

## DESCRIPTION AND OCCURRENCE OF ATOLL PHOSPHATE ROCK IN MICRONESIA\*

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ABSTRACT. Beds of phosphate rock on atolls of the northern Marshall islands are related to other phosphate occurrences on low coral islands in other parts of the world. The rock appears to consist of grains of organic limestone cemented by apatite which fills the interstices. The calcium carbonate is replaced partially or in some cases completely by apatite. The occurrence of these beds under surface layers of acid raw humus subjected to a continued accretion of phosphate guano, under trees of *Pisonia grandis*, suggests a genetic relationship. The finely divided calcium phosphate in the guano is thought to be dissolved by the acids of the humus as it is washed down through the humus by rainwater, and then precipitated out on contact with alkaline limestone sediments below. The quantities of this rock available are not thought large enough for modern commercial exploitation but may very well serve to offset local phosphate deficiency in the coconut plantations of the Marshallese people.

### INTRODUCTION

During field work in the northern Marshall Islands in 1951 and 1952<sup>1</sup> beds of a brown, usually white-speckled, indurated sedimentary rock were encountered on a number of islands. In texture this is a medium to coarse sandstone, resembling the loose calcareous sediments with which it occurs, but cemented by a brown cement. On analysis it proved to have a variable but high percentage of phosphorus. X-ray analysis showed that apatite is an important component, in certain samples making up almost the entire composition.

This occurrence has been treated elsewhere from the pedological viewpoint (Fosberg, 1954), and a paper is in preparation on its ecological significance. Since such rock is of wide distribution and of geological interest, also, it is appropriate to discuss separately such features of its occurrence and putative history as are of significance to geologists.

This material was first studied with some care on Jemo Island, Marshall Islands, Lat. 10°4' N., Long. 169°31' E., and later on several other islands, especially Kwajalein, Ujae, and Bikar, also of the Marshall group.

### GEOGRAPHICAL OCCURRENCE

Although individual occurrences are of small extent, usually not more than a few acres, beds of phosphate rock are found on a number of islands in the Marshall group. These include Jemo Island and Kwajalein (Eniwetok Islet), Bikar, Ujae, Wotho, Arno, and Ebon atolls. Fragments of such rock were found on Ailinginae Atoll (Fosberg in 1956). Similar rock is also known from Wake Island (Fosberg, 1954), from Gaferut (W. A. Niering, personal communication) and Kapingamarangi of the Carolines (W. A. Niering, 1956, p. 20, McKee, 1956, p. 19-21) and Onotoa, of the Gilberts (P. E. Cloud, oral communication, 1953). A piece of rock from the uppermost phosphate bed on Kita Daito Jima, collected by D. E. Flint, resembles the beds under discussion in both appearance and mode of occurrence. A few fragments of rock of ap-

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parently the character described were found on Malé Atoll, Maldives, by the author in 1956. Malé has been intensively utilized for coconut cultivation for centuries. No native vegetation remains in the locality concerned and no actual beds of consolidated material were seen. Occurrences which, from their descriptions, probably belong here have been reported from Palmyra Island, Washington Island, Fanning Island, Rose Island (G. E. Hutchinson, 1950, p. 183-186, 191-192, and 251), and from Wuwulu, Aua, Manu, and the Purdy Group north of New Guinea (R. C. Hutchinson, 1941). Probably Caroline and Flint Island phosphates are also similar, but information on them is very limited (G. E. Hutchinson, 1950, p. 187). The same is true of the deposits on the Paracel Islands (Clerget, 1932). Some or all of the phosphatic "patinas" and sandstones reported from the coral islands of the western Indian Ocean, Bird, Dennis, Aldabra, St. Pierre, Siren (Cargados Carajos Atoll), Cosmoledo, and others may also belong here (Fryer, 1910a, 1910b, 1911; Gardiner and Cooper, 1910; G. E. Hutchinson, 1950).

#### STRATIGRAPHIC OCCURRENCE

The normal occurrence of this rock is as a horizontal indurated bed or series of beds lying immediately under a surface layer of peaty raw-humus and immediately over bedded unconsolidated lime sands and gravels of various depths. The thickness of the consolidated material is usually about 5 to 15 cm rarely up to half a meter or more. Thicknesses of up to 2.5 m have been reported, as on Aua Island (R. C. Hutchinson, 1941, p. 239), but it is not certain from the description that the material is exactly comparable to that described here, though it seems very similar. At times, as on Eniwetak Islet, Kwajalein, there are, in addition, nodules of consolidated material embedded in, and lying on the surface of, the humus layer. Fragments may be scattered or piled on the surface where broken by tree-roots or from other causes. Rarely, as on Bikar Islet of Bikar Atoll, two consolidated beds occur. The lower one is covered by sand and gravel presumably deposited there by storm waves or wind, and the upper one lies on this, is much thinner, and is covered by a layer of humus. In some occurrences, as on Ebon Atoll (Hatheway, 1952) Wake Island, Onotoa Atoll, and the western Indian Ocean islands, the humus layer is absent, presumably destroyed during or after clearing of the land for planting or other reasons.

The actual thickness of a particular bed varies locally, that on Jemo, for example, being from about 10 to 45 cm in different test holes and exposures. On Bikar Islet the deposit of sand and debris overlying the phosphate bed tapers in thickness from perhaps a meter at the western side of the islet to zero on the eastern side, and on this an upper, thinner phosphate bed is developed locally.

#### LITHOLOGY

Lithologically this rock is somewhat variable. It is a medium to coarse sandstone, frequently including larger than sand-size fragments. In texture the cemented fragments are usually like the material of the underlying unconsolidated beds, light-colored grains clearly of organic origin. They may include

foraminiferal tests of different kinds, coral fragments, algal fragments, echinoid spines, and mollusk shells or fragments. All of these are either angular or rounded and worn smooth and usually seem softer than the corresponding uncemented particles. Their outer layers may be softened and brown. The matrix or cement is amorphous and light to dark brown.

In some instances, especially those where the humus layer is lacking and in fragments lying on the surface, the material seems weathered and grayish on the surface, and the cement is darker, and duller brown internally.

#### CHEMICAL AND MINERALOGICAL NATURE

Analyses show varied percentages of phosphorous in different samples, from 2.7 to 14, averaging about 9.5 and percentages of calcium from 31.3 to 26.2, averaging slightly lower than those in the associated calcareous sediments. That part of this Ca in some samples is in the form of  $\text{CaCO}_3$  is suggested by strong effervescence with acid and demonstrated by X-ray patterns for both calcite and aragonite. That some is phosphate (all in certain samples) is shown by X-ray patterns corresponding to apatite. The peaks in these patterns were not sharp enough to indicate with certainty which of the several varieties of apatite were represented. (X-ray analysis by John C. Hathaway, U. S. Geological Survey).

The differences between various samples are doubtless due to different degrees of replacement of the  $\text{CaCO}_3$  by the phosphate. These may reflect differences in age, acidity, or guano supply.

The characteristic brown color of the cement probably has nothing to do with the phosphate itself. It is very similar to the color of the overlying humus and in all probability comes from organic impurities carried down during the leaching process, here assumed to be the cause of the phosphatization.

#### ANALYSES FOR PHOSPHOROUS AND CALCIUM\*

Phosphate rock layer:

Sample number	Atoll	% phosphorous (as P)		% calcium (as Ca)
		(Rapid chemical)	(Spectrographic)	(rapid chemical)
2	Jemo	7.7	9.0	33.4
5	Jemo	13.2	14.0	31.3
6	Jemo	6.0	4.3	36.2
8	Kwajalein	4.0	3.7	35.8
9	Kwajalein	12.0	10.0	32.8
10	Kwajalein	13.4	12.0	31.8
13	Bikar	4.4	4.6	34.5
20	Bikar	5.2	5.0	34.8
16	Bikar	3.0	2.7	34.4
17	Bikar	5.0	7.9	34.0

Unconsolidated layer immediately beneath phosphate layer:

3	Jemo	1.4	1.7	34.5
14	Bikar	0.54	0.5	36.2
18	Bikar	0.56	0.5	35.0

\* Analyses by rapid chemical method by Harry F. Phillips, Katrine E. White, Leonard Shapiro, and Frank Borris (for method used see Shapiro and Brannock, 1952), and spectrographic analyses by Harry J. Rose, all of the U. S. Geological Survey.

## ECOLOGY AND HISTORY

A detailed ecological consideration of this rock is being prepared for presentation elsewhere, but it may be appropriate to summarize the conclusions here.

It is considered that the phosphate rock is of recent or even, in some places, contemporary origin. Its occurrence is usually in association with a layer of acid (pH 4-6) raw humus, which is generally freely spattered with guano from sea birds and is itself also high in phosphorous. This suggests the conclusion that the coincidence of bird guano and acid conditions leads to the cementation of the upper parts of the lime sand layers immediately beneath.

The guano is largely made up of finely divided calcium phosphate originating in the bones of fish eaten by the birds. This, under normal conditions, is washed, probably in solid form, by rainwater down through the highly porous substratum into the ground-water body, and is then commonly flushed out by tidal action. Where the guano is deposited on and washed through a layer of acid humus it is dissolved and percolates down in solution into the calcareous material beneath. Here the solution immediately becomes alkaline, precipitating out the calcium phosphate, which acts as a cement to produce the rock under consideration. It is probable that the characteristic brown color of this cement is due to impurities derived from the humus, which is of more or less the same color. By the continual bathing of the cemented particles by the acid solution from above, the carbonates may be slowly leached out, causing the softening observed in the limey particles. They may gradually be replaced by calcium phosphate, as is suggested by the brown color of the outer parts of the particles in some places. This replacement is substantiated by the X-ray analyses of certain of these samples showing absence of  $\text{CaCO}_3$  as well as the discovery on Kapingamarangi and Gaferut (McKee, 1956; Niering, 1956) of similar rock, containing clastic fragments but proving to be 100 percent phosphorite or apatite.

This process seems to take place only under a very definite set of circumstances, i.e. where there is guano deposition on the surface of raw humus accumulation. The occurrence of raw humus accumulation in lowland tropics is most unusual, almost unique. In the islands under discussion it happens only under one species of tree, *Pisonia grandis*. Although looked for, no such humus was found under any of the dozen or more other common trees in the area. Why *Pisonia*, alone, produces such humus is not known.

*Pisonia grandis* often forms exclusive groves and forests that seem to be favorite nesting and roosting places for several sorts of fish-eating sea-birds, which provide the guano. In the recent past such groves were much more common than now (Agassiz, 1903) but in many places have been cut to give place to coconut plantations (Niering, 1956).

Repeated searches in places where large numbers of these birds roost and nest in other kinds of trees, and of great rookeries where other fish-eating birds nest on bare ground of similar calcareous sediments to those under the *Pisonia* trees revealed no instances of cementation. This is probably because of lack of a source of acid to dissolve the calcium phosphate in the guano.

Many field tests of the guano itself, after it had dried, showed a reaction of pH 6.5 (in one instance pH 7). Within this range the phosphate is scarcely soluble. There also seems to be little or no alteration of coral pebbles which are encrusted with guano, even though they are naturally very porous. Qualitative tests for phosphate in the subsurface layers of a pebble so encrusted gave negative results.

The suggestion has been made (Shaw, 1952; P. E. Cloud and Z. S. Altschuler, personal communications, 1953, 1955) that the sequence may be the reverse of that outlined here, that the presence of previously developed concentrations of bird guano or of phosphate rock may favor the growth of *Pisonia*, and be responsible for the existence of the *Pisonia* forests. This may be possible, though the widespread occurrence of *Pisonia*, both as a component of mixed forests and as pure stands, in places where there is no obvious guano or phosphate rock suggests that this is not so. However this may be, one sequence of beds found in 1952 on Bikar Islet, Bikar Atoll, indicates that the process described above does take place in essentially the order suggested. Pits dug in several parts of Bikar Islet show that the well-developed phosphate beds which cover much of this islet are covered in their western three fourths by relatively recent storm-deposited sand, tapering off eastward and not reaching the eastern side. Where these beds are not buried by sand they are covered by a layer of humus up to 20 cm thick. The beds themselves are from 20 to 60 cm thick. Where they are covered by sand the raw humus has disappeared, though the lower layers of sand are darkened. On the surface of this sand, under a dense *Pisonia* forest, is a miniature of the sequence described. The surface is covered by about 5 cm of brown raw humus spattered with guano. This is underlain by a thin very fresh-looking cemented layer with the cemented particles exactly similar in texture to the sand immediately beneath and above the older consolidated phosphatic layer that extends over much of the island. This is interpreted as resulting from present-day operation of the process by which the phosphate is thought to be formed. It certainly could not be accounted for by the theory that the phosphate preceded the *Pisonia* forest.

Another occurrence that indicates that the phosphate was deposited subsequently to the growth of the *Pisonia* trees was described by Hatheway (1953, p. 58) as follows:

A fragment of rock removed during the excavation of the soil pit was suggestive of the length of time necessary for formation of the hardpan. One side contained a semi-cylindrical cavity approximately 2 inches in diameter. The rock was hardest and darkest around the cavity, which apparently had once been occupied by the root of a tree. It is suggested that the rock must have formed around the root after the latter had attained a diameter of 2 inches, for had the root penetrated the rock after the latter had formed, it surely would have shattered the brittle rock during its increase in diameter. Further, the rock must have formed around the root while the latter was still alive or only recently dead. Coarse, unconsolidated sand would quickly have filled in the cavity left by the decaying root had the latter rotted before the rock was formed. This suggests that the phosphate rock formed very rapidly, perhaps within less than 100 years, although the length of life of the root of an unknown species of tree under the conditions described is of course not known.

This piece of rock is still in the possession of Dr. Hatheway. These occurrences, together with the existence of a humus layer under *Pisonia* with no

phosphatic hardpan where birds are absent, suggest that this alternative theory is untenable. The occasional existence of a hardpan layer without *Pisonia* and without humus does not constitute an obstacle to the theory here accepted, as, in the case of such an occurrence in Kapingamarangi, the *Pisonia* forest is known to have been cleared off within historic time. The same history is at least possible in Onotoa, Gilbert Islands. In Gaferut, another such case, there is evidence of a destructive typhoon in the presence of large blocks of reef-rock thrown up on the reef flat. This storm may well have swept off the *Pisonia* trees as well as the humus, leaving the bare phosphatic rock. Not enough is known about the occurrences of this kind in the western Indian Ocean, but with the long history of human activity there, it is not improbable that the forests were destroyed by human agency leaving the phosphate, much of which was subsequently mined.

The alternative hypothesis held by some (e.g. Altschuler, written communication, 1956) that the normal mode of formation of such phosphate rock as is described here is by direct reaction between guano and limestone seems untenable. It is suggested that the fresh guano contains "acid solutions of relatively soluble phosphate" and that these react with limestone to form apatite. Failure to find phosphate rock under guano deposits without *Pisonia* humus or under trees other than *Pisonia*, the almost neutral reaction of fresh guano, and the powerful ammonia odor obvious around bird rookeries are all indications contrary to this idea. Contrariwise, the frequent coincidence of *Pisonia*, birds, and phosphate rock suggests that the theory advanced in this paper may more probably describe the "normal mode of phosphatization," on these atolls.

It is considered that the process suggested here and especially the evidence that it is a contemporary one, makes unnecessary and unlikely Hutchinson's conclusions (G. E. Hutchinson, 1950, p. 195, 374-376) that the major climatic belts in the Pacific have shifted since the Pleistocene. They may, of course, have shifted but his conclusions were largely based on his assumption that guano in large quantities could not be produced on a wooded island but only on a bare open one where such birds as sooty terns nest in great rookeries. Observations actually show, not only that sufficient quantities of guano are produced by tree nesting and roosting birds, but that the *Pisonia* forests provide a means of fixing and holding the phosphate which otherwise, except on the very driest islands, would be washed away. Examination of sooty tern rookeries, showed that these birds apparently deposit little or no guano on land: at least there seems to be no evident accumulation in their rookeries, even on dry atolls such as Pokak and Bikar. The partial phosphatization of the Christmas Island sands (G. E. Hutchinson, 1950, p. 182-183), which fits into Hutchinson's ingenious explanation, may be equally well explained by the poor development of *Pisonia* on that island. In 1936 there was only one scraggly half-dead little grove of *Pisonia* on the entire atoll. If it should turn out that the phosphatic material on these dry equatorial islands is similar to that described here it would suggest that these areas had formerly been wet enough to support *Pisonia* forest rather than that the present wooded atolls had once been dry enough to be open.

## RELATION TO OTHER ISLAND PHOSPHATE AND GUANO DEPOSITS

The question immediately arises of whether all island phosphate deposits are of the origin proposed here. Because of extremely diverse modes of occurrence this seems very unlikely. Certainly where there are enormous concentrations of some kinds of birds, such as on the Peruvian guano islands, large accumulations of guano not altered to phosphate rock occur. This may also happen on such extremely dry islands as Jarvis, Howland, and Baker, though from the inadequate available descriptions, this is not evident. For the present, because of lack of exact enough information, the dryer Pacific Equatorial Islands can be excluded from the discussion. Existing data on them are summarized by G. E. Hutchinson (1950). Accumulation of guano may also occur on islands where the substratum is solid rock as on Motu Manu near Oahu and Los Coronados, off Baja California. What the effect of this guano is on the underlying material is not certain, though the alteration of the Clipperton Island trachyte to phosphate (Teall, 1898; Lacroix, 1939) may indicate that there is an effect.

The massive, deep, unbedded deposits on such islands as Angaur, Kita Daito Jima, Nauru, Ocean, and Makatea can scarcely be the result of a process comparable to that described here, as those deposits are not in the form of horizontal beds of phosphatic sandstone but are more in the form of a fine-grained silty deposit between limestone pinnacles or irregularities on a buried karst-like surface. It is more likely that they may result from situations comparable to that on Washington Island, where a fresh-water lake bottom is composed of phosphatic mud (Elschner, 1915, 1923; G. E. Hutchinson, 1950, p. 184-185). It is not considered probable that these massive occurrences result from the complicated process suggested by Ranson (Proc. 8th Pacific Science Congress, ined.).

## ECONOMIC SIGNIFICANCE

During the last half of the 19th century and early part of the 20th there was active exploitation of the "guano" of atolls in various parts of the Pacific. The most productive were apparently the drier atolls in the equatorial belt and the nature and origin of the material mined there is not altogether clear. It may have been accumulated under different circumstances from those described above, as there are now no *Pisonia* groves on the islands concerned. However, some of what was generally termed "guano" was definitely comparable to the rock here described. This was true at least on Fanning and Gaferut atolls. The Japanese conducted an extensive survey of material of this sort in their Micronesian islands (Aso, 1940), estimating that on Bikar Islet alone there existed about 12,000 cubic meters. On Ebon, active exploitation was taking place under their auspices right up to 1941. Hatheway (1952) found in 1952 a large heap of mined phosphate rock piled there, ready for shipment, which was said by the natives to have been dug by the Japanese before the war. However, on the scale of modern phosphate operations even the largest such deposits known are probably of trifling economic significance.

Ecological consideration is pertinent here, also. There are indications of phosphate deficiency in the soils of some atolls that have been subject to

heavy copra harvest. Because of a relatively high phosphate content of this crop, exhaustion of the phosphorus in soils of the plantation is, sooner or later, inevitable unless it is replenished. It is also clear that the native owners of these plantations are not likely to be financially able to import commercial fertilizers. It would seem probable that these little deposits would be quite adequate for the use of the natives, to fertilize their coconut plantations. The mode of occurrence as surface beds of soft, friable rock makes it entirely feasible for them to dig it up in small quantities and transport it to where it would be needed. That it would be effective for their purpose is shown by the luxuriance of the coconut trees on the part of Jemo Island where plantations are on soil containing a rather broken-up occurrence of this rock compared with their unhealthy condition on nearby coral sand unmixed with phosphate rock. It is of interest that essentially the same conclusions were reached by Hutchinson with regard to the deposits on the islands north of New Guinea (R. C. Hutchinson, 1941, p. 242).

Exploitation in such small quantities for local use would stretch the available supply over a long period. There is even some indication that this can be regarded as a renewable resource if some *Pisonia* forests are not destroyed and the birds are not driven away from them or killed. The ancient Marshallese custom of regarding certain islets, e.g. Jemo and Bikar, as bird refuges is probably responsible for there still being in existence situations where this interesting phenomenon could be studied.

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