of Prospective Formations for Phosphate in Northern Territory and Western Australia

Prospective Formations	Description	Thickness	Phosphate Content
Miria Marl	Friable calcar. and green-grey marl nodules at base.	2-7' - persistent	Nodules ?
Molecap Gsd.	Greensand and glauconitic sandstone.	30-35'	2' beds at top and bottom dufronite and vivianite-apatite replaces wood.
Gearle Slt.	Dark bentonitic siltstone, claystone and shale. Barite and secondary gypsum. Glauconitic sandstone and greensand.	450-535' - thicker in Cape Range.	Not reported in literature ?
Alinga Fm.	Glauconitic siltstone and greensand.	Thin - 20' ?	Nodules
Mullaman Beds	Radiolarian shale - claystone, leached in Darwin area of latertisation.	Up to 400' in Darwin area ? thicker on Bathurst Island.	Nodules at Lee Pt. presumably derived from Mullaman Beds.
Jowlaenga Fm.	Sandstone, ferruginous well-bedded siltstones and sandy siltstones.	170-400'	Phosphate reported with chamosite and siderite.
Langey Slt.	White glauconitic siltstone with chert concretions.	5' + ?	Rubbly outcrop contains nodules or fragments of apatite. Apatite replaces wood in part.
Bringo Shale	Black shale with phosphatic layers.	7' approx.	Some small nodules seen.
Blina Shale	Blue-grey-yellow shale - claystone, some sandy shale. 10-ft bone beds near base.	Up to 900' ? in bores	Phosphatic Isaura coquines. Low phosphate content.

of the phosphorite is critical to the understanding of the origin of the deposits. With the drilling going on at present, this question probably can be resolved.

Tertiary rocks of Victoria

Much the same situation exists in the Tertiary rocks of coastal Victoria as in the Cretaceous rocks of Western Australia. Small amounts of nodular apatite have been found in an iron-rich rock. The beds are thin and lenticular, and are not associated with chert or carbonaceous rock. The paleolatitudes were high, about 60 degrees.

So far no remotely economic rock has been found and the question to be answered is whether or not these minor occurrences are indicative of higher grade thicker deposits elsewhere. There seems to be little evidence suggesting such deposits, although such matters as paleogeography and sedimentary environments have not been wholly investigated.

Precambrian rocks

Other than the Rum Jungle phosphate deposits, no significant Precambrian phosphorite localities are known. The Rum Jungle deposits have been extensively studied and I have little to add to study. It has been suggested that the Golden Dyke Formation was the source of the Rum Jungle deposits and that the phosphate was moved by some mechanism to its present position. A part of this argument rests on the black shale and chert lithology of the Golden Dyke Formation and the postulation that phosphorite was a member of the rock suite. No phosphorite has yet been found in the Golden Dyke, so there is no direct evidence of this. The chert I saw in the Golden Dyke seemed more likely to be altered volcanic tuff than any sort of biogenic chert (allowing for the existence of silica secreting organism in the lower Proterozoic). However, this question cannot be resolved without a petrographic study. The large thickness of the Golden Dyke suggests rapid deposition and it seems more likely to me that this is a eugeosynclinal assemblage of tuff-dark shale-chert than an upwelling oceanic suite of black shale-chert-phosphorite.

Some question of the association of phosphorite and iron has come up in relation to the Precambrian. Vast deposits of iron formation exist in western Australia, but there is no reason to suppose that this chemical sedimentation would indicate a facies of phosphorite chemical sediments. It seems fairly well established that iron rich sediments are a shore line to terrestrial sediment because of the high insolubility of iron in sea water. The apatite of the important deposits of the world on the other hand is a marine sediment, whose elements were derived from sea water. Though it is possible to find phosphate deposits in association with iron rich sediments, the chances of their being economic is remote.

The use of the chert-phosphorite association in Precambrian rocks as a prospecting tool is open to question. Chert in Phanerozoic phosphatic deposits is biogenic and the association is due to the upwelling deeper marine water origin of both the silica and phosphate. The ocean today and probably throughout the Phanerozoic is kept well below the saturation point of dissolved silica with respect to opal by removal of silica from the water by organisms. If in Precambrian times no silica

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secreting organism was present, the silica content of sea water could be expected to build up to the saturation point and inorganic precipitation would take place. However, there is no reason for this precipitation to occur in areas of upwelling. In fact one would rather expect the silica to be precipitated in a marginal marine environment where river waters were mixed with the salty ocean water. Such a process occurs on a very small scale in waters of the Mississippi River where it mixes with the Gulf of Mexico water. Evidence that supports these postulates is the Precambrian association of chert with iron and Phanerozoic association of chert with phosphorite and the Phanerozoic occurrence or iron rich sediments with no chert. From this one would expect to find phosphorite without chert in the Precambrian. This is all quite speculative of course, so the only action that should be taken on it is not to rely heavily on chert in Precambrian rocks as a clue to phosphate, and to pay more than usual attention to non-cherty rocks.

This project has left the Precambrian rocks alone for the most part, so I have nothing to say concerning their phosphate potential.

Permian rocks of Western Australia

Scattered apatite nodules that contain up to about 20 percent P_2O_5 occur in the Fossil Cliff Formation and Holmwood Shale of Permian age in western Australia. They are associated with dark siltstone and shale that contains secondary gypsum. Thin coal beds occur farther down in the section. Other parts of the Permian contain glacial boulders, some of which are striated. Thus this assemblage probably is not of the upwelling suite of rocks. From both the evidence of glaciation and the paleomagnetism of Permian rocks reported by Irving, (1964), the paleolatitudes at which these rocks were deposited were high, as much as 60 to 70 degrees. It seems unlikely, therefore, that this occurrence of apatite can be traced into economic beds of phosphate rock elsewhere.

Permian rocks of the Bowen Basin, Queensland

The rocks of the Bowen Basin have been prospected for phosphate by one of the mining companies and have been analyzed for phosphate potential by Kaulback (1965). A few nodules of apatite were found in the first case, and Kaulback felt that certain formations showed some potential in the second. It appears to me that the above remarks on the Permian in Western Australia also apply to the Permian in the Bowen Basin. In addition, sedimentation was extremely rapid in the Bowen Basin, and volcanic debris is plentiful. It is questionable how much of the sandstone and mudstone is also of volcanic origin, but it seems likely that some of it is. At any rate it appears to me that the chance of finding economic phosphate deposits is extremely low.

WEATHERING OF APATITE

Weathering of apatite is a very important phenomenon in the economic geology of phosphorite. First, residual deposits formed from rock weathering can be economic, as shown by the Tennessee deposits. Second, phosphate deposits can be spoiled by the alteration of apatite into crandallite or other aluminium phosphates. This same alteration can create a large problem in prospecting. Normally the exploration geologist relies on the nitric acid ammonium molybdate test to identify the phosphate mineral in the field. The aluminium phosphates are not soluble in dilute nitric acid solutions, so the test would not work on them. Thus an apatite deposit may be surficially weathered to aluminium phosphate and be passed over, unless special care is taken in field identification.

The subject of the weathering of apatite has not been well studied. It is known of course that apatite does weather to iron or aluminium phosphate, and a number of minerals can be produced. From chemical considerations, it appears that apatite will remain stable under alkaline weathering conditions, but will alter to the more insoluble iron aluminium phosphates under acid weathering conditions.

In northern Australia apatite occurs immediately under the goethite pisolite laterite, as for example in the Langey Siltstone, so that it appears that such weathering was alkaline in nature. On the other hand, in southern Australia in such deposits as the Cambrian north of Adelaide, the Mansfield deposit in Victoria, and the Dandaragan deposit in the Perth Basin, apatite has been altered at least in part to iron or aluminium phosphates.

It would be quite useful if some generalizations concerning the distribution of the weathered products of apatite could be drawn. It is tempting but dangerous to draw them on the basis of present knowledge. It would also be quite useful if some concept of depth of weathering in the various areas could be formulated.

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