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A NOTE ON SUBMARINE PHOSPHORITE DEPOSITS

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SUMMARY

Submarine phosphorite deposits, believed to be relatively common on the ocean floor, have been most thoroughly investigated off the coasts of California and Mexico. The conditions under which these deposits formed are believed to be applicable to most of the world's phosphorite deposits. Similar conditions may exist on the continental shelf to the south of Australia which therefore seems to be the most logical place to look for submarine phosphorite.

The Californian deposits are of immense size and their economic exploitation seems to be feasible.

INTRODUCTION

Phosphorite nodules on the sea-bed were first recorded by the Challenger Expedition of 1872, on Agulhas Bank off the Cape of Good Hope, off Japan, Chile and Spain. Later expeditions dredged up similar material from the east coast of North America, the Florida Straits, the North Pacific and the Californian coast, and, more recently, from the central Pacific, New Zealand and in Russian waters.* Very little has been recorded about the size and extent of most of these deposits, but it seems likely that phosphorite is relatively common on the ocean floor, particularly in temperate latitudes.

THE CALIFORNIAN DEPOSITS

The largest known deposits of submarine phosphorite appear to be those on the continental shelf and slope off California and Mexico, which were discovered in 1937. At that time they were regarded as being of considerable scientific interest but no real economic significance, the United States having vast reserves of easily accessible phosphate rock with an estimated life of 1500 years. However, the proximity of the deposits to a flourishing oceanographic research institute and the existence on this coast of an important fishing industry resulted in a very thorough study of the deposits and adjacent sea bed and of the physical, chemical and biological oceanography of the region being made.

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* Several authors (e.g.Dietz et al.,1942) have reported that the Challenger Expedition of 1872 recorded phosphorite nodules "to the east of Australia", but no such record is contained in the Report of the Scientific Results (Murray & Renard, 1891). Green sands and muds containing abundant glauconite were recorded at stations 163D, 163E, 163F, 164, 164A and 164B, all just beyond the continental shelf 20 to 40 miles east-south-east of Sydney Heads. (depth 20 to 40 fathoms). These deposits were said (p.165) to resemble "in many respects the deposits at similar depths off the coast of South Africa". The latter are associated with widespread phosphorite nodules, but no phosphorite was recorded near Australia. An analysis of a glauconitic Green Sand from station 164B showed only 0.70% $Ca_3P_2O_8$.

When, in recent years, the possibility of recovering these phosphorite nodules to supply the Californian phosphate industry at a price lower than that of the rock phosphate imported from Florida and Wyoming was investigated, the nature and origin of the phosphorite and the conditions under which it was formed were well known and the estimation of reserves was a fairly simple matter.

Description of Material

The nodules found off California range from flat slabs to irregular masses of clearly accretionary origin; the outer surface is smooth, glazed, and commonly coated with a thin film of manganese oxide. They range from tiny oolites to large nodules up to 60 cms. long and weighing more than 150 lbs; average diameter is about 5 cms. Their structure is in some cases massive, but more commonly is layered and oolitic. The layering is non-concentric and irregular, and represents stages in the growth of the nodule. The oolites usually have as a nucleus a foraminiferal test, glauconite grain or clastic mineral grain, or, in some examples, they may be casts of foraminiferal tests.

Mineralogically the nodules are almost entirely of isotropic collophane (colloidal calcium phosphate), with a small amount of a fibrous anisotropic mineral, probably francolite or dahlite. Chemically they are similar to the continental pebble phosphates of the United States and have the probable chemical structure

$$10Ca_3(PO_4)\ 5CaCO_3\ 4CaF_2\ CaO\ nH_2O \quad \text{(apatite)}$$

The material generally contains 28 to 30% of P_2O_5 and very little iron and alumina. A typical analysis is

CaO	45.53
R_2O_3	0.30
P_2O_5	29.19
CO_2	4.01
F	3.12
Org.	1.90
Insol. in HCl	3.57

MgO, soluble silica and minor elements probably make up the remaining 13%.

The nodules commonly contain rock fragments and organic remains replaced by or coated with phosphorite, and they may easily be mistaken for chert or limestone. They are usually associated with, or even partly buried by, a thin patchy cover of sand composed of glauconite, shell fragments, foraminiferal tests and a small percentage of detrital sand grains. This sand commonly contains some small phosphatic pellets or oolites, and is always weakly phosphatic.

The deposits contain Miocene to Recent fossils, commonly in the one nodule. They seem to have formed extremely slowly although it is not certain that the Miocene fossils are not derived from earlier rocks on the continental shelf.

Distribution and Extent

The Californian deposits extend from Monterey Bay near San Francisco to the Gulf of California, a distance of at least 1200 miles. The total area known is about 6000 square miles which is equivalent to approximately 1,000,000,000 tons per inch of thickness.

The phosphorite is found at depths of 200 to 8000 feet, (but no depth limits are known) and there is clearly a very close relationship between phosphorite deposition and submarine topography. It is found on the tops and sides of banks, on steep escarpments, walls of submarine canyons, some basin slopes and on parts of the mainland shelf that are shallower than their surroundings. Very little has been found close to the shore, the deposits being most abundant on the outer portions of the 150 mile wide continental borderland. None has been found beyond the continental slope.

OTHER DEPOSITS

Phosphorite nodules from other parts of the world appear to be physically and chemically very similar to the Californian material, although relatively very little has been recorded about them. The nodules recovered by the Challenger off South Africa were from two distinct localities, one on the edge of the Agulhas Bank at a depth of 600 to 900 feet, and the other nearly 100 miles south-east of this at 11,500 feet. Subsequently the Cape Government dredged ten further samples from depths of 300 to 3000 feet, from Agulhas Bank and off Cape Point. These nodules, which are again associated with a glauconitic sand, are identical to the Californian material in appearance and structure, but contain rather less phosphate and more iron and alumina (average 19% P_2O_5, 1.2% Al_2O_3 and 2.9% Fe_2O_3). The deposits are thought to be the result of phosphatization of earlier calcareous oozes and glauconitic sands and to be of post Miocene age.

Phosphatized Globigerina occur on the flat top and sides of Sylvania guyot in the Marshall Islands, at a depth of around 5000 feet. They are found in vesicles and cracks in a tuff breccia and are cemented by or crusted over by re-precipitated calcium phosphate. The organisms are of earliest Eocene age and are associated with unphosphatized Miocene forms. Similar material is found on guyots in the mid-Pacific Mountains about 1000 miles to the east of the Marshalls, but in neither case is the amount very great.

From the scant references available the phosphorite nodules in the Florida Straits and Cape Hatteras area are probably of the same type as the Californian deposits. Nodules from the Argentinean, Chilean and Spanish coasts may also be of this type, while those from east of Japan, from the North Pacific and possibly from 'east of Australia' may be similar to the Sylvania guyot occurrence. Deposits off New Zealand were discovered by a recent Scripps Institution expedition (pers.comm.) and may be fairly extensive, but no details have yet been published.

ORIGIN OF SUBMARINE PHOSPHORITE

Many attempts have been made to explain the origin of the phosphorite nodules and the physico-chemical conditions causing precipitation of the phosphate. Blackwelder (1916) and Mansfield (1927) suggested that oxygen deficiency in stagnant waters, by inhibiting the growth of organisms, may allow the concentration of phosphate to the stage where it is precipitated. Murray and Renard (1891) postulated a catastrophic destruction of life by the mixing of warm and cold water masses, of such proportions that much or most of the organic phosphate was not returned to the sea-water, but was precipitated as phosphatic nodules by some comple and unspecified process. Pardee (1917) suggested that glacial lowering of sea temperatures caused dissolution of calcareous remains and consequent concentration of the phosphate, and Mansfield (1940), recognising the high fluorine content of the phosphorites, later proposed that the fluorine in volcanic gases promoted the deposition of phosphorite in times of intense volcanism.

While most of these postulated mechanisms may play a part in the precipitation of phosphates, particularly in the case of the phosphatic shales, the study of the Californian offshore deposits has shown that the nodular phosphorites may accumulate under specific but by no means exceptional physico-chemical conditions. The form, structure, orientation and distribution of the nodules, their layering and manganese coatings and the attached marine life all indicate that the nodules were formed in situ, on topographic highs and areas free from detrital sedimentation, by an extremely slow and discontinuous process of secretion. The crux of the problem lies in the determination of the oceanographic conditions under which the phosphorite forms.

It is known that the deep ocean waters are rich, and possibly saturated, in phosphate and nitrate. In the euphotic surface waters, on the other hand, phosphate and nitrate are minimal, being taken up by the phytoplankton, and the abundance of phytoplankton is very largely controlled by phosphate-nitrate concentrations. Off the Californian-Mexican coast the confluence of the southerly flowing Californian Current with the North Equatorial Current, aided in winter by the strong easterly winds blowing out from the continent, creates a westerly (oceanward) movement of surface waters which is made good by upwelling of cold, nutrient-rich bottom waters of polar origin, along the continental borderland. The phosphate-rich upwelling water, spreading back on to the continental shelf, supports a very abundant phytoplankton population which, because of its magnitude, extracts from the water more phosphate that can subsequently be returned to solution under these shelf conditions. The waters are therefore saturated in $PO_4^{\equiv}$ and a colloidal phase of calcium phosphate may exist in equilibrium with the dissolved phase. Colloidal calcium carbonate may thus be precipitated over the shelf area and calcareous debris replaced, giving rise to concentrations of phosphorite nodules where there is no clastic sedimentation and to weakly phosphatic sediments (e.g. shales) elsewhere.

A similar origin can be postulated for the Agulhas Bank deposits where upwelling may be promoted by the confluence of the warm southerly flowing Agulhas Current below which, it has been postulated, a deep, cold polar current flows in the reverse direction, and the north flowing Benguela Current. The central Pacific deposits also occur in a region of upwelling in the vicinity of the organically productive equatorial divergence; the small size of these deposits may be accounted for by the very limited area of reasonably shallow water (less than 1000 fathoms) and the greater concentration of lime secreting organisms. The other recorded deposits, and the oceanographic conditions in their vicinity are insufficiently well known for consideration of their origin, but it seems most probable that geological and oceanographic conditions similar to or approaching those known off the Californian coast are necessary for any large deposits of submarine phosphorite to accumulate. These conditions can be summarized as :

(a) extensive, relatively shallow shelf areas free from clastic sedimentation.

(b) intense upwelling of nutrient-rich bottom waters over the shelf area.

(c) low productivity of organic calcareous debris.

PROSPECTS IN AUSTRALIAN WATERS

Although relatively little detailed information is at present available on the topography and sedimentation of the Australian continental shelf, nor on the physico-chemical conditions of Australian coastal waters, it is worth speculating very briefly on the possible existence of submarine phosphorite in view of the national need for new sources of cheap phosphate.

The continental shelf off eastern Victoria, New South Wales and southern Queensland is narrow (15-20 miles) slopes steadily seaward with an average gradient of 1 in 150 to 1 in 180 and does not, as far as is known, bear the "basin and swell" type of topography which might give rise to extensive sediment free areas. A considerable amount of clastic material from rivers rising in the Great Dividing Range must certainly be deposited on the shelf, water temperatures are fairly high and there does not seem to be any evidence of upwelling of deep waters along the continental borderland. Because of the reported glauconitic sands east of Sydney, this shelf should be further explored, but it is unlikely that extensive deposits will be found. It is possible that phosphorite, perhaps in recoverable quantities, might be found on the crests of seamounts to the east of Australia or, more likely, on the Lord Howe Rise, where the distribution of water masses is such that some upwelling may occur.

The north Queensland continental shelf is occupied by the Great Barrier Reef, and rates of organic and detrital sedimentation, water temperatures and water composition are such that no concentrations of phosphorite could possibly occur. Seamounts and platforms to the east of the Barrier Reef are similarly covered by coral growth and organic sediments, and deep bottom samples contain a high proportion of calcareous debris.

To the north of Australia, the Torres Straits area, Gulf of Carpentaria and Arafura Sea form a broad shallow water platform of fairly diverse topography. The area is, however, studded with coral reefs and banks and the rate of carbonate production is undoubtedly high. In addition, there is a high evaporation rate in this relatively land-locked area and consequently a high salinity. Saline bottom currents might therefore be expected to flow out through the Torres Straits and/or north-westwards into the Banda Sea, to be replaced by warm, carbonate-rich surface waters driven by the strong, southerly winds, the south-east trades from the Pacific and the south-west Monsoon from the Indian Ocean.

The Sahul shelf is now perhaps the best known continental shelf area in Australia, if not in the world. Topographically the raised lip of this shelf, fronting the Timor Deep and protected from detrital sedimentation by the central shelf basin, would be the ideal place to look for phosphorite deposits. That no phosphorite has in fact been found despite fairly intense sampling by the recent Scripps Institution survey must be the result of unsuitable hydrologic conditions. The scattered coral reefs and abundance of calcareous shelly debris on the shelf edge are indicative of warm, carbonate-rich surface waters. No upwelling is possible from the Timor Deep which is a closed, but not stagnant, basin, and there is little possibility of upwelling over the Ashmore Deep end of the shelf.

The same remarks would apply to the Rowley Shelf and as far south as the Houtman Abrolhos, approximately the southern limit of coral reef growth. There is no evidence that upwelling of cold bottom waters does, or could, occur, and the marine life, coral reefs, water temperatures etc, all indicate a high carbonate productivity. Sporadic sampling has shown that the shelf is, as expected, largely covered by clastic sediment and calcareous debris.

From Houtman Abrolhos south to Cape Leeuwin the continental shelf is fairly narrow and little is known of conditions on it. Clastic sedimentation is known to occur, but sampling and bathymetric data are altogether too meagre to indicate whether or not there may be sediment free areas near the shelf edge. The weak, cool West Australian current may support a small phytoplankton population and carbonate productivity should be fairly low, but there is no evidence of any major upwelling or the impingement of any major cold current. Nevertheless, this area is worthy of some further attention.

The southern Australian continental shelf in the Great Australian Bight, between Albany and Mt. Gambier, seems, on general grounds, to offer by far the best possibilities of phosphorite deposits. It is up to 100 miles wide, flat and shallower than 100 fathoms. Detailed soundings, mainly in the vicinity of harbours, indicate that although the shelf topography is low it is diverse. On the landward side is the Nullabor Plain which can contribute very little clastic material to the shelf area apart from some very fine windborn dust. Carbonate sedimentation too must be negligible and it seems reasonable to conclude that extensive non-depositional areas must exist. To the south is the South Australian Basin, more than 3000 fathoms deep and in the latitude of the great sub-tropical convergence where the warm surface waters of the Indian Ocean meet the westerly drift of cold polar water. This is a region of exceptionally high phytoplankton productivity. Along the northern margin of the confluence the anti-clockwise "swirl" of the warmer surface waters around the Bight may well cause some upwelling of the deeper, colder waters over the shelf edge, particularly at the eastern end of the Bight. If so, and the hydrologic data to prove or disprove this may already exist, there is every reason to believe that phosphorite might be deposited near the shelf edge and may have been so deposited for a very long period.

There remains only the Bass Strait area and the Tasmanian shelf to consider. The latter is narrow, steeply shelving and, being adjacent to mountainous terrain, may be fairly heavily sedimented, but both are well situated with regard to ocean currents. The shallow Bassian Depression (Jennings, 1959) between King Island and Flinders Island is the site of very strong tidal currents reinforced by westerly winds which might allow of some upwelling, but the basin is flat and featureless and is almost certainly deeply sedimented.

EXPLOITATION COSTS

The economics of recovering both phosphorite nodules from the continental shelf and manganese nodules from the deep ocean has been very thoroughly investigated by J. Mero, an engineer from the Institute of Marine Resources in California. Although the full details of Mero's figures and conclusions are not at present available it is possible to get some idea of possible working costs from recently published summaries of his work. (Mero, 1960).

Two methods of recovery have been suggested, the drag and the suction dredge. Estimated production costs for drag dredging range from 5 dollars per ton of nodules in 1000 feet of water to 20 dollars per ton in 5000 feet. Since the limiting factor in drag dredging is the length of time necessary to raise and lower the dredge, costs at depths less than 1000 feet might be proportionately less. Even so, the lower figure quoted compares very favourably with present costs of phosphate-rock mining (e.g. estimated 73/6 per ton F.O.B. for Bellona high grade material).

Given sufficiently large reserves of phosphorite, costs might be cut greatly by using suction dredges. Mero has estimated that a suction dredge suitable for use at depths up to 14000 feet might cost 4 million dollars and that working costs could be as low as 2 dollars at 3000 feet depth and 4 dollars at 14,000 feet. Costs of recovery from the lesser depths at which phosphorite might be expected to occur would be less, and it seems reasonable to infer that, given very large reserves and recovery of say 8000 to 10,000 tons per day (roughly present production from Ocean, Nauru and Christmas Islands) phosphorite nodules might be landed in Australian ports for approximately £1 per ton.

EXPLORATION RECOMMENDATIONS

From very general considerations the possibilities of submarine phosphorite deposits on the Australian continental shelf seem to be fairly good, and the economics of recovering such material may, in the near future, become attractive.

Exploration for submarine mineral deposits is however a difficult and lengthy business and any exploration programme needs to be carefully planned and executed, making the best possible use of all available scientific information and modern methods. The area of the Australian continental shelf alone is such that any programme of reconnaissance sampling and sounding would involve many years of exacting and expensive shipboard work.

The first step should be to assemble the available hydrologic and topographic data, much of which is as yet unpublished, and to endeavour to supplement this, particularly in those areas which are now thought to offer the best prospects, by fairly detailed bathymetric, hydrological and biological surveys (phytoplankton counts) along the lines of the current Division of Fisheries and Oceanography programmes. Where it can be established that the topographic and hydrologic conditions are, or may be, suitable for the precipitation of phosphorite, more detailed bethymetric surveys using an accurate Precision Depth Recorder, reconnaissance bottom sampling and some bottom photography would need to be carried out and finally, if phosphorite is discovered, a very detailed bathymetric, photographic and sampling programme would be needed to estimate reserves. Actual exploitation would be guided by continuous depth sounding and bottom photography or television.

Even on these lines, an exploration programme would be time consuming and expensive, and it is doubtful if such a programme could, or indeed should, be carried out specifically as a search for phosphorite. At least in the initial stages, the programme should be combined with general oceanographic research including geological and geophysical, physical, chemical and biological work.

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