ATOLL RESEARCH BULLETIN

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5. The Soils of Arno Atoll, Marshall Islands

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THE SOILS OF ARNO ATOLL, MARSHALL ISLANDS

SCIENTIFIC INVESTIGATIONS IN MICRONESIA

Pacific Science Board

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I am indebted to Dr. John W. Wells for an introduction to atoll geomorphology and for many stimulating conversations during the preparation of this report.

INTRODUCTION

In preparing this field report I have had in mind the meager knowledge of atoll soils presently available and a realization that subsequent reports to technical journals are much more likely to be found and comprehended by soil scientists than by the laity. Therefore, the first section has been given over to a generalized discussion of soil formation on unraised atolls. The second section, the field report proper, is an account of the summer's work on the soils of Arno.

Part II, Agriculture of Arno Atoll, has already been prepared and because of this slightly illogical sequence a certain amount of overlapping and some minor discrepancies may be found in comparing the separate reports.

> "The soil is fairly productive. Its larger islands are covered with grass, fine groves of coconuts, with magnificent breadfruit, Pandanus and Pisonia, and the usual belt of low growing vegetation growing upon the summit of the beach" -- Alexander Agassiz, of Arno Atoll in 1900.

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Land Formation and Destruction

FORMATION

Land formation can be viewed as the culminating process in atoll development or as a minor consequence, a superficial collection of fragments that happens to protrude above sea level. In terms of mass the land is but an insignificant fraction of the atoll and occupies only a small part of the area. In discussing the soils of the atoll we unavoidably incline to the view that land formation is the culminating process but we will treat it here only to the extent necessary for an understanding of the soils.

There is no evidence that the present atoll surface has been uplifted. (See report of the Geologist.) For our purposes we will assume that the land has formed on a platform of consolidated material having an elevation at or slightly below mean low tide. Ordinarily this platform will be consolidated reef rock but occasionally it may be cemented sandstone or "conglomerate". The nature of this platform can be seen on the typhoon swept areas where land formerly existed and in exposures in the interior of Tinak, L'angar and Bikareij Islands. Although doubtless permeable to some degree this platform is considered much less so than the materials subsequently deposited upon it. On Arno there is no evidence that land has formed over unconsolidated materials and this possibility will not be considered further here.

Even the most cursory examination of the wider islands reveals that two major classes of materials have entered into their composition. Over the greater part of the atoll the seaward side of the land is composed largely or entirely of rock torn from the reef. Often these fragments have been rounded by wave action before deposition but again the pieces may have more or less of their original jagged contour. Most of the rocky land appears to have been formed by the progressive outward building of a rampart composed of these coarse materials thrown up by storms. The younger age of the seaward side of this land is generally recognized and in fact rampart formation is in progress along much of the coast. Since it owes its formation to storms the surface of the rampart tends to mark the highest level to which the largest waves can carry coarse material. Thus this level is higher on the more exposed coasts subject to frequent storms, such as on L'angar Island, and it is lower elsewhere. Occasional great storms such as accompany typhoons may heap rock well beyond the edge of the rampart, even burying inland surfaces. In either case, included with the rock is a greater or lesser amount of sand and gravel ground from the rocks. Usually the stony land slopes downward slightly away from the coast, possibly because of weathering of the older materials.

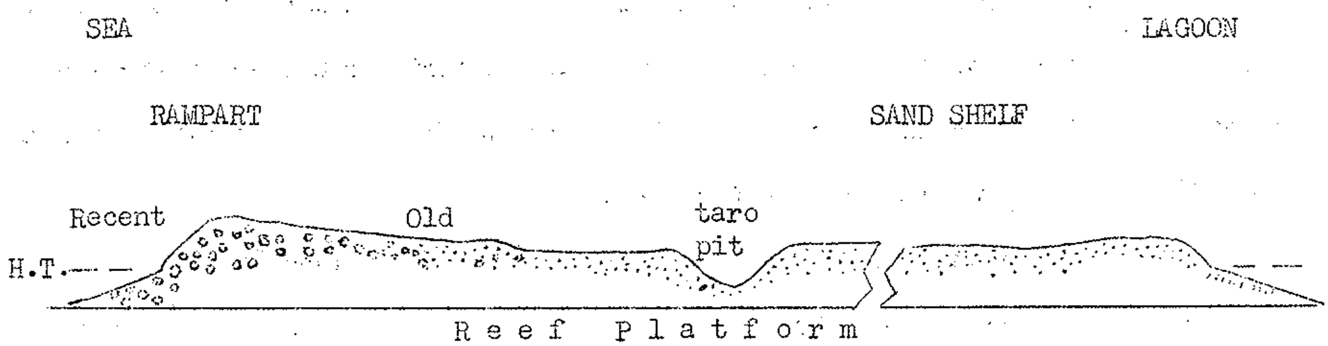
It is not possible to say with certainty that the rampart is always the first formed land but in most cases it is difficult to postulate otherwise. Protected by the rampart, the quieter waters of the lagoon pile sand against it and the resulting sandy shelf often widens more rapidly than the outbuilding rampart. This process is particularly effective where the reef and hence the rampart, forms a sharp concavity. As is generally true along coasts, such embayments are more readily filled by wave-worn sediments and are protected from along-shore currents. The progressive widening of Arno Island, although now slow, is known to the people there because inland and parallel with the beach they find rows of pumice pebbles such as occur along the present beach.

Beach sands are not limited to the lagoon side of the land, although much more common there. On the seaward side the occurrence is most probable on lee coasts and again in embayments concave towards the sea. The narrow land just northwest of Ine village has a sandy seaward beach and in places the soils immediately back of the beach show signs of having been veneered with sand during storm periods. Although at first thought the height of sandy lands would seem limited to high tide level, wave action during storms continues to throw up sands and accumulation is doubtlessly aided by the effect of vegetation in reducing the outward drainage of waters.

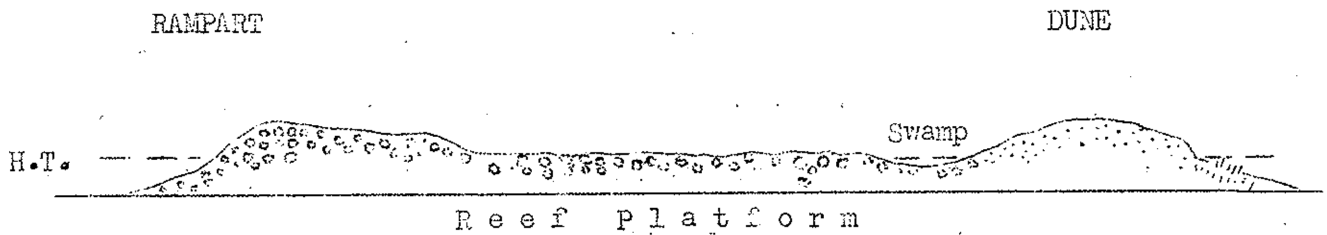
The major element involved in raising the height of land, however, is the formation of sand dunes which are common along the windward lagoon shores. Dune formation proceeds most rapidly where a sandy beach is uncovered at low tide and exposed to the northeast trades. On Arno the maximum dune height observed was perhaps twelve feet above high tide though much higher dunes are known on other low islands in the Pacific. Occasionally small dune areas occur on the seaward side, as at one point on Bikareij Island where a small section of the low rampart has been buried. When supplies of sand are ample the speed of dune formation may be very rapid as exemplified by the high dune northwest of the wide part of Jab'u formed and vegetated since the typhoon of 1918.

The three processes involved in building a rampart, sand shelf and lagoon dune may combine to give a land high on both shores and lower in the center. Such an orderly process of formation is far from common, as the cross-sections and soil maps reveal. Even apart from catastrophies, the vagaries of wind and storm bring cycles of addition and removal, often transferring materials from one point to another nearby. Dunes are often cut away or sometimes left inland when a new cycle of beach building takes place. Unfilled areas may be cut off from the sea by ramparts or dune ridges, giving rise to swamps or wet soils. A single minor storm may sweep away the accumulation of months or, again, heap fine materials on coarse or coarse on fine. The cross-sections of Figure I are diagrammatic sketches of conditions actually found. It may be emphasized that nearby all of the inland basins and low interiors of the islands of Arno are obviously structural; they have been formed in the course of island building, or rebuilding, rather than by solution.

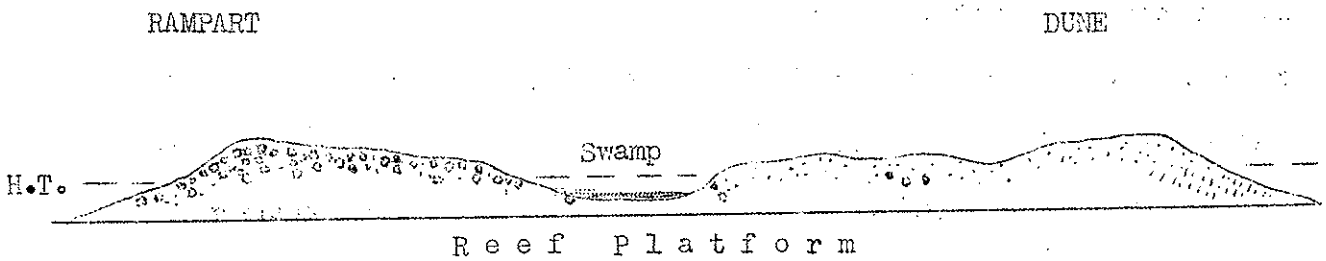
Fig. 1. DIAGRAMMATIC CROSS SECTIONS OF SOME ISLAND TYPES



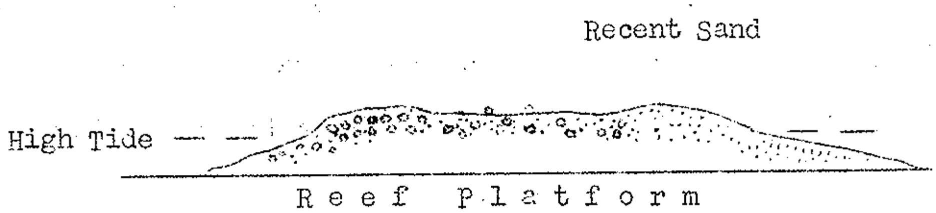
(a) Wide sandy island.



(b) Island with low stony interior.



(c) Island with enclosed basin.



(d) Narrow island.

Although the developing land is subject to the sea there are stabilizing influences that tend to protect its integrity. The slow outward and upward growth of the reef gradually reduces the violence of the waves which beat upon the land. Ramparts and dunes shelter the interior from all but the largest storms and as the land widens there is less likelihood that storm waves can sweep across it. Moreover, the shore itself comes to be underlain with a sandstone or conglomerate formed as outward flowing waters saturated with calcium bicarbonate cement the beach materials. The beach sandstone or conglomerate offers no absolute protection as many offshore blocks of these clearly show, but rapid formation helps to defend additions made to existing lands. The ground water may bring about cementation elsewhere than on the beaches and locally phosphatic cementation may stabilize loose materials. 1/

The stabilizing effects of vegetation are obvious. The root mat binds the surface soil and the tops of plants both large and small reduce the violence of surface flow by wind and water, decreasing erosion and encouraging deposition. The stabilization is probably important in protecting ramparts and dunes but it is easy to overestimate the importance of vegetation; land also forms on dry atolls where the vegetation today is too sparse and small to have major effects.

DESTRUCTION

Despite the stabilizing influences above, the narrower lands cannot be made secure against destruction by major storms; in fact, on a geological time scale such lands may have a somewhat ephemeral existence. Typhoons are considered relatively rare in the southern Marshalls but are well known. Those of 1905 and 1918 have been well documented by the Germans and Japanese then resident. Lijömmar, an old man of Ine village, recalls four typhoons in his lifetime, including the above two, and knew of another in the days of his grandparents. For each of the four he described the windshifts and an intermediate

1/ Current hypothese of beach rock formation seem to rule out the simple assumptions made here.

period of calm that indicate the passage of a typhoon center. Thus, it seems that typhoons and their attendant effects must be considered normal in the sequence of land formation.

On Arno the typhoon of 1905 was clearly the most destructive in a period of perhaps a century. Along the entire east coast of the atoll there was the long island of Namej (the Terranova of Agassiz), an unbroken land from the pass near the east end of Ine Island to the tip of present day L'angar Island. When the storm ended the wider portions of this island lay as isolated fragments, their centers intact. Much of the narrow land had been washed over by the great waves that cut away the land margins and replaced the former surface with primitive rock and sand. Other land had disappeared entirely, leaving the reef platform bare, perhaps as much as it had been before the land formed. In the subsequent 45 years this area has rebuilt to a considerable degree, with sand spits linking the individual islands and a rampart again manteling part of the bare platform. The same typhoon is said to have caused extensive damage on Ine Island; the narrow land between Ine Village and Jab'u was reduced in width and the effects are plainly visible in the condition of the narrower parts of the island from Jab'u west to Lukwöj.

The 1918 typhoon was less destructive but left some effects. The small island of Enen'edrïk is said to have been separated from the southern end of Arno Island by this storm. The narrow land northwest of Jab'u was reputedly washed over for the second time by this typhoon and, at a point where the seaward reef is indented, the land was again trenched through to the reef rock below. Here is demonstrated one way in which typhoones destroy the land surface: The waves coming across the land from the seaward side began undercutting at the lagoon shore; the dense root mat of coconuts presumably held the surface layers but the sand below was readily washed away and thus a shallow "waterfall" retreated across the island. For the most part this waterfall cut only about half way across the island and remains as a deeply scalloped escarpment, 3 to 4 feet high. The individual "scallops" are the "washout pits" that can be recognized elsewhere on Ine Island.

This area, like Namej, indicates rapidity of rebuilding; the channel has vanished entirely although its surface and that below the escarpment are lower than the former land. Along the lagoon shore a high dune has been built and now supports a young coconut grove.

GROUNDWATER

The groundwater is discussed in detail in the report of the Hydrologist and it is sufficient here to mention its existence. The classical Ghyben-Herzberg theory would picture a lens of fresh water floating in and on the salt water, both within a matrix of unconsolidated coral detritus that prevents turbulent mixing. It is evident that this view must be altered somewhat if we consider that the fresh water overlies a more or less impermeable platform beneath. The salinity of the groundwater is influenced by rainfall, of course, and so is subject to possible seasonal changes. Other obvious factors are distance from the shore and subsurface permeability, and the latter, in turn, is affected by the relative coarseness of the materials composing the land.

The hydrological investigations on Arno by D. C. Cox (Atoll Research Bulletin 8) indicate that the reef platform must have an appreciable permeability and that a well developed Ghyben-Herzberg lens is present.

Soil Formation

There are many different rainfall regimes throughout the Pacific and in consequence there are "wet" islands and "dry" islands, as well as others subject to periodicities of rainfall, either annual or at irregular intervals. It is quite obvious that moisture influences vegetation and leaching processes. In addition, the intensity and distribution of dry periods regulates soil salinity and the possible concentration or precipitation of dissolved substances. Thus it should be kept in mind that in the following we are principally concerned with a "wet" atoll having an annual precipitation of some 120 inches with a short and only "relatively dry" season.

Throughout the world there are areas of limestone resembling the atolls in chemical composition but uplifted for various periods. The soils developed on these indicate the course through which the atoll soils would pass if they remained above the sea for sufficient time. In the oldest such areas the calcium and magnesium carbonates, which make up such a large part of the present atolls, have been entirely dissolved from the surface layers and often from a considerable depth; the soil then consists of combinations of aluminum, silica, iron and other constituents originally present as only small percentages. The time required for such formation is great and the solution of several feet of limestone may yield only an inch or two of soil. In contrast the present atoll soils are extremely youthful and are classified as lithosols and regosols. /1. The surface layers have been darkened by addition of organic matter and there has been some solution of carbonates but in the main the materials of the soils have been little altered.

/1 Lithosols "An azonal group of soils with little or no horizon differentation ... if deeper, consisting largely of rocks and stones"

Regosols "An azonal group of soils with little or no horizon differentation, deep ... over bedrock, and generaly non-stony, consisting of materials such as loess, marine and lacustrine sediments and sands."

PHYSICAL AND CHEMICAL NATURE OF THE PARENT MATERIALS

It has been mentioned that much of the sea-derived material is coarse but mixed with this is a varying proportion of fine gravel and sand. /2 Here and there are beaches made up entirely of the finer materials. Many of the cobbles and jagged fragments are made up of somewhat porous corals which hold appreciable amounts of moisture and are penetrated by roots to some extent; thus they are more favorable for plant growth and rather more susceptible to disintegration than size alone would suggest.

The beach deposits formed along the lagoon shores vary in particle size from medium to very coarse sands, often with an admixture of fine gravel; locally they may consist of gravelly sands. The dune sands are finer and relatively uniform in size but mixtures occur when dune sands are reworked or washed over adjacent land. Soils formed from "coral mud" were not found at Arno but have been reported elsewhere.

The coarse materials are very largely composed of stony corals and Lithothamnion rock, whereas the lagoon sands contain a high proportion of Foraminifera tests and Halimeda fragments, as well as ground up coral and shells. Several investigators of "coral" reefs have pointed out that calcareous algae and other organisms often contribute more material to the reefs than the corals themselves; thus Mayor suggested that Rose Atoll was properly a "Lithothamnion atoll".

These distinctions become more significant when the results of chemical analyses of various organisms are compared (Table I). The inorganic parts of the reef building corals consist almost entirely of calcium carbonate, whereas some of the Lithothamnion group contain as high as 25% magnesium carbonate.

/2 The U. S. Soil Survey classification delimits particle sizes as follows: stones (irregular) and cobbles (rounded), 10"-3"; coarse gravel, 3"-1/2"; fine gravel 1/2"-2 mm.; very coarse sand 2 mm.-1 mm.; coarse sand, 1mm.-0.2mm.

Another alga, Halimeda, however, contains only about 1% or less of magnesium carbonate. Moreover, the two minerals species of calcium carbonate, calcite and aragonite, which differ somewhat in solubility, are characteristic of different organisms. Some organisms that contribute little mass to the reef are nevertheless sources of certain elements, such as phosphorus, needed for plant growth.

Table I <u>Range in Inorganic Composition of Some Marine Invertebrates</u>
After Clark and Wheeler (U. S. Geol. Surv. Prof. Paper 124, 1924) and Twenhofel (Principles of Sedimentation, 1939).

	$CaCO_3$ %	$MgCO_3$ %	SiO_2 %	$Ca_3P_2O_5$ %	$(AlFe)_2O_3$ %	$CaSO_4$ %
Alcyonarian corals	73-99	.35-15.7	0.4-1.7	Tr-8.6	Tr-1.0	Tr - 5.4
Madreporian corals	98-99+	.09-1.1	0-1.2	0-Tr	0-0.7	0 - .2
Foraminifera	77-90	1.8-11.0	Tr-15	Tr	Tr-5.0	0
Echinoderms	78-93	5.0-15.0	0-10.0	Tr-1.9	0.1-5.2	Tr - 4.2
Mollusks	94-99.9	0-6.0	0-2.2	0-0.9	0.4-1.9	0 - 0.2
Crustaceans	29-83	3.7-16.0	0-3.8	8.7-27.0	.06-8.9	Tr - 5.3
Calcareous algae	74-99	.02-25.0	.02-2.1	Tr-0.4	.01 to 1.6	.03 to 1.4

Soils formed by weathering of consolidated limestones are not common on Arno and presumably this is likewise true of other atolls that have not been uplifted, since the primary zone of cementation is near tide level. The composition of cemented limesands and conglomerates resembles that of the unconsolidated materials but the former are obviously less suitable for soil and plant development. Such rock is usually permeable to some degree and roots and percolating waters soon develop numerous deep fissures and pockets of soil material.

Brown phosphate rock occurs on many low islands; this is formed by phosphate leaching from guano deposits into limy materials beneath and there forming insoluble calcium phosphates. The calcium carbonate is replaced wholly or in part by the phosphate and thus (excepting peat accumulations) acid soils, if found at all, occur on phosphate areas, e.g. Holei Islet, Palmyra Island, as reported by Christophersen (Bishop Mus. Bul. 44, 1947). During the replacement process the material is usually cemented if not already so, hence imposing the same mechanical limitations to plant growth mentioned above. The three small areas of phosphate rock observed on Arno, however, were highly fissured and contained pockets of unconsolidated sand.

Wave drifted pumice has been found on many low islands and locally its mass may be great enough to affect the soil or plant growth (c.f. the Funifuti report). On Arno, except to provide whetstones for the natives, its significance is probably nil; even where it appears most abundant its weight per unit land area is negligible. Low islands near volcanic areas may benefit from ash deposits but Arno is remote from these.

By the nature of atoll formation other rocks and minerals would not be expected, except for those transported by man or a rare erratic drafted ashore enclosed in tree roots. This expectation is not always a safe one: The sweeping conclusions concerning soil development drawn by Lipman and Shelley (Carnegie Inst. Publ. 340:201-208, 1924) from analyses of a single set of samples from Rose Atoll are entirely vitiated by the discovery of basalt fragments in the reef. Basalt had been reported by the Wilkes Expedition and by Couthovy long before, but these reports were considered erroneous by Mayor (Carnegie Inst. Publ. 340:73-79, 1924) who collected the material analysed. Subsequent collection by L. P. Shultz (Personal communication) has verified the presence of basalt. Likewise David and Sweet (The Atoll of Funafuti, Sect. V,

1904) present a soil analysis but note that a little of the soil from the sample locality had been brought in as ballast from Samoa.

PHYSICAL FACTORS

Once exposed above the sea the land materials are subject to the continuous action of atmospheric and biological agents. The first rains dilute and then rinse out the salt left by the depositing waves. On wet atolls this is repeated when salt is again added by storm waves, spray or evaporating brackish waters whereas on dry atolls the rainfall may be insufficient to remove the salt from the surface layers. Other substances, calcium and magnesium carbonates and the small percentages of other elements that occur with them or in the dead organic materials, are much more slowly dissolved by rainwater.

Solution

Nevertheless solution is the dominant physical process acting upon the land. The carbonic acid released by roots and organic matter decomposition or carried into the soil by rainfall converts calcium carbonate to the soluble bicarbonate which then moves into the groundwater. Some of this precipitates along the shores, cementing sand and rubble to beachrock, but it is lost from the island interiors. We may calculate /3 that carbon dioxide dissolved in rainfall before it reaches the soil is alone sufficient to reduce the land level about 1 cm. per century. This rate may be increased by a few to several-fold by the effects of living organisms and their decomposition products. The estimates of Sayles (Proc. Am. Acad. Arts and Sci. 66:380-467, 1931) on the weathering of consolidated windblown limesand in Bermuda indicated reduction of the land surface at the rate of 6.1 cm. per 100 years. This is little or nothing in one man's span but in a geological sense the process is rapid. Thus

/3 120" rainfall per year, solubility of calcium .52 millimols/liter at 25°C and .0031 atm. CO_2, assumed density of the sand 1.8.

it appears that as an island widens with time so does its interior lower and a few millenia of such weathering would bring its surface to the level of the water table. There is no evidence that this has taken place on Arno atoll but the consideration again demonstrates the youthful condition of the land surface.

Solution progresses rapidly in the upper layers. The innermost margins of the belt of stony land are much less coarse than the outer beach for as they weather the large fragments give rise to smaller. The gravel-sized particles found within the upper organic horizon of the older soils are often soft and easily crushed, and frequently are penetrated by roots. Similarly, the sand particles are most disintegrated within this zone. On Arno the most highly weathered soils often contain much more gravel in the surface horizon than immediately below. Although other explanations are possible, the general concurrence of this suggests concentration of the gravel by solution of the finer particles.

Cementation

Except for beachrock formation, cementation by precipitation of dissolved carbonates in the upper few feet of soil is not of consequence under Arno conditions. Occasionally slight cementation of sand particles in the immediate vicinity of decaying roots was observed and in one instance slight cementation was noted throughout the sand overlying a buried organic layer near the groundwater level. There are, however, no "hardpans" or illuvial horizons within the soil proper on Arno nor would there be expected under the prevailing conditions of rainfall and parent material.

In a few profiles examined lagoon laid sands rested conformably on unweathered strongly cemented sandstone at a depth of 40" or more; likewise several wells penetrated to sandstone. In no case were these layers uncovered sufficiently to determine whether they lacked the slope characteristic of beachrock and hence it is uncertain whether they originated at the time of land formation or later. Near the boundary between Lukwög and Kinajöng on Ine Island is a soft, relatively fine textured sandstone well above high tide level. This is thought to have formed in the lower part of a dune and subsequently been exposed by storm action.

In a sense cementation is merely an incidental consequence of secondary lime deposition and can be expected wherever water saturated with calcium bicarbonate evaporates or loses carbon dioxide, as by warming or escape of excess acquired under the higher carbon dioxide pressure in the upper soil.

In regions of scanty rainfall or frequent alternation of wet and dry periods cementation near the soil surface is possible and may account for the "hardpan" observed in the soils of Christmas and Fanning Islands by Christophersen. Baas Becking's ("The Soils of Coral Atolls", Preliminary Notes on Project E-6, South Pacific Comm., 1950) interpretation of such hardpan, however, suffers from some misapprehension as to the processes involved. One common mode of formation (e.g. the caliche of subhumid soils of the western United States) is through limited penetration of the scanty rainfall, the periods of wetting being followed by drying which causes precipitation of carbonates. Under particular climatic conditions such "hardpans" may be normal but their occurrence elsewhere ought not to be assumed.

Cementations by phosphates leached from guano deposits has been mentioned in the previous section.

Considerable care is necessary to distinguish between "hardpan" or indurated layers formed in the normal course of soil development and somewhat similar layers that originated otherwise and later, by exposure or burial, came to occur beneath a shallow soil horizon. For example, on Palmyra Island Christophersen described a profile with 10 cm. of "mold" overlying a 10 cm.

thickness of phosphatic "hardpan" which in turn rested on coral sands; almost certainly this is more truly seen as a shallow, highly organic soil layer developing on a thin bed of phosphatic rock. The rock, rather than the sand below, is the parent material of the soil and antedates it. Similar soils are found on Arno over deeper beds of phosphate rock which can in no sense be regarded as "hardpan".

Soil Movement and Burial

Likewise, burial of an existing soil, as by the debris thrown up in great storms, followed by soil development on the new material can give rise to an anomolous profile. Such a buried soil with a black horizon at the surface and a second dark horizon at some depth was found on Ine Island (Profile #4). A somewhat similar profile was described, although apparently not recognized as such, on Palmyra Island by Christophersen. Two profiles on Ile aux Canards described by Baas-Becking are almost certainly due to burial of a pre-existing soil, though he curiously regarded the dark layers at depth as illuvial horizons. Unpublished descriptions, photographs and analytical data from profiles taken on Canton Island by Dr. L. H. MacDaniels indicate that two of these have buried organic horizons.

In addition to burial of well developed soils small periodic additions of wind-blow or wave-flung sand on a vegetated area may result in a very considerable depth of "surface" soil colored by organic residues.

The importance of dune formations in raising land height has been referred to previously. Apparently there is little movement of sand inland beyond the dune under the usual Arno conditions where dunes are soon vegetated, thus increasing their effectiveness in trapping sand. Since windbreaks diminish wind velocities for some little distance to windward, as well as to leeward, it may be that tall vegetation, such as the palms, limits dune height.

Despite their texture, newly formed or sparsely vegetated dunes are subject to considerable slope washing during heavy rains. The sand eroded from the steeper slopes is deposited as the water sinks into the soil (Profile #27) and in fact effects a marked flattening of the inland dune slope. This process is intensified by clearing and burning in the coconut groves but the mixture of beach and dune sands found in stabilized soils near older dunes suggests that it has been of general occurrence. It is probable that rapid washing of sand excavated from the taro pits brought about the very gentle slopes of their surrounding rims.

Apart from slope washing, soil movement inland is of negligible proportions except near village areas where rain is concentrated in the hard-packed walks. The resulting accumulation of sand in low places nearby is of no consequence in soil development but numerous sand pits dug to resurface the walks provide excellent profile exposures.

Shore Erosion and Storm Damage

In addition to the drastic typhoon damage already mentioned, there may well be additional effects no longer obvious, such as saturation of organic exchange complex with sodium, etc. Unusual storms or a cycle of shore erosion may cut away the land to such an extent that soils of the interior are exposed along the beach and ultimately modified by the attendant changes in vegetation and environment. In consequence of typhoons and cycles of cutting and deposition, irregular patterns of micro-relief and soil distribution and occasional profile anomalies must be considered "normal".

BIOLOGICAL FACTORS

Organic Matter

From previous paragraphs it is already apparent that living vegetation and its disintegrating products contribute greatly to the solution of calcium carbonate by their production of carbonic acid. Through penetration of roots this process may occur slowly even well within large pieces of porous coral. Baas-Becking has called attention to the abundance of algae which on Arno, as elsewhere on the moist tropics, mantle the surface of rocks and even the sand in open groves.

Apart from the effects on solubility the organic matter itself is of great significance in soil formation. In the absence of the more profound changes that mark mature soils, the presence of organic matter is the principal feature characterizing the atoll soil. It is obviously the principal source of cation exchange capacity. Further, the accumulation of nitrogen parallels that of well decomposed organic matter ("humus") for there is a fixed carbon-nitrogen ratio of approximately 10 or 12 to 1.

The breakdown of organic remains is carried on in large part by micro-organisms but earthworms are often abundant, and small snails locally so, in the darker soils.[/4] The earthworms are presumably significant agents in mixing the surface matter with mineral soil although root growth and decay provides another means of incorporation. Dead woody tissues are generally broken down by termites. In localized areas burrowing crabs accomplish very considerable mixing. Where excessive moisture prevents normal oxidation of organic materials these accumulate giving rise to peats and mucks, the distinction being the higher inorganic content of the muck.

Nitrogen Fixation

Baas-Becking has stressed the possible role of algae as nitrogen fixer and from soil samples collected by him a new group of nitrogen bacteria, Beijerinckia, has been isolated by Derx. Azotobacter has not been reported in atoll soils but would be expected in this habitat.

/4 Collections of these were made by Dr. LaRivers.

On Arno legumes are common and nodules were observed on Vigna marina, Sophora tomentosa and Canavalia sericea. On the latter they occur on the smaller roots at some distance from the root crown and hence they may be easily missed. The Vigna seems particularly important for it forms thick masses in the open groves and extends aggressively onto sand beaches, old dwelling sites and burned areas. The two species of Canavalia, though less abundant, are vigorous vines in lightly shaded areas. Intsia bijuga is the only leguminous tree but its abundance in the original forest cannot be estimated accurately now.

Seabirds

Throughout the dry islands of the Pacific nesting seabirds have created guano deposits and highly nitrogenous soils. Under wet conditions such accumulations do not remain long but the numerous areas of phosphate rock are generally considered to have originated beneath such guano areas. As mentioned, the phosphate was precipitated as the insoluble calcium salt when carried into the calcareous material beneath, whereas the soluble nitrates were washed away. The resulting product is usually well cemented although unconsolidated brown sands may occur with the rock. Phosphate rock, guano, and soils strongly influenced by guano occur only where large numbers of seabirds congregated for long periods. Even away from these areas, however, the birds must have a very considerable effect on the soil. They are common in small numbers on many islands where they roost and nest (see report of the Zoologist); feeding along the beaches and at sea they are the only significant agents adding to the land from the fertility of the sea.

Man

Native man himself is a biological agent although the activities of the island inhabitants a century ago were more localized than now. Many of the soils that originated in dense native forests now support open coconut groves; it is evident that such changes must profoundly alter soil properties but the extent of this cannot be well estimated. The taro pits are an obvious disturbance and the area influenced can be approximated grossly, but there is no way to recognize areas influenced by old house sites and fires.

Man also has an effect on the fertility levels of the soil which in the Marshalls, at least, is curiously counter to that of the seabirds. As the anthropologists have noted, the Marshallese went to the tidal beach or reef to defecate. This custom, however commendable as a sanitary measure, has meant continuing loss from the land of most of the nutrient elements contained in the diet. In Holland the soils about dwelling sites occupied for centuries have in some cases been colored by iron phosphates which accumulated through a concentration of phosphorus from the surrounding areas cropped by man and his domestic animals. It seems probably that the reverse has been occurring in various sections of Arno and its possible importance is greater because of the very limited land area occupied and the relatively dense population.

A recent source of nutrient losses is through the export of copra; for example, each ton carries away the phosphorus equivalent of 25 pounds or more of superphosphate.

SOILS OF ARNO

The soils of Arno atoll have developed under a uniform temperature of about 81° F. and a rainfall approximating 120 inches per year, rather well distributed except for a drier period that usually occurs from January to March. As mentioned, the well drained soils are regosols and lithosols and even those called "well developed" are relatively primitive. In terms of profile nomenclature they are "A-C soils" with an A_1 horizon (zone of incorporated organic matter) and, usually, a narrow A_3 (transitional) horizon passing directly into the relatively unaltered parent material, the C horizon. As a group these soils are a tropical equivalent of the "humus-carbonate soils" of the European workers.

The soils of Arno were classified into series and types on the basis of common properties, particularly those relating to profile morphology. Complexes are recurring associations of various soil and land types that cannot be readily described or mapped as separate units.

TYPES AND MORPHOLOGY

A. Soils developed on sands and gravelly sands.

1. Shioya loamy sand: This unit was first described on Okinawa and subsequently has been mapped on Saipan and several islands of the Pacific. It is a well drained alkaline soil formed principally on lagoon laid sands. The profile consists of a surface horizon 5 to 8 inches deep darkened by organic matter to a light gray, gray, or brownish gray color, resting on light-colored limesands. It is typical of the younger but not recent lands and is widespread particularly along windward lagoon coasts and on narrow lands; it is usually absent from the seaward coasts and wider island interiors.

A characteristic profile is as follows:

0 - 7" Friable loamy sand, dark gray (10 YR 4/1) /5 in color when moist, single-grained or weakly aggregated. pH 7.8

7 - 8" Transitional.

8 - 40"+ Single-grained pinkish white (7.5 YR 9/2) loamy sand composed of forams and ground shells, coral and Halimeda fragments. pH 8.4

On wider islands there is often a transitional zone between this unit and the Arno loamy sand inland. As mapped, the unit contains some areas of the Shioya sand, particularly along aggrading coasts.

The present vegetation of this unit is usually open coconut grove although small areas are in the mixed scrub forest (see Part II). Scaevola, Messerschmidia (Tournefortia), Morinda and Guettarda often form a dense undergrowth in poorly maintained groves. The ground cover depends to some extent on the degree of shading and presumably on salinity although this was not checked in the field. Wedelia, Fimbristylis, Vigna, Triumfetta, Tacca, Centella and the grasses, Thuarea, Eleusine, Lepturus and Paspalum vaginatum are often common in open groves. Under present conditions coconuts are certainly the most suitable crop for this land.

The groundwater underlying this soil may be fresh or brackish but it is doubtful whether the surface soils are normally ever very salty. Exposure and groundwater salinity affect the vegetation and hence, together with age, determine the relative development of the soils within this type. Under favorable conditions their development is fairly rapid; some areas swept by the 1905 typhoon and subsequently well vegetated were mapped as belonging to this unit, although recognizably younger than the modal profile.

Christophersen's descriptions, "sand of a lightish gray brown" on Washington Island, the "grayish brown soil" of the coconut plantations on

/5 The color names and the notations for hue, value and chroma are according to the Munsell system. Unless otherwise noted, they apply to dry samples.

Fanning Island and "lightish gray brown coral sand...mixed with root fibers, but still with a low percentage of organic matter." on the beach crests of Palmyra Island appear to place these soils with either this unit or the Shioya sand later described.

2. Shioya gravelly loamy sand: This type differs from the preceding chiefly in its content of gravel-sized fragments which may be of either lagoon or sea reef origin. Small areas of stony loamy sands are included. Most of the unit occurs on the narrow islands and part of it shows evidence of old typhoon damage.

The profile is similar to that of the loamy sand although sometimes more irregular because of the coarse materials. The vegetation is largely open coconut grove with vigorous invasion of Scaevola and Messerschmidia from the shoreline when clearing is neglected.

3. Shioya sand: The Shioya sand differs from the loamy sand in its lighter colored and generally shallower zone of organic incorporation; the textural distinction does not always exist. As recognized in the field this type includes dune sands, and medium and coarse beach sands, all of recent origin. Small areas of gravelly sand were not separated nor could a salty phase be recognized with certainty in the field.

The largest areas of this unit are recently vegetated swept lands and sands formed after the 1905 and 1918 typhoons. A belt of this type is commonly found between the sandy beaches and the Shioya loamy sand inland but is often too narrow to map.

A typical profile of the Shioya sand follows:

0 - 3 - 6" Single-grained pinkish gray (75 YR 6/2-7/2) (moist) sand or loamy sand, recognizably a mixture of decomposing organic matter, brown roots and white sand. pH 8.2. Changing abruptly through a narrow transitional zone to:

3 - 6 -30"+ White or pinkish white (75 YR 9/1 - 9/2) limesand.

Areas of Shioya sand adjacent to the loamy sand usually have been planted to coconuts; elsewhere the characteristic vegetation consists of Scaevola and Messerschmidia, occasionally with Pemphis or Suriana, along the coast, and a mixture of young trees, such as Calophyllum, Guettarda, Terminalia Morinda and Pandanus. Triumfetta, Fimbristylis and the grasses Thuarea, Eleusine, and Lepturus, and Vigna are characteristic ground cover plants.

In the main this type is regarded as a juvenile stage of the Shioya loamy sand. Its development varies with that of the vegetation it supports which, in turn, is restricted by salinity and lack of fertility. Development is most rapid when the soil adjoins older land and shares its outflowing groundwater, leaf litter and seed supply.

4. Arno loamy sand (tentative series): This is the well-drained, dark-colored calcareous soil formed on old beach and dune sands under the vegetation of the wider island interiors. This soil differs from the Shioya loamy sand in the dark color and very high organic matter content of the surface horizon (Table II). It is literally a black-and-white soil, with extreme contrast between the well defined surface horizon and the light colored limesands beneath. This unit occurs in the interiors of Arno, Tinak, Kilange, Bikareij and the several wider sections of Ine Island.

A representative profile is #25 from Arno Island:

Surface	Scattered twigs and breadfruit leaves.
0 - 11"	Highly organic, granular loamy sand or sandy loam, somewhat plastic when worked. Black when moist, very dark gray (10 YR 3/1) when dry, heavily flecked with lighter sand particles. pH 7.5. Earthworms abundant.
11 - 13"	Abrupt transition from above to
13 - 21"	Single grained, light gray loamy sand stained with organic matter becoming white (10 YR 8/2) at a depth of a few inches. pH 8.4.
21 - 54"+	Friable, pinkish white (75 YR 9/2) limesand becoming coarser at 40".

Since the texture of the surface soil cannot be determined in the field because of the high organic content, the textural class is based on the underlying soil. Size of the sand fraction varies with origin, the beach deposits being coarser or less well sorted than the dune sands. The exact thickness of the dark surface layer and the thickness and color of the transitional zone varies; their combined depth may range from 7 to 20 inches in the profiles observed. The shallower depths are usually found near the lagoon shores where this type passes into well developed Shioya loamy sand, or near the margins of taro pits. Where gravel is present it is often much more abundant in the surface layer and is there highly weathered and frequently "rotten". Its greater abundance may result from the more rapid solution of the sand. The presence of relatively unweathered surface gravel can usually be related to former house sites.

Included in this unit as mapped are small areas of associated less well drained soils with similar profiles as well as a few areas of the Arno gravelly loamy sand and transitions to the Shioya loamy sand that were too small to be separated.

In almost all cases the groundwater beneath this unit is fresh or nearly so and the taro pits are located in areas of this type and the related Arno gravelly sandy loam. The peat or muck of the taro pit bottoms and the varied soils of the excavated slopes are also inclusions in this unit as mapped. The "spoil" from the pits forms at most a scarcely discernible bordering ridge and the profile resembles that of the surrounding areas, although often shallower.

This unit and the following also form a major part of the "breadfruit zone". Individual trees or small groves mixed with tall coconuts are characteristic although not always present. Pandanus is usually common and even in well cleared groves small trees or sprouts of Allophyllus, Morinda, Guettarda and

Pipturus are abundant. Untended groves are occupied by secondary forest, composed of the above species with others such as Premna, Intsia, and on Arno Island, Ixora. Wedelia grows as a rank herb in openings and with Ipomoea tuba climbs liana-like in areas of secondary forest. The three ferns, Polypodium, Asplenium and Nephrolepsis are usually present, principally near the palm bases and on fallen palm logs; mosses are often abundant on these sites as well. Other ground cover plants vary with light intensity; under dense shade the ground may be quite bare or elsewhere sparsely vegetated with tree seedlings, Oplismenus, Ipomoea littoralis, small Tacca and scattered Thuarea and other grasses. In openings Tacca, Vigna and the grasses grow vigorously. The vegetation of the less well drained areas differs chiefly by the presence of Hibiscus tiliaceus and through the effects of dense shade.

Excepting the small areas of phosphatic soils, the Arno series with its less well drained associates are the most fertile soils of the atoll. The breadfruit grows rapidly here and bananas, papayas and limes grow fairly well, although severe iron chlorosis and probably other deficiencies retard their development when grown in cleared areas, as around the villages. Coconuts usually grow well on these Arno soils but on Arno Island itself a malady leading to early barrenness and death of the palms is associated with a portion of the unit. although not with its marginal occurrence or the bordering Shioya soils. In consequence, much of the interior there is now in breadfruit and secondary forests. According to the people this area was well populated for a long time prior to 1900; the malady was also present at that time and the coconut was maintained only by constant replanting.

The development and weathering exhibited by the Arno soils are evidence of their considerable age. They were formed under a native mixed broadleaf forest that was replaced in part by the indigenous agriculture and more or less completely by "copra culture". Thus, their development cannot be related to the existing vegetation.

The generalized profile descriptions given by O. C. Rogers and by Alexander Spoehr for adjacent Majuro Atoll are essentially the same as that of the Arno loamy sand. C. S. Pearson, who has examined my photographs and samples of the Arno soil, states that it is the dominant type on Los Negros Island in the Admiralties.

5. Arno gravelly loamy sand: This unit resembles the previous soil but for the most part it has formed on coarse gravelly beach sands. These are usually of lagoon origin but some areas of highly fragmented outside shore deposits have also given rise to this type. The unit is usually associated with the Arno loamy sand in the wider island interiors but except on L'angar Island, is of much smaller extent on the islands mapped. It will probably be found more abundant in the chain of smaller islands around the windward rim of the atoll.

The profile is similar to that of the loamy sand except for the abundance of gravel, particularly in and on the surface horizon. Much of the gravel there is very rotten and readily crushed but the soil is always calcareous. The gravel of the deeper horizons appears little weathered.

Included with this unit as mapped are small areas of stony or coarse gravelly soils derived from mixed rampart materials but having a profile similar to the type. On Namwi Island a phosphatic soil resembling the Arno gravelly loamy sand in morphology (Profile #21) was not separated from it during the reconnaissance of that area.

The vegetation and uses of this unit are identical with those of the loamy sand except as it may occasionally overlie somewhat brackish groundwater. The presence of coarse material presents obvious difficulties in the use of hand tools.

6. "L'angar gravelly sandy loam": This name is used largely as a matter of convenience for the area of this unit actually observed is too small to warrant proposal of a new series. As the name suggests the unit occurs on L'angar Island where the type locality is marked by a protruding mass of old beachrock associated with a legend concerning discovery of the banana Jorukwor (see Part II).

A typical profile of this area follows:

0 - 20" Very gravelly moist granular sandy loam, plastic when worked, with only a moderate content of organic matter. Surface dark gray when moist, gray (10 YR 5/1) when dry but superficially appearing 6/1 because of the abundance of lime particles, changing to light brown-gray (10 YR 6/2) near the bottom of the horizon. pH of dry samples 7.7 - 7.8. The larger gravel is softened and much of the smaller (less than 1") is porous or rotten.

20 - 35"+ Very gravelly sandy loam appearing lighter colored than the above but with a moderate content of organic matter. When dry, light pinkish gray (75 YR 6/1) in color; pH 7.9. The lower part is heterogeneous, consisting of dark soil material mixed with roots and coral fragments. Bottom of profile not reached.

This soil has a more loamy texture in the deeper layers than any of the well-drained soils examined. As borne out by the analyses in Table II, the organic matter distribution of this soil differs from that of the Arno series in the relatively low (6.5%) content of the surface layer and a surprisingly high (4%) content of the organic matter at the 30" depth.

The mode of origin of this soil is not known but its inland position and the highly weathered gravel indicate considerable age. It is tentatively regarded as a down-drainage associate of the Arno gravelly loamy sand that occurs around it.

The present vegetation consists of abundant Hibiscus tiliaceus with a few tall palms and volunteer coconut seedlings, Pipturus, Morinda and a few bananas. Ipomoea tuba and Wedelia are present as climbers. According to the people this area is the "best place" for bananas and formerly many were grown here.

B. Shallow and Stony Soils and Land Types.

7. Phosphate rock complex: Three small areas of brown phosphate rock occur on Tak-lib, Namwi and L'angar Islands. The soils formed directly on such rock are usually very shallow, ranging from 2-10" in depth. Both rock outcrops and pockets of deeper soil are common. The soil properties vary; in the center of Tak-lib the shallow soil is highly organic and appears mucky when wet whereas on Namwi and L'angar Island the soil is granular and contains considerable brown phosphatic sand.

A characteristic shallow profile from L'angar Island is:

0 - 4"	Black, highly organic granular sandy loam.
4 - 6"	Dark brown, granular loamy sand consisting of organic matter mixed with coarse phosphatic foram sand.
6 -	Brown phosphatic rock containing large unaltered fragments of coral.

The shallow soils comprise most of the phosphate rock complex but associated with them are: (1) small areas of unconsolidated brown phosphatic sand, (2) adjacent limesands with the surface layer enriched in phosphorus, and (3) adjacent sands or gravelly sands with an admixture of phosphate throughout the profile. So far as observed, none of these three were sufficiently widespread on the atoll to warrant separate mapping and because of their affinities they are here considered as a part of the phosphate rock complex. Characteristic profiles of the latter two follow:

Profile #12 - (L'angar Island) limesand with surface influenced by adjacent phosphate deposits:

0 - 10"	Gravelly loamy sand, high in organic matter, granular, black when moist, very dark gray (75 YR 3/1) when dry. pH 7.4. Very possibly not conformable with the underlying sand.
10 - 20"+	White or pinkish white limesand free of gravel.

This profile was observed when traveling with a group of the L'angar people and its relationship to the adjacent phosphate area was not investigated further.

Profile #21 - (Namwi Island) "Namwi gravelly sandy loam", a gravelly limesand influenced throughout by phosphate rock:

0 - 6-9"	Well aggregated, very gravelly loamy sand or sandy loam, high in organic matter. Color very dark brown when moist, when dry dark reddish brown (5 YR 3/2) with particles of 5 YR 3/3 and 4/3 and some coarse white sand. pH 7.20. Earthworms abundant.
9 - 15"	Light brown (75 YR 6/3) loamy sand, less gravelly than above, consisting of white and brown stained foram sand mixed with organic matter. pH 8.1.
16- 25"+	Pinkish white (75 YR 8/2) limesand with some rounded coral gravel. pH 8.1.

In appearance this latter soil is very similar to the Arno loamy gravelly sand and, lacking chemical data, the small area on Namwi Island was included with the surrounding Arno soils. The very large content of extractable phosphorus (Table II), however, indicates that this soil should be distinguished as a phosphatic phase or as a separate series.

The phosphatic area on Tak-lib Island supports a much battered remnant of the original vegetation, apparently the only such on the atoll. A few large Pisonia, Cordia and Intsia were noted here, as well as breadfruit and the introduced kapok, Ceiba pentandra. On the other two areas the vegetation does not appear to differ from the secondary forest found nearby and on Arno Island. Small trees of Pipturus and Morinda are abundant along with Allophyllus, Pandanus and large breadfruit and coconuts. Ground vegetation is sparse in the dense shade but the ferns, Asplenium, and Polypodium, and the climber, Ipomoea tuba, were noted near the profiles.

The people accompanying us on Namwi Island recognized that the deeper soils of the complex are favorable for plant growth and stated that "many" bananas were grown in this locality before the war. The complex should be favorable for coconut and breadfruit wherever the roots can reach a sufficient volume of soil.

Samples of phosphate rocks from each of the three areas were collected and will be analyzed. The deposits are too limited in area and depth to have appreciable commercial significance but the softer materials could be used locally as fertilizer.

8. Dark shallow soils over sandstone: The only area of this unnamed unit occurs in the center of Bikareij Island. Because of the rock beneath and its closeness to the water table, this soil is only moderately well drained. A characteristic "profile" is as follows:

0 - 6"	Highly organic, black, somewhat plastic sandy loam or loamy sand.
6"	Calcareous sandstone, similar to that now found in the very shallow waters along the northwest shore of the island.

Elsewhere the soil depth varies from 0 - 11". A retting pit, or "tou", quarried in the sandstone (perhaps as a well) at the margin of this area shows a 6-inch layer of sandstone overlying about 6 inches of unconsolidated or soft material, which in turn rests on hard sandstone. It is probable that the roots reach the intermediate layer through crevices. After heavy rains the water in this pit was fresh to the taste but is said to be usually slightly brackish. This is probably characteristic of the area in view of the elevation and location.

The unit as mapped includes small areas of mucky soil, one of which is occupied by a tangle of Clerodendrum. The remainder of the unit is largely in poorly kept coconut groves with an understory of secondary forest species, Allophyllus, Morinda, Guettarda, Pandanus and, in less dense areas, volunteer coconut seedlings. This area appears suitable only for the culture of coconut and pandanus.

9. Stony and very stony complex: This term is used to designate the belt of the soils and land materials formed by the outward building of a well

marked beach rampart on the seaward side of the land. Also included are similarly located areas covered with weathered irregular fragments of coral reputedly - and very probably - deposited by ancient typhoons. A "typical" cross-section from the windward beach inland, the synthesis of many observations, would appear as follows:

(a) Present beach rampart; recently deposited coral cobbles and rounded plates with coarse gravel and sand mixed in the lower parts; surface commonly six to ten feet above high tide.

(b) Twenty-five feet inland from (a); surface of rounded cobbles as at (a) but darkened by weathering; vegetation is tall Scaevola passing into Scaevola-Pandanus or Scaevola-coconut mixture inland.

(c) Hundred feet inland from (a); cobbles markedly weathered and covered with algae; many have lost their smooth and rounded surface. Vegetation is coconut plantation with Polypodium, small Wedelia and sprouts from cut stumps of Scaevola, Guettarda and Morinda.

(d) Two hundred feet inland from (a), near junction with sandy soils. Rounded cobbles are no longer recognizable; ground surfaced with very irregular weathered fragments of coarse gravel and small stone dimensions, heavily coated with black algae. Dark soil visible between fragments. Vegetation is coconut plantation, occasionally with breadfruit. Polypodium, Nephrolepsis, and Asplenium are common, especially around the bases and moss-covered lower trunks of the palms. Other groundcover plants are chiefly sprouts and seedlings of Morinda, Allophyllus and Pipturus. The land surface is commonly two to three feet lower than at (b).

The profiles corresponding to the above stations show a progressive increase in the amount of organic matter and content of the finer particle sizes, associated with increased disintegration of surface rock. The change from (a) to (b) is slight, principally the addition of a small amount of organic matter between the coarser particles. At (c) a black organic gravelly loam occupies the space between the weathered rock and all of the porous fragments are well penetrated by roots. At (d) the surface soil approaches that developed from gravelly lagoon deposits, although the deeper layers are not much altered. The coarser rock has broken down to weathered gravel and the percentage of sand and finer fractions have increased. Organic matter makes up 20% or more by weight of the material less than 2 millimeters in size, binding the mineral particles into aggregates.

Periods of rapid outbuilding, of stabilization or of beach erosion, as well as the overwhelming effects of infrequent typhoons, may disrupt any such orderly sequence and the "typical" cross-section above is less common than various atypical forms.

This unit appears fairly well adapted to coconut culture although the outer margins are often obviously less suitable than the remainder. In many cases the palms would probably benefit by retention of the surface organic matter and by effective windbreaks along the beaches.

C. Peats and Mucks.

10. <u>Mangrove peat</u>: This is a somewhat fibrous woody peat, moderately well decomposed and saline, formed under <u>Bruguiera conjugata</u>. When moist, it is dark red in color, drying to dark reddish brown (5 YR 2/2 - 3/2). The odor of hydrogen sulphide is present in the deeper layers. The fresh peat commonly has a pH of 7.2 to 7.4 but this changes to pH 5.6 to 5.9 upon drying. This type is usually less than 2 ft. in depth but the center of the large deposit on L'angar Island is deeper than 40 inches. The shallower areas are often somewhat more decomposed and may contain lime fragments. Limesand particles 1 to 2 mm. in size effervesce very slowly with hydrochloric acid,

indicating a considerable degree of weathering. The groundwater fluctuates with tidal changes but is usually 1 to 2 ft. below the surface. The principal areas of occurrence are on L'angar, Tinak, and Bikareij Islands.

The vegetation is unusual, approaching a monotype of Bruguiera. Along the margins Lumnitzera, Pandanus and the shrubby Clerodendrum may occur but transition from the upland is ordinarily abrupt and, except for a few epiphytic Asplenium, the interior vegetation is wholly Bruguiera. More than one age class may be present but the youngest, forming a low ground cover, is apparently short-lived in the dense shade. The forest is otherwise quite open beneath the canopy and presents a quite unusual aspect with innumerable crabs scuttling about the roots and "knees" that protrude through the cushiony reddish peat. This type is useful only as forest. The Bruguiera is a wood of value, strong and durable in contact with the soil and the younger stems provide long straight poles.

11. Mangrove shallow peat and rock complex: This unit sometimes borders areas of Mangrove peat and occupies the smaller salty depressions. The most common occurrence is a peat over and in the interstices of coral rubble or fissured rock; small areas of rock outcrop and of peat and muck mixed with coral gravel are also included within this type. The organic matter, if peat-like, resembles the Mangrove peat described above; the mucks, however, are blacker, more decomposed and perhaps less saline. The principal areas of occurrence are L'angar Island and Tinak Island and the borders of the north inlet on Bikareij Island, but small patches of an acre or less are met with elsewhere.

The dominant species is Bruguiera which may occur in pure stands. On Bikareij and Namwi Islands only, Sonneratia may be mixed with the Bruguiera. Elsewhere Lumnitzera and, on the margins, Pandanus are minor associates. The only use of such areas is as forest although retting pits are often located within them.

12. Mangrove muck: This unit is properly a land type rather than a soil and occupies too small an area to warrant much comment. It consists of finely divided organic matter principally derived from Bruguiera, or Bruguiera and Sonneratia, mixed with limesand; it is saline, has a high water content and is flooded or nearly so at high tide. Mangroves grow only on the "drier" margins of the unit but the roots of Sonneratia penetrate outward in it for some distance.

The only appreciable area of this type occurs in the deeper basin at the south end of the north inlet on Bikareij Island. A portion of this is reputedly "bottomless", men having thrust sticks tied together to a depth of 75 feet from a canoe without reaching bottom. This had a familiar ring and our investigations showed a depth of some 4 feet of gel-like muck overlying rock in the center of the area. This is covered by perhaps six inches of water at low tide. On exposed margins where the spike-like Sonneratia "knees" arise the muck is two feet or so thick over sand.

Muck from beneath this surface smells very strongly of hydrogen sulphide. A sample taken from the center was dull red in color when removed but although tightly compacted soon turned gray throughout the entire mass. This area is noteworthy chiefly because of reputed effects of the muck on human skin (Appendix C).

13. Coconut-pandanus peat: This unit occupies an inland swamp on Ül-en' Island and is the principal type found in the old taro pits on Arno Island. The peat is shallow, usually 1 to 2 feet deep and fibrous, the more decomposed portions bound together by a mass of living and dead roots.

A description of the typical profile (#24, Arno Island) is:

0 - 24" Well decomposed peat with many root fragments; pH 6.5 at time of sampling, 5.4 after drying. Color after drying and grinding is brown to dark brown (7.5 YR 4/3). Water level at two inches at time of sampling following heavy rains; it stood much lower on a previous visit.

24" + Mucky limesand.

Conductivity measurements on the dry samples indicate that both the Arno and Ül-en' occurrences are fresh-water peats, although it is possible that the Ül-en' swamp may occasionally be subject to flooding with somewhat more brackish water. Included with the unit indicated on the map of Ül-en' is a small area of shallow black muck at the southeast margin of the swamp. In addition to woody sprouts, Wedelia, Colocasia and Cyrtosperma were growing at this point. People stated that these taros could not be grown elsewhere in the swamp although the water had "not very much salt".

On the remainder of the Ül-en' swamp the vegetation is coconut grove with an abundant undergrowth of pandanus. Wedelia and sprouts of Morinda and Allophyllus occur on the slightly higher rises. The peat offers poor footing for the coconuts; fallen logs are numerous and most of the standing trees are curved. Coconut usually grows on the margins rather than directly on the surface of the taro pit peats of Arno Island but the pandanus is in both positions. Here, too, Hibiscus tiliaceus is often a bordering tree and other secondary forest species around the margins contribute some organic matter. In both areas mosses and ferns, Polypodium, Asplenium and Nephrolepsis are abundant on fallen logs although the ferns perhaps do not reach maximum development here. Dryopteris goggilodus, the "kinnen menuel", forms dense colonies in the Arno pits but was not seen elsewhere. Similarly Eleocharis geniculata was observed only on Ül-en' Island where it was fairly common on the peat surface near profile #26.

It is not known whether these peats can be utilized for taro culture. Both areas are subject to immersion after heavy rains and it is said that an attempt to replant some of the Arno pits failed because the small plants were covered with water. The potential fertility of the peat is high and cultivation, exposure to sunlight, etc., would gradually change the peat to the well decomposed muck in which taro normally grows. Palms are apparently growing well in the

Ül-en' peat although the yields are unknown. The possibility of excavating this peat for gardens is mentioned later.

As nearly as can be determined, the Arno pits were abandoned very early in the century and thus the rate of peat accumulation appears to have been extraordinarily rapid. According to Ralph McCracken, peat development in phosphate mining excavations on Angaur Island, in the Palaus, proceeds at a similar rate.

14. Taro pit mucks: If the area involved were more extensive a taro pit complex might be recognized. The steep inner slopes of the taro pits have been subject to slope wash and other disturbance from human traffic and the rooting of hogs. Not uncommonly coconut husks, fronds and brush from grove clearing are thrown over the edge and usually incompletely burned.

The pit bottoms are usually artificial mucks created by long continued additions of organic matter for taro culture. The mucks vary considerably in the admixture of mineral material and in relative "wetness". The groundwater is fresh and its level fluctuates with the tide, the maximum often being with a foot or less of the surface. After heavy rains many of the pits are shallowly flooded for a few days. As noted above, coconut-pandanus peat has formed in the long abandoned Arno pits. Elsewhere abandonment has been less complete or the water level unfavorable for peat accumulation. Taro culture continues in some pits.

A typical profile of a taro pit muck (#5, Ine Island) follows:

Surface	Scattered breadfruit leaves and seedlings of colocasia and a grass.
0 - 10"	Mucky limesand with some coral gravel less than 1 inch in diameter. Matrix very dark gray flecked with light lime particles. pH of moist sample 7.6.
10 - 32"+	Light gray changing to white sand, the organic matter content diminishing gradually with depth. pH 7.4 at 30 inches. Strong smell of hydrogen sulphide at 30 inches. Groundwater level at 28 inches when sampled but the following day, with the rising tide not yet full, at 15 inches.

Except on Arno Island the abandoned pits are often occupied by woody vegetation, such as breadfruit on "drier" sites and Hibiscus tiliaceus. One or two pits on Ine Island were completely dominated by Cyperus odoratus. The mucky pits could be readily returned to taro culture if the people wished to do so. In their present condition the drier mucks and pit margins are well suited for bananas but are utilized to only a limited extent for this purpose.

D. Miscellaneous Land Types.

These include the beaches, limesand drifts, and embayments or inland "flats" of sand, rubble or cemented rock. Since the fragmentation of the long eastern island by the 1905 typhoon much of the remaining land has been reconnected and augmented by wave heaped sands; the same process can be seen elsewhere as well. Where the surface of these rises above tide level it is vegetated by Scaevola, Messerschmidia and coconut seedlings, all often chlorotic in the early stages.

In the course of land formation or repair low areas of the island platform are sometimes cut off between the rampart or gravels thrown up along the seaward coast and the existing land or sand drifts on the lagoon side. This is the probable origin of many of the existing mangrove swamps and certain interior lowlands, such as that near Kinäjong. Rampart formation following typhoon damage has cut off two small basins on Aljaltüen' Mätol-en' and Enërään' Islands; these are not yet vegetated. The larger "flats" of Namwi and Bikareij Islands seem to have been enclosed by extension of existing lands. As long as such areas are open to the sea the higher tides bring in sediments and occasionally rework the surface. Sand banks formed along the margin are rapidly stabilized by vegetation and thus young soils may come to occupy the interior as well as the periphery of an island.

Not otherwise described is the buried soil found 260 feet inland from the sea-beach near Ine Island (Profile #4, Appendix B). The present surface soil is characteristic of a moderately well drained associate of the Arno gravelly loamy sand but extending from a depth of 35 inches to over 58 inches below the surface is a dark horizon containing organic matter. According to Lijömmar of Ine, a typhoon in the "time of his grandparents" threw up rock along the coast at this point and conceivably burial of the original profile occurred at that time. If Lijömmar's statement is taken literally, however, the maximum age of the present surface profile could scarcely be greater than 125 years, which appears too slight for the development noted.

SOME CHEMICAL PROPERTIES

The results of some chemical analyses of the mineral and organic soil samples from Arno are given in Table II. Descriptions of the profiles, identified by numbers, are given in the preceding section and in Appendix B. The material taken for analysis was that passing a 2 mm. sieve except for the organic samples of profiles #16 and #24 which were ground. pH was determined by glass electrode, soluble salts by conductivity measurements, total nitrogen by Kjeldahl, organic matter by the rapid microchemical methods of Peech (Soil Science 59:25-38, 1945), and the "readily soluble" amounts of other elements by the methods of Peech and English based on the use of Morgan's extracting solution (Soil Science 57:167-195, 1944).

pH, Calcium and Magnesium

As expected, the mineral soils are all slightly alkaline in reaction ranging from 7.2 to 7.5 in the highly organic surface soils to a maximum of pH 8.7 in the unweathered material lacking appreciable organic matter. These soils all effervesce with acid and hence analyses for available calcium were not made.

Dried samples of the organic soils have an acid reaction whereas in the field, using indicators, reactions vary from essentially neutral to slightly alkaline. Thus for the same samples:

Table II. CHEMICAL ANALYSES OF SOME SOILS FROM ARNO ATOLL

Profile No.	Soil type or Designation	Depth of Sample (Inches)	pH	Organic Matter %	Total N %	OM/N	Pounds per acre: P	NO_3 N	NH_3 N	Mg	K	Mn	Fe	Al	Soluble salts $K \times 10^5$
25	Arno loamy sand	0-6	7.45	16.68	.88	19.0	80	100	40	750	110	8	1	5	80
	Arno Island	6-11	7.55	11.32	.59	19.2	25	30	40	425	63	8	1	5	60
		14-19	8.40	.28	.04		25	8	18	5000	18	5	1	5	19
		24-30	8.65	.14	.04		40	8	20	3750	15	5	1	5	17
23	Arno loamy sand	0-6	7.55	22.48	.98	23.0	10	60	25	50	63	8	1	5	74
	Arno Island	12-18	8.25	.20	.05		25	8	15	3000	19	5	1	5	20
		30-36	8.40	.10	.05		25	5	15	4500	22	5	1	5	18
29	Arno loamy sand	0-6	7.50	19.04	.88	21.6	120	20	45	950	126	40	1	5	45
	Jab'u Island	18-24	8.40	.20	.04		50	5	25	4000	14	5	1	5	21
		30-36	8.50	.24	.06		60	5	22	5000	15	5	1	5	21
6	Arno gravelly loamy sand	0-6	7.40	32.92	1.16	28.4	110	100	50	1800	203	25	1	5	104
	Ine Island	6-12	7.50	20.44	.70	29.2	25	40	45	750	80	20	1	5	74
		20-26	8.35	.28	.04		30	5	20	5000	18	5	1	5	15
4	Moderately well drained associate of Arno very gravelly loamy sand	0-8	7.55	16.88	.73	23.1	25	25	35	50	135	25	1	5	46
	Ine Island	20-28	8.05	.80	.08		20	8	18	1600	23	5	1	5	24
		38-46	7.85	3.84	.13		8	8	25	280	45	5	1	5	38
21	"Namwi gravelly loamy sand"	0-7	7.20	20.44	.67	30.6	860	80	45	1120	286	5	1	5	104
	Namwi Island	10-16	7.50	3.44	.30		400	20	22	3800	45	5	1	5	57
		20-25	8.10	.52	.07		280	10	25	5000	31	5	1	5	32
12	Phosphate influenced associate of Arno sandy loam. L'angar Is.	0-8	7.40	19.36	.99	19.6	210	70	45	1120	98	8	1	5	70
11	L'angar gravelly loamy sand	0-6	7.70	6.52	.41	16.2	80	45	22	700	57	8	1	5	49
	L'angar Island	14-20	7.80	5.34	.34	17.3	50	40	25	950	45	5	1	5	62
		29-35	7.90	4.02	.28	14.4	50	40	22	1000	55	5	1	5	115

Table II. CHEMICAL ANALYSES OF SOME SOILS FROM ARNO ATOLL (continued)

Profile No.	Soil type or Designation	Depth of Sample Inches	pH	Organic Matter %	Total N %	OM/N	Pounds per acre P	NO_3 N	NH_3 N	Mg	K	Mn	Fe	Al	Soluble salts Kx10[5]
14	Shioya sand. L'angar Island	0-7	7.95	1.82	.16		20	20	25	4250	31	5	1	5	29
27	Shioya sand with recent overburden	2-1/2-4	8.25	.74	.08		25	8	20	4000	25	5	1	5	18
	Jab'u Island	0-4	8.25	.70	.08		25	10	15	4000	19	5	1	5	20
		16-20	8.70	.08	.04		25	5	18	3000	12	5	1	5	17
16	Mangrove peat, L'angar Island	0-6	5.90		1.51		1600	35	130	12000	976	5	1	5	2700
		16-22	5.75		1.24		1200	15	100	16000	1200	5	1	5	3000
18	Mangrove peat, Tinak Island	0-6	5.65		1.82		760	15	130	19000	1400	5	1	5	3000
26	Coconut-pandanus peat, Ul-en' Is.	0-8	6.25		2.60		280	30	190	2000	436	5	1	5	225
24	Taro pit coconut-pandanus peat, Arno Island	0-8	5.40		2.95		320	15	220	1400	310	5	1	5	345

Profile #	pH Fresh	pH Dry
26	6.8	6.25
18	7.2-7.4	5.65
24	6.5	5.4

Changes of this magnitude or greater upon drying in mineral soils containing sulfur have been reported and are attributed to oxidation of the reduced forms to sulphates. This sequence is a very likely one in our samples and probably accounts for the increased acidity noted. The two samples of coconut-pandanus peat, #26 and #24, are the only soils on the atoll that were acid at the time of collection.

As might be expected from the discussion of parent material, readily soluble magnesium is relatively high in all soils.

Salt Content

The content of soluble salts is expressed as specific conductance, $K \times 10^5$ at 25° C, of a 1:2 soil:water mixture (by weight). As a basis for comparing the samples of mineral soils from Arno, unfertilized leached soils of the humid regions commonly have K-values below 15 whereas heavily fertilized greenhouse soils may range from 100 to 200. A K-value of about 200 is about the maximum permissible for salt sensitive plants and values greater than 300 result in severe injury to common greenhouse plants. High organic matter contents raise the critical level at which injury occurred. For soils flooded with sea water the critical K-value is 100 for sensitive plants since the toxicity of a single salt is greater than that of mixtures.

Thus values for mineral soil in Table II fall within a range well below the level of plant injury. The higher values of the dark surface soils of the Arno and similar series is due in part to the content of soluble nitrogen salts.

The allowable levels mentioned above do not apply to the organic soils because of their very high moisture contents. The two samples of coconut-pandanus peat fall well within the usual range of "fresh water" peats. The mangrove peats, of course, are highly saline.

Organic Matter and Nitrogen

The extreme color contrast between the surface and subsoil in the Arno series and its associates is paralleled by the contrast in organic matter content. That of the surface soils is surprisingly high, ranging from over 16 to nearly 33% in the surface six inches. Where this horizon is sufficiently deep for a second sample above the transition zone it, too, is high. Thus the average content of organic matter to a depth of eleven inches in profile #25 is 14% and 26.7% to a depth of twelve inches in profile #6. These values do not take into account the gravel excluded in sample preparation. Organic matter decreases very abruptly through the narrow transition zone and the white lime-sand beneath contains only a fraction of 1%. The notable exception is profile #4 where increased organic matter and nitrogen indicate a former soil surface long since buried by the material on which the present soil developed. Total organic matter as mass per unit area cannot be calculated without data on bulk density and excluded matter, but it would seem to be of the order of 200,000 to 400,000 lbs. per acre.

As already mentioned, the L'angar gravelly loamy sand has a relatively much lower content of organic matter in the surface horizon but the deepest samples taken still contain some 4%; again these values are on a gravel-free basis. The two samples of Shioya sand contain low amounts of organic matter.

In mineral soils total nitrogen generally parallels organic matter with the ratio between the two indicating the degree of decomposition. The OM/N ratios calculated do not depart far from 20, which is usually considered characteristic of well decomposed "humus". As might be expected, the amounts of "available" ammoniacal and nitrate nitrogen are moderately high in the dark surface soils and low in both the deeper horizons and in the Shioya sand.

Organic matter in the peat samples will be determined later but may be expected to exceed 80%. The total nitrogen contents are high, ranging up to nearly 3% for a sample from a taro pit on Arno Island. Of the available nitrogen forms, ammonia is far in excess of nitrate.

Phosphorus

Estimation of readily soluble phosphorus is an empirical procedure at best and the extractant used (pH 4.8) is not well adapted to calcareous soils. Thus the data presented characterize phosphorus status to only a limited degree. The low organic limesands of the subsoils and Shioya soils usually fall within a range of 20 to 30 lbs. P/acre (= 10-15 ppm) whereas the content of the dark surface layers is usually much higher, the notable exception being the 0-6" sample of profile #23 from the area of short-lived coconuts on Arno Island. The samples from profile #21 and #12, adjacent to phosphate deposits contain relatively large amounts of the element.

The quantity present in peat is generally several-fold greater than in mineral soils but by humid temperate region standards the phosphorus levels of the Arno peats are high.

Potassium

As with phosphorus the low organic limesands yield a minimal amount of potassium to the extracting solution. This value is about 15-25 lbs. per acre whereas the range in surface soils, having much higher exchange capacity, is commonly 50-200 lbs. per acre. These levels would be considered adequate for plant growth if they can be sustained but information on the reserve potassium is needed.

The mangrove peats are very high in potassium, reflecting the influence of sea water, and the coconut-pandanus peats are reasonably high.

Iron, Aluminum and Manganese

The constant amounts of iron and aluminum in Table II are the minima reported by the procedure used and thus any lesser variations are concealed. A much greater range is shown by the manganese contents; the minimal amount, less than 5 lbs. per acre, characterizes the low organic limesands, the peats, and the high phosphorus soils but the remaining surface soils contain 5 to 49 lbs. per acre.

SOME EFFECTS ON PLANTS

No field moisture determinations were made but some obvious relationships may be noted. The moisture sources of importance are soil water, held by capillary forces throughout the soil, and the ground water, which is of unusual importance here because of the proximity to the surface and its possible salt content. Shallow rooted plants and those growing some distance above the ground water, as on dunes, must depend exclusively on water held in the soil; only an actual examination of the root system will reveal to what extent the deeper rooted plants normally reach the region affected by the ground water. It is quite possible to have a considerable depth of soil containing salt-free soil water overlying brackish groundwater.

The moisture holding capacity of the coarse textured soil is usually assumed to be low but in the surface layers this property is augmented by the content of organic matter. The possible moisture capacity of porous coral has already been suggested. During our stay on Arno, the longest period without rain was not more than a few days and the soil in excavations was never thoroughly dry. Some plants exposed in openings showed temporary wilting during the brief periods of dry sunny weather but recovered overnight. Thus, to judge by mere observation, soil moisture was not a direct factor in plant survival, other than for seedlings, during the June to August period, although it certainly may have influenced plant growth and competition. Observations in the drier months, however, might well reveal critical soil moisture levels.

In many areas the ground water level is closer to the surface and here, the problem is obviously not water but salt. Although the conductivity data in Table II indicate how well rainfall removes soluble salts from the upper soil layers they do not fairly represent conditions for plant growth on a considerable part of the atoll. Many areas of Shioya sand and loamy sand, and the outer parts of the stony land complex undoubtedly have brackish ground water. Moreover, groundwater salinity often increases during the later winter "dry" season. In this environment salinity, like soil moisture, should be considered a fluctuating soil property for the critical levels that determine plant survival may persist for only brief periods.

The question of "atmospheric salinity" is not considered here although it is fairly obvious that salt spray can influence plants near windward coasts and under unusual storm conditions. As Mr. Cox has pointed out, water samples from the wells of Ine and Arno Islands and from cisterns on Ine have a very low chloride content indicating no appreciable spray contamination on those leeward islands.

Apart from variations due to the seasonal rainfall differences, it is evident that the pattern of groundwater salinity will be affected by permeability of the substrate and by the land width, height, etc. Some sensitive plants may grow almost to the shores where the outward flowing sheets of fresh water prevents movement of salt water inland. Thus breadfruit, which is not considered salt tolerant, has been observed within 35 ft. of a low beach on Ül-en' Island.

The several considerations mentioned above and the very considerable differences in soil fertility levels suggested by Table II indicate that salinity, important as it is in controlling plant distribution, should not be overstressed.

Thus a plant species or community growing in an area of limesand or Shioya sand may well be exposed to atmospheric and groundwater salinity but these soils are also characterized by low nitrogen, exchange capacity, potassium, etc. Thus the presence of the plant or community elsewhere may suggest low fertility levels, salt content, or both. In a similar vein, the occurrence of certain plants in the island interiors only may be a response to the higher fertility levels there as well as to the salt-free groundwater.

The yellow leaved palms seen on several areas were attributed to excess salinity, largely on the basis of land position, although the possibility of nitrogen deficiency cannot be excluded. A surface soil sample from one such area showed little salinity, a not unexpected finding considering the high rainfall of the period previous to sampling.

Another coconut malady affects an appreciable area in the interior of Arno Island. As already noted, a surface soil sample from a badly affected spot there is unusually low in readily soluble phosphorus. Considering the long occupancy of the land and the relatively high phosphorus demand of the coconut, the possibility of phosphorus deficiency on the area must be considered.

On Mokil, Bentzen (Pacific Science Board CIMA Report, 1949) found an area in the center of each of the three islets composing the atoll on which coconuts were no longer productive. The largest, on Urak Island, is known to have grown breadfruit prior to 1890 when it was cleared and planted to palms. For some years it produced well but yields declined after 1913 and by 1925 it was given up as a commercial venture, although the palms still stand. Inasmuch as Bentzen mentions neither dead trees nor foliar symptoms this condition appears to differ from the Arno syndrome, at least in severity. Both, however, occur on island interiors, cropped to coconuts and in both areas breadfruit trees still grow well. It seems likely that similar maladies will be found on other atolls.

As might be expected, iron deficiency is common on Arno in village areas and clearings or wherever organic matter additions are lacking. Some of the sensitive exotics such as banana, lime and hibiscus become strikingly chlorotic but more or less severe symptoms were noted in fourteen other genera, native and introduced. Experimentally, this condition in the banana was overcome by suitable applications of iron to the leaves but a more practical means is through organic matter additions and mulches. This deficiency may influence plant competition on areas of exposed limesands since Thuarea, Vigna, Tacca, and Centella are at least moderately affected. Under closed forest conditions symptoms are rarely noted.

Mr. Anderson sent a variety of vegetable and flower seeds with our party as a gift to the Arno people. The resulting plantings observed were largely failures either because of cultural or soil difficulties.

A small "garden" was established in Ine Village with the hope of detecting soil factors affecting plant growth. The area had been long cleared and hence presumably did not correspond to similar areas of Arno loamy sand under forest. Onions, radishes, lettuce and tomatoes failed after germination and slight initial growth; pole beans, corn and curcurbits were stunted and their eventual failure appeared certain. Growth was not greatly affected by applications of nitrogen (as ammonium sulphate), potassium or boron. Iron chlorosis masked other symptoms in the tomatoes and curcurbits; the remaining species did not display characteristic phosphorus deficiency symptoms. These considerations together with the prevailing alkalinity and the data of Table II suggest minor elements, other than boron, and possibly phosphorus as the limiting factors for growth.

Coconut-pandanus peat from a taro pit on Arno Island (Profile #24) was potted and sown to tomatoes, lettuce and onions. A photograph by Dr. LaRivers a few weeks later shows that tomatoes and lettuce grew rather well in the peat fertilized with ammonium sulfate, potassium chloride and crushed phosphate rock, whereas the onions, a salt-sensitive crop, grew much better in the unfertilized material. Wherever peat deposits occur near village areas they could be excavated to surface seed beds and very small garden spots for plants not readily grown otherwise.

On the basis of observations thus far there is no reason why a large number of exotic plants cannot be grown on the atoll soils under garden condition. Alkalinity of the mineral soils will exclude several but the neutral peat can provide a medium for some of these. In the absence of specific information on limiting elements "complete" fertilizers including minor elements seem necessary, or in their stead, heavy applications of organic matter incorporated with the soil or as mulches. Under the conditions of Arno the latter is the only feasible means. In addition to soil factors other cultural requirements, such as adapted varieties, pest control and protection of small seedlings against rain, wind and drying must be considered. Recommendations for the peasant style agriculture of Arno necessarily must be very different from those employed under a more modern agriculture.

DISTRIBUTION

Maps

Soil distribution was mapped in detail on the larger islands. In some instances mapping was limited by time or heavy rains and has been supplemented by notes and sketches made on preliminary tours with the local citizens. The attached maps have been prepared by transferring field sheets and notes to base maps enlarged from 1/30,000 aerial photographs. Unfortunately the photographs were not available in time to be of use when most of the field mapping was done and subsequent interpretation from them has been limited by their scale and quality. In some cases the mapping precision is not commensurate with the relatively large scale of the maps.

LEGEND FOR SOIL MAPS

SOIL AND LAND TYPES

Light colored soils of narrow lands and shores	Sl	Shioya loamy sand
	Sg	Shioya gravelly loamy sand
	Ss	Shioya sand
Dark soils of the island interiors	Al	Arno loamy sand
	Ag	Arno gravelly loamy sand
	Ll	L'angar gravelly sandy loam
Undifferentiated soils and land types	P	Phosphate rock complex
	Ts	Dark shallow soils over sandstone
	S.C.	Stony land complex
Peats and mucks	Mp	Mangrove peat
	Msr	Mangrove shallow peat and rock complex
	Mm	Mangrove muck
	Cp	Coconut-pandanus peat

OTHER SYMBOLS

Limesand shore deposits

Dune

Beach rampart and juvenile phases of stony land complex

Beach sandstone

Reef rock, conglomerate and sandstones

Depression

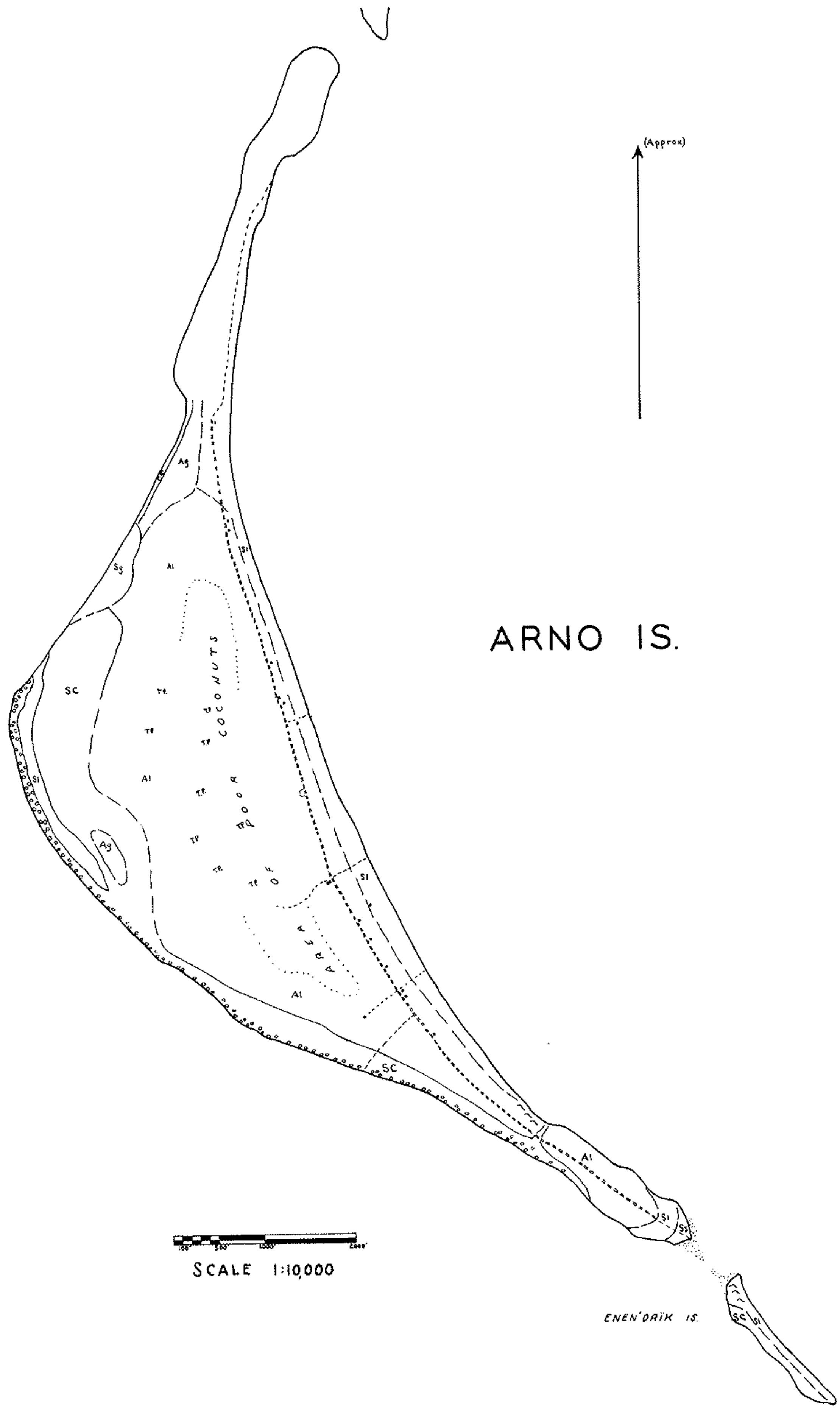
Erosion escarpment

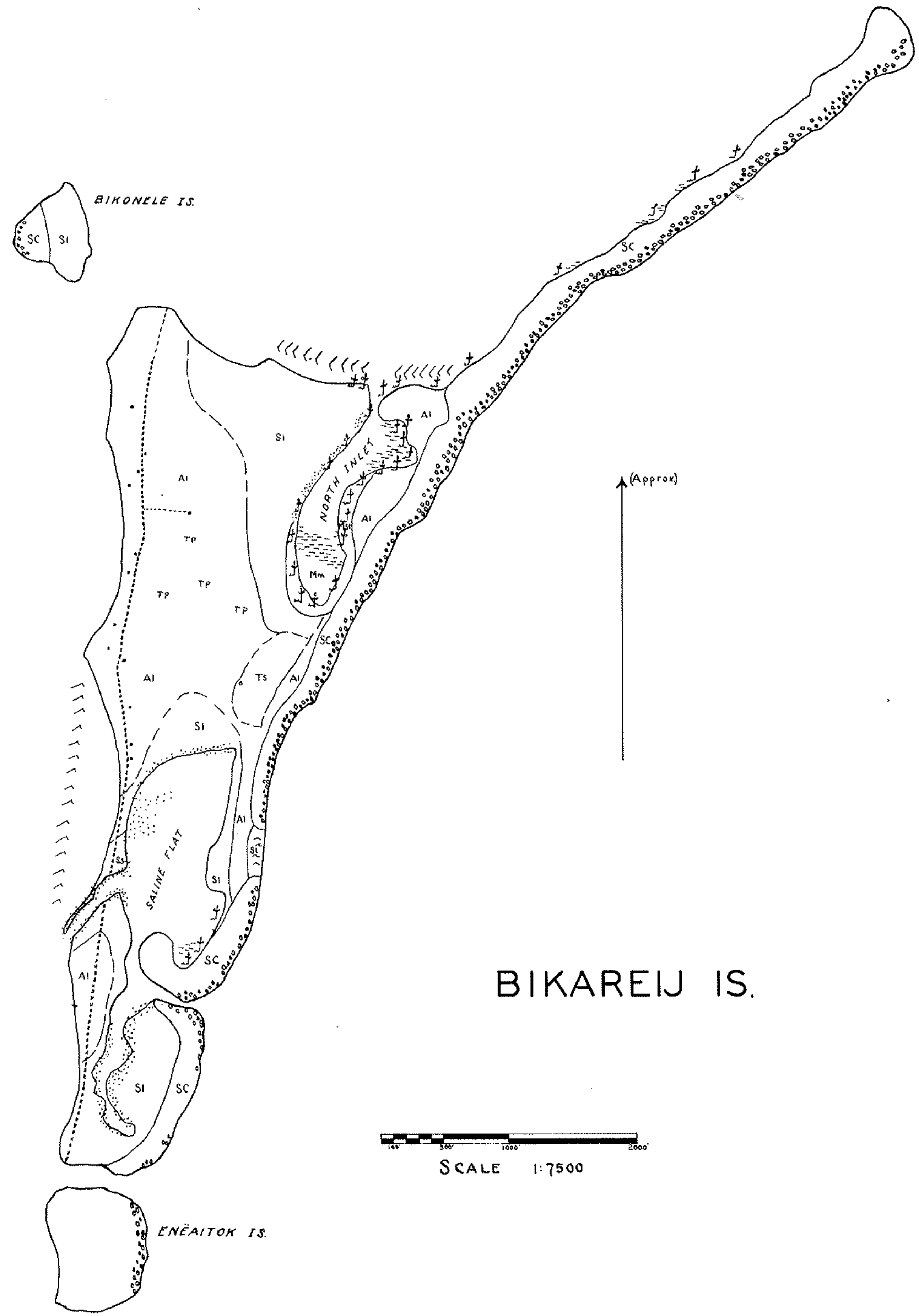
Well

TP Taro pit area

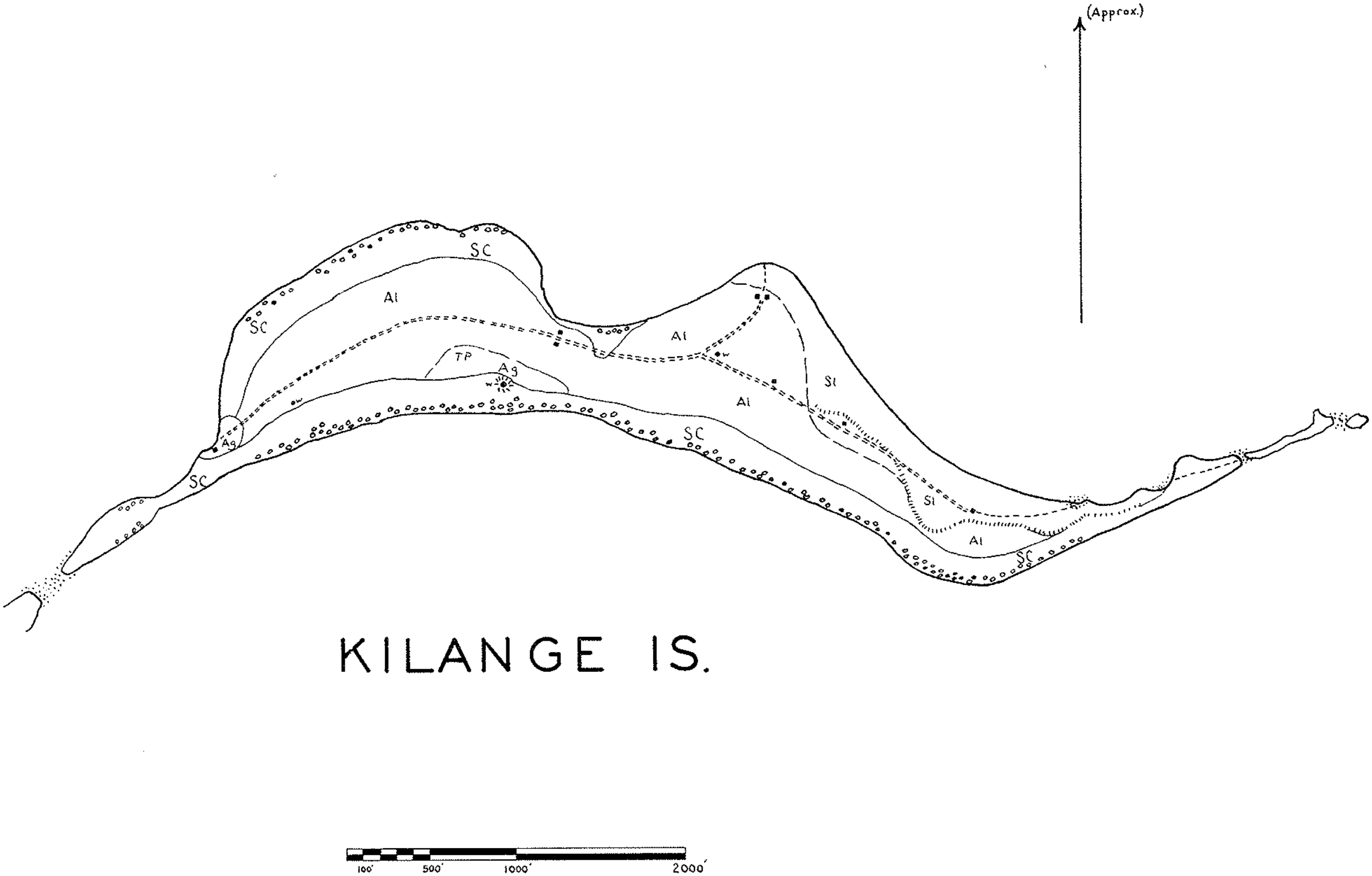
Mangroves

Main walks and trails


ARNO IS.
(Approx)
AREA OF POOR COCONUTS
SCALE 1:10,000
ENEN'ORÏK IS.

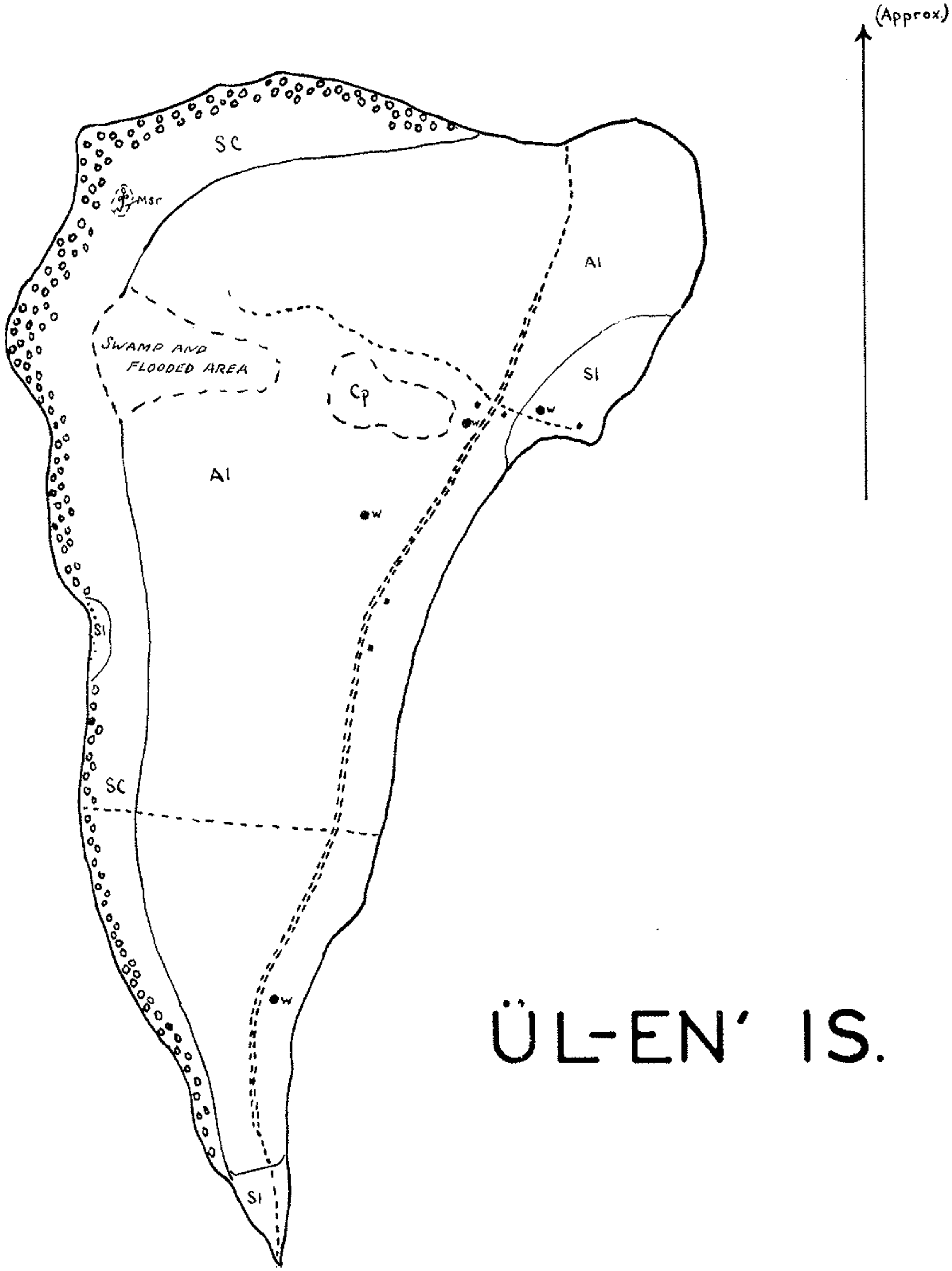


BIKONELE IS.
SC
SI
AI
TP
TS
NORTH INLET
Mm
SALINE FLAT
(Approx)
BIKAREIJ IS.
SCALE 1:7500
ENËAITOK IS.

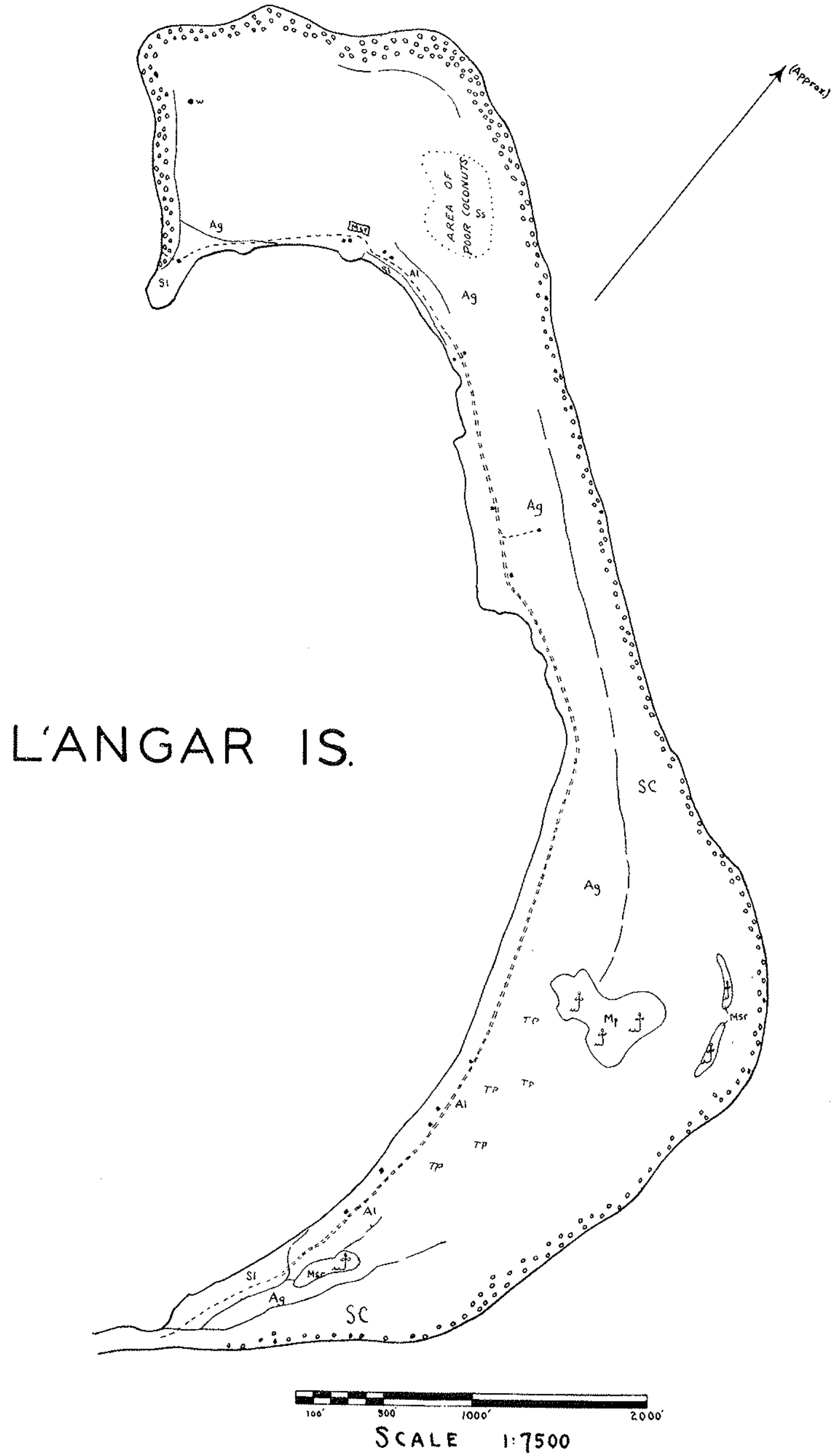


KILANGE IS.

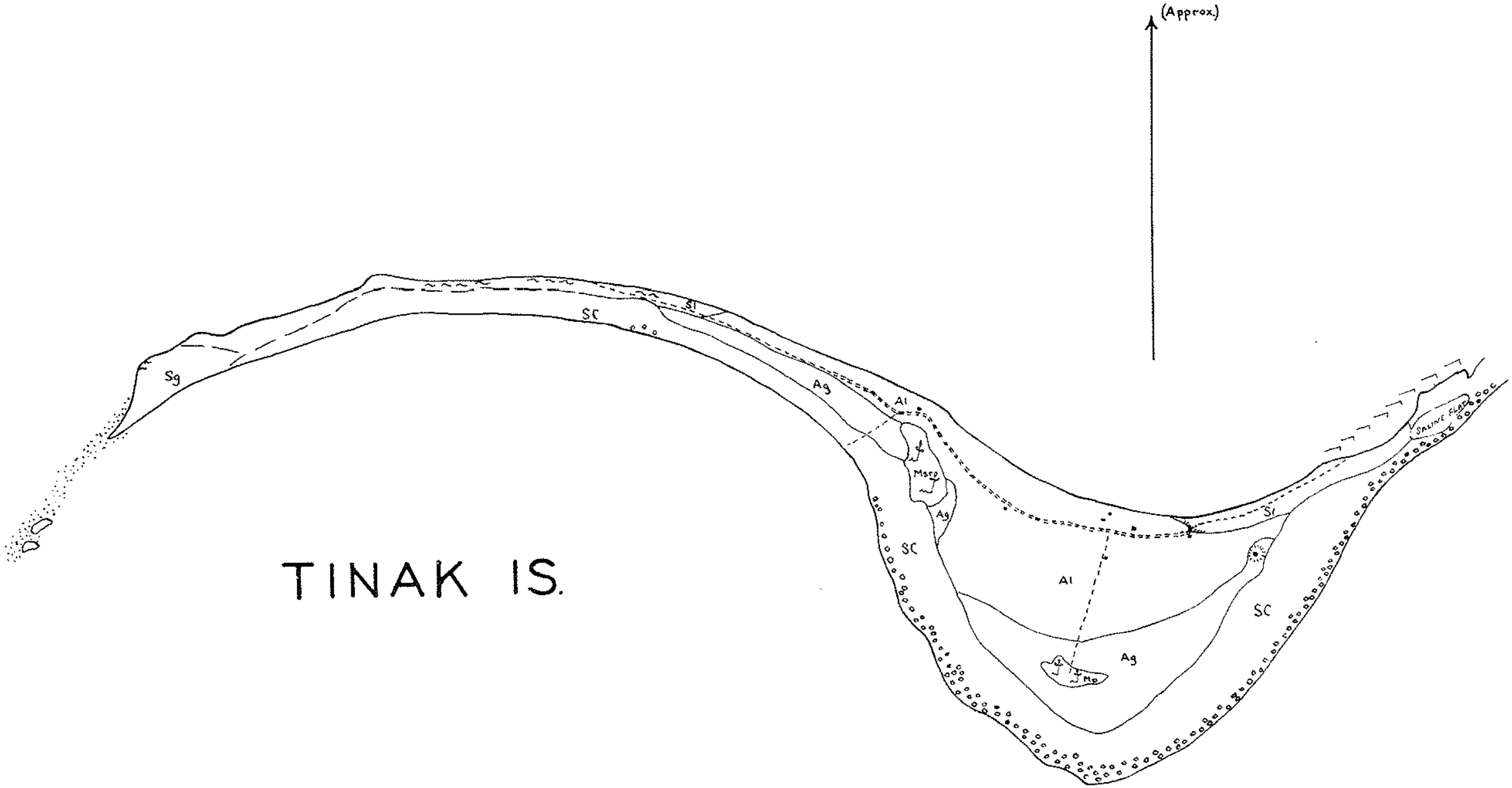
SCALE 1:7500



ÜL-EN' IS.

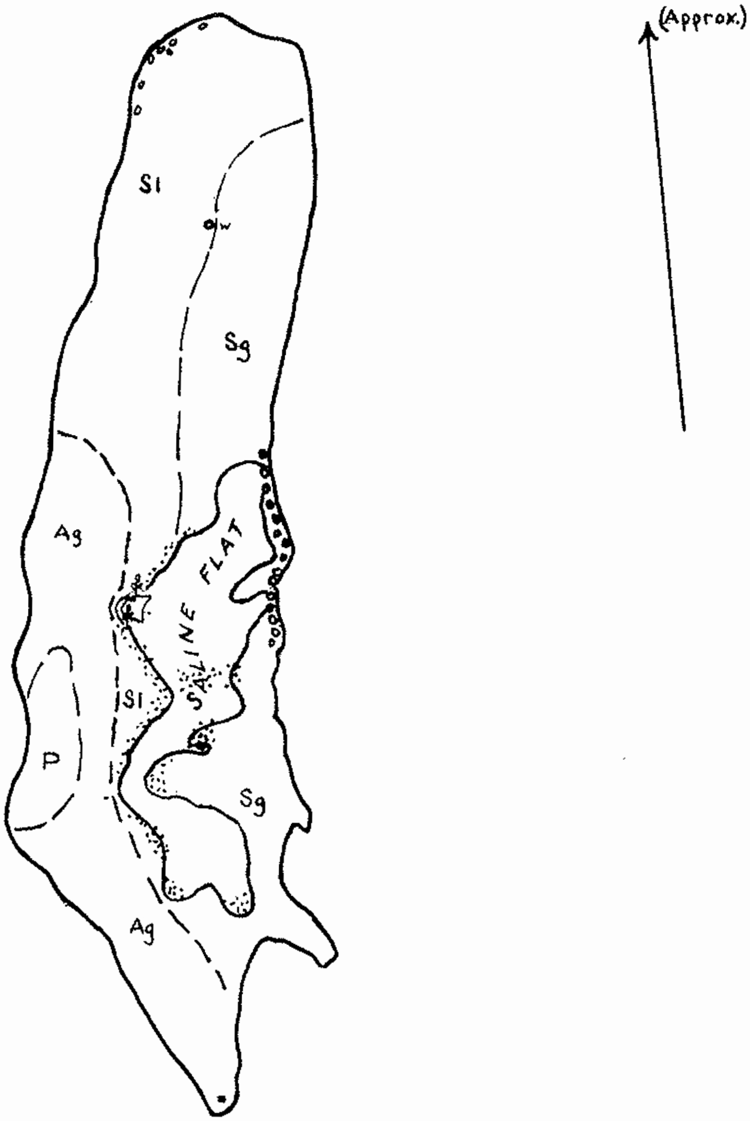


L'ANGAR IS.
(Approx)
W
AREA OF POOR COCONUTS
Ss
Msr
Ag
Sl
Al
SC
Mr
TP
100'
500
1000'
2000'
SCALE 1:7500

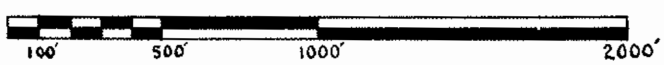


TINAK IS.

SCALE 1:7500



NAMWI IS.



SCALE 1: 7500

Notes on Land Conditions to Accompany Maps

ARNO ISLAND - This, the largest island on the atoll, occupies a sharp curve in the reef and extends along it in either direction. A belt of the stony complex margins the sheltered sea coast but its center seems to have been much disturbed. Areas of Shioya loamy sand occur here, the sand sometimes clearly overlying or mixed with the coarse material below. The wide interior is occupied by the Arno loamy sand and its inclusions, and a narrow belt of the Shioya loamy sand fringes the lagoon coast. The boundary of the "poor" coconut zone can be recognized at several points. The groundwater is fresh under most of the island and wells are common near the lagoon coast. A small extent of inland dune occurs on the southeast limb of the island, affording a site for one of the two graveyards on the island. Near this a stony dry channel, apparently swept by storm waters at one time, crosses the island.

The southeast tip of the island is composed of recent sands; a sandspit, covered at high tide, connects with Enen'edrik Island which is said to have been continuous with Arno Island prior to the 1918 typhoon. An indentation in the reef at this point apparently allowed breaching; it also provides the local anchorage. Enen'edrik Island follows the general pattern with rubble on the seaward side and sand along the lagoon but most of the soils appear quite immature.

BIKAREIJ ISLAND - This island may be thought of as composed of five major divisions: (1) A narrow strip of stony land fringes the entire eastern side and extends in an arc to the northeast, forming a long narrow peninsula. (2) A central lowland is composed of the saline interior sand flat in the south, the deep, mangrove-fringed inlet in the north and a low sandstone belt between. (3) A large area of Arno loamy sand makes up the center and western side of the island and (4) a very small area of this type occurs south of the western opening to the interior flat. (5) Less well developed and presumably younger Shioya soils occur between the Arno soils and the lowland.

It is evident that the history of land development has been complex. The off-shore beachrock and the exposure of the Arno soil on the very edge of the western coast suggest that considerable erosion has taken place; the southern occurrence of this soil may well have once been part of a larger area. Away from the beach, the southern part of the stony complex appears older than the northern arc and is fringed with the Arno soils. The western side of the peninsula rests on sandstone which affords footing for a few stunted Bruguiera on its corroded surface.

Limesand banks are now forming in places along the sides of the interior sand flat and an appreciable area of younger soils surround the flat, suggesting centripetal filling. A zone of soils intermediate in character between the Arno and Shioya loamy sand occurs north of the flat. Similar soils grading into the Shioya series occupy a large sector west and northwest of the north inlet. Where this sector borders the inlet is a narrow belt of recent sand deposits; here and for some little distance west the burrowing of crabs has disrupted any profile formation. Between the inlet and the southern flat is the low area described as having dark soil shallow over sandstone. It seems probable that this sandstone is continuous with that of the inlet exposure and the rock underlying the southern flat.

The small northwest island of Bikonele consists of Shioya soils and stony soils equivalent in age. A considerable quantity of pumice "pebbles" were found on the soil surface inland but their total mass is negligible.

KILANGE ISLAND - The western half of the island occupies an unique position on a reef flat that separates two narrow lagoons. Although somewhat protected by the broad reef to the north it has stony belts on both sides of the land. The northern belt ends near the lagoons but the southern one is continuous along the seaward coast. Most of the remainder of the island consists of Arno loamy sand and gravelly loamy sand, but an irregular belt of Shioya soils occurs along the northeast coast. Although not precisely located, its inland boundary coincides in part with a low (3 to 4 ft.) escarpment that merges with the seaward rampart as the land narrows to the east. Presumably the escarpment and the younger soils are the consequence of the 1905 typhoon.

Only three fresh water wells were reported on this island although many more could and may exist. One near the fork in the main trail is some 5-1/2 ft. deep in beach sands and was dry at mid-tide. Another near the western end of the wide land is "usually fresh." The third well is at the bottom of a large deep (8 to 10 ft.) depression at the inner edge of the rampart. A reported joñ swamp proved to be but a small mucky depression with two Bruguiera trees.

L'ANGAR ISLAND - The seaward coast of L'angar is fully exposed to the northeast trades and it is fringed with a high coarse rampart for its full length. Vegetation rises as a wedge with the flattened Scaevola at the rampart edge becoming a taller Scaevola-Messerschmidia scrub which, in turn, mixes with and gives way to pandanus trees. The tall pandanus, with occasional broadleaved trees, taper upward to the palms inland, the whole consisting an excellent windbreak.

For convenience the island may be considered in three sectors although the soils in all are similar, for the most part very gravelly or stony with continuous sands near the lagoon coast only. The wide northern sector is in densely overgrown coconut groves and secondary forest, and the features inland were not well located. Clearing of the groves is in progress but at no rapid rate. A tangle of Clerodendrum on moist soils west of the lagoon path provided the only truly impenetrable thicket encountered on the atoll. The phosphate deposit and area of "L'angar gravelly sandy loam" have been described. An appreciable area of Shioya sand (Profile #23), mapped from the aerial photos, is associated with a coconut malady that has "always" been present. Seedlings are yellow and the mature trees soon cease bearing, become sparsely leaved and die. A well 250 ft. inland from the rampart is reputedly the only fresh water well on the island. The bottom, some 9 ft. below the surface, was dry when seen because of sand fallen from the sides.

Inside the rampart the middle sector is made up of Arno gravelly loamy sand with a fringe of sand along the lagoon.

The large southeast sector contains several taro pits lying back of a broad dune ridge area of Arno loamy sand. The taro is said to have been killed when the pits were last flooded by salt water during the 1918 typhoon. Waves of the 1905 typhoon swept over the southern end of the island and the boundary of wave action, as recalled by the people, corresponds with that of the younger

Shioya soils. The stony complex occupies a large fraction of the sector and the remainder seems to correspond with the Arno gravelly loamy sand. This sector also contains three mangrove swamps; the easterly has a brackish pool in exposed beachrock which is another of the local marvels.

NAMWI ISLAND - Like Ül-en' Island, Namwi was seen only in a wandering tour with our hosts of the day. The island consists of four divisions: (1) About three-fourths of the western half is older land and contains the phosphate rock. (2) East of this is an extensive saline flat which is now closed off from the sea or nearly so by (3) a rampart and young gravelly land along the south and east. (4) The northern quarter or third of the island also has younger soils, chiefly Shioya gravelly sand and loamy sand.

The older land may once have extended further to the west for the marginal rampart is very narrow and highly weathered. The phosphate deposit was roughly estimated to be at least an acre in extent; at one point where the rock is exposed along the coast it shallowly overlies unaltered coral conglomerate. As noted, the dark phosphatic soil, "Namwi gravelly loamy sand", adjacent to the phosphate deposit was not distinguished from the surrounding Arno gravelly loamy sand.

The interior flat is said to be flooded 5 or 6 inches deep by high water at the bimonthly spring tides. Only the lowest parts are barren; the slight rises have a sparse growth of small Scaevola, Messerschmidia and very yellow sprouting coconuts. Along the margin are two small saline pools, the larger fringed with Sonneratia and Bruguiera.

Approximately in the center of the northern division is a shallow fresh water well. The young planted coconuts north of the well exhibit some yellowing but no severe symptoms.

TINAK ISLAND - The wide land coincides with a marked convexity of the reef. The coastal stony belt is markedly higher than the expanse of Arno soils which extend from it almost to the lagoon beach. A low dune ridge now fronts the lagoon and a cross-section from the rampart to the lagoon would show a slightly undulating surface, suggesting a series of old beach lines or ridges.

Two mangrove swamps occupy depressions. The only existing well is in an unusual natural basin, perhaps 100 ft. across, and some 8 to 9 ft. below the surrounding land surface. The "well" is a pool about 5 x 9 ft. and 3 ft. deep in reef rock or beach conglomerate. It is never dry and at high tide the fresh water rises nearly to the rock surface. Within the depression and perhaps 2 feet higher than the rim of the well is a patch of shallow mucky soil that serves as a hog wallow; water seeps into this at high tide. Elsewhere on the island two former wells are now filled.

The Shioya soils which fringe part of the lagoon coast come to border the rampart at the narrow neck of land where Tinak Island passes into Enëräen Island. An included low area of Shioya sand in young palms was flooded by high water in 1947. Further to the northeast is a small inland flat cut off between land that survived the 1905 typhoon and a rebuilt rampart.

For part of its length the gooseneck peninsula extending to the southwest shares the soil pattern of the wide island. The lower two-thirds, however, has been washed over and the soils are of younger age.

ŬL-EN' ISLAND - This island consists of a belt of stony land along the seaward coast with lagoon sands, chiefly mapped as Arno loamy sand, making up most of the remainder. The northwest tip of the island, which borders the channel separating the next islet, shows numerous narrow overlapping layers of beachrock that mark successive minor advances and now a minor retreat. Thus this edge has been relatively stable. The southeast point of the easterly bulge, however, is composed of younger soils and people recognize that it is building out, and further south the beach is said to have eroded about 12 ft. in the past 30 years. The extreme southern tip is again composed of younger sand.

The unique swampy areas were seen in a circuitous route and hence are not precisely located. The area of coconut-pandanus peat has been described. Nearby, but apparently separated from that swamp, is another containing a narrow pool, some 10 x 50 ft., surrounded by peat about 16 inches deep and mucky sands; the water is sufficiently fresh that soap can be used. West of the pool is a low area flooded at high tide; the sandy soil has a darkened surface crust but no profile development. Adjacent to this area and extending towards the higher rampart, is an immature gravelly soil with "yellow" coconuts. The syndrome resembles that observed on L'angar Island, although less severe, and suggests soil salinity. Further north a small mangrove swamp occurs in a depression in the rampart.

Four of the five wells of the island are located on the map. All are in sand near the lagoon shore and are said to be never dry or salty. Oddly, the one closest to the beach, 150 ft., apparently has the least tidal fluctuation.

APPENDIX A

SCIENTIFIC NAMES OF PLANTS REFERRED TO BY GENUS.
(According to lists kindly supplied by R. Fosberg and D. Anderson.)

Allophyllus timorensis
Artocarpus altilis
Asplenium nidus

Bruguiera conjugata

Calophyllum inophyllum
Canavalia microcarpa
" sericea
Centella asiatica
Clerodendrum inerme
Colocasia esculenta
Cordia subcordata
Cyrtosperma chamissonis

Eleusine indica

Fimbristylis cymosa
Guettarda speciosa
Intsia bijuga
Ixora casei

Lepturus repens
Lumnitzera littorea

Messerschmidia (Tournefortia) argentea
Morinda citrifolia

Nephrolepis acutifolia

Ochrosia oppositifolia
Osplismenus compositus

Pandanus tectorius
Pemphis acidula
Pipturus argenteus
Pisonia grandis
Polypodium scolopendria
Premna integrifolia

Scaevola frutescens
Sonneratia caseolaris
Suriana maritima

Tacca leontopetaloides
Terminalia samoensis
Thuarea involuta
Triumfetta procumbens

Vigna marina

Wedelia biflora

APPENDIX B

ABRIDGED DESCRIPTIONS OF PROFILES SAMPLED FOR CHEMICAL ANALYSES (Table II)
(See also descriptions of numbered profiles in text.)

Profile #23 - Arno loamy sand. From area of poor coconuts, interior of Arno Island:

0 - 6"	Black (10 YR 2/1) granular organic loamy sand or sandy loam, heavily flecked with limesand particles.
6 - 8"	Rapid transition from very dark gray to light gray limesands.
8 - 48"+	Single grained loamy sand containing some coarser forams, very pale brown (10 YR 8/3) becoming pinkish white (7.5 YR 9/2) at depth. Soil moist at 30-36" but no water encountered.

Profile #29 - Arno loamy sand. Wide portion of Jab'u (Ine Is.).

Surface	Two-thirds covered with decomposing breadfruit and Guettarda leaves.
0 - 8"	Very dark gray (10 YR 3/1), highly organic, somewhat plastic sandy loam or loamy sand containing some gravel and small stones. Earthworms present.
8 - 12"	Transitional.
12 - 36"+	Single grained loamy coarse sand, pinkish white (7.5 YR 9/2) becoming white (5 YR 9/1), containing some gravel and small stones.

Profile #6 - Arno gravelly loamy sand. Ine Island, southeast of village.

0 - 1/4"	Incomplete cover of pandanus and coconut leaflets, etc.
0 - 15"	Very dark gray (10 YR 3/1 or 2.5/1), coarsely granular, highly organic gravelly loam becoming sandier near the bottom. Earthworms abundant. Much of the large content of gravel is rotten and can be crumbled.
15 - 18"	Transitional.
18 - 56"+	Pinkish white (7.5 YR 8/2), single grained limesands containing some gravel. Slight localized cementation around coconut root at 36" but no general cementation.

Profile #4 - Moderately well drained associate of the Arno series developed over a buried profile. Ine Island, southeast of village.

0 - 8-12"	Very gravelly, dark gray (10 YR 4/1), somewhat plastic organic loam flecked with light sand grains. Earthworms abundant. Gradually changing to

8-12 - 16-20" Heterogenous transitional zone consisting of mixed limesand or a pure foram sand flecked with black from decaying coconut roots and with tongues of organic matter penetrating from above. Earthworms still abundant in this horizon.

16-20 - 28" White (5 YR 8/1) loamy sand.

28 - 35" Transitional. The loamy sand becoming grayer and slightly cemented.

35 - 58"+ Gray (10 YR 5/1) loamy sand heavily flecked with white sand grains. Many roots occur in this horizon and large stones are found near the bottom of the profile. Groundwater level at 58" near the high tide peak.

Profile #14 - Shioya sand. Area of poor coconuts in interior of L'angar Island.

0 - 10" Pinkish gray (7.5 YR 7/2) single grained loamy sand.

10 - 36"+ Pinkish white beachsand appearing quite fresh and unweathered.

Profile #27 - Shioya sand with surface deposit. Narrow land revegetated after the 1918 typhoon, Jab'u (Ine Is.).

+4" - 0 Overburden of sand washed from dune above. White (10 YR 8/1) with some varicolored fragments, single-grained, already well penetrated by small coconut roots.

0 - 6" Light gray (7.5 YR 7/1) limesand mixed with some coarse gravel, densely penetrated by coconut roots. No worms present. Becoming somewhat lighter and coarser without the gravel at the bottom of the horizon.

6 - 70"+ Gradual transition from above to pinkish white (7.5 YR 9/2) limesand somewhat spotted with decaying coconut roots in the surface six inches and locally below. Coconut roots common to at least 36". Groundwater level at 42 inches after heavy rains.

Profile #18 - Mangrove peat. Tinak Island.

0 - 8" Fibrous woody peat from Bruguiera. Dark reddish brown (5 YR 2/2) crumbs mixed with a large mass of small rootlets. Fine coral fragments present.

8 - 16" Similar but with fewer roots and more coral fragments. Groundwater at 15".

Profile #26 - Coconut-pandanus peat. Ũl-en' Island.

0 - 26" Very fibrous woody peat consisting of dark organic crumbs mixed with a mass of root fragments, many of them hollow. Water level at 8" below surface when sampled, 3-8" above the next morning after heavy rains.

APPENDIX C

EFFECTS OF MANGROVE MUCK FROM BIKAREIJ ISLAND

The following is an account of the reputed effect of the muck on human skin as given by several people on this island:

At high water during the spring tides, schools of a desirable fish, "Beleo", enter the inlet and can be prevented from leaving as the water falls by a stone weir. On special occasions, formerly designated by the King, this area is "fished." By custom the entire village is required to go as a group. At low water the men wade about in the muck, churning it until the mud "soaks up" the surface layer of water. Thereupon the fish stick their heads out of the ooze and are caught or speared, the catch being very large, "more than a thousand" by Marshallese arithmetic.

If a man remains in this mud for as much as "three hours" his body below the point of immersion will swell greatly. For four days he will suffer headache, fever, loss of appetite, etc. On the fifth day these symptoms subside and the small blisters on the skin, resembling those of heat rash, break. The old skin can be peeled off "like a glove," exposing new epidermis beneath. An exposure of two hours has some effect so the general rule has been to limit exposure to one hour. (All time intervals as given by Kieotak.)

The details of this malady and its occurrence were clear and consistent in the accounts given by different people. A Japanese who visited the island to investigate this phenomena gave no explanation and only suggested swabbing with Lysol solution after exposure. It is clear that prolonged exposure is required for injury and that this is superficial. The cause can only be conjectured but there are two likely agents: (1) sulphites or sulphides in the alkaline slurry and (2) (suggested by Dr. Steven Kliman) tannins derived from the mangroves.

In addition to its external effects the mud is reputedly toxic if it accidentally enters the mouth when one is tired. A small amount (= "one finger joint") is sufficient to cause dizziness and unconsciousness. Two persons are said to have been lost in the mud after having been so overcome. Wading waist deep in the viscous slurry is a very fatiguing task, however, and it is possible that these latter effects might be due to over exertion.

APPENDIX D

DISPOSITION OF PLANT COLLECTIONS

Since Mr. Donald Anderson had collected the higher plants of the atoll just previous to the visit of our party, my collection of these was largely for orientation. Fertile material of Dryopteris goggilodus and Oplismenus compositus and two additional plants, Nasturtium sarmentosum and Eleocharis geniculata believed not collected by Anderson have been placed with his collection; the remainder of my partial collection will go to the herbarium of the Botany Department and the Bailey Hortorium at Cornell.

The few lichens were sent to Dr. Joyce H. Jones of the University of Michigan Herbarium who has identified them as follows:

1044 - Pannaria mariana (Fries) Müll. Arg.

1065 - Physcia picta (Sw.) Nyl.

1081 - no spores found

1119 - gray wider lobes - Coccocarpia cronia var. isidiosa (Müll.Agr.) Vainio, greenish gray - Physcia integrata var. sorediosa Vainio

1120 - Parmelia corraloidea (Mey. & Flot.) Vainio

1145 - crustose - no spores found

1150 - Physcia picta (Sw.) Nyl.
a, b and c. are the same

1151 - found no fruiting bodies

1152 - Coccocarpia cronia var. isidiosa (Müll. Arg.) Vainio

1157 - Leptogium sp. - found no fruiting bodies.

A few collections of terrestrial algae were sent to Dr. R. H. Thompson, Department of Botany, University of Kansas. A number of fungi were turned over to Dr. Clark Rogersen, Department of Botany and Plant Pathology who has sent the Basidiomycetes to Dr. Don Rogers of N. Y. Botanical Garden. The mosses and hepatics were identified by Professor A. L. Andrews of Cornell.

MOSSES AND HEPATICS FROM ARNO ATOLL, MARSHALL IS., 1950

Mosses

1039	Calymperes thyridioides Broth.
1041(a)	Ptychocoleus pycnocladus (Tayl.) Steph.
1042	Ectropothecium sandwichense (Hook. & Arn.) Mitt.
1043	Leucophanes smaragdinium (Mitt.) Par.
1115	Trichosteleum hamatum (Dozy & Molk.) Jaeg.
1116	Ectropothecium sandwichense (Hook. & Arn.) Mitt.
1154(a)	Meiothecium papillosum (Broth.) Broth.

Hepatics

1040	Riccardia fuscescens (Steph.) ?
1041(b)	Lejeunea sp., (Subgenus Cheilolejeunea)
1154(b)	Lopholejeunea subfusca (Nees) Steph.
1155(a)	Drepanolejeunea Riddleana Steph.
1155(b)	Lejeunea sp.

The above workers will retain material for their own herbaria and in accordance with the National Academy of Science agreement duplicate collections will be sent to the National Museum. Any additional material will go to the Bishop Museum.