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PACIFIC ATOLL SOILS:

CHEMISTRY, MINERALOGY AND CLASSIFICATION

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Atolls are essentially reefs of variable thickness built up by corals (and other organisms) resting on a volcanic base; they are unique to tropical and certain subtropical oceans since the reef-building organisms require water temperatures in excess of 22°C. Atolls are widespread in the South Pacific occurring from Oeno and Ducie east of French Polynesia to Papua New Guinea in the west, from the Northern Marshall Islands in the north to New Caledonia in the south. Some countries consist entirely of atolls e.g. Kiribati, Tuvalu, Tokelau, others contain atoll groups e.g. the Tuamotu Archipelago in French Polynesia; and some countries consist of mainly volcanic islands with a few isolated atolls e.g. Ontong Java in the Solomon Islands.

The classical form of an atoll is a more or less continuous emerged or slightly emerged calcareous reef surrounding a lagoon but Cumberland (1956) has identified six types of island in the Pacific partly or wholly associated with coral reefs. In this paper we shall consider atolls as being of two major types;
(a) low atolls where the maximum height of the emerged portion (usually less than 5 m) is made up of accumulations of broken reef material deposited by storms, e.g. Takapoto in French Polynesia, Tarawa in Kiribati, and
(b) raised atolls where the whole island has been tectonically uplifted and the atoll morphology largely

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fossilized (new fringing reefs may have developed around them) e.g. Lifou in the Loyalty Islands (New Caledonia), Nauru and Niue. This latter group is also often referred to geologically as raised coral platforms.

The deposition and accumulation of volcanic ash and/or pumice has occurred on many atolls, but the extent of this occurrence decreases on moving from the tectonically active zone of recent volcanism (10-25° S) in the south-west Pacific towards the equator.

The widely varied nature of atolls makes it difficult to generalise about them but many have some features in common. They usually have limited land area and few natural resources. Low atolls, particularly in the eastern Pacific have limited supplies of fresh water and many are subject to prolonged droughts. The groundwater is often brackish (slightly salty). This peculiar environment has resulted in the development of a specialised flora - a plant community adapted to saline, alkaline soils, subject to water stress and salt spray. The natural vegetation is mostly strand species recruited from the Indo-Pacific strand flora of the shores of islands of all kinds in the region. The agriculture is also rather specialised, often being restricted to coconuts, pandanus, breadfruit and such root crops as Colocasia and Cyrtosperma grown in pits dug down to the groundwater table.

The raised atolls frequently have significantly greater land areas and usually have received additions of volcanic or other non-calcareous materials. The greater land area usually has a larger associated groundwater lens that can be exploited for human consumption or irrigation but the rainfall is still generally related to location and in the central and eastern Pacific prolonged droughts are common. On the raised atolls the soils are usually older and better developed as is the native vegetation. Substantial forests of Calophyllum and related species have developed on many of these raised islands.

A more detailed discussion of the chemistry and mineralogy of the soils from a number of islands is included later in this paper, but some general points about atoll soils can be made at this point. Soil properties are to a large extent dominated by the calcareous nature of the parent material, whether or not this is covered with volcanic ash or other materials. The soils tend to be shallow, alkaline, coarse textured, having carbonatic or (where non-calcareous deposits have accumulated and weathered e.g. Lifou, Niue) oxidic mineralogy except where there have been relatively recent additions of volcanic ash. The soils are generally of very low silica content. The fertility is highly dependent on the organic matter content. Organic matter can be high in undisturbed soils under natural vegetation, but can decrease dramatically as a result of inappropriate cultivation techniques e.g. land clearance and weed control by fire.

As for all tropical soils, organic matter in atoll soils performs an important role in the concentration and cycling of plant nutrients. In atoll soils, however, a second role - that of moisture retention - is equally important. Since atoll soils are frequently sandy and excessively well drained, the moisture retention in the absence of organic matter is very low; the total amount of water retained often remains low and plants are subject to water stress unless the rainfall is high and relatively constant or they can tap the freshwater lens.

Guano deposition is common on atolls, giving reasonable supplies of phosphorus. Potassium levels, on the other hand, are frequently extremely low, and the neutral to alkaline pH of these soils can make several of the trace elements, particularly iron, manganese and zinc, unavailable to plants. The coarse texture, high pH and calcium domination of the exchange complex of many atoll soils would tend to indicate a low capacity to retain sulphur, but some sulphur is made available continuously by solution of the coralline materials which typically contain 0.2-0.3% sulphur plus atmospheric sulphur derived from sea-spray.

For the purposes of this discussion, atoll soils will be considered in 2 groups - low atolls and raised atolls. For the low atolls information from Tarawa, Tuvalu, Cook Islands and the French Polynesian atolls of Takapoto and Tikehau will be considered, while discussion of raised atolls will be restricted to Lifou in New Caledonia, Nauru and Niue.

CHEMISTRY OF LOW ATOLL SOILS

Tarawa in Kiribati (173°E, 1°20'N) is a typical example of a low atoll. It is roughly triangular in shape with the southern arm being one of the most densely populated areas in the Pacific islands. Recently the soils of two areas have been studied in detail (Seru and Morrison, 1985; Morrison and Seru, 1986). The chemical data obtained are typical of those for soils of low atolls.

Many of the properties are related to the organic matter content of the topsoil. Organic carbon values vary from about 2-20% depending on the age of the soil, the vegetation and soil management. In the subsoils organic carbon values are always low (<0.5%) unless there has been considerable soil disturbance,e.g., due to the digging of Cyrtosperma pits. Nitrogen values follow the organic contents closely as C:N ratios usually range from 9-12 for topsoils and 8-12 for subsoils. Water retention against 15 bar pressure is closely correlated with organic matter content; values of 5-25% have been obtained for topsoils, while for subsoils the values are always low (2-4%). Cation exchange capacity is also closely related to organic matter for topsoils with values in the range 6-60 cmol/kg while the values for the sandy calcareous subsoils are usually less than 2 cmol/kg. Exchangeable magnesium values are generally around 4-6 cmol/kg, sodium contents are about 0.2 cmol/kg but potassium values are always low rising about 0.1 cmol/kg only in topsoils with substantial organic matter contents.

The calcium carbonate content is always high ranging from 55-90% for topsoils and being greater than 90% for subsoils. This dominance of the enviroment by carbonate leads to high pH values; pH (water) values for topsoils were in the range 7.5-8.5 and for subsoils 8.5-9.1; pH ($CaCl_2$, 0.01 mol/L) values were in the range 7.1-7.6 for topsoils and 7.5-8.0 for subsoils.

Extractable phosphorus (Olsen procedure) values are generally low (5-15 mg/kg) for topsoils and very low (<1 mg/kg) for subsoils. The total phosphorus contents vary considerably ranging from 500-30,000 mg/kg for topsoils and from 300-5000 mg/kg for subsoils. Phosphate extractable sulphate values range from 20-50 mg/kg for topsoils but are generally low (<20 mg/kg) in subsoils. Total sulphur values are fairly constant at around 4000 mg/kg for all soils.

Tuvalu consists of 9 islands lying between 5° and 10° S latitude and 175° and 180° E longtitude. The islands are all low atolls, free of any major deposits of volcanic materials although phosphatic materials are concentrated in small areas. As part of a programme to develop some intensified agriculture (S.Caiger, personal communication) a number of soil samples have been analysed at the Land Resources Development Centre Laboratory (UK) and at the University of the South Pacific Institute of Natural Resources Laboratory in Suva. Examination of these data (Table 1) shows that there are many similarities with that obtained on Tarawa. One major difference is the presence in Tuvalu of areas of known phosphate accumulation. These may be related to bird nesting activities associated with

TABLE 1. Chemical Data for Some Tuvalu Soils

Determination		TOPSOILS Range	SUBSOILS Range
pH 1:5 H_2O		7.4-8.6	8.1-9.1
E.C. ms/cm 1:5 H_2O		0.13-0.45	0.10-0.21
$CaCO_3$ %		42-96	80-966
Exchangeable	Na	0.1-0.9	0.2-0.3
Cations	K	0.0-0.2	0.0-0.2
(cmol/kg)	Mg	2.1-7.6	3.8-5.9
CEC (cmol/kg)		3.7-27.1	1.8-4.2
Total N %		0.2-0.65	0.05-0.13
Org C %		1.97-14.66	0.3-1.12
Olsen P ppm		9-480	4-560
Total	P	560-58500	845-54500
(mg/kg)	K	100-400	100-200
	Mn	15-60	20-100
	Cu	25-90	45-95
	Fe	10-400	10-500
	Zn	10-250	10-280
Hot H_2O sol B ppm		0.3-1.9	0.3-0.4

specific vegetation types in the past. These areas give very high total phosphorus values (2-5% P) and high Olsen extractable phosphorus values (> 50 mg/kg).

The data here also clearly indicate the very low levels of certain micronutrients found in the soils of low atolls. Iron, manganese, copper and zinc are all present in extremely low (total) amounts, such that the plant available supplies of these elements must be minimal in the absence of external supplies.

Data obtained for the soils of Manuae and Palmerston in the Cook Islands (Bruce, 1972) show very similar patterns to those described above. pH values from 7.1-8.3, organic carbon contents of 2-6%, C/N ratios of 11-18, total phosphorus levels of 100-1600 mg/kg and available phosphorus of 20-80 mg/kg were recorded. CEC values were generally low (5-26 cmol/kg) with very low levels of potassium.

Tercinier (1969) in his discussion of Takapoto also stresses the importance of the organic matter content. He observed a relationship between organic matter and water retention. Organic matter increases in moving from the ocean sides, bombarded by waves to more stable areas near the lagoon. The cation retention capacity of the soils is also closely related to the organic matter content and the accumulation of nitrogen, phosphorus and potassium in the organic rich surface layers was observed.

On Tikehau, Jamet (1985) found that the calcium carbonate content of topsoils was 80-90% with generally more than 90% in the subsoils. Total potassium content was always low (<0.05%) as was exchangeable potassium (<0.3 cmol(p+)/kg) while the phosphorus levels varied depending on whether or not significant guano deposition had occurred. Subsoil pH values usually were between 8 and 9, but in the topsoils with relatively high organic matter contents the values ranged from 7.0-7.5.

Thus it can be seen that in the low atolls the soils are alkaline, with most of the soil "fertility" related to the accumulated organic material. Under these conditions nitrification is favoured but toxic accumulations of nitrate are unlikely unless there are unusual hydrological conditions. Volatilization of nitrogen as NH_3 from ammonium and urea fertilizers will occur, with particularly large losses occuring if these materials are not incorporated. The availability of phosphorus is controlled by calcium activity and much fertilizer P will be precipitated as calcium phosphates or adsorbed on the surfaces of the carbonates. Band applications of P are recommended so that P will be available to seedlings soon after emergence. K availability is decreased by high Ca and/or Mg levels; the low levels of K in the coral limestone parent materials mean that this element will always be in short supply.

Supplies of available Ca and Mg are plentiful in low atoll soils but imbalances with K and micronutrients cause significant plant nutrition problems. Sulphur is usually available in small quantities from solution of limestone and from rainwater but if crops with large S requirements are grown intensively, external additions will be required. Available B decreases moderately with increasing soil pH, but few B deficiencies have been reported on calcareous soils. Mo solubility and availability increase with increasing pH but low Mo contents in the parent rock may lead to deficiencies.

Solubilities of Cu, Fe, Mn, Zn decrease with increasing soil pH. Cu deficiencies are less related to soil pH than are those of the other micronutrients. Zn forms relatively insoluble zincates in calcareous soils and Fe uptake is reduced by high bicarbonate concentrations in the soil solution. With the relatively low contents in coral limestone all of these elements are likely to be highly deficient in soils of the low atolls.

MINERALOGY OF LOW ATOLL SOILS

As the soils of the low atolls are dominated by calcium carbonate the mineralogy is almost exclusively carbonate. The dominant minerals are calcite and aragonite, the common forms of calcium carbonate deposited by reef forming and reef living organisms. Calcite contains varying amounts of magnesium (substituting for calcium in the mineral structure). If the magnesium content is >1%, the mineral is described as high magnesium calcite; other forms are referred to as low magnesium calcite. There is considerable variation in the mineral content of low atoll soils as illustrated below.

The results of the mineralogical analyses of samples from several pedons on Abatao Islet, Tarawa are summarised in Table 2 (Morrison and Seru, 1986). These confirm the dominance of the 2 principal forms of calcium carbonate-calcite and aragonite. In contrast to the lagoon sediment mineral samples, (Weber and Woodhead, 1972) calcite is the dominant mineral in all of the soil samples with aragonite being the minor component. The relative proportion of high and low magnesium calcite varies but there is no particular pattern to this variation except that high magnesium calcite tends to dominate in soils on the lagoon

TABLE 2. ABATAO SOILS : APPROXIMATE MINERALOGICAL COMPOSITION
(< 200 MESH SAMPLES)

SOIL	DEPTH (cm)	ARAGONITE	CALCITE (High Mg)	CALCITE (Low Mg)	OTHERS
TRW 7	6 - 31	3	5 (> 70%)	2	
8	31 - 60	2	5 (> 70%)	2	
9	0 - 15	3	4	3	Apatite 2
9	50 - 60	2	5 (> 70%)	2	
10	45 - 55	2	5 (> 70%)	1	
11	40 - 50	3	5 (> 70%)	1	
12	0 - 18	3	2	5	
13	0 - 25	2	2	5 (> 70%)	
16	0 - 6	2	4	5	
17	0 - 11	3	5	3	
17	40 - 55	3	5 (> 70%)	2	
18	0 - 13	2	4	5	

5	> 50%
4	30 - 50
3	15 - 30
2	5 - 15
1	< 5%

side of the islets. Apatite was detected in only one sample.

The mineralogy data for the Tarawa soils are in general agreement with the observations of Hathaway (1965) for soils of the Northern Marshall Islands. Hathaway found that high magnesium calcite was the dominant mineral in most soils, except for the coarsest fragments is some profiles where aragonite was the major constituent. Low magnesium calcite was present in only one sample. Hammond (1969) in a study of soils of Christmas Island (Kiritimati) found that aragonite was the dominant component, this mineral being present in the greatest amounts in the coarse fragments. Calcite was more abundant where foraminifera dominated the deposits. Most calcite was high in magnesium but low magnesium calcite was present mainly in the coarse sand, very fine sand and silt fractions.

Samples from Manuae and Palmerston showed a general dominance of aragonite over calcite with the aragonite content being greatest in the coarser soils (Bruce, 1972). Significant amounts (10-20%) of apatite were also detected and a small amount of an unknown amorphous material was present in all samples.

Aragonite which forms the hard parts of corals or algae and high magnesium calcite from algal skeletal material are more abundant in most shallow water marine environments than low magnesium calcite, but among deep sea oozes rich in calcitic foraminifera and coccoliths, the more stable low magnesium calcite is the predominant phase (Chave, 1962). It should be noted that low magnesium calcite is the thermodynamically stable phase under the conditions prevailing at the Earth's surface.

The presence of substantial quantities of low magnesium calcite in the surface horizons of four Abatao pedons is of considerable interest. While this mineral was found on Christmas Island it was always a minor component (Hammond, 1969) and was only detected in one Northern Marshalls sample (Hathaway, 1965). The presence of this mineral may be caused by surface addition of algal skeletal material of low magnesium content or may be the result of alteration of aragonite to calcite, although the latter process was considered to be of little importance in the Northern Marshalls (Hathaway, 1965). Chave (1962) in a study of carbonate sediments found an increase in low magnesium calcite content with decrease in particle size and ascribed this to a selective loss of unstable minerals due to inversion (to a more stable form) or solution.

CLASSIFICATION OF LOW ATOLL SOILS

One of the major difficulties encountered when considering the classification of atoll soils is the major change that has taken place in soil classification over the last 50 years. Much of the early work on atoll soils was carried out by American scientists working in the central and western Pacific Islands in the 1940's and early 1950's. At that time soil classification was based on the system developed for publication in the 1938 "Soils and Men" monograph (Baldwin et al., 1938). As pointed out by Smith (1983) this system of classification was produced hurriedly to meet the publication deadline and as a consequence many facets were incompletely developed and defined. Although the '1938' system underwent a series of modifications up until 1959, it was recognized by 1950 that major difficulties could not be overcome and that the development of a new system was essential if a satisfactory taxonomy was to be obtained. The new taxonomy was developed through a series of approximations and published in 1975 as Soil Taxonomy (Soil Survey Staff, 1975). Soil Taxonomy is now widely used throughout the world and is continually being modified as new information or better criteria for grouping soils become available. In this paper all soils are classified according to Soil Taxonomy but, where appropriate, relationships to the '1938' system (and its modifications) are included. Prior to discussing the details of the classification of individual soils, some introductory comments on the two systems are presented.

In the '1938' system (particularly after the revisions up to and including 1949) soils were classified in a hierarcheal system having six categories - order, suborder, great soil group, family, series and type. Three soil orders (Zonal, Intrazonal and Azonal) were developed. Atoll soils were included in the Halomorphic and Calcimorphic suborders of the Intrazonal soils plus the Azonal soils (no suborders were prepared for this order). The principal great groups were Rendzina soils, Lithosols and Regosols. Rendzinas were soils having dark coloured base-rich surface horizons formed from calcareous parent materials in humid areas mainly under forest. Lithosols were soils with thin, and often irregular, horizons over rock while Regosols were developed mainly from soft or unconsolidated parent materials with or without thin coverings of true soil.

In Soil Taxonomy there are six categories in the hierarcheal system. The basis for the groupings in each category is summarised in Table 3. Low atoll soils will usually be found in the orders of Entisols (i.e., recent soils, having no major diagnostic features), Inceptisols (soils near to point of inception, showing evidence of profile development beyond that of the Entisols) or Mollisols (base-rich soils having relatively deep dark coloured, organic rich, well-structured surface horizons- the mollic epipedon).

TABLE 3 The Differentiating Characteristics of the Categories in Soil Taxonomy (after Buol et al., 1980)

Category	Nature of Differentiating Characteristics
Order	Soil-forming processes as indicated by presence or absence of major diagnostic horizons.
Suborder	Genetic homogeneity. Subdivision of orders according to presence or absence of properties associated with wetness, soil moisture regimes, major parent material, and vegetational effects as indicated by key properties; organic fibre decomposition stage in Histosols.
Great group	Subdivision of suborders according to similar kind, arrangement, and degree of expression of horizons, with emphasis on upper sequum; base status; soil temperature and moisture regimes; presence or absence of diagnostic layers (plinthite, fragipan, duripan).
Subgroup	Central concept taxa for great group and properties indicating intergradations to other great groups, suborders, and orders; extragradation to "not soil."
Family	Broad soil textural classes averaged over control section or solum; mineralogical classes for dominant mineralogy of solum; soil temperature classes °based on mean annual soil temperature at 50 cm (20 in.) depth§
Series	Kind and arrangement of horizons; colour, texture, structure, consistence, and reaction of horizons; chemical and mineralogical properties of the horizons.

A major difference between the '1938' system and Soil Taxonomy relates to the grouping of soil series into families. The '1938' system introduced soil families as a category between the great soil groups and soil series, but considerable difficulty was encountered in determining what characteristics to use for such groupings. As late as 1949 Riecken and Smith commented "At present there is little published material for guidance in the grouping of series into families". In contrast, Soil Taxonomy has soil families defined as groupings of soil series "having similar physical and chemical properties that affect their management and manipulation for use".

The soils of the low atolls frequently consist of accumulations of organic matter, guano, pumice or other transported material on top of a calcareous sand (calcareous algae, forams, shells, etc.) or limestone substratum. Little profile development has occurred and the development of any significant B horizons is not expected because of the nature of the parent material (calcium carbonate), the relative youth of many low atolls (<5,000 years) and the geographical isolation which has restricted (together with the environment) the development of the flora. Repeated removal of A horizons has occurred on some atolls as a result of cyclones, requiring soil formation to recommence periodically.

As a result the vast majority of soils of the low atolls are Entisols (Soil Survey Staff, 1975) consisting of the accumulation of a thin layer of organic rich coral sand over the coralline substratum. At the suborder level the Entisols are subdivided on the basis of the soil moisture regime or the particle size distribution in the control section (25 cm - 1 m, 25 cm to a lithic contact if one is present within a depth of 1 m). Soils having the groundwater table near the surface have an aquic soil moisture regime and are classified as Aquents.Many atoll soils are sandy i.e. the texture of the fine earth is sand or loamy sand that contains less than 50 per cent very fine sand and rock fragments make up less than 35 per cent by volume (and do not have an aquic soil moisture regime) and qualify as Psamments (Regosols in the '1938' system) at the suborder level. Soils having more than 35 per cent coarse fragments such as coral gravel, stone, and rocks qualify as Orthents (Lithic Regosols or Lithosols in the '1938' system). In both the Psamments and the Orthents the great groups are separated (with the exception of the Quartzipsamments) on the basis of the soil moisture and temperature regimes. The temperature regime for most low atolls is isohyperthermic (i.e., the average annual temperature at 50 cm depth is >22°C, with the variation from summer to winter <5°C), and the soil moisture regimes in the absence of groundwater influence are ustic (i.e., the soil profile dries out for extended periods in most years) or udic (i.e., the soil profile dries out for only short periods in most years). Thus the great group classifications for the Psamments or Orthents of the low atolls are Ustipsamments or Tropopsamments and Ustorthents and Troporthents. The common subgroups are Typic, Lithic or Aquic.

At the family level all the low atoll Entisols have an isohyperthermic soil temperature regime and carbonatic mineralogy. The Psamments do not require a separate statement of particle size class as this is already designated at the suborder level by the Psamm- prefix; the Orthents have sandy-skeletal particle size class indicating that rock fragments greater than 2 mm make up 35% or more of the volume and there is enough sand to fill intersticies larger than 1 mm. The Aquents usually have a sandy or sandy-skeletal particle size class.

Where the soils have been relatively undisturbed or have had a good vegetation cover for a reasonable time period Mollisols (Soil Survey Staff, 1975) may be found. These are so classified because of the presence of mollic epipedon and the fact that this rests on coral sand where the base saturation will obviously be greater than 50%. A mollic epipedon is characterized by depth, dark colours, high organic matter content, high base saturation, good structure and the presence of sufficient moisture for 3 months or more to facilitate plant growth. The structure of the surface horizons of many low atoll soils is not strong enough to meet the requirements of the mollic epipedon but limited areas of Mollisols have been identified.

The suborders identified on low atolls are Ustolls and Rendolls (Rendzinas in the '1938' system) depending on the soil moisture regime, while the Hapl- great group and Entic subgroup would be expected to be the most common. The family classes are usually sandy or sandy-skeletal, carbonatic, isohyperthermic.

Calcareous soils of low atolls have been studied in a number of locations. The quality and detail of the work varies considerably and it has been difficult in some cases to compare the soils of the different atolls.

1. Tarawa

About 20 pedons in South Tarawa have been classified at the family level in Soil Taxonomy (Seru and Morrison, 1985; Morrison and Seru 1986). The soils generally have an ustic soil moisture regime, except where there is a marked groundwater influence. The subgroups identified were Typic Ustipsamments, Aquic Ustipsamments, Lithic Ustipsamments (all Regosols) ,Typic Troporthents, Lithic Troporthents (Lithosols), Entic Haplustolls and Typic Tropaquents (wet Regosols). In one area (Bikenibeu) three profiles were found that differed significantly from the others because of the incorporation of organic matter to a considerable depth (found as pockets in the subsurface material) and the associated pockets of material exhibiting structure. The structural features and organic matter incorporation are obviously the result of human activities. One profile showed a fairly uniform incorporation of organic matter (with the associated darker colours) to a depth of about 1 metre. These soils have obviously been subjected to considerable disturbance as they occur in an area of high population and consequent subsistence agricultural activity. This is entirely expected as the Bikenibeu area is one of the most densely populated in the South Pacific.

The classifications of 2 of these profiles as Typic Ustipsamments (Regosols), however, gives no indication of the influence of human activity with the incorporation of organic matter, nutrients and structure to considerable depths in the profile; the third is classified as an Aquic Ustipsamment. These latter features may have considerable agronomic importance in these low atoll soils which otherwise are featureless below the A horizon. The incorporation of organic matter will increase the otherwise low moisture retention capacity at depth. Thus it may be necessary to provide a separate subgroup (Anthropic) of the Ustipsamments for separation of soils which as a result of human activity, have organic materials and associated properties incorporated to depth in the profile.

2. French Polynesia

The soils of a number of low atolls in French Polynesia have been described by Tercinier (1956, 1969) and Jamet (1985). Some of the atoll soils of French Polynesia are considered to have an udic soil moisture regime (C. Garnier, personal communication) and are therefore Tropopsamments (Regosols) and Troporthents (Lithosols) while others have recently been shown to have an ustic soil moisture regime (Service de la Meteorologie, French Polynesia, personal communication) and are therefore, Ustipsamments, Ustorthents with possibly limited areas of Haplustolls.

3. Cook Islands.

The soils of 2 atolls in the Northern Cooks were studied by Bruce (1972). The Muri series was dominant; this is considered to have an udic soil moisture regime and is classified as Typic Tropopsamment (Regosol).

4. Arno Atoll and the Northern Marshalls

The soils of Arno atoll were studied in some detail by Stone (1951) who identified four major soil series. The limited meteorological data indicate that Arno has an estimated annual rainfall >2500 mm and the soils of Arno atoll therefore are considered to have an udic soil moisture regime and the Arno series is thus a Typic Rendoll (Rendzina) and the Shioya series a Typic Tropopsamment (Regosol).

Soils showing surface accumulations of phosphatic material as found in the Jemo series (Fosberg, 1956) were not identified on Tarawa, French Polynesia or in the Cook Islands. However, the Northern Marshalls are considerably drier than the southern group (estimated annual rainfall 1000-2000 mm) and there is a marked dry season November-April leading to the conclusion that they would have an ustic moisture regime. The soils examined in the Northern Marshalls were correlated with those of Arno, (Fosberg, 1956) but in terms of Soil Taxonomy this would now appear inappropriate. A comparison with soils of Tarawa or Christmas Island (Kiritimati) would appear more relevant and the presence of Typic Ustipsamments, Typic Ustorthents and Entic Haplustolls is indicated by the original report (Fosberg, 1956).

5. Christmas Island (Kiritimati), Kiribati

Hammond (1969) produced a detailed report on the soils of Christmas Island. He attempted a correlation with the soils of the Marshall Islands and with the coastal sandy soils of Hawaii. Since Christmas Island has relatively low rainfall (approximately 800 mm annually on average; Taylor, 1973) the soil moisture regime is ustic in the absence of any groundwater influence. Thus comparison with the udic soils of Arno is again inappropriate. The soils of Christmas Island are dominated by Typic Ustipsamments (dry Regosols) but they generally do not have as well developed A horizons as the soils of Tarawa and should therefore be considered as separate series. Analysis of Hammond's report would also indicate that areas of Typic Ustorthents (Lithosols) are also present on Christmas which would correlate with the Bonriki series on Tarawa.

6. Tuvalu

The soils of Tuvalu have received limited study as part of a Land Resources Survey (UNDP, personal communication). The soils have been classified according to the FAO/UNESCO (1974) Legend mainly as Calcaric Regosols; data available in some cases is insufficient to fully classify the soils by Soil Taxonomy. Tuvalu soils have udic soil moisture regimes in the absence of groundwater influence and most will therefore, be Tropopsamments (Regosols) or Troporthents (Lithosols). Insufficient detail on colour and structure prevents the confirmation of mollic epipedons and hence the presence of Mollisols.

7. Ontong Java, Solomon Islands

This isolated low atoll, north of the main Solomon Islands group also has soils that show similarities in morphology to those on Tarawa (Wall and Hansell, 1976). However, the climate on Ontong Java is sufficiently wet to obtain an udic soil moisture regime and the dominant soils are consequently Typic Tropopsamments (Regosols) and Typic Troporthents (Lithosols).

8. Hawaii

The Jaucas series, mapped in coastal sands on several of the Hawaiian islands, is derived from coralline sand and is classified as a Typic Ustipsammment, carbonatic, isohyperthermic (Foote et al.,1972). Examination of the Jaucas data indicates that this soil has a less well developed A horizon than the Abatao series on Tarawa as evidenced by higher values and chromas and lower organic carbon contents. There would appear to be greater similatity between the Jaucas series and the soils of Christmas Island assigned to the Shioya series by Hammond (1969).

9. Micronesia other than the Marshall Islands

Five soil surveys conducted in the Federated States of Micronesia (Laird, 1982; Laird, 1983 a,b; Smith, 1983 a,b) indicate that substantial areas of soils derived from coralline materials are found. These soil series, e.g., Ngedebus, Insak, Dublon have an udic or perudic (i.e., soil profile never dries out to any extent) soil moisture regime as the rainfall in the area ranges from 3000-5000 mm annually with no marked dry season. The coralline soils have therefore been classified in the Tropo- great groups of Entisols rather than in Usti- great groups.

Thus it can be seen that the dominant soils of the low atolls are Entisols, being mainly classified in the Psamments or Orthents suborder. Trop- and Ust- great groups occur depending on the soil moisture regime. Limited areas of Aquents and Mollisols may also be found.

SOILS OF THE RAISED ATOLLS

As the soils of the raised atolls show considerably greater variation than is found in the low atolls, the individual islands will be considered separately.

Lifou, in the Loyalty Islands of New Caledonia is a raised atoll of area 1,149 km^2. The proximity of the volcanic zones of Vanuatu has led to the deposition of substantial quantities of pyroclastic materials on the limestone. These pyroclastic materials have weathered to give products of the allophane family in the youngest deposits and bauxitic materials in the oldest deposits. Three major soil environments have been identified (Latham, 1981).

On the west coast, steep cliffs of a rampart overhang a narrow coral sandy beach. On the rampart a karstic microrelief is found; organic matter accumulates giving soils up to 1 m deep in the deepest pockets. Within the former lagoon two soil series are found. One is a shallow calcareous soil with an organic rich surface layer but of variable depth (Lithic Troporthent or Lithosol). The other is a red-brown oxide rich soil of 30-80 cm depth resting on the limestone. On the east (windward) coast there is a a coastal plain 100-200 m wide with sandy or gravelly soils containing large quantities of pumice. They are rich in organic matter which accumulates to a depth of 30-50 cm. These are fertile soils and many crops thrive on them if sheltered from the prevailing winds. On the coastal plains, silicate - containing breakdown products of the allophane family have been identified, but on the rampart and in the old lagoon the non-calcareous materials are geologically older and have lost all the silica to give soils dominated by gibbsite, boehmite, haematite and goethite.

These oxidic soils are of variable depth, but cover a major part of the surface of the island. They have pH values from 6-7.5 and have high levels of organic matter (often >10% for topsoils) under natural vegetation. In the absence of silicate clay minerals, adsorption and availability of nutrients is dependent on the organic matter content. CEC values are correlated to organic matter levels. Exchangeable base contents are reasonable in the topsoils, but are often very low in subsoils (sum of bases <1.5 cmol/kg) and potassium levels are frequently particularly low (<0.1 cmol/kg). Water retention is greater than on the low atolls as the oxides contribute along with the organic matter to this property. Zinc, manganese and boron deficiencies have been observed and silicon deficiency is expected for crops like cereals that require significant quantities of this element.

The classification of these soils presents problems. Several have a mollic epipedon overlying an oxide rich subsoil where the CEC is near the borderline for the oxic horizon. In the subsoils the base saturation is frequently low so those soils that do not qualify as Oxisols (Typic Acrustox - Laterite soils in '1938' system) are often Oxic Humitropepts (Latosols in '1938' system). Latham (1982) has argued that the Typic Acrustox classification does not give any indication of the presence of substantial quantitites of organic matter.

Nauru is a raised atoll (0°32'S, 167°03'W) of 22.6 km^2 with its highest point approximately 70 m above mean sea level. The limestone has been covered with a substantial deposit of phosphatic material, the origin of which has not yet been fully explained. The soils of Nauru are being rapidly removed by phosphate mining operations. A stockpile of topsoil is being accumulated and, after the completion of mining activities around 1995 A.D., may be spread over a limited area and used for small scale agricultural production to support the remaining population. The terrain remaining after mining is so rugged that an extensive agricultural development would be prohibitively expensive.

A recent study has been made of the soils in areas remaining undisturbed (Manner and Morrison, unpublished data). Three separate soil series occupying significant areas have been identified. The first series has a dark epipedon overlying a layer of mixed surface material and broken limestone, which in turn lies on limestone rock. This profile has been classified as a Lithic Haplustoll (Rendzina in '1938' system). The second series has a thin (<10 cm) dark epipedon directly overlying the limestone substratum and is classified as Lithic Ustorthent (Lithosol). The third series occurs in areas where the phosphatic material has accumulated between limestone pinnacles. The phosphatic material is frequently reddish yellow (7.5 YR 7/4) coloured between 25 cm and 75 cm depth, changing to pinkish gray (5 YR 7/2) colour at greater depths. The Bw horizon is occasionally stony or bouldery with lumps of limestone occurring throughout. Soils of this third series have epipedons that meet the criteria for mollic, and have therefore, been classified as Typic Haplustolls. There are limited areas of shallow sand deposits, particularly near the coast, on which Lithic Ustipsamments (Regosols) or Ustorthents (Lithosols) have formed. In the very limited wet areas close to the old lagoon shallow Tropaquents (Hydromorphic soils) are found.

Chemical data from the analyses of some 50 Nauru soil samples (Morrison and Manner, unpublished data) show that the soils usually have pH (H_2O) values from 6.0 - 8.0, pH (KCl) values from 5.5 - 7.8 and free calcium carbonate was found in all samples, the extent varying from 2-24%, being highest in subsoils. Organic carbon contents ranged from 1-11% for topsoils, the values varying widely with the impact of mining. For subsoils the values from 0.1-1.9%, decreasing with depth in undisturbed profiles but varying significantly within the mined areas. C:N ratios for topsoils ranged from 7-24 with the highest values being found on highly disturbed sites. CEC values for topsoils varied from 12-61 cmol/kg, while for subsoils the range was 4-21 cmol/kg. There was a reasonable correlation between CEC and organic matter contents. Exchangeable magnesium values ranged from 5-14 cmol/kg for topsoils and from 0.1-3 cmol/kg for subsoils while exchangeable potassium values were uniformly low (< 0.5 cmol/kg). Total phosphorus levels varied from 2-18%, the lowest values being found in soils on the fringing reef surrounding the island. Phosphate extractable sulphate values varied from <1-90 mg/kg, but most values were < 20 mg/kg. The highest values were found for undisturbed forest soils.

Mineralogical analysis of a limited number of samples showed a dominance of fluoroapatite and hydroxyapatite with limited amounts of calcite and aragonite in the soils of the fringing reef surrounding the island. The apatites appeared very pure and carbonate-apatite was not detected in any samples (Morrison, unpublished data). It is interesting to note that one sample from Makatea in French Polynesia (where phosphate deposits are also located) gave effectively an identical mineralogy to the Nauru samples. The mineralogy class of most Nauru soils is mixed according to the criteria given in Soil Taxonomy but it would appear that the use of phosphatic or apatitic would be more appropriate.

A major problem that has arisen in the classification of soils of Nauru is the determination of the soil moisture regime. No direct measurements of soil moisture are available and the estimation of soil moisture regimes has to be based on meteorological data. Data for Nauru (40 years) show a mean annual precipitation of 2000 mm with 4 months having rainfall below 100 mm. Annual rainfall has, however, varied from 280 mm to 4500 mm. Air temperatures range from 23-32°C with the relative humidity averaging 71%. Nauru is periodically affected by droughts and several droughts of more than 12 months duration have been recorded this century. However, taking the average rainfall data available and assuming evapotranspiration rates averaging 4 mm per day in the non-drought years it would appear that the soils of Nauru not influenced by the effects of groundwater fit best into the ustic moisture regime (udic tropustic in the tentative sub-divisions of moisture regimes proposed by ICOMMORT (Van Wambeke, 1981)).

The soils of Niue (19°S, 169°54'W), a raised atoll of area 259 km^2 have been extensively studied (Wright and Van Westerndorp, 1965; Leslie, 1985). The rocks at the surface and around the cliff coastline are all coral reef limestone. There is considerable evidence of past changes in sea level, with shelly and soft makatea* forms in certain areas of the island, indicating that the sea probably covered all of the island at some time. The limestone and makatea have been covered by a thin layer of submarine sedimentary material (P. Rankin, personal communication). Thus limestone, makatea and sedimentary materials are the parent materials for Niuean soils. The sedimentary material has been very strongly weathered and has virtually all been converted to oxides.

The basic soil pattern is basically a concentric set of the main soil groups with a more complicated pattern existing within the broader one due in part to the occurence of makatea or coral limestone pinnacled outcrops. Three orders of Soil Taxonomy (Soil Survey Staff, 1975) have been identified on Niue. The Fonuakula series with an oxic horizon is found in areas of deeper accumulation of the highly weathered sedimentary material. This soil meets the criteria for an Oxisol and since Niue has an ustic soil moisture regime and an isohyperthermic soil temperature regime is placed in the Ustox suborder. Since the base saturation in the major part of the oxic horizon is greater than 50% the Fonuakula series meets the

* makatea: A raised reef becomes severely eroded with long exposure because of the solubility of the limestone in rainwater. The surface becomes rough, rugged, full of pinnacles and solution holes and the limestone becomes cavernous and porous. This landform is called 'makatea' in Polynesia (literally 'white rock' or 'white cliff').

requirements for inclusion in the Eutrustox great group and is a Typic Eutrustox (Laterite soils in the '1938' system). The family designation is clayey, gibbsitic, isohyperthermic.

Two soil series, Avatele and Tafolomahina, are classified as Ustropepts (Latosols in '1938' system) at the great group level on account of having ochric epipedons and cambic horizons and base saturation greater than 50% in all horizons. The Avatele satisfies criteria for Typic Ustropepts (family designation fine, oxidic calcareous, isohyperthermic), while the Tafolomahina soils having a Lithic contact within 50 cm of the soil surface and a relatively low CEC (< 24 cmol/kg) are classified as very-fine, gibbsitic, Oxic Lithic Ustropepts.

The great majority of the soils of Niue are Mollisols (10 out of 13 series) in that they have mollic epipedons overlying base-rich subsurface materials. At the suborder level they are all Ustolls (Niue has an ustic soil moisture regime) and are classified as Haplustolls at the great group level since they lack other diagnostic features. However, none meet the criteria defined for the Typic subgroup of Haplustolls. Some lack soft powdery lime and are therefore Udic Haplustolls, others lack soft powdery lime and do not have a cambic horizon and are therefore Udorthentic Haplustolls. The presence of lithic contacts within 50 cm leads, together with other criteria to including series in the Lithic Ruptic-Entic and Ruptic-Lithic Udorthentic subgroups. Low CEC values in the subsoils of some series lead together with other data to their inclusion in the Oxic Udorthentic and Oxic Ruptic-Lithic Udorthentic subgroups.

Most of the soils of Niue are strongly weathered and the dominant minerals are gibbsite, goethite and crandallite (Ca, Sr, Pb)$_2$Al$_7$(PO$_4$)$_3$(OH)$_{16}$.3H$_2$O with a virtual absence of silicate materials. The presence of large amounts of crandallite in some soils has led Leslie (1985) to propose that a crandallitic mineralogy class be established in Soil Taxonomy. To qualify for designation as having a crandallitic soil mineralogy class soils would have to contain more than half crandallite by weight in the control section.

Micronutrient deficiencies have been identified in a number of crops grown on Niue (Miller, 1980). The highly weathered nature of the Niue soils means that those that are not calcareous (having similar problems to those of low atoll soils discussed earlier) are oxidic or crandallitic being dominated by materials having extremely limited supplies of trace elements like zinc and manganese required for good crop production.

CONCLUSION

In this paper information on soils of some low and raised atolls in the South Pacific has been reviewed. For the low atolls many similarities are observed in that the soils show minimal profile development and are highly calcareous and highly dependent on organic matter for moisture and nutrient retention and availability. The soils are usually Entisols (Regosols or Lithosols), the major differences being in the soil moisture regime and the particle size class. Micronutrient and potassium deficiencies are encountered widely.

The raised atolls show much greater variability in soils due at least in part to the additions of non-calcareous materials. The soil patterns are usually more complex than on the low atolls. While Soil Taxonomy can be utilized quite successfully in the classification of atoll soils some modifications may be required to fully accommodate this unique group of small island soils.

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