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# THE PHOSPHATE DEPOSITS OF THE PACIFIC

by

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CANBERRA

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## ADDENDA

Page 5. Table 1 first line
change 0.53% to 0.60%.

Page 8. Add a footnote, referring to "1941/42"* under Table 2.

* 1953-54 figures are Nauru 85.39 4.140 .60
Ocean I 86.76 2.76 .61

Replace page 9.

Page 11. Attach a footnote, referring to "40 feet"*, third paragraph, 6th line.
* The deepest excavation on Nauru is 104 feet.

## INTRODUCTION

The phosphate deposits of the Pacific are of great importance to Australia, as, except in time of war, they have supplied, with cheap but very high-grade material, almost the whole of Australia's requirements of phosphate rock. With increased pasture improvement and more intensive agriculture, these requirements have increased rapidly in recent years, and Australian agricultural economy has become largely dependent on superphosphates. It has now been estimated that at lease one third of the total earnings of the pastoral and agricultural industries depends on the use of phosphate fertilizers (Strong, 1954). Investigations, particularly during the two world wars, have failed to locate any major deposits of phosphate in Australia, so Australia will probably be forced to continue importing supplies.

Before 1900 small amounts of phosphates were imported from the Southern Line Islands and the Phoenix Islands; since then Australia's needs have been met by the deposits on Nauru and Ocean Island, worked by the British Phosphate Commissioners, and on Christmas Island, worked by the Christmas Island Phosphate Commission. These phosphates are the richest large scale deposits ever discovered, and their landed cost per ton is at present much less than that of Moroccan phosphate, which would probably be the alternative source should Pacific supplies fail to meet the needs of Australian consumers.

The conditions governing the formation of guano have been studied more extensively on the islands immediately off the coast of Peru and Chile than anywhere else; it may therefore be necessary to make passing reference to these islands, though they will not be discussed in detail. However the deposits on Christmas Island in the Indian Ocean will be considered, as, in origin and occurrence, they are very similar to major deposits in the Pacific, and they form an important source of supply for Australia.

Most of the material on which this report has been based was obtained from a very detailed publication on all aspects of guano deposits, and phosphate deposits derived from them, by G.E. Hutchinson. It was published in 1950 in the Bulletin of the American Museum of Natural History, vol. 96, with the title: Survey of Contemporary Knowledge of Biogeochemistry. 3. The Biogeochemistry of Vertebrate Excretion. The extensive bibliography in this bulletin has been particularly useful.

Acknowledgement must also be made of the assistance continually given by the British Phosphate Commissioners and Commonwealth Government Departments.

## ORIGIN OF PHOSPHATE DEPOSITS IN THE PACIFIC

The Phosphate deposits are of three main types:

(i) concentrations of apatite in igneous rocks

(ii) phosphate rock of marine sedimentary origin

(iii) deposits which have resulted, indirectly or directly, from the excreta of sea birds, and, to a lesser extent, of bats.

All the phosphate deposits of the Pacific are of the third type.

Although apatite in igneous rocks is the primary source of all phosphates, it seldom forms concentrations of sufficient size to be of economic importance. Most of the world's supplies of phosphates are obtained from marine sedimentary deposits; among these are the deposits in Egypt, Algeria, Morocco, and Tunisia, and Montana, Idaho, Wyoming, Florida, Utah and Nevada in the United States.

Climatic conditions controlling formation of guano

The phosphate deposits of the Pacific have formed on coral islands which have been, for thousands of years, the breeding grounds of certain species of sea birds. During successive breeding seasons large deposits of bird droppings accumulate; these deposits are termed guano, a word first applied to enormous deposits of bird droppings found on the Peruvian coast. On some islands guano is still accumulating; others have long ceased to be bird colonies. The oldest deposits are believed to have originated in Pleistocene, or possibly late Tertiary, time.

Fresh guano is rich in both nitrogen and phosphorus compounds. Where the aridity is extreme, as it is along the Peruvian coast, guano is quite stable and may persist with little change in its nitrogen and phosphorus content for centuries. Thus deposits of guano, large enough to be of commercial significance, are accumulated. As these are rich in nitrogen and soluble calcium phosphates they make excellent fertilizers which may be applied to the ground without chemical treatment.

On the other hand, if the rainfall is excessive, the droppings are washed away as they are formed and are of no interest either economically or geologically.

Under less extreme conditions Hutchinson (1950) shows that four processes may operate:

(1) Decomposition may take place in situ, resulting in a loss of organic matter and ammonia and a concentration of inorganic material, principally calcium phosphates. Moisture is the first essential for these changes, but observations on Malden Island, in the Southern Line Islands, indicate that they are also favoured by high temperatures. They are therefore most conspicuous in warm climates of low, and usually strictly seasonal, rainfall.

(II) The more soluble constituents - oxalates, urates, alkalis and portion of the phosphates-may be removed by percolating waters draining into the sea.

(III) Waters containing the soluble constituents of the guano may evaporate depositing various inorganic salts as minerals; the minerals formed depend on the stage of decomposition reached by the guano.

(IV) The guano solutions may react with the underlying rock.

The last of these processes has been responsible for the formation of all the island deposits (Nauru, Ocean Island, Christmas Island, and Makatea) which are of commercial importance to-day. The guano solutions have reacted with the coral limestone, which underlies most of the islands, to produce the almost insoluble tricalcium phosphate which forms the deposits.. The reaction takes place accordingly to the following equation:

$$2H_3PO_4 + 3CaCO_3 = Ca_3P_2O_8 + 3H_2O + 3CO_2$$

Rodgers (1948) comments "The phosphoric acid would be sufficiently concentrated to attack the limestone only above the water table, hence the restriction of such deposits to raised coral islands." Although the major deposits of rock phosphate do occur on well elevated islands, minor deposits are not restricted to them. Hutchinson (1950) lists fourteen "slightly elevated islands" and six "unelevated atolls" carrying phosphate. The only description of many of these islands is given by Aso (1940) and is very incomplete. However, it appears that he is definitely referring to deposits of phosphate rock and not merely to guano from which the soluble constituents have been removed. The origin of the deposits on these low lying islands and the development of rock phosphate down to 9 feet below sea level on Angaur and Nauru can probably be explained by submergence after phosphatisation.

Where igneous rocks form part of the bedrock they, too, have been phosphatised, producing ferric and aluminium phosphate minerals. Occurrences of phosphatised igneous rocks are rare in the Pacific, but a trachyte in which the silicates have been replaced by hydrated phosphates has been described from Clipperton in the eastern Pacific (Teall, 1898), and phosphatised volcanic rocks occur on Christmas Island; phosphatised pumice has been mined extensively in Kita Daito Jima in the Borodino Islands south of Japan (Hutchinson, 1950). The phosphatised igneous rock is everywhere associated with phosphatised limestone.

The phosphatised limestone has sometimes been termed guano-phosphate, to distinguish it from the marine sedimentary deposits, but it will be referred to here as phosphate rock, the former term being reserved for deposits intermediate between guano and phosphate rock.

The control which a low annual rainfall has on the accumulation of guano is particularly noticeable in the central Pacific, where all the islands on which guano is still being formed, or was being formed last century - the Phoenix Islands, Howland Island, Baker Island, Jarvis Island, Malden Island, Starbuck Island and Johnston Island - lie in relatively dry zones with average annual rainfalls of less than 40 inches. All but the last of these islands are found in a belt just south of the equatorial wet belt; Johnston Island lies 16°45' north of the Equator in another relatively dry area.

Further evidence of the part rainfall plays in determining the distribution of phosphate deposits is provided by the not infrequent absence of contemporary phosphate deposits from islands where large bird colonies are known. Among these islands are many of the islands in the Riu Kiu group south of Japan, Palmyra and possibly Fanning Islands in the northern Line Islands, and Medinilla Island in the Marianas. They all have a high annual rainfall. The small amount of statistical information available suggests that an average annual rainfall of 60 inches is approximately the upper limit permitting contemporary phosphatisation.

Although climatically Johnston Island is very similar to the islands to the south, its guano deposits are far less extensive than those on Howland, Baker, and Malden Islands. Hutchinson (1950) believes that this difference is to be correlated with differences in circulation in the surrounding waters which have produced a variation in the concentration of phosphate and consequently of plankton on the surface. Lower concentrations of plankton have led to smaller numbers of fish and ultimately to fewer guano-producing birds on Johnston Island.

Guano-producing birds

Hutchinson points out that not all marine birds produce guano. He shows that only ground-breeding species lead to the accumulation of large deposits and states that "significant deposits are known to have been formed by colonies of penguins (Sphenisciformes), albatrosses and perhaps diving petrels (Procellariiformes), and terns (Charadriiformes), but it is probable that all these deposits are small compared with those produced by a relatively few species of Pelecaniformes, namely, certain pelicans, boobies, and cormorants.---- In contrast ---- only one doubtful case of a gull producing guano is known." As all these birds form large breeding colonies the reason for the marked difference in the amount of guano produced by gulls and Pelecaniformes is believed to be that the gulls characteristically drop their excreta at sea, whereas the Pelecaniformes tend to retain their droppings until they return to the nesting ground. The suggestion that a bird may retain its droppings is supported by recent experiments (Vogt, 1942,) in which the amount of food consumed and the amount of guano deposited have been determined and compared for guanays, a species of Pelecaniformes, which are the main guano-producing birds in the islands off the coast of Peru.

Unfortunately the species of birds responsible for the deposits of guano on the Phoenix Islands and the Line Islands have never been reliably identified. Today terns are the commonest birds on these islands, so it has always been tacitly assumed that two species of tern, *Sterna fuscata* and *S. lunata*, formed the deposits. However, as species of Pelecaniformes also are found, it is possible that last century, before accurate scientific observations were made, they were much more abundant, and so may have been more important guano producers than the terns, as they are on the coast of Peru. Sudden changes in the bird population have been recorded on the Peruvian islands within historic time.

Effect of geomorphology on formation of phosphate rock

Geomorphology, also, plays an important part in the formation of phosphate rock: the guano solutions are less likely to be lost to the ocean where the islands are flat topped, or have an area of internal drainage, than where they have steep seaward slopes. Unfortunately, this generalization is of little practical value in guiding a search for additional phosphate deposits, as it is the geomorphology of the island at the time of phosphatisation that must be considered.

Relation of phosphate to underlying rock

As mentioned previously, most deposits of phosphate rock occur on elevated atolls, overlying coral limestone. Wherever the underlying limestone has been analysed (Makatea, Ocean Island, Nauru, Christmas Island, and Kita Daito Jima in the Borodino Islands south of Japan) it has been found to be dolomitized (43-45% magnesium carbonate.). In 1923 Owen suggested that most of the magnesium was derived from the guano, but this seems quantitatively impossible, as analyses of modern guano quoted by Hutchinson (1950) show a maximum magnesia content of 1.4%. Also, numerous Pacific islands consist of Tertiary dolomitized limestone without phosphate cappings. More probably magnesium in the sea water replaced some of the calcium in the limestone, and dolomitization was complete before the deposition of the guano.

Except in the few cases where it occurs on unelevated or only slightly elevated atolls, the phosphate lies in and over deep depressions between limestone pinnacles up to sixty feet high. Usually, especially towards the base of the depressions, the phosphate is associated with variable amounts of terra-rossa-like residual soil which introduces alumina and ferric oxide impurities into the mined product. The phosphate from Nauru, Ocean Island, and Makatea is almost free from these impurities, but on other islands, notably some of the Mariana Islands and Riu Kiu Islands south of Japan, they may form 30% of parts of the deposit. This wide range in the ferric oxide and alumina content of the phosphate deposits is shown in Table I.

TABLE I.
(After Hutchinson)

$(Al,Fe)_2O_3$ content of Pacific Island Phosphate Deposits.

| Pacific Island | $(Al,Fe)_2O_3$ |
|---|---|
| Nauru | 0.30-0.53% |
| Ocean | 0.20-0.70 |
| Makatea | 0.40-0.92 |
| Fais (Caroline Is.) | 1.53-2.17 |
| Augaur (Palau Is.) | 1.57-2.70 |
| Peleliu (Palau Is.) | 2.22-15.49 |
| Makaraku ( Palau Is.) | 4.27-18.31 |
| Urukutaburu (Palau Is.) | 13.97-24.40 |
| Rota (Marianas) | 1.12-12.08 |
| Saipan (Marianas) | 1.35-29.67 |
| Tinian (Marianas) | 0.86-28.02 |
| Kita Daito Jima (Borodino Islands) | mainly aluminium phosphate |
| Yoron Shima (Riu Kiu Islands) | 3.87-31.00 |

The iron and alumina have sometimes been attributed to an admixture of volcanic ash with the limestone from which the phosphate has been derived, but this theory has been disproved by finding the limestone underlying the phosphates on Nauru no lower in iron and alumina than the limestone beneath the deposits at Kito Daito Jima, which consist almost entirely of aluminium phosphate. The iron and alumina must therefore merely represent terra rossa left after the chemical weathering of the limestone.

The most satisfactory explanation for the virtual absence of these sesquioxides on Nauru, Ocean Island, and Makatea has been supplied by Hutchinson (1950), who points out that they would readily have been removed during the submergence which, on these islands, followed the formation of the limestone pinnacles; during this submergence coral debris accumulated in the depressions. On other islands, where there is no record of any corresponding submergence, the terra rossa has been perforce retained. When phosphatic solutions were carried down from the guano they attacked first the less coherent material between the pinnacles. Owen (1923) states that on Ocean Island the guano solutions have rounded the outlines of the pinnacles and, in some cases, have converted them "partly or wholly into a compact mass of phosphate". However, this latter effect is rare; the pinnacles are usually regarded as barren limestone and are left standing after the phosphate has been mined.

Owen believed that the pinnacles had been formed by subaerial denudation which occurred before the phosphate had been deposited, and this has been accepted by most later writers. Rodger's (1948) suggested that they "have been formed by normal processes of weathering and solution that attacked the limestone under the soil cover" seems hardly tenable as some pinnacles are known to reach 60 feet in height.

On many islands the phosphate deposits are richest on, or are even confined to, the highest part of the island, indicating that they were formed on a rising land surface.

Age of phosphate deposits.

Hutchinson (1950) summarises the little definite information available on the age of the phosphate deposits on the elevated islands.

The only detailed palaeontological study he records is by Hanzawa (1938), who concluded that the limestone immediately underlying the phosphate on Kito Daito Jima was Plio-Pleistocene: all the foraminifera found in it belong to Recent species. The limestone and dolomite on Nauru are regarded as Tertiary by Elschner (1913) and Bohne (1926) and those on Makatea as Tertiary by Agassiz (1903), but none of these authors records any of the forms on which his determination was based. Andrews (1900) assigns a Miocene age to the uppermost limestone underlying the phosphates on Christmas Island. Speaking of limestone on Ocean Island, Owen (1923) states: "Practically all the fossil remains found in the deposit are so altered as to be indeterminable, the only specimen in good preservation being a single tooth of Carcharodon megalodon, which would indicate that the age of the deposits is post-Miocene".

Evidence of a different type is provided by Tayama (1939) who studied the marine terraces on the Micronesian islands. This work showed that the phosphates of the Palau and Mariana Islands rest on terraces which probably range in age between Plio-Pleistocene and late Pleistocene, and suggested at least two phases of phosphatisation, one in early and one in late Pleistocene time.

According to Hutchinson, Tayama based his conclusions on litholgoy and palaeontology.

Tokunaga (1940) records the discovery of two fossils, the molar of an elephant and fragments of bone and antlers of a deer, in the phosphates on Miyako Jima in the Riu Kiu Islands. The elephant tooth is compared with Elephas trogontherii and Palaeolokodon namadicus and indicates a Middle Pliocene or older age; the remains of the deer suggest Capreolina mayai. This is the only reliable reference to fossils in the phosphate deposits themselves.

Using completely different reasoning Hutchinson develops the theory that all phosphate deposits on elevated atolls were probably formed during short periods in Pleistocene time. By comparing the amount of phosphorus deposited on a square centimeter on Nauru with that developing on a similar unit area each year on the most productive of the Peruvian sites, he concludes that, under conditions similar to those existing on the coast of Peru to-day, the Nauru deposit would have taken about 3,000 to 4,000 years to form. This figure seems much more likely than the hundreds of thousands of years it would have taken to develop under the most favourable equatorial conditions known to-day. Hutchinson therefore believes that the Nauru deposit reflects a time when the Central Pacific had a much lower rainfall, and was much more biologically productive than it is to-day; the oceanographic principles he considers suggest that such a variation is likely during the Pleistocene interglacial periods.

The change responsible for the initiation of guano production on Howland and other Central Equatorial Islands, where guano was still being produced in the nineteenth century, is correlated with the change which resulted in a shift in guano deposition on the South American coast, probably in the first millennium B.C.

As Hutchinson himself admits, much more research must be done before the age of these phosphate deposits is known definitely.

## DESCRIPTION OF PHOSPHATE DEPOSITS

The only areas now producing phosphates in the Pacific are Nauru, Ocean Island, and Makatea. Nauru is administered by Australia under a Trusteeship Agreement from the United Nations to the governments of the United Kingdom, Australia, and New Zealand. Ocean Island is a British colony and Makatea a French possession. However, other islands, including Angaur in the Caroline Islands, where operations ceased only on 30th June, 1955, have been important sources of phosphates in the past.

As far as possible the islands will be grouped as geographical units and will be discussed in order of their importance.

### Nauru and Ocean Island

Nauru and Ocean Island, two small islands lying less than 1° south of the Equator and between longitudes 167° and 170°, contain the largest and richest island deposits of rock phosphate ever discovered. The tonnage exported from these two islands has been more than double that provided by all other Pacific sources. The high grade of Nauru and Ocean Island phosphates is evident from Table 2, in which incomplete analyses of phosphates from various areas are compared.

Both deposits were discovered in 1899, and the Pacific Islands Company, in 1902 replaced by the Pacific Phosphate Company, began mining on Ocean Island in 1900. Production rose rapidly from 13,350 tons in 1901 to almost 108,000 tons in 1905, but it was insufficient to meet demands and in 1907 the same company began work on Nauru. Since 1916 the annual export from Nauru has always exceeded that from Ocean Island, except in the period 1946-48 when war damage was still being repaired.

After the first world war the Governments of the United Kingdom, Australia and New Zealand were given a joint mandate over Nauru; in 1920 these three governments purchased the Pacific Phosphate Company's undertakings on Nauru and Ocean Island and set up a board of three Commissioners, which has operated under the name of the "British Phosphate Commissioners", to work the deposits on their behalf.

TABLE 2.

| Source | Analysis on dry basis | | |
|---|---|---|---|
| | $Ca_3P_2O_8$ | $CaCO_3$ | $(FeAl)_2O_3$ |
| Nauru | 85.31 | 5.00 | 0.72 |
| Ocean Island | 87.80 | 3.27 | 0.75 |
| Makatea | 83.04 | 5.55 | 2.20 |
| Christmas Island | 86.50 | 4.70 | 2.07 |
| Casablanca | 75.26 | 0.42 | 0.80 |
| Saudi-Arabia (Safi) | 70.40 | 10.20 | 1.00 |
| Florida | | | |
| 75/74 Pebble | 74.50 | 3.91 | 2.20 |
| 77/76 Conceptrate | 76.58 | 5.54 | 1.83 |
| Algeria (Bona) | 66.88 | 15.38 | 2.02 |
| Egypt (Safaga) | 65.90 | 10.20 | 1.50 |
| Egypt (Kosseir) | 62.92 | 14.10 | 1.68 |

Note: Except for Nauru and Ocean Island figures, which are averages of analyses for shipments in the year 1941/42, the above figures are buyers' analyses of shipments selected at random and therefore provide a basis for broad comparison only. Florida phosphate varies in grade from about 70% to 77%.

When the workings were taken over by the British Phosphate Commissioners the annual output capacity of the island was 360,000 tons. Technical improvements in mining, the installation of a cantilever loading plant at Nauru in 1931 and increased demand from Australia and New Zealand, caused production to increase, as shown in the following table. The low figures for 1928-32 reflect the economic depression.

TABLE 3.

Exports of Phosphate Rock from Nauru & Ocean Island, 1920-1940.

| Period of 4 years | Tons * | Average per annum |
|---|---|---|
| 1/7/20 - 30/6/24 | 1,491,577 | 372,894 |
| 1/7/24 - 30/6/28 | 1,957,749 | 489,437 |
| 1/7/28 - 30/6/32 | 1,898,280 | 474,570 |
| 1/7/32 - 30/6/36 | 2,739,150 | 684,787 |
| 1/7/36 - 30/6/40 | 4,631,442 | 1,157,860 |
| | 12,718,198 | 635,909 |

* Except where otherwise stated all tonnages given in this report are expressed in long tons (2,240 lb).

Exports continued fairly regularly during the first year of the last war, but in December, 1940 five phosphate ships were sunk, and later in the same month loading installations at Nauru were shelled and severely damaged by a German raider. The last shipments left in November, 1941. The following August, some time after the plant had been immobilised, the islands were occupied by the Japanese. After the war mining and loading installations were repaired and shipments recommenced in July, 1946. Post-war export figures are given in Table 4.

TABLE 4.

Exports of Phosphate Rock from Nauru & Ocean Island 1946-1955

| Year | Nauru | Ocean Island | Total. |
|---|---|---|---|
| 1946/47 | 96,473 tons | 117,402 tons | 213,875 tons |
| 1947/48 | 263,507 | 205,332 | 468,839 |
| 1948/49 | 680,746 | 117,078 | 797,824 |
| 1949/50 | 1,009,266 | 276,732 | 1,285,998 |
| 1950/51 | 950,744 | 219,721 | 1,170,465 |
| 1951/52 | 1,061,797 | 268,358 | 1,330,155 |
| 1952/53 | 1,227,103 | 292,211 | 1,519,314 |
| 1953/54 | 1,103,726 | 278,031 | 1,381,757 |
| 1954/55 | 1,237,236 | 312,634 | 1,549,870 |
| | 7,630,598 | 2,087,499 | 9,718,097 |

For comparison, figures of imports into Australia from July, 1946 to June, 1954 are given in Table 5 (figures from Oversea Trade. Bull. 44-51. Common. Bur. Census Stat.)

TABLE 5.

Imports of Phosphate Rock into Australia, 1946-1954.

| Year | Source | | | | |
|---|---|---|---|---|---|
| | Nauru | Ocean I. | Christmas I. | Other sources | Total |
| 1946/47 | 96,911 | 67,636 | 30,148 | 526,315 | 726,010 |
| 1947/48 | 174,849 | 210,783 | 110,578 | 205,391 | 701,601 |
| 1948/49 | 520,178 | 211,075 | 77,403 | 101,108a | 909,764 |
| 1949/50 | 723,206 | 249,583 | 202,477 | 10,136 | 1,185,402 |
| 1950/51 | 735,516 | 159,288 | 192,499 | 14,374 | 1,101,677 |
| 1951/52 | 551,948 | 160,840 | 301,307 | 5 | 1,014,100 |
| 1952/53 | 762,900 | 169,503 | 338,730 | 6 | 1,271,139 |
| 1953/54 | 692,821 | 161,495 | 286,062 | 2,953b | 1,143,331 |

a. includes Solomon Is: 18,880 tons, b. British Borneo: 2,953 tons, other Pacific Is: 3,670 tons.

At 30th June, 1955, the British Phosphate Commissioners estimated that Nauru still had a reserve of 71 million tons and Ocean Island 9½ million tons. These estimates are made of the material in the ground which contains 10 per cent moisture. Tonnages available of shipping phosphate are accordingly reduced to 64 and 8½ million tons respectively.

The uneven surface of the bedrock underneath the phosphate deposits makes exact estimation of reserves difficult. Estimates are checked annually and are based on analytical surveys and yields per acre.

Neither Nauru nor Ocean Island is now a bird island and, as already mentioned, the little evidence available suggests that the phosphate deposits are probably of Pleistocene age. Nauru has an average annual rainfall of about 84 inches, Ocean Island about 69 inches.

The Ocean Island deposits have been described in detail by Owen (1923, 1927) who examined the island while employed by the Pacific Phosphate Company before the first world war. Other accounts have been given by Power (1905, 1925) and Elschner (1913), Power, Elschner and Bohne

(1926) have described the deposits on Nauru, but no recent geological account of either island is available, and many questions relating to the origin of the deposits remain unsolved.

Ocean Island is a low conical island less than 2 miles long and about 1½ miles wide. Except in the far south the entire coast is formed of nearly vertical cliffs up to 30 feet high. It is surrounded by a platform, about 100 yards wide, which all observers interpret as a platform of marine denudation because on its surface the remains of pinnacles, similar to those on the higher part of island, can be recognised. The central part of the island, which reaches a height of about 300 feet, is relatively flat, and Power (1905) considered that it marked the site of an original lagoon. Owen (1923) believed that the form of the dolomite underlying the phosphate did not support this view and regarded Ocean Island as an uplifted coral re ef. The little evidence available could probably have been just as easily used to reach either conclusion.

Practically the whole of the island is covered with a deposit of phosphate, sometimes as much as 80 feet thick, but usually less than 50 feet thick. The phosphate fills depressions between dolomite pinnacles, and mining is commonly discontinued before the base of the depression is reached, the phosphate either becoming so narrow that recovery is no longer economic, or the pinnacles threatening to crumble at the base and fall when the phosphate is removed by blasting. The deepest excavation on Ocean Island reaches about 65 feet. When the phosphate is removed the dolomite is found to be cut by at least three marine terraces which according to Owen dip to the south-south-east at 0°17'.

There are two main types of phosphate, which Power termed alluvial and rock phosphate. Although Owen recognised t that these terms were genetically misleading and renamed the two varieties incoherent and coherent phosphate, the terms introduced by Power are still used in descriptions of the Nauru and Ocean Island deposits.

Incoherent phosphate consists of pisolitic and oolitic grains, together with larger angular or rounded fragments, up to 2 inches in diameter, and fine dust; it is apparently dominant in the upper portion of the deposit. The coarser material was clearly formed by phosphatisation of pisolitic grains of calcium carbonate which are common on coral reefs, but Owen believed that the finer material was partly drived from the insoluble residue of the original guano.

Within coherent phosphate Owen includes three distinct varieties. The first is described as fragmental, and consists mainly of blocks of phosphatised coral limestone which are irregularly distributed through the incoherent phosphate. In places it grades imperceptibly into the incoherent phosphate and, like it, has been developed from reef debris which accummulated between the pinnacles during a period of submergence. The coherent phosphate is usually slightly richer in tricalcium phosphate than the incoherent material surrounding it. As previously mentioned, a few dolomite pinnacles have been partly or wholly converted to tricalcium phosphate. The phosphate rock formed in this way constitutes Owen's second variety of coherent phosphate. The third variety, described as translucent, occurs as finely laminated masses, as a cementing ingredient, as a coating on phosphatised coral, and as a lining in cavities within the unphosphatised coral. It frequently contains casts of bubbles indicating that it formed from the solidification of a liquid. Owen, noting that it contained smaller amounts of impurities than the other varieties, and that under the microscope it was completely isotropic, concluded that it was a colloid formed from guano solutions enriched in calcium after reacting with the limestone. Elschner (1913) gave a similar substance from Nauru the name of nauruite. X-ray analysis has since shown (Frondel, 1943) that both consist of a sub-microscopic aggregate of crystallites of apatite.

Owen states that over the whole island the tricalcium phosphate content of the deposit ranges between 79% and 92%, but that at any locality the variation between top and bottom of the deposit is seldom more than 1%. The phosphate content shows a general increase from the coast to the central elevated part of the island, Owen claims that this variation is very regular. From the consideration of a large number of analyses he concludes that the percentage of tricalcium phosphate at any locality is a linear function of the distance of that point from a plane inclined at $0^{\circ}17'$ to the present sea level; he thence derives a formula by which he claims it is possible to predict the tricalcium phosphate content to within 0.2%.

The deposits on Nauru are similar to those described on Ocean Island. They consist almost entirely of material corresponding to Owen's incoherent phosphate and fragmentary coherent phosphate; very little material so hard that explosives are needed to mine it is found. Excavations have seldom reached more than 40 feet. The island, unlike Ocean Island where the ground rises rapidly from the coast, is surrounded by a coastal plain, but the phosphate deposits are restricted to the central plateau, about 215 feet above sea level. A deep depression containing a small lake in the south-west part of the island probably marks the site of a lagoon.

No detailed work on the phosphate content of the deposit has been published. According to Elschner (1913) the percentage of tricalcium phosphate ranges from 81.75 in fine sandy phosphate to 89.33 in coarser fragments. On the whole it is a lower grade deposit than that on Ocean Island, the tricalcium phosphate content of the two ores, calculated on a dry basis, averaging about 85.5% and 88%.

The two deposits have apparently been formed in the following way, outlined by Owen (1923) for Ocean Island.

1. Elevation of coral reef, accompanied by subaerial erosion producing a mass of limestone pinnacles up to 80 feet high.

2. Submergence. During this period the limestone was replaced by dolomite, reef corals became attached to the pinnacles and detrital and oolitic limestone collected between them.

3. Gradual uplift. Birds colonised the islands in enormous numbers and solutions, leached from the guano, phosphatised the underlying dolomite pinnacles and, more markedly, the unconsolidated material collected between them. Owen points out that the richest and deepest phosphate deposits would naturally develop in the central more elevated part of the island where bird colonies could have existed for longer periods.

4. After the formation of the phosphates another submergence of at least 9 feet, the greatest depth below sea level at which deposits have been found, took place on Nauru. Owen asserts that on Ocean Island there is no evidence of a submergence, but he believes there was tilting of about $0^{\circ}17'$ along a E.N.E. - W.S.W. axis.

Power (1905, 1925) proposes a much more complicated history on very little evidence.

Detailed analyses are given in Table 5. Only those quoted from Elschner appear reliable. All early workers except Elschner believed that the CaO in excess of that necessary to satisfy $CO_2$, $SO_3$, and $P_2O_5$ (as $Ca_3P_2O_8$) was combined with organic matter, but recent work (Frondel, 1943; Jacob, Hill, Marshall and Reynolds, 1933) has shown that such an excess of lime does not really exist because most of the lime in insular phosphate deposits occurs as francolite, hydroxyl-fluor-carbonate apatite, $Ca_{10}((P,C)O_4)_6(OH,F)_2$.

TABLE 6.

Analyses of phosphate rock from Nauru & Ocean Island.

| | Ocean Island | | | Nauru | | |
|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI |
| $H_2O$ ... / Ign. loss | 3.62% | 2/50% | 1.88% | 1.70% / 3.30 | 3.40% | 2.78 |
| $Na_2O$ | n.d. | n.d. | 0.49 | n.d. | n.d. | 0.45 |
| $K_2O$ | n.d. | n.d. | tr. | n.d. | n.d. | tr. |
| CaO | 52.95 | 50.05 | 54.08 | 52.47 | 52.06 | 54.42 |
| MgO | 0.08 | 0.03 | abs | 0.21 | 0.27 | abs |
| $Al_2O_3$ | - | 0.07 | 0.20 | 0.53 | 0.13 | 0.30 |
| $Fe_2O_3$ | - | | | | 0.24 | |
| (Al,Fe)PO4 | 0.81 | - | - | - | - | - |
| $P_2O_5$ | 39.05 | 40.10 | 40.32 | 38.72 | 39.35 | 38.92 |
| $CO_2$ | 1.93 | 1.54 | 1.06 | 1.88 | 2.12 | 2.04 |
| $SO_3$ | 0.07 | 0.29 | abs. | 0.22 | n.d. | abs. |
| $SiO_2$ | 0.39 | 1.00 | 0.40 | n.d. | n.d. | 0.20 |
| F | 2.05 | 1.46 | 2.97 | 1.60 | 1.80 | 2.62 |
| Cl. | n.d. | n.d. | 0.01 | n.d. | n.d. | 0.01 |
| | 100.95 | 97.04 | 101.41 | 100.63 | 99.37 | 101.74 |

I, IV, V. Elschner (1913)

II. Owen (1923)

III, VI. Jacob, Hill, Marshall and Reynolds, (1933).

## Tuamotu Archipelago

The Tuamotu Archipelago, part of French Oceania in the south-west Pacific, lies between longitudes 149°W and 134°W and latitudes 14°S and 2.3°S. Phosphates have been recorded from Makatea, Niau, Matahiva and Henderson Islands, but apparently only those on Makatea are of any commercial importance. The company working Makatea holds concessions over the deposits on Niau and presumably has also investigated those on Matahiva nearby; neither has been worked. According to the authors of the Admiralty Geographical Handbooks (1945) both the atoll rim and the lagoon floor on Niau carry deposits of phosphate, but Hutchinson (1950), following brief reports on the island by Agassiz (1903) and Privat-Deschanel (1910), believes that phosphate may only occur as a cement to conglomerate partly covering the atoll rim.

Hutchinson states, without giving his authority, that Henderson Island appears to have been examined at least three times for commercially significant phosphate deposits. Like Nauru and Ocean Island it consists dominantly of a plateau 50 feet to 100 feet high, but no deposits of any value have been found. In 1900 officers of the Pacific Phosphate Company visited the island and obtained samples of "alluvial" phosphate. They were analysed and found to contain only 8.5% to 18% of $Ca_3P_2O_8$, plus 10% to 45% $CaCO_3$ and 25% to 37% of organic matter, suggesting that they represent only partially leached guano mixed with variable amounts of coral sand.

### Makatea.

Makatea (15° 50'S, 148° 13'W), an elevated coral atoll on the western edge of the Tuamotu Archipelago, is about 130 miles north-east of Tahiti. In all important respects its phosphate deposits are similar to those on Nauru and Ocean Island. The description given by Hutchinson is based on accounts by Agassiz (1903), Elschner (1913) and Wilder (1934).

From the coast, which is surrounded by a fringing reef up to 160 yards wide, the island rises rapidly to at least 250 feet; Wilder gives the highest point as 370 feet. The seaward slope is marked by four or five marine terraces. The site of the original lagoon is preserved as a wide central depression; the phosphate deposits are found only within this hollow and mainly on its northern flanks.

The phosphate is described as somewhat softer than that on Nauru and Ocean Island, consisting mainly of yellow phosphatised coral sand and gravel, often showing an oolitic structure, and a few larger fragments. Aso (1940) speaks of the deposit as a "stratum averaging 1 to 2 meters in depth" but this is in complete opposition to all other reports, which state that, as on Nauru and Ocean Island, it fills hollows between dolomite pinnacles.

There is no suggestion that the higher deposits are any thicker than those lower down, so presumably all parts of the island now containing phosphate were colonised by birds at approximately the same time. The rainfall at that time must have been very low or phosphate deposits would have developed at the base of the depression as well as on its sides.

The phosphates are slightly inferior in grade to those from Nauru and Ocean Island, though they are high grade by world standards. Aso quotes four representative analyses of Makatea ore imported into Japan which contain 87.27%, 83.66%, 82.84%

and 77.13% of $Ca_3P_2O_8$ and 0.71%, 0.48%, 1.05% and 0.41% of $(Fe,Al)_2O_3$. Two fluorine determinations by Jacob, Hill, Marshall and Reynolds (1933) gave 3.25% and 3.42%; the $F:P_2O_3$ ratio in these samples is the highest recorded for any insular phosphates.

The phosphates deposits on Makatea were discovered at the end of the last century, and in 1907 two companies were formed to develop them. Production began the following year and has continued ever since under the Compagnie Francaise des Phosphates de L'Oceanie.

Production reached about 72,000 tons in 1914 and 218,691 tons in 1929, but it was reduced to less than half this amount during the depression; by 1941 it had gradually risen to 171,000 tons. In early years Makatea phosphate was exported to Europe and important sales were also made at times to Australia, New Zealand, and Hawaii, but between 1935 and 1941 the output went almost exclusively to Japan.

When production on Nauru was reduced by German raids in December, 1940 the British Phosphate Commissioners immediately attempted to obtain supplies for Australia and New Zealand from Makatea. Owing to previous commitments to Japan only small amounts were available, but in 1942 exports to Japan were prohibited and until mid-1950 Australia and New Zealand absorbed the entire Makatea output. Since then Japan has again become the chief market for the phosphate with occasional small sales to India, Hawaii and Chile. Exports over the last five years have ranged between 150,000 tons and 200,000 tons per annum.

Estimates of the size of the deposit on Makatea differ tremendously. Aso states that it was originally thought to contain 10,000,000 metric tons and that excavations steadily increased this figure to 30,000,000. Later Johnson (1952) lists a reserve of 9,800,000 tons. Other sources suggest an even lower figure for the reserves.

## Christmas Island

Christmas Island, latitude 10°25'S and longitude 105°42'E, is approximately 180 miles south of Java and 800 miles south of Singapore, from which it is administered. It contains phosphate deposits comparable with those on Nauru and Ocean Island in both size and grade.

Before the last war almost the entire output of Christmas Island was sold to Japan, but in 1941, when supplies from Nauru had been severely reduced by German raids, further shipments to Japan were prohibited, and until the island was occupied by the Japanese in April, 1942, all exports went to Australia. Here, as on Nauru and Ocean Island, the plant was immobilised before the evacuation of the island to prevent its use during the Japanese occupation.

These wartime conditions re-emphasised the importance of Christmas Island phosphate to Australia and New Zealand and in 1948 the Governments of the two countries jointly purchased the undertakings of the Christmas Island Phosphate Company, which had worked the deposits since 1897. Control of the undertaking was vested in the Christmas Island Phosphate Commission who appointed the British Phosphate Commissioners as its managing agents.

By the Christmas Island agreement Australia and New Zealand are equal partners and phosphate is to be made available to the two countries in conjunction with phosphate from Nauru, Ocean Island and other sources in the way that results in the lowest possible average c.i.f. cost for phosphate supplied to Australia and New Zealand. In practice all bulk phosphate is delivered to Australia, most of it to Western Australia. Bagged phosphate dust is sold to Malaya.

From January, 1949 to January, 1954, output capacity was increased by over 50% to 330,000 tons per annum. Production figures for the last three years are:

| | Bulk Phosphate | Dust to Malaya |
|---|---|---|
| 1952-53 | 317,418 tons | 14,724 tons |
| 1953-54 | 296,988 " | 25,744 " |
| 1954-55 | 348,033 " | 25,398 " |

The latest estimate of the proved reserves on the island is 25,000,000 tons. Further surveys are in progress and figures available suggest that the total may be increased to 37,000,000 tons, which will include some "top-level phosphate" which contains a higher percentage of iron and alumina.

The following analysis of Christmas Island phosphate is quoted from Jacob, Hill, Marshall and Reynolds (1933).

| | |
|---|---|
| $CaO$ | 52.50% |
| $MgO$ | 0.10 |
| $Na_2O$ | 0.53 |
| $K_2O$ | 0.05 |
| $(Al,Fe)_2O_3$ | 0.80 |
| $P_2O_5$ | 39.46 |
| $CO_2$ | 2.28 |
| $SO_3$ | abs |
| F | 1.32 |
| Cl | 0.02 |
| Loss of ignition | 2.05 |
| | 99.11 |

Recent average analyses of Christmas Island bulk phosphate on a dry basis are:

| | $Ca_3P_2O_8$ | $CaCO_3$ | $(Al,Fe)_2O_3$ |
|---|---|---|---|
| 1952-53 | 85.74 | 4.79 | 2.06 |
| 1953-54 | 85.97 | 4.73 | 1.84 |

No satisfactory description of the phosphate deposits has been published. However, from the accounts given by Andrews (1900) and Aso (1940), and from official reports of the nature of the deposits and the difficulty in estimating their size, it appears that they differ considerably from those already described. Much of the high interior of the island, where the main deposits are found, is dissected into dolomite pinnacles, but Hutchinson (1950) states that there is nothing in Andrew's description to suggest that the phosphate fills depressions between these pinnacles; it is described as irregular blocks up to 10 feet thick overlying the dolomite. At the time Andrews examined the island phosphate rock was also found lying loose below the main deposit and incorporated in raised reefs between the main deposit and the sea. If these observations are correct it seems certain that the island has been submerged and subsequently elevated in several stages, and the dolomite pinnacles and the residual soil of the island developed, all since the phosphates were formed. The deposits may, therefore, prove to be older than those on Nauru which has been submerged only about 9 feet since phosphatisation, and Ocean Island, where there is no evidence of submergence.

Marianas, Caroline and Marshall Islands.

Phosphate deposits occur on numerous scattered islands of the Marianas, Caroline, and Marshall groups, which together stretch from latitude 1° to 20°N and from longitude 130° to 170°E. The only justification for treating the three groups as a unit is the similarity of their political history over the last sixty years. The Marshall Islands were annexed by Germany in 1885, and in 1899 the other groups, with the exception of Guam in the Marianas, were ceded by Spain to Germany by purchase. On the outbreak of war in 1914 they were occupied by the Japanese and in 1920 they were handed over to Japan under mandate from the League of Nations. After the 1939-45 war the islands were brought under the International Trusteeship system of the United Nations with the United States as the administering authority.

At present none of the islands is being worked for phosphate, though production on Angaur, in the Palau group of the Caroline Islands, has ceased only during the last year. Between 1909 and 1945 deposits were worked on Angaur, Peleliu, Tobi (Togobei, Tokobei, Lord North) and Sonsorol in the Palau group; on Fais (Feys, Trommelin) and Gaferut (Grimes) in other parts of the Caroline Islands; on Rota, Saipan, and Tinian (Tenian, Buenavisa) in the Marianas; and on Ebon (Boston) in the Marshall Islands. By far the most important of these are the Angaur deposits. Possibly others were mined too, because Rodgers (1948) states that production has been recorded from sixteen different islands; he names only the seven most important.

Smaller deposits have been reported by Aso (1940) from Urukutaburu (Urukthapel), Makaraku (Eil Malk), Panna and Puru in the Palau Islands; Greenwich Atoll and Udot in the Carolines; Bikar Atoll in the Marshall Islands, and Aguijan in the Marianas. The Admiralty Geographical Handbooks (vol. 4, 1945) mention phosphates on Pilo Anna in the Palau Islands, and on Agrihan in the Marianas, and Hutchinson (1950) speaks of good quality phosphate on Ngatik in the Carolines. Aso makes no mention of any of these deposits being worked before 1940, but from Rodgers' statement above it appears that some may have been worked during the last war. The Admiralty Geographical Handbooks also mention that natives were brought to Agrihan from time to time to work the phosphate deposits.

History. Phosphate deposits in this area were first discovered on Angaur, Peleliu and Fais by a research expedition sent out in 1903 from Germany. The deposits on Gaferut may have been discovered at the same time and those on Saipan were also partly known during the German administration. The German Government immediately gave the sponsors of the expedition concessions over the deposits on Anguar and Peleliu; later they also acquired rights over Fais. In 1909, as the South Sea Rock Phosphate Corporation, they began mining on Anguar, but the deposits on Peleliu and Fais had not been worked when the islands were taken over by the Japanese in 1914. During the war operations on Angaur continued under the management of the Japanese navy. In 1920, when Japan was given mandate over the islands, phosphate mining rights on Angaur Peleliu and Fais were purchased by the Japanese government.

Until 1937 the phosphate workings on Angaur were run by the government as a source of income. In that year they were taken over by the South Seas Colonization Corporation, but the government held more than half the shares in this company and the change in practice was slight.

Angaur does not appear to have been badly damaged during the 1939-45 war, and shipping of phosphate to Japan was resumed in 1946. For the first three years work was organised mainly by the United States army and navy employing Japanese labour. From 1949 until operations ceased on 30th June, 1955, when it was felt that further mining would seriously affect agriculture, mining was conducted by the Phosphate Mining Company of Japan, under an agreement with the government administering the trust territory (the United States) and the people of Angaur. Under this agreement the company was required to refill all areas mined so they could be restored to agricultural production.

No other deposit was developed until 1935, but between then and 1938 mining began on six more islands - Peleliu, Tobi, Fais, Gaferut, Rota and Saipan. The order in which these islands were developed and their relative importance is shown in Table 7.

TABLE 7.

Islands mined for phosphate in Mariana, Caroline & Marshall Groups.

| Island | Company mining deposit | Date of first production | Production to 1944 (in thousands of long tons) | Estimated original reserves (in thousands of long tons) |
|---|---|---|---|---|
| Peleliu | South Seas Development Corporation | 1935 | 123 | 270 |
| Tobi | " | 1937 | 23[a] | Approx.90 |
| Fais | South Seas Colonization Corporation | 1938 | 255 | 630 |
| Gaferut | South Seas Trading Corporation | 1937 | b | 5-8 |
| Rota | South Seas Development Corporation | 1937 | 212 | 450 |
| Saipan | " | 1938 | 80 | 90 |

a. 23,000 tons represents production between 1937 and 1942. No additional figures available.

b. Complete figures not available. Aso states that about 300 tons were removed at a time by ships that called irregularly. 747 tons were exported in 1938 (Hutchinson, 1950).

Mining on Sonsorol, Tinian and Ebon started in 1940 or 1941. Aso (1940) reports 27,000 tons containing less than 1% of $(Al,Fe)_2O_3$ on Sonsorol. On Tinian less than 8,000 tons existed, and much of this was low-grade ore containing an average of 25% $(Al,Fe)_2O_3$. 3,600 tons were exported in 1941 and 1942, and this probably represents all the material of economic value. The deposit on Ebon was larger, an unconfirmed estimate of 54,000 tons being given by Aso, but little of this can now remain: 27,900 tons were exported in 1940-42 alone, and work continued after this date.

No deposits other than those on Angaur have been mined since the war.

From Table 7 it appears that reserves of some economic value may still exist on Fais, Rota and Peleliu; but this view was not held by Rodgers (1948) who visited these islands, as well as Saipan and Angaur, in 1945 and 1946. He believed that of all the deposits which had been worked by the Japanese only those on Angaur and Kito Daito Jima (Borodino Islands) held any promise of future production. He states: "In the late thirties, the Japanese made an exhaustive search for phosphate deposits in the islands under their control. Thereafter they worked all the significant deposits discovered, regardless of cost. Thus most of the deposits, which were originally rather small, have been practically exhausted under uneconomic conditions." It therefore seems unlikely that further search will lead to the discovery of new deposits which can be worked economically to-day.

The form of the islands on which these phosphate deposits occur varies considerably. Angaur, Peleliu, and Fais are all elevated coral islands, the elevation reached 165 feet on Angaur. Other coral islands such as Ebon, Bikar Atoll, Ngatik and Greenwich Atoll show no evidence of elevation, while Panna, Puru, Sonsorol, Tobi, and Gaferut have been raised only 3 to 6 feet. Rota, Saipan and Tinian in the Marianas are volcanic islands in which the underlying rock is only partly covered by coral limestone. Limestone terraces rise to nearly 1600 feet on Rota and Saipan, and to about 650 feet on Tinian. Hutchinson believes that Urukutaburu and Makaraku have a similar structure although no volcanic rock is now exposed.

All the deposits have been described by Aso (1940), but the significance of many of the terms he uses is not clear and he seldom records the relationship of the phosphate to the underlying rock. However, from his accounts, from the descriptions of the deposits on Fais, Rota and Angaur provided by Rodgers (1948), and from other information collected by Hutchinson, it appears that the deposits on all the elevated islands, such as Angaur, Fais and the Mariana Islands, are essentially similar to those on Nauru and Ocean Island, while those on islands which show little or no evidence of elevation, with the possible exception of Ebon, are superficial deposits of much later age.

The deposits on Fais and Rota and part of the deposit on Angaur filled crevices between limestone pinnacles (Rodgers); the phosphates on Saipan and Tinian also probably occur in this way - Aso describes them as similar, in properties and origin, to those on Rota. On Fais and Rota the crevices average only 6 feet in depth; on Angaur, where Rodgers records depths of 25 feet, they are comparable with those developed on Nauru. Angaur and Fais phosphates are relatively low in alumina and ferric oxide, but in the Mariana Islands, where the phosphate consists of nodular or powdery ore low in sesquioxides, mixed with a phosphatic clay high in sesquioxides, these impurities may reach nearly 30% in the material mined. However, Aso says that they can be removed from the high-grade ore by washing and so do not affect the value of deposits substantially.

On Fais, and possibly on other islands, hard phosphate rock has been formed from the alteration of the limestone pinnacles, but it has not been mined. Apparently no analyses have been made to determine if the limestone underlying the phosphates has been dolomitised.

Two types of phosphate were worked on Angaur. The first, which filled the crevices between limestone pinnacles on ridges bordering swamps, was made up of hard red or brown oolitic grains, about the size of coarse sand, associated with a very small amount of clayey material. The second type, a white or pale grey clay-like phosphate often showing traces of a pisolitic texture, formed extensive lenticular deposits, up to 15 feet thick in the centre, under the swamps. Deposits of the first type were worked out before 1946 and the others have since been exhausted. The clay-like phosphate has a high moisture content, but when it is dried it is found to contain about 3.5% more $P_2O_5$ (40.69 compared with 37.09, Table 8) than the granular ore. The genetic relationships of the two types of ore are not properly understood, but from their distribution it might be inferred that they developed simultaneously during a period of moderate rainfall, part of the phosphates leached from the guano reacting with the coral sand immediately beneath, part being carried down into the nearby hollows.

The deposits on the low-lying islands are typified by the phosphate from Tobi, which forms three indistinct layers: an upper layer of black soil, rich in organic matter and containing very fine phosphatised coral and foraminiferal sand; a middle layer consisting of the fine phosphatised sand of the upper layer cemented, apparently by tricalcium phosphate, into composite grains less than a quarter of an inch in diameter; and a lower layer containing larger aggregates of coral sand ("nodules") in which only the outer part of the sand grains has been phosphatised. The whole deposit is less than 3 feet thick. It contains less than 1% $(Fe,Al)_2O_3$; the $P_2O_5$ content ranges between 15% and 37% but, according to Aso, averages about 28%.

The islands on which these deposits occur have an annual rainfall of over 100 inches and are covered by thick vegetation; phosphatisation, therefore, although obviously much later than that on the elevated islands, cannot be due to modern bird colonies. If, as Tayama (1939) believes, the Tobi deposit rests on a post-Pleistocene marine terrace, phosphatisation must have taken place during some post-Pleistocene period of low rainfall.

The description that Aso gives of the deposit on Ebon, an apparently unelevated atoll on the southern edge of the Marshall group, suggests that it is considerably older than the deposits on other low-lying islands. He describes it as very high grade rock phosphate filling basin-like depressions in the underlying limestone, and likens it to the deposit on Rota.

Incomplete analyses of phosphate from Angaur, Peleiu, Rota, Ebon and Tobi and a more detailed analysis of Angaur phosphate are given in Table 8. All but the last, which is quoted from Elschner (1913), are taken from Aso.

## Marcus Island

Hutchinson states that between 1907 and 1920, 6 113 tons of phosphate were removed from Marcus Island, an isolated island (24°16'N, 154°00'E) about 900 miles north-east of the Marianas. The deposit consisted in part of a black phosphatic soil and in part of granular phosphate which was mixed with lumps of coral and contained 31.02% $P_2O_5$. The deposit was probably exhausted in 1920 or it would have been reworked when the Japanese carried out their intensive search for phosphates before the last war.

TABLE 8.

Analyses of phosphates from Marianas, Caroline and Marshall Islands.

| Island and type of ore. | $H_2O$ | Total N | $P_2O_5$ | $(Al.Fe)_2O_3$ | CaO | MgO | F | $CO_2$ | $SO_3$ |
|---|---|---|---|---|---|---|---|---|---|
| Angaur | | | | | | | | | |
| Undesignated | 1.90% (Ignition loss on dry material) | 0.15% | 38.20% | 1.70% | 52.70% | 0.46% | 0.80% | 2.60% | 0.48% |
| White clayey (average of 5 analyses) | Analyses calculated water free | | 40.69 | 1.19 | | | | | |
| Brown granular (average of 3 analyses) | | | 37.09 | 1.98 | | | | | |
| Peleliu | | | | | | | | | |
| Low terra rossa content | 1.51 | | 38.89 | 2.22 | | | | | |
| High terra rossa content | 3.69 | | 30.63 | 15.49 | | | | | |
| Rota | | | | | | | | | |
| Nodular (average of 2) | | | 37.10 | 2.66 | | | | | |
| Fine-grained (average of 2) | | | 34.63 | 9.89 | | | | | |
| Phosphatic soil (average of 2) | | | 18.90 | 32.45 | | | | | |
| Ebon | | | | | | | | | |
| Sandy | | | 33.22 | 0.35 | | | | | |
| Nodular | | | 37.80 | 0.23 | | | | | |
| Tobi | | | | | | | | | |
| Black earthy | Analyses calculated water free. | (1.10 | 23.40 | 0.80 | | | | | |
| " " | | (0.80 | 30.80 | 0.30 | | | | | |
| Brown granular | | (0.09 | 23.90 | 0.50 | | | | | |
| " " | | (0.05 | 25.10 | 0.30 | | | | | |
| Tuffaceous | | (0.12 | 33.60 | 0.60 | | | | | |
| " | | (0.08 | 35.40 | 0.50 | | | | | |

Central Equatorial Islands

Until the deposits on Nauru, Ocean Island, and Makatea were discovered at the end of last century, the Central Equatorial Islands were the most important source of phosphate in the Pacific. Mining was never on a large scale by modern standards, but several of the islands, particularly Howland, Baker, Jarvis, Malden and Enderbury, yielded amounts of phosphate which were commercially important at the time they mined. As in the Admiralty Geographical Handbooks (1945) the Line Islands, Phoenix Islands, Howland Island and Baker Island are all included in this group, although the southernmost Line Islands are more than 11° south of the Equator.

The first definite proof of phosphate deposits in the Pacific was obtained in 1855 when samples from Jarvis and Baker Islands were taken to the United States and analysed. Hutchinson quotes a claim by the United States Guano Company that guano was discovered on McKean and Malden Islands in 1842, but regards this as unreliable.

The American Guano Company began work on Jarvis and Baker in 1858 and the following year extended operations to Howland. The Phoenix Guano Company, a subsidiary of the American Guano Company, worked the deposits on McKean from 1859 to 1870, those on Phoenix from 1860 to 1871, and those on Enderbury from 1860, to 1877. The three islands held by the American Guano Company were abandoned in 1878 and 1879, but the deposits were not completely exhausted and Baker and Howland were later reworked by the Melbourne firm of John T. Arundel. Another relatively large deposit on Fanning Island, in the northern Line Islands, was worked a little later, between 1877 and 1887, apparently by a third American firm.

Arundel, working either on his own behalf or in the interests of various British companies, was also responsible for the development of phosphate mining on Starbuck, Flint and Caroline Islands, in the southern Line Islands, between 1870 and 1892, and on some of the smaller Phoenix Islands, such as Canton and Sydney, which had not been touched by American companies. Starbuck had earlier (between 1861 and 1870) been worked by a New Zealand firm.

The largest deposits in this area occurred on Malden Island, where they were worked without interruption from about 1860 to 1927 by a Melbourne company, first known as Grice Sumner and Company, and later as Malden Island Proprietary Limited. It is reliably estimated that, even after this long period of exploitation, about 100,000 tons of material, containing 40% to 50% of phosphate, remained in 1943.

It is exceedingly difficult to estimate the exact size of the deposits which originally existed on these islands. Few accurate surveys were made before mining began and no complete production figures are available. The figures in Table 8 are all probably too high. For all the islands except Flint they are quoted from Hutchinson, who based his calculations on various export and import figures that were available. The deposits on the islands not listed in this table were very small and probably in no case did they yield more than 10,000 tons of phosphate. The authors of the Admiralty Geographical Handbooks apparently favour higher figures than those calculated by Hutchinson; they state: "it is possible that on a very rough estimate the total production from all the islands in the area was only in the region of two million tons," but the evidence on which they arrived at this conclusion is not given.

TABLE 9.

Estimates of phosphate deposits originally existing on Central Equatorial Islands

| Island | Deposit (in tons) |
|---|---|
| Howland | 112,000 |
| Baker | approx. 225,000 |
| Jarvis | approx. 225,000 |
| Malden | approx. 360,000 |
| Enderbury | approx. 90,000 |
| McKean | approx. 227,000 |
| Starbuck | approx. 45,000 |
| Fanning | approx. 36,000 |
| Flint | approx. 27,000 |

With the possible exception of the 100,000 tons estimated to exist on Malden it is very unlikely that any of the islands now contain workable deposits; they were abandoned, in some cases after being worked successively by two different companies, before they had to meet competition from the larger and richer deposits on Nauru, Ocean Island, Christmas Island, and Makatea.

It is equally unlikely that deposits exist on other islands. After phosphates were discovered on Jarvis and Baker an Act of Congress (generally referred to as the Guano Act) was passed, which provided that when an American citizen found phosphate on an island not previously claimed by another government and took peaceable possession of the island, it might, at the discretion of the President, be considered as appertaining to the United States. The Act conferred upon the discoverer, if he fulfilled certain requirements, including the filing of a bond, the exclusive right of extracting guano from the island. Under this Act claims were made to some forty-eight islands, many of them in the Central Equatorial area, but more thorough investigation proved that many contained no guano. Hutchinson lists all the islands bonded and gives evidence that many of them were either non-existent or synonymous with an island claimed under a different name. Power (1925) says that every likely island has been examined two or three times.

The three remaining islands in the Phoenix group - Birnie, Hill and Gardner - have all at times been reported as guano islands, but there is no reliable account of any of them being worked. Arundel is known to have visited Birnie, and Vostok in the southern Line Islands; it is probable that he also investigated Hull and Gardner. The fact that he did not attempt to work them implies that no commercial deposits exist. Hutchinson considers the conflicting accounts of phosphate deposits on Christmas Island, in the Pacific, and concludes that phosphatic soils, but no significant deposits of phosphatic guano, occur on the island.

Analyses of the deposits, again quoted from Hutchinson. are given in Table 10. Most of the analyses were made before 1900, and some (Jarvis and McKean) as early as 1860 and 1862, so they are probably not accurate. The analyses from Malden and Starbuck, noticably higher in $P_2O_5$ than the others, are of "crust guano", which is always richer in phosphate than the powdery material with which it is associated.

With the exception of Fanning and Flint, all the islands listed in Table 9 and Table 10 have certain features in common. They are slightly elevated coral atolls with an annual rainfall of less than 40 inches and a maximum height above sea level of between 12 and 24 feet. There is reasonably good evidence that, at the time of their discovery, they were occupied by very large colonies of ground-breeding birds. Each island has the same general form: a rim surrounding a lower central area which may now be completely dry or contain small remnants of the original lagoon. On McKean the area of the lagoon has been considerably enlarged by guano digging. The central depression, forming an area of internal drainage, has favoured the retention of phosphate derived from guano, and there all phosphate deposits have been found.

The phosphates on Jarvis were closely associated with deposits of gypsum, but in other respects the phosphate deposits on Howland, Baker, Jarvis, Malden and Starbuck appear to have been very similar. They consisted of two layers of powdery brown material, the upper layers always being richer in plant roots and fibres, darker, denser and more coarse-grained than the lower one. On all the islands, with the possible exception of Howland, this powdery material was accompanied by a hard layer, referred to as "crust guano", which may underlie or overlie the "powder", and has even been described as interstratified with it, in bands about an inch thick, in parts of the Baker deposit. Christophersen (1927), described the base of the Jarvis deposit as consisting of phosphatised coral sand, but on the whole phosphatisation of the bedrock appears to have been rare, or at least was not recognised, on these islands. The powdery material obviously represents guano completely leached of all its soluble constituents, which have been precipitated to form the "crust guano". The organic matter determined in the analyses was almost entirely vegetable impurities.

No descriptions of the phosphate deposits on the Phoenix Islands have been found, but, as the islands are similar in geomorphology, rainfall, and bedrock to those just discussed, the characteristics of the phosphate developed on the two groups of islands are probably also similar.

It can be seen that the deposits on this first group of seven islands might have been predicted, as the islands satisfy all the conditions which are now regarded as necessary for the accumulation of guano. On the other hand, no such prediction would have been possible for the deposits on Fanning and Flint Islands. Both islands have a relatively high rainfall, Flint between 40 and 80 inches a year and Fanning over 80 inches, and Fanning differs from all other important phosphate-bearing islands, including Flint, in consisting of a narrow, broken land rim with a very extensive lagoon. The higher rainfall has produced thick vegetation which has restricted ground-breeding birds to areas along the shores. These facts, and the evidence that both deposits were covered with soil, indicate that they are not of contemporary origin. Hutchinson (1950) suggests that they can only be explained by postulating that the rainfall over the whole Pacific area was once much less than it is to-day, or that the equatorial wet belt at one time lay south of its present position. A change of the second type would also account for variations observed in Peruvian guano deposits.

## Hawaiian Islands

The Hawaiian Leeward Islands and Johnston Island, 700 miles to the south, which is politically part of the Hawaiian group, yielded small amounts of nitrogenous and leached guano in the latter half of the last century. Commercially they were never of any importance compared with the Central Equatorial Islands, which were worked at the same time. The total quantity imported into the United States between 1853 and 1893 was only 5,622 tons (Hutchinson, 1950), but this figure presumably does not include phosphate from Johnston Island. Nothing is known of exports to other countries.

TABLE 10.

Analyses of phosphates from Central Equatorial Islands.

| | Howland | Baker | Jarvis | Malden | Enderbury | McKean | Starbuck | Fanning | Flint |
|---|---|---|---|---|---|---|---|---|---|
| $H_2O$ | 11.59% | 10.21% | 5.02% | 2.60 (H O-) | 8.54 | 20.88 | 10.01 | 8.00 | 13.26 |
| Organic | 11.84 | 6.80 | 8.45 (Ign. loss) | 6.45 ($+H_2O+$) | 7.63 | 8.07 | | 12.82 | |
| CaO | 40.07 | 41.40 | 42.17 | 43.45 | 41.36 | 37.70 | 44/96 | 42.84 | 43.43 |
| MgO | 1.05 | 1.23 | 1.02 | 3.97 | | 1.98 | | 0.61 | |
| $SO_3$ | 0.48 | 2.43 | 3.06 | 0.62 | 9.12 | 2.14 | 4.87 | 0.19 | 5.99 |
| $CO_2$, alkal..r, Chloride, etc. | 1.51 | 5.16 | .81 | tr. | | 5.96 | | 1.30 | |
| $P_2O_5$ | 32.30 | 32.23 | 34.01 | 43.04 | 33.26 | 23.28 | 40.12 | 34.16 | 37.13 |
| $SiO_2$ insol | - | - | 0.60 | - | 0.08 | abs. | 0.04 | - | 0.19 |
| Fe | 0.65 | 0.54 | - | tr. | - | - | - | - | - |

Although extensive bird colonies are common and the rainfall is low, probably less than 43 inches a year over all the area, phosphate deposits have seldom accumulated because most of the islands are volcanic with steep seaward slopes from which bird droppings are washed soon after they are deposited.

Few details are available of the small phosphate deposits that were worked commercially on four coral atolls: Laysan, Lisiansky Island, French Frigate Shoals, and Johnston Island. The British Admiralty Geographical Handbooks (1945) refer to two men from an American ship collecting guano from Johnston Island in 1858, and Bryan (1942), says that "from 1869 onward occasional cargoes of guano were removed, and in 1909 the island was leased to a private individual who began systematic exploitation. The project was, however, soon abandoned, as the quality and quantity of the material were insufficient to pay for the work of collecting it."

Lisiansky Island was leased to the North Pacific Phosphate and Fertilizer Company in 1890, but Elschner (1915), states that they mined only the richest parts of the deposit. He describes the whole surface of the island as still consisting of partly phosphatised coral sand; one analysis that he made of surface sand near the lagoon showed a $P_2O_5$ content of 27.47% (equal to 62.06% $Ca_3P_2O_8$). Elschner also analysed fresh nitrogenous guano and "brown phosphates" from Laysan, but it is impossible to tell if both these types were represented in the material exported from the island. His analysis of "brown phosphate" follows:

| | |
|---|---|
| $H_2O$ | 7.16% |
| Total nitrogen | 0.68 |
| CaO | 46.63 |
| MgO | 0.37 |
| (Al.Fe) $PO_4$ | 0.36 |
| $P_2O_5$ | 41.14 |
| $CO_2$ | 1.14 |
| $SO_3$ | 0.74 |
| F | strong traces |

It has a similar composition to the "crust guano" on the Line Islands and presumably has a similar origin.

The French Frigate Shoals can have yielded very little phosphate. Hutchinson describes them as consisting of a variable number of unstable islands surrounding two rocks; his only reference to mining there concerns a party of twenty men who were landed from a ship in 1859 to collect phosphate.

## Clipperton Island

The best description of this isolated coral atoll in the Pacific (10°17'N, 109°13'W) is given by Snodgrass and Heller (1902). With the exception of a mass of trachyte 60 feet high on the south-east side of the island, the rim, which completely encloses the lagoon, is composed entirely of irregular fragments of coral. It is apparently a relatively dry island with a winter rainfall, but reliable climatic data are lacking. At the end of last century the lagoon was at least 120 feet deep and estimates of over 300 feet have been given.

Both the coral rock and trachyte have been phosphatised but it is not clear if the hydrated iron and aluminium phosphates, to which the trachyte has been converted, were ever mined commercially. Hutchinson records that concessions over the deposit were held by a British firm, the Pacific Islands Company, which worked the deposit between 1898 and 1914, but according to Power (1925) mining was still going on in 1925. Mining was intermittent owing to difficulties in landing in bad weather. The authors of the Admiralty Geographical Handbooks state that "an export of 200 tons per annum has been reported, but it seems probable that the deposits have now been virtually exhausted". Elschner (1913) described the deposits as consisting in part of a white chalk-like substance and in part of yellowish grey, coarse powder. The material exported is said to have averaged between 70% and 80% phosphates. Hutchinson (1950) quotes the following analysis:

| | |
|---|---|
| $H_2O$ | 3.80% |
| Organic | 4.83 |
| CaO | 49.31 |
| MgO | 0.25 |
| $(Al_2Fe)_2O_3$ | 0.04 |
| $P_2O_5$ | 36.06 |
| $CO_2$ | 2.96 |
| $SO_3$ | 0.46 |
| $SiO_2$ | 0.28 |
| NaCl | 0.15 |
| | 98.14 |

Islands off New Guinea

Small phosphate deposits are known to exist on two groups os islands, the Purdy Islands and Ninigo Islands, in the Trust Territory of New Guinea. G. Hutchinson (1950) mentions that the Purdy Islands phosphate deposits were worked twice during the period of German administration, once in 1890, when 1,000 tons were exported to Germany, and again about 1910, but at least 27,000 tons of low-grade material still remain (Hutchinson, 1941). The deposits on the Ninigo Islands have never been worked; they have been estimated to contain at least 80,000 tons.

The Purdy Islands lie about 100 miles south-west of Manus and consist of five small, slightly elevated coral atolls which are known as Rat, Mole, Mouse, North Bat and South Bat. Hutchinson (1941) describes phosphate deposits on all the islands except the smallest, Rat. On Mole and Mouse Islands they occupy the low lying central part of the island; on the two Bat Islands they are eccentrically situated, but Hutchinson suggests that here too they might once have occupied the site of the central lagoon and their present position is due to recent erosion of the islands. The phosphates occur beneath a few inches of sandy soil as lumps of rock weighing between 2 and 10 pounds. They are light and porous, and very heterogeneous, small particles of shell and coral being included within the brown phosphatic masses. Analyses given below show that all the deposits are low grade.

TABLE 11.

Composition of Purdy Islands' Phosphates.

| | Mole | Mouse | North Bat | South Bat |
|---|---|---|---|---|
| $H_2O$ | 8.9% | 5.7% | 5.9% | 7.2% |
| Ignition loss | 24.6 | 32.9 | 26.4 | 26.4 |
| CaO | 52.2 | 53.2 | 49.7 | 50.5 |
| $P_2O_5$ | 11.7 | 11.2 | 10.4 | 10.0 |
| Insol. | 0.15 | 0.27 | 0.14 | 0.21 |

Hutchinson gives the following estimates for the amount of phosphate on the four islands:

TABLE 12.

| Island | Deposits (in tons) |
|---|---|
| Mole | 10,200 |
| Mouse | 5,000 |
| North Bat | 2,400 |
| South Bat | 9,400 |
| Total | 27,000 |

The estimates are conservative as they are based on a mean thickness of phosphate of 3 inches, compared with an average depth of 5 inches calculated from 32 determinations. Nevertheless the deposits appear too small and too low grade to be of any value except for local use.

In 1929 an officer of the British Phosphate Commissioners examined phosphate deposits on Wuvulu (Maty), Aua (Durour) and Manu (Allison) islands, the three southernmost islands of the Ninigo group, about 300 miles west of Manus (Hutchinson, 1941). The deposits on Manu were described as small; apparently those on Wuvulu are also small but they were not investigated in detail as the island is covered with dense jungle; Aua was reported to contain a maximum of 80,000 tons of phosphate. In general appearance the phosphate is said to be very similar to that from the Purdy Islands but no analyses are available.

Obviously the deposits on these two groups of islands are not of recent formation as they are covered by soil and thick vegetation, and all the islands on which they occur have a very high rainfall: Hutchinson (1930) believes it to be between 80 and 120 inches a year, or possibly more.

From Ajawi, a small island at the north-west end of the Schouten group, Wichmann (1915) describes phosphate deposits which appear similar in many ways to the phosphates on Nauru;

they should be further investigated. They are associated with pinnacles of Globigerina limestone but Wichmann gives no details of the relationship of the phosphatic rock to the limestone and no estimate of the size of the deposit. The main mass of phosphate is light yellow and amorphous; it contains dark patches of organic matter and cavities lined with banded, agate-like phosphate. The following analysis is recorded.

| | |
|---|---|
| CaO | 37.38% |
| MgO | 2.17 |
| $Fe_2O_3$ | 2.83 |
| $P_2O_5$ | 31.53 |
| $CO_2$ | 7.31 |
| $H_2O$ at 110°C | 1.48 |
| $H_2O$ at 110°-125°C | 3.86 |
| Insol. | 0.19 |
| | 86.75 |

The Ajawi rock differs from the rock phosphates on Nauru, Ocean Island and Makatea on its apparently high organic content, which Wichmann believes amounts to most of the 13% unaccounted for in the analysis.

R. Hutchinson (1941) lists over forty other islands in the New Guinea area which have been unsuccessfully searched for commercial deposits of phosphate.

## Islands off New Caledonia.

Three areas near New Caledonia have been worked for phosphate. They are the Chesterfield Islands about 300 miles west-north-west of New Caledonia; the Huon Islands (D'Entrecasteaux Reefs), about 65 miles north-west of New Caledonia; and Walpole Island, about 150 miles south-east of New Caledonia. All are French possessions and are administrated from New Caledonia.

From export figures recorded by Hutchinson (1950) it is clear that phosphate mining started at least as early as 1880 on the Chesterfield Islands and 1879 on the Huon Islands. However there appear to have been breaks in production as Power (1925) suggests that none of the islands was being worked in 1925. More recent information is supplied by the authors of the Admiralty Geographical Handbooks. They state that in 1939 all the deposits were leased by the Austral Guano Company of Melbourne, who were then working Surprise Island in the Huon group, and Walpole Island. Production might still have been going on in the Chesterfield Island, which are variously reported as having deposits of 175,000 tons and 750,000 tons, but had stopped on Fabre and LeLeizour Islands in the Huon group. No record has been found of mining on any of these islands since the war. The absence of more frequent references to the Chesterfield Islands in literatur on phosphates in the Pacific suggest that the lower estimate of their reserves is more reasonable, but the islands merit further investigation.

In a normal year Walpole Island is reported to have produced 10,000 tons of phosphate and the Huon Islands 6,000 tons; no production figures are available for the Chesterfield Islands. If these figures are correct much of the output must have been absorbed in New Caledonia, as only a few thousand tons were exported each year: an average of 9,000 tons per annum in 1920-8, about 11,000 tons in 1935, about 2,000 tons in 1936, 1,582 tons in 1938, and 3,767 tons in 1939.

The Huon Islands and Chesterfield Islands are groups of low-lying coral atolls less than 20 feet high. The deposits on Surprise Island consist of about 2 feet of leached guano overlying another 2 feet of partly phosphatised coral sand and shell grit cemented together by phosphate (Power, 1925); other deposits are presumably similar, resembling those on many low-lying islands of the Pacific. According to Hutchinson (1950) the Chesterfield Islands deposit contained the equivalent of 40% to 62% $Ca_3P_2O_8$; Dixon's (1879) analyses of guano phosphate from two of the Huon Islands gave higher values for $P_2O_5$, equivalent to 65% to 74.5% $Ca_3P_2O_8$. Power states that the Surprise Island deposit had a sesquioxide content of 0.68% $Fe_2O_3$ and 0.22% $Al_2O_3$. The following analysis of phosphate from one of the Huon Islands (Chevron, 1880) also indicates a low sesquioxide content.

| | |
|---|---|
| $H_2O$ | 9.74% |
| Organic matter (including N=1.16) | 19.90 |
| $Fe_2O_3$ | 0.24 |
| CaO | 37.60 |
| MgO | 0.09 |
| $K_2O$ | 0.28 |
| $Na_2O$ | 0.18 |
| $P_2O_5$ | 28.59 |
| $SO_3$ | 0.44 |
| $SiO_2$ | 0.08 |
| $CO_2$ | 3.01 |
| Cl | 0.11 |
| F | tr. |
| | 98.26 |

The deposits on Walpole Island, an elevated coral island at least 210 feet high, consist of incoherent, dark brown earthy material which fills the depressions between limestone pinnacles on the highest part of the island. No full chemical analysis is available but Power reports a $Fe_2O_3$ content of 6.72% and an $Al_2O_3$ content of 12.57%. Obviously they are closely comparable with the deposits on the elevated Mariana islands.

## Tonga and Fiji

Both the Admiralty Geographical Handbooks (1945) and An Economic Survey of Colonial Territories (1951) state that two small islands, Hunga Tonga and Hunga Ha'apai, in the Tonga group, are reported to contain phosphate deposits, and imply that lack of an anchorage has been mainly responsible for their not being developed; the more recent publication adds that "exploitation is not considered a commercial proposition". It is extremely unlikely that the deposits are anything more than small local accumulations of guano: the two islands on which they are reported to occur are small volcanic islands with steep slopes rising to 400 feet and 480 feet above sea level and so are obviously unsuitable for either the retention of large deposits of guano or the formation of phosphate rock.

No phosphate deposits have been reported from any of the limestone islands of the Tonga group. In Fiji small deposits are known on Vatoa, Ongea Nariki and other islands of the Lau group, where the main outcrops of coral limestone are found; they are not mentioned by Hutchinson and have not been worked for export.

The apparent absence of large phosphate deposits in this area, relatively well known compared with the Central Equatorial Islands where numerous deposits were discovered, suggests that, either biologically or climatically, it has never been suitable for guano production.

## Solomon Islands

The Solomon Islands are dominantly volcanic, but outside the main chain of islands are several coral atolls and two markedly elevated atolls, Bellona and Rennell. The authors of the Admiralty Geographical Handbooks state that commercial phosphate deposits were believed to exist on Rennell, but a survey carried out in 1927 showed they were of poor quality. Both this island and Bellona, which apparently was not examined in 1927, may merit further investigation.

## CONCLUSIONS

A study of phosphate mining in the Pacific over the last hundred years has shown that it is extremely unlikely that further search will lead to the discovery of any new major deposits. However small deposits, which could become strategically important in wartime, might still exist on any coral island between about 25° north of the Equator and 25° south of the Equator, and more particularly in the south and west of this region.

These areas are recommended partly on the distribution of known phosphate deposits and partly because they now have, or could have had at some time since the Tertiary, the low rainfall coupled with high concentrations of plankton in the surrounding waters which is essential for the accumulation of guano deposits. They include the Caroline and Marshall Islands, which the Japanese investigated for commercial phosphate deposits before the last war, the Ellice Islands and the Central Equatorial Islands, where relatively small deposits were extensively exploited last century, islands north of New Guinea, the Solomon Islands, and the Chesterfield Islands north-west of New Caledonia. Small deposits may also exist on some of the more isolated islands of the Tuamotu Achaepelago, where they are already known at the eastern and western ends. The fact that large deposits have not been discovered on the limestone islands in the relatively well known Fiji, Tonga and Society groups is believed to indicate that either biologically or climatically they have never been suitable for guano production.

Unfortunately it is not possible to restrict the search for phosphates to islands which now have a low rainfall as most deposits were formed during Pleistocene time when climatic conditions were very different from those known at present.

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# PHOSPHATE DEPOSITS CENTRAL PACIFIC OCEAN

SCALE 1:27,500,000 AT THE EQUATOR

REFERENCE

- ○ Phosphate in production September, 1955
- ▲ Guano producing areas in period 1858 to 1927
- ● Guano-phosphate producing areas in period 1858 to 1942
- + Phosphate rock producing areas in period 1890 to June, 1955
- ◇ Areas containing deposits of phosphate meriting investigation

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