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A SURVEY OF PHOSPHATE DEPOSITS IN THE SOUTH-WEST PACIFIC AND AUSTRALIAN WATERS

BY

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SUMMARY

In 1955 a programme of search for phosphate, to supplement the diminishing reserves of Ocean, Nauru, and Christmas Islands, was agreed upon by the Australian and New Zealand Governments. This Bulletin describes the search of islands of the South-West Pacific and Australian waters by the Bureau of Mineral Resources. Islands off the northern coast of Australia were investigated in 1957, the British Solomon Islands and islands off Papua and New Guinea in 1958, and Fiji, Tonga, and the Gilbert and Ellice Islands in 1959.

The deposits of Bellona Island, B.S.I.P., are the only ones investigated by the survey that could be exploited and exported ; they contain about 500,000 tons of grade 30·3 percent P_2O_5 and 4,500,000 tons of grade 22·3 percent P_2O_5. Other, smaller, deposits were found in : the Purdy Islands, Sae, and Manu (New Guinea) ; Tamana, Vaitupu, Abemama, Nukufetau, Tabiteuea, and Nui, in the Gilbert and Ellice Islands ; Vanua Vatu, Ogea Driki, and Tuvuca in Fiji ; and islands in the Ashmore Reef, Northern Territory. Many other islands contained traces of phosphate.

The origin and uses of various types of phosphate deposit are reviewed.

INTRODUCTION

BY

O. N. WARIN

Since the discovery at the beginning of the century of the rich phosphate deposits at Nauru and Ocean Islands in the Pacific Ocean and of Christmas Island in the Indian Ocean, most of Australia's increasing phosphate requirements have been met from these sources. Australia imports annually from these three islands about 1½ million tons of phosphate rock ; and the life of the deposits, even in the unlikely event of a steady rather than a rising demand, will not be more than 30 to 40 years. The phosphate these islands provide is extremely high-grade and its cost is considerably lower than the price of the cheapest phosphate rock on the world market.

The need has been felt for some time to find new deposits to supplement these dwindling reserves. During the last war Ocean Island and Nauru were over-run and the acute shortage of phosphate that resulted was an unpleasant reminder of Australia's good fortune in having access to these high-grade, low-cost sources. In 1955 the Australian Government decided to invite the New Zealand Government to share in a survey to determine what phosphate deposits exist in Australia, New Zealand, and their Territories. Proposals were outlined by the Department of National Development for a three-stage search :

(1) Geological surveys where evidence suggested that phosphate deposits might occur ;

(2) Testing any deposits found—by drilling, trenching and shaft sinking ;

(3) Assessment of deposits, including an assessment of the economic feasibility of exploiting the deposits.

It was proposed to investigate four areas :

(1) The Australian continent and Territories ;

(2) New Zealand and her Territories ;

(3) British Pacific possessions and territories ;

(4) Any other islands in the region to which access could be obtained.

W. C. White, of the Bureau of Mineral Resources, was appointed to co-ordinate the search. State mines authorities and instrumentalities within the various island groups where a search was intended were approached and their co-operation obtained. In the British Solomon Islands Protectorate and in Fiji the Overseas Geological Survey staffs undertook reconnaissance investigations which formed a basis for the later work of the Phosphate Survey.

To visit every island and reef in the South-western Pacific and Australian coastal waters would obviously have been a very time-consuming, and often fruitless, undertaking. The survey was therefore planned to visit first those islands from which phosphate had been reported but which had not been adequately tested. In addition, all islands which, by virtue of their geographical positions, climate, geology, and geomorphology, were considered to be possible phosphate prospects were explored and a reconnaissance was made of many less promising islands. During the course of the survey, as the condition of phosphate deposition became better known, the selection of islands for detailed investigation was made with increasing confidence.

Progress of the Search

In July and August of 1957 the field work of the survey began with an inspection of groups of islands off the north coast of the Northern Territory. This phase of the work was completed by a visit to Cartier Island and the Ashmore Reefs in August, 1958, and the results were incorporated in a report (McQueen, 1958).

In November 1957, Warin was sent by the Bureau to Christmas Island, Indian Ocean, to study the extensive phosphate deposits at present being quarried there as a preliminary to a search on island groups in the Pacific (Warin, 1958).

The search in the Pacific began with the 1958 field season, during which islands in Papua, New Guinea, and the British Solomon Islands Protectorate (Plate 1) were prospected (Warin & Jensen, 1959). The phosphate deposits of Bellona Island, B.S.I.P., which had been located during a reconnaissance by the Geological Survey of the Solomon Islands, were surveyed during this field season (White & Warin, 1959).

During the 1959 field season the survey was extended to other British dependencies in the Pacific: the Gilbert and Ellice Islands (Plate 4) (White, 1960), the Fiji group (Plate 5) (Warin, 1960b), and the Kingdom of Tonga (Plate 7) (Warin, 1960a).

Meanwhile the New Zealand Geological Survey had searched the New Zealand dependencies of Chatham Island, Samoa, and the Cook Group.

The results of the search in all these island groups were, on the whole, disappointing. Several previously unknown deposits were discovered: on Nauna and on Sae in the Admiralty Islands, on Vatu Vara in Fiji, and on some of the Gilbert and Ellice Islands. In addition, a number of previously known deposits were surveyed, including Vanua Vatu and Ogea Driki in Fiji, the Purdy Islands, and Aua, Manu, and Wuvulu in New Guinea. But the deposits are all small and could not be economically worked except perhaps for use as a source of fertilizer for the groups within which they occur. Only the deposits on Bellona Island, B.S.I.P., showed any promise as a commercial source of phosphate, and in October, 1960, a party from the British Phosphate Commissioners, with a geologist from the Bureau of Mineral Resources, returned to the island to investigate mining, handling and shipping problems and to obtain further information on the nature and extent of the higher-grade material (Warin, 1961 ; Adams, 1961).

Method of Survey

Many of the smaller islands surveyed are not regularly visited by local ships and a vessel had to be chartered for both the main field seasons. In 1958 the Motor Vessel *Kokoda* under Captain C. R. Bignal was chartered from Burns Philp Ltd of Port Moresby for the survey of Papua, New Guinea, and the British Solomon Islands. For the survey of Fiji and Tonga, during 1959, the Auxiliary Ketch *Mororo* under Captain S. R. Brown was chartered from the Mororo Cruise and Charter Co., Suva, Fiji. In the Gilbert and Ellice groups local shipping was used. The islands off the north coast of Australia were surveyed by a local charter and with the help of the Royal Australian Navy.

Most of the islands visited in Papua, New Guinea, and the Solomon Islands are small and steep-to, and have poor anchorages ; in Fiji and Tonga anchorages in sheltered lagoons are more common. Landings were often made from a surf boat or dinghy on to the edge of the reef at low tide or on to the beach at high tide.

Access differs greatly from island to island. On uninhabited islands and uncultivated parts of inhabited islands the natural vegetation is commonly a thick rain forest. On the high-standing limestone islands traversing is slowed because of pinnacled and solution-eroded limestone ; volcanic islands generally are covered by grass rather than by rain forest and movement is easier. On inhabited islands tracks to gardens and to the sea were generally sufficient for reconnaissance exploration—cut-lines were only necessary if a deposit had to be accurately delineated. On uninhabited islands cut-lines were necessary all the time. In most places the only means of travelling was on foot ; on two islands trucks were available, occasionally canoes were used, and on one island horses were borrowed. It was usually necessary to camp on the island, as the ship had normally to anchor some way from the shore and had to be ready to run to safer anchorage. In Fiji and Tonga the survey party were commonly the guests of the head of the village.

Men for hand-auger drilling gangs, guides, and carriers were generally taken on locally as needed, but during the 1958 season twelve Trobriand Islanders were employed continuously for the whole field season.

Method of Testing

Deposits were tested by hand-auger drilling. The hand-augers used were Jarrett augers with 3-inch-diameter heads and 4-foot extension rods made from ¾-inch water-pipe with conventional couplings. These augers have the great advantage of cheapness and lightness. They are particularly effective in clays—and many of the deposits tested were of phosphatic clay. In loose sandy material, such as oolitic phosphate, the 3-inch auger head is sometimes too wide and the sand is not retained. In cemented phosphate deposits a crowbar was used to break through the upper crust.

Three other types of equipment were tested during the 1958 field season : a large, hand-operated, percussion-type drill, made to the same design as others operated by Bulolo Gold Dredging Co.; the Empire hand-drilling equipment ; and a diamond drill, the Mindrill E-100. For the type of deposit commonly tested the Jarrett augers were the most efficient and allowed a large number of holes to be completed in a short time.

The auger holes were spaced at regular intervals along existing tracks or along cut traverse lines. Their position was determined by pace and compass or tape and compass traverses.

Samples for chemical analyses were collected from the auger holes. Most were retained for phosphate estimation in the laboratory, but some were estimated in the field by rough quantitative methods. In one method the phosphorus is precipitated as ammonium phosphomolybdate, the precipitate is centrifuged, and the volume of the precipitate is estimated from calibrations on the centrifuge tubes. A more refined colorimetric field method was developed before the 1959 field season, but was not used in the field as no deposits were found large enough to merit spending the time needed. A colorimetric spot test, was, however, used as a rough guide to the grade of phosphate in a deposit.

Types of Phosphate Deposits (by W. C. White)

Most of the world's phosphate comes from four main types of deposit, of which only the last need be considered further here :

1. Primary bedded phosphorites of marine sedimentary origin ;
2. Secondary phosphorites formed by the erosion of weakly phosphatic rocks ;
3. Deposits of igneous or metamorphic origin, usually associated with alkaline igneous rocks or carbonatites ;
4. Deposits resulting directly or indirectly from the excreta of sea-birds, and to a lesser extent of bats.

Deposits of the fourth type, on remote islands in the Pacific and Indian Oceans, have been of the greatest importance to Australia, supplying as they have for many years almost the whole of her requirements with cheap but high-grade material. Before 1900 small amounts of phosphatic guano were imported from the Southern Line Islands and the Phoenix Islands. Since the discovery by Sir Albert Ellis in 1899 of high-grade phosphate rock on Ocean and Nauru Islands almost all Australia's needs have been met by material from these two islands and, since 1948, from Christmas Island in the Indian Ocean, where mining commenced in 1897.

All insular phosphate deposits are generally believed to be derived from the accumulated droppings of certain species of sea-birds which at some time inhabited the islands. Hutchinson (1950) in a very detailed review of the literature of deposits of this type distinguished between *nitrogenous guano*, *phosphatic guano*, and *leached guano*. Nitrogenous guano contains a large part of the original nitrogenous organic matter of the excreta ; phosphatic guano is that in which the organic nitrogenous fraction has been lost, leaving a material that usually consists of calcium phosphate minerals ; the term leached guano is properly limited to the formation of phosphatic guano by percolating waters, resulting not only in the loss of soluble salts and organic nitrogen, but of the phosphate ions as well. Hutchinson further subdivided the deposits into *modern*, *old*, and *ancient* guano : modern where the deposits are being added to by contemporary bird colonies ; old where there is an historical record of bird colonies, which have since disappeared ; and ancient where the birds deserted the island at some remote period.

This genetic classification, though useful, fails to distinguish between many important phosphate deposits which differ greatly in form and type of material. Phosphatic guanos formed by *in situ* decomposition can seldom be distinguished from leached guano, and the term phosphatic guano is hardly descriptive of those ancient phosphate deposits formed by metasomatic replacement of calcareous, or in some cases igneous, rocks, even though the active solutions responsible for replacement stemmed from guano. Commonly several types and ages of phosphate may be present in the one deposit.

Other writers, noting the tremendous variety of insular phosphate deposits, have avoided any genetic classification other than the use of the terms modern, old, and ancient guano, and have confined themselves entirely to terms descriptive of the type of material.

For present purposes a simple classification, broadly based on Hutchinson's genetic classification, would seem to suffice :

1. Nitrogenous guano—modern, old, ancient.
2. Phosphatic guano and phosphatic crust—deposits formed by decomposition of nitrogenous guano, consisting essentially of calcium phosphate and including crusts of lime sand cemented by and more or less replaced by calcium phosphate.
3. Phosphate rock deposits—ancient deposits of calcium, iron, or aluminium phosphate minerals formed by the action of percolating phosphatic solutions from guano on the underlying rocks. Replacements of limestones and lime sands are the most common in the oceanic areas, but phosphatized igneous and metamorphic rocks are also known.

Clearly these deposits can, and do, form a gradational series. Ancient nitrogenous guano cannot always be distinguished from phosphatic guano, and a phosphatic guano crust formed by replacement of lime sand is essentially the same rock as a phosphatic rock produced by replacement of a calcarenite. In practice, however, the three types are generally quite distinctive and usually have a very different post-depositional history.

Nitrogenous guano

The phosphatic material making up the three types of deposit varies considerably in appearance and to some extent in chemical and mineralogical composition. Fresh nitrogenous guanos are rich in nitrogen, phosphorus, and organic material, and contain alkalis, urates, oxalates, and purines. Decomposition results in a loss of ammonia and organic matter and a concentration of inorganic material, principally calcium phosphate, while the more soluble oxalates, urates, and alkalis, and some of the phosphates, may be removed by percolating water. The deposits usually form extensive and thick, often white, capping. One of the best known, on the Peruvian Chincha Islands, reached a thickness of 150 feet.

Phosphatic guano and phosphatic crust

The phosphatic guano deposits consist essentially of calcium phosphates derived either by very complete leaching of guano, or by cementation or replacement of calcareous sands immediately beneath the guano to form a thin crust of phosphatized sand. The leached guano generally occurs as a flat layer of pale to dark brown or reddish brown pulverulent material which may contain a small amount of organic matter. In the phosphatic crusts the nature of the original sand is usually apparent. The colour of the material ranges from light yellow brown to dark brown and is usually porous and of light weight. It is described more fully in the chapters on the Gilbert and Ellice Islands and the New Guinea Islands, on some of which it was found. Similar material has been recorded from the Marshall Islands (Fosberg, 1957) under the name 'atoll phosphate rock,' and from the New Caledonia area (Koch, 1957). Much of the 'guano' recovered from central Pacific islands such as Howland, Baker, Jarvis, Starbuck, Enderbury, and McKean was of this type.

Deposits of this type are generally confined to the flat, low-lying sand cays and atoll islands. They are seldom large and the phosphate content is very variable. They consist essentially of collophane and calcite.

Phosphate Rock Deposits

The phosphate rock deposits, which, though few, are by far the most important of the insular phosphate deposits, are generally found on elevated atolls and limestone islands. Their age is in most cases post-Miocene and probably Pleistocene.

The deposits commonly occur on intensely eroded limestone surfaces, often of the 'Karrenfeld' type; the limestone in every known example has been extensively dolomitized. Mineralogically the deposits are of collophane, a cryptocrystalline hydrated mineral closely related to apatite, some dahllite, and, in some instances, minor amounts of crandallite. Some of the deposits are remarkably low in alumina and iron, but others contain so much that they are unsuitable for superphosphate manufacture. The type and chemical composition of the material is largely controlled by the geomorphological history of the island.

The materials of the deposits are of several distinct types. Power (1905) classified the materials as alluvial and rock phosphate, but Owen's (1923) terms ' coherent ' and ' incoherent ' are more descriptive and have less genetic significance, as well as being more widely used.

Incoherent phosphate is of three main types : fragmental phosphate, oolitic phosphate, and phosphatic clay. Fragmental phosphate includes all the fine, ' loose ' phosphatic material which is not distinctly oolitic or clayey. It is derived in general by the phosphatization of the finer reef debris and foraminiferal sands, shell fragments, clastic limestone detritus, calcareous muds, silts, etc. It is commonly off-white to pale brown and many of the larger fragments retain the structure of the original coral or shell. Much of the finer dust phosphate is probably, as Owen suggested, residual phosphate from leached guano. Incoherent phosphate is largely tricalcium phosphate and may contain up to 41 or 42% P_2O_5.

Oolitic phosphate is composed of small, usually spherical buckshot grains of collophane generally $\frac{1}{8}$ inch–$\frac{1}{4}$ inch in diameter. The grains rarely show well defined concentric structure or contain a nucleus of sand or shell fragment. They commonly have a dark, iron-stained outer shell but otherwise they are generally structureless. They contain up to 40% P_2O_5 and very little iron or alumina, but clayey interstitial phosphate between the oolites often accounts for the higher iron and alumina in bulk samples.

Most of these ' pseudo-oolites ' are undoubtedly a replacement of the oolitic and pisolitic bodies found in modern reefs and particularly in intertidal solution basins. Some, however, were simply small water-worn fragments of reef limestone, while others are clearly the result of phosphatization of small reef-dwelling Foraminifera such as *Calcarina*.

Phosphatic clay is commonly a yellow to dark brown, porous, clayey-looking material containing from 1 or 2% up to more than 30% of P_2O_5. When dry it crumbles to a fine, even-textured yellowish powder and it is accordingly included with the incoherent phosphates.

The clay commonly contains 10% to 12% Fe_2O_3 and up to 40% Al_2O_3 and is believed to be formed by the admixture of terra rossa from the solution erosion of limestone with fine incoherent calcium phosphates. It is very often found as a blanket deposit overlying oolitic phosphate, and complete gradation from oolitic phosphate, through light-coloured phosphatic clay with a remnant oolitic structure, to darker, even-textured aluminous phosphatic clay is common ; elsewhere typical terra rossa in solution hollows grades laterally and vertically into weakly phosphatic clay.

Some of the alumina and probably most of the iron are believed to exist as the oxides, but under wet to swampy conditions such as exist in the centre of many elevated atolls, the alumina at least is known to combine with phosphate to form the calcium-aluminium phosphate crandallite. No minerals of the iron-bearing strengite-variscite series have been identified in clays from the South-west Pacific area.

Clays of this type would be difficult to distinguish from phosphatized volcanic ash or pumiceous clays.

Coherent phosphate also is of three types ; accretionary phosphate, phosphatized bedrock, and subvitreous phosphate.

Accretionary phosphate is probably the most common of the coherent phosphates. It generally occurs as large blocks and boulders, or extensive lenses of tough compact phosphate, particularly at the base of a thick deposit. Thin sections of the rock show it to be composed of small oolites and fine fragments of phosphate which have become lithified by accretion and, to a lesser extent, cementation by phosphate.

Phosphatized bedrock, notably limestone, is also common, but seldom exists in large quantities in insular deposits. The weakly acid phosphatizing solutions leached down from the guano were apparently unable, in most instances, to attack and replace more than a thin surface skin of either the bedrock or the larger detrital fragments.

The rare examples of phosphatized igneous and metamorphic rocks also belong to this type. The best known occurrences are the phosphatized trachyte on Clipperton atoll (Teall, 1898; Obermüller, 1959) and phosphatized andesite on Malpelo Island (McConnell, 1943), both in the east Pacific. Part of the economically important deposit on Kito Daito Jima is believed to be a phosphatized pumiceous clay (Yamanari, 1935, quoted in Hutchinson, 1950). Cannac Island in the Solomon Sea has a deposit consisting partly of fresh guano and partly of phosphatized slate and volcanic rocks. The mineralogy of these deposits is complex. Silica is commonly replaced by hydrated phosphates, and amygdules are transformed into secondary quartz, chlorite, and phosphate minerals. Variscite and meta-variscite, strengite, phosphosiderite, and possibly wavellite are the most common phosphate minerals.

Subvitreous phosphate occurs as vein and cavity fillings in limestones, where it is deposited from colloidal phosphate solutions by gelation. The phosphate is a tough, compact, subvitreous to translucent material, often showing precipitation-banding and crustification. Material of this type from Nauru was formerly considered to be a distinct mineral species and was given the name *Naurite* ; but the name is no longer used, as the mineral has been shown to be carbonate-hydroxy-fluor-apatite of the collophane group (McConnell, 1950).

Previous Investigations in the South-west Pacific

During the late nineteenth century guano was vigorously sought throughout the Pacific. The prospectors were not generally given to exact scientific recording of their operations ; some had such doubtful title to the islands they exploited that silence was a necessity rather than a virtue. The guano trade appears to have been a valuable one, and it is likely that most islands in the Pacific were visited during this time.

Table 1

TYPES OF PHOSPHATE DEPOSIT

Type of Deposit	Type of Material	Percentage P_2O_5	Chemical Composition	Mineralogy	Occurrence	Formation	Deposits Examined
GUANO	Nitrogenous to leached guano	Variable, seldom over 15	Complex	Complex	Cappings, mainly on low rainfall islands	Accumulation of excreta of sea birds (also bat guano in caves)	Marakei and Tabiteuea, Gilbert Islands
PHOSPHATIC GUANO	Leached guano	15–20	Mainly calcium phosphates	....	Mainly on low flat islands	Leached guano	....
PHOSPHATIC CRUST	Phosphatized lime sand	2–25	Tricalcium phosphate and calcium carbonate	Collophane, calcite	Sand cays, atoll islands	Cementation and replacement of lime sands	Aua, Wuvulu, Sae, Manu, Purdy Islands, Gilbert and Ellice Islands
PHOSPHATE ROCK	Incoherent phosphate Fragmental oolitic....	Up to 40	Tricalcium phosphate	Collophane	On elevated atolls and limestone islands	Action of phosphatic solutions on limestone detritus, reef debris and terra rossa	Ocean, Nauru, Christmas, Vanua Vatu, Vatoa, Ogea Driki, Nauna, Bellona
	Phosphatic clay	1–25	Calcium and aluminium phosphate and iron	Collophane, crandallite and ? iron oxides			
	Coherent phosphate Accretionary	Up to 40	Tricalcium phosphate	Collophane and dahllite	On elevated limestone islands	Accretion and cementation of oolitic and fragmental phosphate	Ocean, Nauru, Christmas, Bellona
	Phosphatized limestone	Up to 40	Tricalcium phosphate	Collophane	On elevated limestone islands	Action of phosphatic solution on large limestone fragments and bedrock	Ocean, Nauru, Chrristmas
	Phosphatized igneous and metamorphic rocks	Low, variable	Iron-aluminium and calcium phosphate	Crandallite, variscite-strengite and collophane	Mainly on volcanic islands	Action of phosphatic solution on bedrock	Cannac (phosphatized slates)
	Subvitreous phosphate	Up to 43	Tricalcium phosphate	Collophane and dahllite	In cracks and cavities in elevated limestone islands	By gelation of colloidal solutions	Ocean, Nauru, Christmas, Bellona

The guano seekers came to the Pacific from many countries, but probably the United States provided the majority. Captain George E. Netcher of New Bedford, the discoverer of Howland Island, was possibly the best known. The search was primarily for guano and was directed at low coral islands ; the phosphate deposits of Ocean and Nauru escaped detection, although the islands were visited by experienced guano prospectors during this period.

Guano and ' crust guano ' (in most instances probably phosphatized lime sands) were being exploited from a large number of Pacific islands from about 1850 to the early 1900's. Three typical islands, Howland, Baker, and Jarvis, were exploited by American guano interests from 1860 to 1880, from 1857 to 1879, and from 1859 to 1878 respectively. Of the islands visited during this survey a record exists that in 1890 a thousand tons of phosphate were exported from the Purdy Islands, New Guinea, to Germany ; but with the coming into production of Ocean Island in 1900 and of Nauru in 1906 the trade in guano and crust guano from the south-west Pacific declined rapidly.

Sollas et al. (1904) recorded the presence of phosphate in swamps and in a limestone conglomerate on Funafuti, and guano was exploited on Nuilakita, Ellice Islands.

In New Guinea a search was undertaken in 1909 by the Hanseatic Pacific Expedition led by Dr Georg Friederiei. A number of islands were explored, apparently without any new source of phosphate being found. In 1929 the British Phosphate Commissioners sent Mr K. M. Fennell to New Guinea to investigate the phosphate deposits, and in 1941 Mr R. C. Hutchinson, an officer of the Administration's Department of Agriculture, examined the known phosphate islands to assess the reserves with a view to their local use.

Less attention was paid to the islands of Papua. In 1917 E. R. Stanley, the Government Geologist of Papua, visited Cannac Island (see p. 53) and examined the deposit of guano and phosphate on it.

The Fiji group were apparently largely ignored by the early guano hunters because the islands are mainly high and would have been considered unlikely prospects. Hutchinson (1950) makes no mention of guano or phosphate deposits in Fiji except to record that two rocks inside the Reid reef were reported to have some guano on them. A small deposit of phosphatic clay and oolitic phosphate on Ogea Driki in the southern Lau was examined in 1941 by Professor F. T. M. White, who was then the Inspector of Mines for Fiji (White, 1942). This deposit was investigated in greater detail in October 1942 by Mr Bridges, a representative of the British Phosphate Commissioners, as at that stage of the Second World War Australia had lost access to Ocean and Nauru and urgently needed phosphate supplies.

With Australia's announced intention of searching for phosphate deposits in the south-west Pacific the Fiji Geological Survey undertook in 1957 a reconnaissance survey of the Lau group, discovering two deposits which had not hitherto been recognized; Vatoa and Vanua Vatu (Guest, 1957). Dr J. A. Staargaard of Aluminium Laboratories Limited, from a reconnaissance of the Lau islands in 1958, reported an aluminous phosphatic clay on Tuvuca.

Stanley (1929) recorded traces of phosphate on Rennell Island in the Solomons group, and in 1956 high-grade phosphate rock was discovered in nearby Bellona Island. The Solomon Islands do not, however, appear to have been greatly troubled by the early guano prospectors.

BELLONA ISLAND, B.S.I.P.

BY

W. C. White and O. N. Warin

Bellona Island (Plate 2) is situated ninety miles south of Guadalcanal (long. 159° 50′ E, lat. 11° 15′ S). It is one of the smallest and most isolated islands in the British Solomon Islands Protectorate, being only six miles long and less than two miles wide, elongated east-south-east. The large island of Rennell is twenty miles to the south-east.

The island was apparently discovered by Captain Butler of the *Walpole* in 1801; it was at that time inhabited by Polynesian people whose descendants live there today.

The present population of Bellona is about 500. Their villages are spaced out along the main central track. Gardens appear to grow well in the phosphatic clay of the central valley floor; roots, ¼ inch in diameter, of growing coconut palms were found as deep as 20 feet from the surface in a test pit. The villagers were employed on daily wages for hand-auger drilling, pit-sinking, and as survey assistants during the surveys. They have few opportunities to earn money and are keen to work for short periods.

The isolated position and, now, Government orders regulating shipping visits have kept Bellona and Rennell free of malaria and some of the other diseases prevalent throughout the Solomon Islands.

There is a poor anchorage for small vessels at Ahanga which was surveyed in detail during the 1960 survey. The cliff at Ahanga (about 65 feet) is lower and less steep than that round most of the island. The foreshore is a narrow strip of sand with low rocky patches, and the fringing reef, which elsewhere is almost horizontal and has a well marked ridge along its seaward edge, here shelves gently out until it drops away steeply about 50 yards from the shore. The gently shelving upper surface of this reef would be suitable for building a slipway and wharf, while the steep outside edge of the reef would allow large craft to approach close to the shore provided that deep-sea moorings, similar to those in use at Ocean Island, could be secured.

A good track leads from the beach of Ahanga for the full length of the island. The initial slope from the beach to the cliff top is steep, rough, and rocky; beyond that the track is mostly gently graded and wide enough for a jeep to travel along it except in a few places where low outcrops of limestone (one to two feet high) encroach on it. A light motor cycle and bicycles were carried up the initial slope and used on the tracks during the 1960 survey.

Fairly dense forest covers much of the island, particularly round the rim, but large areas in the centre have been cleared and cultivated.

Fresh water is scarce on Bellona. In a few places just above the high-water mark, freshwater springs enter the sea; for example at Ongoba in One Bay, at Tingoa at the east end of the island, and at Angau. There are no rivers or creeks on the island, the surface of which is either of cavernous, pinnacled limestone (the rim) or of porous clay (the central valley floor). The island people catch rain water for drinking, cooking, and washing. Two auger holes drilled during the 1958 survey intersected wet clay and might provide a small supply of relatively good water if deepened into the underlying limestone. A determined attempt made during the 1960 survey to deepen one limestone chimney exposed in Pit 2 (see Fig. 1) to reach water was frustrated by large phosphate boulders at a depth of 30 feet.

No statistics are available on Bellona's climate. The island lies in a part of the Pacific Ocean subject to two clearly marked seasons, known, from the prevailing winds, as the north-west and the south-east seasons. A lull generally occurs at the change of seasons in April or May. The first survey was made during this lull and the weather was warm and dry for most of the time ; the second survey was made during November in mostly dull weather with heavy rain.

Physiography and General Geology

Bellona Island is an elevated coral atoll standing about 250 feet above sea level (Pl. 2). It is elongated in an east-south-east direction and consists of a relatively narrow, flat, central depression or valley surrounded by a wide double rim of limestone. The outer rim is about 135 feet and the inner rim 250 feet above sea level. The outer rim is almost continuous and is generally extremely steep on the seaward side, with a prominent wave-cut notch at about 100 feet above sea level marking an early stage of emergence. A more recent emergence is represented by a narrow terrace at 10 feet above sea level, outside which is a narrow, shallow lagoon and fringing reef.

From the inner rim, which is deeply notched in several places (notably at the east end near Tingoa and Tegaigai), and altogether absent along the coast near Ahanga, the rough solution-etched limestone surface drops gently to the flat soil-covered floor of the central depression. The lowest part of the central depression, near Ngotokanava village, is about 50 feet above sea level ; from there to the east the floor rises gradually to about 100 feet above sea level at auger hole 61 (west of Matangi village). To the east of auger hole 61 the central valley floor rises sharply to a platform at about 160 feet above sea level (the Matangi platform). A similar, though lower, platform occupies the west end of the central valley from just to the west of Ngotokanava village to the coast at Ahanga (the Matahanua platform).

On the seaward slopes of the island the limestone is intensely eroded into tall pinnacles, pits, and crevices, often of great complexity and fantastic shape. The upper slopes of the central valley and the Matangi and Matahanua platforms, however, show much less intense solution-erosion. The limestone here is furrowed and pitted by solution along cracks and joints, but the surface is relatively smooth and large pinnacles and potholes are absent. In the centre of the valley, on the other hand, the surface of the limestone beneath the cover of phosphate is very irregular and shows evidence of large-scale solution. It seems likely therefore that the central valley is a former atoll lagoon which has been deepened by solution-erosion after emergence. The Matangi and Matahanua platforms, standing at around 160 and 100 feet above the present sea-level, are believed to represent the bottom of the original lagoon.

The island has a slight but distinct tilt towards the north-west which, as pointed out by Grover (1958a), contrasts strongly with the marked south-easterly tilt of nearby Rennell Island. On Bellona the tilting is most noticeable in the central valley and on the inner rim. It is less apparent on the 100-foot wave-cut notch and is absent on the 10-foot terrace, which suggests that it took place at an early stage of the island's emergence. As Bellona and Rennell are tilted in opposite directions and are emerged to different heights (Bellona 250 feet, Rennell 360 feet) the emergence was most probably due to tectonic uplift rather than to a general lowering of sea level.

Volcanic rocks do not crop out on Bellona, and auger holes put down through the clay which blankets the central valley floor all bottomed on limestone or phosphate rock. Grover (1958a) comments on igneous pebbles brought to the island by human and other agencies.

Palaeontology

Microfossils from limestone samples collected by Grover indicate an age not older than Pleistocene (Crespin, 1956a, 1956b). The forms identified include *Lithothamnium*, *Halimeda* sp., *Operculinella venosa*, *Orbulina universa*, *Globigerina* sp., and some indeterminate corals and bryozoa.

Summary of Phosphate Investigations

Although Rennell was investigated in 1927 by Stanley (1929) and traces of phosphate were noted, Bellona does not appear to have been visited until J. C. Grover, Senior Geologist of the British Solomon Islands Geological Survey, discovered phosphate in May 1956 during a reconnaissance of the two islands. A sample of clay from a village pit near Ngotokanava was found to contain 23·3% P_2O_5 and vein fillings and mamillary crusts from the sea cliffs near Ahanga at the north-west end of the island were found to contain up to 33·6% P_2O_5 (Grover, 1958a).

Grover made a second visit later in the same year and over 30 pits were sunk to depths of up to 28 feet. Later a more extensive programme of pitting was carried out (Grover, 1958a) which showed that a large tonnage of phosphate material existed and that although the bulk of the material was highly aluminous, high-grade oolitic and incoherent phosphate, the extent of which was unknown, commonly occurred at the base of the deposits.

In 1958 a Bureau of Mineral Resources field party tested the phosphate deposits by a programme of drilling and sampling designed to cover the entire soil-covered area of the central depression. It was estimated from this auger drilling that the island deposits contained 4½ million tons of phosphatic clay with an average grade of 22·3% P_2O_5 and 700,000 tons of oolitic and incoherent phosphate with an average grade of 30·3% P_2O_5 (White & Warin, 1959).

In 1960 a party of seven British Phosphate Commission officers, led by Mr W. Adams, Assistant General Manager, and accompanied by one of the authors, visited Bellona from November 2nd to November 19th to re-examine the better-grade material and to investigate the probable cost of development and exploitation of the deposits.

The results of the survey have been incorporated in two unpublished reports (Adams, 1961 ; Warin, 1961). No difficulties were expected with regard to transport, handling, storage, loading, anchorage, and labour, but testing suggested that only 400,000 to 500,000 tons of high-grade material could be exploited as some is contained in chimneys too narrow to work and some is beneath thick clay overburden.

Methods of Testing

Hand-operated augers were found to be the most efficient for drilling and sampling. Holes were drilled every 300 feet on lines 600 feet apart at right angles to the main track, and at 300-foot intervals along the main track itself. The positions of these holes were surveyed with chain and compass and are shown in Plate 2. The total footage drilled was approximately 1900 feet, the deepest hole being 36 feet. Samples were taken at 2-foot intervals in the holes and all holes were continued until they bottomed in limestone. A representative number of samples were rapidly analysed for phosphate in the field by precipitation of the phosphate as ammonium phosphomolybdate and measurement of the compacted volume of the precipitate after centrifuging. Six deposits, A to F, were delineated in 1958. Deposits A, B, and C are of phosphatic clay ; D is of phosphatic clay underlain by a thin layer of incoherent phosphate ; E is of phosphatic clay underlain by a considerable thickness of incoherent and oolitic phosphate ; F is of oolitic phosphate. These deposits are shown on Plate 2 (the original Deposit E is now divided into two, Deposits E and T).

The testing of the 1960 survey was mainly at the east end of the central valley in Deposits E and F. Three methods of testing were used :

1. Pits were dug, chiefly at the east end of the island in the deposits of oolitic phosphate (F) and of incoherent phosphate overlain by clay (T) ;
2. Auger drilling to extend the 1958 coverage, particularly on the Matahanua platform, and to intensify the 1958 drilling at the eastern end of the island (Deposits T and F) ;

3. Auger drilling on close-spaced grids at particular localities in the eastern deposits in an attempt to explore further the contour of the limestone surface below these deposits.

Twenty-eight pits were sunk. The first pits were 30 feet x 8 feet in surface area, but smaller pits, 20 feet x 8 feet and 6 feet x 6 feet, were used later. The depth of the pits differed of course, as an attempt was made to reach the limestone surface in each pit. The positions of the pits are shown on the map, Plate 2. Figures 1 to 5 are from various pits and are discussed in the section on the particular deposits in which they were sunk.

Most of the auger drilling of individual holes on a broadly spaced grid was at the west end of the island to cover areas that had not been covered during the 1958 survey. The positions of these auger holes, the ' V ' holes to the immediate west of Ngotokanava and the ' X ' drilling at Matahanua, are shown on the map, Plate 2 ; sections of the auger holes are shown diagrammatically in Plate 3. This drilling showed that the phosphatic clay of Deposit A does not extend westward beyond the limits of the 1958 drilling. The drilling near Matahanua, however, disclosed Deposit X, a small tonnage of oolitic phosphate contained in chimneys in the limestone.

Table 2
SUMMARY OF AUGER DRILLING, BELLONA (1960 SURVEY)

Test Area	Number of Holes Attempted	Number of Holes Deeper than 3 feet	Average Depth of Deeper Holes (feet)	Material
A	54	3	$10\frac{1}{2}$	c
B	27	9	9	op, peb, c
C	35	14	9	op, peb
D	20	1	$9\frac{3}{4}$	c, op
E	12	3	11	op
F	12	1	$5\frac{1}{2}$	c
G	16	1	$3\frac{3}{4}$	Ts, op
H	12	7	$7\frac{1}{4}$	op, c
I	12	4	$12\frac{1}{4}$	op
J	12	3	$10\frac{1}{2}$	op, c
K	Limestone	outcrop		
L	9	5	5	op, peb, p
M	12	1	$6\frac{1}{2}$	c, op
N	Limestone	outcrop		
O	Limestone	outcrop		
P	3	3	16	c, p
Q	12	10	$6\frac{1}{2}$	op
R	8	7	9	op
S	12	0	All limestone	with top soil
W_1	4	4	$15\frac{1}{4}$	op, p
W_2	12	1	8	op, c
W_3	Not drilled—probably	mainly	limestone outcrops	
W_4	4	4	16	c, p
W_5	5	5	$5\frac{3}{4}$	c, p
W_6	2	2	19	c, p
W_7	12	4	10	c

c = phosphatic clay
op = oolitic phosphate
p = incoherent off-white to white phosphate
Ts = Topsoil
peb = phosphate pebbles

Pattern auger drilling was used chiefly in Deposits F and T. Closely spaced auger holes were put down in order to determine the average depth of the phosphatic material and the relief of the underlying limestone surface. The holes were placed 10 feet apart along lines spaced 10 feet apart. In the first of these test areas drilled (Test Area A) 54 holes were attempted ; later it was found that 12 holes, 3 rows of 4 holes each, were sufficient (see Table 2). The positions of the test areas are shown on the map, Plate 2, and sections from the logs are shown diagrammatically in Plate 3.

The Phosphatic Material

Phosphatic Clay.—The phosphatic clay on Bellona Island is a damp, tenuous, even-textured, yellow-brown clay with the consistency of drying putty. It is highly permeable and becomes sticky when wet. It commonly contains 15 to 25% P_2O_5 (average of 360 determinations is 22·2%) with 2 to 12% Fe_2O_3 and up to 40% Al_2O_3. The ratio of Fe_2O_3 to Al_2O_3 is however fairly constant and this, together with the consistently low CaO/P_2O_5 ratio, low CO_2 and fluorine, and high loss on ignition, suggests that much of the phosphate may be present as hydrated ferric and aluminophosphates. Optical and X-ray determinations confirmed the presence of the minerals collophane (tricalcium phosphate) and crandallite (calcium-aluminium phosphate), but no iron-bearing phosphates could be detected.

Incoherent Phosphate.—The *oolitic phosphate* consists of hard spherical grains up to $\frac{1}{8}$ inch, or rarely $\frac{1}{4}$ inch, in diameter. Microscopic examination shows that the grains rarely have a well developed concentric structure, and none of those examined contains any nucleus. They are composed entirely of collophane and dahllite and the faint concentric banding is the result of iron staining. They are, more correctly, pseudo-oolites.

The oolitic phosphate of Deposits F and T contains 29·2% P_2O_5 (average of 70) with some samples reaching 39%. Fe_2O_3 is relatively low at 2·9% (average of 5), but Al_2O_3 is very variable, ranging from 1% to 15·3%. The CaO/P_2O_5 ratio is high and CO_2 is low. The fluorine content lies between that of the clay and the coherent phosphate. The oolites are commonly found with a clayey matrix, which may account for the very variable alumina content of the samples.

The *fragmental incoherent phosphate* is a fine, light coloured, friable material, crumbly when dry, but pasty when wet. It consists mainly of fine clay-size particles of collophane (phosphate dust) with fine fragmental phosphate and some oolitic material. It is a high-grade material, commonly containing more than 35% P_2O_5 and very little iron and alumina. Much of it has undoubtedly been derived by phosphatization of fine calcareous silts and muds, but some may represent the insoluble residues of phosphatic (leached) guano.

Table 3

PARTIAL ANALYSIS OF PHOSPHATE SAMPLES FROM BELLONA ISLAND (1958 SURVEY)

Sample No.	Type of Material	P_2O_5	CaO	CO_2	Loss on Ignition	F	Fe_2O_3	Al_2O_3	TiO_2	CaO/ P_2O_5	Remarks
A42–20′	Phosphate rock	39·1	52·7	0·40	1·82	4·67	0·55	1·1	n.d.	1·34	
A64/4–10′	Oolitic phosphate	31·4	32·5	0·66	11·1	2·04	4·57	14·5	0·24	1·03	
A64/4–14′	Oolitic phosphate	29·8	32·4	1·02	10·9	2·04	4·26	15·3	0·2	1·08	
A60/3–4′	Oolitic phosphate	35·9	45·6	0·84	6·67	3·46	1·52	3·2	n.d.	1·28	
A68–8′	Oolitic phosphate	31·3	34·3	0·77	11·9	1·83	3·85	13·9	0·1	1·09	
A57–20′	Phosphate rock	38·6	52·8	0·24	1·82	3·70	0·65	1·0	n.d.	1·36	
A16/2–6′	Phosphatic clay	25·1	10·4	0·13	17·1	0·31	10·5	31·8	0·60	0·41	
A16/2–22′	Phosphatic clay	24·6	10·3	0·13	18·1	0·10	10·1	33·1	0·45	0·42	
A24/5–8′	Phosphatic clay	26·4	10·9	0·12	16·7	0·41	9·41	30·3	0·55	0·41	
A36/1–5′	Phosphatic clay	30·4	39·8	1·91	7·82	2·42	2·96	7·8	0·10	1·30	Sample heated during field assay.
A36/2–4′	Phosphatic clay	19·8	7·86	0·07	17·4	0·21	11·2	39·6	0·50	0·39	
A44/3–8′	Phosphatic clay	24·6	10·6	0·10	17·2	0·36	10·4	34·8	0·50	0·43	
A6/3–6′	Phosphatic clay	24·2	10·3	0·06	17·1	0·31	8·91	33·5	0·45	0·42	
A46/1–15′	Saturated white clay	15·8	37·9	14·75	12·2	1·91	0·6	1·8	n.d.	2·4	MgO = 13·1%

Loss on ignition (950°C) does not include CO_2.
All results refer to samples dried at 105°C.

Analyst : S. Baker.

Coherent Phosphate.—Coherent phosphate includes both the amorphous collophane deposited in cracks and cavities in the limestone and the phosphate rock formed by metosomatic replacement of the larger limestone fragments and bedrock. The latter is typically a fairly soft, cream coloured cavernous rock which commonly contains up to 39% P_2O_5 (average of 23 determinations is 33·8%) with less than 2% $(FeAl)_2O_3$. The high fluorine content and CaO/P_2O_5 ratio and low CO_2 content are consistent with optical and X-ray determinations which showed only collophane and a little calcite to be present.

Some of the coherent phosphate may be due to cementation or accretion of oolites.

Magnesian Phosphate.—Partial analysis of a white, water-saturated clay found below the phosphate deposit in auger hole A46/1 at a depth of 15 feet suggests that this material may be a calcium-magnesium phosphocarbonate. It is probably the result of phosphatization of a dolomitic marl.

THE PHOSPHATE DEPOSITS

The phosphate deposits occupy a large part of the central depression, covering an area of about 350 acres.

The clay deposits, A to E, are blanket-like deposits covering an irregular limestone surface in the lowest part of the central valley floor. In Deposit T, the clay is underlain by a considerable thickness of high-grade incoherent phosphate thickest at the eastern end. A thinner layer of incoherent phosphate underlies the large clay deposit, Deposit D.

At either end of the central valley, on the Matangi and Matahanua platforms, are Deposits X and F of oolitic phosphate. The oolitic phosphate occurs in limestone chimneys beneath 1½ to 2 feet of soil. The Matahanua deposit, Deposit X, is isolated from the clay of Deposit A by an outcrop of massive limestone on the rise west of Ngotokanava village. At the east end of the central valley, however, the oolitic phosphate of Deposit F extends down the slope from the Matangi platform and joins the east edge of Deposit T.

The individual deposits are separated from each other by, and grade out to the north and south into, areas of outcropping limestone with steep-sided narrow chimneys and shallow pockets containing phosphatic material.

The overall picture of the Bellona deposits is of incoherent phosphate in chimneys on the platforms at the east and west ends of the central valley, and, between them, a line of deposits, mainly of clay with some incoherent phosphate filling broader depressions in the limestone surface. These deposits are deepest where the floor of the central valley rises towards its eastern end, and here the clay is underlain by an increasing thickness of incoherent phosphate.

Deposit A, near the village of Ngotokanava, covers an area of about 60 acres. The deepest hole drilled went to 26 feet in phosphatic material and several others approached 20 feet. On the other hand several holes drilled in the centre of the deposit entered limestone at 4 to 6 feet depth, showing that the bottom of the deposit is very irregular. The true maximum depth of the deposit, allowing for test holes which may have entered chimneys or crevices in the limestone, is probably about 20 feet.

The material of this deposit is almost entirely phosphatic clay, which generally rests directly on the limestone. A very thin layer of incoherent phosphate with traces of oolitic phosphate was seen in a few of the deeper test holes but mostly the contact between clay and limestone is sharp, though irregular.

Deposit B, near Kapata village, consists of two small shallow basins filled with phosphatic clay, and several small clay-filled pockets in the adjoining limestone, with a total area of 33 acres. South of the main track the clay reaches a depth of 26 feet, but again the base of the deposit is very irregular and this depth may only be achieved in chimneys. Pits sunk in this area by Grover (1958a) show that chimneys 9 or 10 feet deep occur under the deposit.

The clay is again very uniform and rests directly on the limestone. Fairly large pockets of clay to the north and west of Kapata village appear to be filling dolines ; hole 16/8 was put down in a small topographic depression and encountered very loose clay which caved frequently, suggesting that it is located on a doline which is deepening under the clay cover.

Deposit C is a shallow irregularly-shaped body of phosphatic clay, approximately 37 acres in extent. Four adjoining holes in the northern part of the deposit were drilled to a depth of 20 feet or more, and it seems likely that they are all located in a single broad, steep-sided solution hollow. Some of the shallower holes in the centre of Deposit C intersected a thin layer of incoherent phosphate immediately above the limestone.

Deposit D, with an area of 106 acres, is the largest single deposit on the island. It is uniformly thicker than any of the other deposits and is generally 8 or more feet thick, with several deep areas extending down to more than 20 feet. It is steep-sided, commonly going down to 20 feet or more within a few feet of the margin, and the drilling results together with the sections exposed in Grover's pits (Grover, 1958a) suggest that the bottom, though irregular and uneven, is not deeply pocketed. The test holes therefore generally indicate the true depth of the deposit.

The bulk of the phosphate again is phosphatic clay, but most of this clay deposit is underlain by 1 to 4 feet of incoherent and coherent phosphate rock. In one or two holes more than 4 feet of phosphate rock was recorded, but this may be the result of intersecting this horizon at an acute angle on the undulating floor of the deposit. In general the layer of incoherent phosphate is thinnest, or is absent, in the deepest parts of the deposit.

The junction between clay and phosphate rock appears generally to be sharp and well defined, but in a few instances the phosphatic clay becomes slightly gritty and oolitic near the base and contains scattered small fragments of phosphate rock.

In hole A46/1 the clay is underlain by a water-saturated white clay which contains 13·1% MgO (see Table 3) and may have resulted from the phosphatization of a dolomitic marl. This may be a useful place for a deeper boring into the limestone for water.

Deposit E comprises two small well defined deposits of phosphatic clay, one of which is contiguous with Deposit T. The larger, western, deposit, which was tested to a depth of 34 feet, in phosphatic clay, occupies a slightly elongated basin : the clay rests directly on limestone. In the eastern deposit this clay grades into clay overlying the buff-coloured incoherent phosphate of part of Deposit T.

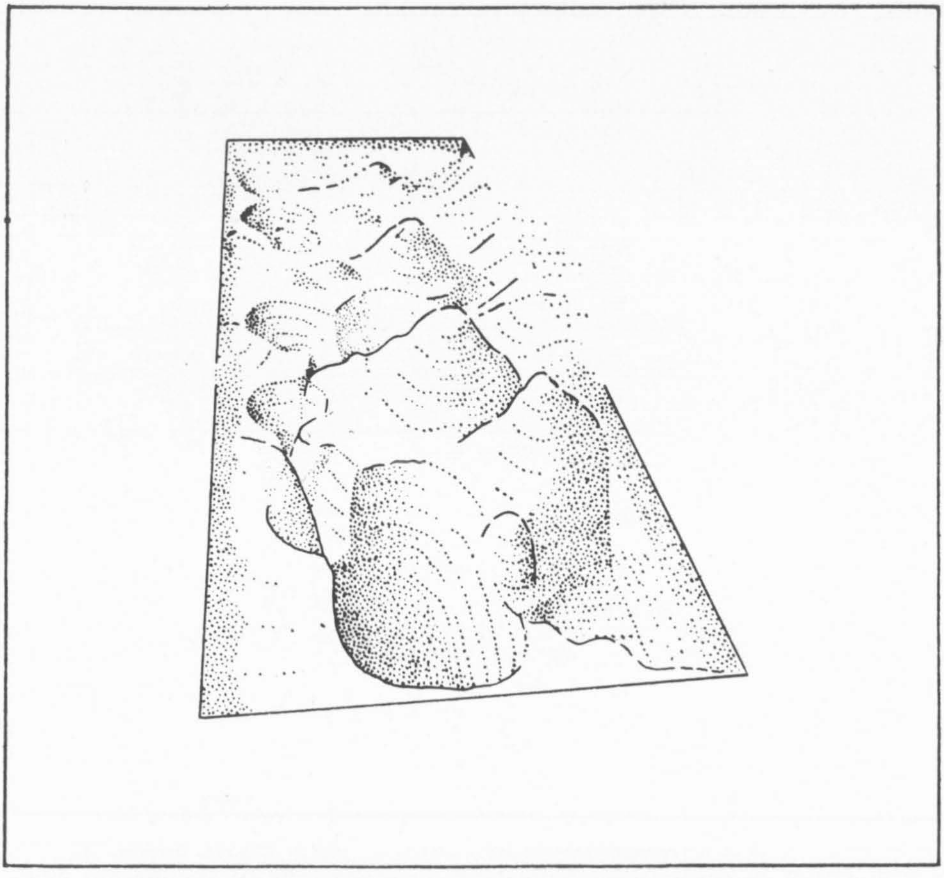
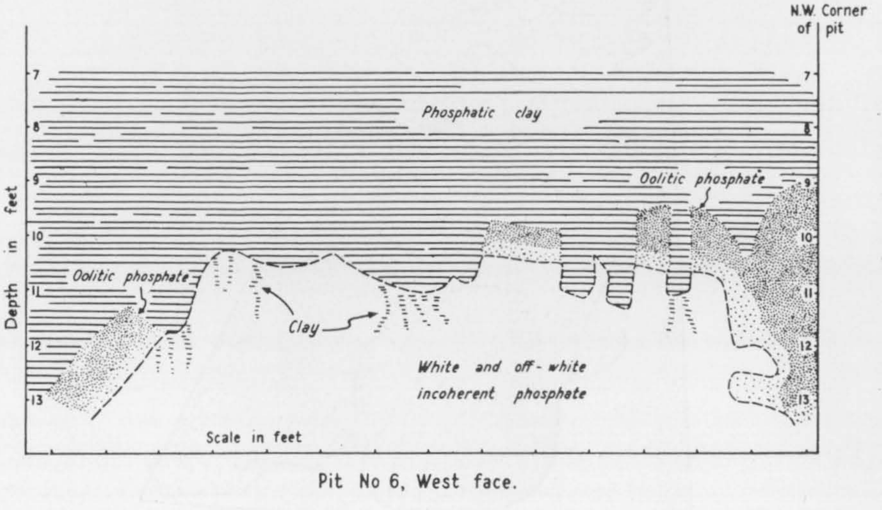


Fig. 1.—Limestone surface exposed in Pit No. 2. (from a field sketch)

In *Deposit T* a thick blanket of phosphatic clay overlies a deposit of incoherent oolitic phosphate and white to off-white incoherent fragmental phosphate. The contact of the incoherent phosphate with the underlying limestone was not exposed in the pits sunk during the 1960 survey, but auger drilling into the floor of the pits suggests that the surface of the limestone is relatively even and is not eroded into deep chimneys or pinnacles. The incoherent phosphate towards the base of the deepest pits, close to the contact with the limestone, is diluted with fragments of porous crumbling limestone intimately mixed with phosphate. The contact of the incoherent phosphate with the overlying clay is shown in Figures 2 and 3. The clay either directly overlies the incoherent fragmental phosphate or is separated from it by a layer of oolitic phosphate of variable thickness. The oolitic phosphate is much lighter in colour and finer in texture close to the fragmental phosphate, although the contact is sharp ; the contact of the oolitic phosphate with the overlying clay is very clearly defined and there are flecks of pasty white phosphate along the surface of the contact.

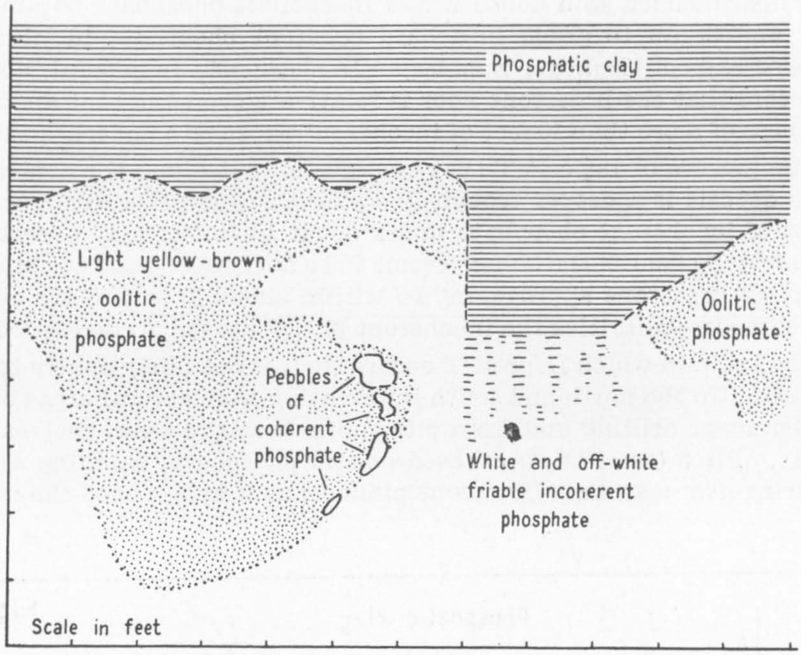
Fig. 2



Pit No 6, West face.

The 1958 auger drilling gave long intersections of incoherent phosphate in this area ; for example, hole 58 intersected 15 feet of incoherent phosphate below 13 feet of clay. The pits of the 1960 survey confirmed that these depths represent a genuine thickness of high-grade phosphate and were not caused by low-angle intersections with phosphate clinging to the sides of irregularities in the limestone floor.

Fig. 3



PART OF EAST WALL, PIT No 7

Deposit T is clearly contained in a single large basin. The basin structure is seen in the present topography, and is revealed on air photographs ; it is borne out also by the depths of the pits and hand auger holes at different parts of the deposit. The basin is elongated east-west and has a deeper trough along its axis in which the deepest incoherent phosphate lies. The gradient at the eastern end appears to be very steep and the deepest part of the axial trough may be close to this end, near pit 4. At the west end and to the north and south the basin appears to shelve out more gradually. There may be another local deepening near auger hole 58. The incoherent phosphate is commonly more than 10 feet thick in this narrow central trough, whose narrowness is emphasised by the exposures in pit 5, about 110 yards south of the axis of the trough, where the incoherent phosphate becomes very thin.

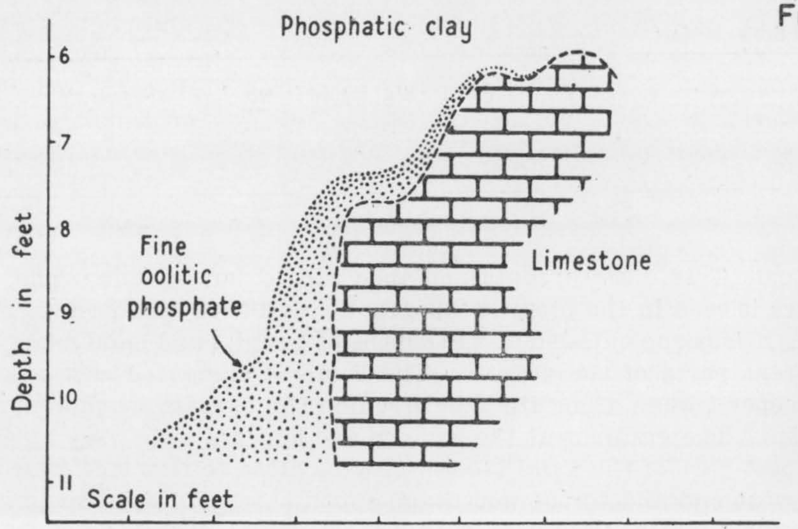
74895 (2)

From the auger holes and pits (areas P, W1, and W4 and pits 4 and 6) in the central part of Deposit T the average depth of clay overburden is calculated to be about 10 feet. The average thickness of the incoherent phosphate below the clay is less easy to determine, as neither of the pits and few auger holes reached the limestone floor. The pits had to be discontinued when heavy rain caused caving and the auger holes had generally to be discontinued at a depth where incoherent phosphate became very thick and began to grade into hard coherent phosphate in which the threaded ends of the auger rods began to shear off. In general, however, it appears that the limestone floor is relatively even and that an average thickness of more than 10 feet of incoherent phosphate underlies the clay.

The picture of Deposit T that emerges is that along the central axis of the deposit is a deeper trough in which there is generally more than 10 feet of incoherent phosphate under about 10 feet of clay overburden ; the limestone floor of the trough seems to be fairly even but has occasional stumps of limestone approaching to within about 10 feet of the surface. Over these irregularities the incoherent phosphate thins correspondingly.

The basin in which Deposit T occurs shelves out fairly gently towards the west. To the north and south information from several areas of close pattern auger drilling and from pits shows that the basin shelves fairly rapidly. Pit 5 (see Fig. 4) exposed oolitic phosphate, thinning and disappearing over a stumpy limestone pinnacle as it approached the surface.

Fig. 4



PART OF EAST WALL, PIT No 5

Pits sunk in *Deposit F* show that the oolitic and coherent (pebble) phosphate which make up the deposit are entirely contained in small chimneys in the limestone. Nowhere do there appear to be any larger depressions similar to that in which Deposit T occurs. Moreover the chimneys in different parts of the deposit differ markedly and unpredictably in width and depth.

Auger drilling from test areas in Deposit F is shown diagrammatically in Plate 3.

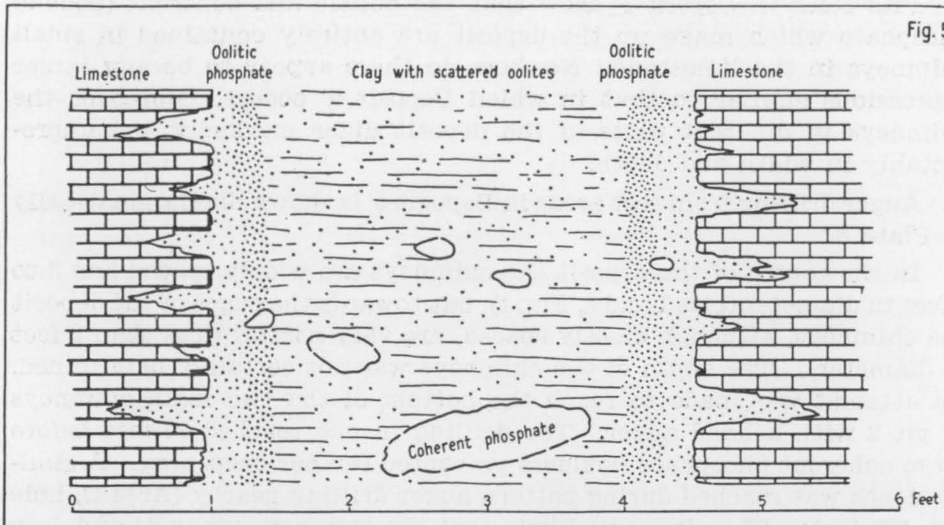
In the centre of the deposit the chimneys are widely spaced and 3 to 4 feet in diameter (pits 1 and 2, Fig. 1), but towards the edges of the deposit the chimneys, although closely spaced, are very narrow (less than 2 feet in diameter). The depth of the chimneys was not certainly determined. An attempt was made to reach the bottom of the two main chimneys in pit 2 with a hand auger. The drilling in one reached 30 feet before large coherent phosphate boulders prevented further deepening. A similar depth was reached during pattern auger drilling nearby (Area C, hole d 4—28¾ feet). Thus it seems likely that the chimneys are wide and deep only in the central part of Deposit F, rapidly becoming narrower and shallower towards the north and south edges of the deposit, towards the east, and on the sloping ground to the west which links Deposits F and T. Nowhere do the individual chimneys coalesce to form larger cavities with pinnacles of limestone.

The material in the chimneys in Deposit F is oolitic phosphate with pebbles and some boulders (2 feet x 1 foot x 1 foot) of coherent phosphate. The pebbles and boulders are composed of oolites and fragmental phosphate. The centres of the wider chimneys contain phosphate clay (see Fig. 5). The oolitic phosphate close to the limestone is lighter coloured and fills horizontal irregularities in the wall of the chimney ; under these small overhangs the individual oolites are coarser (up to ⅜ inch in diameter) and less regularly shaped, and are packed intimately into minor furrows in the limestone surface.

Figure 1 is a sketch of the limestone surface exposed in pit 2. It shows the very short stumpy pyramidal pinnacles of limestone which are characteristic of the first two or three feet below the soil surface and the vertical, commonly neatly cylindrical, chimneys which occur below that depth.

Deposit X was tested during the 1960 survey by hand auger drilling at convenient points along existing tracks, supplemented by two holes along cut traverse lines. This deposit was not drilled at all during the 1958 survey, though the presence of oolitic phosphate in chimneys in this area had been noted by Grover (Grover, 1958a) and in the report of the 1958 survey.

Matahanua village is on a flat platform about 110 feet above sea level between the north and south arms of the limestone rim. To the northwest the platform falls away steeply to the sea without the usual inter-



GENERALIZED VERTICAL SECTION THROUGH CHIMNEY, PIT No 2

vening rim ; to the south-east the platform falls away gently towards the lower parts of the central valley floor at Ngotokanava village and farther east. The oolitic phosphate occurs on this platform mostly to the east of Matahanua.

The deposit appears to be similar to Deposit F at the east end, in both position and make up. There seems to be no clay in any of the chimneys of Deposit X, however ; the oolitic phosphate here is quite clean and runs easily—auger drilling had often to be discontinued before reaching limestone because of caving.

A village pit at Matahanua shows that the chimneys in the limestone are about 3 feet in diameter. By analogy with Deposit F, it seems most likely that chimneys closer to the centre of Deposit X would not be narrower than this.

Tonnage and Grade

Phosphatic clay.—The tonnage of phosphatic clay available in the Bellona deposits has been calculated from thickness contours or isopachous lines which were drawn from the 1958 auger-drilling results. In drawing the isopachous lines the probable pitted and etched nature of the limestone surface was taken into account by ignoring isolated deep holes. In calculating the tonnages of phosphatic clay available a further cut of 25% was made to allow for the volume which may be occupied by pinnacles of limestone projecting up into the base of the deposit.

The calculated (wet) tonnages are as follows (on the basis of 15 cubic feet to 1 ton).

Deposit	Surface Area (square feet)	Calculated Volume (cubic feet)	Tonnage (tons)
A	2,632,000	20,964,000	1,400,000
B	1,446,000	10,336,000	700,000
C	1,637,000	10,710,000	700,000
D	4,656,000	30,150,000	2,000,000
E & T	2,819,000	20,138,000	1,350,000
Total	13,190,000	92,298,000	6,150,000

Calculated tonnage : 6,150,000 tons
Less 25% cut : 4,600,000 tons
Average grade (of 360 samples) : 22·3% P_2O_5

Incoherent phosphate.—The incoherent phosphate of Bellona is contained in four deposits ; Deposit D, Deposit T, and Deposits F and X. The assessment of all four deposits is difficult ; the incoherent phosphate of Deposits D and T is beneath a considerable overburden and its thickness is incompletely known ; the phosphate of Deposits F and X is contained in chimneys whose depth is incompletely known and whose diameter, which may differ unpredictably from place to place, controls the availability of the phosphate since chimneys less than three feet in diameter cannot be worked mechanically.

Deposit D contains about 150,000 tons of higher-grade phosphate, but this is not added to the total since it occurs under a thick cover of low-grade phosphatic clay and is, under present conditions, inaccessible.

The central trough of Deposit T is 600 yards long and 125 yards wide, giving a total surface area of 675,000 square feet and a volume of 6,750,000 cubic feet, since the phosphate is 10 feet thick on the average. Taking the density of the phosphate as 20 cubic feet to the ton, the calculated tonnage for the central area is about 300,000 tons.

In assessing the volume of the phosphate in Deposit F a cut of 2/3 has been made for the space occupied by the limestone, and the area over which workable-size chimneys may be expected has been taken as only the central area, 600 yards long by 100 yards wide. The average depth of the chimneys has been taken as 15 feet. This gives a volume of phosphate of 2,700,000 cubic feet and an exploitable tonnage of a little over 100,000 tons.

The boundaries and the depth of Deposit X are less completely known, but making the same basic assumptions as in the calculation of tonnage for Deposit F it appears that there is probably a further 100,000 tons of phosphate in this deposit. However, little is known of the diameter of the chimneys in this deposit as no pits were sunk there.

These totals are tabulated below (on a basis of 20 cubic feet to 1 ton).

Deposit	Surface Area (square feet)	Average Depth (feet)	Calculated Volume (cubic feet)	Tonnage (tons)
T	675,000	10	6,750,000	300,000
F	540,000	15	2,700,000	100,000
X	....	....	....	100,000
Total	....	....	....	500,000

Average grade (of 93 samples) : 30·3% P_2O_5.

OTHER ISLANDS IN THE SOLOMONS GROUP

BY

W. C. White

None of the larger islands in the Solomons group was visited, since they were considered unlikely to have any large concentrations of guano or its products and they have, in any case, been mapped in considerable detail by the Geological Survey of the British Solomon Islands Protectorate. Rennell Island also was omitted as it has been geologically explored several times and only a few traces of phosphate found (Stanley, 1929 ; Grover, 1958b).

Only the more remote and less well known islands of the protectorate were considered to be possible phosphate prospects. Those visited were Santa Ana and Santa Catalina at the southern end of San Cristobal, Ndeni and Tinakula in the Santa Cruz Islands, the Reef or Swallow Islands, Ndai, at the northern end of Malaita, and Ramos Islet in the Indispensable Straits.

Santa Ana is a small, reef-fringed, elevated atoll in the deep central depression of which coarse volcanic rocks crop out. No trace of phosphate was found.

Santa Catalina, only a few miles west of Santa Ana, is an elevated table reef with two broad emerged reef-terraces and an eroded reef-flat between tide levels. On the highest part of the island, some 200 feet above sea level, a weakly phosphatic yellow-brown to cream clay was drilled to a depth of 17 feet, at which depth it was saturated with water and further drilling became impossible. The clay was found to contain less than 2% of P_2O_5.

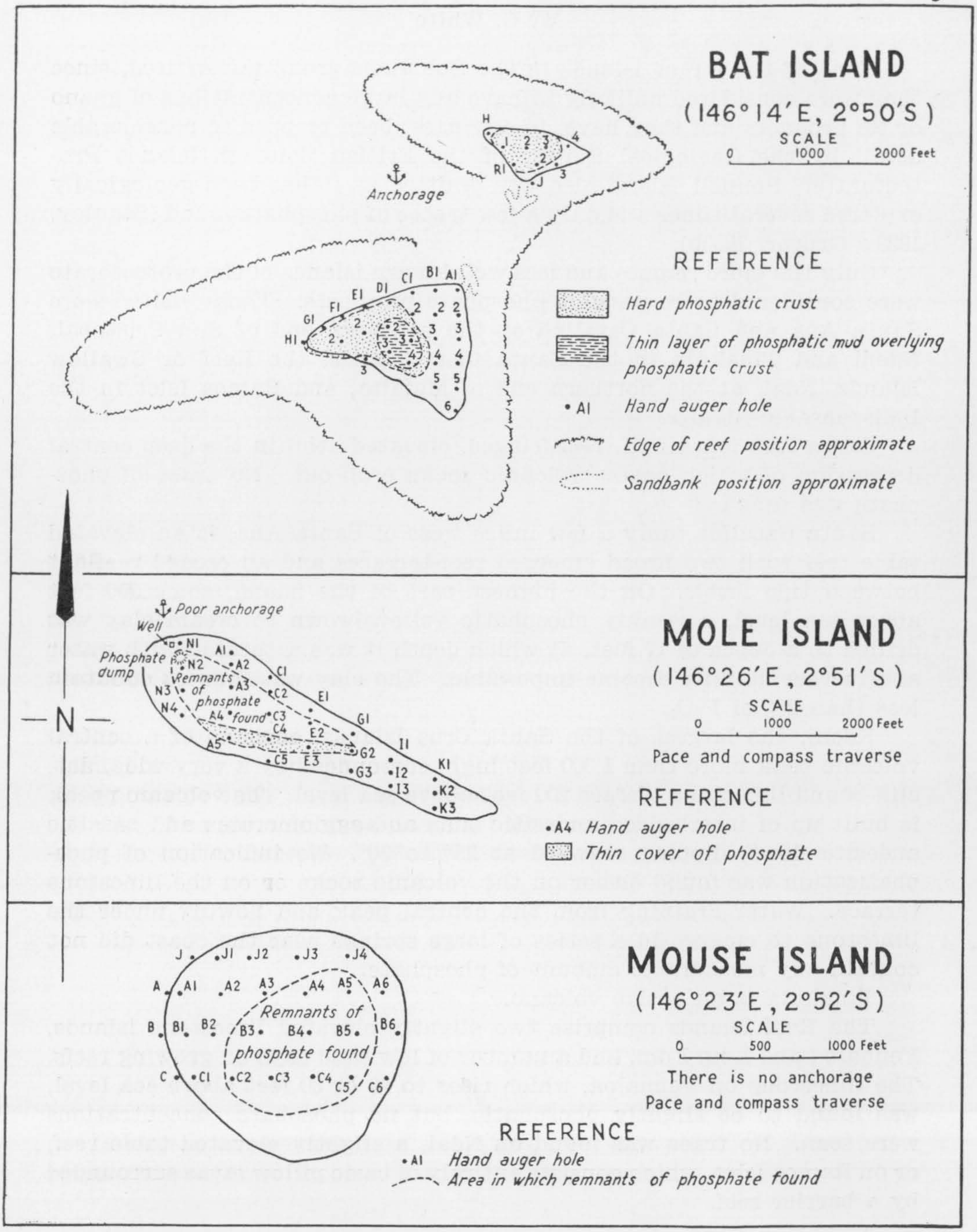
Ndeni, the largest of the Santa Cruz Islands, consists of a central volcanic peak more than 1,300 feet high, surrounded by a very wide, flat, cliff-bound limestone terrace 200 feet above sea level. The volcanic peak is built up of interbedded andesitic tuffs and agglomerates and basaltic andesite flows, dipping seaward at 25° to 30°. No indication of phosphatization was found either on the volcanic rocks or on the limestone terrace. Water draining from the central peak and flowing under the limestone to emerge in a series of large springs near the coast did not contain any measurable amount of phosphate.

Tinakula is an active volcano.

The Reef Islands comprise two slightly elevated limestone islands, Fenualoa and Lom Lom, and a number of low sand cays on growing reefs. The limestone on Fenualoa, which rises to 20 or 30 feet above sea level, was found to be slightly phosphatic, but no phosphate concentrations were seen. No trace was found on Ndai, a slightly elevated table reef, or on Ramos Islet, which consists entirely of basic pillow lavas surrounded by a barrier reef.

PURDY ISLANDS

Fig. 6



ISLANDS IN PAPUA AND NEW GUINEA

BY

O. N. Warin

Twenty-two islands and island groups in Papua and New Guinea were visited during the 1958 field season of the survey. The area has two seasons which are named from the prevailing wind directions : the south-east season (April to November) and the north-west season (December to March). The wetter in most places is the north-west season, but some rain, from less violent storms, falls during the south-east season. In certain areas, such as the south coast of New Britain, the distribution of rainfall is reversed, i.e., rainfall is heavier in the south-east season.

Close to the equator the seasons are less well marked and alternating short periods of calm and bad weather are common.

Of the islands visited, phosphate, in small quantities, was found on the Purdy Islands, Sae, Manu, Aua, Warulu, Nauna, and Cannac ; the remainder were barren of phosphate.

THE PURDY ISLANDS (Fig. 6)

The Purdy Islands, North and South Bat Islands (2° 50′ S, 146° 14′ E), Mole Island (2° 51′ S, 146° 26′ E), Mouse Island (2° 52′ S, 146° 23′ E), and Rat Island (2° 57′ S, 146° 20′ E), lie about fifty miles south of Manus Island in the Admiralty Group of New Guinea.

The islands are small and uninhabited. The land area of the four islands together is less than a third of a square mile. Rat is a small sand bank surrounded by a reef but without any vegetation ; the other islands of the group are larger and have been planted with coconuts.

The islands were worked for phosphate in 1890, when 1000 tons were exported to Germany, and again for a short time in 1910 (Hutchinson, 1950). They were visited by Dr G. Friederiei of the Hanseatic Pacific Expedition in 1909 and by Mr K. M. Fennell of the British Phosphate Commissioners in 1929. These two visits are noted by R. C. Hutchinson (1941) in his account of his own work on the islands.

Hutchinson's account describes the islands, the nature of the phosphate occurrence and, broadly, the distribution of the phosphate. His estimate of the tonnage of phosphate present was probably inaccurate as he does not seem to have excluded the areas from which phosphate had been stripped.

The islands are shown in Figure 6. All are of similar form, and consist of table reefs on which sand banks have been built up. A rampart of storm-beach material along the margins of the banks gives them a slightly saucer-shaped cross-section.

The phosphate, which occurs as a crust of hard, porous, brown material, evidently used to occupy the central area of each island. The only islands which still have phosphate deposits intact now, however, are North and

South Bat. Mouse has been completely worked out ; only a few scattered lumps of phosphate and a slight phosphatic enrichment of the top inch of the sand remain to show the area that was once covered by a phosphate deposit. Mole has also been worked out ; a heap of phosphate blocks stacked for shipment remains at the western tip of the island. As on Mouse the original area of the phosphate can be easily traced.

The deposits on North and South Bat are displaced slightly west of the centre of the islands. No phosphate occurs along the east edge of either island ; phosphate crust crops out along the south-west shore of South Bat and along the south-west and north shores of North Bat. The shape of these islands has changed since the upper layer of the sand was phosphatized. Islands such as these have little ability to withstand erosion by storms. At the time of the survey a storm had evidently caused severe erosion along the south-west shore of North Bat ; a number of palms had been undercut and had fallen into the sea.

The phosphate of North and South Bat is of fairly uniform thickness. The average thickness in the five auger holes which intersected phosphate on North Bat was 15 inches ; the maximum was 27 inches. On South Bat the average of nine holes was 21 inches, and the maximum 36 inches. A thin grey to black phosphatic mud about two inches thick overlies the hard phosphate in the centre of South Bat. This mud is highly phosphatic and occurs where the water table is at the surface.

The phosphatic guano is medium to dark brown and very porous. It consists of cemented and replaced coral sand. Small unreplaced fragments of limestone are visible throughout the rock. Collophane replacements of foraminifera, echinoid spines, etc., are visible in thin section.

Tonnage and Grade

Field assays of the phosphatic crust showed an average of 27·5% P_2O_5 (7 analyses). The phosphatic mud overlying the hard crust is of high grade ; the average of three analyses is 38% P_2O_5. Carbonate sand below the phosphatic crust shows only a trace of P_2O_5.

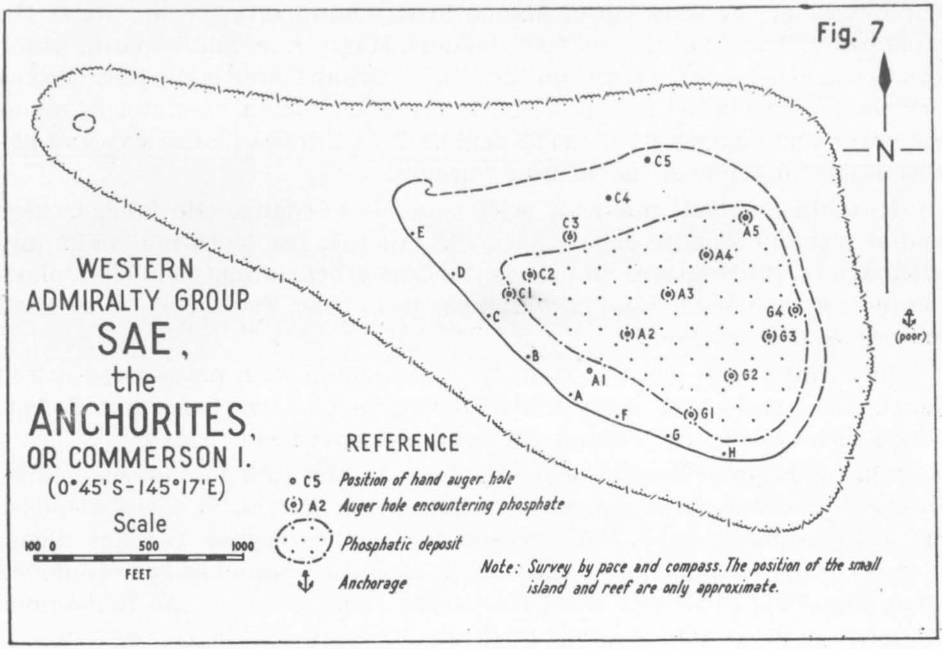
The tonnage of phosphate on North Bat is estimated to be 12,000 tons, on South Bat 36,000 tons. The phosphatic mud overlying the phosphatic crust on South Bat is estimated to be 1200 tons. The only other reserves in the group are contained in the two heaps of phosphate at the west end of Mole, which together contain about 1000 tons.

Hutchinson (1941) estimated the average depth of the phosphate as 5 inches—on 32 determinations. The 80 auger holes put down during the present survey have made it possible to define the areas where the phosphate crust is intact and to ignore in the determination of the size of the deposit those places where the phosphate has been stripped. The phosphate crust was found to be deeper than Hutchinson supposed, but of smaller areal extent.

SAE (Fig. 7).

Sae Island (0° 45′ S, 145° 17′ E), sometimes called Commerson or the Anchorites, lies 120 miles north-west of Manus Island in the Admiralty Group. One small uninhabited island with an area of about 56 acres is surrounded by a fringing reef which extends to the west to enclose a small islet. It is evidently the presence of this small islet which has led to the singular and plural names of the island.

Sae was evidently not visited by Friederiei or Hutchinson. There is some evidence that the island is known to masters of small ships operating in these waters as an island with a bird population and a phosphate deposit.



The form of the island and the phosphate occurrence are almost exactly the same as those of the Purdy Islands. The maximum height of the storm-beach material is about 4 feet above high tide level. There is no raised coral on Sae, and the centre of the island is very close to sea level. Sae has not been planted with coconut palms ; it has a cover of rain forest with a beach fringe of palms.

The phosphate, as on the Purdy Islands, is a crust of cemented and replaced coral sand. The phosphate occupies all the centre of the island and has not been disturbed by man, although locally uprooted trees have destroyed the original profile. No mud overlies the phosphate, and the interior of the island was dry, not swampy, at the time of the survey. In places the phosphate has evidently formed on coarse coral debris and specimens with coral fragments only partially replaced were found.

Tonnage and Grade

Ten auger holes passed through the phosphate. The average depth in these holes was 28 inches, with a minimum of 9 inches and a maximum of 48 inches. Eleven analyses of the phosphate gave an average value of 23% P_2O_5. The tonnage estimated for an average depth of 24 inches is 70,000 tons.

A few boobies were found nesting at the south-east tip of the island, but no accumulation of their droppings was visible.

MANU (Fig. 8)

Manu or Allison Island (1° 18′ S, 143° 35′ E), lies about 180 miles west-north-west of the west tip of Manus in the Admiralty Group. It is the most easterly of the three isolated islands, Manu, Aua, and Wuvulu, which run in a south-westerly arc from the Ninigo Group towards the New Guinea mainland (see Plate 1). It is roughly circular, with a diameter of about 800 yards and an area of about 93 acres. It is a copra plantation and has a small population of indentured workers.

Hutchinson (1941) makes a brief mention of Manu. He landed there and saw the phosphate deposit, but did not test its depth nor make any estimate of its tonnage. He evidently knew before his visit that phosphate existed on the island, which suggests that Friederiei or Fennell had visited it previously.

Like the Purdy Islands, Manu is a low island with no exposed raised coral. The maximum elevation above high-tide level is about 5 feet. There is a storm beach along the east and north-east coasts.

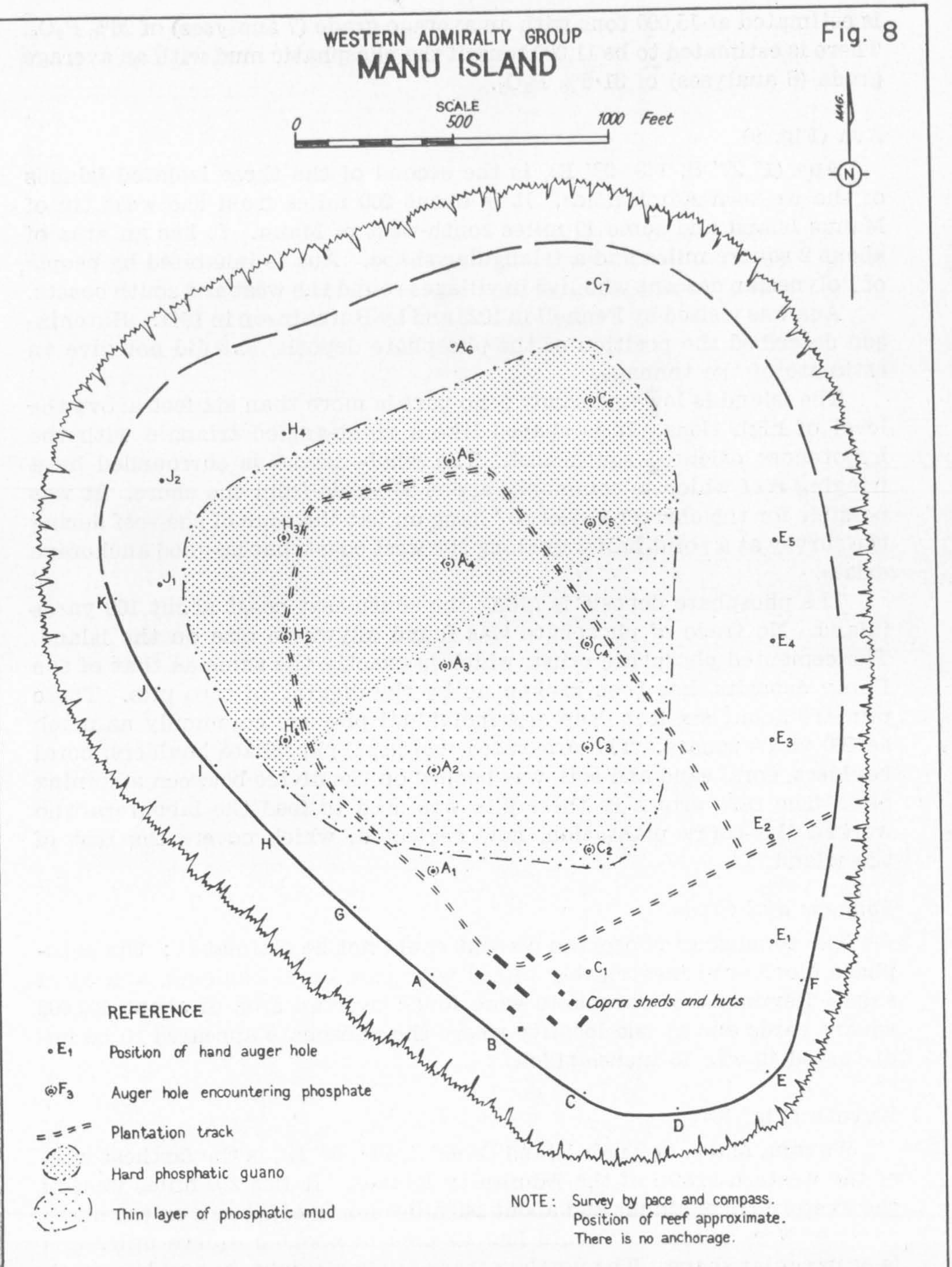
The phosphate deposit occupies most of the interior of the island. In the north-west it is composed of phosphatic guano, in the south-east of soft phosphatic mud. The reason for the two types was not clear. A most likely explanation is that the phosphatic guano has been removed from the south-east part of the deposit ; unfortunately no indigenous islanders remain who might recall the working of the deposit and no record of shipments from the island has been noted. There is no clear difference in elevation between the two parts of the deposit, though the north-west part may be slightly higher. The phosphatic guano along the western edge of the deposit is very porous and light in colour and weight.

Another possibility is that the mud may be decomposed guano which has not reacted with the underlying sand. The sand underneath the phosphatic mud appeared to be unaltered.

The phosphatic guano crust of Manu is lighter in colour and not so dense as the material from Sae and the Purdies. The phosphatic mud is similar in texture and appearance to the mud from South Bat.

Tonnage and Grade

The average depth of both the phosphatic mud and the phosphatic guano is 6 inches with little variation. The tonnage of phosphatic guano


WESTERN ADMIRALTY GROUP
MANU ISLAND
Fig. 8
SCALE
0
500
1000 Feet
MAG.
N
C_7
A_6
C_6
H_4
A_5
J_2
H_3
C_5
E_5
A_4
J_1
K
H_2
C_4
E_4
A_3
J
H_1
C_3
E_3
I
A_2
E_2
H
C_2
A_1
G
E_1
C_1
A
F
Copra sheds and huts
REFERENCE
B
E_1 Position of hand auger hole
F_3 Auger hole encountering phosphate
E
Plantation track
C
D
Hard phosphatic guano
Thin layer of phosphatic mud
NOTE: Survey by pace and compass.
Position of reef approximate.
There is no anchorage.

is estimated at 15,000 tons with an average grade (7 analyses) of 26% P_2O_5. There is estimated to be 11,000 tons of the phosphatic mud with an average grade (6 analyses) of 31·5% P_2O_5.

AUA (Fig. 9)

Aua (1° 27′ S, 143° 03′ E), is the second of the three isolated islands of the western Admiralties. It is about 200 miles from the west tip of Manus Island and some 40 miles south-west of Manu. It has an area of about 2 square miles and a triangular shape. Aua is inhabited by people of Polynesian descent who live in villages round the west and south coasts.

Aua was visited by Fennell in 1929 and by Hutchinson in 1941. Hutchinson described the position of the phosphate deposit, but did not give an estimate of the tonnage.

The island is low and sandy ; no part is more than six feet above the level of high tides. It is shaped like a right-angled triangle with the hypotenuse oriented south-west. The whole island is surrounded by a fringing reef which is commonly about 50 yards from the shore. It was possible for the charter vessel to ' hang on ' at the edge of the reef during the survey at a point half way along the west coast, but no good anchorage exists.

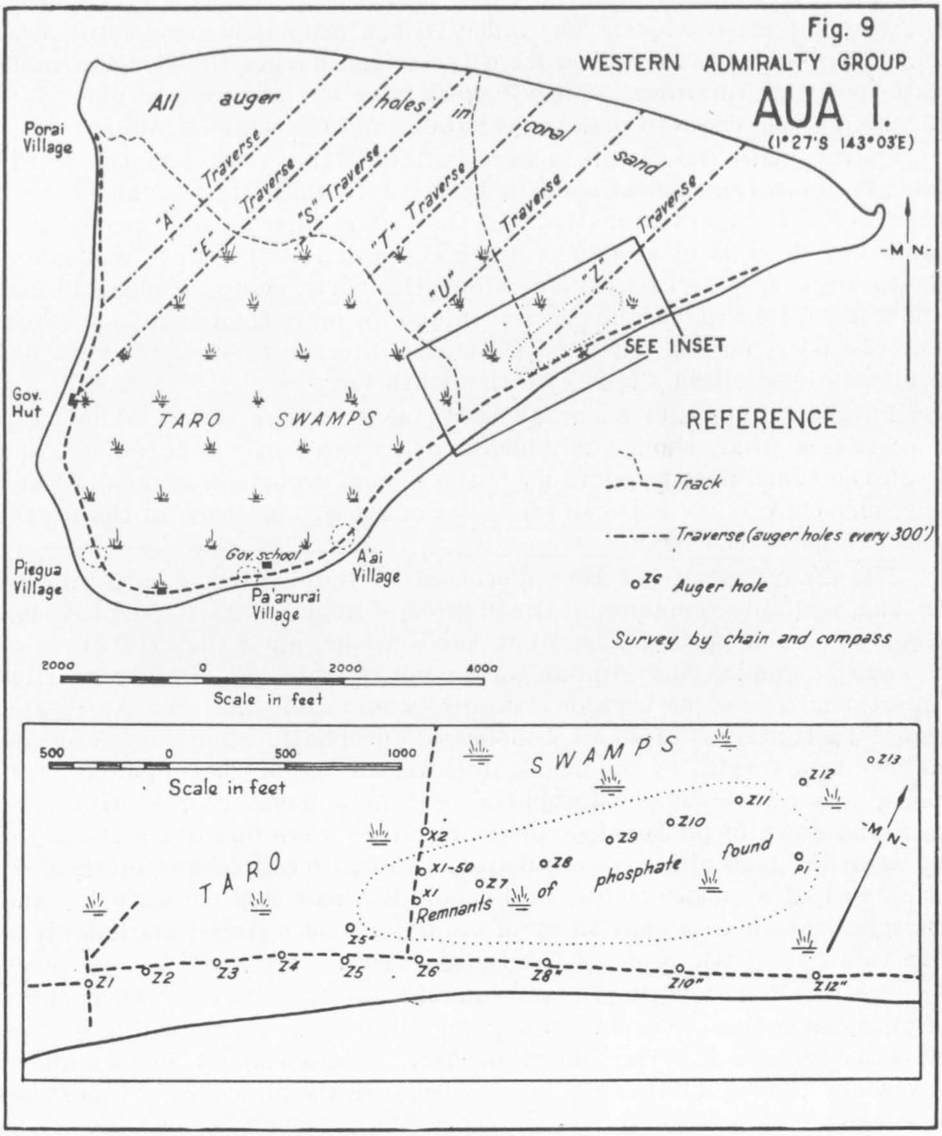
The phosphate deposit is along the south-east coast about 100 yards inland. No trace of phosphate was found anywhere else on the island. The cemented phosphate crust, which is exactly the same as that of the Purdy deposits, has been broken up by the digging of taro pits. These pits are about six feet deep and individual pits are commonly as much as 100 yards square. The excavated material, phosphate boulders, coral boulders, coral sand and soil, was heaped on the divide between adjoining pits. The taro grown in these pits was used to feed the labourers who worked the copra plantation, now neglected, which covers the rest of the island.

Tonnage and Grade

The tonnage of phosphate present could not be estimated ; the phosphate blocks are inextricably mixed with soil, coral boulders, and coral sand. Remnants of phosphate were found over an area of about 100,000 square yards and at one locality where the phosphate appeared to be undisturbed it was 18 inches thick.

WUVULU (Fig. 10)

Wuvulu, Maty, or Tiger Island (1° 43′ S, 142° 50′ E), is the farthest west of the western group of the Admiralty Islands. It lies 250 miles west of the western tip of Manus and about 140 miles north of Wewak on the north coast of New Guinea. Wuvulu has an area of about 5 square miles and is of irregular shape. The north coast is fairly straight, but on the south coast two promontories form a wide bay, Maloe Bay. A copra plantation, Agita Plantation, occupies the greater part of the island ; the owner



and his wife live on the island at Agita homestead on the shores of Maloe Bay. There are two main villages, at the north and south ends of the west coast. The island people are of Polynesian descent. Access throughout most of the island is easy.

Hutchinson (1941) visited Wuvulu Island and saw the main phosphate deposit. He evidently knew it existed before going there and it seems most likely that Fennell visited the island during his 1929 investigations. Some phosphate may have been exported. A heap of phosphate occurs between two taro pits near Auna village ; this may be a heap of phosphate prepared for shipment, or it may simply have been heaped there during the taro pit excavations. The older village people seem to think that some phosphate was removed from the island during the German mandate over the Territory. The villagers have cut and shaped phosphate blocks and use them to make gravestones and the walls of wells.

In the main the island is exactly like Manu, Aua, and the Purdy Islands : low-lying coral sand nowhere more than six feet above high tide level. It differs from them in that some raised coral, eroded into pinnacles, does occur along the north shore and at the south-west phosphate deposit. The raised coral along the north shore is about 12 feet above sea level and does not persist inland for more than about 150 yards. Lumike Islet, off the north coast, is also of raised coral. Wuvulu has evidently been tilted slightly to the south-east.

Phosphate deposits occur at two places on the island. The main deposit is similar, though not identical, to the Purdy occurrences, and is on the south-west promontory ; the second deposit is very small and is of phosphatic clay between pinnacles of raised limestone in the north-west corner of the island.

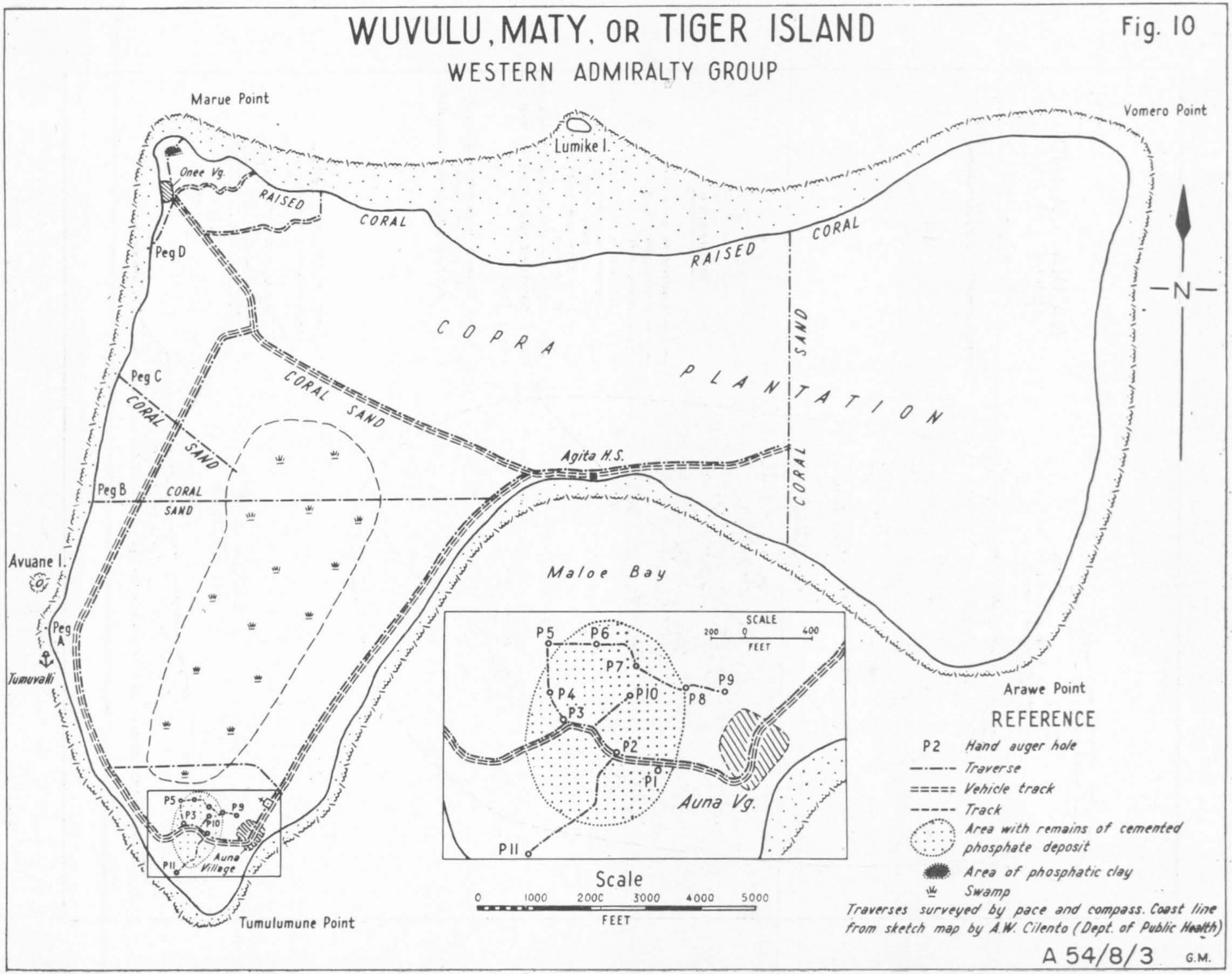
The main deposit has been disturbed by the digging of taro pits, as on Aua, and only remnants of the phosphate remain. At P_1 (see Fig. 10), along the track leading west from Auna village, an 18-inch thickness of phosphatic guano, very similar to the Purdy material, directly overlies limestone. The same type of exposure occurs at P_4 and P_7. At P_8 and near P_2 a thickness of about 2 inches of phosphatic sand which appears to have been formed by the mechanical weathering of the cemented phosphate was found. This phosphatic sand may have resulted from the breaking down of phosphate blocks after they were dug out and heaped up when the taro pits were excavated. At P_9 limestone was intersected at a depth of 30 inches below coral sand. It seems that cementation and phosphatization of a thin cover of coral sand over limestone has given rise to a phosphatic crust of the Purdy type.

The northern deposit is quite different. It consists of small pockets of phosphatic clay occurring over a very limited area between pinnacles of raised limestone. The limestone here is raised about 12 feet above sea level ; the maximum depth of clay between the pinnacles of limestone is 4 feet.

The occurrence of the two types of deposit on the same island suggests that at an initial stage there may have been a sand bank at the southern deposit, and weathering raised limestone, producing a terra rossa, at the northern deposit. Phosphatization of the sand produced the phosphatic crust, while phosphatization of the terra rossa produced the phosphatic clay.

Tonnage and Grade

The northern deposit is very small indeed ; the clay occurs in scattered pockets over about 5000 square yards, none of the pockets being deeper than 4 feet. The tonnage therefore is only a few hundred tons.



WUVULU, MATY, OR TIGER ISLAND
WESTERN ADMIRALTY GROUP
Fig. 10
Marue Point
Lumike I.
Vomero Point
Onee Vg.
RAISED
CORAL
RAISED
CORAL
Peg D
COPRA
PLANTATION
SAND
Peg C
CORAL
SAND
CORAL SAND
Agita H.S.
CORAL
Peg B
CORAL
SAND
Avuane I.
Maloe Bay
Peg A
Tumuvalli
Arawe Point
P5
P6
P7
P8
P9
P4
P10
P3
P2
P1
P11
SCALE
200
0
400
FEET
Auna Vg.
Auna Village
Tumulumune Point
Scale
0
1000
2000
3000
4000
5000
FEET
N
REFERENCE
P2 Hand auger hole
Traverse
Vehicle track
Track
Area with remains of cemented phosphate deposit
Area of phosphatic clay
Swamp
Traverses surveyed by pace and compass. Coast line from sketch map by A.W. Cilento (Dept. of Public Health)
A 54/8/3 G.M.

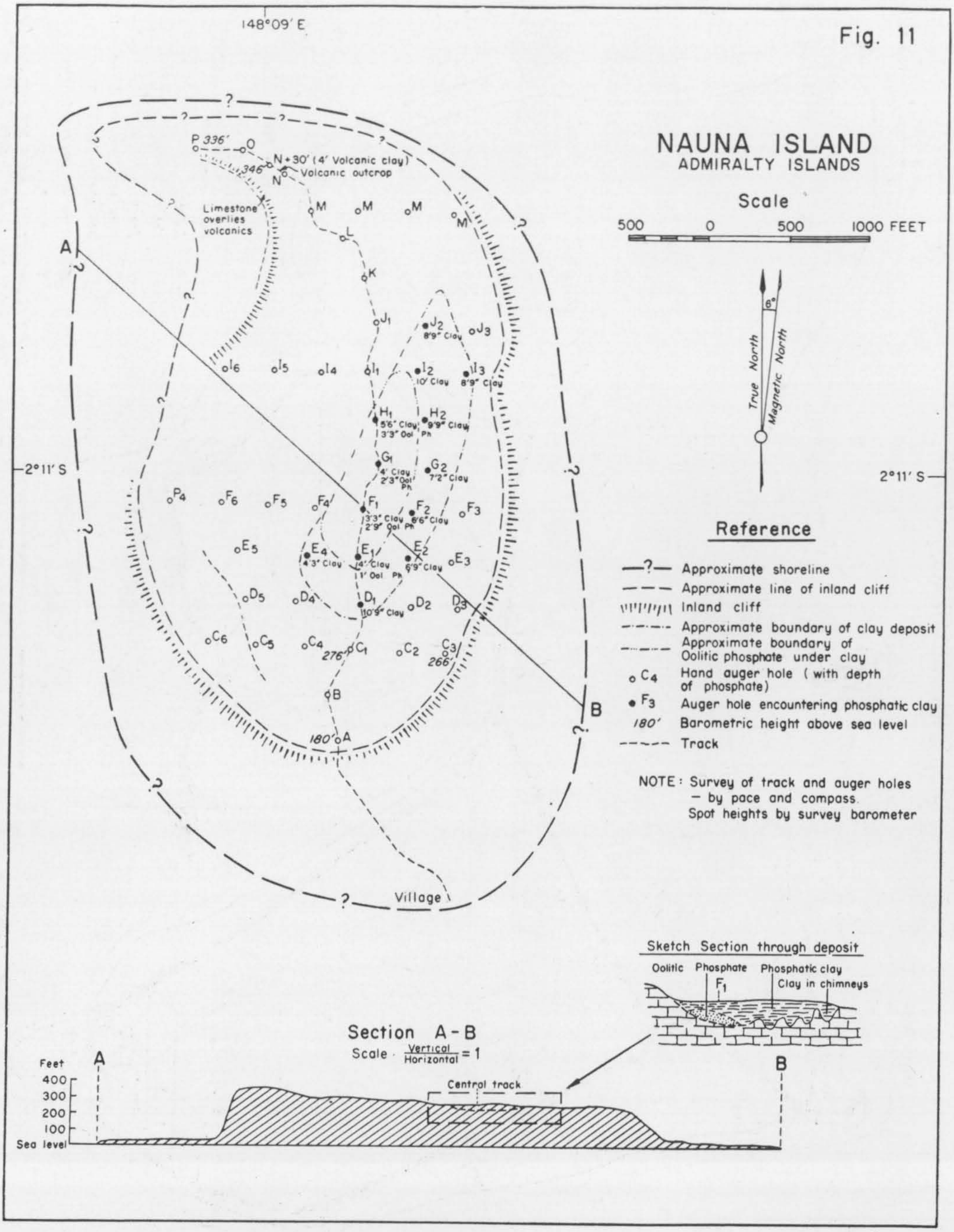
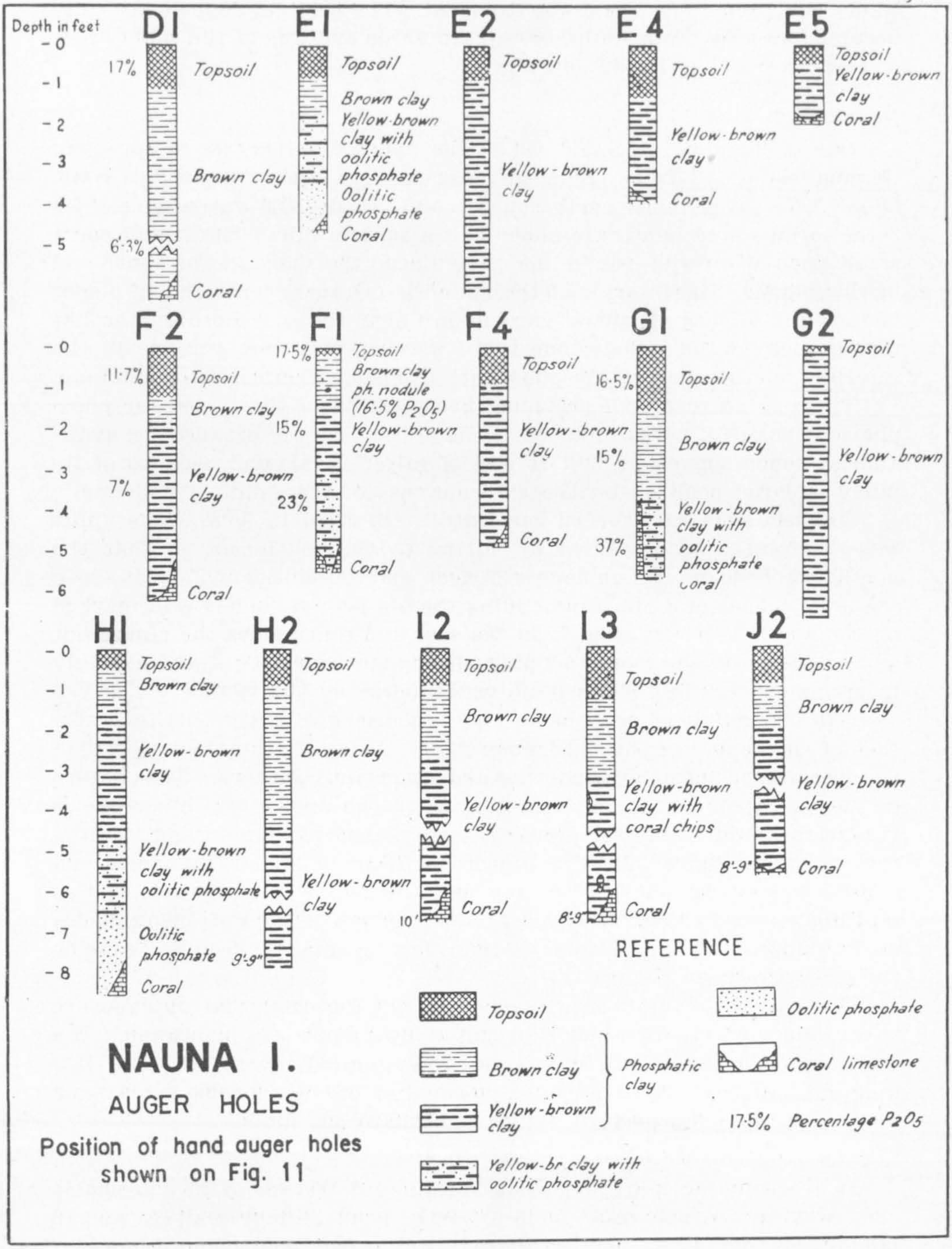


Fig. 11
NAUNA ISLAND
ADMIRALTY ISLANDS
Scale
500 0 500 1000 FEET
148°09' E
2°11' S
True North
Magnetic North
6°
Reference
Approximate shoreline
Approximate line of inland cliff
Inland cliff
Approximate boundary of clay deposit
Approximate boundary of Oolitic phosphate under clay
Hand auger hole (with depth of phosphate)
Auger hole encountering phosphatic clay
Barometric height above sea level
Track
NOTE: Survey of track and auger holes – by pace and compass. Spot heights by survey barometer
Limestone overlies volcanics
Volcanic outcrop
N + 30' (4' Volcanic clay)
Village
Sketch Section through deposit
Oolitic Phosphate
Phosphatic clay
Clay in chimneys
Section A - B
Scale · Vertical/Horizontal = 1
Feet
Sea level
Central track

Fig. 12



NAUNA I.

AUGER HOLES

Position of hand auger holes shown on Fig. 11

The main deposit has been disturbed by the digging of taro pits and it is no longer possible to say what tonnage of phosphate is present. It seems likely that some phosphate was exported. The original deposit probably occupied an area of about 100,000 square yards and was of the same order of thickness as the Purdy deposits.

NAUNA (Fig. 11)

Nauna Island (2° 11′ S, 148° 09′ E), lies about 60 miles east of Lorengau (Manus Island) (Plate 1). It is the most easterly of the Admiralty Group, about 1700 yards long (north/south), and about 1000 yards wide. Its total surface area is a little under half a square mile. The island has a small population who live in one village near the shore at the south end of the island. The interior of the island is of raised coral and in places is rugged. All the villagers' gardens are near the sea shore on the flat terrace behind the village, but there were at one time gardens in the interior, on the area of the phosphate deposit. There is no anchorage.

There is no record of previous investigation of the island for phosphatic deposits. It was included in the present survey because the available evidence suggested that it was of raised coral, and because of its fairly isolated position on the extreme east of the Admiralty Group.

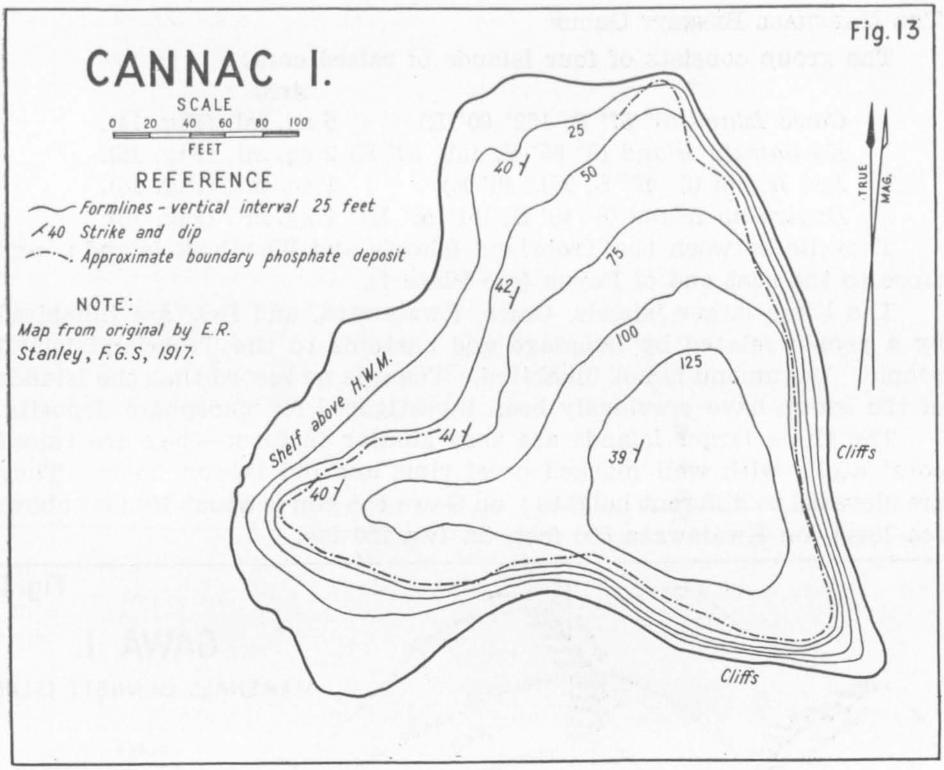
The island is an elevated coral atoll, elliptical in form. The uplift was apparently accompanied by tilting to the south-east so that the north end of the old lagoon floor is 320 feet, and the south end 270 feet above sea level. The coral rim surrounding the old lagoon floor is well marked on the north and west sides. On the east and south sides the rim is not appreciable, and the gently sloping old lagoon floor falls away suddenly in precipitous cliffs. There is no watercourse on the island.

The deposit is of phosphatic clay, occurring slightly to the south-east of the centre of the old lagoon floor. Along the north-west half of the area oolitic phosphate underlies and grades into the clay. The contact of the oolitic phosphate and the clay with the underlying limestone is gradational and irregular. Sections established by hand auger drilling are shown in Figure 12. The limestone forms a field of pinnacles and chimneys and the phosphatic clay and the oolitic phosphate occur as infilling between them. Over most of the deposit the tops of the pinnacles do not appear at the surface. Some clay occurs in chimneys outside the area shown on Figure 11.

The clay is a yellow-brown colour, darkening somewhat on exposure to air, and with a consistency like that of drying putty or plasticine. The oolitic phosphate is made up of small round oolitic grains all about 1/10 inch in diameter. The grains are in a matrix of the phosphatic clay and all gradations from clay to oolitic phosphate are found.

Tonnage and Grade

It is estimated that the deposit contains 125,000 tons of the phosphatic clay with an average grade of 15·9% P_2O_5 (from 13 field analyses and 10 laboratory analyses). This estimate has allowed a deduction of one half



for the volume occupied by the limestone of the pinnacles in determining the volume of the clay. The oolitic phosphate is estimated to make up 15,000 tons with an average grade of 32·5% P_2O_5 (from 5 field analyses and 5 laboratory analyses). Again the same supposition has been made regarding the volume occupied by the limestone pinnacles. The density of the clay and oolitic phosphate has been taken to be 1 ton to 25 cubic feet.

CANNAC (Fig. 13)

Cannac Island, or Cannac Rock as it is also known, is about 11 miles west of the Laughlan Group. No landing was attempted on the island in 1958 owing to bad weather, but the island is the subject of a report by E. R. Stanley (1917). He described it as a large triangular rock with sides less than 100 yards long, rising steeply to a gently sloping top whose highest point is 130 feet above sea level. The island is composed of slate with a few fine-grained basic igneous intrusives, which Stanley considered were similar to rocks cropping out along the south coast of Woodlark Island.

He described the phosphate as being partly fresh guano and partly phosphatized slate and igneous rock, the whole forming a cover about three feet deep over the island. He estimated the total tonnage at about 8000 tons ; and the average grade (three analyses) was 39% P_2O_5.

THE MARSHALL BENNETT GROUP

The group consists of four islands of raised coral :

	Area
Gawa Island (8° 57′ S, 152° 00′ E)	5 sq. ml. (Fig. 14).
Kwaiawata Island (8° 55′ S, 151° 53′ E)	2 sq. ml. (Fig. 15).
Iwa Island (8° 42′ S, 151° 40′ E)	1 sq. ml. (Fig. 16).
Dugumenu Island (8° 49′ S, 151° 55′ E)	½ sq. ml. (Fig. 16).

They lie between the Trobriand Islands and Woodlark Island ; and close to the east end of Papua (see Plate 1).

The three larger islands, Gawa, Kwaiawata, and Iwa, are inhabited by a people related by language and customs to the Trobriand Island people. Dugumenu is not inhabited. There is no record that the islands of the group have previously been investigated for phosphate deposits.

The three larger islands are very similar in form—they are raised coral atolls with well marked coral rims and old lagoon floors. They are elevated to different heights ; on Gawa the rim is about 450 feet above sea level, on Kwaiawata 500 feet, on Iwa 250 feet.

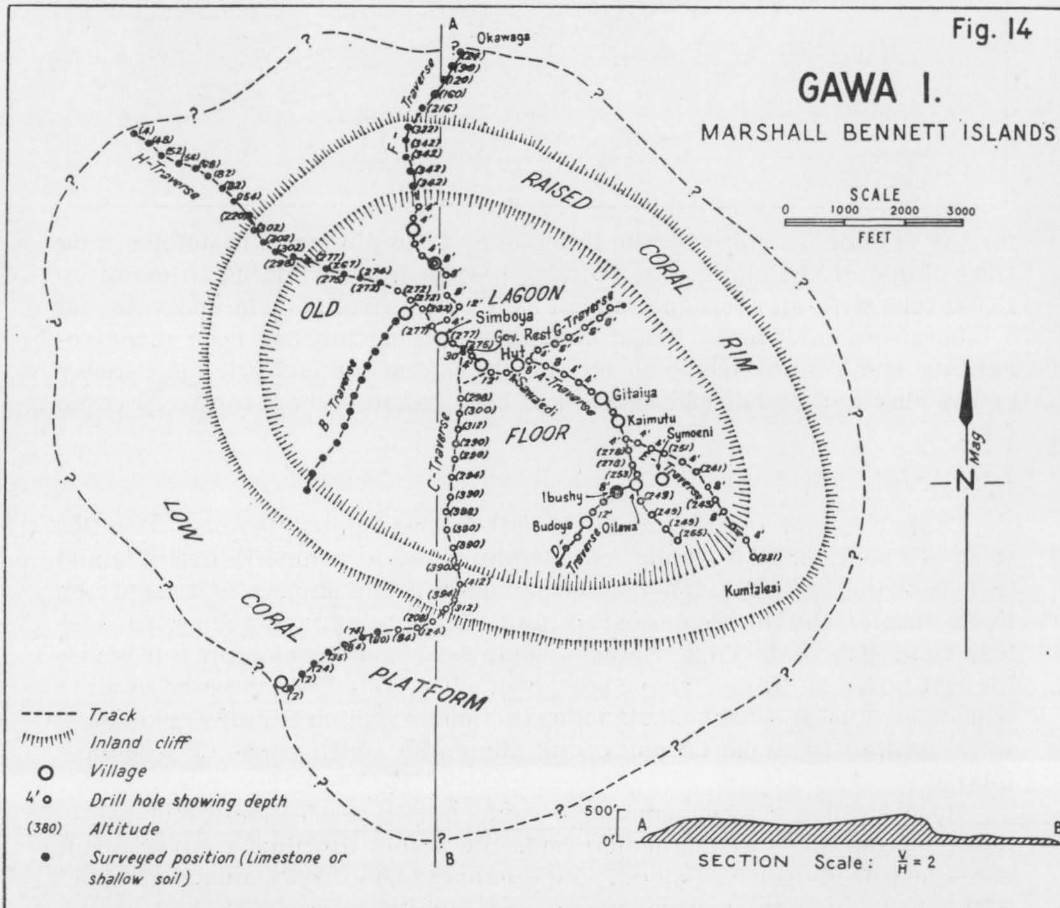
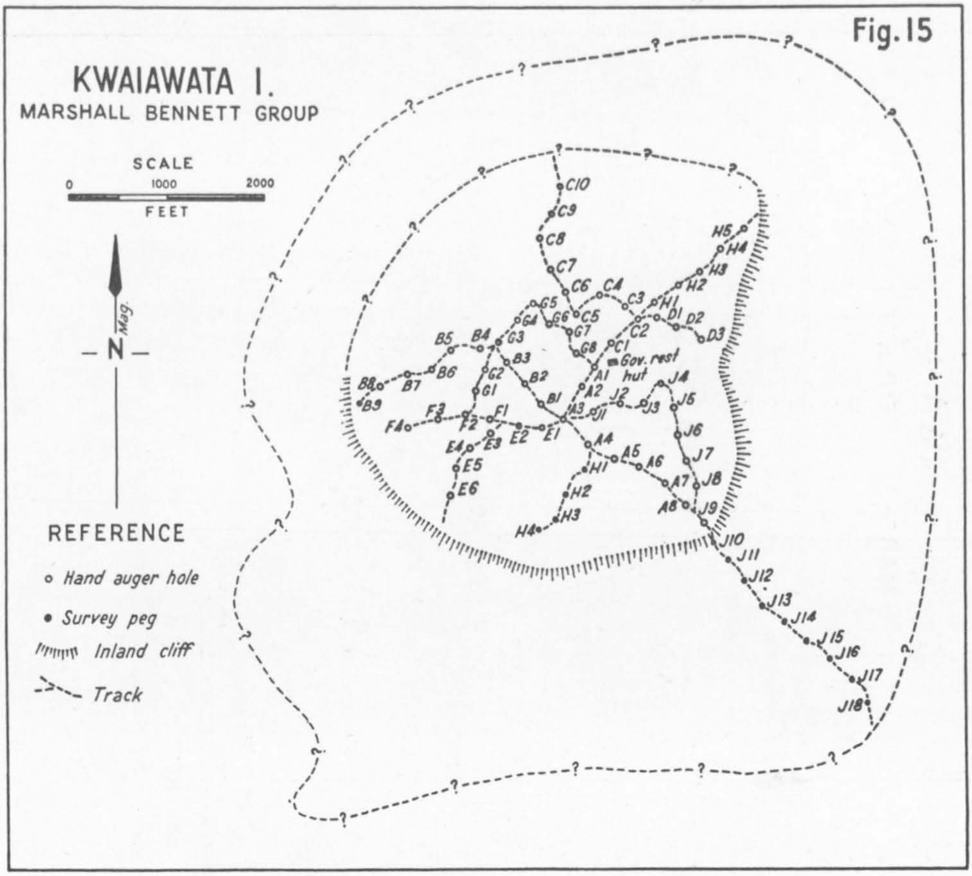


Fig. 14



On these three islands an aluminous clay, derived from the weathering of the limestone, occurs in patches on the old lagoon floor. Some samples of the clay are phosphatic (maximum 16% P_2O_5) on Kwaiawata, but these samples were isolated and did not constitute a deposit.

Testing was by evenly spaced hand auger holes along tracks. No chemical testing was done on the islands, but a representative number of the samples collected were tested in the laboratory.

Dugumenu Island does not show the clearly defined rim and old lagoon floor of the other islands. It has only a small area of raised coral near the north-west shore, with a maximum elevation of about 50 feet. About a quarter of the island near the east shore is low-lying and swampy ; the rest is composed of coral sand.

Alcester Islands (Fig. 17)

The Alcester Islands (9° 33′ S, 152° 25′ E) are a group of two ; the first is an island six miles long (east-west) by one mile wide ; the second is a small islet situated off the east tip of the main island. A very few people

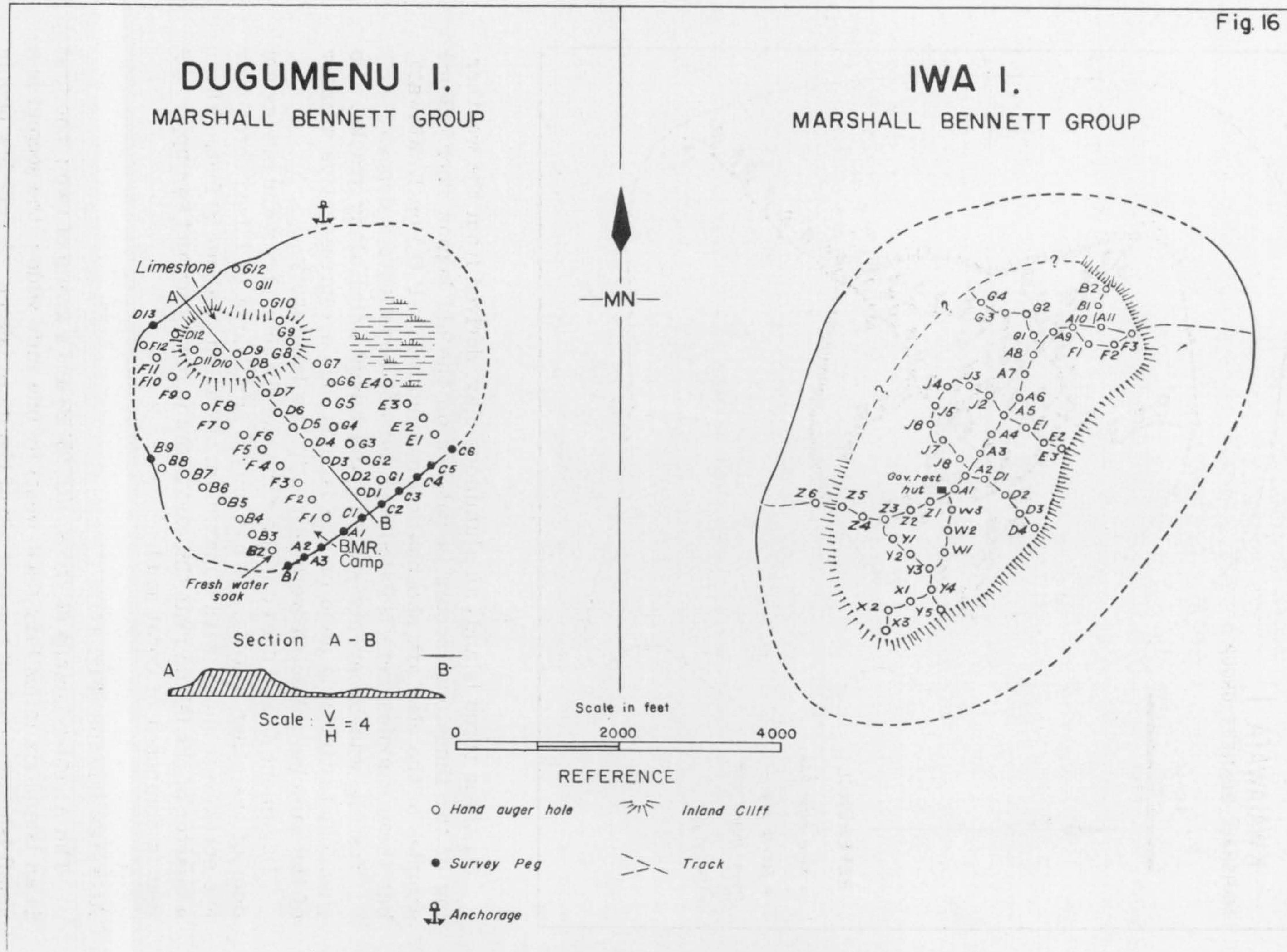


Fig. 16
DUGUMENU I.
MARSHALL BENNETT GROUP
Limestone
Fresh water soak
B.M.R. Camp
Section A - B
Scale : V/H = 4
MN
IWA I.
MARSHALL BENNETT GROUP
Gov. rest hut
Scale in feet
0
2000
4000
REFERENCE
Hand auger hole
Inland Cliff
Survey Peg
Track
Anchorage

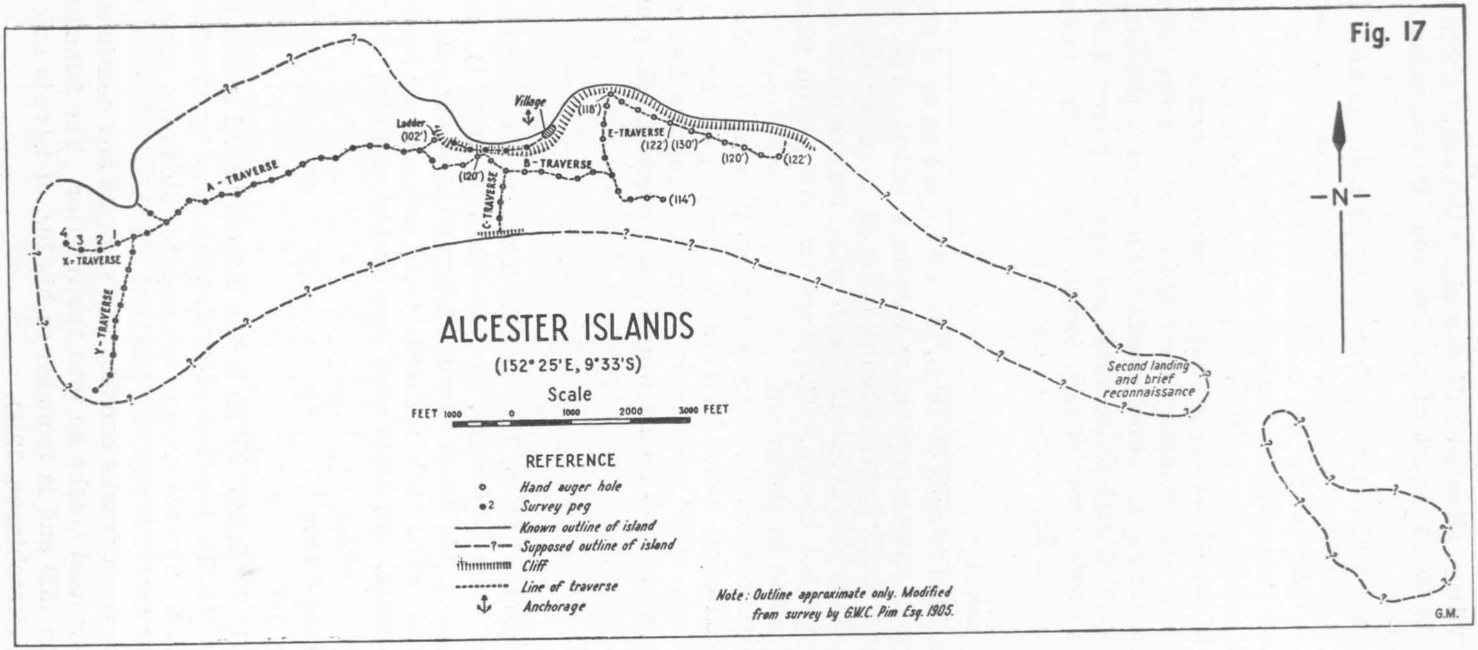


Fig. 17
ALCESTER ISLANDS
(152° 25' E, 9° 33' S)
Scale
FEET 1000 0 1000 2000 3000 FEET
REFERENCE
Hand auger hole
Survey peg
Known outline of island
Supposed outline of island
Cliff
Line of traverse
Anchorage
Note: Outline approximate only. Modified from survey by G.W.C. Pim Esq. 1905.
Village
Ladder
(102')
(118')
(120')
(122')
(130')
(114')
A - TRAVERSE
B - TRAVERSE
C - TRAVERSE
E - TRAVERSE
X - TRAVERSE
Y - TRAVERSE
4 3 2 1
Second landing and brief reconnaissance
N
G.M.

live in one village situated half-way along the north shore of the larger island. There is no report of any previous investigation of the island for phosphate.

The islands, which are physiographically a single unit, are of raised coral, with a maximum elevation of 200 feet above the present sea level. They form a long narrow arc concave towards the south. The islands appear to have been tilted at the time of the uplift, because the cliffs along the north coast are about 120 feet high (aneroid barometer readings) and the surface of the island slopes gently towards the south. The cliffs along the south coast are certainly lower than those on the north, but they were not measured. The limestone in the interior of the island is cavernous and pinnacled and only small patches of humic soil occur. The island has a dense cover of rain forest. None of the limestone or soil specimens showed any trace of phosphate.

Laughlan Islands

The Laughlan Islands (9° 18′ S, 153° 40′ E), are an atoll group situated 35 miles east of the eastern tip of Woodlark Island. The islands of the group ring a circular lagoon about 2 miles in diameter and are low-lying and sandy. They are about 100 yards wide, but were not surveyed, and their areas are not known. There are two villages on Budelun Island, the largest island in the group.

The islands are mainly composed of coral sand. Budelun Island has slightly raised coral along its seaward, easterly-facing, edge and good exposures of cemented ' beach rock ' along its lagoonward shore. Budelun and the second largest island were both traversed. No phosphate was discovered.

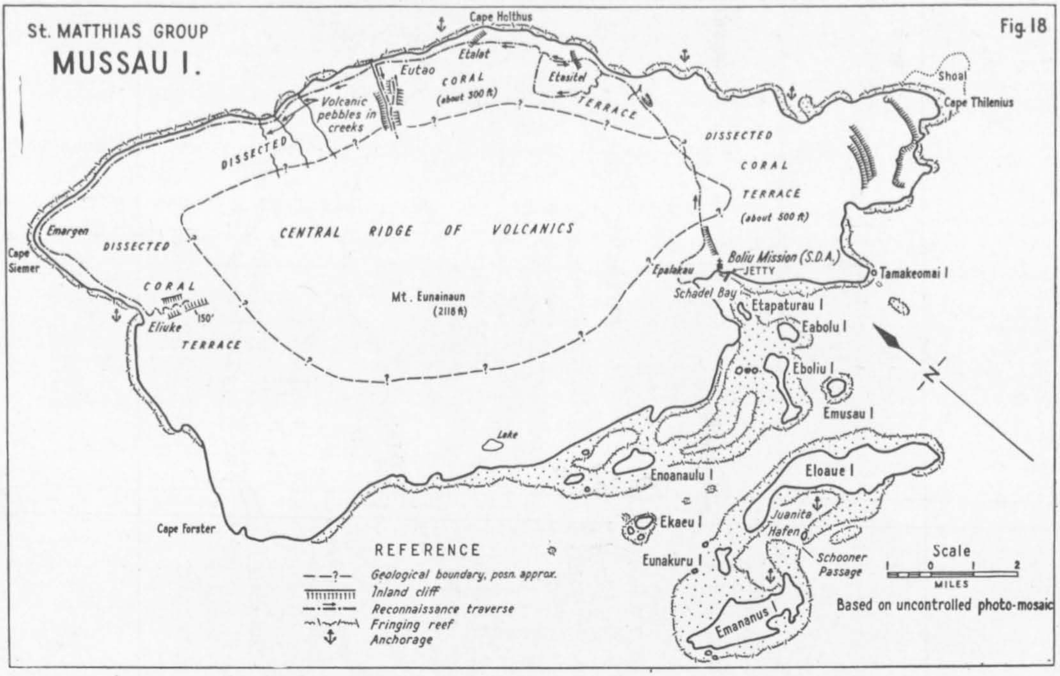
Sable

Sable Island (3° 42′ S, 154° 40′ E), in an isolated position 120 miles north-east of Cape St George, New Ireland (see Plate 1), was found to be a small sand bank, about 30 yards long and 15 yards wide. No landing was attempted as the bank obviously could not carry an important quantity of phosphate. No birds were seen in the vicinity.

Saint Matthias Group

Mussau (Fig. 18)

Mussau (1° 25′ S, 149° 35′ E) is the largest island in the St Matthias Group. It is 22 miles long (north-west/south-east) by 10 miles wide, with an oval outline. Several villages are situated along the north-east coast. An important centre is opposite the best anchorage, Schadel Bay, on the south coast. Good tracks connect the villages and continue round the coast, but few used tracks go into the interior. The island was visited by Fennell in 1929 and is included in his list of islands not thoroughly investigated (Hutchinson, 1941).



The island consists of a central ridge of hills rising to 2118 feet (Mt Eunainaun), surrounded by a dissected terrace of raised limestone with an average height of 500 feet in the south-east and 300 feet in the east and north-east. The central hills are of volcanic origin. Basalts and tuffs were recognised. No phosphate was found.

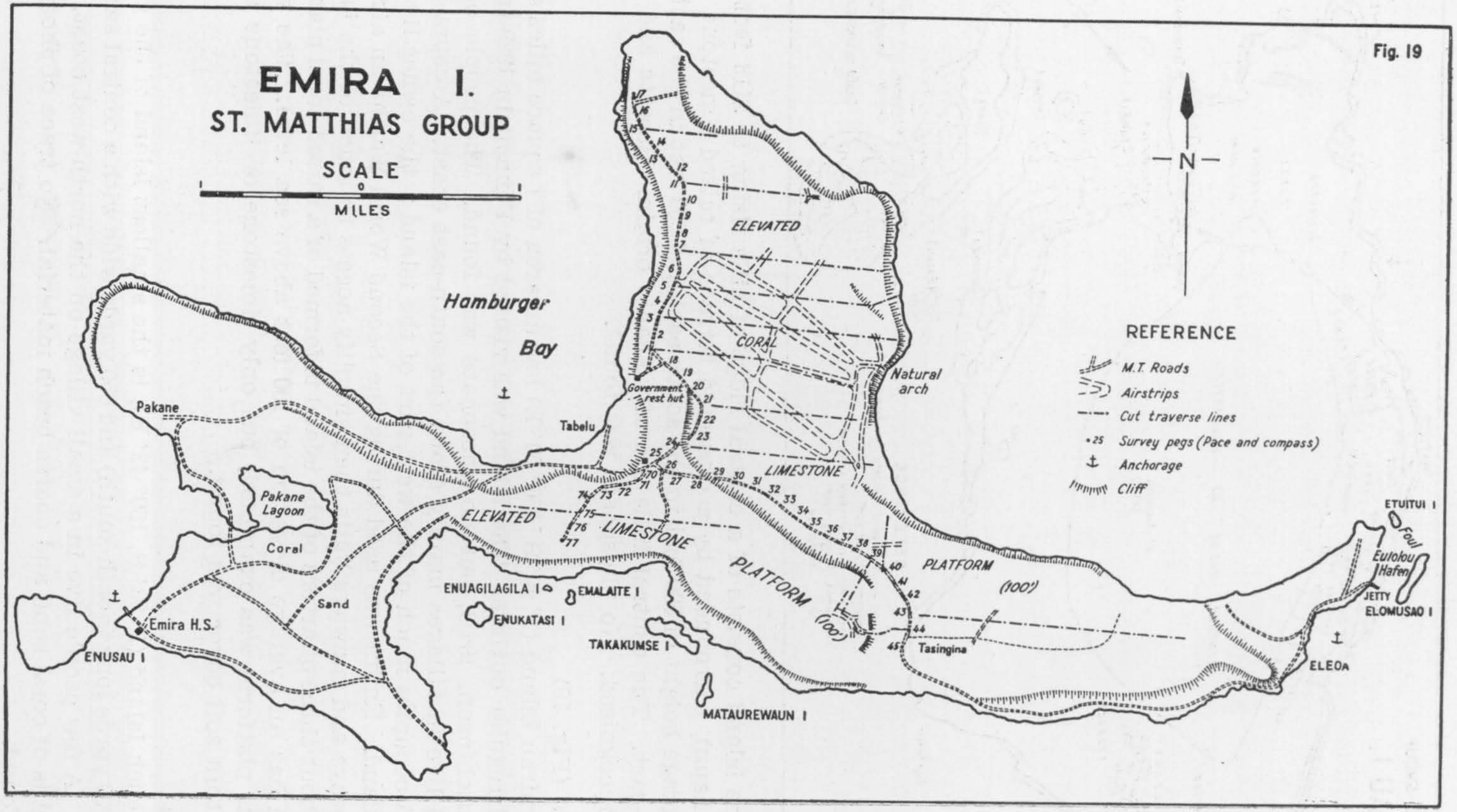
Emirau (Fig. 19)

Emirau Island (1° 40′ S, 150° 00′ E) has an area of 7 square miles and a very irregular outline. The island was visited by Fennell in 1929 (noted by Hutchinson, 1941), but no phosphate was found. The people of the island live in villages mainly along the south-east coast. A copra plantation occupies much of the west part of the island ; the owner lives on the island. Emira was used during the Second World War as an airbase. Roadways and runways built then simplify access to much of the island.

About three quarters of the island is formed of a raised coral platform which has an average elevation of 100 feet above sea level. The whole of this platform was examined, but only limestone or limestone under very thin soil cover was found.

Tench

Tench Island (1° 38′ S, 150° 42′ E), is the smallest island of the group. It is 900 yards long (north-south) and 650 yards wide with a central swampy area. A few people live in a small village on the north-west coast. The island is of coral sand and coarse beach material. No trace of phosphate was found.


EMIRA I.
ST. MATTHIAS GROUP
SCALE
MILES
N
REFERENCE
M.T. Roads
Airstrips
Cut traverse lines
Survey pegs (Pace and compass)
Anchorage
Cliff
Hamburger
Bay
ELEVATED
CORAL
LIMESTONE
ELEVATED
LIMESTONE
PLATFORM
(100')
PLATFORM
(100')
Natural arch
Government rest hut
Tabelu
Pakane
Pakane Lagoon
Coral
Sand
Emira H.S.
ENUSAU I
ENUAGILAGILA I
EMALAITE I
ENUKATASI I
TAKAKUMSE I
MATAUREWAUN I
Tasingina
ETUITUI I
Foul
Eulolou Hafen
JETTY
ELOMUSAO I
ELEOA
Fig. 19

Rambutyo (Fig. 20)

Rambutyo Island (2° 18′ S, 147° 48′ E) is the second largest of the Admiralty Group. It is about 30 miles east-south-east of the east tip of Manus Island.

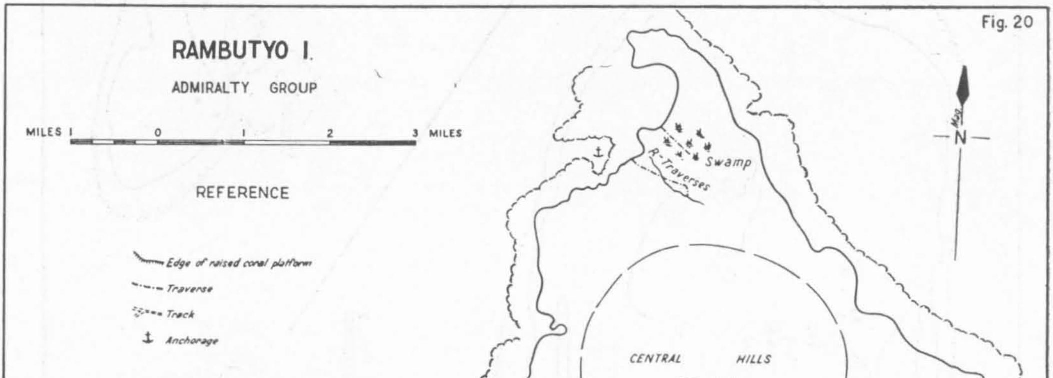
A reconnaissance of the island was made after a deposit of phosphatic clay was found on Nauna Island, which is 20 miles to the east. Rambutyo consists of a central core of hills of volcanic rocks surrounded by broad terraces of raised limestone. A clay, derived from the weathering of the volcanic rocks, spreads out over parts of the limestone terraces and fills in between limestone pinnacles. This clay was extensively tested by hand-auger drilling, but in no place was it found to be phosphatic.

Alim

Alim Island (2° 53′ S, 147° 05′ E), is ¾ mile long and 300 yards wide, elongated north-north-east. The east side and the north end of the island are of coral sand; the west and central areas are of mangrove swamp. The island is surrounded by a wide fringing reef.

The island was visited by Friederiei during his 1909 reconnaissance but no phosphate was found. However, G. E. Hutchinson in his review of the Pacific Islands listed Alim as ' doubtfully phosphatic ' (Hutchinson, 1950, p. 226). The present survey showed that there is only a trace of phosphate in the upper layers of the coral sand of which the major part of the island is made.

Fig. 20



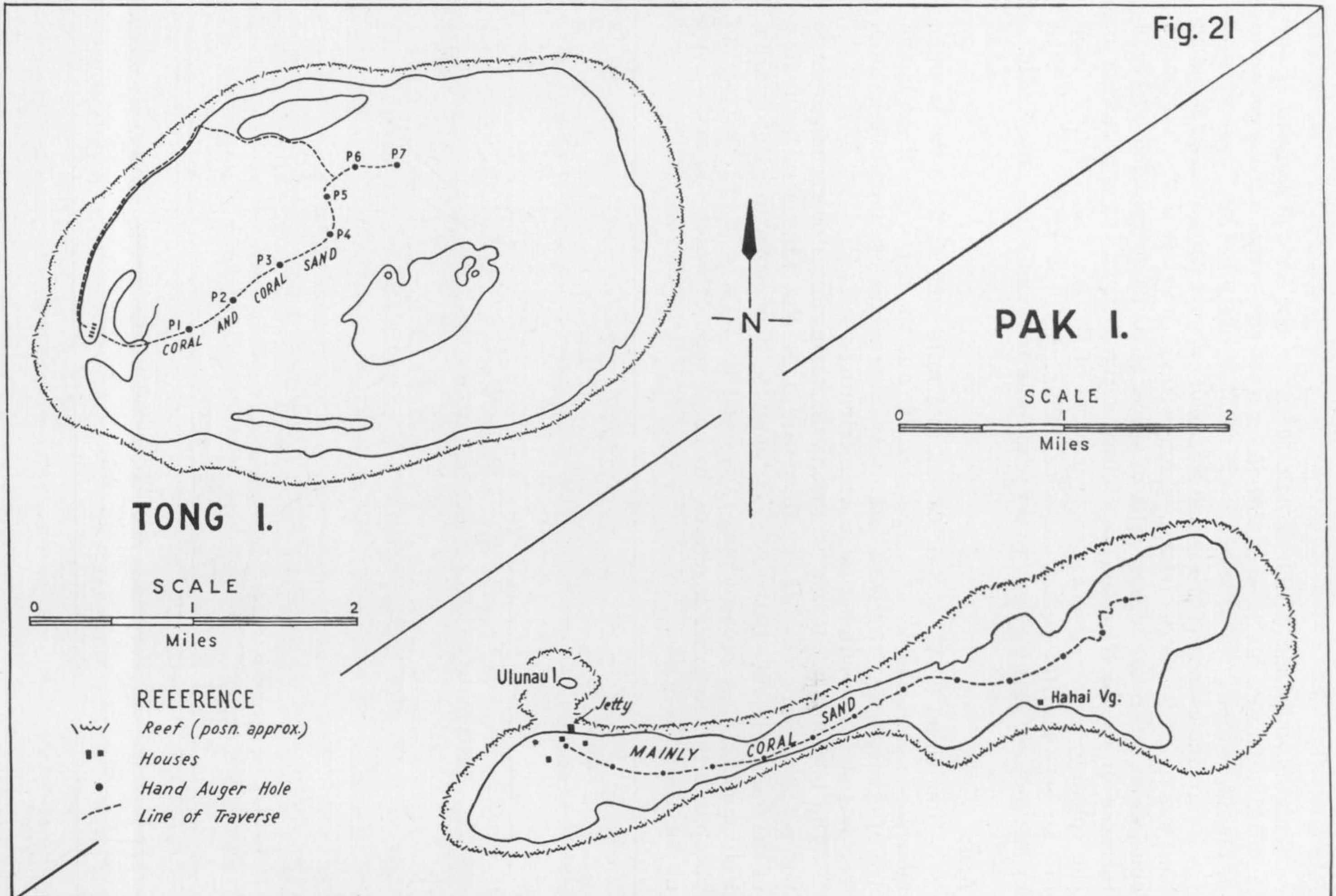

TONG I.
PAK I.
P1
P2
P3
P4
P5
P6
P7
CORAL AND CORAL SAND
N
SCALE
0
1
2
Miles
SCALE
0
1
2
Miles
REEERENCE
Reef (posn. approx.)
Houses
Hand Auger Hole
Line of Traverse
Ulunau I.
Jetty
MAINLY CORAL SAND
Hahai Vg.

Fig. 21

PAK (Fig. 21)

Pak Island (2° 04′ S, 147° 37′ E), is a low-lying island, five miles long and half a mile wide, trending east-west. It lies about 15 miles from the east tip of Manus Island in the Admiralty Group. It is composed of coral sand with a small area of slightly raised coral. No phosphate was found.

TONG (Fig. 21)

Tong Island (2° 03′ S, 147° 45′ E), is another low-lying island, almost circular in shape, 3½ miles east-west by 2½ miles north-south. It is about 20 miles to the east of the east tip of Manus Island in the Admiralty Group.

The island was found to be composed of coarse coral debris with areas of slightly raised coral. No phosphate was discovered.

THE GILBERT AND ELLICE ISLANDS

BY

W. C. White

A reconnaissance survey of the Gilbert and Ellice Islands was carried out during 1959 as part of the Bureau of Mineral Resources' search for phosphate deposits in the Western Pacific. From the beginning it was recognised that these flat, low-lying atolls and table reefs offered very poor prospects of workable deposits, but their relatively isolated position in the vicinity of the organically productive South Equatorial current and the comparatively dry climate of many of the islands made their inclusion in the phosphate survey desirable. It was known also that many of the islands had been visited by guano prospectors in the 19th century, but no records seem to have been preserved. More recently, small amounts of phosphate and doubtfully phosphatized sand were recorded by Catala (1950) and Cloud (1952).

The Gilbert and Ellice Islands form a long north-north-westerly chain of atolls and low-lying reefs between latitudes 4° N and 11° S and longitudes 172° E and 178° E (Plate 4). Tarawa atoll, the main port of entry and administrative centre of the colony, which includes also the Phoenix Islands, Christmas, Fanning, and Washington Islands and Ocean Island, is 1200 miles north of Suva and 240 miles east of Ocean Island. Access is normally through Ocean Island, which is well served by British Phosphate Commission ships, but communications within the colony are infrequent and irregular.

CLIMATE

The climate of the islands is warm and fairly humid, but pleasant. The prevailing winds are easterly, with occasional strong westerlies between November and March. The rainfall is very variable. In the Gilbert group annual rainfall ranges from a few inches to 150 inches. The northern Gilberts, Makin, Butaritari, Marakei and Abaiang, generally have the heaviest rainfall, but even these islands are subject to serious droughts, which sometimes last for several years. According to the available figures droughts seem to affect the whole group rather than individual islands. As an example of the extreme variability of the rainfall, the annual figures for Kuria, in the central Gilberts, for the years 1954 to 1958 are: 22·13, 8·84, 19·91, 78·23 and 109·72 inches.

The Ellice group farther to the south has, in general, a heavier and rather more reliable rainfall. Although the severe droughts of the Gilbert Islands are reflected in the rainfall figures for the Ellice group, actual droughts are rare.

The accumulation of avian guano and the formation of deposits of calcium phosphate by the interaction of solutions leached from the guano and calcium carbonate is thought to be seriously affected by rainfall.

Hutchinson (1950) has shown that with an annual rainfall of more than 2000 mm. (85 inches) it is unlikely that any phosphates would remain, and that with a rainfall of 1000 mm. (42 inches) it is unlikely that deposits of any appreciable size would be found. The Ellice Islands normally have a rainfall exceeding 85 inches and the mean annual rainfall in the Gilberts appears to approach closely the lower figure (42 inches).

Rainfall figures for the years 1950 to 1958 are given in Table 4, and annual maximum, minimum and mean rainfall for these years is plotted as a function of latitude in Figure 22 with the location of phosphate deposits shown.

Scope of the Survey

The Gilbert Islands comprise 16 atolls and table reefs and the Ellice Islands nine. The atolls range from 2 or 3 miles in length to 30 miles or more and are generally of very irregular shape. Land area is small, consisting usually of a narrow strip or a chain of small islets, usually only on the east (windward) side of the atoll, the westward reef being submerged. The table reefs, of which there are four in the Gilbert group and three in the Ellice, appear to have been small atolls in which the lagoon has become filled, or almost filled, with calcareous sediments and reef debris.

Twenty of the twenty-five islands were visited during the present survey. Of the Ellice Islands only Nuilakita was not visited. In the Gilbert Islands it was not possible to get to Nonouti and Beru ; Butaritari was visited by night only, and an attempt to reach Aranuka by canoe from Kuria was defeated by bad weather. The time available for the investigation on the islands visited varied from two hours to two weeks and depended mainly on the available shipping in the area. As far as possible a longer visit was made on one island of each type (atoll and table reef) in each of the distinct rainfall belts. Thus, a fairly thorough examination was made of Tamana and Tabiteuea in the southern Gilberts, of Kuria and Abemama in the central and Marakei in the northern Gilbert, and of Nanumea and Nui in the wetter Ellice Islands. Sufficient time was available on most of the other islands for a reasonable assessment of the phosphate potentialities to be made.

The investigation attempted on each island involved an examination of the land surface for signs of phosphatization and drilling of hand-auger holes to water level in likely areas or to obtain information on the subsurface material. In most cases observations were plotted on enlargements made from Admiralty chart No. 731, with topographic corrections made by tape and compass survey.

Samples were assayed in the field by rapid colorimetric method, using ammonium molybdate and benzidine, which gave an accuracy of $\pm$ 5%. A representative number of samples was later checked by more accurate laboratory methods and found to be within the range given by the field method.

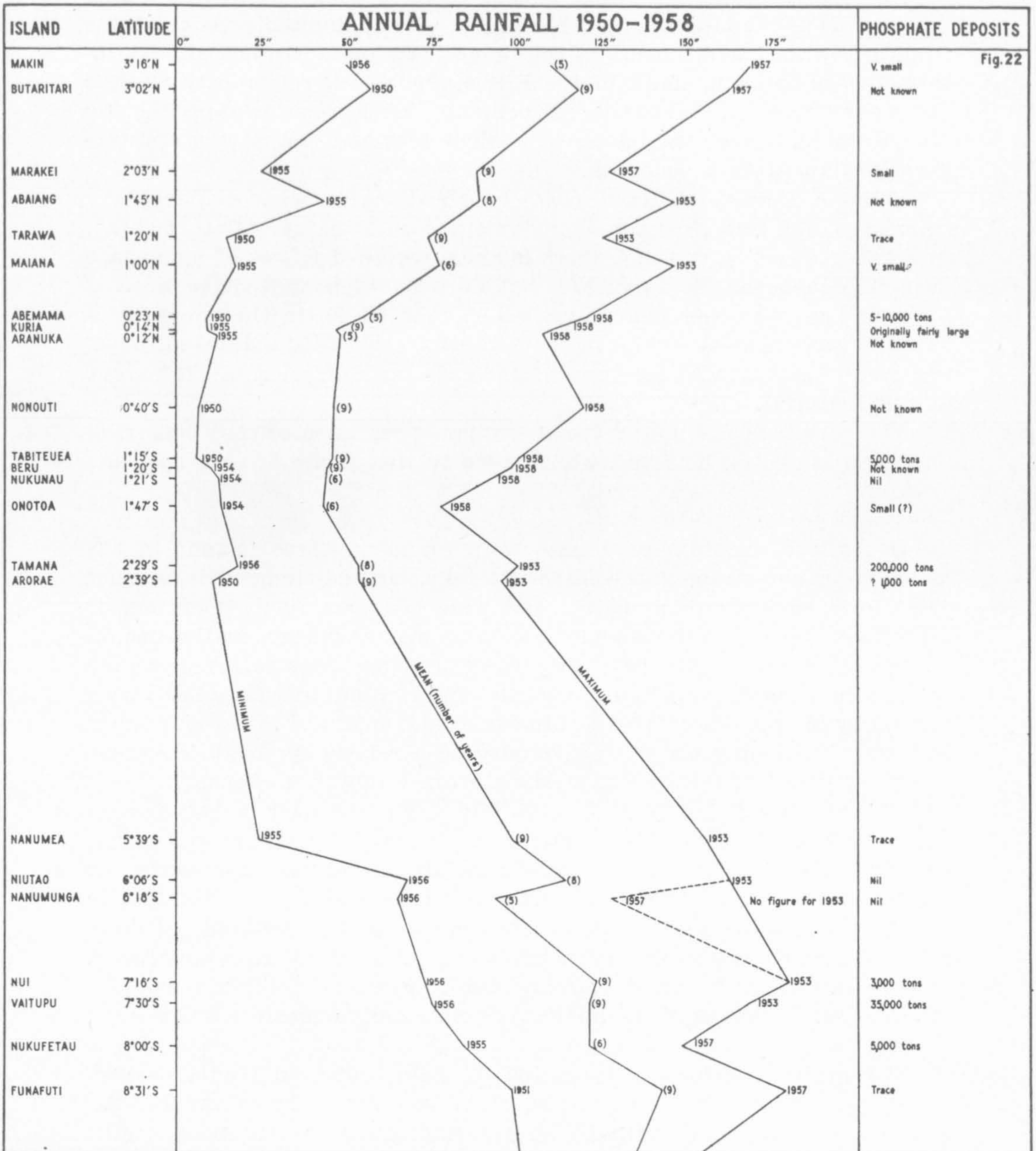
74895—(3)

Table 4

GILBERT AND ELLICE ISLANDS

ANNUAL RAINFALL

Station	1950	1951	1952	1953	1954	1955	1956	1957	1958
Little Makin	....	....	....	....	77·23	52·06	106·92	168·81	147·04
Butaritari	56·86	153·83	149·05	157·77	119·01	60·35	90·13	159·94	158·87
Marakei	....	....	....	124·42	70·71	25·57	65·78	127·21	107·20
Abaiang	....	87·33	97·53	146·20	71·08	42·99	48·38	111·90	98·90
Tarawa	15·34	103·88	73·55	124·73	50·47	25·42	38·89	120·97	116·82
Maiana	....	....	....	146·99	51·24	18·54	23·35	112·46	114·11
Kuria	....	....	....	....	22·13	8·84	19·91	79·23	109·72
Abemama	7·69	78·90	49·00	84·68	31·27	12·33	19·55	86·90	119·15
Aranuka	....	....	....	....	16·41	11·67	17·70	87·59	107·88
Nonouti	6·46	47·43	40·90	84·74	18·40	10·95	12·05	76·09	118·27
Tabiteuea	6·67	55·98	40·13	71·90	24·88	17·08	11·43	84·28	101·15
Beru	9·77	61·35	45·43	61·56	12·95	15·24	17·15	72·14	97·51
Nikunau	....	....	....	73·03	13·78	16·75	14·24	72·53	95·97
Onotoa	....	....	....	64·78	12·48	19·97	15·35	72·10	77·66
Tamana	....	70·51	60·09	99·92	20·22	27·65	17·04	69·85	58·08
Arorae	11·43	82·79	67·93	95·09	17·79	23·55	17·11	66·57	95·96
Nanumea	79·25	99·29	111·04	155·23	97·27	23·57	58·08	121·91	141·99
Niutao	84·98	....	122·77	163·90	110·22	74·69	67·42	144·37	143·87
Nanumanga	....	....	....	....	92·03	66·91	64·75	115·98	127·42
Nui	98·16	124·64	142·64	178·93	122·47	93·80	72·08	148·58	129·27
Vaitupu	74·52	104·19	157·27	167·50	120·78	98·02	80·90	143·65	148·92
Nukufetau	....	....	....	118·07	127·66	84·81	103·30	148·19	144·68
Funafuti	99·66	98·81	143·20	166·74	135·88	160·89	116·46	178·87	176·72
Nukulaelae	....	....	....	142·59	147·54	100·44	119·69	141·05	145·84


ISLAND
LATITUDE
ANNUAL RAINFALL 1950-1958
PHOSPHATE DEPOSITS
Fig. 22
0" 25" 50" 75" 100" 125" 150" 175"
MAKIN 3°16'N V. small
BUTARITARI 3°02'N Not known
MARAKEI 2°03'N Small
ABAIANG 1°45'N Not known
TARAWA 1°20'N Trace
MAIANA 1°00'N V. small
ABEMAMA 0°23'N 5-10,000 tons
KURIA 0°14'N Originally fairly large
ARANUKA 0°12'N Not known
NONOUTI 0°40'S Not known
TABITEUEA 1°15'S 5,000 tons
BERU 1°20'S Not known
NUKUNAU 1°21'S Nil
ONOTOA 1°47'S Small (?)
TAMANA 2°29'S 200,000 tons
ARORAE 2°39'S ? 1,000 tons
NANUMEA 5°39'S Trace
NIUTAO 6°06'S Nil
NANUMUNGA 6°18'S Nil
NUI 7°16'S 3,000 tons
VAITUPU 7°30'S 35,000 tons
NUKUFETAU 8°00'S 5,000 tons
FUNAFUTI 8°31'S Trace
NUKULAELAE 9°22'S Nil
MINIMUM
MEAN (number of years)
MAXIMUM
No figure for 1953

Previous Investigations

No records of their findings appear to have been left by the guano prospectors of the late nineteenth century, who undoubtedly visited these islands prior to the discovery of rock phosphate on Ocean Island. Nuilakita, in the extreme south of the Ellice group, was apparently worked for guano about the end of the last century, but no records of production are available. Later the island was taken over as a plantation and was densely planted with coconuts.

Sollas & Edgeworth David (1904) recorded the presence of phosphate in swamps and in a limestone conglomerate on Funafuti. Catala (1950), in a general survey of the Gilbert Islands, recorded traces of phosphate near Bikenebue on Tarawa atoll, but does not appear to have noticed it on any of the other islands visited. Cloud (1952), in the course of a detailed investigation of the reefs of Onotoa, recorded 'indurated, phosphatized (?) limesands (old dunes),' but gave no indication of the extent of this material.

The occurrence of phosphate of similar appearance to that occurring on Ocean Island is, however, well known to the people of the Islands.

The Phosphate Deposits

Deposits of calcium phosphate were found on three islands in the Ellice group and on ten of the Gilbert Islands. In addition, small deposits are known to occur on Funafuti, but were not seen during the present survey, and several of the islands not visited may also have small deposits.

All the deposits examined, with the exception of a small fresh guano deposit on Tabiteuea atoll, are essentially very similar. They have been formed by phosphatization of a thin surface layer of the calcareous sands and gravels forming the islands, producing a relatively tough, coherent crust composed of tricalcium phosphate and calcium carbonate.

The phosphatic material is typically a pale to dark brown porous rock with a distinctly oolitic appearance. It is light in weight and rather friable in the hand, but in the mass it is fairly tough and tenacious. It is composed of round to ovoid grains usually one or two millimetres in diameter, but occasionally coarser, with more angular fragments of shell, coral, and coralline algae. In general the rounded grains are predominant, but in some examples finely comminuted *Halimeda* debris forms the bulk of the rock. Deposits of the latter type commonly contain a fairly large proportion of coarse coral gravel.

The grains are loosely cemented by pale brown to reddish-brown, more or less translucent collophane, which has also replaced much of the finer fragmentary material. Under the microscope the rounded grains show no trace of concentric or other oolitic structure other than a thin outer rim or shell of darker, iron-stained collophane. Many of the grains, however, are incompletely replaced and it is clear that, though some of them represent small abraded coral fragments, the majority are small foraminiferal tests, the commonest being the reef-dwelling form *Calcarina*.

The percentage of unreplaced calcium carbonate varies considerably from deposit to deposit and within a single deposit ; the unreplaced cores of small grains give the rocks a characteristic speckled appearance and react vigorously with acid. In a few instances, such as the southern deposit on Vaitupu Island, the original sand was fine and probably contained a high percentage of lime mud. In these cases replacement by collophane is more complete than in the uniformly coarse sands, but the percentage of phosphate in the deposit as a whole is kept low by the amount of scattered coarse shell and coral gravel embedded in the fine groundmass.

The grade of all the deposits is remarkably uniform. Most of them carry between 15% and 20% P_2O_5 (determined by field assay) and any variation from this range can usually be attributed directly to the amount of unaltered coral gravel present (where coarse coral gravel was present it was not possible to include this in the sample assayed). The percentages of iron and alumina present were not determined, but, judging from the very small insoluble residue left after dissolving the samples in dilute hydrochloric acid, they are small.

The deposits examined vary considerably in size, from a few tons to a few thousand tons. This is, without exception, a function of areal extent rather than thickness, the mean thickness of all deposits being almost identical. The actual thickness of any one deposit varies from a few inches to 25 to 30 inches, often within a very short distance, but the mean thickness in each case is around 10 to 12 inches. The continual and, in places, sudden changes in thickness are due to a very irregular lower limit of phosphatization, the upper surface of the deposits being flat. The reasons for this are not clear, but may be related to the position of suitable nesting trees at the time of guano accumulation.

The base of the zone of phosphatization is commonly sharp, with an abrupt change from the coherent phosphate rock to unconsolidated sand. In some deposits it is gradational over four or five inches, owing, it is believed, to the continued dampness of the surface brought about by a thick cover of natural vegetation.

Only one deposit, on Arorae, was buried, and in this case the thin cover of sand was almost certainly scattered over the deposit during the excavation of nearby babai* pits. Nor is there any evidence that the deposits have been eroded since their formation, and the often patchy distribution of the phosphatized sand, with areas of loose sand between outcrops, must be very largely an original feature.

Downward leaching of phosphate by percolating rainwaters, and reprecipitation at the water table, is not much in evidence. A calcarenite rock at the water table on Tamana was found to be weakly phosphatic, but elsewhere no phosphate was recorded below the base of the surface crust, even in damp deposits which have a gradational base.

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* Babai : a root vegetable similar to taro and grown in swamps and pits.

Small deposits of fresh guano were found to be accumulating on Tenon and Namurae islets, Tabiteuea atoll, but no phosphatization of the underlying calcareous material was apparent. A similar guano deposit on Numatong islet, Nonouti atoll, was not examined.

THE GILBERT ISLANDS

TAMANA (Fig. 23)

Tamana (2° 29′ S, 175° 58′ E) lies in the extreme south of the Gilbert Islands, some 300 miles south-east of Tarawa, and is typical of the small table reefs or ' reef islands ' of the southern Gilberts and northern Ellice Islands. It also contains the largest phosphate deposit in the group and was therefore investigated in more detail than the other islands.

The island is just over three miles long and three-quarters of a mile wide, with the long axis lying north-west. It is bordered by a wide fringing reef consisting of a broad zone of algal flats with a prominent, slightly raised *Lithothamnium* ridge, cut by numerous surge channels, at its seaward edge. Inside the reef the island is encircled by a broad flat storm beach, 12 to 14 feet above mean sea level, the interior of the island forming a shallow saucer-shaped depression which is deeper and more marked in the south-eastern half of the island.

A well developed boulder rampart forms the outer part of the storm beach at the southern end and extends northwards, along both sides of the island, for more than a mile, becoming progressively thinner and lower. The boulders, which are entirely of coral, are fairly uniformly about 12 to 15 inches long and are oval and slab-like. They are tightly packed and form a steep seaward slope. Towards the north the boulders become smaller and the boulder rampart passes laterally into the normal coral gravel and sand storm-beach. At the extreme southern end of the island, a second, smaller, boulder rampart, representing an earlier storm beach, occurs 50 to 100 yards inside the later one.

In the south of the island the wide flat central depression is no more than one to two feet above the high tide level. Damp black humic soil overlies a thin layer of loose gravel and pebbly sand and the water table is, in places, only a few inches below the surface. The area is wet and swampy after high spring tides.

In the northern half of the island the average elevation is slightly higher. Along the east side, directly behind the storm-beach there is a broad shallow ' trench,' extending northwards from the low-lying southern area, in which a dark damp humic soil overlies loosely cemented coral gravel. To the west of this the ground slopes gently up towards the western storm beach and the loosely cemented coral gravel and sand at the water table are overlain by an increasing thickness of unconsolidated clean foraminiferal sand on the top of which most of the phosphate occurs.

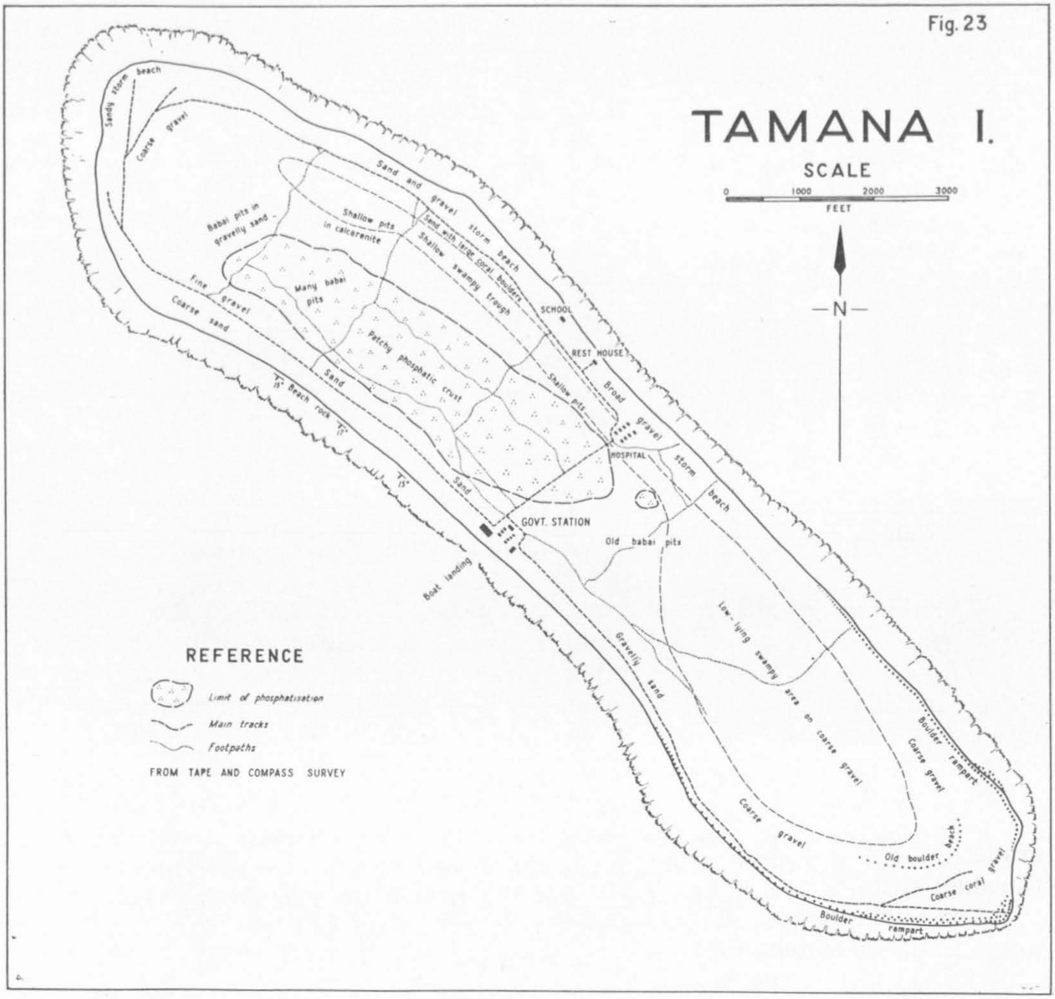


Fig. 23

The typical crust of phosphatized sand forms patches from a few square feet to several hundred square yards in extent and varies in thickness from an inch or two to just over two feet. That it formerly covered most of the northern half of the island is shown by the widely scattered blocks and fragments of phosphatized sand on the surface and in the sand excavated from the babai pits, and by the weakly phosphatic nature of the spongy black humic soil between outcrops of phosphatized sand.

The phosphatic material is uniform in appearance and field assays indicated a fairly uniform grade of between 15% and 20% P_2O_5. There is little coarse shelly material, and where gravelly layers are included in the phosphatized zone, the coral fragments are unaltered. The lower limit of phosphatization is generally sharp and clear-cut, but very irregular, with no sign of a gradation into the underlying unaltered sand.

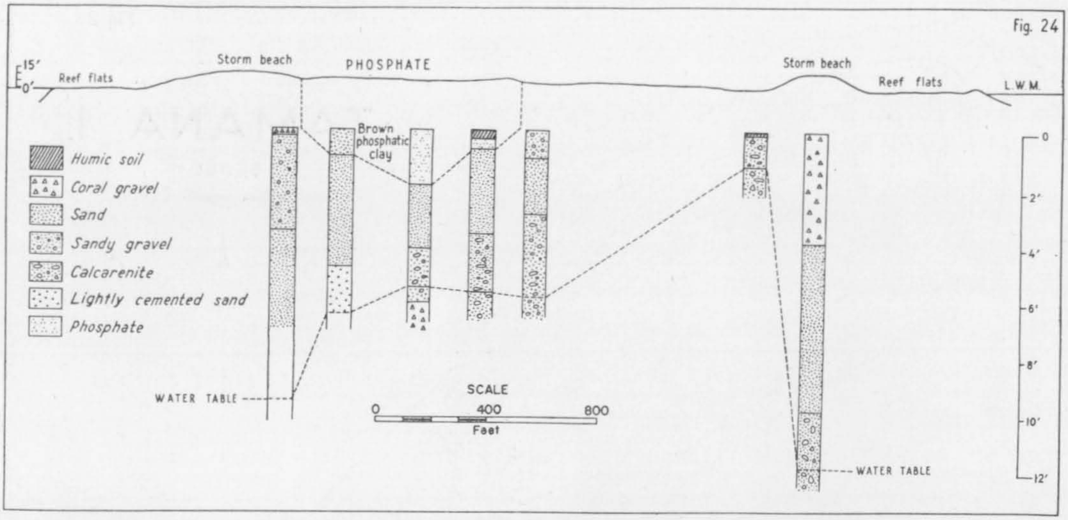


Fig. 24.—Surface profile and vertical section, Tamana Island.

The underlying loose sand and thin gravel layers of which the island is formed are, near the water table, loosely cemented by calcium carbonate to form a relatively tough calcarenite which extends for several feet at least below the water table. Where the phosphatic crust is well developed the topmost portion of the calcarenite is weakly phosphatic, owing, apparently, to reprecipitation at the water table of phosphatic solutions percolating down from the surface deposit. In places the calcarenite assayed as much as 10% P_2O_5, but was generally much lower grade. By carefully crushing a sample of phosphatic rock and separating the shell and gravel fragments, it was shown that the phosphate is largely confined to the cementing material ; no replacement of the detrital fragments could be detected. Despite a careful examination of all the babai pits, however, and the excavation of several large test pits, no compact layer of good-grade chemically precipitated amorphous collophane, such as is commonly found under phosphate deposits, could be found.

Typical sections from pits and test holes, and an approximate profile across the northern half of the island are shown in Figure 24.

The phosphatic crust extends, in the southern half of the island, for a short distance south of the trench between the government station and the hospital, but is thin and irregular. The remainder of the southern half is low-lying and, in part, swampy, with a thin black humic soil overlying loose gravel and pebbly sand. Neither the sands and gravel nor the black soil contain any detectable trace of phosphate.

Tonnage and Grade

Estimation of the tonnage of phosphatic material is made difficult, in a deposit such as this, by the very irregular thickness of the deposit and by the large number of man-made excavations which have broken through the phosphatic zone into the underlying sand. Assuming, as seems reasonable, that the phosphatized sand was originally continuous over most of the northern half of the island, then drilling and pitting results suggest that the average thickness was about 12 inches and the total tonnage of phosphatic material approximately 200,000 tons containing 15% to 20% P_2O_5. However, allowing for the patchy nature of the deposit, the very variable thickness and the large areas now or in the past under babai cultivation, it is doubtful if even half this figure could ever be extracted. Mining and handling of the phosphate would be difficult owing to the patchy nature of the deposit, and the high calcium carbonate content would make treatment expensive and direct application ineffective. It is not recommended that any attempt be made to utilize this phosphate, even for local use.

Arorae (Fig. 25)

Arorae, the most southerly of the Gilbert Islands (2° 39′ S, 176° 49′ E), is approximately 6 miles long and 1½ to 2 miles wide. It is a typical 'reef island,' very similar in form to Tamana. It is made up largely of fine unconsolidated sands with coarse gravel layers and is encircled by a low, sandy, storm beach and a wide fringing reef.

Towards the northern end of the island, some two miles north of the government station, a thin crust of phosphatized sand and gravel occurs over an area of about 400 square yards. It is partly buried under a layer of loose sand and gravel, but this appears to have been thrown up from nearby babai pits, and is not a natural feature.

Near the northern end of the deposit a section exposed in a shallow trench illustrates the irregular nature of the deposit (Fig. 26). In this section the base of the deposit is clear-cut except in the deeper portions, where the phosphatized sand grades into unaltered sand. This may be related to the position of nesting trees at the time of deposition of the guano.

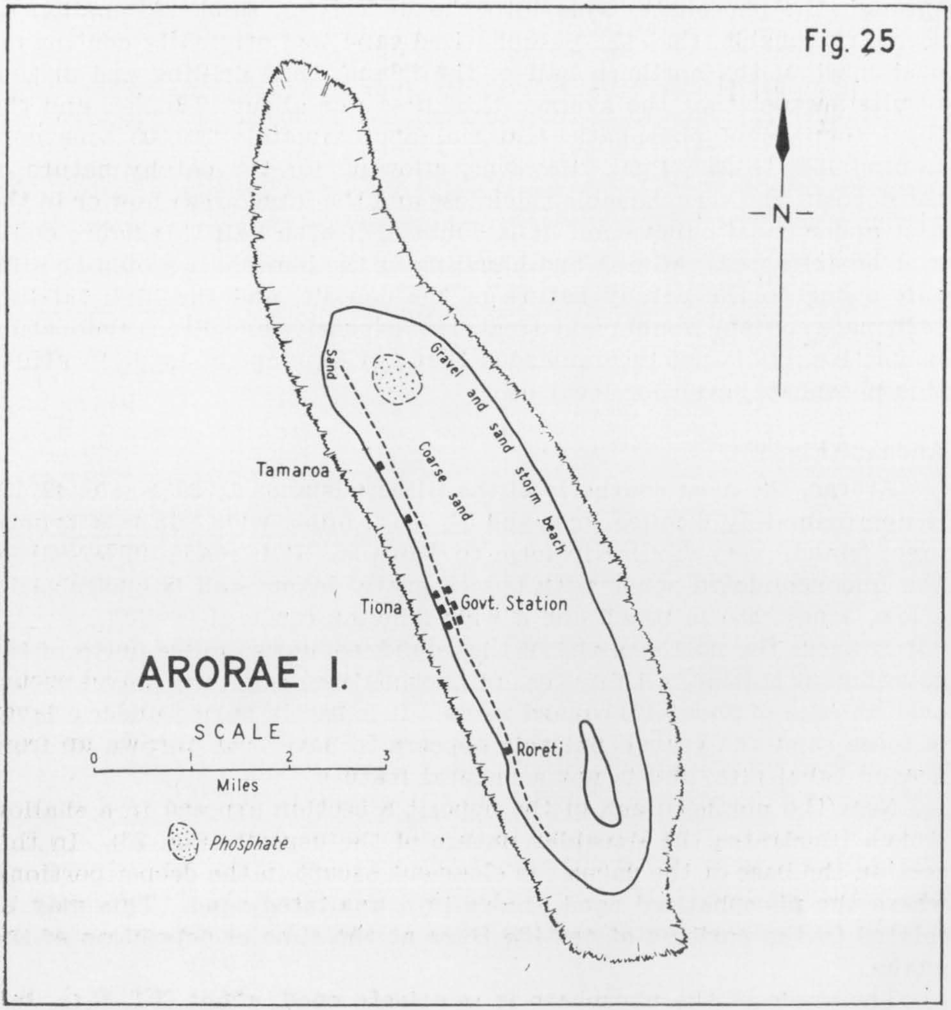
The grade of the phosphate is relatively good, about 20% P_2O_5, but the tonnage available is negligible.

The southern part of the island was not examined, but local inhabitants knew of no phosphate deposits on the island apart from that described above.

Onotoa (Fig. 27)

Onotoa (1° 47′ S, 175° 29′ E) is the southernmost of the true atolls in the Gilberts and lies in the dry belt. A very thorough investigation of the atoll was made by Cloud (1952), who recorded the presence of 'indurated, phosphatized (?) limesands.'

The localities at which these indurated sands occur are not shown on Cloud's map and they were not found by the present survey in the few hours that were spent here. It seems likely, however, that the indurated limesands referred to are indeed the crust of phosphatized sand seen on



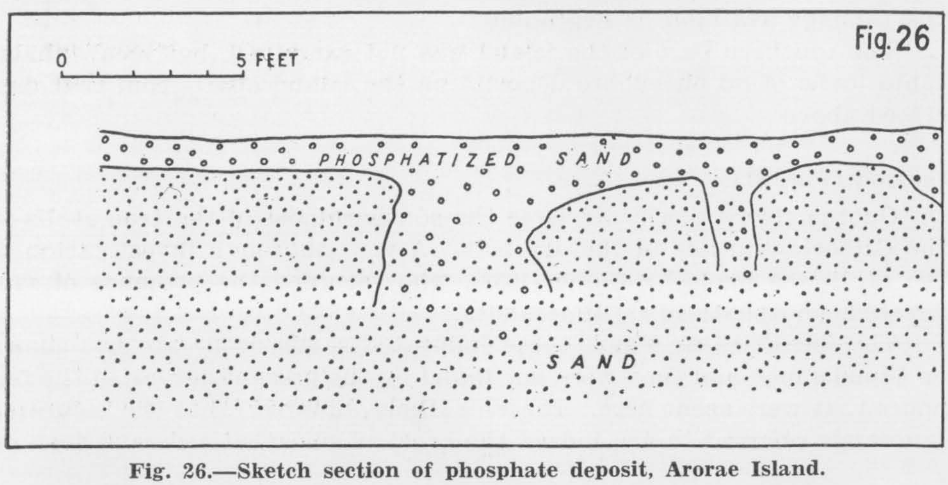
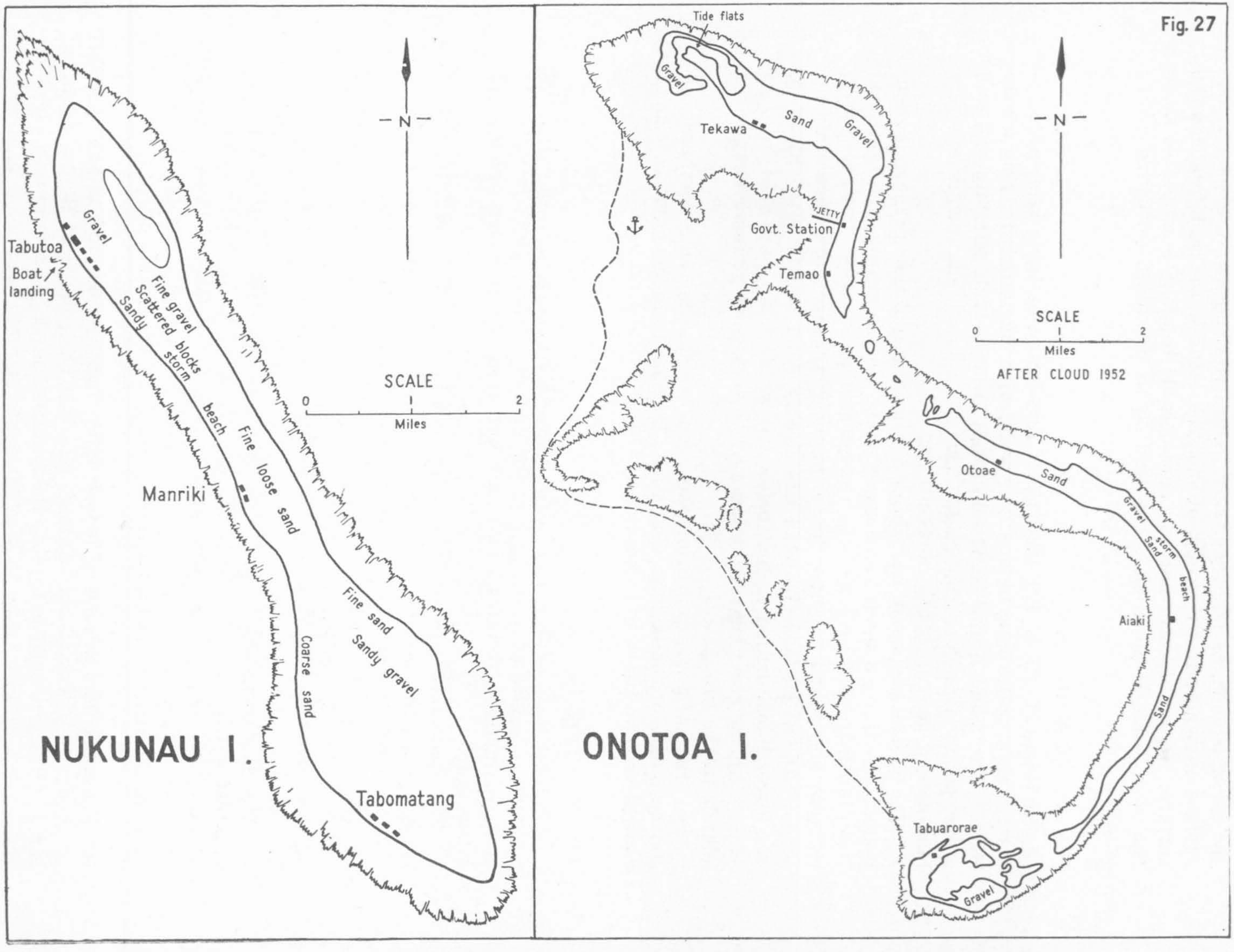


Fig. 26.—Sketch section of phosphate deposit, Arorae Island.



NUKUNAU I.
N
SCALE
0
1
2
Miles
Tabutoa
Boat landing
Gravel
Fine gravel
Scattered blocks
Sandy storm beach
Fine loose sand
Manriki
Fine sand
Sandy gravel
Coarse sand
Tabomatang
ONOTOA I.
Tide flats
Gravel
Tekawa
Sand
Gravel
JETTY
Govt. Station
Temao
SCALE
0
1
2
Miles
AFTER CLOUD 1952
Otoae
Sand
Gravel
Sand
storm beach
Aiaki
Sand
Tabuarorae
Gravel

Fig. 27

the other islands, as no other truly indurated deposits were seen at the surface anywhere in the group, except where the water table reaches the surface. It is unlikely that any considerable tonnage is available since the occurrence is apparently too limited to be shown on Cloud's very detailed map.

NUKUNAU (Fig. 27)

Nukunau (1° 20′ S, 176° 28′ E) is a reef island or table reef, approximately eight miles long by one mile wide, with the long axis lying northwest. The island is low-lying and sandy, with a wide fringing reef and a low, poorly defined storm-beach. There is a small, shallow, completely land-locked lagoon at the northern end.

The central section of the island, 5 miles south of the northern lagoon, is made up of loose sands and coral gravel. Coarse gravel with scattered large blocks of coral occurs near the government station, but gives way, towards the south, to fine, loose, slightly angular coral-foraminiferal sands. At the surface the sand has clearly been redistributed by wind, and auger holes drilled to just below the water table were still in loose sand ; this suggests that Nukunau may be somewhat younger than other islands in the group.

No trace of phosphatization was seen, but the extreme northern and southern ends of the islands, which may be older than the narrower sandy central section, were not examined.

TABITEUEA (Fig. 28)

Tabiteuea (1° 15′ S, 174° 45′ E, at Peacock Anchorage) is an elongated irregularly shaped atoll and one of the largest in the Gilbert Islands. It is approximately 30 miles long in a north-westerly direction and 6 to 12 miles wide.

The eastern (windward) reef is occupied by a great many small sandy islands, with the longer, but narrow, islands of Eanikai and Naguti at the northern and southern ends. The lee reef, which is entirely submerged, is close to the windward reef at the northern end, forming a long, narrow, shallow lagoon, but opens out towards the south to enclose a lagoon some 6 to 10 miles wide. There are two passes into the southern lagoon.

The northernmost island, Eanikai, is seven miles long and has a greatest width of half a mile. It is low-lying, with only a poorly defined storm-beach, and is made up of unconsolidated reef debris ; foraminiferal and shelly sand, coral sand and gravel, and, in the lower-lying parts, lime mud. At its northern end Eanikai sweeps round in a westerly direction to enclose the small shallow lagoon Te Kapuipui which, like the extensive flats around it, is floored by foetid lime mud and fine sand.

About half way along Eanikai, close by the village of Buota, there is a small deposit of the typical phosphatized sand. It occurs as a series of small low outcrops over an area 600 feet in diameter and has a maximum

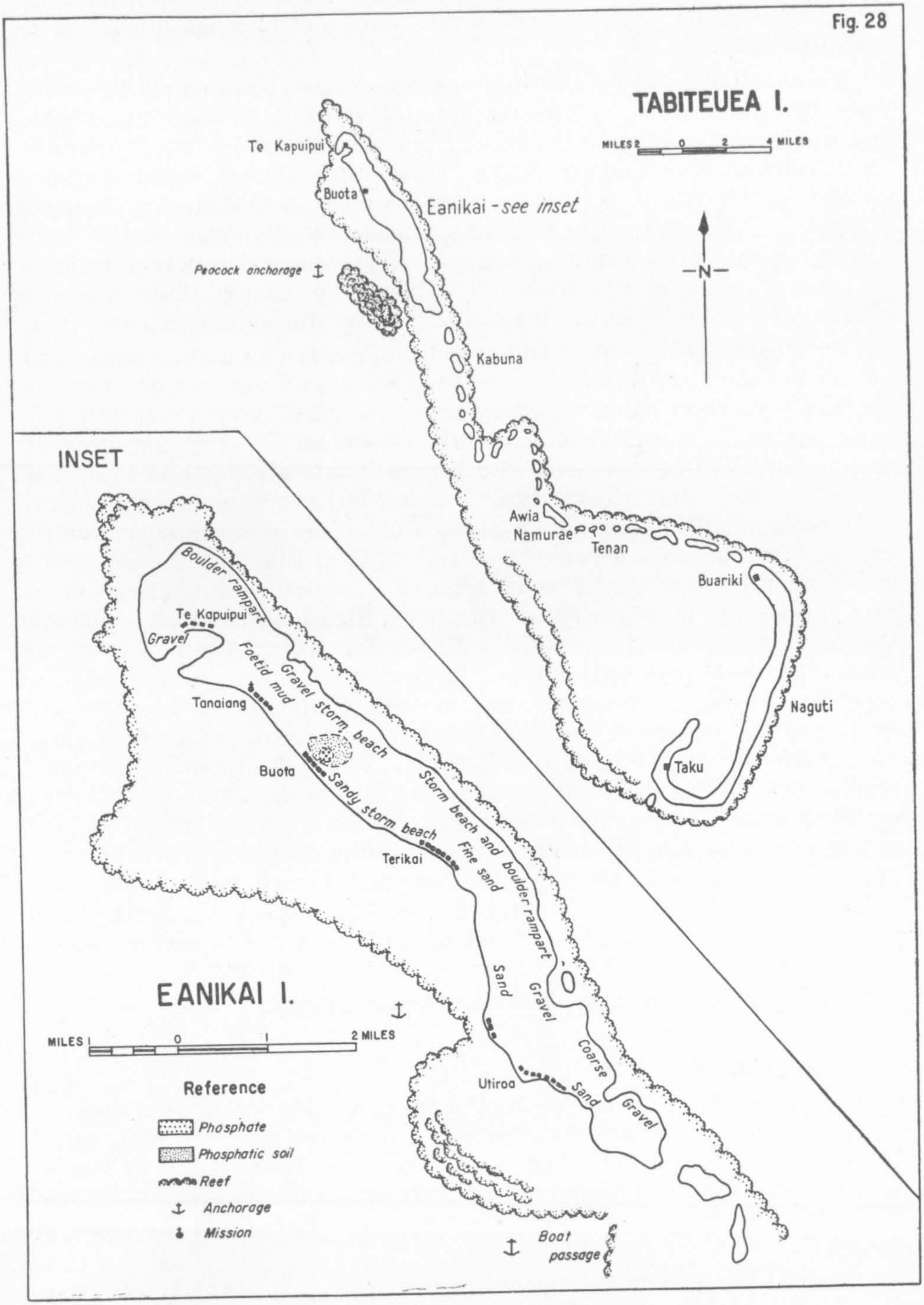


Fig. 28
TABITEUEA I.
MILES 2 0 2 4 MILES
N
Te Kapuipui
Buota
Eanikai - see inset
Peacock anchorage
Kabuna
Awia
Namurae
Tenan
Buariki
Naguti
Taku
INSET
Boulder rampart
Te Kapuipui
Gravel
Foetid mud
Gravel storm beach
Tanaiang
Buota
Sandy storm beach
Storm beach and boulder rampart
Fine sand
Terikai
Sand
Gravel
Coarse
Utiroa
Sand
Gravel
EANIKAI I.
MILES 1 0 1 2 MILES
Reference
Phosphate
Phosphatic soil
Reef
Anchorage
Mission
Boat passage

thickness of only 18 inches. The phosphate content as determined by field assays is 18% P_2O_5 and the total tonnage of phosphatic sand is of the order of 5000 tons.

Between the outcrops the unaltered loose sands are covered by a thin layer of black oolitic-looking humic soil which is weakly phosphatic and was probably derived, in part, from phosphatized sand. A similar black soil, also weakly phosphatic, extends for a considerable distance beyond the phosphate deposit and, at one point, was drilled to a depth of 5 feet. This soil appears to have a considerable influence on the vegetation and the cultivation of coconuts : the people of Eanikai claim that coconuts do not normally grow well at Buota, but that in times of severe drought Buota is the only village with a plentiful supply of nuts.

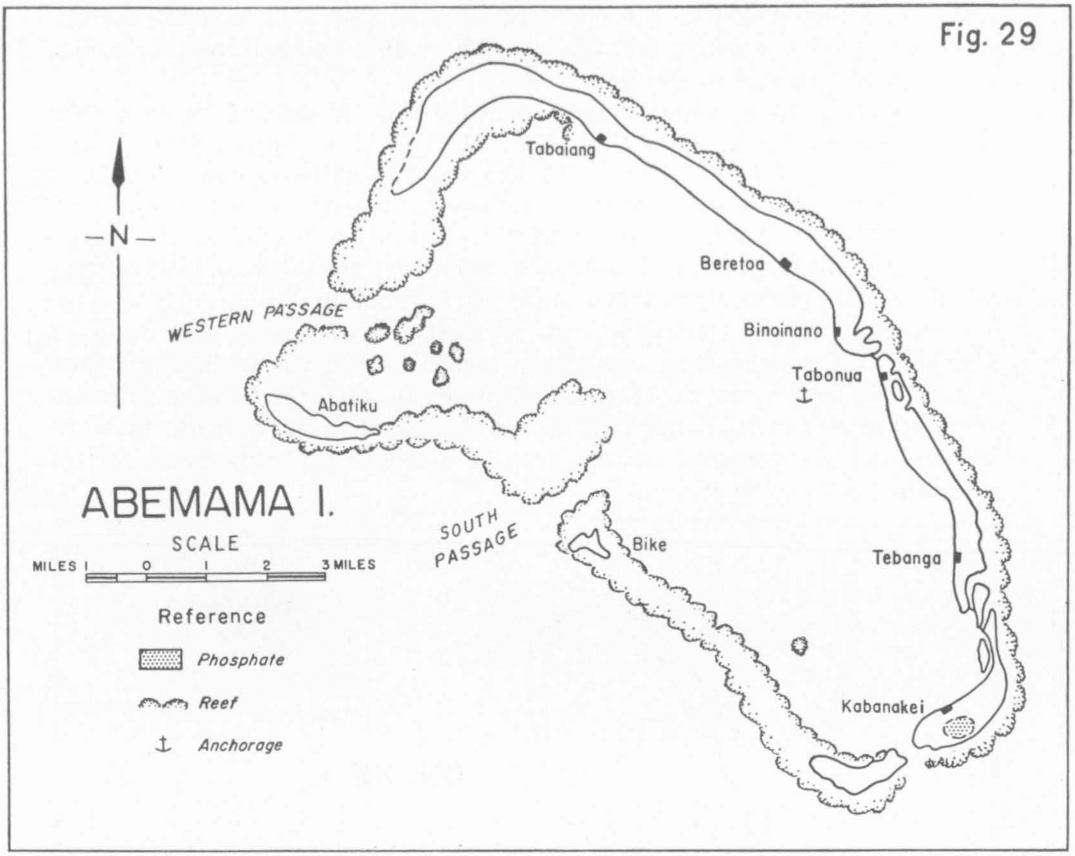
The chain of small islets to the south of Eanikai is mainly sandy and no trace of the typical phosphatized sand was found. On the uninhabited islets of Tenan and Namurae, however, just south of Aiwa about half way down the atoll, a small quantity of fresh guano is being deposited at present by breeding sea birds. Both these islets are flat and low-lying and are formed almost entirely of coarse coral debris without any soil. A few coconut palms have been planted but there is no intensive cultivation. On the eastern (windward) side of both islands there are small stands of large, spreading Pisonia trees (*P. grandis*?) in which large numbers of sea birds, chiefly noddies, with fewer frigate birds, roost. Beneath the trees the ground is carpeted with a thick spongy layer of black or darker brown humus containing a large proportion of guano. Pebbles, coral fragments, tree branches, etc., are commonly whitened by the bird droppings, but otherwise the deposit has the appearance of a normal acid humus deposit some 6 to 12 inches thick. Rough field assays, however, showed that the P_2O_5 content varied from 5% to nearly 20%. Distribution of the material is patchy, being thickest directly under the trees and thinning out to almost nothing between trees in much the same way that the thickness of the phosphatized sand deposit varies. The base of the deposits is sharp and clear, and there is no evidence of any replacement of the underlying coral gravel by phosphate. This may be partly due to the coarseness of the gravel and the dry climate.

The southernmost islet, Naguti, was not visited.

Abemama (Fig. 29)

Abemama (0° 23′ N, 173° 55′ E) is a roughly rectangular atoll approximately 15 miles long and 6 miles wide. A narrow strip of land, half a mile wide, occupies the reef on the eastern side, broken only by narrow shallow channels at Binoinano and Tebanga. Only two small islands, Bike and Abatiku, lie on the western reef, in which there are two ship passes.

Most of the land on the eastern reef consists of the typical loose foraminiferal and coral sands some 8 to 10 feet thick and resting on solid reef.



Close to the water table, which is seldom more than about 12 inches above sea level, the sand is commonly cemented to a coarse calcarenite.

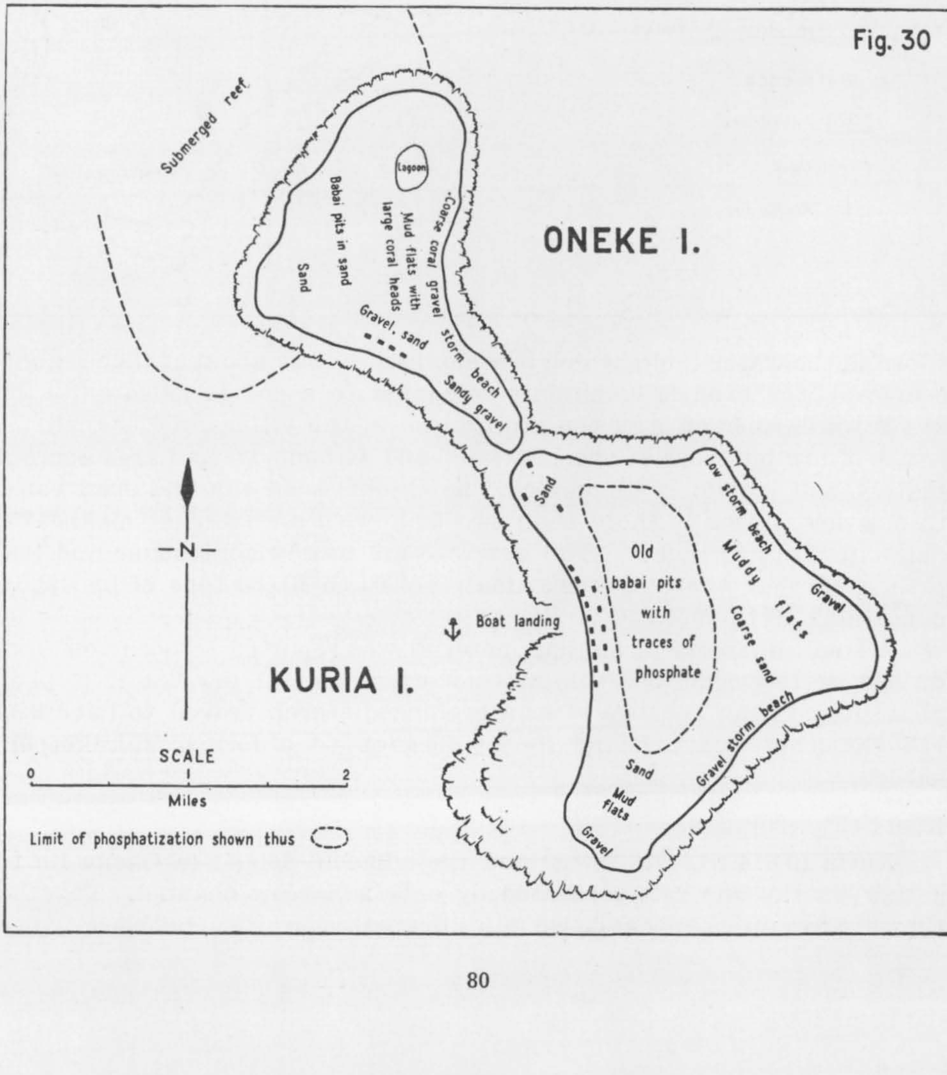
Towards the south of the atoll, close to the village of Kabanakei, a series of low outcrops of phosphatized sand extends over an area approximately half a mile in diameter. The thickness of this material varies from a few inches to more than two feet, with an average thickness of approximately 15 inches. The outcrops are nearly continuous and it is estimated that there is approximately 5000 to 10,000 tons of phosphate containing 15 to 20% P_2O_5.

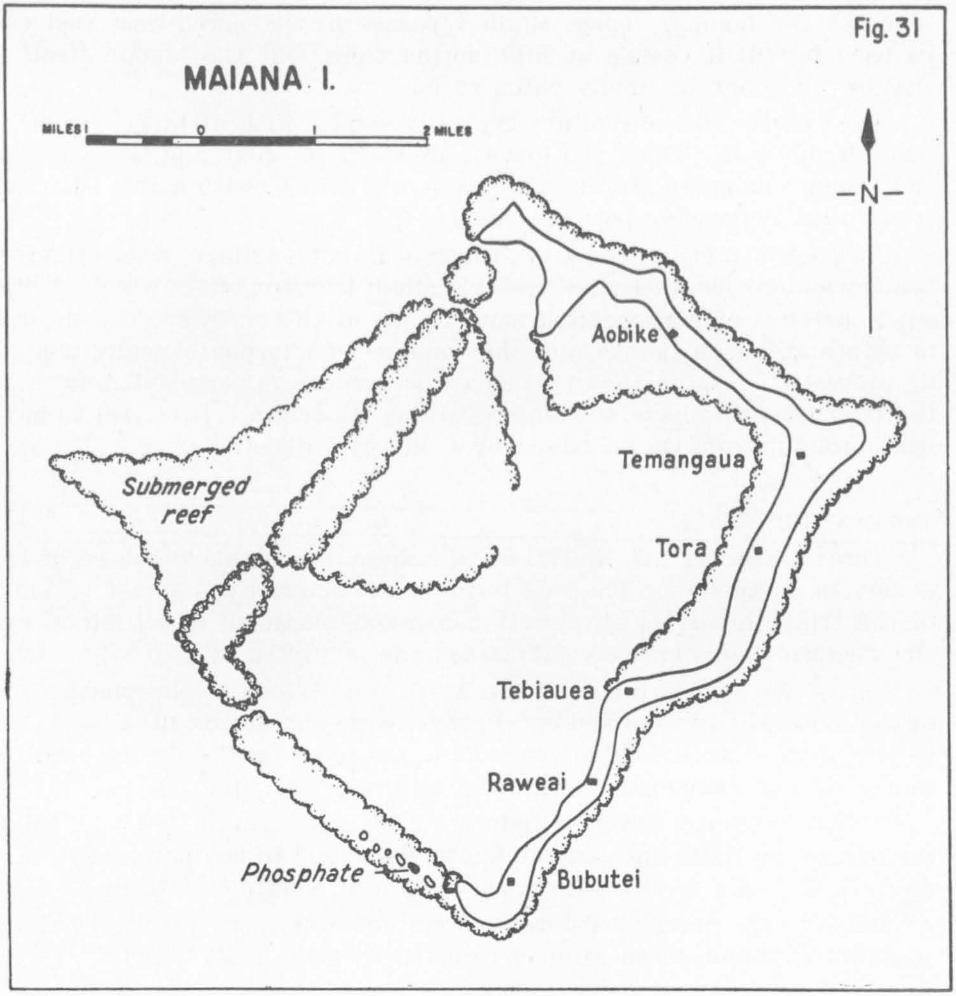
A small quantity of similar material was reported to occur on Bike, on the western side, but this was not examined. A few traces of phosphate found near Tebanga after a prolonged search proved to have been brought from Ocean Island for application to a former storekeeper's garden.

Kuria (Fig. 30)

Kuria (0° 14′ S, 173° 29′ E) and the adjacent island of Oneke lie together on the one reef separated by only a narrow channel. Together they are five miles long and two miles in greatest width. Both are typical reef islands, encircled by a broad storm-beach with a lower central area underlain by loose sands and gravel. There is a small brackish lagoon at the northern end of Oneke.

On Kuria, the southern island, a broad zone along the western side is entirely covered by old babai pits. Most of them have collapsed and are now partly filled in, and, with the mounds of loose sand dug from them, constitute a tract of hummocky country, barren except for clumps of salt-bush (*Scaevola*). Throughout this area many fragments and large blocks of phosphatized sand occur scattered over the surface, in the loose sand and in the pits. A few flat slabs of this rock are apparently *in situ*, and it seems likely that there was formerly an extensive thin crust of phosphatized sand over most of the western half of the island, but that it has been broken up, scattered, and mixed in with the sand during the excavation and subsequent infilling of the babai pits. The old pits are almost entirely confined to this area, which was probably more fertile than the rest of the island.





Possibly more than 10,000 tons of phosphate rocks formerly existed, but the amount now remaining in a recognisable form is negligible. Samples collected from loose blocks assayed 15 to 18% P_2O_5 and a brown humic soil from the sides of some pits and apparently derived from the phosphatic crust assayed 11% P_2O_5.

No trace of phosphatization could be found on the eastern half of Kuria or on Oneke.

MAIANA (Fig. 31)

Maiana atoll (1° 00′ N, 173° 01′ E) is rectangular, with the longer side lying north-east/south-west. The north-east and south-east sides of the rectangle are formed by a broad reef on which lies a continuous narrow strip of sandy land. On the north-west and south-west side the reef is awash at low tide and there is no break in the reef to allow ships to enter the lagoon. Three shallow passes in the north-west reef can be used by small vessels at high spring tides, but the lagoon itself is shallow and contains many patch reefs.

The islands on the reef are typically sandy, with a thin covering of black humic soil. There is a low storm-beach on ocean and lagoon sides, the former composed largely of coarse coral gravel, with a very shallow, trough-like depression between them.

At the south end of the atoll, south of Bubutei village, where the reef is abnormally wide, there is a cluster of small islets on one of which several small patches of phosphatized sand occur on the surface. The deposit is thin and discontinuous and the tonnage of phosphate negligible. It is interesting to note that this small occurrence is very well known to the islanders, who have a legend regarding its origin : it is said to have been brought from Ocean Island by a powerful ghost.

TARAWA (Fig. 32)

Tarawa atoll (1° 20′ N, 172° 55′ E), the administrative centre of the colony, is triangular. The reef forming the southern and eastern sides of the triangle carries an almost continuous chain of small islets, but the western side is entirely submerged and is broken by two ship-passes.

Along the southern side of the atoll some traces of phosphatization of the loose, shelly sand and coral gravel were noted near Bikenibeu, but the amount of phosphate is very small and much has probably been removed during the construction of babai pits, roads, etc.

A hard, compact layer of indurated fine lime sand a few feet below the surface on Betio islet and at Buota was found to be due to downward migration of oils used in the construction of wartime airstrips.

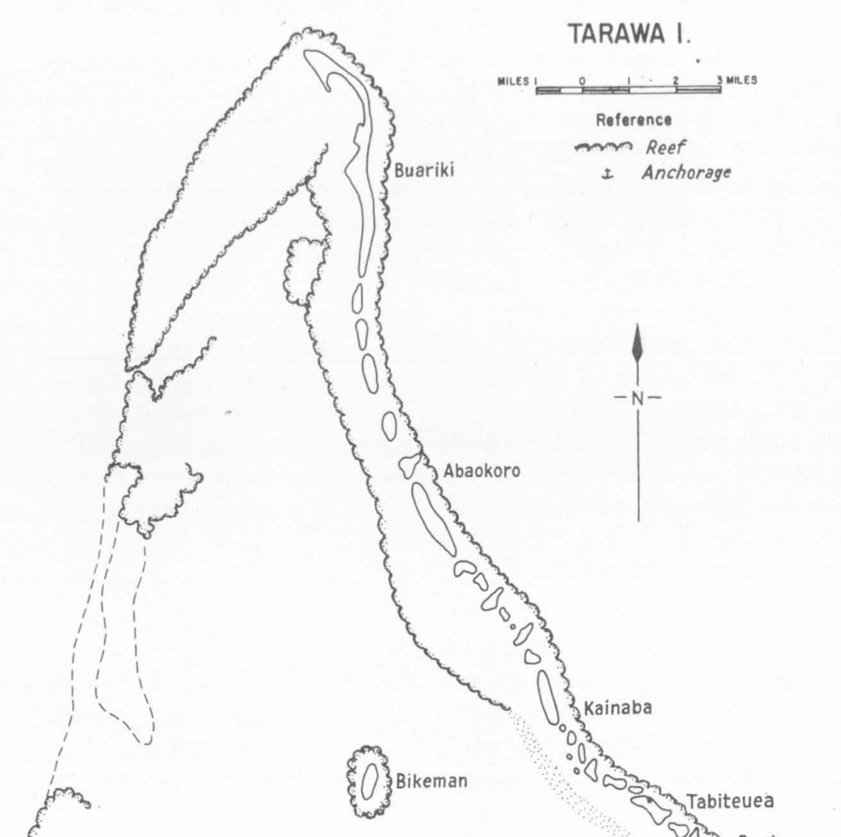
Islets to the north of Tabiteuea were not examined, but a very small amount of phosphatized sand is believed to exist near Buariki.

ABAIANG (Fig. 33)

Abaiang (1° 45′ N, 172° 59′ E) is a large, rectangular atoll, 16 miles long by 5 miles wide and elongated in a north-north-westerly direction. The wide reef on the eastern side is occupied by a continuous narrow strip of low-lying land formed of loose sand and coral gravel, stretching from the northern tip of the atoll to the southern boat passage, a distance of 20 miles. On the northern and western sides there are numerous small separate islands and many passes in the reef, several of which are navigable.

Less than two hours was spent on this atoll, and no phosphate was observed. Small deposits reported to occur on some of the small islands on the western reef are probably the typical surface crust of phosphatized sand. From the little that was seen of Abaiang and from questioning of the local inhabitants it is reasonably certain that no large deposits exist.

Fig. 32


TARAWA I.
MILES 1 0 1 2 3 MILES
Reference
Reef
Anchorage
N
Buariki
Abaokoro
Kainaba
Bikeman
Tabiteuea
Buota
Bonriki
Betio
Bairiki
Bikenibeu

Marakei (Fig. 33)

Marakei (2° 03′ N, 173° 25′ E) is a small pear-shaped atoll measuring approximately 5 miles by 3 miles. The narrow land rim is almost continuous, broken by only two very narrow channels which are dry at low tide. The seaward margin of the rim has a wide rampart of coarse coral debris, while the lagoon beach is commonly low and swampy with a long narrow inner lagoon parallel to the shore.

Phosphate occurs as a fairly widespread but discontinuous surface deposit on the southern part of the atoll. The phosphatized foraminiferal and shelly sand and sandy gravel forms several low outcrops 40 to 60 feet in diameter, but is more commonly represented by loose blocks and scattered boulders, the remnants of an originally continuous phosphatic crust. Traces of the phosphate rock are found for more than a mile along the atoll, but it is largely concentrated on the lagoon side and probably not more than 50,000 tons originally existed. Of this only a small fraction now remains and very little of this is recoverable. Samples of the phosphatized sand assayed 20% P_2O_5, but the overall grade must be considerably less owing to the great number of large unphosphatized coral fragments present.

A large number of sea birds (noddies and frigate birds) still roost on this part of the island, but no large concentrations of fresh nitrogenous guano are apparent nor is there any trace of contemporaneous phosphatization.

A small patch of phosphatized sand reported to occur near the northern end of the atoll was not examined.

Makin (Little Makin or Makin Meang) (Fig. 34)

Makin (3° 16′ N, 172° 58′ E), the most northerly of the Gilbert Islands, is separated from the large atoll of Butaritari by a channel little more than a mile wide. Together with the small islets of Kiebu and Onne it lies on a narrow north-north-east-trending reef that is virtually a continuation of the Butaritari reef.

Makin itself is a sandy reef island with slightly raised storm-beach round the periphery and a shallow saucer-shaped central area. There is a small enclosed lagoon at the northern end and much of the central area is swampy as a result of the excavation of very large shallow babai pits.

No phosphate was seen on Makin, but fragments of phosphatized sandy gravel which had been carried from Kiebu for the fertilization of gardens were examined. This material assayed 15 to 20% P_2O_5. It was reported to occur as scattered fragments and small surface patches. Time did not permit a visit to Kiebu.

Other Islands

Beru, Nonouti, and Aranuka could not be visited during the survey owing to lack of time and suitable transport. Butaritari was visited during the night, when no work was possible. All of these are low-lying

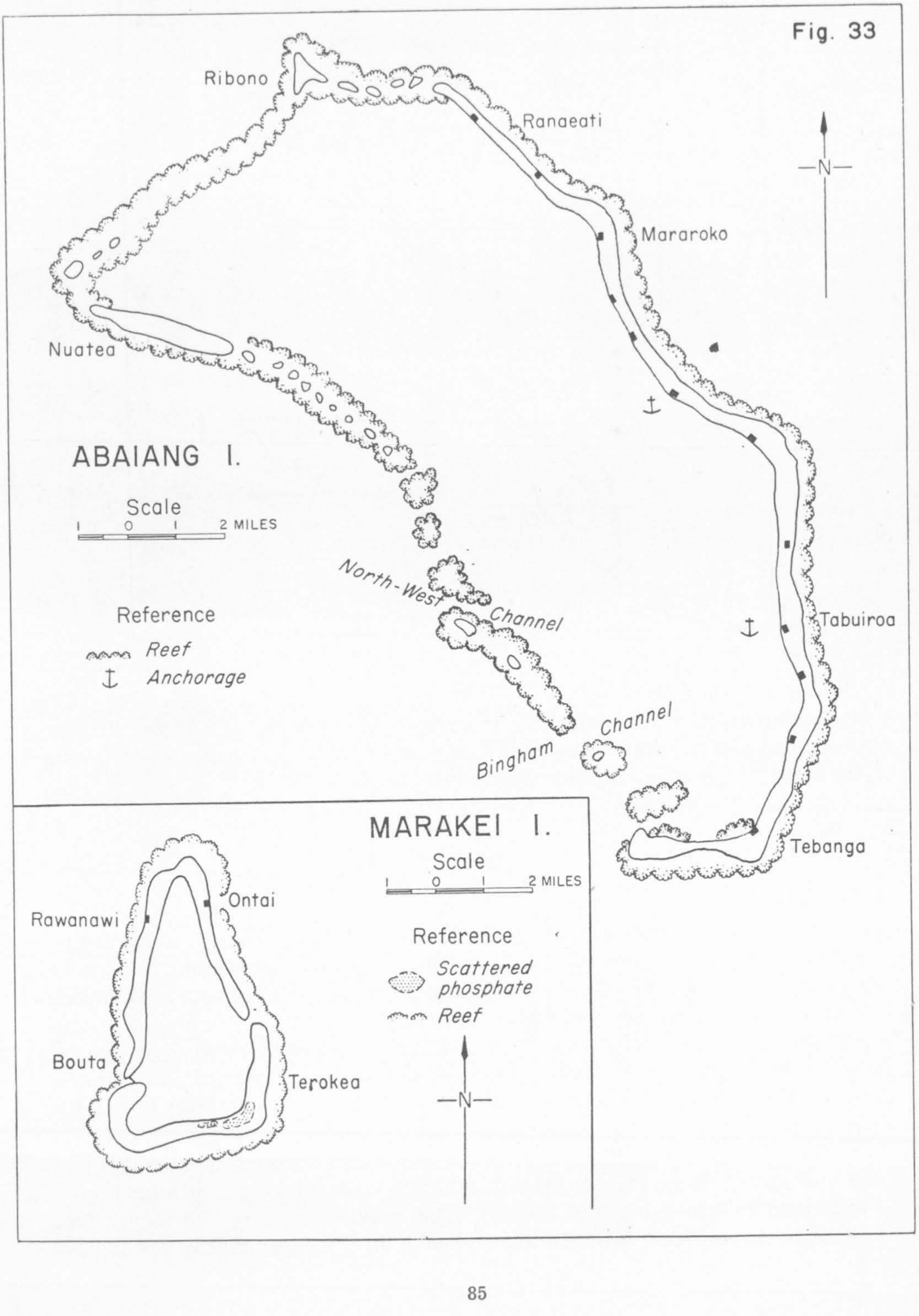
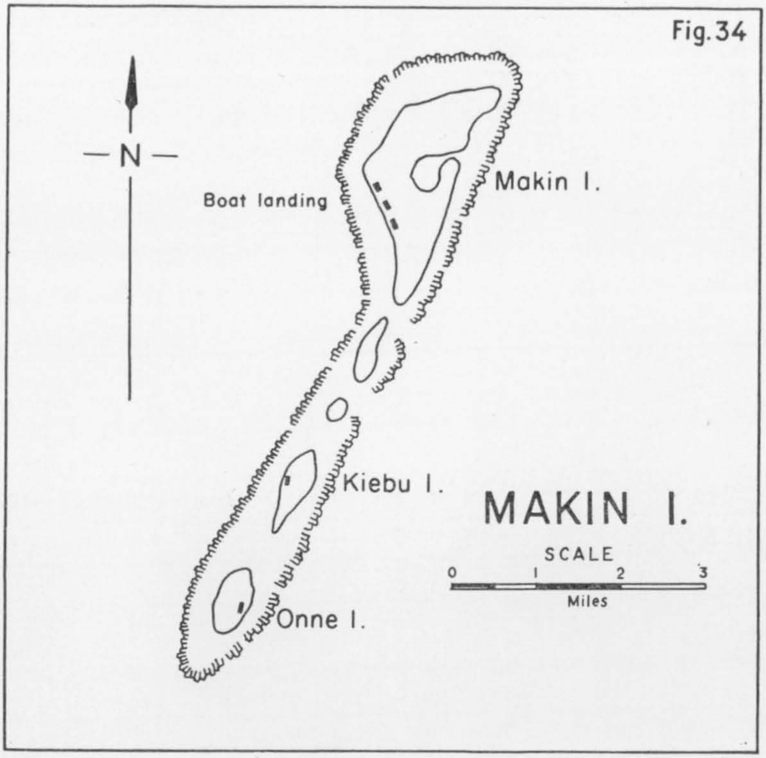


Fig. 33
Ribono
Ranaeati
Mararoko
Nuatea
N
ABAIANG I.
Scale
1 0 1 2 MILES
North-West
Channel
Reference
Reef
Anchorage
Tabuiroa
Bingham
Channel
Tebanga
MARAKEI I.
Scale
1 0 1 2 MILES
Ontai
Rawanawi
Reference
Scattered phosphate
Reef
Bouta
Terokea
N



atolls on which no deposits of any greater magnitude than those already described can be expected. Small deposits probably occur, but they are unlikely to be of economic importance.

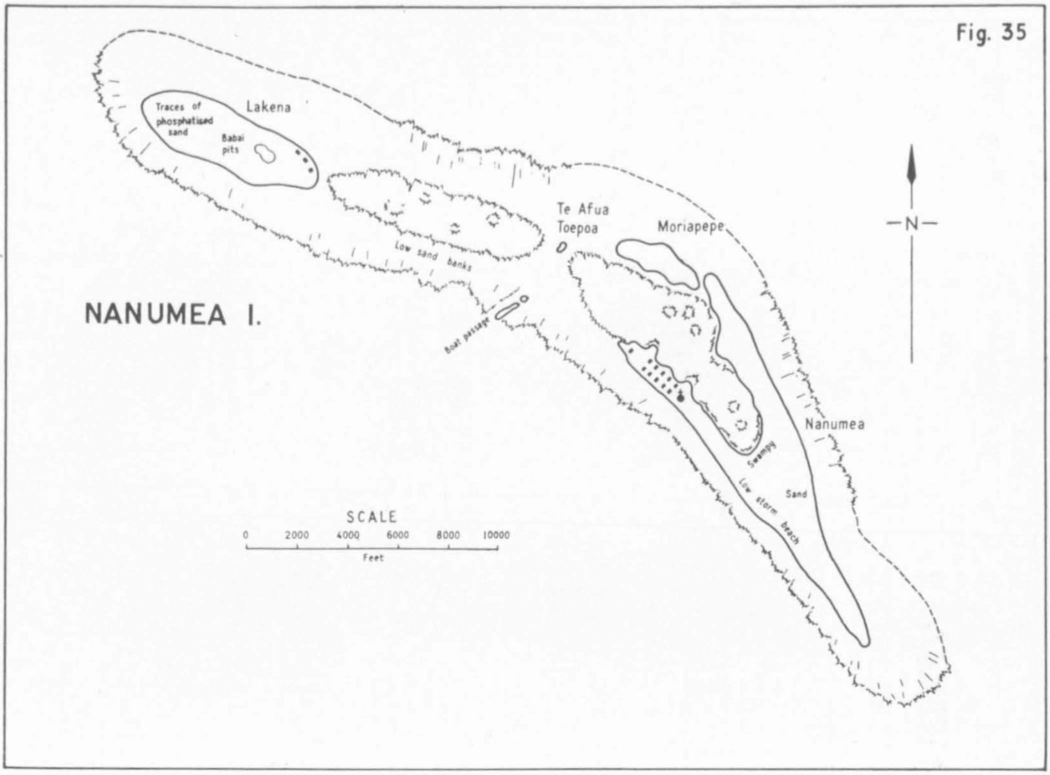
The Ellice Islands

Nanumea (Fig. 35)

Nanumea (5° 39′ S, 176° 06′ E) is the most northerly atoll in the Ellice Islands. It has a crescentic shape, with a very broad reef and a relatively small shallow lagoon. There are two main islands on the reef : Nanumea proper in the south and Lakena in the north. The reefs connecting them are exposed at low tide, and the westerly or lee reef is partly covered by low sandbanks. The central portion of the lagoon is shallow, with many patch reefs, some of which are dry at low tide. The entrance is narrow and difficult.

The main island, Nanumea, is V-shaped and forms the southern rim of the atoll. It is about three miles long and three-quarters of a mile wide and is low-lying and sandy. The maximum elevation of 12 feet above mean sea level is on the storm-beach on the ocean side of the island.

Fig. 35



The lagoon beach, inside the V, is shallow and muddy and shows evidence of rapid sedimentation by foraminiferal and shelly debris and by precipitation of lime mud.

Lakena, in the north, is oval, about 2 miles long, and contains a small freshwater lagoon. The island is sandy and is so studded with babai pits that little if any of the original surface of the island can be seen. Close to the small lagoon, however, traces of phosphatization, in the form of a few broken blocks and small fragments of phosphatized sand, were seen. Similar material is believed to have existed on Nanumea Island, but was destroyed by construction of the wartime airstrip.

Nanumunga (Fig. 36)

Nanumunga (6° 18′ S, 176° 20′ E) is a small table reef about a mile by a mile and a half in area, surrounded by a narrow unbroken fringing reef. Maximum elevation is approximately 14 feet above mean sea level, at the beach-crest on the western (lee) side, which is several feet higher than the windward beach-crest. From this encircling storm-beach the ground drops gently towards two small brackish-water lagoons near the centre.

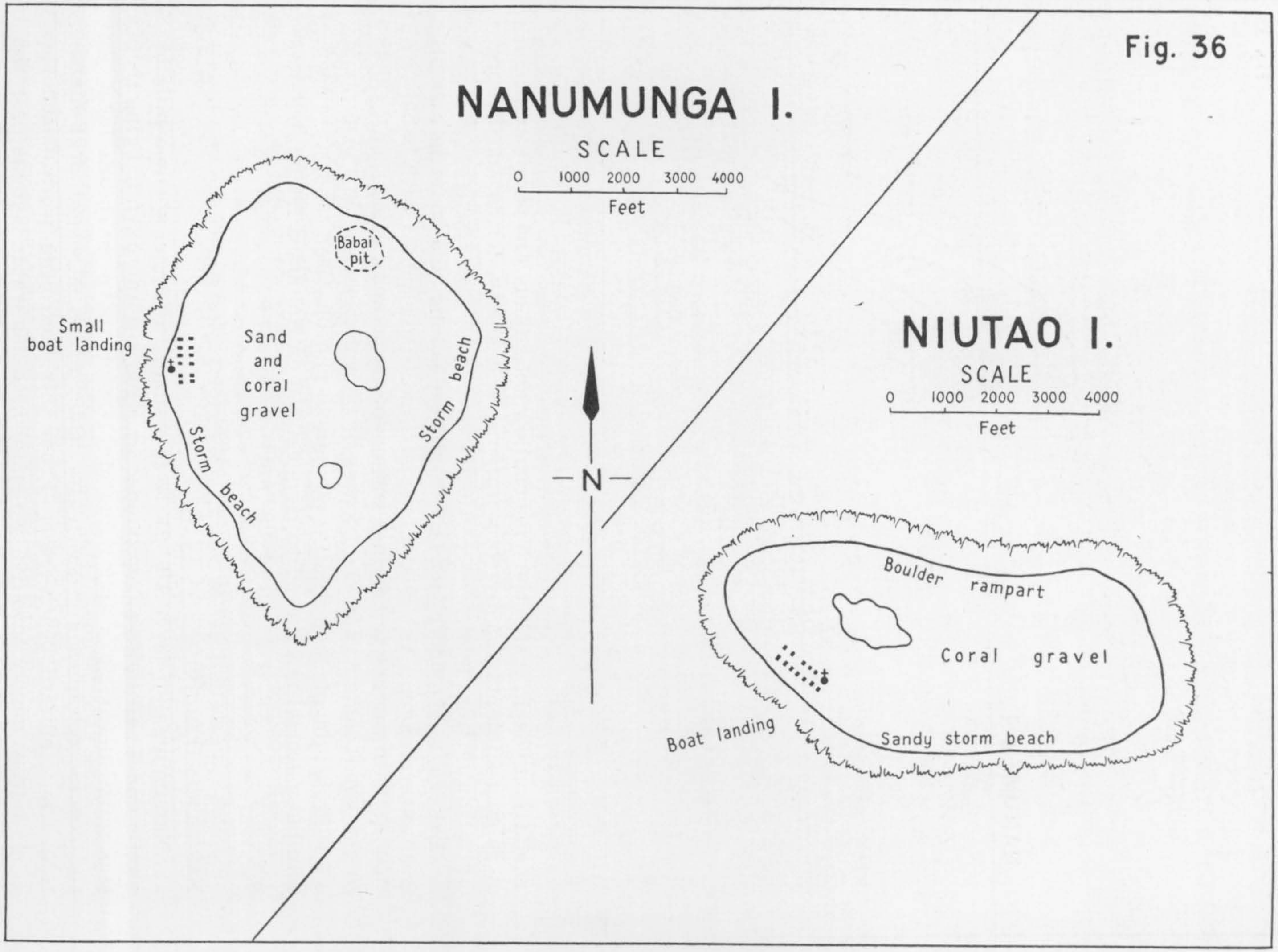

NANUMUNGA I.
SCALE
0 1000 2000 3000 4000
Feet
Babai pit
Small boat landing
Sand and coral gravel
Storm beach
Storm beach
N
NIUTAO I.
SCALE
0 1000 2000 3000 4000
Feet
Boulder rampart
Coral gravel
Boat landing
Sandy storm beach

Fig. 36

The island consists entirely of coarse loose coral and foraminiferal sands with infrequent gravel layers. Several auger holes were drilled to depths of 7 to 8 feet, below which the sand was too loose for further drilling. Sections in a large pit near the eastern shoreline show that loose sands, containing a high percentage of foraminiferal tests, continue to well below groundwater level and below the level of the present fringing reef, suggesting that this table reef was formed by filling up of the lagoon of a small atoll with calcareous sediments.

No indication of phosphatization was seen.

NIUTAO (Fig. 36)

Niutao (6° 06′ S, 177° 16′ E) is a triangular table reef a short distance to the east of Nanumunga, similarly surrounded by a narrow unbroken fringing reef, and encloses a small brackish-water lagoon. The flat centre of the island is floored almost entirely by coarse coral gravel with scattered large blocks of coral. In places there is a thin cover, 3 inches to 6 inches thick, of gravelly humic soil. No phosphate was found.

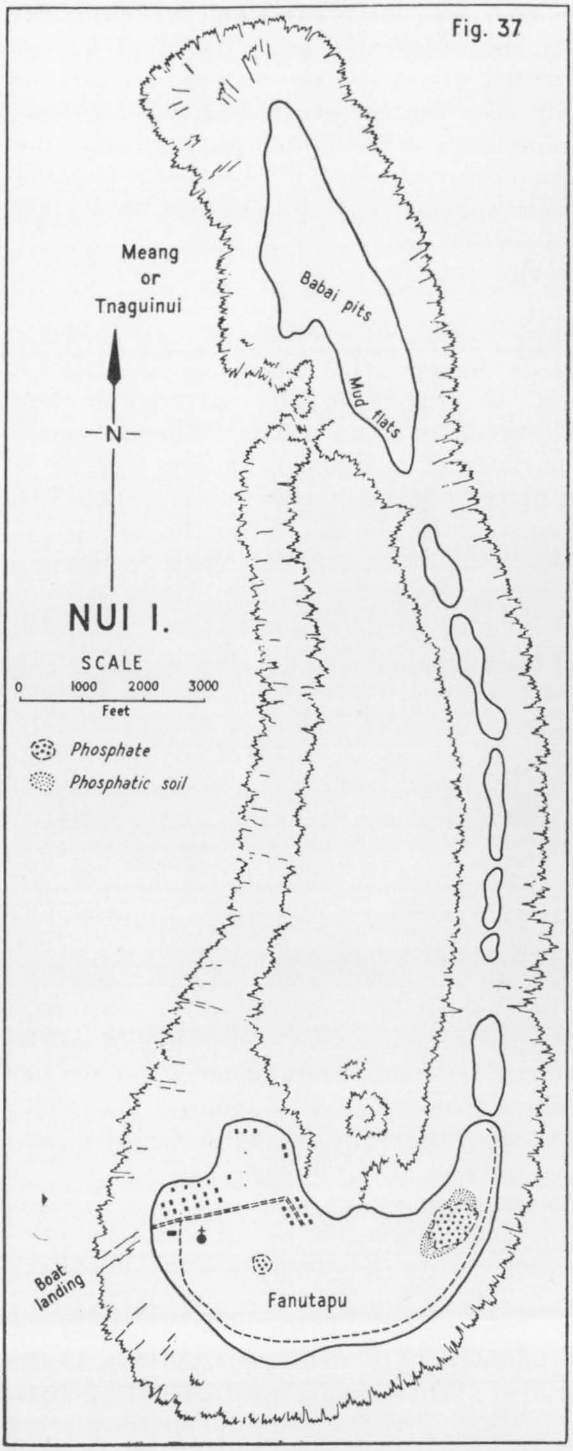
NUI (Fig. 37)

Nui atoll (7° 16′ S, 177° 10′ E) is crescentic and some three miles long by one mile wide. There are two main islands, situated at the north and south ends, with a chain of small islets strung out along the eastern reef. The western reef is awash at low tide, but supports several low sandbanks near the northern end. There is no entrance to the lagoon, which is shallow and contains many patch reefs, and shows evidence of infilling by deposition of calcareous debris and muds, particularly at the northern and southern ends.

Fanutapu, the largest island, is one and a half miles long and half a mile across at the widest point. It is roughly U-shaped, following the southern rim of the atoll. Maximum elevation is 14 feet at the beach crest on the ocean side, from where the surface slopes gently down to a low, indistinct storm beach on the lagoon shore.

In the centre of Fanutapu, some three-quarters of a mile east of the village, a small deposit of phosphatized sand occurs under a thick cover of 'salt-bush.' The material is the normal oolitic-looking phosphate formed by replacement of coarse foraminiferal sand and differs from the typical deposits on other islands only in that the base of the deposit is everywhere gradational into the underlying loose sands. This is thought to be due to the thick cover of natural vegetation, which keeps the phosphatized zone in a continually moist state that permits some downward leaching of the phosphate.

The deposit measures 300 feet by 250 feet and the average thickness is about 10 inches. Maximum thickness is 15 inches, but the base of the deposit is irregular and gradational. The tonnage available is approximately 3000, containing 10 to 15% P_2O_5. Traces of similar material were found in gravelly sand 300 yards to the south-east of the village church.

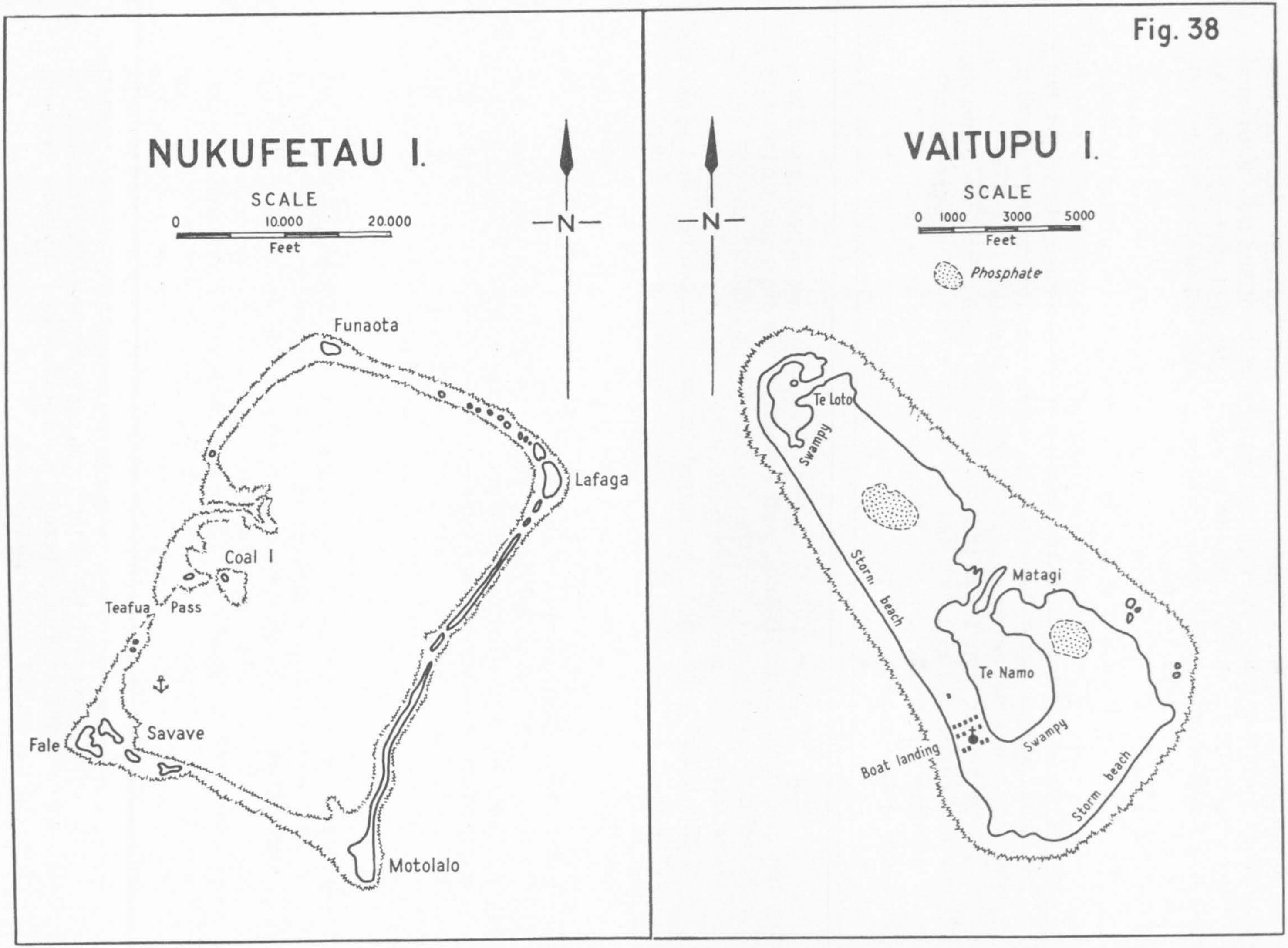


The islets along the eastern side of the atoll are all small and of relatively recent origin. Many of them are partly submerged and swampy at high spring tides. Meang, the larger island at the north end of the atoll, is completely covered by very large babai pits, many of them 100 to 200 yards across. Coarse sand and gravel dug up from the pits is heaped between them, and little of the original surface can be left. No phosphate other than that on Fanutapu was found.

Nukufetau (Fig. 38)

Nukufetau atoll (8° 00′ S, 178° 29′ E) is almost square in shape, with seven-mile sides and the diagonal lying north-south. A very narrow, almost continuous strip of land occupies most of the south-eastern side of the atoll, with a large number of separate small islets on the north-eastern and south-western sides. There is a good ships' passage into the lagoon on the western side, and a good anchorage off Te Anamu, the only inhabited islet.

Only two islets were examined. Te Anamu, at the western end of the atoll, is a low sandy islet almost entirely occupied by the village and adjacent babai pits. Coal Islet, a small sandbank near the entrance



NUKUFETAU I.
SCALE
0
10.000
20.000
Feet
N
Funaota
Lafaga
Coal I
Teafua
Pass
Savave
Fale
Motolalo
VAITUPU I.
SCALE
0 1000 3000 5000
Feet
Phosphate
N
Te Loto
Swampy
Storm beach
Matagi
Te Namo
Swampy
Boat landing
Storm beach

Fig. 38

to the lagoon, measures 1000 feet by 500 feet and is no more than 4 to 5 feet above mean sea level. Almost the entire surface of the islet is covered by a layer of phosphatized sand to an average depth of twelve inches. At the margins this passes laterally into a tough calcareous beach rock dipping gently down the beach.

The phosphatic crust is fairly uniform in appearance and, although the island has been lightly planted with coconuts, it is completely undisturbed. The gradation into beach rock at the edge of the island shows that there has been little, if any, erosion of the surface of the island, but phosphatization is nevertheless patchy, indicating that the original guano deposition was not uniform over the entire island.

Between 5000 and 10,000 tons of phosphatic material are probably present, containing 15% P_2O_5, but the patchy distribution, unpredictable thickness, and thin cover of black humus reduce any estimate to little more than a guess.

VAITUPU (Fig. 38)

Vaitupu (7° 30′ S, 178° 41′ E) is perhaps the most populous and productive of the Ellice Islands, and probably owes its high productivity as much to an extensive, but thin, covering of phosphatic material as to its relatively high and reliable rainfall.

The island is roughly pear-shaped, about 3½ by 2 miles, and is surrounded by a broad fringing reef over which landing can be difficult in bad weather. There are two small lagoons, Te Loto at the northern end and Te Namo to the south. Both are landlocked, with only a narrow shallow entrance across the reef to the east. Both are bordered by wide flats of fine calcareous debris and lime mud.

Most of the island consists of coarse to fine, loose coral and foraminiferal sands, coarsest on the low storm beach surrounding the island and grading into very fine material near the lagoon edge. In the centre of the island, about half way between the two lagoons, an area of approximately 75,000 square yards is covered with a thin crust of phosphatized sand. The material forms low blocky outcrops and is a few inches to 20 inches thick. The average grade as determined by field assay is 20% P_2O_5 and the total tonnage of phosphatic material is estimated at 25,000 tons.

In the south-east of the island, on the eastern shore of Te Namo, surface phosphatization is again apparent. It occurs over an area approximately 1000 feet in diameter and the average thickness is about 8 inches. The material is, on the whole, finer-grained and more compact than the other deposit, but contains much broken shell and fine coral gravel which is only partly phosphatized. The average grade for the bulk material is therefore lower at 10 to 15% P_2O_5. Estimated tonnage of this deposit is 10,000 tons, but as with the northerly deposit, not all of this would be recoverable owing to the shallowness of the deposit, the very variable thickness and patchy distribution, and the heavy growth of vegetation rooted in the phosphate.

Funafuti (Fig. 39)

Funafuti (8° 31′ S, 179° 12′ E) is the largest atoll in the Ellice group and geologically the best known, having been very fully described in ' The Atoll of Funafuti ' by Sollas, David, et al. (1904).

It is roughly pear-shaped, with the narrow end to the south. The lagoon, 10 miles long by 8 miles wide, is approximately 25 fathoms deep and can be entered by three ship-passes on the south-east and north sides. A chain of islets forms an almost continuous line on the eastward (windward) reef, but islets are more scattered on the lee reef. There are about 30 islets altogether, of which the largest, Funafuti, extends for seven miles.

Sollas, David, & Judd, in ' The Atoll of Funafuti ' described phosphatic material from several localities. Sollas recorded a phosphatic conglomerate on Amatuka Islet on the northern rim of the atoll in which coral pebbles up to 5 inches in diameter (average 1 inch) are cemented by a reddish brown phosphate. The rock was said to contain up to 26% calcium phosphate, the matrix carrying 32·5% and the pebbles 5·8%. Sollas believed that the deposit had originated by precipitation of guano solutions percolating down through the pebble bed.

The conglomerate crops out in a low cliff up to 5 feet above high water mark as two beds separated by lime sandstone, but no estimate of the tonnage has been given. A similarly coloured sandstone at Mateika was also thought to be phosphatic, but this does not seem to have been verified.

Samples of a dark brown rock from behind the mangrove swamp on Fongafale yielded 21·64% and 29·07% of calcium phosphate, while soils from the taro swamp near this point were found to contain 6% P_2O_5.

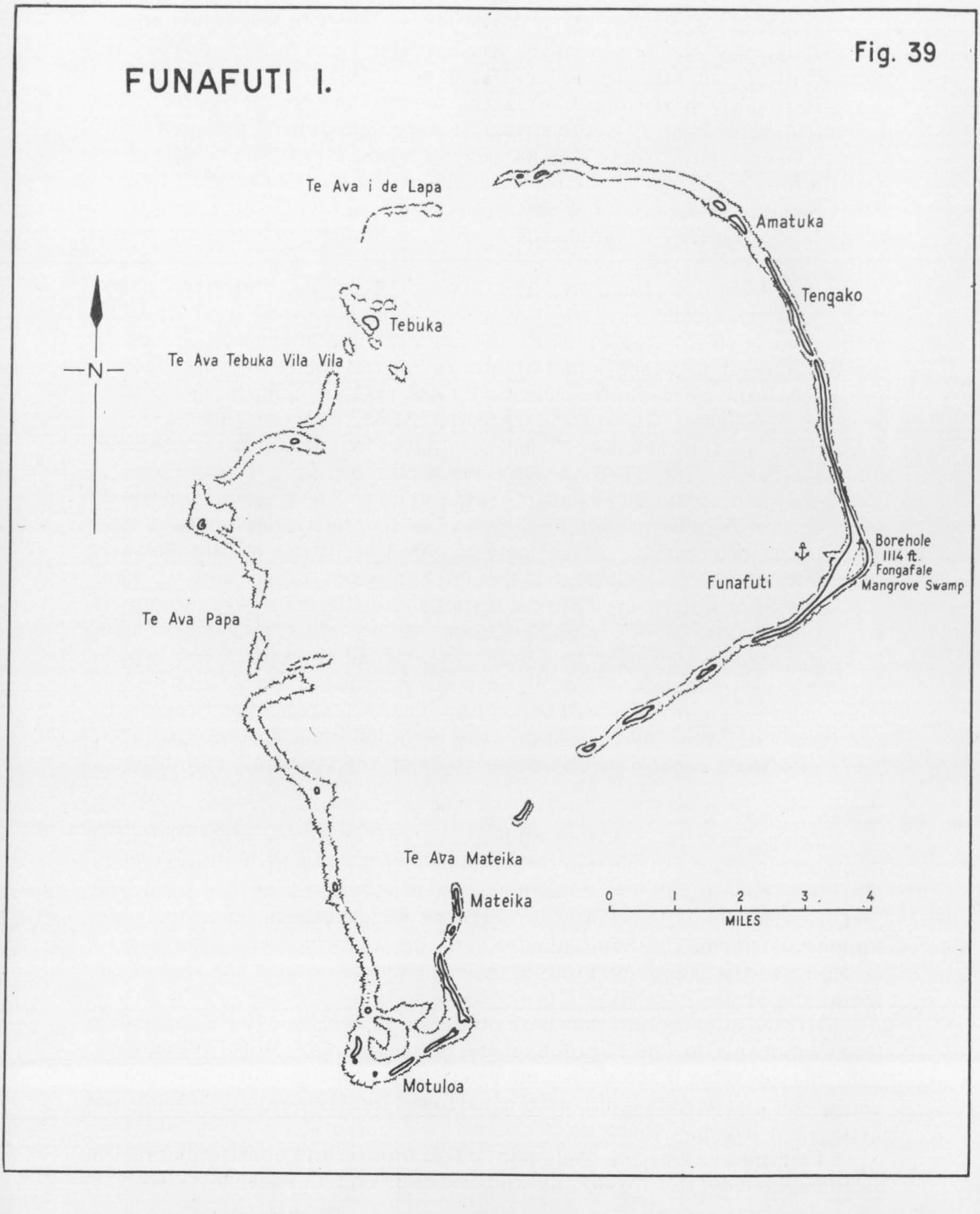
Our visit to Funafuti, lasting only a few hours, was too brief to get more than a general idea of the geology of the largest islet (Funafuti), and it was not possible to examine the recorded phosphate occurrences. The deposits do not, however, appear to be of any economic significance.

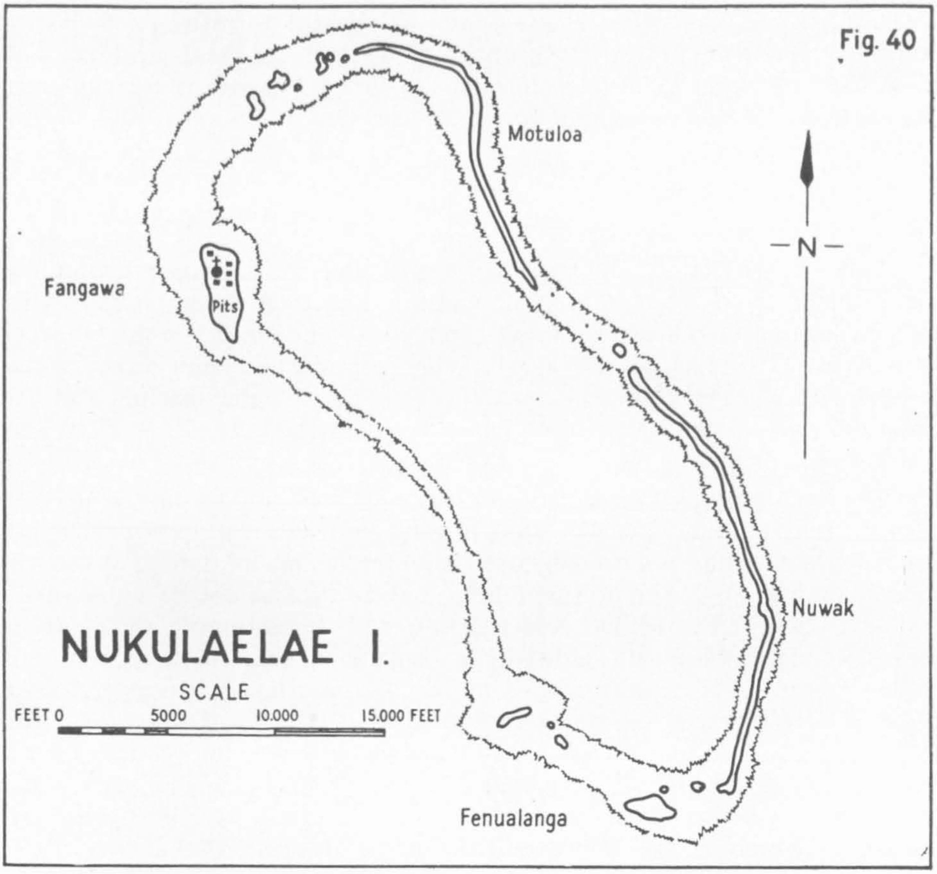
Nukulaelae (Fig. 40)

Nukulaelae (9° 22′ S, 179° 50′ E) is a long, rather narrow atoll elongated in a north-westerly direction, with dimensions 8 miles by 3 miles. There is a very narrow, almost continuous strip of land along the windward reef, several small islets at the northern and southern ends, and one, Fangawa, the only inhabited islet, on the western reef. There is no entrance to the lagoon and only a poor anchorage outside the reef in the lee of the atoll.

No trace of phosphate was seen on Fangawa, which is little more than a flat sandbank, nor on Motuloa on the northern side. Motuloa is a long, very narrow islet made up of low sandy and gravelly storm beaches on the ocean and lagoon sides with a narrow, slightly swampy trough-like depression between them.

The remainder of the atoll was not examined and questioning of the island people did not reveal any knowledge of typical phosphate deposits.


FUNAFUTI I.
Fig. 39
Te Ava i de Lapa
Amatuka
Tengako
Tebuka
Te Ava Tebuka Vila Vila
N
Borehole
1114 ft.
Fongafale
Mangrove Swamp
Funafuti
Te Ava Papa
Te Ava Mateika
Mateika
0
1
2
3
4
MILES
Motuloa



NUILAKITA

Nuilakita (10° 45′ S, 179° 30′ E), the most southerly of the Ellice Islands, was not visited. It is a low sandy island about 3 miles by 2 miles in extent on a low table reef. Guano is supposed to have been exploited on the island in the late nineteenth century, but no records have been preserved and it is believed that the deposit was worked out.

PHOSPHATE RESOURCES

The phosphate resources of the Gilbert and Ellice Islands (excluding Ocean Island) are small and too scattered to be of economic importance. Deposits occur on most of the Gilbert Islands and on several of the Ellice Islands, but in no case is either the tonnage or the grade of the phosphatic material sufficiently high to warrant commercial exploitation, particularly as handling and loading of the ore would be difficult.

The largest single deposit is on Tamana, where approximately 150,000 to 200,000 tons of material containing 15 to 20% P_2O_5 was originally present, of which probably less than half could now be recovered.

Small deposits of nitrogenous guano at present forming on islets on Tabiteuea and Nonouti might profitably be used on local gardens, but use of the relatively insoluble phosphatized sand deposits in gardens and babai pits would not repay the labour of breaking it up and transporting it even a few yards.

Origin of the Phosphate Deposits

There seems little doubt that the small phosphate deposits found in these islands are derived from avian guano. Features which point to this are localization of the deposits and their occurrence only on the surface, the nature of the phosphatic material, the irregular and sometimes gradational lower boundary and the patchiness of the phosphatization, and the presence beneath the deposits of loose, unconsolidated sediments of undoubted reef origin.

The only alternative source of the phosphatization is by marine deposition at a time when the islands were submerged to a considerable depth. Marine phosphorite deposits found on the ocean floor, notably on the continental shelf and on seamounts, have a typical oolitic appearance similar to that of the Gilbert and Ellice Island deposits (and to the great Ocean Island and Nauru deposits) and contain foraminiferal tests, many of which are replaced by calcium phosphate. The similarity of appearance is so great that a marine origin has frequently been suggested even for the Ocean Island deposit. However, when the Gilbert and Ellice Island material is examined it is clear that the oolitic appearance is largely due to the replacement, often only partial, of foraminiferal tests, the commonest of which is the reef-dwelling form *Calcarina*. Other reef foraminifera, fragments of shallow-water mollusca, and *Halimeda* and *Heliopora* debris are common, indicating that the phosphatized sand is a typical reef deposit. The underlying loose sand is made up of the same foraminifera and reef debris, and a typical profile or section across almost any of the deposits shows quite clearly, from the general distribution of sands and gravels, storm-beaches, and other conspicuous features in relation to the reef, that these sands have been deposited since the emergence of the reef and that they were not subsequently resubmerged.

Cloud (1953) has correlated the emergence of the reefs forming the Gilbert and Ellice Islands with a six-foot eustatic drop in sea level following the post-glacial climatic optimum some 3000 to 5000 years ago. Although no indisputable evidence of this recent change of sea level could be found, the evidence from other Pacific islands (e.g. Stearns, 1941, 1945 ; MacNeill, 1950 ; Cloud, 1953) strongly supports it and the phosphate deposits must be of relatively recent origin. The presence of considerable numbers of breeding seabirds in the vicinity of some of the phosphate deposits such as Marakei, Nui, and Vaitupu suggests that phosphatization may be continuing even now. The absence of deposits which are transitional between the common phosphatized sand and the small accumulation of fresh guano as on Tenan Islet, Tabiteuea, is a puzzling feature which may be explained by the completeness with which reaction between calcium carbonate and phosphoric acid takes place, particularly during the wetter periods. It seems probable that the water plays an active part in the reaction.

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OCEAN ISLAND AND NAURU ISLAND

BY

W. C. White

These two islands, which, together with Christmas Island in the Indian Ocean, have supplied most of Australia's phosphate requirements since the early part of the century, are the most important phosphatized islands in the Pacific. The original reserves, before exploitation, have been estimated at 90 million tons on Nauru and 20 million tons on Ocean Island. The grade of both deposits is between 38% and 40% P_2O_5 and the iron and aluminium content is very low. Both islands were examined very briefly during the present survey.

The phosphate deposits of Ocean and Nauru Islands have been very fully described by Owen (1923, 1927), Power (1905, 1925), and Elschner (1913, 1923) and their descriptions have been excellently summarized by Hutchinson (1950, pp. 214–222). Very little new evidence has been revealed by the extensive phosphate workings since then. The principal features of the islands and their phosphate deposits are as follows.

Ocean Island

The island is roughly elliptical, 1¾ miles long by 1½ miles wide, and rises to a height of about 250 feet above sea level. It is surrounded by an eroded reef flat, 100 yards wide, on the surface of which stumps of phosphate rock and the remains of limestone pinnacles can be recognised. A new fringing reef is developing at the outer edge of the eroded bench. Inside the reef flat the entire coast of the island, save at the south end, is formed by vertical cliffs 12 to 30 feet high.

The central part of the island at a height of about 250 feet is flat and may mark the site of a former very shallow lagoon. Removal of the phosphate has shown that the central plateau is surrounded by three broad terraces, which according to Owen (1923), dip to the south-east at an angle of 17 minutes. Over the entire surface of the island the coralline limestone, which fossil evidence shows to be post-Miocene and probably Pleistocene, has been dissected into pinnacles to form a Karrenfeld, and the pinnacles have been dolomitized. The pinnacles are tall, parallel-sided, and commonly fluted. Their walls are smooth and close to vertical, in contrast to the deeply pitted, rather conical-shaped pinnacle usually produced by normal sub-aerial erosion. Below the surface they are commonly joined together by an irregular wall of dolomitized limestone to form a series of tortuous ' septae ' similar to ridge and crevasse karst. The well rounded pits between the pinnacles may be as deep as 80 feet but are usually less than 50 ; many of the pinnacles are insecurely rooted and fall over when the phosphate has been removed from between them. The tops of the pinnacles form a remarkably level plane.

Practically the whole of the island is covered with a thick phosphate deposit which fills the deep pits between the limestone pinnacles and originally covered all the pinnacles except at the edges of the terraces. There are two main types of phosphate, which Power termed alluvial and rock phosphate, but which Owen renamed incoherent and coherent. Coherent phosphate consists of translucent and amorphous tricalcium phosphate deposited in cracks and cavities, irregularly distributed blocks of phosphatized limestone, and, rarely, phosphatized limestone pinnacles. Incoherent phosphate, which makes up the bulk of the deposit, comprises small phosphatized limestone fragments and reef debris, and fine phosphate dust. The reef debris includes fine fragments of coral and coralline algae, shell fragments and clearly recognisable foraminiferal tests, and pisolitic and pseudo-oolitic grains. The phosphate dust was believed by Owen to be derived mainly from the insoluble residues of the original guano.

The deposit is found generally to be thickest in the centre of the island ; Owen claimed that the variation in thickness away from the centre of the island was very regular and that in any one locality the phosphate content did not vary more than 1% between the top and the bottom of the deposit. The phosphate content of the whole deposit ranges from 36% to 42% P_2O_5.

NAURU ISLAND

The Nauru deposit is essentially similar to the Ocean Island deposit. The island is elliptical, measuring about 3¾ miles by 3 miles and rising to a maximum height of a little over 200 feet above sea level. It is surrounded by a fringing reef flat up to 300 yards wide and a narrow coastal plain. The interior of the island rises suddenly from the coastal plain to a central plateau at about 215 feet above sea level. The highest point, on the south-west corner, overlooks a deep depression containing a shallow lake which is thought to represent a former atoll lagoon.

The entire central plateau is dissected to form a Karrenfeld, but the pits between the pinnacles are nowhere as deep as those on Ocean Island. On the south-western part of the island the pinnacles are inclined as much as 20° to the north-east.

The pinnacles are dolomitized and the phosphate occurs in pits up to 40 feet deep between them. The phosphate, containing 37% to 40% P_2O_5 and less than ½% $(FeAl)_2O_3$, is almost identical with Ocean Island material, although there is generally rather less coherent phosphate.

Dolomitized pinnacles within the tidal zone on the coastal plain and tubular stumps of phosphate rock on the reef flats indicate that there has been slight recent submergence, but there are no well marked elevated terraces.

CHRISTMAS ISLAND

BY

O. N. Warin

During November 1957 Warin paid a brief visit to Christmas Island, Indian Ocean, as the guest of the British Phosphate Commissioners, who are quarrying the extensive phosphate deposits of the island. The purpose of the visit was to study the phosphate occurrences and the methods of exploration drilling employed on the island in preparation for the search of islands in the Pacific. The Commissioners asked that the island should be examined geologically to see if any other mineral prospects exist.

History of Exploration

The first landing of which we have a record was made by Dampier in 1688, and nothing further was recorded until the visit in 1886 of the *Flying Fish* under the command of Captain Maclear and a year later of H.M.S. *Egeria*, Captain Pelham-Aldrich. Specimens collected by Captain Pelham-Aldrich were examined by Sir John Murray of the British Museum. He recognised some of the specimens as phosphate rock and, realizing the importance of the discovery, he informed the British Government. The island was annexed in the following year by the British Crown and a settlement was founded on the previously uninhabited island by Mr G. Clunies-Ross, the brother of Mr Andrew Clunies-Ross of Cocos Island. Sir John Murray remained interested in the exploration of the island as an example of an oceanic type, and under a grant from him Mr W. C. Andrews, also of the British Museum, undertook a study of the island in 1897. The results of Andrews' work were published as a monograph in 1900.

More recently the phosphate deposits of the island have been quarried ; first by the Christmas Island Phosphate Company and subsequently by the British Phosphate Commissioners as managing agents for the Christmas Island Phosphate Commission, the body appointed by the Australian and New Zealand Governments when they acquired the undertaking on 1st January 1949.

The island was under the control of the Straits Settlement Government, with a resident District Officer from Singapore, until 1957, when the island became a Territory administered by Australia.

Position and Size

Christmas Island is in a particularly isolated position 190 miles south of the south coast of Java and 900 miles from the north-west coast of Australia. The nearest islands are the Cocos-Keeling group 550 miles away in a direction a little to the south of west.

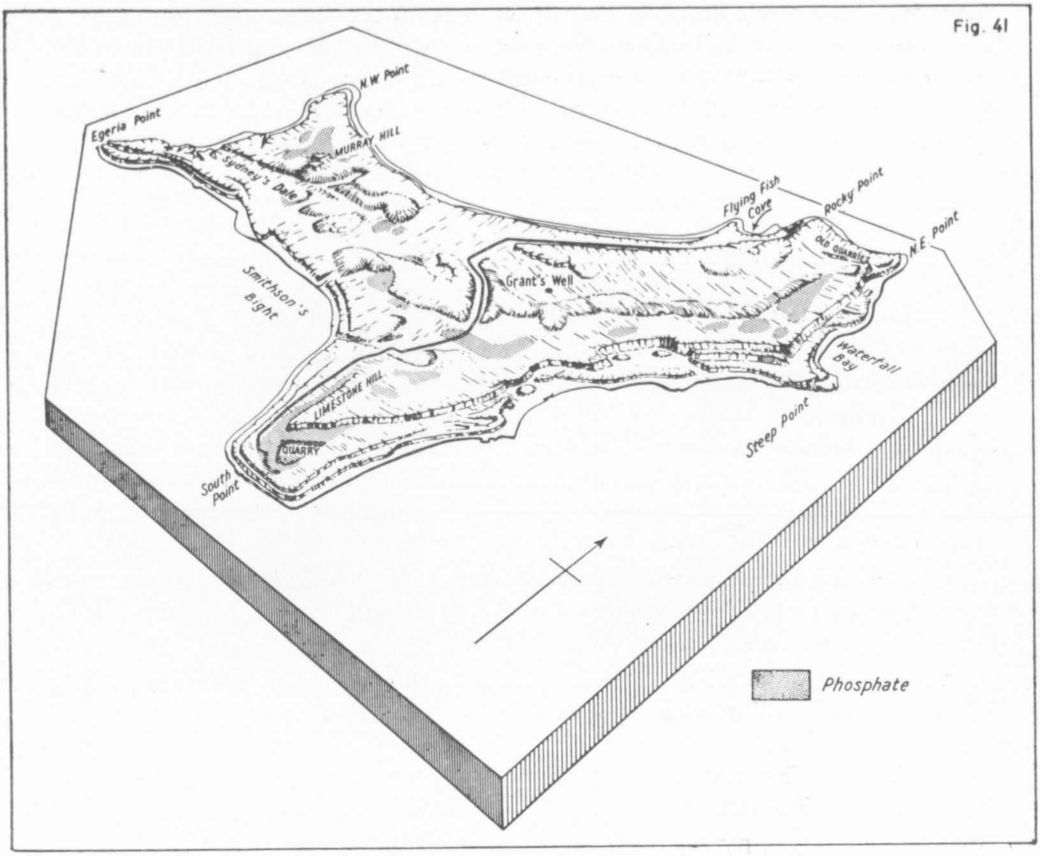


Fig. 41.—Physiography of Christmas Island.

The island is 55 square miles in area and is shaped roughly like the outline of the letter 'T.' The stem of the 'T' runs from east to west and is 9 miles long, and the cross bar of the 'T' is from north to south and is 11 miles long.

PHYSIOGRAPHY (Fig. 41)

The island rises in a series of wave-cut terraces and cliffs to a height of 1000 feet above sea level. The Maclear Deep, to the north, and the Wharton Deep, to the south and south-west, are both more than three miles deep.

The most constant of the terraces is the first shore terrace, which varies from rather less than 100 yards to half a mile wide and represents a relative fall in sea level of some 50 feet. The cliff on its seaward edge is an almost unbroken feature of the island's coast and makes landing along most of the coast very difficult. From the sea cliffs the profile slopes gradually up to the foot of the first inland cliff, some 150 to 300 feet high, with wave-cut notches and caves at its foot. Less continuous cliffs and terraces occur at higher levels until the central plateau is reached. The plateau is slightly saucer-shaped, rising towards its eastern margin along the line joining Phosphate Hill and Limestone Hill and towards its western margin at Murray Hill, though the area to the east of Murray Hill is more dissected, and the physiography is not so clear. The highest hills are a little more than 1000 feet above sea level.

General Geology

The island is built up on a core of volcanic rocks rising precipitously from 14,000 feet below sea level. The oldest sedimentary rocks are the Eocene foraminiferal limestone which rests on the Lower Volcanic Series of alkali-trachyte, trachybasalts, olivine basalt, limburgite, and probably nepheline basanite (Campbell-Smith, 1926). The Eocene limestone is succeeded by the Upper Volcanic Series of submarine basalt and limburgitic basalt flows and palagonite tuff, followed by the orbitoidal Miocene limestone which makes up the main mass of the island.

In post-Miocene times detrital limestone and lagoon limestone were deposited, after which a series of relative falls of sea level have given the island its present terraced structure.

The succession at Flying Fish Cove is as follows (after Andrews, 1900) :

Upper Orbitoidal Limestone	160 feet
Upper Volcanic Series	180 feet
Yellow (Eocene) Limestone	60–140 feet
Lower Volcanic Series	200 feet +

A major fault, striking slightly south of west, runs right across the island from Gladys' Beach on the east coast to Sydney's Dale on the west. It cuts all the rocks on the island except the limestones on the first or 50-foot inland terrace.

Palaeontology

During his 1899 survey Andrews collected specimens of limestone containing molluscs, corals, and foraminifera.

All the molluscs he collected were modern. The fossil corals (examined by Dr J. W. Gregory) were mostly Astreans, all reef builders, and none reckoned to grow at depths greater than six to eight fathoms. Dr Gregory identified twelve species of Astreans, three of Perforata, one of Fungida, and one species of *Pocillopora*.

The Foraminifera collected by Andrews were of particular interest. They were mostly *Orbitoides*, and therefore he assigned a Miocene age to his upper or C limestone. *Discocyclina oceanica* from the limestone exposed beneath the Upper Volcanic sequence at Flying Fish Cove indicated an Eocene age for the Lower Limestone (Andrews, 1900 ; Nuttal, 1926).

With more recent work on the Foraminifera of the Indo-Pacific region a great need has arisen for the re-determination and re-description of the *Orbitoides* of Christmas Island. Unfortunately I was unaware of this at the time of my visit, and collected widely from localities not visited by Andrews, mostly on the higher land of the island, and ignored the older localities. The specimens collected have almost all proved to be altered recent limestones without Foraminifera of assistance in solving the problem of the *Orbitoides*.

The Phosphate Deposits

The distribution of the phosphate deposits is shown in a generalized way on the physiographic diagram (Fig. 41). The boundaries of the deposits are taken from exploration maps and represent areas where enough phosphate is thought to exist to make quarrying possible ; they are not precise.

The deposits of Christmas Island are very similar to those of Ocean Island and Nauru. They occur as thick blankets, mainly of oolitic and pisolitic phosphate, over a deeply etched limestone surface. The phosphate varies from white through buff to brown, depending on the amount of iron oxide and alumina present. These sesquioxides seem to be mainly present in the clay-size fraction of the phosphate, which forms a fine dust when the phosphate is dried and a sticky clay when wet. The upper levels of the phosphate are contaminated with soil and are termed ' overburden '; there is commonly a well-marked transition to higher-grade, whiter phosphate towards the base of the deposit. There are large deposits of pebble phosphate on the island, particularly at the west side of the main South Point quarries. The pebbles are commonly about two inches in diameter and have the typical smooth, undulating surface.

The contact between the phosphate and the underlying limestone was very well exposed at the time of my visit in a limestone quarry at South Point. The limestone is being quarried from beneath the old phosphate quarry and the work is exposing residual phosphate left at the foot of the limestone pinnacles. The pisolitic and oolitic phosphate is fairly close-packed and appears bedded; between it and the limestone there is a layer of vuggy, open, whiter incoherent fragmental phosphate which crumbles when disturbed. Cracks in the limestone pinnacles are filled with coherent phosphate and the porous, vuggy incoherent phosphate appears to have formed first as crack-fillings and perhaps by replacement of the limestone. Subsequently the limestone itself has been dissolved out by ground water leaving an insecure open ' boxwork ' of phosphate.

Besides filling cracks, coherent phosphate also occurs on Christmas Island as larger masses of phosphatized limestone, commonly with the macrostructure of coral preserved. Coherent phosphate also occurs as boulders at the surface deposits, over which it appears at some time to have formed a crust. The coherent phosphate of these boulders is clearly banded and individual bands may be strongly oolitic. The colour is commonly white, grey, or pale buff but may be brown or pale green. In thin sections parts of this coherent phosphate which appear homogeneous are found to be made of oolites with a cement of dahllite or collophane.

There are no deposits along the north side of the island, and none at levels below 600 feet, although phosphate from upper terraces has been washed over on to lower levels in some places. This distribution of the deposits may be due to two factors : (1) the height of the island above sea level at the time that it was colonized by birds and (2) the direction of the prevailing wind. If the island has emerged by about 600 feet since the phosphate was formed the vertical distribution of the phosphate is simply explained. As for the areal distribution at the present time, the nesting sites chosen by the Guanay flocks on the Peruvian islands are controlled by the direction of the prevailing winds, the birds preferring the windward side of the island—probably because of the lower ground temperature (Hutchinson, 1950, p. 15).

THE FIJI ISLANDS—THE LAU GROUP

BY

O. N. Warin

The Lau Group comprises about 100 small islands that make up the eastern part of Fiji (Pl. 5). The largest of the Lau islands, Vanua Balavu, is about 24 square miles in area ; the smallest islets are less than ½ square mile. Twenty islands in the Lau group were visited, of which five are uninhabited. The visits to all the islands were brief. Three or four days were spent on the islands known to have phosphate deposits ; but some islands were only visited for a few hours. Six islands—Vanua Vatu, Ogea Driki, Tuvuca, Vatoa, Vatu Vara, and Marabo—proved to contain phosphate. The survey took two months from 18th June to 19th August 1959, with a brief return visit to two islands from 21st to 25th October.

The climate of the Lau group is normally equable. The Lau islands, unlike the main islands of Fiji, are not high enough to affect the amount of rain to any degree.

The Geology of the Lau

The geology of the Lau has been investigated by Ladd & Hoffmeister (1945). Previous authors who have visited the Lau include Dana (1890), Gardiner (1898, 1931), Agassiz (1898), Andrews (1922), Davis (1927), and Foye (1917) ; all of whom were principally interested in the coral reef problem.

The six formations which Ladd & Hoffmeister were able to recognize in the Lau are shown in Table 5.

Table 5
FORMATIONS IN THE LAU
(From : Ladd & Hoffmeister, 1945)

SYSTEM	East Indian Stage	FORMATION
Quaternary		MAGO ODINITE
		VULAGA LIMESTONE
Tertiary	h	DALICONI LIMESTONE
	g	KORO BASAGA VOLCANICS
	f	FUTUNA LIMESTONE
		LAU VOLCANICS

The rocks of the oldest formation, the *Lau Volcanics*, are andesitic flows and agglomerates and tuffs which are exposed as the cores of many of the islands and are believed to form the cores of the others. Above the Lau Volcanics is the *Futuna Limestone*, tuffaceous limestone, coral limestone, and algal calcilutite. It is at least 600 feet thick and is dated as Tertiary ' f ' stage (lower Miocene). The *Koro Basaga Volcanics*, which occur above the Futuna Limestone in a few places, consist of flows, agglomerates, and tuffs, mostly of basaltic composition. Flows are more numerous than in the Lau Volcanics. The most common rock type is an olivine basalt. In a very few places Ladd & Hoffmeister found a coral limestone which they named the *Daliconi Limestone*, above the Koro Basaga Volcanics and containing a fauna of fossil foraminifera, molluscs, corals, and crabs which indicates a late Miocene to Pliocene age. The younger formations, the *Vulaga Limestone* and the *Mago Odinite*, are not exposed in such a way that their relationship to each other and to the other formations can be established by superposition.

Ninety percent of the rocks of the Lau are of the two oldest formations, the Lau Volcanics and the Futuna Limestone, and on most of the islands only these two formations have been recognised.

Phosphate Deposits in Fiji

Hutchinson (1950) makes no mention of phosphate deposits in the Fiji islands, except to record that two rocks inside the Reid reef are reported to have some guano on them. However, a small deposit of phosphatic clay and oolitic phosphate on Ogea Driki in the south Lau was investigated in 1941 by F. T. M. White, who was then the Inspector of Mines for Fiji (White, 1942). This deposit was investigated further in October 1942 by Mr Bridges, a representative of the British Phosphate Commissioners, with a view to its immediate utilization to replace supplies normally obtained from Ocean and Nauru islands (Bridges, 1942). The Fiji Geological Survey found phosphate deposits on two other islands in the Lau group (Vatoa and Vanua Vatu) during 1957, and an aluminous phosphatic clay was reported on Tuvuca by Dr J. A. Staargaard, of Aluminium Laboratories Limited, during a reconnaissance of the Lau islands made in 1958.

The present survey covered nearly all the islands of the Lau and led to the discovery of two new deposits, both very small. In addition the tonnage of the known deposits was assessed by hand auger drilling and mapping, and field estimates were made of the grade. Though none of the deposits in Fiji is large enough to be exploited commercially outside Fiji, the deposit on Vanua Vatu island should be investigated further by the Administration of Fiji as a possible source of cheap phosphate fertilizer within the Colony.

Vanua Vatu

Vanua Vatu (Pl. 6) is an almost circular island with an area of a little more than one square mile, surrounded by a close fringing reef. It is in the western part of the Lau group, about 155 miles from Suva. There is a poor anchorage in a bight in the reef off Taira village, the only village on the island.

The island was visited by Ladd & Hoffmeister (1945) but only a sketchy account is given as the visit, by only one of the authors, was brief. The phosphate of the central basin was mistaken for silicified oolitic limestone. In 1957 renewed interest in phosphate throughout the south-west Pacific led Dr N. S. Guest, of the Geological Survey of Fiji, to make a brief reconnaissance of the raised limestone islands of the Lau. He visited Vanua Vatu and discovered the phosphate deposit. Later in the same year the boundary of the phosphate occurrence was mapped and the deposit extensively pitted by Mr Ratuyawa of the Fiji Survey.

The island has a narrow fringing reef and is entirely of limestone, presumably the Futuna Limestone (Ladd & Hoffmeister, 1945). It has a well defined rim on the north, west, and south sides, reaching a maximum height of 330 feet above sea level. At the north-west corner there is a gap in the rim, and a fairly broad gentle slope leads up from Taira village on the shore to Maumi basin, where much of the phosphate occurs. The island's shape suggests a raised coral atoll, but Ladd & Hoffmeister found foraminiferal rather than coral limestone round the rim. Possibly the island is an original atoll that has been sufficiently eroded to remove the coral limestone of the upper part of the rim while still preserving or even accentuating the basin shape.

The phosphate occurs as oolitic grains and pebbles and phosphatic clay between pinnacles of limestone. In the Maumi basin (Pl. 6), the tops of the pinnacles commonly protrude about a foot above the surface of the phosphate. In area ' B,' where the ground slopes down towards the shore, the limestone pinnacles protrude further above the surface of the phosphate. Towards the west edge of Area ' B ' the phosphate fills shallow pockets between limestone outcrops.

The oolites are up to one-third inch in diameter. Fresh surfaces of broken oolites are white, grey, light brown, or white streaked with black. They show some signs of concentric structure, particularly near their edges, but this is mainly iron-staining. The oolites are generally bonded by a small amount of clay, but in some places there is practically no clay and the oolitic phosphate runs like a coarse sand and is difficult to recover in a hand auger. Most of the pebbles occur with the oolitic phosphate on the western slope (Area ' B ') ; they are mostly formed of oolitic grains cemented together, though a few, which appear to be phosphatized coral fragments, appear structureless on broken surfaces. All the pebbles have a mamillated exterior and do not appear to have been abraded.

The oolitic phosphate grades, over a short distance, into phosphatic clay on the north, east, and south sides of the deposit. There are scattered occurrences of the clay elsewhere, notably at Bukidalivou and Sapuga.

Tonnage and Grade

The tonnage of phosphate on Vanua Vatu was estimated from a calculation of the volume based on the area and the depth of the deposit, with a 50% reduction to allow for the space occupied by the limestone pinnacles. Ratuyawa of the Geological Survey of Fiji, in a previous survey, had mapped the boundaries of the phosphatic material by means of a field chemical test and had further proved the deposit by pits spaced along north/south traverses. His work was extended by hand-auger drilling within the area of the deposit.

The Maumi basin (Area ' A ') is estimated to contain 100,000 tons of medium to good grade phosphate which would be easy to recover. There is no overburden and very little vegetation, and the limestone pinnacles rarely protrude more than a foot above the ground. A further 100,000 tons of similar material from the sloping ground leading down to the north-west coast, Area ' B,' would be less easy to recover as it lies in shallow pockets between upstanding pinnacles.

The average phosphate content of twelve samples is 25·8% P_2O_5 ; they have an average alumina content of 21·6% Al_2O_3. The phosphatic clay which surrounds the oolitic deposit is of lower and very variable grade ; the average of three determinations on the clay is 15·3% P_2O_5, and a much higher alumina content, 38·4% Al_2O_3.

It may be profitable for this deposit to be worked by the villagers to supply phosphate fertilizer within the Fiji Islands. Recent work by Cassidy (1952) suggests that this type of phosphate may have value as a fertilizer for direct application to wet rice fields. If this is so the cost of working the deposit should be studied to see if the phosphate could be landed at Suva at a competitive price : it might prove a valuable source of phosphate fertilizer for rice growers.

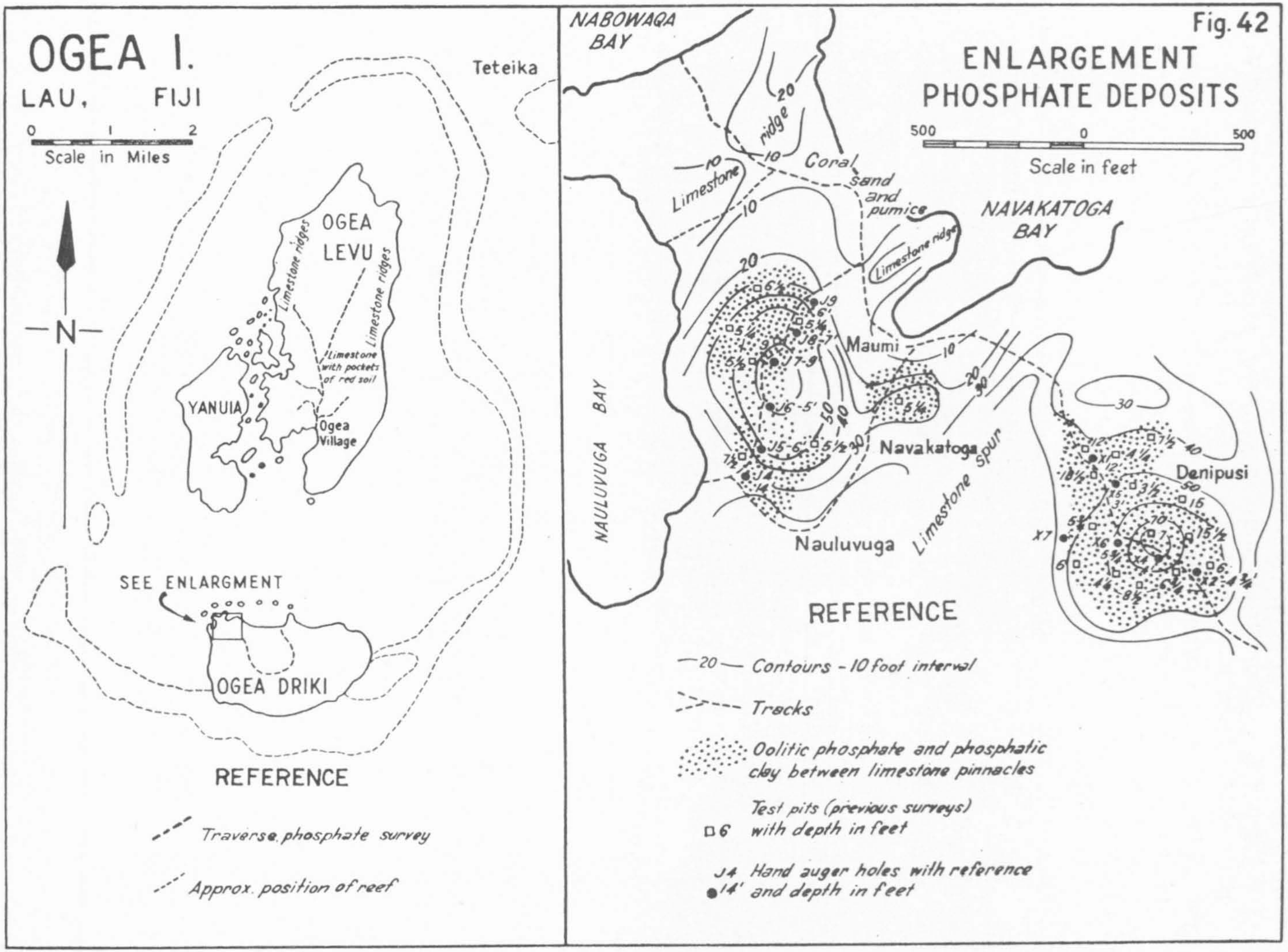
The land of Area ' A ' is at present planted with coconuts but little else, as the villagers say the oolitic phosphate is unsuitable for the planting of root vegetables. Most of the gardens seem to be in the Sapuga and Bukadalivou areas and on the phosphatic clay of Area ' C.'

The Maumi deposit and the deposit of Area ' B ' could probably be exploited without seriously reducing the area of land under cultivation on the island.

Ogea Driki (Fig. 42)

Ogea Driki is one of a group of islands, known collectively as Ogea, which are encircled by a single extensive reef. Ogea is in the South Lau, 220 miles from Suva. There is good anchorage within the reef at many points between Ogea Driki and Ogea Levu (Little Ogea and Great Ogea). The entrance to the lagoon is from the west. There is one village on Ogea Levu, but Ogea Driki and Yanuia are uninhabited. It appears that most of the land of Ogea Driki is owned by men from Vulaga, a neighbouring island, rather than from Ogea Levu.

The phosphate deposits of Ogea Driki were first investigated in 1941, when they were visited by the then Inspector of Mines for Fiji (White, 1942). A comprehensive survey was made in October 1942, by Mr Bridges of the British Phosphate Commissioners ; he assessed the tonnage and


OGEA I.
LAU, FIJI
0 1 2
Scale in Miles
N
Teteika
OGEA
LEVU
Limestone ridges
Limestone ridges
Limestone with pockets of red soil
YANUIA
Ogea Village
SEE ENLARGMENT
OGEA DRIKI
REFERENCE
Traverse phosphate survey
Approx. position of reef
Fig. 42
ENLARGEMENT
PHOSPHATE DEPOSITS
500 0 500
Scale in feet
NABOWAQA BAY
NAVAKATOGA BAY
NAULUVUGA BAY
ridge
Limestone
Coral sand and pumice
Limestone ridge
Maumi
Navakatoga
Limestone Spur
Nauluvuga
Denipusi
REFERENCE
20 Contours - 10 foot interval
Tracks
Oolitic phosphate and phosphatic clay between limestone pinnacles
Test pits (previous surveys) with depth in feet
J4 Hand auger holes with reference 14' and depth in feet

the grade and reported fully on the possibility of exploiting the deposits (Bridges, 1942). The islands were investigated geologically by Ladd & Hoffmeister (1945), but they made no note of the phosphate.

Since then the island has been visited from time to time by geologists of the Fiji Survey Department, and an assistant of the Lands Department spent some time there re-mapping the boundaries of the phosphate deposits and prospecting over Ogea Levu for similar material.

The three islands of Ogea together evidently form a raised coral atoll. Ladd & Hoffmeister (1945) found exposures of reef limestone round the rim of Ogea Levu, Yanuia, and Ogea Driki. In most places they found a thin veneer of limestone with moulds of corals in a position of growth overlying a dense recrystallized limestone which they took to be older.

The rim of the raised atoll has gaps along the east and west sides and part of the old lagoon floor has been reflooded. Much of the old lagoon floor is preserved on Ogea Levu, where it is composed of uneven weathered limestone with a fairly extensive red clay soil filling pockets and smoothing the irregularities of the limestone surface.

The present lagoon between the islands is shallow at its north end close to Yanuia and Ogea Levu. The floor dries extensively here at low tide, exposing fine lime sands and muds and some cemented pavements ; the whole area is dotted with undercut ' mushroom ' islands of limestone.

The phosphate deposits occur only on the north-west tip of Ogea Driki. The phosphatic material consists of clay and oolitic phosphate similar to that described for Vanua Vatu, but with a higher proportion of clay. Two features of the deposits suggest that they were formed by bird colonies which lived in restricted areas. First, the deposits occur only on the tops and on the slopes of rises : the three main deposits, Maumi, Navakatoga, and Denipusi, all fill surface irregularities in gentle limestone rises. Secondly, the yellow-brown phosphatic clay of the deposits merges abruptly into the normal red clay soil of the old lagoon floor to the east. The deposits have probably been formed by phosphatization of this red clay and of the limestone, in the limited areas colonized by the birds. There is no trace of phosphate elsewhere on Ogea Driki or Ogea Levu, although there is abundant red clay, and it seems unlikely that the present deposits are the remains of more extensive deposits which have been eroded.

Tonnage and Grade

Bridges estimated the tonnage of the three deposits as follows :

Denipusi	39,000
Maumi	28,000
Navakatoga	10,000

Analyses made at the same time gave the average P_2O_5 content as 25%, and Al_2O_3 and Fe_2O_3 as 12%.

A few auger holes were drilled during the present survey ; these tend to confirm Bridges' estimate of the tonnage available. White's estimates were much larger but were based on a very short reconnaissance only.

TUVUCA (Fig. 43)

Tuvuca is in the centre of the Lau, 190 miles from Suva. It is 4 miles long and 2 miles wide, elongated in a north-north-west direction. The only village, situated towards the south end of the west coast, is small and has no radio station. Surprisingly large areas in the centre of the island have been cleared for gardens and the whole island is well served with tracks internally, but the first part of the track from the village to the interior has a steep climb over the limestone rim. There is no anchorage, but ships commonly hang on opposite the village.

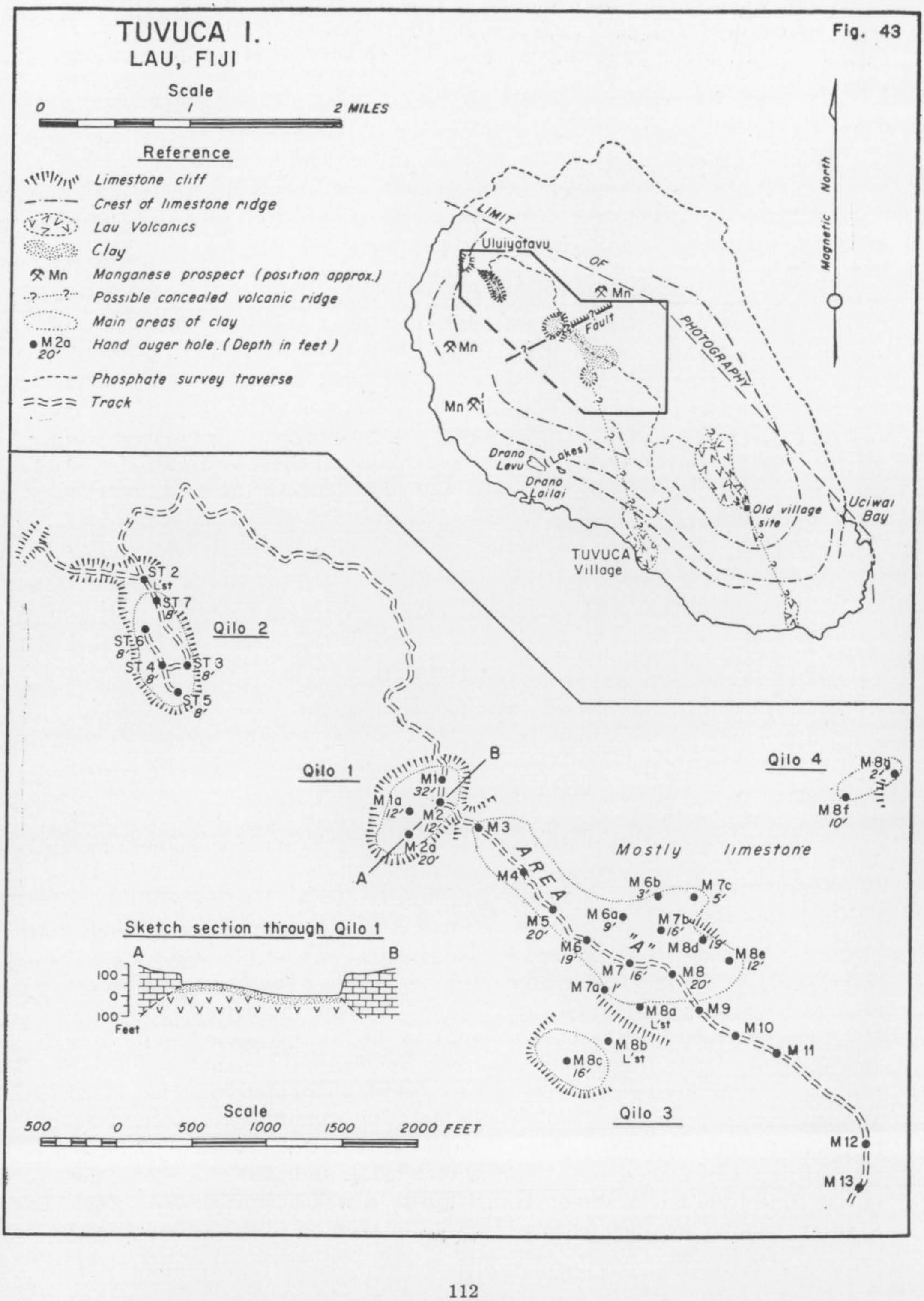
The island was traversed extensively by Ladd & Hoffmeister during their study of the Lau group. In 1958 the island was visited by Dr Staargaard in the course of his investigations for bauxite on behalf of Aluminium Laboratories Ltd. He reported finding phosphatic bauxite on the island and his company retained a Prospecting Licence for bauxite over the island.

Tuvuca is of raised limestone with a series of discontinuous narrow limestone terraces reaching a maximum elevation of 750 feet surrounding an irregular central basin. The limestone belongs in the main to the Futuna Limestone, though Ladd & Hoffmeister found two small areas of Daliconi Limestone on the north coast. The terraces are commonly narrow and they have flat soil-covered floors and a narrow wall of limestone, 5 to 100 feet high, along their outer edges (Fig. 44).

The volcanic rocks which crop out as a long ridge at the south end of the central basin and along the south coast belong to the Lau Volcanics and consist of flows and some agglomerates. The long ridge of volcanics in the central basin appears to continue under a limestone cover and to crop out again along the south coast. The air photographs suggest that there is a second ridge, parallel to the first and about half a mile to the west of it, which is only exposed at its southern end, close to the village.

The air photographs do not substantiate Ladd & Hoffmeister's division of the central basin into three. Probably a better way of visualizing the interior of the island physiographically is as a single basin with an uneven floor and many spurs and ridges of limestone running across it.

A major feature of the physiography is the large clay-floored circular depressions in the limestone which are known in Fiji as 'Qilos.' A 'Qilo' is commonly two to three hundred yards in diameter and has steep, almost vertical limestone walls rising on every side fifty to one hundred feet above the level of the floor. Hand-auger drilling showed that the clay filling is in places more than 30 feet thick and that below the clay is not limestone but a steady transition to a weathering volcanic rock. Similar, though smaller, features were later seen on Cikobia-i-lau Island.


TUVUCA I.
LAU, FIJI
Fig. 43
Scale
0
1
2 MILES
Reference
Limestone cliff
Crest of limestone ridge
Lau Volcanics
Clay
Mn
Manganese prospect (position approx.)
Possible concealed volcanic ridge
Main areas of clay
M 2a 20'
Hand auger hole. (Depth in feet)
Phosphate survey traverse
Track
Magnetic North
LIMIT OF PHOTOGRAPHY
Uluiyatavu
Mn
Fault
Mn
Mn
Drano Levu
(Lakes)
Drano Lailai
Old village site
Uciwai Bay
TUVUCA Village
ST 2
L'st
ST 7
8'
ST 6
8'
ST 4
8'
ST 3
8'
ST 5
8'
Qilo 2
Qilo 1
B
M1
32'
M 1a
12'
M2
12'
M 2a
20'
A
M3
AREA "A"
M4
M5
20'
M6
19'
M7
16'
M 7a
1'
M 6a
9'
M 6b
3'
M 7c
5'
M 7b
16'
M 8d
19'
M 8e
12'
M8
20'
M 8a
L'st
M9
M10
M11
M12
M13
M 8b
L'st
M 8c
16'
Qilo 3
Qilo 4
M 8g
2'
M 8f
10'
Mostly limestone
Sketch section through Qilo 1
A
B
100
0
100
Feet
Scale
500
0
500
1000
1500
2000 FEET

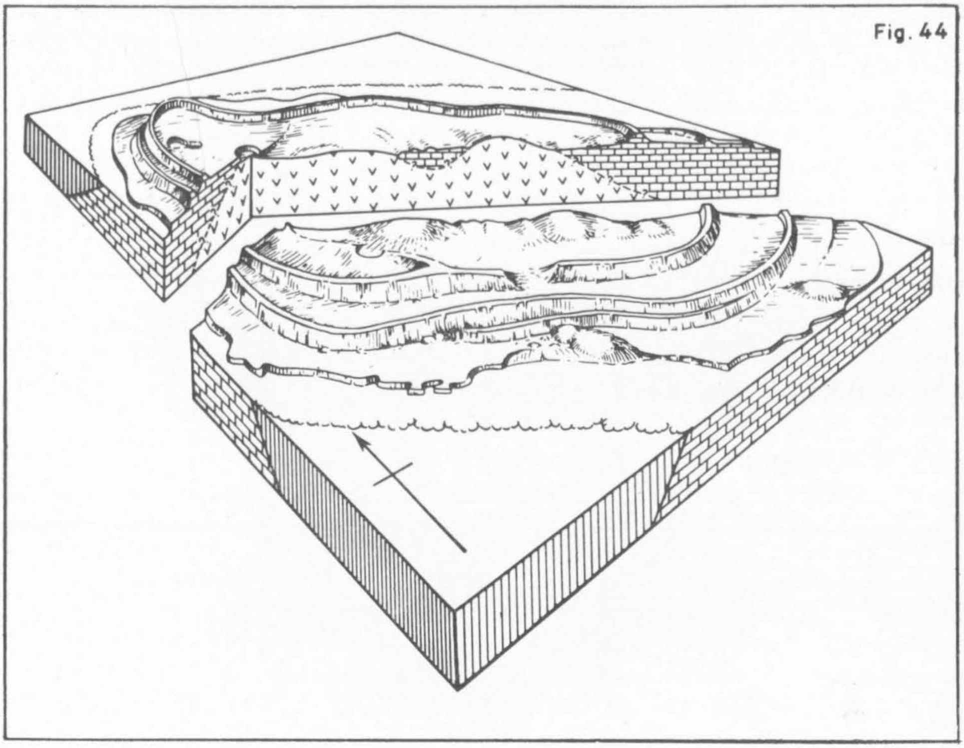


Fig. 44.—Physiographic sketch of Tuvuca Island.

The clay which partly fills the ' Qilos ' and other depressions on the central basin floor is partly phosphatized. Figure 43 shows the areas which were investigated by hand auger drilling. A large area at the north end of the central basin and the four ' Qilos ' numbered on the Figure together would yield about 700,000 tons of clay. The tonnages were calculated on the basis of the area of clay at the surface and the average depth of the hand-auger holes, with a subtraction for pinnacles of limestone projecting into the base of the clay in the central basin. In the ' Qilos ' the floor is of weathered volcanic rock and no subtraction need be made. There is more clay on the island than is shown in these calculations ; there are other ' Qilos,' spoken of by the islanders, which were not visited ; there are other areas on the central basin floor, and possibly more clay exists on the terraces, particularly at the north end of the island. In all there is likely to be about 2 million tons of clay on Tuvuca, mostly at the north end of the central basin ; the soils of the south end on the slopes of the ridge of volcanics and below the ridge are thin and no accumulation of clay is seen.

Aluminium Laboratories report that five samples taken by their prospecting team range from 9·8 to 21·3%P_2O_5. Thirty-six determinations on samples collected during this survey range from 2·1 to 22·9% P_2O_5, and average 9·4% P_2O_5. Five of these samples were also assayed for iron oxides and alumina: the average value for the five samples was Fe_2O_3 16·2% and Al_2O_3 32·3%. From these five values there seems to be very little variation in the content of iron oxide and alumina. The sesquioxide content is thus uniformly high, too high for the manufacture of superphosphate by present methods; and this, coupled with the very variable and rather low content of P_2O_5, means that the deposit is certainly unworkable at present.

VATOA (Fig. 45)

Vatoa Island is somewhat less than two square miles in area and is in the far south of the Lau, 250 miles from Suva. It is actually slightly closer to Nuku'alofa, Tonga, than Suva. There is good anchorage within the reef at a number of places along the northern part of the west coast. The passage through the reef is at the north-west corner and is narrow: it is advisable to wait for a pilot from the village, which is close to the south end of the west coast on low-lying land near the sea shore. Much of the island is uneven and difficult to traverse.

Vatoa was not visited by Ladd & Hoffmeister. The phosphate was discovered by Dr Guest, of the Fiji Survey, during his 1957 reconnaissance of the Lau. Later in the same year Mr Ratuyawa, of the Fiji Survey, investigated the deposit by pitting along the main tracks.

The exposed part of the island is of limestone; presumably of the Futuna Limestone, by analogy with the other islands of the Lau.

Vatoa does not have a simple physiographic form. The highest part is a limestone rim which runs round the north-east and north-west sides of the Lomanivanua basin, and reaches 200 feet above sea level. There is a terrace at 60 to 80 feet above sea level on the north and east sides of this rim; inside the rim the basin floor slopes gently to the south-west and is about 80 feet above sea level. The 60-foot terrace has several discontinuous ridges on its east side and is elongated to the south. Two prominent limestone hills close together rise 40 to 50 feet above the gently shelving surface of the terrace on this southern elongation (Muanivatu).

The phosphate of Vatoa consists of a clay of very variable phosphate content, which occurs in shallow pockets scattered over much of the island. A small amount of oolitic phosphate occurs beneath the clay at the foot of the rise from the village to the school (Busabusa) and in pockets in the limestone along the western side of the island.

The clay was examined by hand-auger drilling. No sizeable clay-filled basins were found—the Lomanivanua basin and the Busabusa area, which appeared to be the most likely areas, both have only scattered shallow pockets of the clay on their surfaces. The clay is friable and brown to yellow-brown, the lighter coloured clay being the higher in phosphate content. The oolitic phosphate consists of pink hard oolites about $\frac{1}{8}$ inch in diameter. In parts of the island the clay grades down into oolitic phosphate in pockets and crevices in the underlying lime-

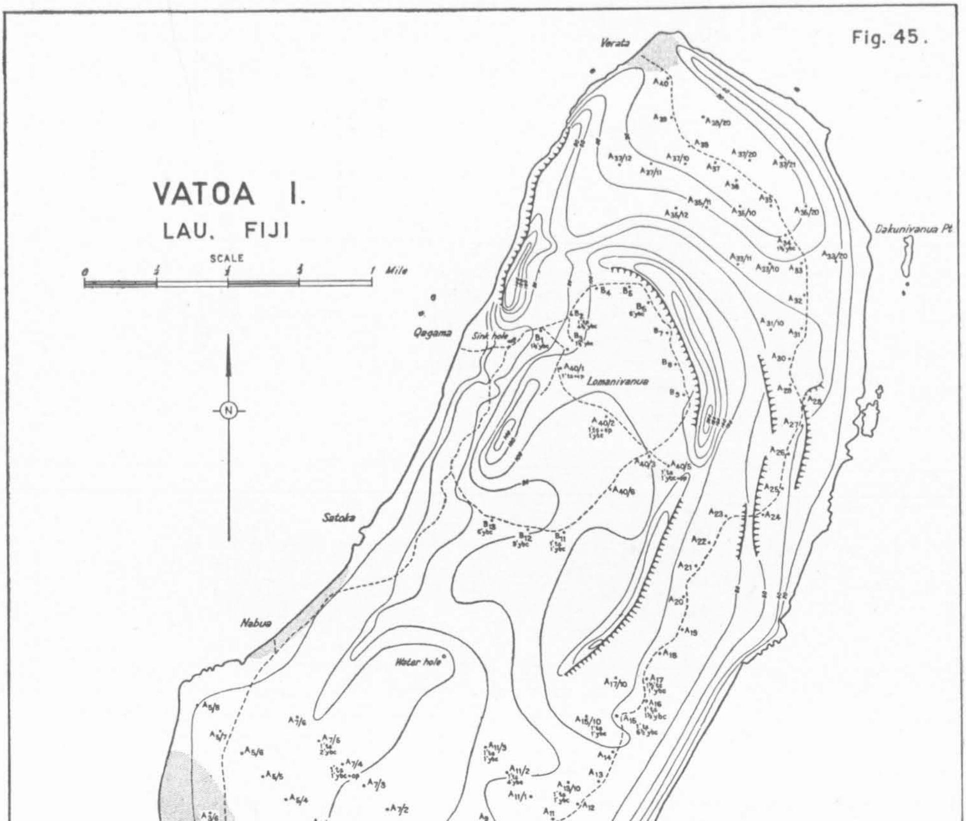
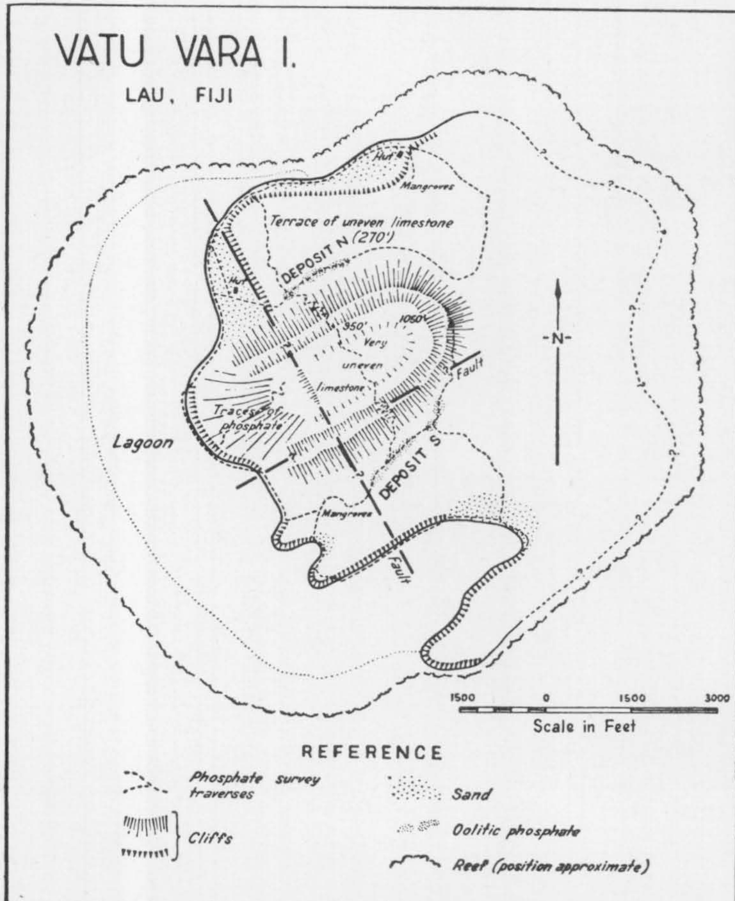
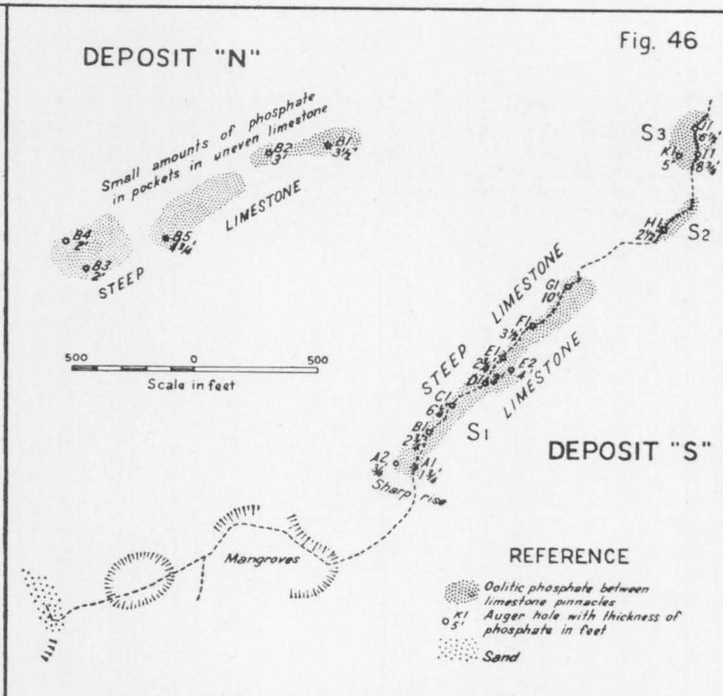


Fig. 45.
VATOA I.
LAU. FIJI
SCALE
0 ¼ ½ ¾ 1 Mile
N
Verata
Dakunivanua Pt
Qagama
Sink hole
Lomanivanua
Satoka
Nabua
Water hole
Busa-busa
VATOA VILLAGE
Buladovu
Muanivatu
Tuvana
REFERENCE
Form lines - Interval: 20 Feet
Tracks
Cliffs
Hand auger hole
with depth in feet of ybc : yellow brown clay
ts : topsoil
op : oolitic phosphate
Holes for which no depth given are in limestone, limestone with Shallow (<1') soil, or non-phosphatic clay.
Main areas of sand
Outline, tracks and form lines from survey by Fiji Department of Lands, Mines and Surveys
Reef not shown.





DEPOSIT		AVERAGE DEPTH	ESTIMATED VOLUME (CU. FT.)	DEDUCTION FOR LIMESTONE	ESTIMATED TONNAGE
S1	Oolitic phosphate	5 ft.	640,000	2/3	8,500
S2		2½ ft.	64,000	2/3	400
S3		7 ft.	246,000	2/3	3,300
N	Oolitic phosphate	3 ft.	336,000	3/4	3300
				TOTAL	15,500

stone and it is clear that much of the phosphatic clay is formed by breakdown of the oolites and admixture with terra rossa from limestone weathering.

No estimates of the tonnage are given as the deposits are too scattered to be assessed accurately and are obviously too small to be worth exploiting. Less than half a million tons of clay would cover the entire surface of the island to a depth of more than six inches.

A fragment of weathering pumice was found in one auger hole in the Lomanivanua area at a depth of 5 feet.

VATU VARA (Fig. 46)

Vatu Vara, one of the smallest islands in the Lau, is not more than one and a half miles across in any direction. It has a very irregular coastline—in particular it has a large bay at the south end of the west coast. It is in the northern Lau, 145 miles from Suva. The island is not inhabited but it is leased as a copra plantation. Men from Yacata occasionally live there for a few days cutting copra for the owner. There are two huts and a water catchment. There is no anchorage and the boat passage through the reef along the north-west coast can only be used at high tide. At other times it is possible to land on the edge of the reef and wade ashore.

There is no record of previous search for phosphate on the island and it was not visited by Ladd & Hoffmeister.

Vatu Vara is nicknamed 'Top Hat' Island, which aptly describes its silhouette. The only rock exposed on the island is limestone ; the central mass rises to 1050 feet, making the island the highest in the Lau. The central mass is surrounded by a broad terrace, the surface of which is about 250 feet above sea level.

The central mass is elongated north-east in plan and has a saucer-shaped cross-section. It has been cut across at the south-west end by a north-westerly fault with the downthrow on the south-west side. The fault cuts the 250-foot terrace north of the central mass, and is visible on the south face of the central mass. The outside slopes of the central mass are very steep and made up of jumbled blocks of limestone, commonly very large, stabilized by rain-forest growth. On the south side signs of a recent slip were seen. The top 100 feet or so form a vertical cliff, free of vegetation.

The 250-foot terrace is not continuous round the island and has been affected by the same faulting that has dropped the south-west end of the central mass. The terrace from a distance can be seen to slope gently seaward ; its surface is very irregular, however, and pitted by solution—the pits commonly ten to twenty feet across and as much as twenty feet deep.

The highest point on the island is at the north-east end of the central block, and there are some signs on the south face of bedding dipping to the west. The general appearance of the central mass suggests that it was tilted down to the south-west during the uplift which preceded the formation of the lower terrace.

No volcanic rocks are exposed on the island.

Small deposits of phosphatic clay and oolitic phosphate were found on the north and south sides of the central mass at the foot of the scree slope. Close to the scree slope the otherwise empty hollows in the surface of the limestone of the terrace are filled or partly filled with this phosphatic material. Traces of phosphate were found in cracks in the limestone most of the way up the sides of the central mass, suggesting that the phosphate may have formed there by leaching of guano from birds nesting in the cliffs and then been washed down and trapped in its present position.

The deposits are very small and the total tonnage of phosphatic material available is estimated at 15,000 tons.

MARABO

Marabo is a small island in the southern Lau off Kabara. It is 190 miles from Suva and has an area of about $\frac{3}{4}$ square mile. It is uninhabited, but is often visited by men from Kabara for fishing and copra cutting.

The island is entirely of limestone ; it does not have any easily described physiographic form, but in general the highest points (160 feet) are in the centre and towards the north-east coast. The rest of the island is formed of discontinuous terraces and ridges. A narrow terrace along the south-west side contains a few hundred tons of phosphatic clay between the limestone pinnacles of the terrace surface. The material has not been analysed, but qualitative testing in the field suggests that the clay is low-grade.

VULAGA (Fig. 47)

Vulaga is sub-quadrate in outline, has a clearly marked rim of raised limestone which reaches a maximum height of 260 feet above sea level, and has a central lagoon which is open to the sea through a passage on the east side. The island could be contained within a circle of $5\frac{1}{2}$ miles diameter. Ladd & Hoffmeister, from the evidence of the physiography and because of finding many corals in a position of growth in the raised limestone of the rim, concluded that the island was a raised coral atoll. It appears that the island was tilted during uplift as the rim is higher and broader on the south-west side and is broken into lower, narrow islands along the north-east side. The rim is not regular—the two highest points, Delai Korolevu and Na Wiriwiri, in particular are even-crested ridges markedly higher than the rest of the rim.

No volcanic rocks crop out on Vulaga.

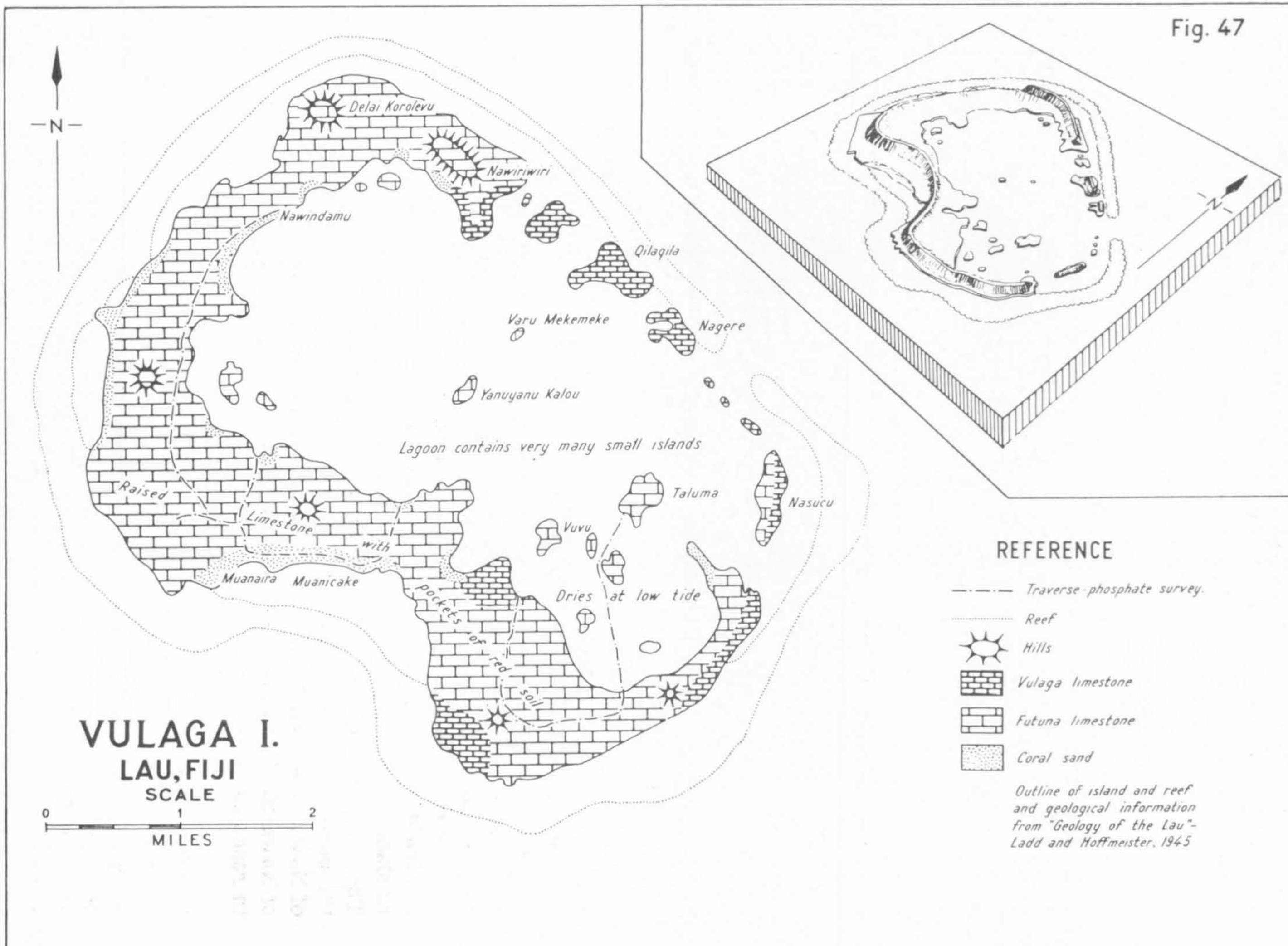


Fig. 47
N
Delai Korolevu
Nawiriwiri
Nawindamu
Qilaqila
Varu Mekemeke
Nagere
Yanuyanu Kalou
Lagoon contains very many small islands
Raised Limestone with pockets of red soil
Taluma
Nasucu
Vuvu
Dries at low tide
Muanaira
Muanicake
VULAGA I.
LAU, FIJI
SCALE
0
1
2
MILES
REFERENCE
Traverse-phosphate survey
Reef
Hills
Vulaga limestone
Futuna limestone
Coral sand
Outline of island and reef and geological information from "Geology of the Lau" - Ladd and Hoffmeister, 1945

The lagoon is shallow throughout but particularly so at the south end, much of which dries at low tide. This part of the lagoon is dotted with many ‘ mushroom ’ islands of limestone some of which have been undercut so far that they have toppled over.

The crest of the rim is commonly a very narrow ridge with a low cliff on the lagoon-ward side as well as the marked cliff towards the outside. The limestone surface throughout the island is deeply pitted and difficult to traverse.

Soils exist on the lower parts of the island and filling hollows elsewhere. They are most commonly reddish purple in places with a light brown granular topsoil. They were nowhere found to be deeper than 8 feet.

NAMUKA (Fig. 48)

Namuka, one of the larger islands of the south Lau, is about five miles long and about a mile and a half across. Its east-west elongation is unlike any other islands in this part of the Lau. The island is entirely formed of raised limestone with a steep, sharp ridge 200 feet high along the north coast and a lower, less continuous ridge along the south coast, broken in the centre by a broad shallow bay across the front of which the ridge forms a chain of islands. There are no well marked ridges across the narrow east and west ends of the islands, so the island does not have the typical form of a raised atoll. However, Ladd & Hoffmeister found fossil reefs forming the top 75 feet of part of the northern ridge and they thought it was quite possible that the present island was formed by the uplift and erosion of an elongate atoll. They further held that faulting had occurred at the time of the uplift—particularly along the north-west coast, where deep water borders the cliffs, and at the west end of the island, where they found vertical and steep north-west-dipping fissures trending north-east. Faulting in a north-easterly direction is also suggested by a step in the central valley floor along a north-east line from Burotu.

The central valley floor is fairly flat and considerable areas of it are cultivated. Hand-auger drilling showed that the soils are fairly thick—in places more than eight feet of a distinctive purple clay was penetrated. The Namuka islanders are known throughout this part of the Lau for the purple stain this clay gives to their hands and clothes. To the west of Nawatia Village the floor of the central valley is swampy. Just south of Nawatia is a large sink hole with slightly brackish water which moves in response to tides.

KABARA (Fig. 49)

Kabara is more-or-less oval in outline with the longer axis north-south (four miles long) and the shorter east-west (three miles long). The north-west coast is straight and probably faulted. The main part of the island is composed of raised limestone in a near-perfect basin shape with an even crested rim at about 200 feet above sea level. The basin floor has no major relief, but in detail it is extremely uneven ; much of it is

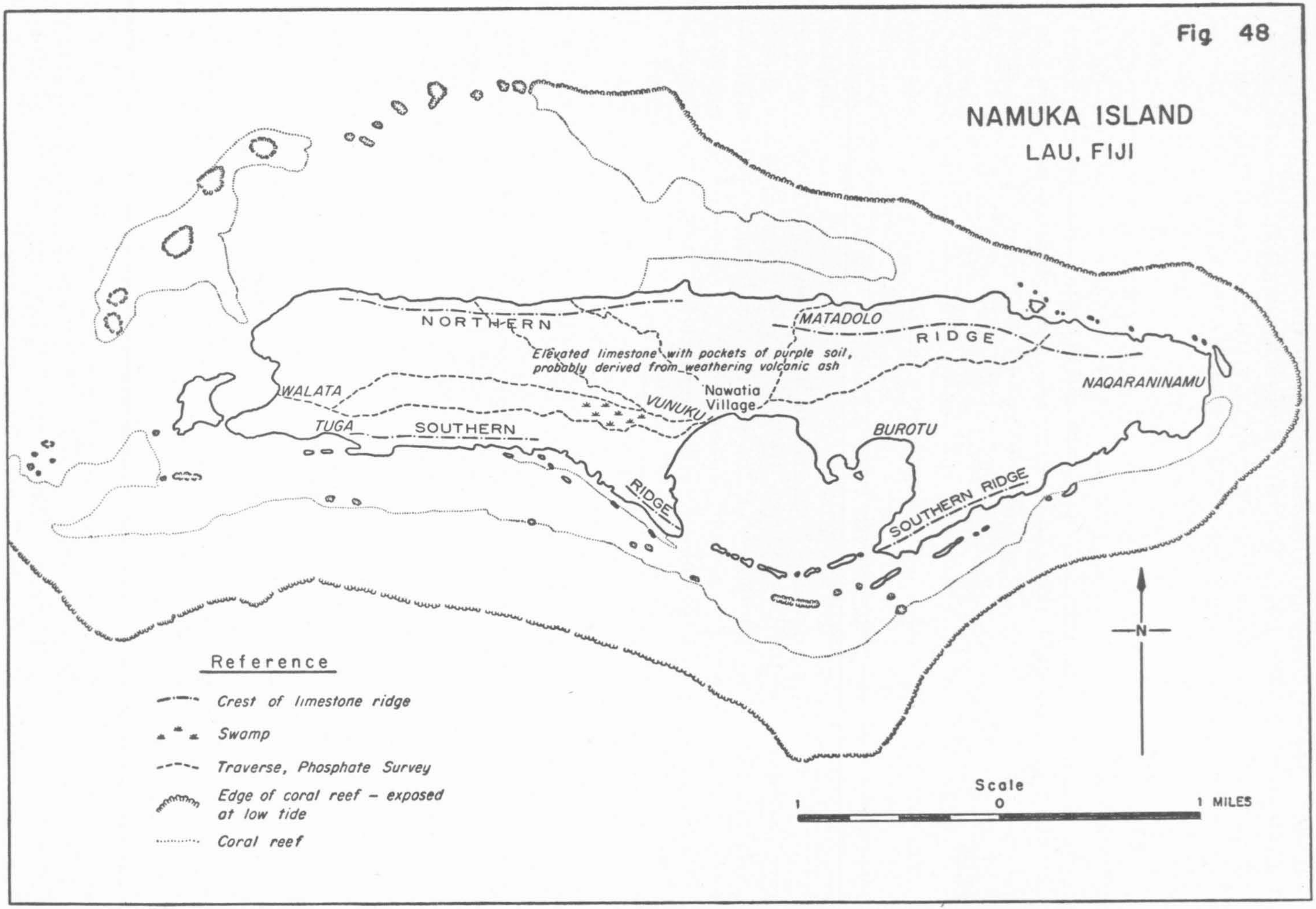


Fig 48
NAMUKA ISLAND
LAU, FIJI
NORTHERN
MATADOLO
RIDGE
Elevated limestone with pockets of purple soil, probably derived from weathering volcanic ash
Nawatia Village
NAQARANINAMU
WALATA
VUNUKU
TUGA
SOUTHERN
BUROTU
RIDGE
SOUTHERN RIDGE
Reference
Crest of limestone ridge
Swamp
Traverse, Phosphate Survey
Edge of coral reef – exposed at low tide
Coral reef
N
Scale
1
0
1 MILES

made of jumbled boulders of limestone honeycombed with solution cavities and evidently collapsing onto one another as solution proceeds below. Through much of the interior there is very little soil, although there is a prolific growth of rain forest. The limestone rim is interrupted to the north of the centre of the west coast by a double-peaked hill of volcanic rocks, Delai Oloi, which rises to 440 feet above sea level. The slopes of the hill are thickly covered with a soil derived from the weathering of the volcanics, which obscures the contact of the volcanics with the limestone and spreads out over the surrounding limestone areas. Small nodules of manganese occur at the surface near a swampy area towards the centre of the basin floor ; the accumulation appears to have taken place in a soil which has since been partly removed.

Ladd & Hoffmeister describe the volcanics as similar to the Mago Odinite and later than the limestone. On the slope of the hill, 330 feet above sea level, they found blocks of limestone which they consider had been carried up to this height by the activity of the volcano. Ibbotson (1959) studied the limestone/volcanic contact on Kabara and concluded that the volcanics are older. This view is more acceptable, as an emerging volcano is more likely to engulf material and cover it with lava and ash than to carry material higher. If the volcanics were later than the limestone one would expect an ash cover over much of the limestone, whereas there is none. The limestone at 330 feet on the hill slope is probably all that remains of an initial limestone developed at the first still-stand of the rising island.

Vuagava

Vuagava is a close neighbour of Kabara and is very similar in form. It appears to be a raised atoll, whose rim is about 300 feet above sea level. It is smaller and narrower than Kabara (3 miles by 1 mile) and is elongated in a north-east direction. As on Kabara there is evidence of faulting along the north-west coast. No volcanic rocks crop out on Vuagava. Part of the central basin floor is occupied by a brackish-water lake whose waters rise and fall with the tide.

Oneata (Fig. 50)

Only a few hours were spent on the small (2½ square mile) island of Oneata in the central Lau. The island was thoroughly investigated by Ladd & Hoffmeister, whose map is reproduced here. They found that the outcrops of Lau Volcanics in the southern part of the island protrude through 60 feet of tuffaceous foraminiferal limestone of Miocene ('f' stage) age that forms a basal unit to the crystalline limestone covering most of the rest of the island. The volcanics of the north end are basaltic and are tentatively correlated with the Koro Basaga Volcanics.

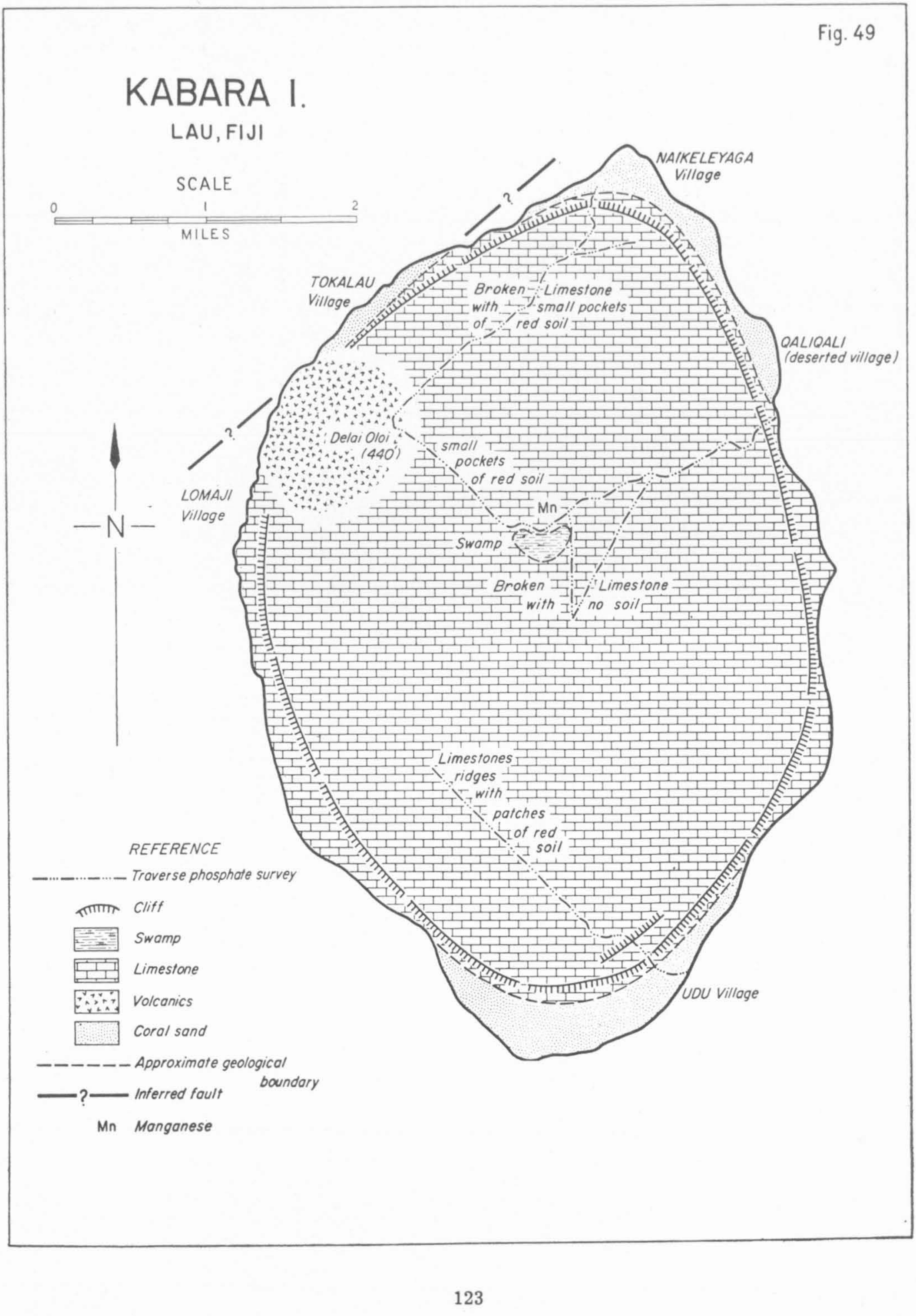


Fig. 49
KABARA I.
LAU, FIJI
SCALE
0
1
2
MILES
N
NAIKELEYAGA Village
TOKALAU Village
QALIQALI (deserted village)
LOMAJI Village
UDU Village
Delai Oloi (440')
Broken Limestone with small pockets of red soil
small pockets of red soil
Mn
Swamp
Broken Limestone with no soil
Limestones ridges with patches of red soil
?
REFERENCE
Traverse phosphate survey
Cliff
Swamp
Limestone
Volcanics
Coral sand
Approximate geological boundary
Inferred fault
Mn Manganese

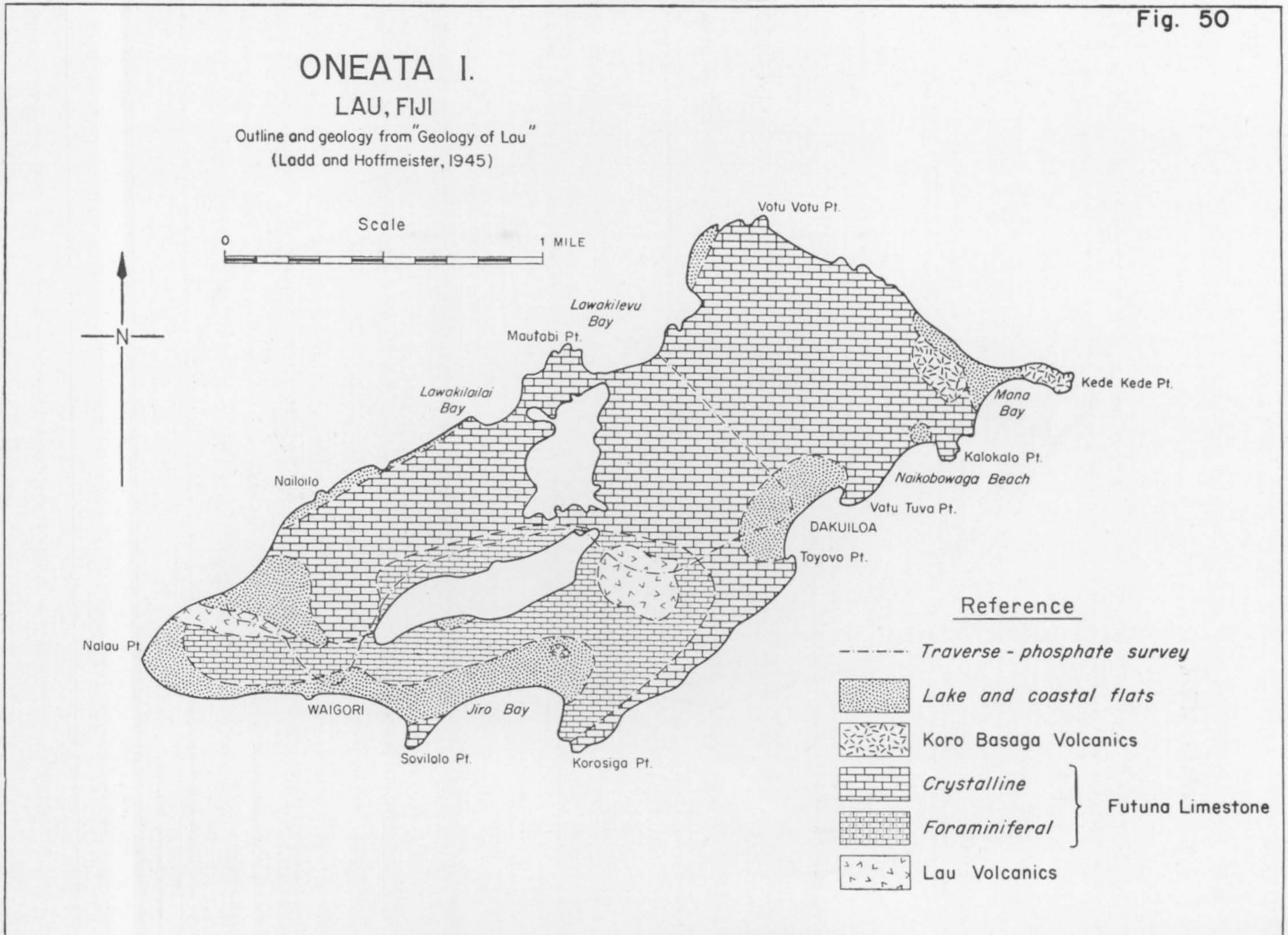

ONEATA I.
LAU, FIJI
Outline and geology from "Geology of Lau"
(Ladd and Hoffmeister, 1945)
Scale
0
1 MILE
N
Votu Votu Pt.
Lawakilevu Bay
Mautabi Pt.
Kede Kede Pt.
Lawakilailai Bay
Mana Bay
Kalokalo Pt.
Nailoilo
Naikobowaga Beach
Votu Tuva Pt.
DAKUILOA
Toyovo Pt.
Nalau Pt.
WAIGORI
Jiro Bay
Sovilolo Pt.
Korosiga Pt.
Reference
Traverse - phosphate survey
Lake and coastal flats
Koro Basaga Volcanics
Crystalline
Foraminiferal
Futuna Limestone
Lau Volcanics

Fig. 50

The soils of Oneata are mostly red or black and seem to be derived from the weathering of the volcanics. The northern part of the island is thickly covered with rain forest growing on limestone with very little soil.

NYAU

Only a few hours could be spent on Nyau, which is one of the larger islands of the central Lau. The island was not examined in detail by Ladd & Hoffmeister, and its geology is not well known. Nyau, which is about 4 miles long (north-west) by 3 miles broad, has a rim of limestone reaching 550 feet above sea level and enclosing an oval basin. The flat floor of the central basin, which is about 250 feet above sea level, is covered with a red-brown to purple soil, supporting a growth of reeds and short palms, very different from the normal rain-forest vegetation. The limestone rim is incomplete along the north-east coast, where volcanic rocks reach 500 feet above sea level. A deposit of manganese is being worked on the slope below this gap.

CIKOBIA-I-LAU (Fig. 51)

Cikobia-i-lau is within the large lagoon which also encloses Vanua Balavu and Munia. There are two ages of volcanic rocks on the island : andesitic agglomerates and flows of the Lau Volcanics are exposed beneath the limestone at the south-west point and at various places in the centre of the island ; whereas the large ridge of agglomerate which forms the east coast is later than the limestone and so is placed in the Koro Basaga Volcanics. Steep-walled depressions in the limestone, ' Qilos,' are common here as they are on Tuvuca. A fault running along the centre of the island in a north-east direction is an important tectonic feature. It is shown by scarps inland whose continuity can be seen on air photographs.

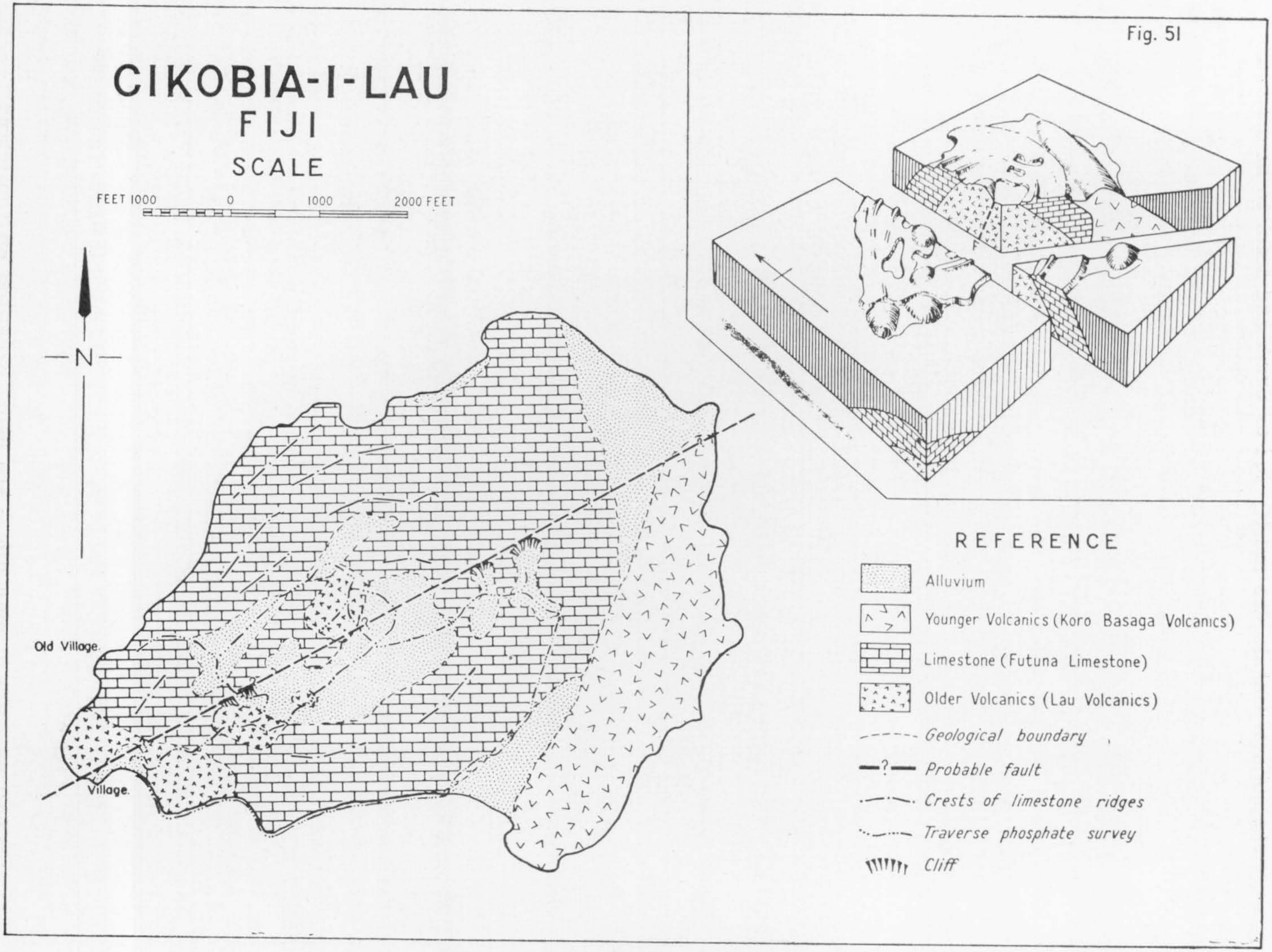
CICIA (Fig. 52)

Cicia is a roughly circular island, 4 miles in diameter, in the central Lau. Geologically it is very simple. The central mass, rising to 540 feet above sea level, is of eroded andesitic volcanics and is probably a single eroded volcanic cone. It is surrounded by a discontinuous terrace of raised limestone reaching to about 400 feet above sea level.

At the junction of the limestone with the volcanics an inward-facing cliff in the limestone has commonly been formed by differential erosion.

The soils of the central area are commonly very thin, but valleys leading down to the coast have a thick fill of clay.

Small deposits of manganese are being exploited on the island.



CIKOBIA-I-LAU
FIJI
SCALE
FEET 1000 0 1000 2000 FEET
N
Old Village
Village
REFERENCE
Alluvium
Younger Volcanics (Koro Basaga Volcanics)
Limestone (Futuna Limestone)
Older Volcanics (Lau Volcanics)
Geological boundary
? Probable fault
Crests of limestone ridges
Traverse phosphate survey
Cliff

Fig. 51

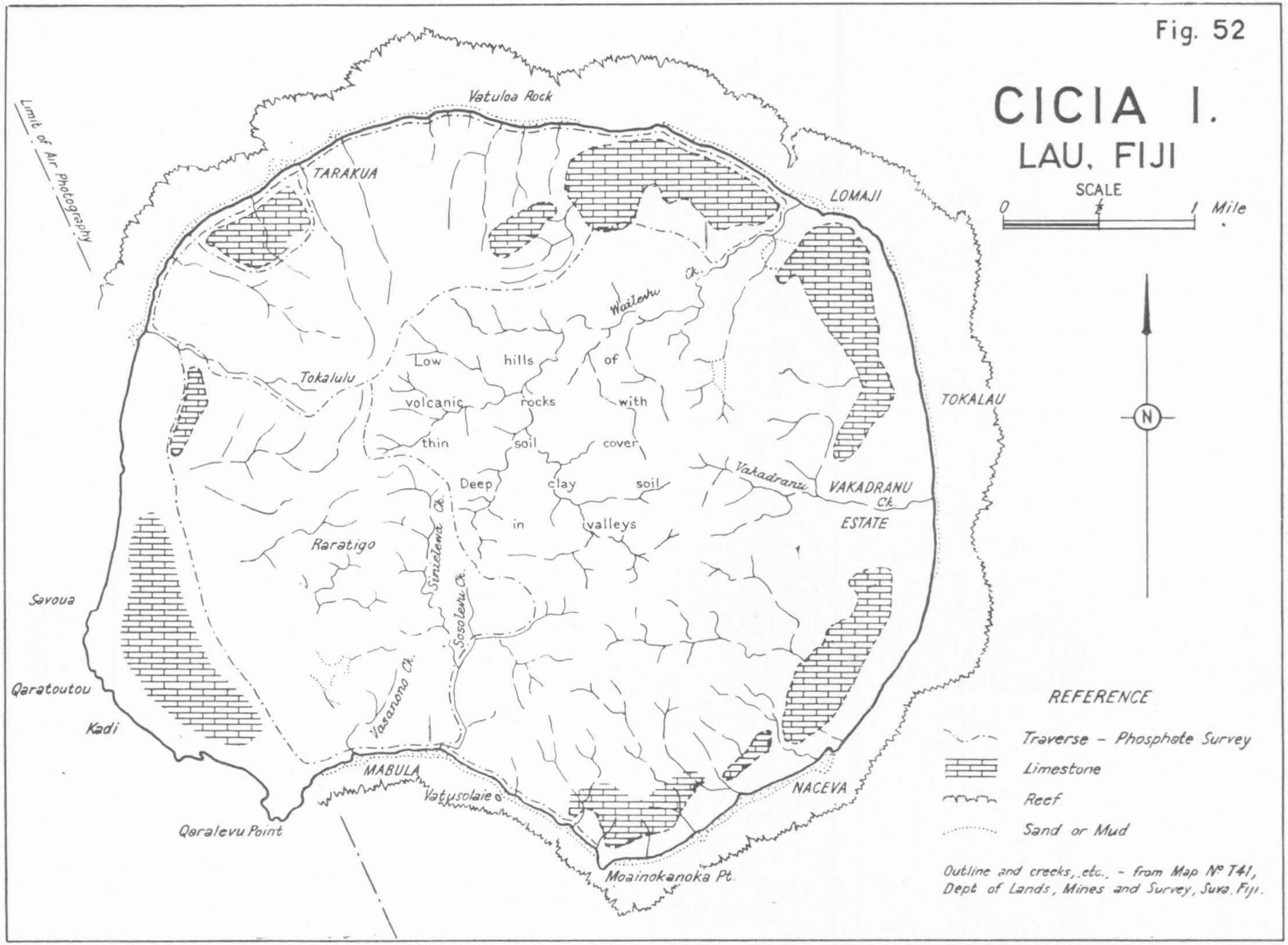


Fig. 52
CICIA I.
LAU, FIJI
SCALE
0
½
1 Mile
Limit of Air Photography
Vatuloa Rock
TARAKUA
LOMAJI
Wailevu Ck.
Tokalulu
Low hills of volcanic rocks with thin soil cover
Deep clay soil in valleys
TOKALAU
Vakadranu
VAKADRANU Ck.
ESTATE
Raratigo
Simielewa Ck.
Sosolevu Ck.
Vasanono Ck.
Savoua
Qaratoutou
Kadi
MABULA
Vatusolaie
NACEVA
Qaralevu Point
Moainokanoka Pt.
N
REFERENCE
Traverse - Phosphate Survey
Limestone
Reef
Sand or Mud
Outline and creeks, etc., - from Map Nº T41,
Dept of Lands, Mines and Survey, Suva, Fiji.

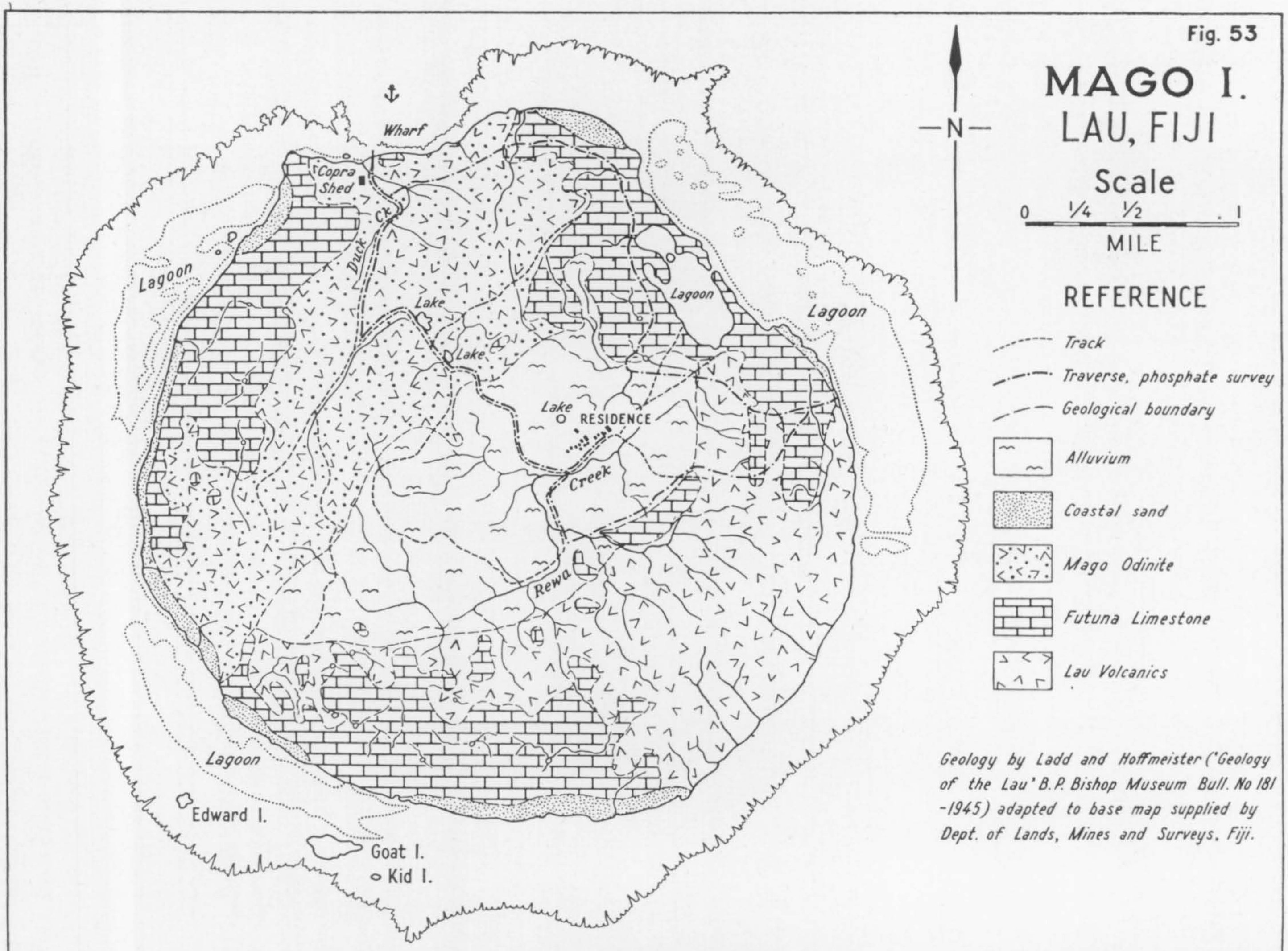


Fig. 53
MAGO I.
LAU, FIJI
Scale
0 1/4 1/2 1
MILE
N
REFERENCE
Track
Traverse, phosphate survey
Geological boundary
Alluvium
Coastal sand
Mago Odinite
Futuna Limestone
Lau Volcanics
Geology by Ladd and Hoffmeister ("Geology of the Lau" B.P. Bishop Museum Bull. No 181 -1945) adapted to base map supplied by Dept. of Lands, Mines and Surveys, Fiji.
Wharf
Copra Shed
Duck Ck
Lagoon
Lake
Lake
Lake
RESIDENCE
Creek
Rewa
Lagoon
Lagoon
Lagoon
Edward I.
Goat I.
Kid I.

74895—(5)

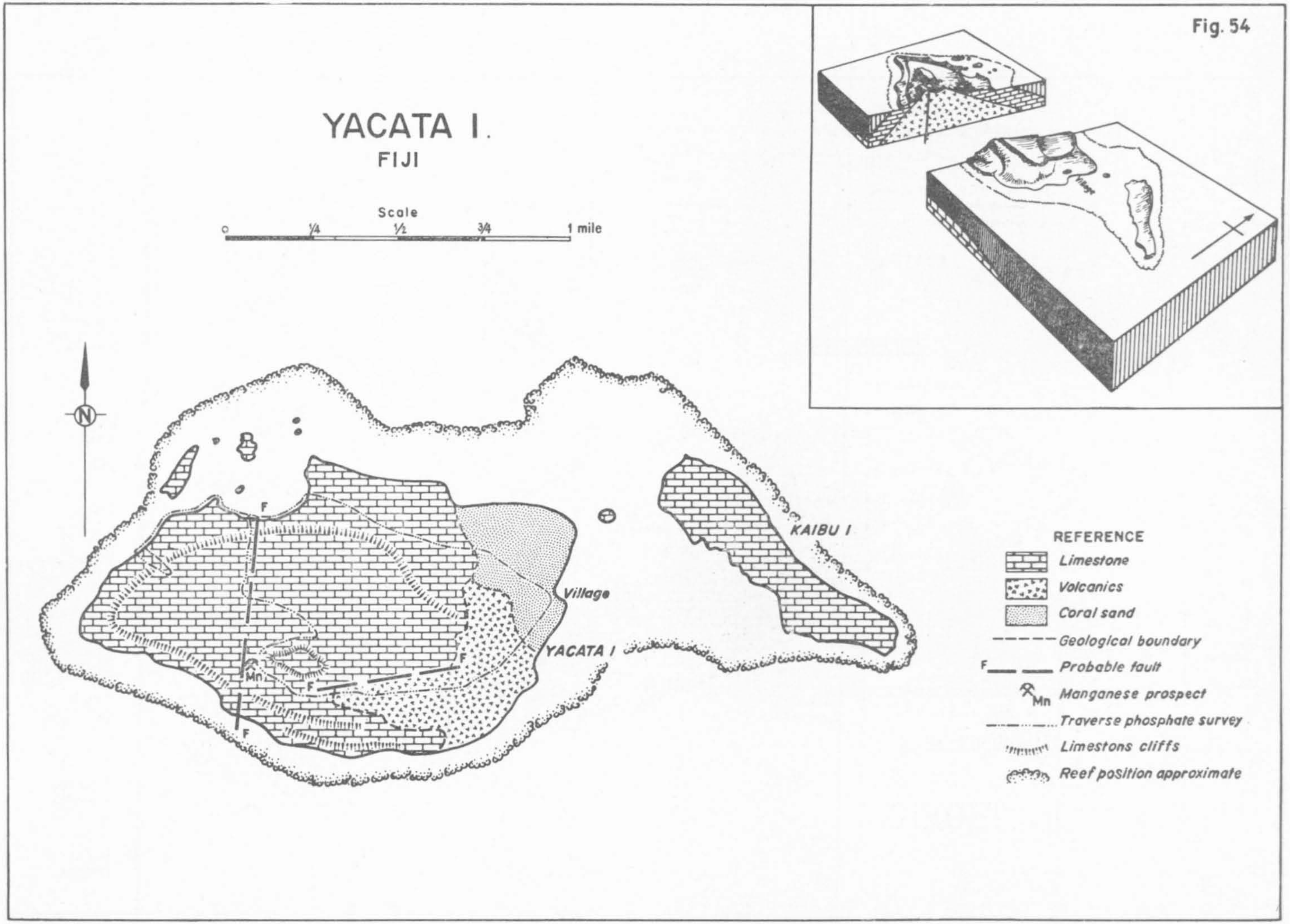


Fig. 54
YACATA I.
FIJI
Scale
0
1/4
1/2
3/4
1 mile
N
Village
KAIBU I
YACATA I
F
Mn
REFERENCE
Limestone
Volcanics
Coral sand
Geological boundary
Probable fault
Manganese prospect
Traverse phosphate survey
Limestons cliffs
Reef position approximate

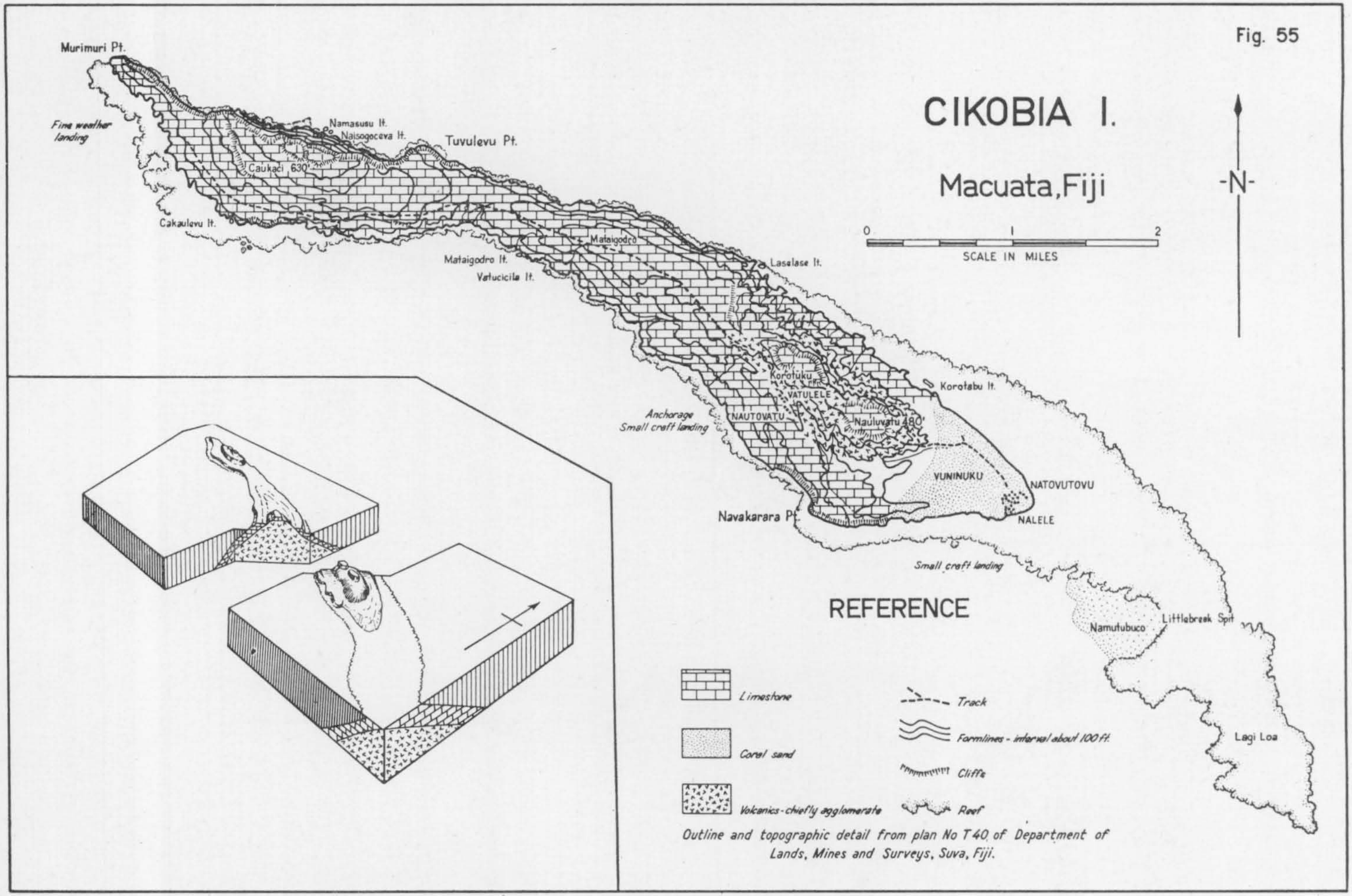


Fig. 55
CIKOBIA I.
Macuata, Fiji
-N-
0 1 2
SCALE IN MILES
Murimuri Pt.
Fine weather landing
Namasusu It.
Naisogoceva It.
Tuvulevu Pt.
Caukaci 630'
Cakaulevu It.
Mataigodro
Mataigodro It.
Vatucicila It.
Laselase It.
Korotuku
VATULELE
NAUTOVATU
Nauluvatu 480'
Korotabu It.
Anchorage
Small craft landing
YUNINUKU
NATOVUTOVU
NALELE
Navakarara Pt.
Small craft landing
Namutubuco
Littlebreak Spit
Lagi Loa
REFERENCE
Limestone
Coral sand
Volcanics - chiefly agglomerate
Track
Formlines - interval about 100 ft.
Cliffs
Reef
Outline and topographic detail from plan No T 40 of Department of Lands, Mines and Surveys, Suva, Fiji.

MAGO (Fig. 53)

Mago island was examined in detail by Ladd & Hoffmeister. An attempt has been made to adapt the geological boundaries they mapped to a recent, more accurate, base map that was evidently not available at the time they were mapping. The island is interesting in having two ages of volcanic rocks exposed, one older and one younger than the Futuna Limestone. During a short reconnaissance it was not possible to study the geology in any detail. The soils of the island appear to change rapidly with the type of material they overlie.

KATAFAGA

Katafaga is a small island in the central Lau. The south and centre of the island are composed of the Lau Volcanics ; at the north end the volcanics are covered by the Futuna Limestone. A small amount of manganese occurs in cracks and hollows in the limestone.

YACATA (Fig. 54)

Yacata, a large island in the north of the Lau, is considered, from the point of view of administration, part of Cakudrove Province (Vanua Levu). It was not visited by Ladd & Hoffmeister. Figure 54 is an approximate picture of the geology.

Volcanic rocks, commonly with a thick soil cover, occur at the east end of the south coast and form a prominent west-trending ridge which disappears under limestone to the west. The highest point on the island (840 feet, according to the Admiralty Chart) is a prominent narrow ridge of limestone slightly to the south of the centre of the island ; below this the limestone is terraced, but no measurements of the height of the terraces are available. The northern boundary of the main outcrop of volcanics is a prominent linear feature with a high limestone cliff on its northern side ; it is probably faulted. Part of the northern slopes below the highest limestone are thickly soil-covered and are certainly underlain by volcanics.

Kaibu Island, to the east of Yacata and enclosed within the same reef, appears to be a single platform of slightly raised limestone about twenty feet above sea level.

A small occurrence of manganese, similar to the other occurrences in the Lau, was noted on the slope leading to the highest ridge.

CIKOBIA (Fig. 55)

Cikobia is an island about 6 square miles in area north of Vanua Levu, 200 miles from Suva. It is elongated slightly south of east, a trend which links it structurally with the outer Lau islands to the south-east. Clearly it is not related to the well marked north-west trends in the northern part of Vanua Levu. The easterly elongation of Cikobia is continued under sea for some distance at the east end of the island.

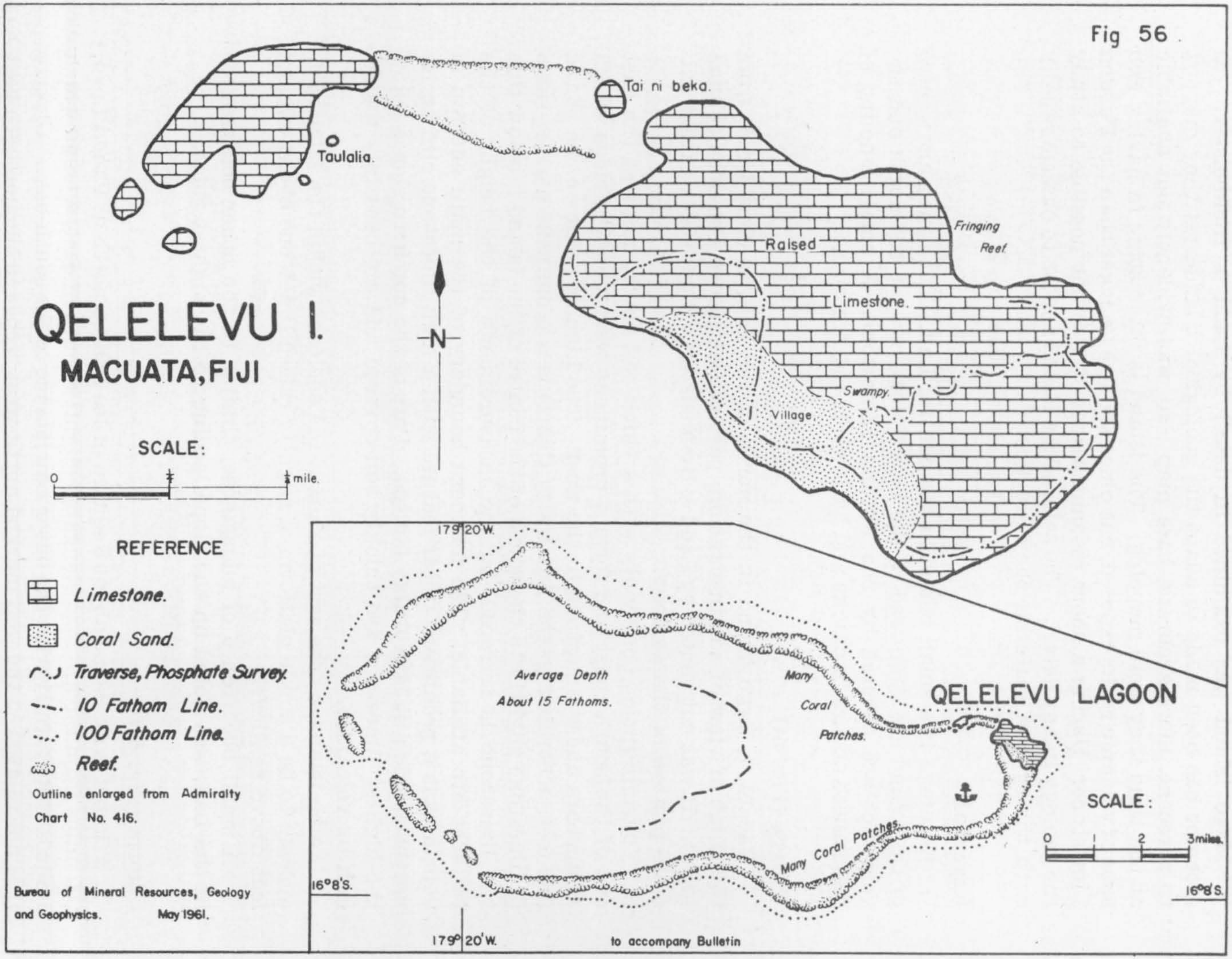


Fig 56.
QELELEVU I.
MACUATA, FIJI
Tai ni beka.
Taulalia.
Raised
Limestone.
Fringing
Reef.
Swampy.
Village.
N
SCALE:
0
¼
½ mile.
REFERENCE
Limestone.
Coral Sand.
Traverse, Phosphate Survey.
10 Fathom Line.
100 Fathom Line.
Reef.
Outline enlarged from Admiralty
Chart No. 416.
Bureau of Mineral Resources, Geology
and Geophysics. May 1961.
179°20'W.
16°8'S.
Average Depth
About 15 Fathoms.
Many
Coral
Patches.
Many Coral Patches.
QELELEVU LAGOON
SCALE:
0
1
2
3 miles.
to accompany Bulletin

The island is composed of limestone and volcanics. The limestone, which is terraced, makes up the west and central parts of the island. It is underlain by the volcanics, chiefly an andesitic agglomerate, which crop out at the east end of the island. The highest point at this end, Nauluvatu, is a residual of limestone resting on the agglomerate.

The limestone appears to have been a thin cover over a steep-sided narrow ridge of volcanic material extruded along an east-trending fissure. The island has subsequently been raised above sea level and terraced, and part of the limestone cover removed.

Some manganese occurs on the island in a similar geological setting to other occurrences in the Lau.

Qelelevu (Fig. 56)

Qelelevu is a very small island at the east end of a large lagoon. The island consists of deeply pitted limestone raised about 20 feet above sea level. There is practically no soil on the island, but the villagers are able to scrape together what little there is in the pockets in the limestone to grow bananas and other crops.

The elongation of Qelelevu lagoon is similar to the trend of Cikobia. The two islands are probably structurally related.

Naitaba

Not enough time was spent on Naitaba to get a clear picture of the geology. The island has not been described previously. It has a basin-shaped interior and is of raised limestone.

THE TONGA GROUP

BY

O. N. Warin

The survey for phosphate deposits in the Kingdom of Tonga was undertaken during the 1959 field season.

Towards the end of August 1959, the survey party was joined by Mr H. E. Fyfe of the New Zealand Geological Survey in Suva, Fiji, and a joint survey of the phosphate prospects of part of the Group was made. The survey was carried out from a 100 ton auxiliary ketch, the A.K. *Maroro*, chartered in Suva. Assistants throughout the survey were S. Ratuyawa and L. Koto of the Geological Survey of Fiji.

The Tonga group, or the ' Friendly Islands ' (Plate 7) as they were once known, consists of more than 150 islands lying between Lat. 18° S and 23° S and Long. 173° W and 177° W. Tonga's nearest neighbours are the Fiji group to the west and north-west and Samoa to the north-east.

The Tongan people number about 35,000 and are a Polynesian people closely allied by their physique, their language, and their customs to the Samoans. There are very few people of other race than Tongan in Tonga ; possibly fewer than 500 Europeans. The Tongans are amongst the tallest people of mankind—the average height of the men being 5 feet 8 inches and of the women 5 feet 4 inches.

There has been some difficulty in the past in the spelling of written Tongan. Different Europeans used different letters to represent sounds in Tongan which are intermediate between two European sounds. For example ' p ' and ' b ' are often interchanged. Here I have used the official spelling of place names. Official spelling includes the glottal stop in such names as Vava'u and 'Eua.

Phosphate Deposits

No phosphate deposits were discovered ; reported phosphate occurrences were investigated and were found to be non-existent.

Phosphate deposits were previously reported to exist at two localities in the Tonga Group—at 'Ata, in the south, and at Hunga Tonga and Hunga Ha'apai towards the centre of the Group (see Plate 7). The Pacific Islands Handbook for 1958 remarks on the presence of phosphate at these two localities ; adding for 'Ata, that the deposits have not been worked owing to the lack of a good anchorage.

A landing was made on 'Ata during this survey. The geology of the island is described in a later section. The cliffs along the west coast and isolated rocks along the south coast are stained by bird droppings. No significant accumulation of guano appears to be taking place ; nor is it likely that it will accumulate on such steep slopes. The interior of the island is a fairly flat platform at about 300 feet above sea level, with a strongly marked ridge rising to 900 feet along the west coast and a less marked rise (500 feet above sea level) towards the north-east corner of the island (see Fig. 57). The flat platform, where phosphate is likely to accumulate, was examined, but no phosphate was found. The reports of phosphate deposits seem to have arisen from the guano stainings on the cliffs and rocks.

The same is probably true of Hunga Tonga and Hunga Ha'apai. Both are very steep islands, the remnants of the rim of a blown out volcano, with steep cliff faces on the inside and gentler slopes on the outside (i.e., towards the north and west). From the sea it is clear that no place exists where large amounts of guano could accumulate ; as at 'Ata, there are a few sea birds and some guano stainings on the north side of Hunga Tonga.

On Lalona Island in the Otu Tolu Group, along the east edge of the Nomuka platform, a few sea birds nest in the trees and their droppings are noticeable on the coral sand of which the island is formed. No accumulation is taking place and no cementation or replacement of the coral sand was seen.

GEOLOGY OF TONGA

The geology of the Tonga Group has previously been reported on by Lister (1891). He divided the islands into those formed entirely of limestone, those formed partly of limestone and partly of tuff, and those purely of volcanic origin. Hoffmeister has written a very full account of the geology of the most interesting island in the Tonga Group—'Eua (Hoffmeister, 1932). He described two limestone and two volcanic formations, the older limestone containing Eocene foraminifera. He also visited other islands in the group but has not published an account of them.

The islands of the Tonga Group (see Plate 7) divide simply into four types :

(a) Volcanic islands
(b) Islands of tuff and limestone
(c) Islands of raised limestone
(d) Vegetated sand cays on coral reefs, with only small areas of raised limestone.

The volcanic islands form a remarkably straight chain more than 450 miles long, from 'Ata (22° 20′ S) to Tafahi (15° 51′ S). Also along this line are a number of shoal patches of less than 50 fathoms depth. Several of the volcanoes have been active within recent historic time, particularly Falcon, active 1885–6 and 1927, Tofua, active 1906 and at present emitting steam, Late, 1854, and Fanualei, 1847, as well as a number of submarine volcanoes along the chain. Falcon, in the 1885 eruption, produced a basic augite andesite (Harker, 1891, p. 257) and in the 1927 eruption a diabasic pyroclastic (Hoffmeister, Ladd, & Alling, 1929). A hand specimen collected from Tafahi during the Capricorn Expedition was thought to be an andesite (Raitt, Fisher, & Mason, 1955). A number of specimens collected on 'Ata appear to be basaltic andesites.

The islands of the other three types occur along the main Tonga ridge, which is separated from the volcanic chain to the west by a shallow trough 15 to 20 miles in width and with a general depth of 700 to 850 fathoms. The islands rise from four large platforms on the ridge between 21° 30′ S and 19° 30′ S ; the Tongatapu platform, the Nomuka platform, the Ha'apai platform and the Vava'u platform—which are outlined by the one hundred fathom contour. The surfaces of the platforms slope gently to the west and they are separated from each other by narrow passages more than 400 fathoms deep. The platforms end rather abruptly to the north and the south.

The islands composed mainly of tuff, type (b), are concentrated on the western side of the two central platforms, Nomuka and Ha'apai. Some have raised limestone exposed beneath the tuff.

The two largest islands in the Tonga Group, Tongatapu and Vava'u, belong to the third type, type (c). Both islands have thick soils covering the raised limestone.

Islands of the fourth type, type (d),—vegetated sand cays on reefs—are usually small and occur scattered throughout Tonga, but particularly they occur along the eastern edge of the Nomuka Group (Telekitonga, Lalona, Telekivava'u, etc.).

'ATA (Fig. 57)

'Ata, the most southerly of the Tonga Group, lies at Lat. 22° 20′ S, Long. 176° 12′ W, 85 nautical miles south-west of Tongatapu. The island has no trustworthy anchorage and even slight swells make landing difficult. It is completely surrounded by cliffs, at the foot of which are boulder screes.

The island is lozenge-shaped, about 1½ miles along each coast. It is a volcanic remnant ; but there is no record of activity during historic time. It is directly on line with the other volcanoes of the Tonga group. A traverse was made along the base of the cliffs on the north-east and north-west coasts into the centre of the island by way of an old landslip on the north-east coast, and across the central platform to the high ridge along the west side.

There appear to have been two centres of eruption : one along the west coast, where the landing was made ; the second, a smaller centre, at the opposite corner of the island. At the main centre dykes are common and the various stacks and pinnacles at the landing appear to be plugs or the remnants of a single plug. The second centre was only seen from the sea, but the lava flows exposed in the cliffs along the south-east coast appear to rise towards it.

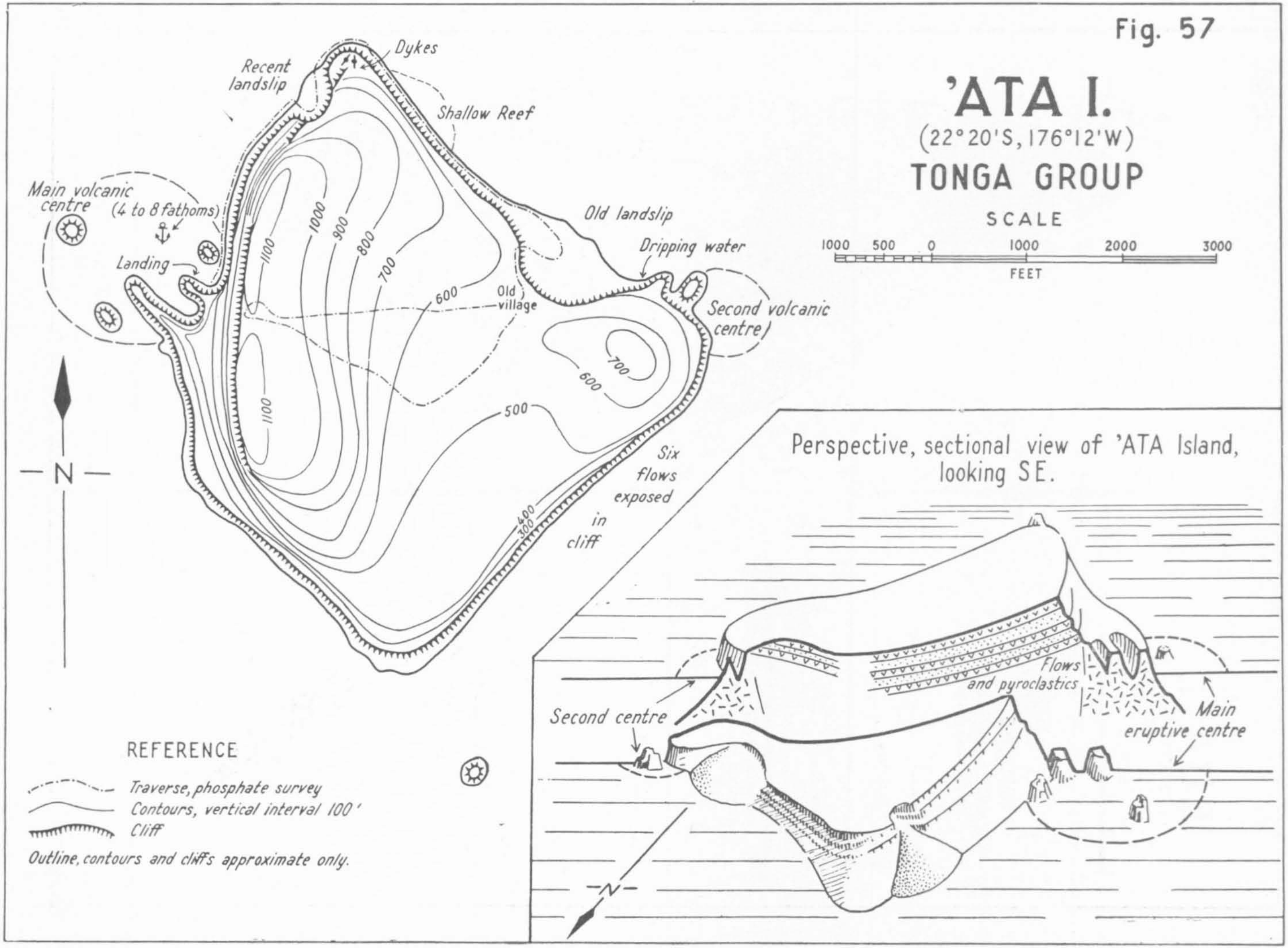


Fig. 57
'ATA I.
(22° 20'S, 176°12'W)
TONGA GROUP
SCALE
1000 500 0 1000 2000 3000
FEET
Recent landslip
Dykes
Shallow Reef
Main volcanic centre
(4 to 8 fathoms)
Landing
Old landslip
Dripping water
Old village
Second volcanic centre
Six flows exposed in cliff
1100
1000
900
800
700
600
500
400
300
N
REFERENCE
Traverse, phosphate survey
Contours, vertical interval 100'
Cliff
Outline, contours and cliffs approximate only.
Perspective, sectional view of 'ATA Island, looking SE.
Flows and pyroclastics
Second centre
Main eruptive centre
N

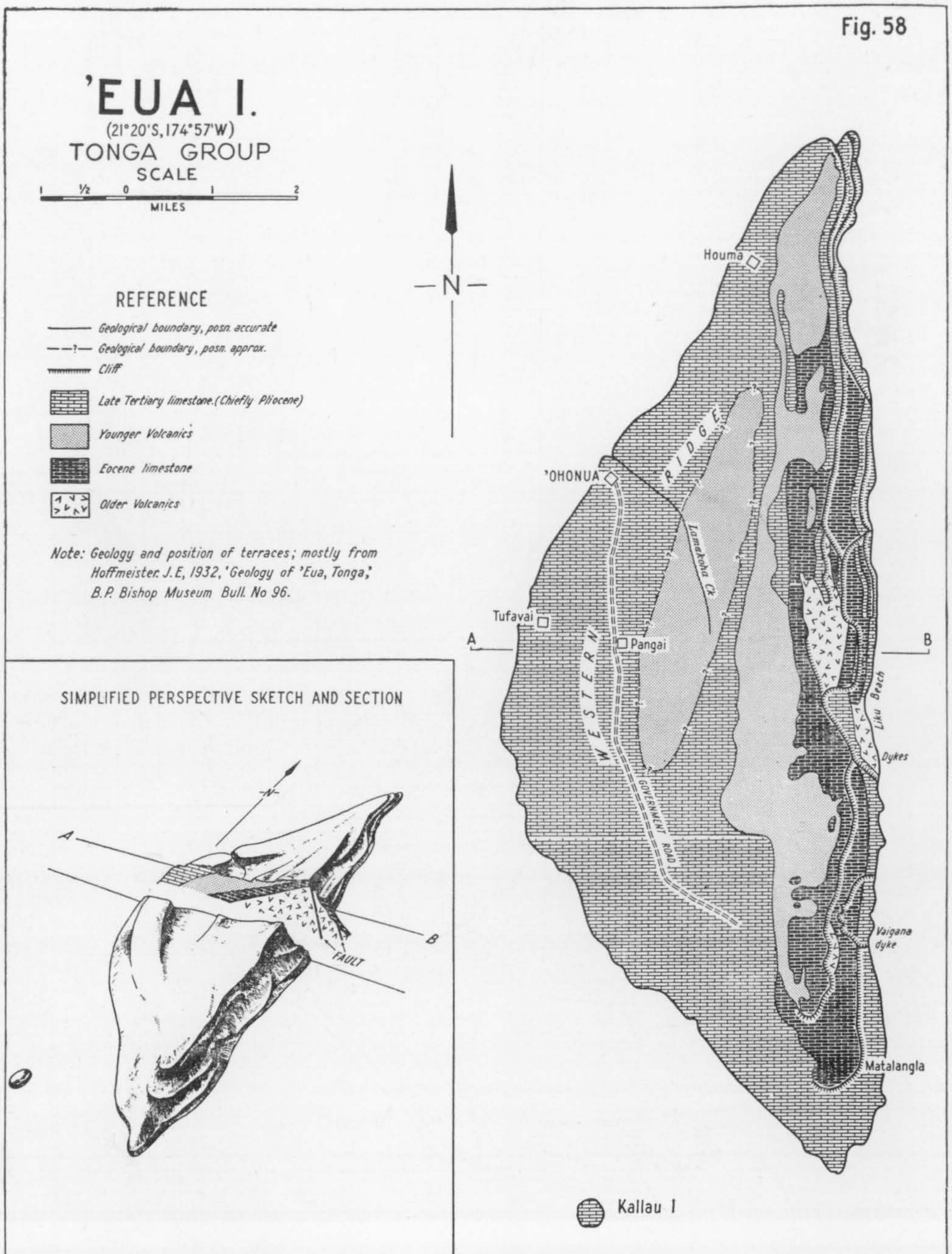


Fig. 58
'EUA I.
(21°20'S, 174°57'W)
TONGA GROUP
SCALE
1 ½ 0 1 2
MILES
REFERENCE
Geological boundary, posn. accurate
Geological boundary, posn. approx.
Cliff
Late Tertiary limestone. (Chiefly Pliocene)
Younger Volcanics
Eocene limestone
Older Volcanics
Note: Geology and position of terraces; mostly from Hoffmeister. J. E, 1932, 'Geology of 'Eua, Tonga,' B.P. Bishop Museum Bull. No 96.
N
Houma
'OHONUA
RIDGE
Lomekoha Ck
Tufavai
A
Pangai
B
WESTERN
GOVERNMENT ROAD
Liku Beach
Dykes
Vaigana dyke
Matalangla
Kallau I
SIMPLIFIED PERSPECTIVE SKETCH AND SECTION
N
A
B
FAULT

A fresh land-slip along the north-west coast exposed a great deal of fresh material from a flow (apparently an olivine andesite) about 40 feet thick. There is much scoriaceous material between the flows, and some agglomerate. Strongly marked cross-bedding was seen in one exposure of agglomerate along the north-east coast about 200 yards west of the old village.

Dykes are common along the north coast. At the north tip three intersecting dykes occur ; one radial to the first centre (230°), one radial to the second centre (310°), and one slightly east of north (05°). The last is a significant direction in Tonga—it is the trend of the line of volcanic islands.

There may be a third centre of activity at the southern tip of the island.

'EUA (Fig. 58)

The geology of 'Eua Island was studied in detail by Hoffmeister (1932). His map, slightly modified, is included here.

Hoffmeister described four formations : (1) the older volcanics, (2) the Eocene limestone, (3) the younger volcanics, (4) the late Tertiary, chiefly Pliocene, limestone.

The older volcanics are exposed at two places where the cover of Eocene limestone has been removed along the rocky backbone of the Island, and at one locality in the centre of the east coast at sea level. The older volcanics consist of tuffs, agglomerates, ash beds, and rhyolitic flows. The high area in the central part of the main ridge appears to have been closest to the focus of volcanic activity. Hoffmeister discovered boulders of diabasic norite along the east coast.

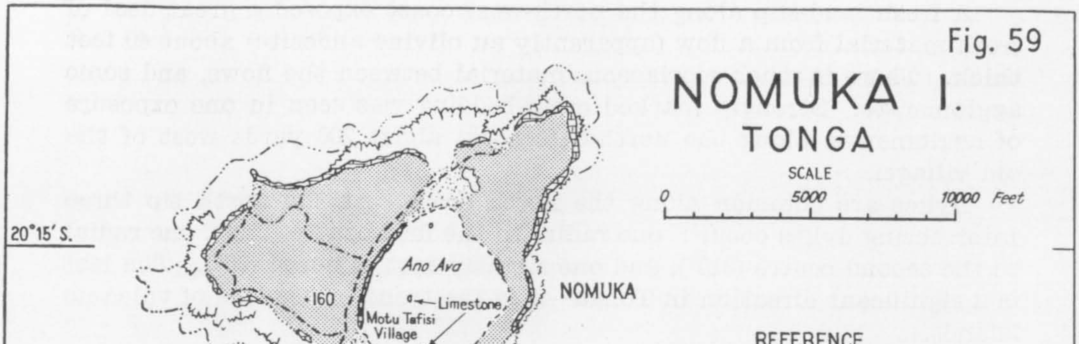
The older volcanics are overlain by a limestone which can be definitely determined as upper Eocene. The limestone consists chiefly of foraminifera, although molluscs and echinoids contribute appreciably to its bulk.

Overlying the Eocene limestone are bedded tuffs which contain numerous foraminifera. Alling (in Hoffmeister, 1932) says that these younger volcanics are similar in composition to the older volcanics, but suggests that the second volcanic outburst was more explosive and produced ash beds with less common flows. They are in turn overlain by a coral reef limestone chiefly of Pliocene age.

During the survey the soils of the central valley and the eastern terraces were examined. No phosphate was found. Hand-auger drilling on the central valley floor showed that the soils there are underlain by weathering tuffs and not by the later limestone, as Hoffmeister believed.

NOMUKA (Fig. 59)

Nomuka and Nomuka Iki (' Little Nomuka ') are two islands close together on the north-west part of the Nomuka platform. Nomuka is a triangular island with sides about 2¼ miles long ; Nomuka Iki is about



1 mile long, and has a maximum width of a little more than ½ mile. About one-third of the interior of Nomuka is taken up by a shallow, salt-water lagoon, four to five feet deep, the Ano Ava.

Nomuka Iki has good exposures of bedded andesitic tuff in a 40-foot cliff along the southern part of its west coast. The tuff there is very soft and deeply weathered, in beds from 1 inch to ¼ inch in thickness.

Hand-auger drilling through the deep soils in the centre of Nomuka indicates that the soil there is underlain by tuff. Raised limestone, about 8 to 10 feet above sea level, crops out round the Ano Ava and forms three small islets in it. It also crops out round much of the coast of Nomuka, except along the low sandy south-west coast, facing Nomuka Iki, and at the northern tip of Nomuka Iki. Just back from the shore the limestone here is covered by a thick soil which appears to be derived from the weathering of tuff.

Tonumea and Kelefesia

These two islands occur in a complex area of reefs and shoals just south of the centre of the Nomuka platform. Both islands are about $\frac{1}{8}$ square mile in area; Tonumea is roughly circular and Kelefesia is elongated north-west.

Fifty feet of poorly sorted, coarse to fine, andesitic tuff crops out in the cliffs on the west side of Tonumea. Manganese nodules occur commonly over the surface of the island, particularly along the top of the north-westerly ridge which forms the cliffs along the west side of the island. The nodules are also found in the present reef.

Kelefesia is very similar to Tonumea; tuff is exposed in the cliffs at the north, south-west, and south-east tips of the island. No manganese nodules were seen on Tonumea. No raised limestone was seen on either island.

Harker (1891) recorded the presence of minute garnets and tourmaline in the tuffs on Tonumea.

Tofua

A few hours were spent on Tofua. The island is a volcano with a lake filling part of the old crater floor. The rim has an average height of about 1500 feet, rising in places above 1600 feet; the water level in the lake is about 140 feet above sea level. The island is roughly circular, with a diameter of about five miles.

The volcano was in active eruption in 1890, and in 1939 it was emitting a great deal of steam. At present the largest of three scoria cones along the north of the central lake is emitting steam.

The flows which make up the main cone are exposed in cliffs along the north coast and appear to be andesitic in composition. No thin sections of specimens collected have so far been examined. The northerly slope of the cone is mostly of loose scoria. The rim along this northern side is triple, and much of the lava exposed is ropey.

Tongua

Tongua is a low, square island in the southern part of the Ha'apai group, with an area of about $\frac{3}{4}$ square mile. Much of the surface of the island is of coral sand only a few feet above sea level; but cliffs of raised limestone 25 feet high line the western coast and thick soil lies above them and spreads out and thins to the east.

Oua

Oua, in the south of the Ha'apai group, is about half a square mile in area, entirely surrounded by cliffs of raised limestone about 25 feet high. Above the raised limestone the surface is covered with a deep soil.

Oua is on a large reef and has a rocky bar of ' beach rock ' dipping to the north; extending out from its western coast are the remnants of an island, Kangalota Island, which existed at the time of the Admiralty Survey, in 1898, but which the villagers of Oua say was destroyed by a hurricane in 1912.

LOFANGA

Lofanga, near the centre of the Ha'apai group, is about ¾ square mile in area and has low cliffs of raised limestone round part of its circumference. The island is covered with a thick soil through which limestone does not protrude. A recently dug well near the village shows an excellent section through 20 feet of loose ash and pumice. A one-foot-thick bed of pumice, about 5 feet from the top of the well, consists of rounded pumice fragments not more than 1 inch in diameter. Limestone is not exposed now at the bottom of the well, which has caved since it was first dug, but the villagers say the limestone occurs at a depth of about 25 feet.

LIFUKA (Fig. 60)

Lifuka is the main island of the Ha'apai Group and has on it the town of Pangai, the third largest town in Tonga and the ancestral home of the Royal family.

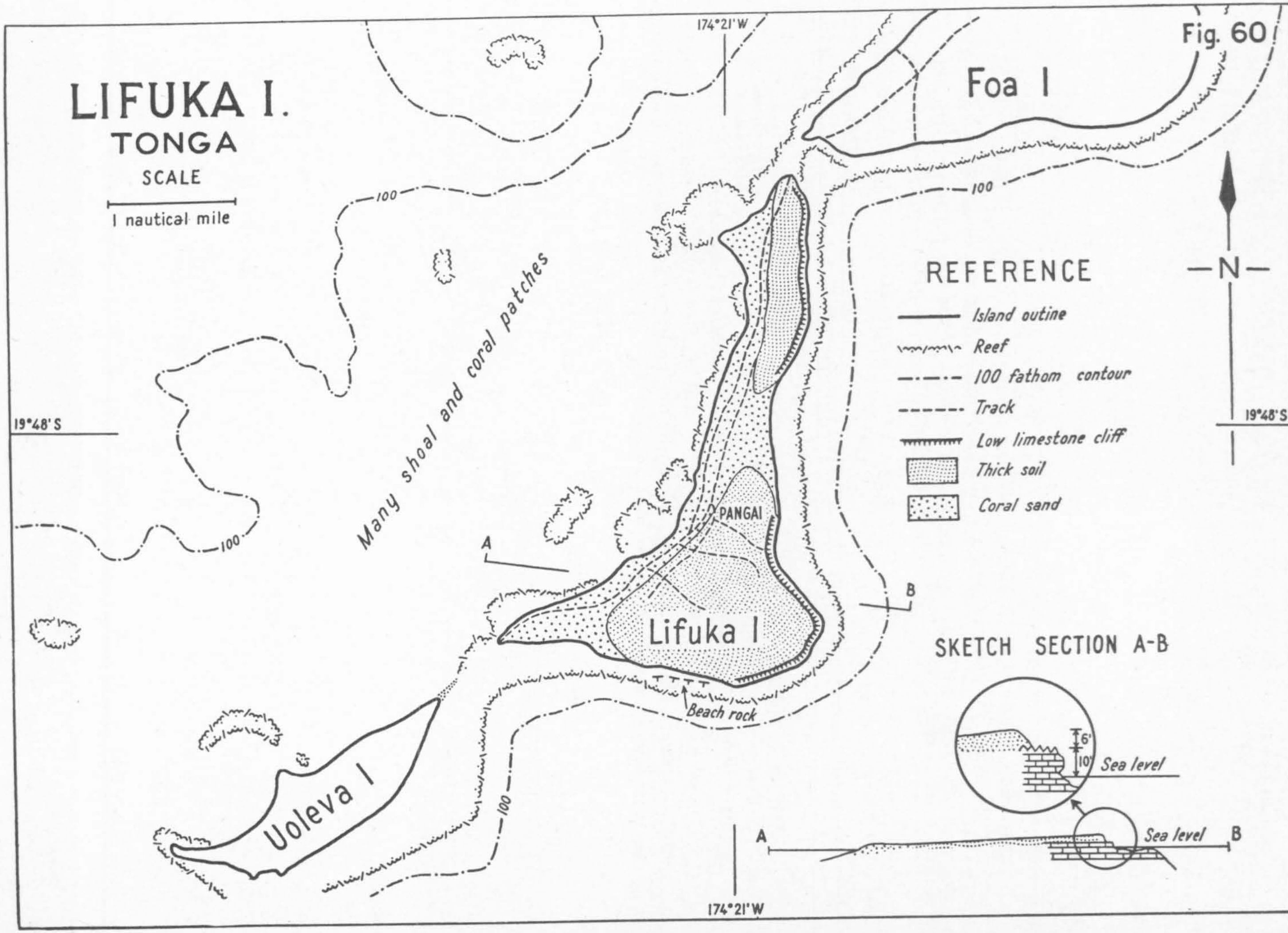
Lifuka is about 4¾ miles long (north/south) and 2¾ miles across at the wide southern end, but only ¾ mile wide for most of its length.

A traverse was made round much of the south coast and across the southern part of the island.

The west coast is generally low and shelving and composed of coral sand. The north and south ends of the east coast have a low, narrow terrace (10 feet high) of raised limestone. Behind this terrace the ground rises gently for a further 6 feet or so. Pumice fragments are very common along the top of this rise. The soil inland is similar to soils seen elsewhere in the group. Along the south coast an exposure of beach rock, apparently marking an old strand-line, curves out from the present beach. This beach rock is black when seen from a distance and in hand specimen is seen to be crowded with fragments of brown clay material similar to the volcanic clay soil on the south-east point.

UIHA

Uiha has the same general form as Lifuka. It is about 2¼ miles long (north-north-east) and about ¾ mile wide. The west part of the island is, as on Lifuka, low and shelving, and composed of coral sand. The eastern half is higher, with a thick yellow-brown clay soil formed from weathering tuff or ash. The north half of the east coast has a 10-yard-wide terrace of raised limestone—highest in the north (about 10 feet above sea level) and becoming gradually lower and narrower until in the centre of the east coast it has disappeared altogether. A bank of soil rises


LIFUKA I.
TONGA
SCALE
I nautical mile
Fig. 60
Foa I
174°21'W
100
Many shoal and coral patches
19°48'S
PANGAI
Lifuka I
Uoleva I
Beach rock
A
B
REFERENCE
Island outine
Reef
100 fathom contour
Track
Low limestone cliff
Thick soil
Coral sand
N
SKETCH SECTION A-B
6'
10'
Sea level
Sea level

gently some six feet or so higher than this limestone terrace and pumice fragments are common along its top. A hand-auger hole drilled near the centre of the island passed through 10 feet of yellow-brown clay with purple flecks before passing into coral sand ; the clay was not phosphatic.

Along the central part of the east coast a $\frac{3}{4}$-inch band of black sand, consisting of augite and olivine crystals, occurs in the present beach.

VAVA'U

The islands of the Vava'u Group form the north end of the main Tonga chain. The group comprises about 40 islands, all close together ; the area of the largest, Vava'u itself, being about 30 square miles. The town of Neifafu, on Vava'u, has a good harbour and is the second largest town in the Kingdom of Tonga. Vava'u is well served with motor roads.

The islands of the Vava'u Group are very different from the other islands in Tonga, as they are of high raised limestone. The highest part of the Group is along the north coast of Vava'u, where the cliffs rise 500 feet from the sea and the highest points are 670 feet above sea level, and at the isolated ridge of Mo'ungalafa on the south-west tip of Vava'u, where the limestone is 610 feet above sea level.

It was not possible, in the time available, to form anything more than a general idea of the geology of Vava'u. The raised limestone is terraced and is covered with a thick mantle of red volcanic ash, probably derived from the activity of such nearby centres as Late and Fanualei. Gardens were spoilt in Vava'u by ash from an eruption of Fanualei in August 1847 and again in 1937 and 1938.

The channels between the various islands are unexpectedly straight and the intersections between the different channels unexpectedly angular—the channels may be situated on a series of north-east and north-west fractures.

ISLANDS OF THE NORTHERN TERRITORY OF AUSTRALIA

BY

O. N. Warin

Mr W. F. McQueen visited a number of islands off the coast of the Northern Territory during July and August 1957 and Cartier Island and the islands of the Ashmore Reef during August 1958. Only one, very small deposit of phosphatic crust was discovered, on the Ashmore Reef. This section is based on the unpublished report of McQueen's inspection (McQueen, 1958).

McQueen travelled to the islands close to the Northern Territory coast by hired motor launch, spending a few hours on each ; the visit to Cartier and the Ashmore Reef was made aboard H.M.A.S. *Cootamundra* by courtesy of the Royal Australian Navy.

Islands tested during the 1957 investigations are shown on Fig. 61 ; they fall into three groups :

1. Croker Island and the nearby islands.
2. The Crocodile Islands and
3. The Wessel Islands and islands in the Gulf of Carpentaria.

Croker and Adjacent Islands

These islands are composed of remnants of almost flat-lying Cretaceous sediments lying disconformably on an almost flat-lying basement of quartzite, probably of Upper Proterozoic age.

On Sims Island, where the basement is exposed, massive quartzite, in places graded-bedded and cross-bedded, with thin lenses of quartz pebble conglomerate, dips at 1° to 2°. The quartzite has a well developed joint pattern ; the two sets of joints strike 305° and 035°.

The Cretaceous remnants have a maximum elevation of about 70 feet and are generally strongly lateritized. The thickness of the laterite ranges from a thin cover of about one foot to a complete profile 60 to 70 feet thick. Practically all the laterite is tubular, the pisolitic zone having been eroded away ; but pisolitic and bauxitic laterite has been reported from the northern part of Croker Island.

No phosphate was found on any of these islands. A pile of coral washed up on Croker Island showed only a trace of phosphate. The topography and geology of the islands make them very unlikely phosphate prospects.

The Crocodile Islands

The Crocodile Islands are a group of very low-lying islands not more than nine to ten feet above sea level. Each island is flat but has an outer rim slightly higher than the centre. The islands are part of an old deltaic region. Laterite is exposed at the surface but a bore hole on Millingimbi has shown that the quartzite basement is present at depth. No phosphatic material was located during the survey.

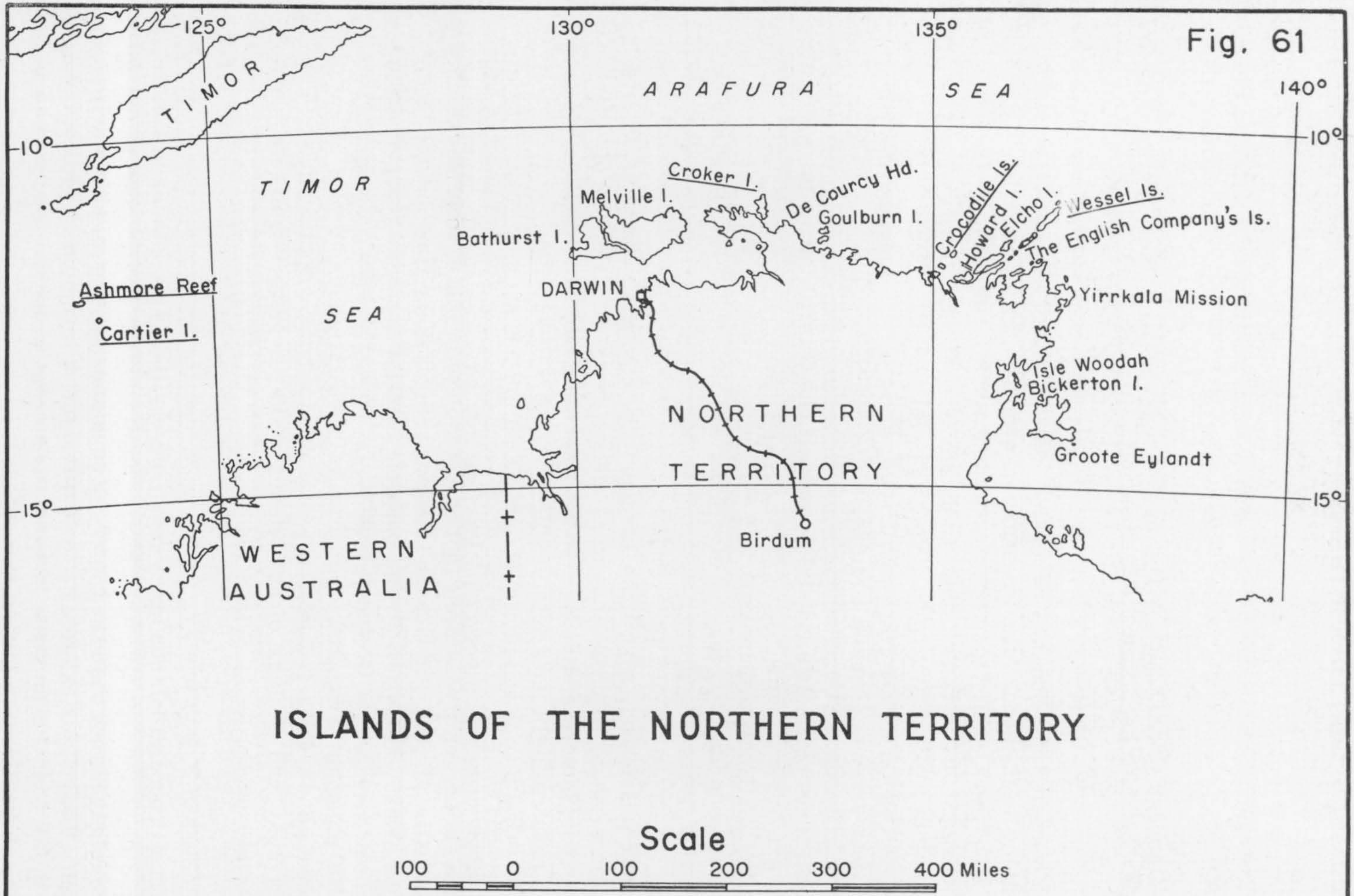


Fig. 61

ISLANDS OF THE NORTHERN TERRITORY

The Wessel Islands and islands in the Gulf of Carpentaria

Interbedded feldspathic sandstone, quartzite and boulder conglomerate, probably of Upper Proterozoic age, are exposed on these islands. Dips of up to 15° are seen ; the configuration of the Wessel Islands is the result of the outcrop of two thin quartzite beds dipping gently to the north-west. The surface of the islands is a dip slope ; cliffs rise vertically out of the sea to as high as 200 feet on the east coast and slope gently down the two or three miles to white sand beaches along the north-west coast.

Cross and current bedding, ripple and wave marked sandstone are visible, particularly in the islands near Groote Eylandt.

The rocks have been lateritized but most of the laterite has been eroded. Raised beaches and wave-cut platforms show that sea level has fallen about 8 to 10 feet in recent times.

No phosphate was discovered.

Islands in the Ashmore Reef, and Cartier Island

The Ashmore Reef (approx. 12° S, 123° E) and Cartier Island (12° 31′ S, 123° 29′ E) rise from the western corner of the Sahul Shelf, the extension of the Australian continental shelf which lies below the south-western part of the Timor Trough.

Ashmore Reef is roughly triangular in shape ; the south and east sides of the triangle are unbroken but the north-west side is broken by two or three major channels. A long bar of sand and coral debris running across the reef from west to east is exposed at low tide, and at high tide this bar forms four islands (East, Middle, unnamed, and West Island).

Colonies of birds live on the islands and reaction between solutions from their droppings and the shelly material of the sand bar has led to a slight phosphatization of the upper layers.

McQueen reports that thin layers of cemented material on East and West Islands have an average grade of 24% P_2O_5 ; but the total tonnage of the material is not more than 100 tons. The upper 1½ feet of the materials of the islands generally shows phosphatic enrichment (average between 4% and 5% P_2O_5) and there is probably about 270,000 tons of this material on the three islands East, Middle, and West.

Cartier Island is of shelly sand with a small area of consolidated material. Specimens of this material did not show more than 1% P_2O_5.

ECONOMIC SIGNIFICANCE OF THE PHOSPHATE DEPOSITS

BY

O. N. Warin

Australia's Phosphate Supplies

Sales of superphosphate in Australia during 1962 reached a record level of 2,710,247 tons. This superphosphate was almost entirely manufactured from 1,694,108 tons of phosphate rock imported from Nauru, Ocean, and Christmas Islands.

Most of Australia's soils are deficient in phosphorus and as agriculture expands and becomes more intensive there is an increasing demand for cheap superphosphate. At the moment this demand can be met by our imports of high-grade, low-cost phosphate from these islands. The life of these deposits is limited, however, and the cost of exploitation is likely to increase in the last years of their lives because the areas then being worked will be less accessible.

The predicted life of the deposits on these three islands is in the region of 30 years at the present rates of extraction. As they become exhausted Australia will have to buy phosphate rock on the world market unless she can find new deposits.

The deposits examined during this survey have not altered the position with regard to supplies of high-grade insular phosphate rock. *Bellona Island*, the largest deposit examined, could provide at most about 500,000 tons of medium-grade material ; less than a third of Australia's needs for one year. The second largest deposit of medium-grade material occurs on Vanua Vatu, Fiji (200,000 tons).

To understand the requirements of the superphosphate manufacturer it is necessary to outline briefly the phosphate fertilizers, their composition and their action (Table 6).

Natural Phosphate, Available Phosphate, and Superphosphate

The process of superphosphate manufacture makes the phosphate of *natural phosphates* (such as phosphate rock, apatite, bone and dry guano) available to plants by making it soluble in water. In natural phosphates much of the phosphate is combined with calcium and is practically insoluble. If natural phosphates are applied directly to the soil, however, particularly if they are first finely ground, the phosphate becomes slowly available through the action of soil acids.

So called *available phosphates* are produced as by-products of industrial processes (notably the basic slag produced when iron is smelted from phosphatic ores) or by specific processes, such as calcining and defluorination of phosphate rock. These phosphates are only sparingly soluble in water, but readily dissolve in weakly acid solution such as are present in some soils. Their value to crops is not universally accepted ; certainly the phosphate in them is not readily available to the

Table 6

PHOSPHATE FERTILIZERS

Type of Fertilizer	Source	Composition	Solubility	Percentage P_2O_5	Rate of Action
Natural phosphates	Phosphate rock .... Apatite (crystalline) Bone Dry guano	Mainly calcium phosphate	Phosphate insoluble, becomes slowly available in acid soil	Variable	Slowly acting. Best in acid soils or under water
Available phosphate	Basic slag .... Calcined phosphate rock De-fluorinated phosphate rock	Mainly calcium phosphate	Phosphate, sparingly soluble but soluble in weak acids	Variable	Slowly acting. Best in acid soils
Superphosphate	Manufactured from phosphate rock by acidulation with sulphuric acid	Acid calcium phosphate	Soluble phosphate	15 to 23	Very fast acting, large proportion of phosphate wasted after heavy rain
Triple superphosphate	Manufactured from phosphate rock by acidulation with phosphoric acid		Soluble phosphate	40 to 50	Very fast acting

plant as it is from superphosphate. The strength of these 'available phosphate' fertilizers is expressed as their solubility in a 2% solution of citric acid or neutral ammonium citrate.

In *superphosphate* manufacture raw phosphate rock is treated with sulphuric acid and the insoluble tricalcium phosphate of the raw rock is converted to a mixture of the monocalcium phosphate and gypsum: $Ca_3(PO_4)_2 + 2H_2SO_4 + 6H_2O \Rightarrow CaH_4(PO_4)_2 + 2H_2O + 2(CaSO_4 \cdot 2H_2O)$. This is the basic reaction, but the chemical composition and the nature of the superphosphate differ slightly with the composition of the original rock. Superphosphate contains less phosphate than the phosphate rock from which it is manufactured (for example, phosphate rock of 34 to 38% P_2O_5 yields superphosphate of 17 to 23% P_2O_5), but the phosphate is soluble.

Triple Superphosphate (containing 40% to 48% P_2O_5) is prepared by acidulating phosphate rock with concentrated phosphoric acid instead of sulphuric acid. It is a popular fertilizer in America, where its low bulk per unit of available P_2O_5 cuts down freight costs, although the direct cost per unit of available P_2O_5 is higher.

The relative value of natural phosphates, available phosphates, and superphosphate as fertilizers varies greatly with the type of soil to which they are applied and with the amount of rainfall. The rapid increases in plant growth and crop yield associated with the use of superphosphate are not generally found with the slower acting fertilizers. However, some soil scientists claim that the slower acting fertilizers are in the long run as effective as the highly soluble fertilizers and more economical because proportionately more phosphate is lost by fixation when a water-soluble phosphate is applied to a soil. (Fixation is a process by which soil constituents, notably free iron oxides and alumina, form insoluble compounds with the phosphate.) Soluble phosphates may produce a strong solution of phosphate, much of which is washed through the soil and fixed by precipitation at lower soil horizons. Sparingly soluble phosphates, on the other hand, under suitable conditions, release P_2O_5 at a rate more nearly conforming to the rate at which the plant can use it, so that proportionately less is washed through, precipitated, and lost to the plant.

Requirements of Phosphate Rock for Superphosphate Manufacture

In most phosphate rock, the phosphate is chemically combined with calcium and to a much smaller extent with iron and aluminium. The superphosphate manufacturer objects to rock with a high iron and aluminium content for two reasons:

(1) These impurities give rise to hygroscopic products which clog seed drills when the superphosphate is spread;

(2) They cause reversion of the phosphate to an insoluble form (C.S.I.R.O., 1943).

There is, however, considerable difference of opinion as to the maximum amount of iron and aluminium that can be successfully handled in rock for superphosphate manufacture. Various authorities estimate from 2% to 5% total iron oxides and alumina. Pebble phosphate and rock phosphate from Florida has between 23% and 36% P_2O_5 and between 1% and 4% iron oxides and alumina, but is generally sold with a guarantee of not more than 3% iron oxides and alumina. In the ' black rock ' phosphate of Arkansas, the percentage of iron oxides and alumina is as high as 9·5, and in the ' brown rock ' and ' blue rock ' phosphates of Tennessee upper limits of 8% and 7% are reported (Waggaman, 1952), although Tennessee rock is apparently not sold with more than 6% iron oxides and alumina. It is generally agreed that increased care and experience are necessary to process successfully rock with high iron oxides and alumina content. Phosphate rock from Ocean Island and Nauru generally contains less than 1% total iron oxides and alumina, and generally the maximum accepted by superphosphate manufacturers in Australia is 3%, although during the war rock with up to 6% of these impurities was accepted. A slightly higher iron and alumina content is acceptable in the phosphoric acid process for manufacture of triple superphosphate.

Another common impurity in phosphate rock is calcium carbonate. When this impurity forms about 5% of the rock the carbon dioxide formed during the acidulation has a desirable leavening effect on the superphosphate formed. If more than 5% calcium carbonate is present, acid is wasted by reaction with it.

Natural phosphates also contain significant amounts of fluorine ; for example Florida phosphate has up to 4·4% CaF_2 ; Ocean Island phosphate 1% ; Christmas Island phosphate 3·44% ; and Morocco phosphate from 5·2% to 9·4%. The amount of fluorine present appears to control the solubility of phosphate in natural phosphates and some processes are in operation or proposed which produce available phosphate by defluorination of natural phosphates.

Deposits Examined during this Survey

The deposits examined during this survey are summarized in Table 7. What follows is an amplification of the information presented in that table.

The deposits can be considered in three categories :

(1) Deposits which may be exploited and exported beyond the island groups in which they occur ;

(2) Deposits which may be exploited for use within the island group in which they occur ;

(3) Deposits which are so small that they can be ignored.

Deposits which may be exploited and exported.—The only deposit which clearly belongs to this category is the Bellona deposit. The oolitic phosphate has an average grade of 30·3% P_2O_5 and the average combined iron oxide and alumina content of four samples was 15·25%. The oolitic phosphate is bound in a matrix of clay which contains the bulk of the alumina and iron oxides. The grade could certainly be improved by screening or washing to remove this clay fraction.

There does not seem to be any immediate prospect of utilizing the phosphatic clay which makes up the bulk of the Bellona deposits for the manufacture of superphosphate, although it must be regarded as a reserve of phosphate. Interest centres on the higher grade phosphate which occurs in the deepest part of the deposit, towards the east end (Deposit T, Plate 2). This part of the deposit contains about 300,000 tons of medium-grade phosphate under an average 10 feet of phosphatic overburden in a single basin. There are also about 200,000 tons of oolitic phosphate in deposits at the east and west ends of the central valley (Deposits X and F of Plate 2), so that altogether 500,000 tons of medium-grade material are available.

This does not significantly affect Australia's supply position, but it may prove sufficiently large to merit exploitation for export beyond the British Solomon Islands Protectorate.

The deposits of Vanua Vatu amount to 200,000 tons of medium-grade oolitic phosphate. These are included in the second category but may possibly prove worthy of export from Fiji.

Deposits suitable for Local Use.—In this category fall the deposits on Vanua Vatu, Ogea Driki, and Tuvuca in Fiji, and Nauna, Manu, Sae, and the Purdy Islands in New Guinea.

Vanua Vatu and *Ogea Driki* have similar types of oolitic phosphate deposits with some phosphatic clay. They could possibly be beneficiated by screening to remove the clay fraction. Together they make up about 170,000 tons of easily recoverable medium-grade phosphate with a further 100,000 tons of more doubtfully recoverable material.

The phosphate occurs, with no overburden, between pinnacles of limestone. It is like a loose gravelly sand and could be easily dug up and bagged by the villagers. On Ogea Driki most of the surface of the deposit is under cultivation but probably the loss of cultivable land would not be serious as the island is uninhabited and nearly all the rest of the island is uncultivated. On Vanua Vatu the area of the main phosphate deposit (Area A on Plate 6) is at present planted with coconuts, but with very little else as the villagers find the oolitic phosphate is unsuitable for the planting of root vegetables. Most of the gardens seem to be in the Sapuga and Bukidalivou areas and on the phosphatic clay of Area 'C.' The Maumi deposit and Area 'B' could probably be exploited without seriously reducing the amount of land under cultivation.

Table 7

PHOSPHATE DEPOSITS

Group	Island	Type of Deposit	Availability	Tonnage	Average Grade ($\%\ P_2O_5$)	Anchorage
British Solomon Islands Protectorate	Bellona	Clay	Ready	4,600,000	22·3	Poor
		Incoherent phosphate, some coherent phosphate	Ready in part	400,000	30·3	
Fiji	Vanua Vatu	Phosphatic clay	Doubtful			
		Oolitic phosphate		200,000	24	Fair
	Ogea Driki	Oolitic phosphate and phosphatic clay	Ready	77,000	25	Good
	Tuvuca	Phosphatic clay	Difficult	1,000,000 to 2,000,000	1 to 25	Medium
	Vatoa	Phosphatic clay	Too scattered	Small	....	Good
	Vatu Vara	Phosphatic clay and oolitic phosphate		Very small	....	None
Papua/New Guinea (Admiralty Group)	Nauna	Oolitic phosphate	Difficult	15,000	32·5	Poor
		Clay		125,000	15·9	
	Aua	Phosphatized lime sand	Ready	Small	....	Poor
	Wuvulu	Phosphatized lime sand	Ready	Small	....	Poor
	Manu	Phosphatized lime sand	Ready	15,000	26·5	Poor
		and phosphatic mud	Ready	11,000	31·5	
	North & South Bat	Phosphatized lime sand	Ready	48,000	27·5	Fair
		and phosphatic mud	....	1,200	38·0	
	Sae	Phosphatized lime sand	Ready	70,000	23	Poor
Gilbert and Ellice	Tamana	Phosphatized lime sand	Difficult, scattered	75,000 to 100,000	15 to 20	None
	Tabiteuea	Phosphatized lime sand	Ready	5,000	(approx.) 18	Poor
	Abemama	Phosphatized lime sand	Ready	5,000 to 10,000	20	Good
	Nui	Phosphatized lime sand	Ready	3,000	10 to 15	None
	Nukufetau	Phosphatized lime sand	Ready	5,000 to 10,000	15	Good
	Vaitupu	Phosphatized lime sand	Ready	25,000 (max.)	20	None
				10,000 (max.)	10 to 15	
Off Northern Australia	Ashmore Reefs	Phosphatized sand	Not known	270,000	4 to 5	Not known

Ogea Driki has a good anchorage in the lagoon between the two islands, Ogea Driki and Ogea Levu. The phosphate deposits are along the north coast of Ogea Driki facing the lagoon, and very conveniently placed. Vanua Vatu has a poor and rather exposed anchorage in a bight in the reef along the north-west coast. The phosphate deposits are not more than a quarter mile from the shore. The track to the central basin, the Maumi basin, is well made and has only a moderate gradient.

Some examination of the cost of local exploitation of these deposits is warranted. The phosphate could be dug and bagged by the villagers and shipped to Suva in the same way that manganese ore is dug and shipped from some of the Lau Islands at present. Three possible ways of using the phosphate which should be explored are :

(1) By direct application after fine grinding ;

(2) By direct application on wet rice-fields ;

(3) For local production of superphosphate or triple superphosphate.

The deposit on *Tuvuca Island* contains a large tonnage of low-grade discontinuously phosphatized clay. The highest grade material appears to be that in the main ' Qilo ' at the north end of the central valley. Tuvuca is topographically a rugged island—the final 50 feet or so of the track from the village over the rim is sheer and much of the lower part of the track is very steep. The island is one of the larger islands in the Lau and haulage would be a major problem in exploiting the deposit. The value of deposits of this type will depend on finding some cheap way of utilizing aluminous phosphate.

Islands in New Guinea which have deposits which might be worked locally are Nauna, Sae, Manu, and the Purdy Islands.

Nauna has a small deposit of phosphatic clay and oolitic phosphate on the old lagoon floor. The island has only a very poor anchorage and the climb over the rim to the old lagoon floor (200 feet) is steep and in places, almost sheer. The same considerations hold for Nauna as for Ogea Driki and Vanua Vatu ; except that on Nauna the total amount of oolitic phosphate present is small—probably about 15,000 tons.

The cemented phosphate of Sae, Manu, and the Purdy Islands is equivalent to about 134,000 tons with an average grade of 24·9% P_2O_5. On these islands the phosphate is very easy to remove, handle, and transport because the islands are so small. None of these islands has inhabitants at the present, however, and all have very poor anchorage and landings.

The cemented phosphate of the Gilbert and Ellice amounts to about 130,000 tons in all, in widely scattered small deposits. The relatively insoluble phosphate of these deposits would be valueless for local use by direct application and their removal might well be detrimental to existing coconut plantations.

The Utilization of Aluminous Phosphatic Clay

The Bellona phosphatic clay commonly contains between 9 and 10% Fe_2O_3, up to 40% Al_2O_3, and an average of 22·2% P_2O_5. Material of similar composition is known from other islands and from other parts of the world and attempts have been made from time to time to find ways to utilize phosphate of this type.

In some countries material high in alumina as well as phosphate has been applied directly to soils. In Japan the aluminous phosphatic clay of Kito Daito Jima was used in this way (Yoneyama, 1923, quoted in Hutchinson, 1950). At present the fine fraction of Christmas Island phosphate, containing the bulk of the aluminous and iron phosphates, is exported to Malaya for use as a direct-application fertilizer. Work by Cassidy (1952) suggests that Ogea Driki material (which is oolitic phosphate with some clay) may be useful for direct application on rice paddies. For direct application to be successful a high rainfall and acid soil appear to be necessary.

The 'availability' of the phosphate in some aluminous phosphates is improved by calcining. This process has been used in a number of countries, notably in Japan and in France, to produce fertilizers in which the phosphate is soluble in acid. Tests on the Bellona phosphatic clay have been made by the Mineral Resources Division of the Overseas Geological Surveys. Calcining for two hours at 550°C. renders virtually all the phosphate of the clay specimens tested 'available' (that is, soluble in neutral ammonium phosphate solution), compared to the one and two percent of the original samples. This change is due to the breakdown of the mineral crandallite ($Ca\ Al_3\ (PO_4)_2\ (OH)_5\ H_2O$) and it would appear from the completeness of the change that much of the phosphate of the clay is present as crandallite. This is confirmed by X-ray determinations. The iron and some of the alumina probably occur as the oxides and could possibly be removed relatively easily.

As yet no markets exist in Australia for an 'available' phosphate fertilizer of this type.

A third possibility for the utilization of the aluminous phosphate is in the manufacture of fused phosphates and phosphoric acid. Material from Bellona is at present being examined in America with a view to determining its possible use as a raw material for phosphoric acid production, but probably only the better grade material could be so utilized.

Fixation of soluble phosphates in soils has been mentioned in other parts of this Bulletin. It occurs when free iron oxides and alumina form insoluble compounds with soluble phosphate in the soil. Soil chemists have for a number of years been examining this problem to see if a way can be found to prevent fixation and also to make available to plants phosphate previously fixed in this way. Any major developments in this field could speedily change the status of aluminous phosphates as a source of phosphate.

THE FORMATION OF INSULAR PHOSPHATE DEPOSITS

BY

W. C. White

In considering their origin and mode of formation and preservation the insular phosphate deposits can, for convenience, be grouped into four broad classes.

(1) Avian guano deposits.
(2) Phosphatized sands on cays and atoll islands (phosphatic guano).
(3) Ferruginous-aluminous deposits on elevated limestone islands.
(4) High grade phosphate-rock deposits on elevated limestone islands.

Avian Guano Deposits

The distribution and extent of modern and recent guano deposits formed from the excreta of breeding sea-birds (cormorants, boobies, pelicans, etc.) are apparently closely controlled by oceanographic and climatic conditions. The largest and most important deposits occur, in general, under relatively arid conditions in regions where upwelling of cold, deep ocean waters provides the nutrient to supply a large marine biological population on which vast numbers of birds can subsist. Where suitable breeding grounds are scarce and of restricted area, great quantities of guano can accumulate rapidly. Under ideal conditions the rate of deposition of modern deposits can be as high as 8 to 10 cms. per year, while the ancient Peruvian deposits can be shown, from archaeological and stratification studies, to have accumulated at an average rate of 2 to 2·7 cms. per year (Hutchinson, 1950).

Fresh guano is rich in both nitrogen and phosphorus. Under extremely arid conditions, such as exist on the west coasts of South America and South Africa, guano is stable and may persist for centuries without any noticeable change. Where rainfall is high, or heavy rainstorms are frequent during the breeding season, on the other hand, guano is quickly decomposed and washed away, and no accumulation can take place.

Under less extreme conditions four processes may operate.

(1) Decomposition in situ, partly by bacterial activity, with loss of organic matter and ammonia. This process is accelerated by warm, humid conditions.
(2) Removal, by percolating waters, of the more soluble constituents, the oxalates, urates, alkalis, and some of the phosphates.
(3) Precipitation by percolating waters of various salts, including the sulphates, oxalates, and phosphates of alkalis and ammonia.
(4) If they are not lost to the ocean or precipitated by evaporation, the percolating solutions may attack the underlying rock, producing metasomatic phosphatization.

Phosphatized Sands on Cays and Atoll Islands

The cemented and phosphatized carbonate sands of the low-lying atolls and sand cays occur mainly as a thin crust overlying unconsolidated foraminiferal-coral sands. The degree of cementation and replacement varies considerably ; all the deposits examined appeared to be of very recent origin.

The structure of the replaced sand is commonly well preserved, particularly near the base of the deposits, where replacement may be least intense ; many recognizable foraminiferal tests are present, the commonest being the reef-dwelling form *Calcarina.* The deposits commonly grade downwards into unaltered sands which clearly have not been submerged since their deposition, and the phosphatization must have resulted from solutions leached out from avian guano.

Hague (1862) gave the first description of phosphatized sands of this type in his account of Baker's, Jarvis, and Howland Islands. He suggested that the phosphatic crust had been formed from guano during periodic flooding by heavy rains. Hutchinson (1950), however, pointed out that under these conditions the guano and the solutions derived from it would most probably be lost to the ocean and that a fairly dry climate was necessary for preservation of the phosphate. He accounted for the distribution of the deposits and the presence of phosphatic crusts on wet islands by post-Pleistocene climatic changes.

Fosberg (1957), noting the almost neutral reaction of fresh guano and the strong smell of ammonia prevailing in modern rookeries, suggested that the theory of direct reaction of acid guano with calcareous sands and limestone was untenable. Finding that indurated sedimentary phosphate deposits overlying lime sands in the Marshall Islands occurred only under a layer of peaty humus, he put forward the idea that reaction with calcium carbonate could only take place where the guano had been deposited on, and washed through, a layer of acid humus. Acid humus, however, is rare on low-lying tropical islands and in the Marshall Islands occurs only under one tree, *Pisonia grandis*, which is also the favourite nesting place of many seabirds. Since he found no phosphate where *P. grandis* was not growing, Fosberg concluded that the *Pisonia* forests provided a means of fixing and holding phosphate which would otherwise be washed away, and that the distribution of *P. grandis* rather than climatic changes was responsible for the somewhat irregular distribution of these ' atoll phosphate rock ' deposits.

Observations during this survey seem to indicate that both views may be partly correct. The size and distribution of the deposits in the Gilbert and Ellice Islands and, to a lesser degree, those in Fiji and the New Guinea area, seem definitely to be related to rainfall distribution and incidence. Most deposits of this type were found on islands which have a notoriously unreliable rainfall even though the total annual rainfall may, on occasion, be high. On the other hand, acid humus was commonly found associated with the deposits.

Fresh guano, it is true, is essentially neutral, but the unpleasant ammoniacal smell associated with such deposits does not normally persist for long. Dixon (1878b) showed that on Malden Island the odour of ammonia disappeared from guano deposits within three months of the end of the breeding season without rain having fallen. Ammonia loss and bacterial decomposition of the guano would leave a slightly acid residue, particularly if acid humus was also present. Heavy rainfall might result in mechanical removal of most of the guano at any stage, but a long dry period between rainstorms would, provided the air was warm and humid, promote decomposition in situ and, after rain had fallen, reactions between slightly acid phosphatic solutions and the under-lying carbonate sand would take place.

A feature of most of the atoll deposits examined in the South-west Pacific area is the absence of any transitional zone between guano and phosphatized sand. Only on Marakei Island in the northern Gilberts was a phosphatic crust seen in association with small amounts of fresh guano, but even here no transition from one to the other could be seen. Similarly, Sae Island, to the north of New Guinea, was reported, in 1958, to be a particularly malodourous place inhabited by a very large number of breeding sea birds. Yet less than a year later, at a time when few birds were present, no guano accumulation was visible and only phosphatized sand and coral debris were found.

On ' wet ' islands with a high and reliable rainfall only traces of phosphate were found, usually as weakly phosphatic muds (e.g. Funafuti ; Marshall Bennett Islands). On some islands with a moderate to low rainfall, phosphatized sand was found to be overlain by a thin layer of phosphatic mud (e.g. South Bat in the Purdy Islands) which is similar to guanos found in the Line and Phoenix group, on islands which were undergoing phosphatization (guano deposition) at the time of their discovery. On very dry islands or those with a very unreliable rainfall such as in the Gilbert and Ellice groups patches of phosphatic crust, possibly once of much greater extent, were commonly found to be preserved under thick scrubby vegetation or low branching trees where the ground was continually damp and some humus was accumulating.

Consideration of these facts and the published descriptions of other similar deposits (mainly from Hutchinson, 1950) leads to the conclusion that the phosphatized sand deposits are the result of in situ decomposition of guano under warm arid conditions. Slightly acid solutions leached from the decomposed guano during a subsequent rainstorm react directly with the underlying carbonate rocks, the rainwater playing an active role in the metasomatism. The insoluble residues and organic constituents of the guano may in many instances be removed from the deposit by the rain, so that no transition from guano to phosphatized sand remains. Where the guano was deposited with acid humus, decomposition and phosphatization may be greatly accelerated.

Ferruginous-Aluminous Deposits on Elevated Limestone Islands

Low-grade phosphate deposits of this type seem to be relatively common in the tropical Pacific. The deposits on Bellona Island, Nauna, and the Lau Islands of Fiji are mainly of this type, and similar deposits have been described on Tiga in the Loyalty Islands (Koch, 1957), Angaur, Fais, Rota, Saipan, Peleliu, Kita Daito Jima, etc., in the north-west Pacific (Hutchinson, 1950; Irving, 1953; Rodgers, 1948, etc.). Many phosphatic clays of too low grade to be termed phosphate deposits also belong to this class.

Nugent (1948) pointed out that while the great deposits of high-grade phosphate occurred on elevated limestone islands with a flat or only slightly saucer-shaped profile, deposits of low-grade phosphatic clays rich in iron and alumina were almost entirely confined to those islands which had a well defined central depression surrounded by a high, unbroken rim. The origin of both types of deposit is now believed to be essentially similar, the differences in the nature and grade of the deposits being mainly a function of the geomorphological history of the island.

The geological history of the Bellona Island deposits, which are fairly typical of all the deposits of this type, begins with the emergence of a small elongate atoll, the long axis of which lay parallel to the prevailing winds (south-east) (Fig. 62). The atoll rim was fairly complete, with few, if any, deep passes. That the atoll emerged in stages is shown by the prominent solution notch at 100 feet above sea-level in the present sea cliffs, and the 14-foot raised beach. These also show that the island was progressively tilted to the north-west, which suggests that the emergence was due to tectonic uplift rather than a eustatic lowering of sea-level.

At an early stage of emergence the uplifted atoll was colonized by breeding sea-birds roosting, probably, on the upper slopes of the central depression (former lagoon). Very large amounts of guano accumulated, and under warm humid conditions with a meagre and infrequent rainfall phosphatic solutions were leached from the guano to replace the fine calcareous sands and muds and oolites of the old lagoon shore.

Sub-aerial solution erosion and axial drainage in the direction of tilt of the island meanwhile had deepened the central depression and a typical karst topography was developed in it, with a line of large dolines occupying the deepest part. The upper slopes of the depression were pitted, furrowed, and creviced by solution erosion, but pinnacle fields were developed only on the outer rim of the island, where they were formed, it is believed, in the spray zone and intertidal zone, during emergence. Dolomitization of the coral limestone seems also to be confined to the outer rim and present sea-cliffs.

The phosphatized lagoon sediments and guano residues, less soluble than limestone, were gradually washed down towards the central valley and collected in the dolines and solution pits and hollows, together with a considerable amount of ' terra rossa ' clay derived from solution of the limestone. Choking of the dolines and therefore the axial drainage of the island probably gave rise to swamps in the central depression, under which conditions the coarser fragmental and oolitic phosphate separated to the bottom of the deposit, leaving the finer incoherent phosphate and terra rossa clay at the top. Terra rossa material from erosion of the limestone continued to be added to the deposits long after active phosphatization had stopped.

In the swamps phosphate was able to combine with the alumina of the terra rossa to form crandallite possibly by iso-electric precipitation of oppositely charged particles as suggested by Yamanari (1935, *fide* Hutchinson, 1950) for the aluminous phosphate deposits of Kito Daito Jima. The upper layers of the underlying oolitic phosphate also began to decompose under these conditions to form a clayey, aluminous phosphate much of which retained traces of the original oolitic texture, and the wet phosphatic clays tended to move towards the north-west, in the direction of tilt of the island, leaving a greater concentration of the higher-grade oolitic and fragmental phosphate near the higher south-eastern end.

With further elevation of the island, or perhaps decreasing rainfall, the swampy central valley began to dry out. Colloidal solutions of phosphate percolated down into the underlying limestone and precipitated by gelation in narrow cracks and joints. The form of the deposits at this stage was much as it is today, with, in general, coarse fragmental and boulder phosphate at the bottom of the dolines (representing phosphatized limestone fragments and oolite agglomerations), overlain by oolitic and finer incoherent phosphate and a thick blanket deposit of phosphatic clay. Some oolitic phosphate remains in solution pits outside the main deposits, particularly at the higher south-east and north-west ends of the island.

The stages in the evolution of the Bellona deposits are shown diagrammatically in Fig. 62.

A similar history can be assigned to the deposit on Nauna in the Admiralty Islands and, with very slight modifications, to the deposits on Vatoa, Vanua Vatu, Ogea Driki and Tuvuca in the Fijian Lau Islands. The deposits described by Rodgers, Irving, Yamanari, etc., in the North-west Pacific must also have a similar history. On Angaur Irving (1953) found that half the phosphate ore was phosphatic clay in swamps below sea level, four-tenths was oolitic phosphate forming blanket deposits overlying karsted limestone benches, and the remainder was phosphate nodules in pits in large-scale karst topography. Much of the clay ore he found was originally oolitic, decomposed in swamps. On Kito Daito Jima, Yamanari (1935, *fide* Hutchinson, 1950) found terra rossa clay between limestone pinnacles associated with aluminous phosphate, while on Peleliu a slightly elevated, karsted central area contains many sink-

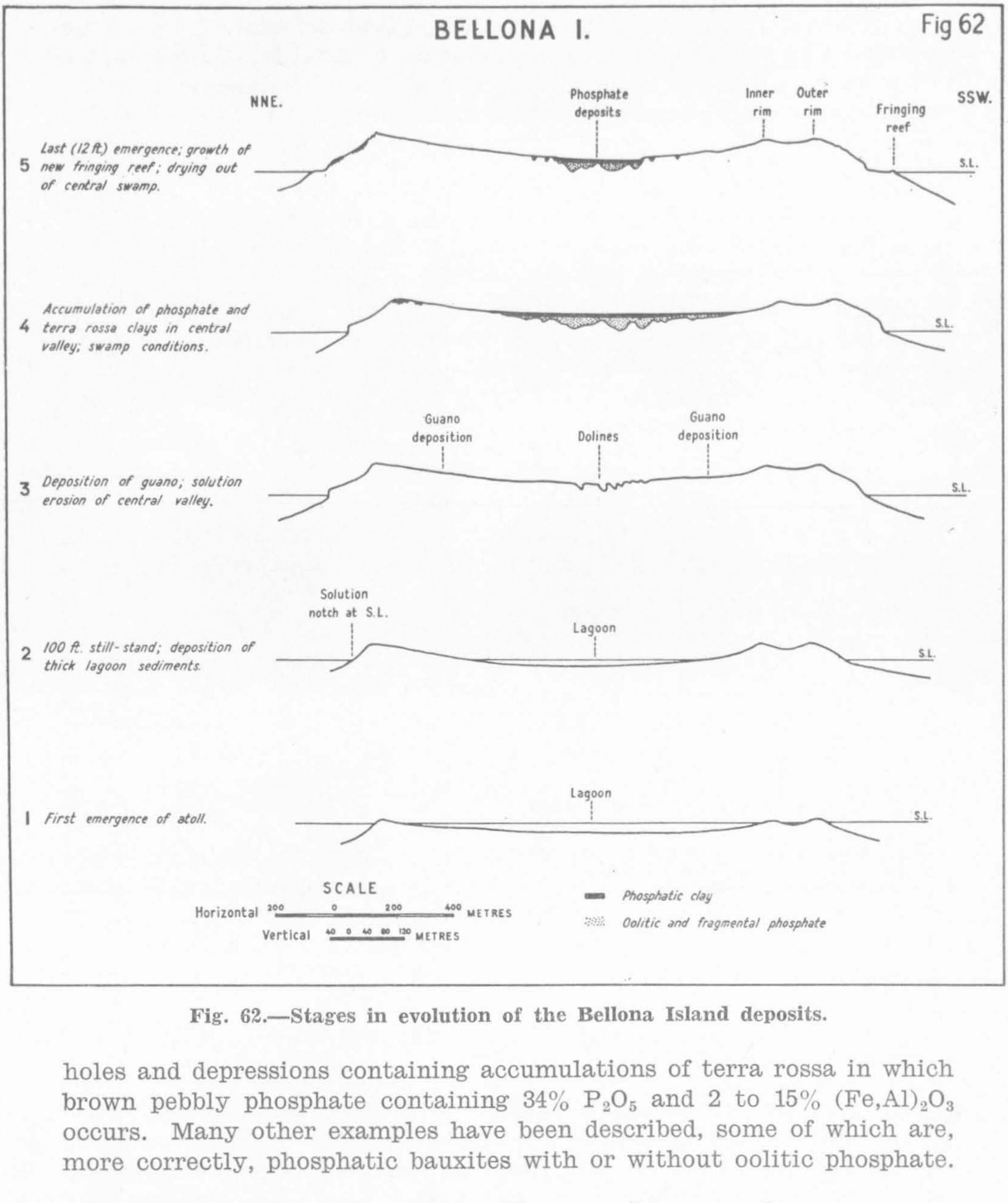


Fig. 62.—Stages in evolution of the Bellona Island deposits.

holes and depressions containing accumulations of terra rossa in which brown pebbly phosphate containing 34% P_2O_5 and 2 to 15% $(Fe,Al)_2O_3$ occurs. Many other examples have been described, some of which are, more correctly, phosphatic bauxites with or without oolitic phosphate.

High-Grade Phosphate Deposits on Elevated Limestone Islands

In contrast to the aluminous phosphate deposits the largest insular deposits of high-grade phosphate rock are found on flat-topped or only slightly saucer-shaped elevated limestone islands, the best examples being Ocean, Nauru, and Christmas Islands. Makatea, having a deep central depression, would seem to be an exception to this rule, but the island is kidney-shaped, the rim is not continuous, and the central depression is believed by most authors to represent an original lagoon which has not been deepened by erosion. The deposits on all these islands are remarkably similar and in every case the phosphate is found between and overlying tall pinnacles of dolomitized limestone.

Because of their parallel, smooth-sided form Power (1905, 1925) suggested that the limestone pinnacles on Ocean and Nauru Islands were due to marine erosion. He considered that phosphatization took place by the filling of cracks in the limestone with phosphate and removal of the limestone by marine denudation, leaving the more resistant phosphate as an alluvial or incoherent deposit which might later be cemented to form coherent phosphate. Such a process seems very improbable and was rejected by Owen (1923), whose postulated history of the island can be summarized as follows :

1. Elevation in at least three stages.
2. Sub-aerial dissection producing Karrenfeld.
3. Submergence, during which the insoluble residues of solution erosion were removed and reef debris could collect between the pinnacles.
4. Regular, slow emergence and colonization by birds. Solutions leached from the guano phosphatized the underlying reef debris between the pinnacles and, to a small extent, the pinnacles themselves. Evaporation of such solutions deposited amorphous collophane in cracks and cavities in the limestone. Magnesium for dolomitization was derived from the guano. (This seems quantitatively impossible).

Owen's views were strongly supported by the uniformly high phosphate and low iron-alumina content of the deposit, and by the presence of typical reef debris in the phosphate, and phosphatized corals found in situ attached to pinnacles. They could be applied equally well to the other deposits of this type, but it is difficult to see how the tall, slender, and often insecurely rooted pinnacles on these islands, particularly those on the elevated terraces, could possibly survive submergence and emergence *after* their formation.

Rodgers (1948) suggested that on the elevated phosphate islands in the Palau, Caroline, and Mariana groups the Karrenfeld was contemporaneous with the phosphate and was the result of guano solutions attacking the coralline limestone along cracks and joints. The oolitic structure of much of the phosphate was, he thought, similar to pisolitic texture in bauxites. On Ocean, Nauru, and Christmas Islands however, most of the oolitic phosphate is clearly phosphatized reef debris and is commonly identical in appearance to the phosphatized atoll sands of the low islands. Foraminiferal tests, including, probably, the reef-dwelling form *Calcarina*, are present, although their state of preservation is not good enough for accurate specific determination. Further, phosphatization of the pinnacle limestone is rare, and, considering the neutral to slightly acid character of fresh guano, it would seem to be quantitatively impossible to explain either the pinnacles or their dolomitization in this way.

Ellis (1935) put forward the idea that the phosphate was entirely of marine origin, but this does not seem to be possible in view of the geomorphology of the islands and the nature of the phosphatic material.

In the course of investigating the phosphate prospects of a great many limestone islands in the south-west Pacific it was found that Karrenfeld of the type found beneath phosphate deposits of Ocean and Nauru Islands is not particularly common. Solution-etched surfaces with large dolines, pits, furrows, lapies, and solution-enlarged joints exist on most of these islands, but Karrenfelds of tall slender pinnacles, and narrow walls and trenches, are common only on the seaward side of the islands where they have been formed, and are forming, in the inter-tidal and spray zones. Dolomitization too seems to be most common in this region, although no quantitative data are available to support this statement.

The formation of a Karrenfeld in the spray and inter-tidal zones takes place partly by the solvent action of sea spray, but mainly by inter-tidal solution-potholing as described by Emery (1946). Shallow hollows in the limestone between tide marks are filled by sea water and support a relatively large biological population including algae, molluscs, arthropods, echinoderms, worms, etc. Lowering of the pH of the water by biological influences during the night causes enlargement of the hollows by solution of the limestone. During the day the pH is increased rapidly by the photosynthetic action of algae and calcium carbonate may be precipitated, probably as spherical oolites which would collect in the bottom of the pothole. On a slowly emerging coast solution pits may be deepened steadily as the sea-level drops to form a field of very deep potholes separated from each other by parallel-sided smooth pinnacles and walls. Some further solution erosion and dolomitization of the emerged pinnacles would take place in the spray zone.

If Ocean Island, for example, is considered as an elevated table reef or atoll with a very shallow lagoon on which inter-tidal solution potholing has taken place during emergence, then a very simple late geological history can be propounded (Fig. 63).

1. Very slow, steady emergence of table reef or atoll.

2. Solution potholing in inter-tidal zone and dolomitization of emerged limestone in the spray zone. Growing corals might become attached to the pinnacles near low-tide level and the insoluble residues of solution erosion removed by the sea.

3. With continued emergence, deepening of potholes to form Karrenfeld, and growth of a new fringing reef. Filling of potholes by atoll sands from the old surface, by debris thrown up from fringing reef, and by oolites

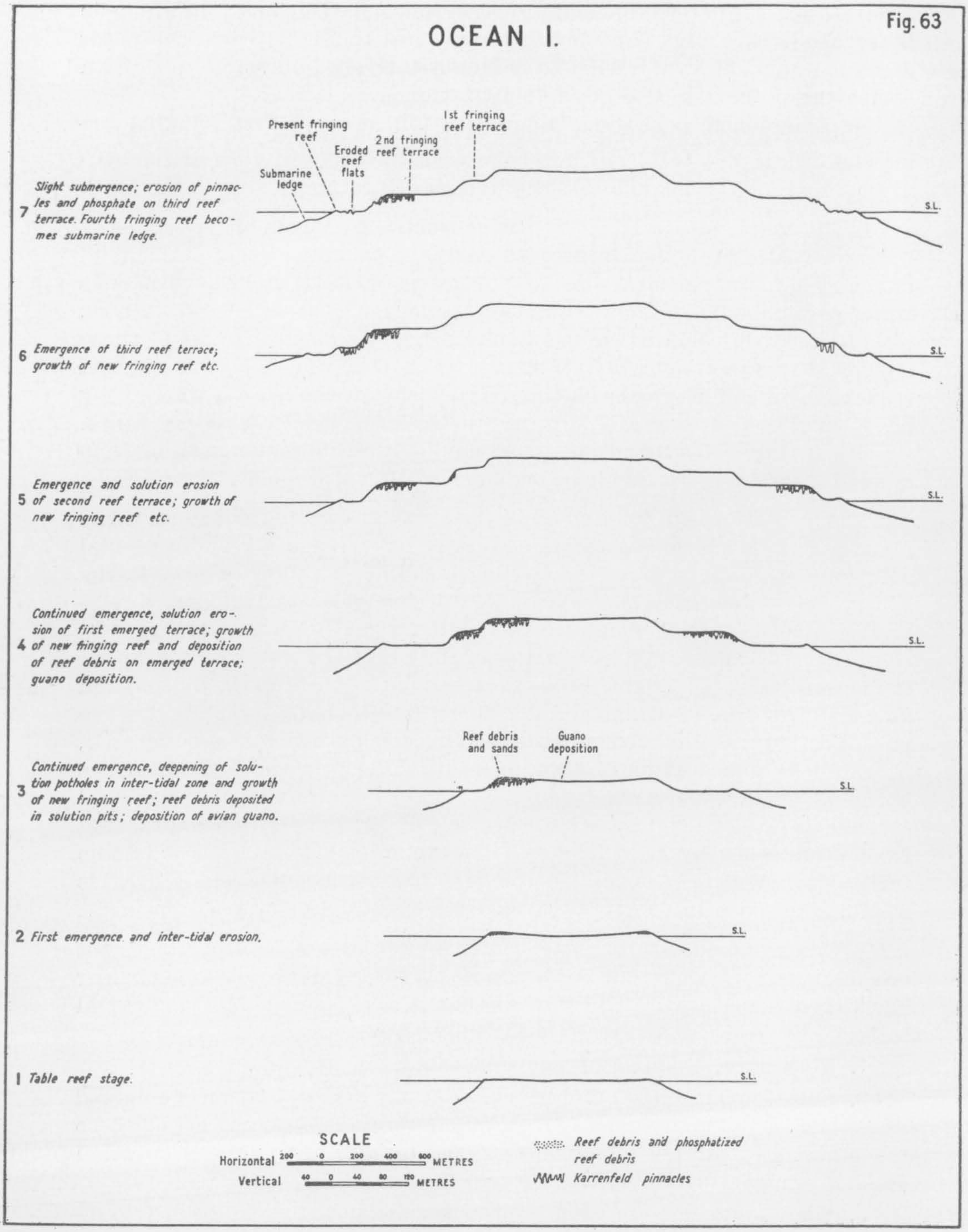


Fig. 63.—Stages in the evolution of the Ocean Island deposits.

formed in the potholes. Development of new fringing reef may correspond to a short period of still-stand. Colonization by birds at early stage of emergence and phosphatization of reef debris and oolites between pinnacles.

4. Emergence, potholing, dolomitization, etc., of first fringing reef terrace and development of a new fringing reef. Deposition of reef debris on first reef terrace and continued phosphatization.

5. Emergence, potholing, dolomitization, etc., of second fringing reef terrace ; phosphatization, etc. Development of new (third) fringing reef.

6. Emergence, etc., of third fringing reef terrace and development of new (fourth) fringing reef. Phosphate deposition is now greatest in the centre of the island, least on the third reef terrace.

7. Tilting towards south-east and slight submergence ; erosion of pinnacles and phosphate on third reef terrace. Fourth fringing reef becomes a submarine ledge.

A similar history can be envisaged for the other phosphate islands of this type. On Nauru more rapid emergence or, more probably, fewer periods of still-stand would account for the presence of only one reef terrace (the present eroded reef flats). Steeper seaward slopes may account for the relatively narrow terraces found on Christmas Island and Makatea, while the higher proportion of soft incoherent phosphate on those islands and Nauru when compared to Ocean Island may be due to the phosphatization having taken place within a shallow central depression which the larger limestone fragments and pebbles eroded from the coastal area and the growing reef could not reach.

Conclusions

The insular phosphate deposits, ranging from fresh nitrogenous guano to phosphate rock of considerable antiquity, are all believed to be derived from avian guano. The considerable differences in the form of the deposits and the nature of the phosphatic material are a function of their post-depositional history. The size and distribution of the deposits are closely related to oceanographic and climatic conditions at the time of deposition ; the type and grade of the deposits are controlled by climatic factors and the geomorphological history of the island. The dolomitized Karrenfeld commonly found underlying the largest deposits is believed to be a feature of marine solution erosion on a slowly emerging limestone coast.

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Appendix 1

FOSSILIFEROUS LIMESTONE OF QUATERNARY AGE FROM NAURU

BY

N. H. Ludbrook*

In November, 1961, a block of limestone from Nauru rich in molluscan moulds was submitted to the writer by the Bureau of Mineral Resources, which had received the material from the Administrator of Nauru. It was hoped that the mollusca might give some clear indication of the age of the phosphatized limestones of the island.

Although Nauru has been one of Australia's principal sources of phosphate rock since 1919, very little information on the geology of the island has been published. Some geographical data are contained in a paper by Power (1905, pp. 213–220) and passing reference to Nauru is made by Owen (1923, pp. 1, 3).

Acknowledgments

Information on the occurrence of the fossiliferous limestone and on what is known of the geology of the island has been furnished through Dr J. M. Dickins by Mr W. C. White, both of the Bureau of Mineral Resources.

For assistance in providing material for comparison, the writer is indebted to the British Museum (Natural History), Drs H. Ladd and H. A. Rehder of the United States National Museum, Dr Myra Keen of Stanford University, and Dr Stearns MacNeil, United States Geological Survey, Menlo Park.

Geographical and Geological Setting

Nauru is situated near the equator in latitude 0° 32′ 54″ S, longitude 166° 55′ 0″ E. Its area is 4692 acres, greatest length 3¾ miles and greatest width, 2¾ miles. It rises to a height of about 210 feet, and is surrounded by a flat shore reef 100 to 130 yards wide (Power, 1905, p. 217). From surface indications only, the island is regarded as an atoll.

The generally accepted view is that the top part of the limestones forming the island has been phosphatized by downward movement of phosphate from guano deposited on the island by sea birds, although this is not proven.

* Senior Palaeontologist, Geological Survey of South Australia. Published with the permission of the Director of Mines, South Australia, and of the Administrator of Nauru.

The samples containing molluscan impressions were collected from the base of the phosphatized layer about 18 feet below the original surface during the mining of phosphate at Anderson's Hill, which was originally 188 feet above sea level. Mining here revealed more than usually fractured limestone pinnacles and limestone agglomerate masses. The location is some 20 chains south-east of Buada Lagoon.

No material from below 170 feet above sea level was submitted.

Lithological Correlation of the Limestone

As known from the material submitted, the limestone is fairly hard but variable in texture. It has been leached and phosphatized and carries numerous solution channels in which calcareous and phosphatic material has been redeposited. Colour varies from cream-white to light brown.

Although molluscan impressions are abundant, none of the original shell material has been preserved.

Lithologically, the limestone may be compared with the Yontan Limestone of Okinawa (MacNeil, 1960, p. 11), material from which, through the courtesy of Dr MacNeil, the writer was able to examine in the United States Geological Survey Collection at Menlo Park, California. The Yontan Limestone occurs at a maximum altitude of 450 feet, its presence above 250 feet being regarded as due to faulting ; it is from 40 to 200 feet thick.

Fauna and Age of the Material

The limestone is crowded with moulds of mollusca, mostly pelecypoda with isolated gastropoda. Preservation is poor on the whole and identification was made from latex casts. These were compared with specimens in the British Museum (Natural History), the United States National Museum, and the Geology Department of Stanford University.

The most abundant species is *Fragum fragum* (Linné) which constitutes probably 90 percent of the fauna. This is a common species of the Great Barrier Reef and the Indo-Pacific Region, and it is identified without doubt in the Nauru limestone. Other species present are : *Gafrarium pectinatum* (Linné), the impressions of which may be compared with examples of the species from Samoa ; cf. *Pitar (Pitarina) striata* (Gray), the identification of which, from two latex casts, is approximate only since the adductor scars of the one Nauru specimen showing the internal features are set higher under the hinge than they are in *Pitar (Pitarina) striata* ; and *Terebralia palustris* (Linné). There are some slight differences mainly in the apparent number of axial ribs between the fossil material and Recent examples of *Terebralia palustris.*

All of these species are living in the Indo-Pacific Region at the present day.

The presence of *Terebralia palustris*, which inhabits swampy mud flats, mangrove swamps and estuarine swamps, suggests that the material was deposited in the lagoon.

From the available evidence, it is therefore considered that the limestone on Nauru at least above 170 feet above sea level is of Quaternary (Pleistocene) age, probably contemporaneous with the Yontan Limestone of Okinawa.

Guano would therefore have been deposited not before late Pleistocene or Recent time.

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PAPUA, NEW GUINEA
AND THE
BRITISH SOLOMON ISLANDS PROTECTORATE
SCALE
MILES 50 0 50 100 150 200 250 MILES
Islands investigated.......... Emira I.
NEW GUINEA
PAPUA
BRITISH SOLOMON ISLANDS PROTECTORATE
INSET
SEE INSET
QUEENSLAND
GULF OF PAPUA
Torres Strait
Sae I.
NINIGO GROUP
Manu I.
Aua I.
Wuvulu I.
Hermit I.
ADMIRALTY IS.
Lorengau
Manus I.
Tong I.
Pak I.
Nauna I.
Rambutyo I.
PURDY IS.
Bat I.
Rat I.
Mole I.
Mouse I.
Alim I.
ST. MATTHIAS GROUP
Mussau I.
Emira I.
Tench I.
New Hanover
Kavieng
TABAR IS.
LIHIR GROUP
NEW IRELAND
Wewak
SCHOUTEN IS.
Manam I.
Karkar I.
Bagabag I.
Madang
Long I.
Umboi I. (Rooke I.)
VITU IS.
Rabaul
NEW BRITAIN
Finschhafen
Lae
Nuguria Is.
Sable I.
FENI IS.
Green Is.
Kilinailau Is.
Tauu Is.
Nukumanu Is.
Ontong Java Is.
Buka I.
Sohano
BOUGAINVILLE
Shortland I.
Choiseul I.
Vella Lavella I.
Ganonnga I.
Kolombangara I.
New Georgia I.
Rendova I.
Vangunu I.
Santa Isabel I.
Ndai I.
Ramos I.
RUSSELL IS.
Nggella Group
Honiara
Guadalcanal I.
Bellona I.
Rennell I.
Malaita I.
Guadalcanal I.
Ulawa I.
Ugi I.
San Cristobal I.
Santa Ana I.
Santa Catalina I.
Tinakula I.
Reef or Swallow Is.
SANTA CRUZ ISLANDS
Ndeni I.
Lusancay Is. and Reefs
Trobriand I. (Kiriwina)
MARSHALL BENNETT IS.
Iwa I.
Dugumenu I.
Kwaiawata I.
Gawa I.
Woodlark I.
Cannac I.
Laughlan Is.
Goodenough I.
Fergusson I.
Alcester Is.
Normanby I.
Port Moresby
Samarai
Louisiade Archipelago
Misima I.
Rossel I.
Tagula I.
140° 145° 150° 155° 160° 165°
0° 5° 10°
Bureau of Mineral Resources Geology and Geophysics July 1961
PNGG 33-1


PLATE 2.
BELLONA I.
(159°50'E, 11°15'S)
BRITISH SOLOMON ISLANDS PROTECTORATE
SCALE
0 1/4 1/2 3/4 1
MILE
REFERENCE
Areas of abundant limestone outcrop
Phosphatic clay
Phosphatic clay underlain by incoherent or oolitic phosphate
Oolitic phosphate in chimneys
Position and number of hand auger hole
Depths in feet c = phosphatic clay op = oolitic phosphate p = incoherent white or off-white phosphate rock
Test Areas of auger drilling, A to T and W1 to W7
Test Pits P1 to P28 – See note
Crest of limestone ridge or abrupt change of slope
COASTAL FEATURES
Cliff, commonly about 100 ft
Beach
Raised reef, 8 to 12 ft above sea level
Edge of reef-waves break at low tide
Note: The position of Test Pits P22 and P25, and of Test Area K not shown.
Central track and position of auger holes by pace and compass survey.
Island outline, topographic and other detail from uncontrolled air-photographs.
0/X/32
G.M.
TRUE
MAG.
8°15'
Gogogava
Onetea
Matautua
One Bay
Ahanga
Shelving reef and coral patches
Limit of coral patches
Matahanua
Angau
Te Hatumotu
Kapata
Ngongona
Ngotokanava
Gongau
Te Hatungoa
Matangi
Tingoa
Tegaigai
A
B
C
D
E
F
T
X
PROFILES
BELLONA I.
Vertical scale 1¾ x horizontal scale; relief generalised.
Feet
Matahanua
Track
Beach
Te Hatungoa
Bureau of Mineral Resources, Geology & Geophysics. July, 1961.

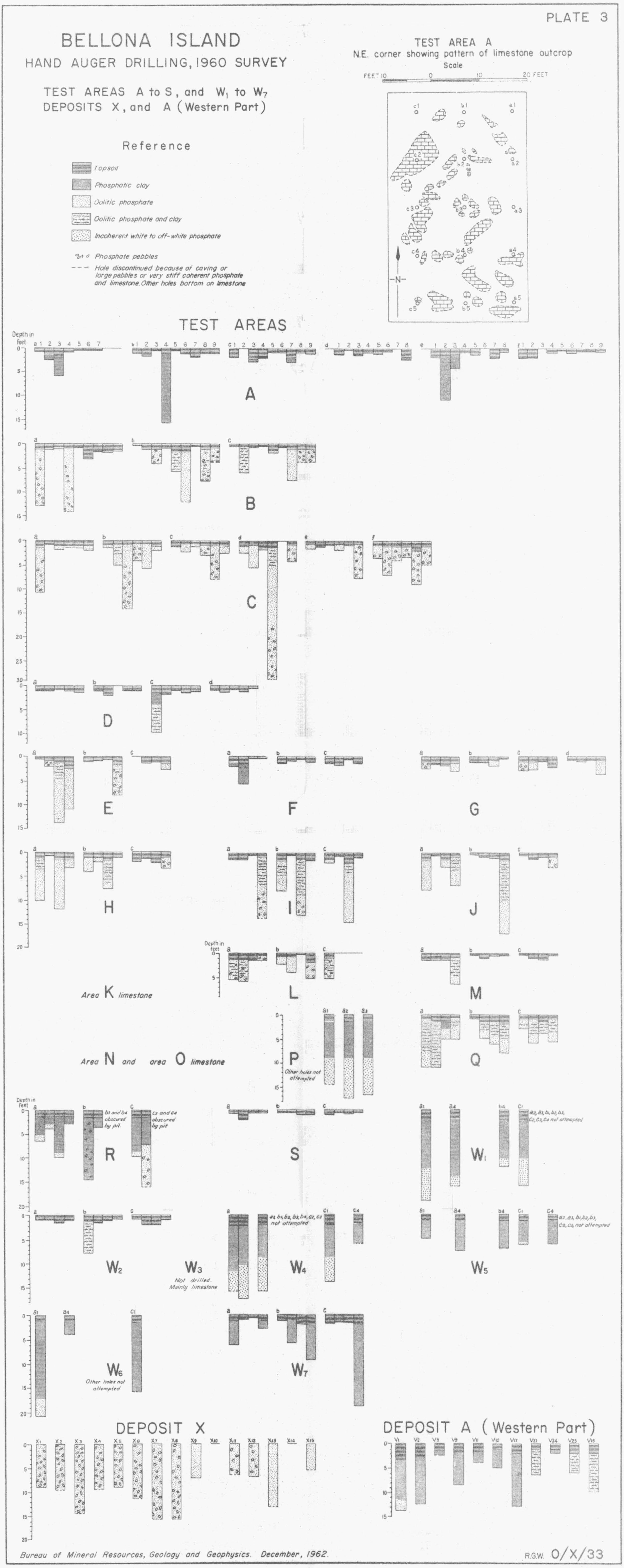


PLATE 3
BELLONA ISLAND
HAND AUGER DRILLING, 1960 SURVEY
TEST AREAS A to S, and W_1 to W_7
DEPOSITS X, and A (Western Part)
Reference
Topsoil
Phosphatic clay
Oolitic phosphate
Oolitic phosphate and clay
Incoherent white to off-white phosphate
Phosphate pebbles
Hole discontinued because of caving or large pebbles or very stiff coherent phosphate and limestone. Other holes bottom on limestone
TEST AREA A
N.E. corner showing pattern of limestone outcrop
Scale
FEET 10 0 10 20 FEET
N
TEST AREAS
Depth in feet
A
B
C
D
E
F
G
H
I
J
Area K limestone
L
M
Area N and area O limestone
P
Other holes not attempted
Q
R
b3 and b4 obscured by pit
c3 and c4 obscured by pit
S
W_1
a2, a3, b1, b2, b3, C2, C3, C4 not attempted
W_2
W_3
Not drilled. Mainly limestone
W_4
a2, b4, b2, b3, b4, c2, c3 not attempted
W_5
a2, a3, b1, b2, b3, C2, C3, not attempted
W_6
Other holes not attempted
W_7
DEPOSIT X
DEPOSIT A (Western Part)
Bureau of Mineral Resources, Geology and Geophysics. December, 1962.
R.G.W. 0/X/33

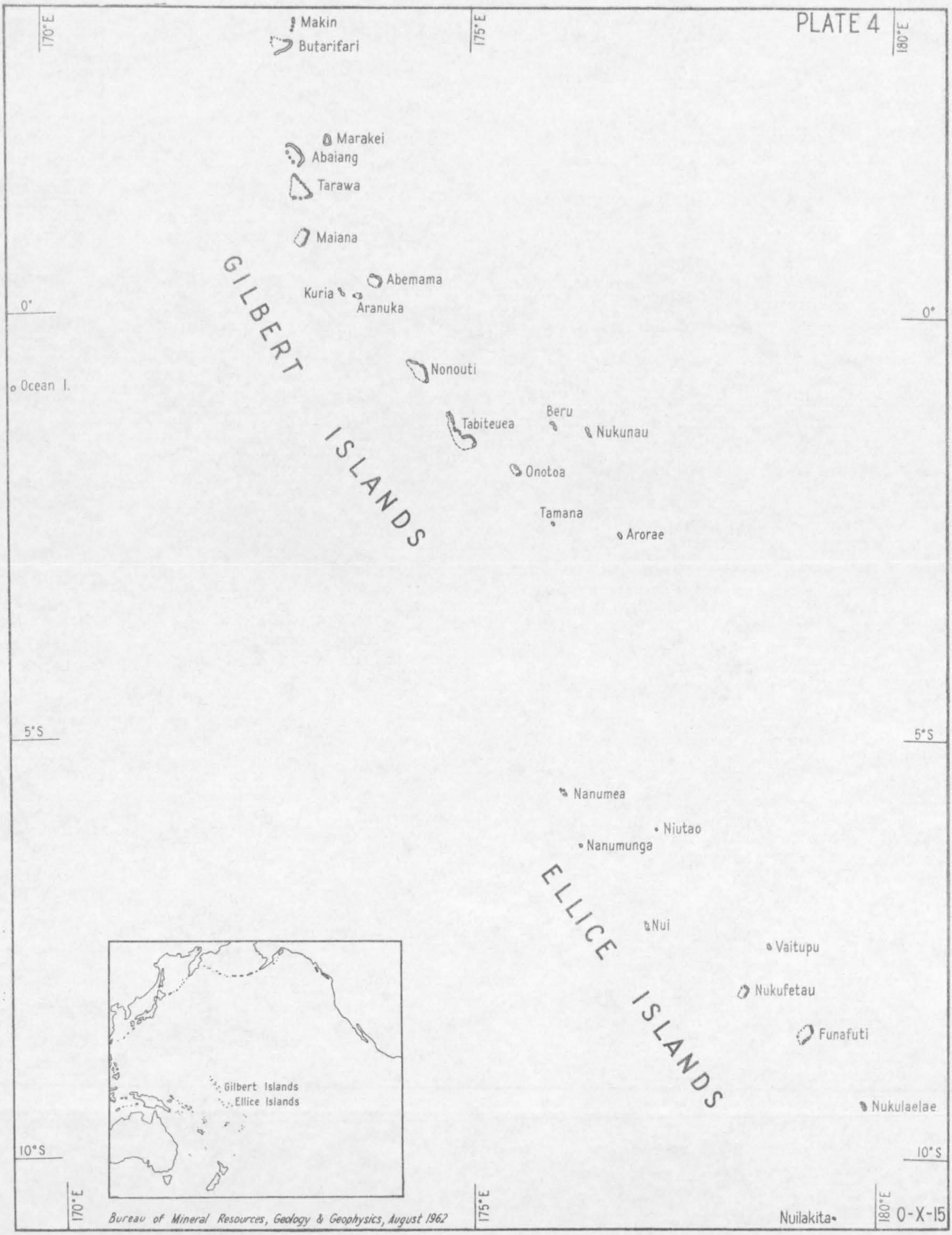
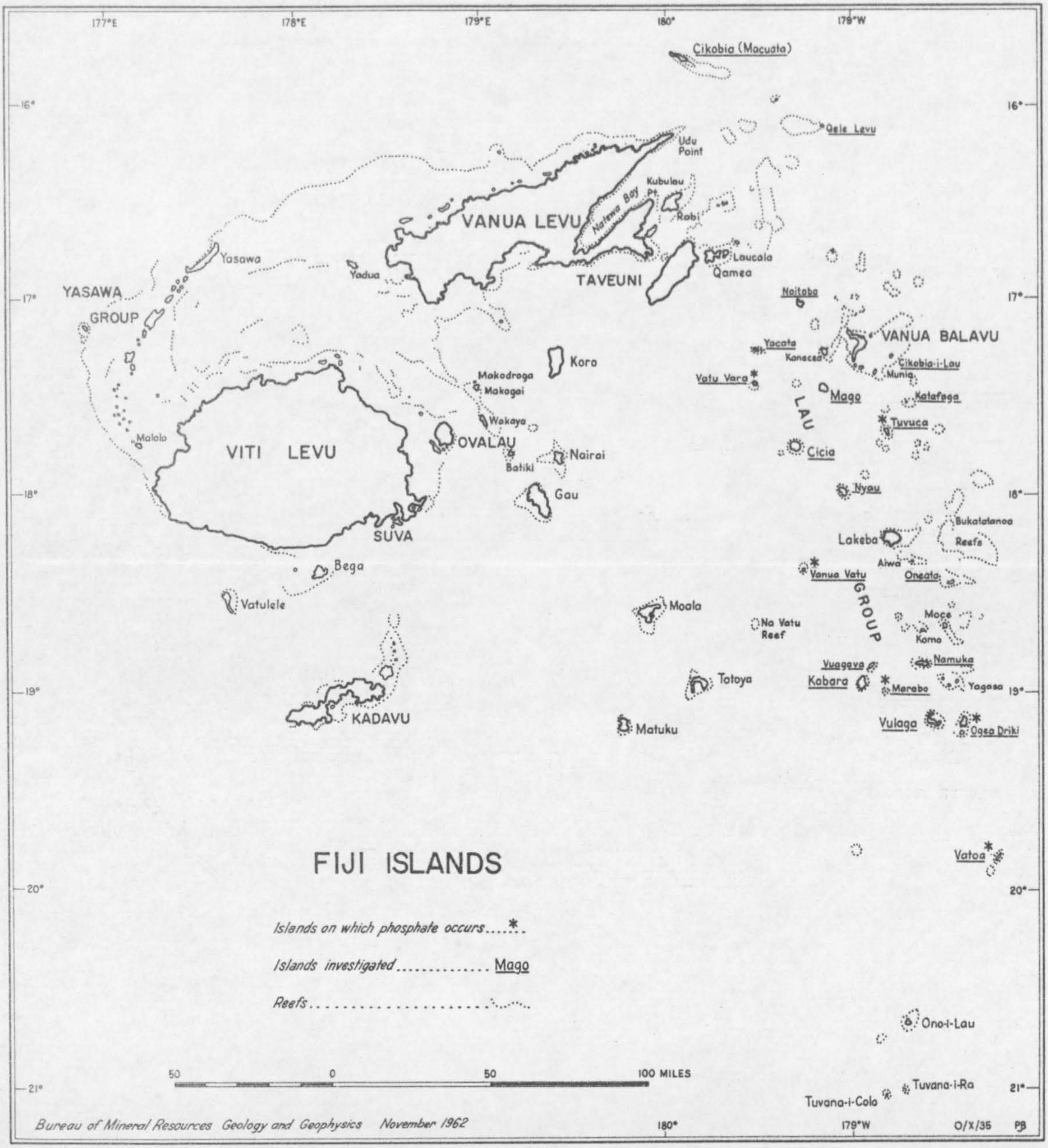


PLATE 4
170°E
175°E
180°E
0°
5°S
10°S
Makin
Butarifari
Marakei
Abaiang
Tarawa
Maiana
Abemama
Kuria
Aranuka
Nonouti
Ocean I.
Tabiteuea
Beru
Nukunau
Onotoa
Tamana
Arorae
GILBERT ISLANDS
Nanumea
Niutao
Nanumunga
ELLICE ISLANDS
Nui
Vaitupu
Nukufetau
Funafuti
Nukulaelae
Nuilakita
Gilbert Islands
Ellice Islands
Bureau of Mineral Resources, Geology & Geophysics, August 1962
0-X-15

PLATE 5

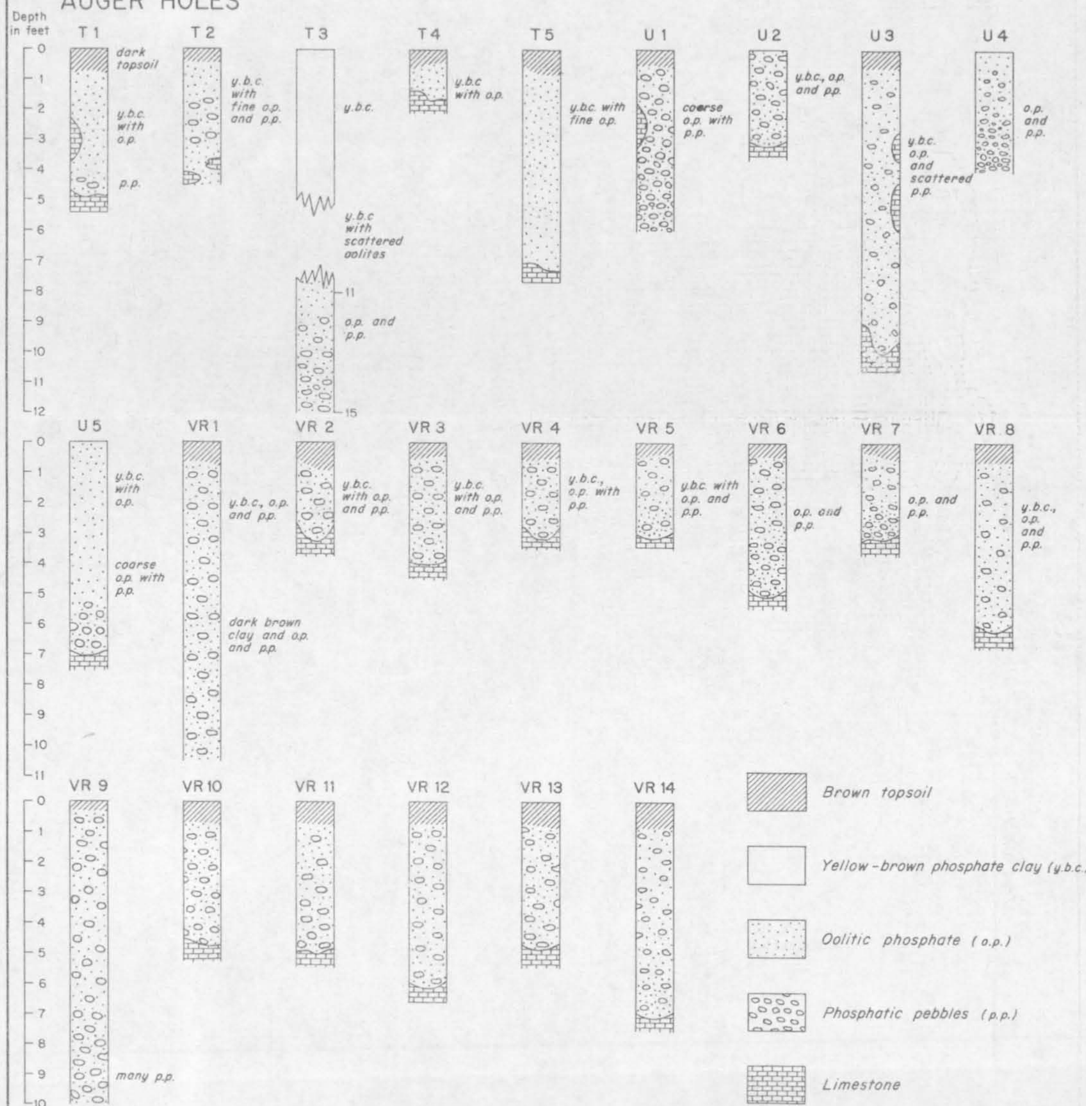


177°E
178°E
179°E
180°
179°W
16°
17°
18°
19°
20°
21°
Cikobia (Macuata)
Qele Levu
Udu Point
Kubulau Pt.
Natewa Bay
Rabi
VANUA LEVU
Laucala
Qamea
Yasawa
YASAWA GROUP
Yadua
TAVEUNI
Naitaba
VANUA BALAVU
Yacata
Kanacea
Cikobia-i-Lau
Munia
Koro
Makodroga
Makogai
Vatu Vara
Mago
Katafaga
LAU
Tuvuca
Wakaya
Malolo
VITI LEVU
OVALAU
Batiki
Nairai
Cicia
Gau
Nyau
SUVA
Bukatatanoa Reefs
Lakeba
Aiwa
Vanua Vatu
Oneata
Bega
GROUP
Vatulele
Moala
Na Vatu Reef
Moce
Komo
Namuka
Vuaqava
Kabara
Marabo
Yagasa
Totoya
KADAVU
Matuku
Vulaga
Ogea Driki
Vatoa
FIJI ISLANDS
Islands on which phosphate occurs .... *
Islands investigated .... Mago
Reefs ....
Ono-i-Lau
50
0
50
100 MILES
Tuvana-i-Ra
Tuvana-i-Colo
Bureau of Mineral Resources Geology and Geophysics November 1962
O/X/35 PB

PHOSPHATE DEPOSITS

Area			Average depth	Estimated volume (cubic feet)	Deduction for limestone	Estimated tonnage	Availability
A	Oolitic and pebble phosphate in Maumi Basin		5 feet	5,200,000	½	100,000	Recoverable
B	Oolitic and pebble phosphate between Maumi and Taira		6 feet	8,160,000	⅔	100,000	Doubtfully recoverable
C	Phosphatic clay with some oolitic phosphate		?	?	?	?30,000	
						Total : 230,000	

AUGER HOLES



Bureau of Mineral Resources, Geology and Geophysics. June, 1963.

PLATE 6

VANUA VATU I.
LAU GROUP, FIJI

Scale

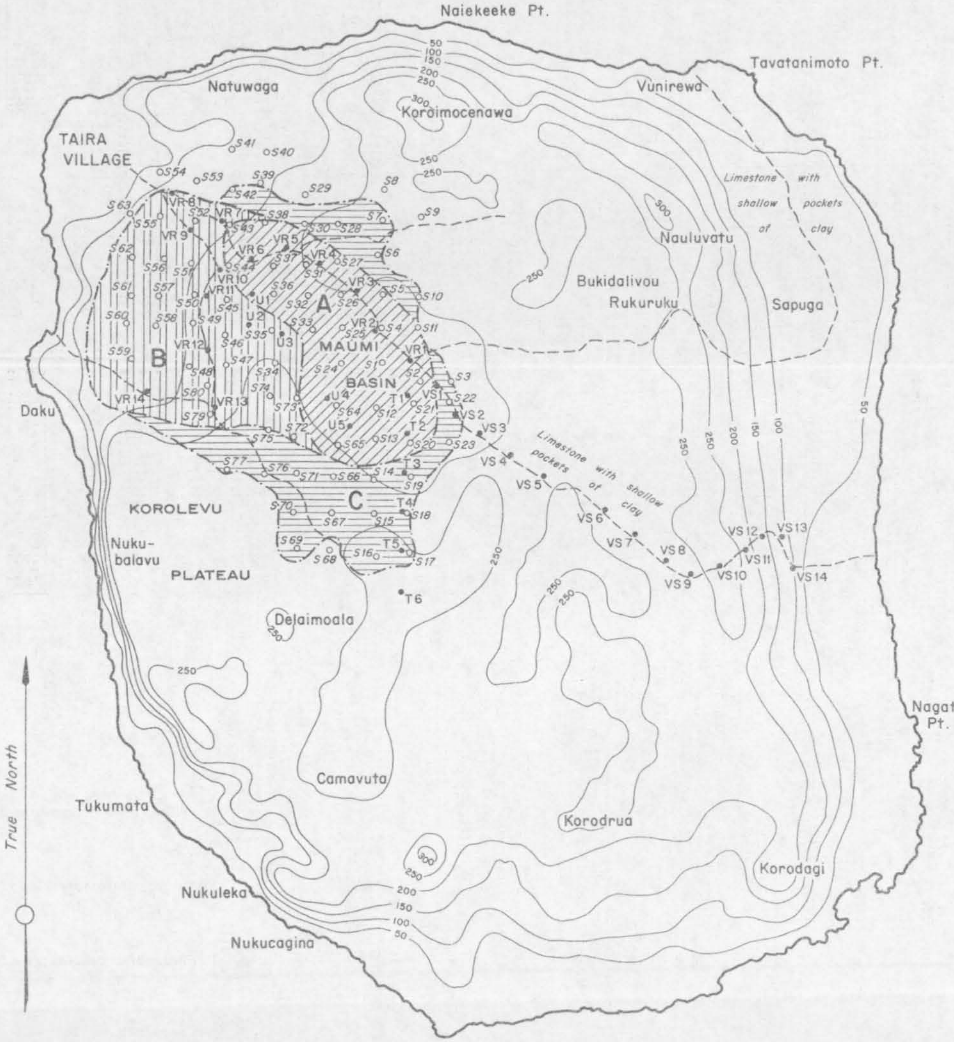
1000 0 1000 2000 FEET

0 ½ MILE

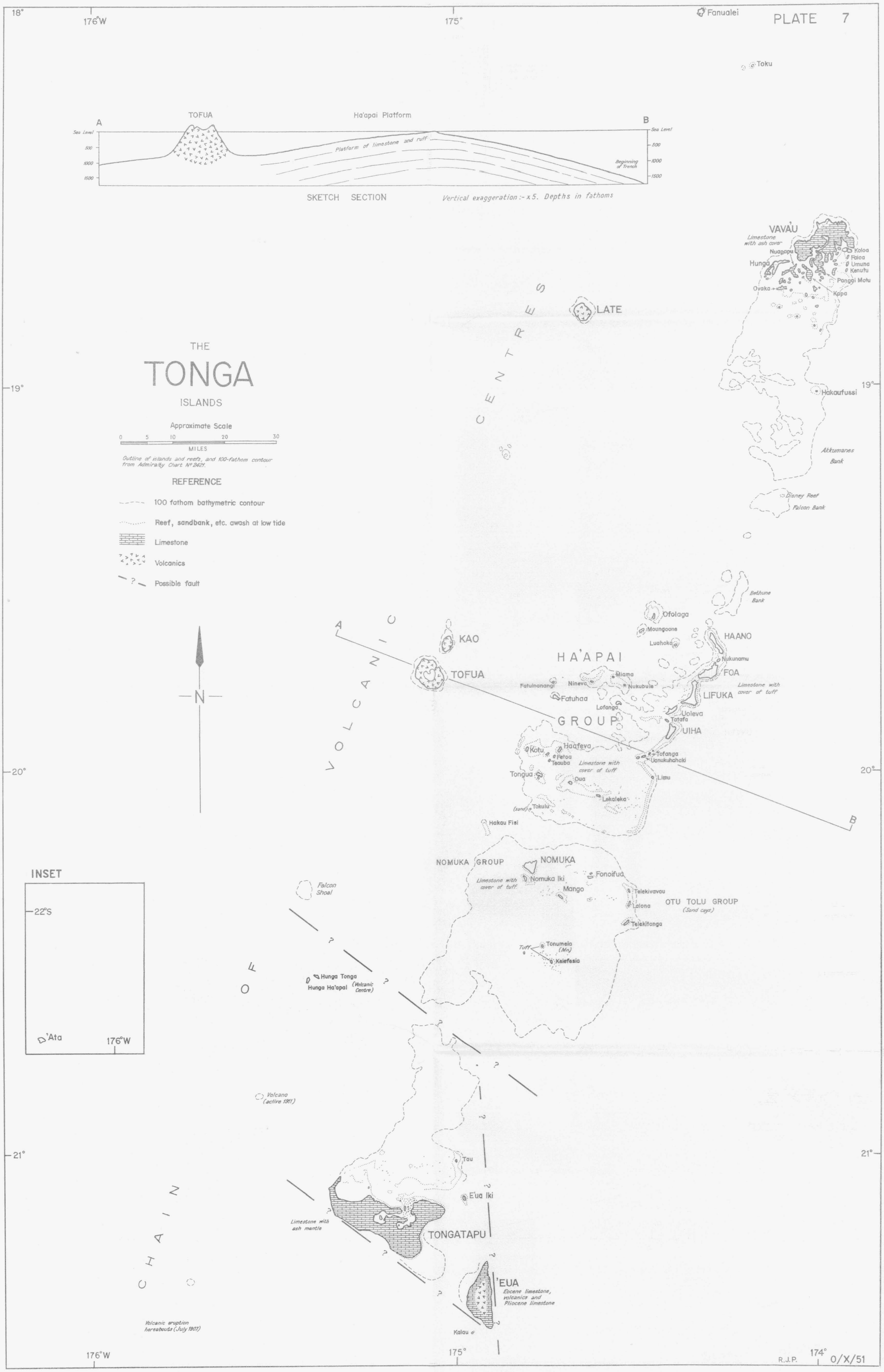
Base map by Department of Lands, Mines and Surveys. Suva, FIJI.

Reference

- *Boundary of phosphate deposit*
- *Oolitic and pebble phosphate*
- *Oolitic and pebble phosphate in pockets between limestone outcrops*
- *Mostly phosphatic clay*
- •VS7 *Position and number of auger hole, 1959 survey*
- ○S69 *Position and number of test pit, 1957 survey*
- —250— *Form line — vertical interval of 50 feet*
- *Track*



F.J.R. 0/X/36


THE
TONGA
ISLANDS
Approximate Scale
0 5 10 20 30
MILES
Outline of islands and reefs, and 100-fathom contour from Admiralty Chart Nº 2421.
REFERENCE
100 fathom bathymetric contour
Reef, sandbank, etc. awash at low tide
Limestone
Volcanics
Possible fault
N
TOFUA
Ha'apai Platform
A
B
Sea Level
500
1000
1500
Platform of limestone and tuff
Beginning of Trench
SKETCH SECTION
Vertical exaggeration :- x 5. Depths in fathoms
18°
176°W
175°
174°
19°
20°
21°
Fanualei
Toku
VAVAU
Limestone with ash cover
Nuapapu
Hunga
Ovaka
Koloa
Faioa
Umuna
Kenutu
Panggi Motu
Kapa
LATE
Hakaufussi
Akkumanes Bank
Disney Reef
Falcon Bank
Bethune Bank
VOLCANIC CENTRES
Ofolaga
Moungoone
Luahoko
HAANO
Nukunamu
FOA
Limestone with cover of tuff
LIFUKA
Uoleva
Tatafa
UIHA
KAO
TOFUA
HA'APAI
GROUP
Miama
Nukubula
Niniva
Fatuinonangi
Fatuhaa
Lofanga
Kotu
Haafeva
Fetoa
Teauba
Limestone with cover of tuff
Tofanga
Uanukuhahaki
Tongua
Oua
Limu
Lakaleka
(sand)
Tokulu
Hakau Fisi
NOMUKA GROUP
NOMUKA
Limestone with cover of tuff
Nomuka Iki
Fonoifua
Mango
Telekivavau
Lalona
OTU TOLU GROUP
(Sand cays)
Telekitonga
Tuff
Tonumeia
(Mn)
Kelefesia
Falcon Shoal
INSET
22°S
'Ata
176°W
CHAIN OF
Hunga Tonga
Hunga Ha'apai
(Volcanic Centre)
Volcano (active 1911)
Tau
E'ua Iki
Limestone with ash mantle
TONGATAPU
'EUA
Eocene limestone, volcanics and Pliocene limestone
Kalau
Volcanic eruption hereabouts (July 1907)
R.J.P.
0/X/51