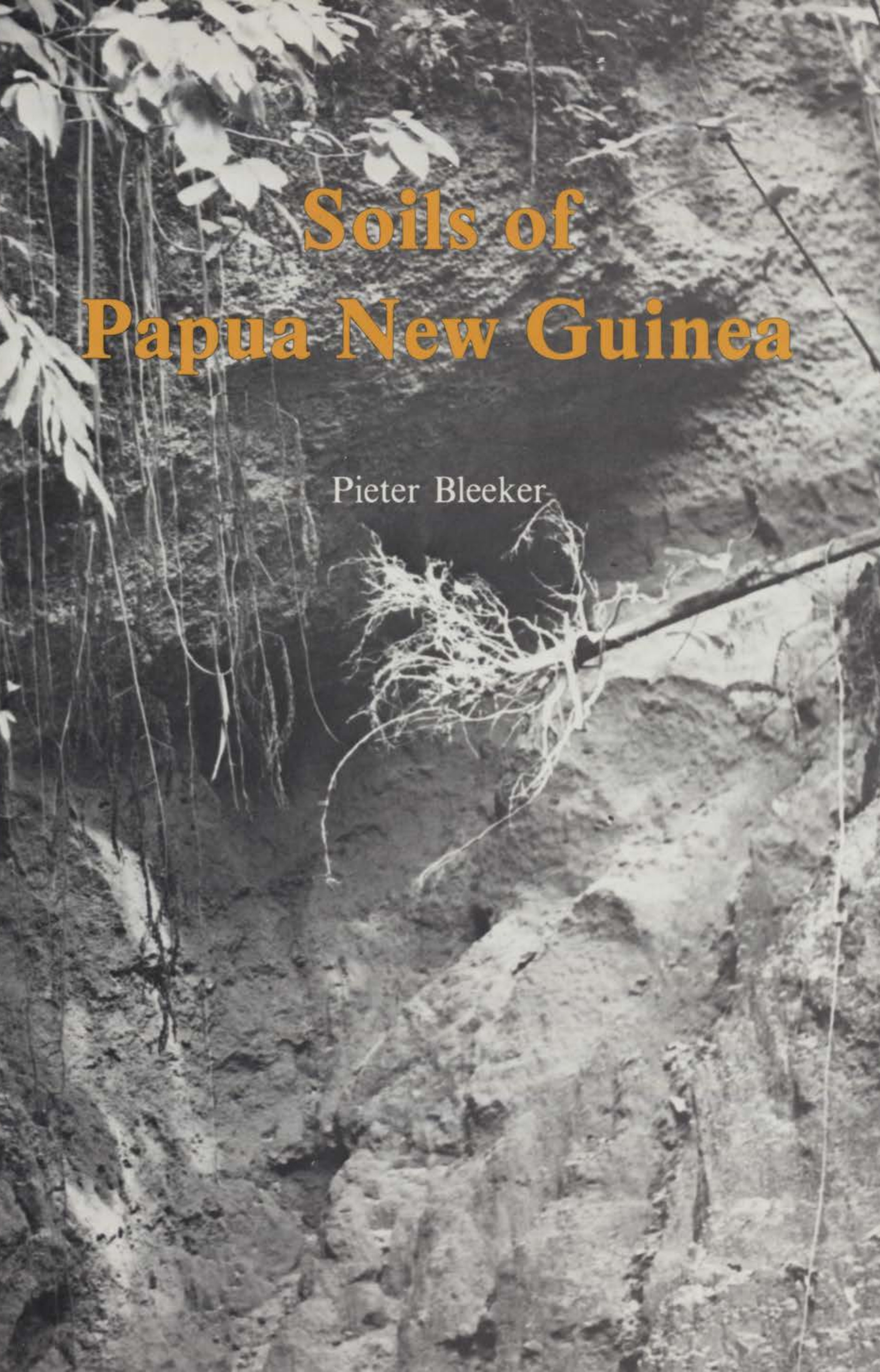
Soils of Papua New Guinea

Pieter Bleeker



The aim of this book is to bring together and summarise our present knowledge of the soils of Papua New Guinea. Although much of it is based on data collected during CSIRO's land resource surveys, the book also attempts to incorporate the widely scattered and relatively inaccessible information gathered by other researchers.

The US Department of Agriculture's soil taxonomy classification has been used, since it is now internationally widely accepted and makes the data accessible to scientists working in other parts of the tropics. Eight orders, twenty-six suborders and sixty-one great soil groups have been identified in Papua New Guinea. Following an introductory section on the environment and a discussion on soil classification and mapping, the next chapters describe the soils at great soil group level according to the eight orders (Entisols, Histosols, Inceptisols, Vertisols, Mollisols, Alfisols, Ultisols, and Oxisols). For each great group separate sections on morphology, genesis, occurrence, association, fertility, and land use are given.

The second part of the book discusses soil related subjects, attempting as far as possible to synthesise the available information. A review of the various land inventory methods, including land system surveys is given, and soil erosion and conservation are discussed, as is the possible application of the Universal Soil Loss Equation (USLE) to Papua New Guinea conditions. Type, depth, rate and the assessment of the degree of weathering are dealt with, together with some examples from Papua New Guinea. The author examines the content of primary nutrients (N, P and K) in some typical great soil groups and trace element deficiencies in tree crops. A review of soil microrelief features at various locations in Papua New Guinea is given, while the last chapter briefly examines traditional food crop agriculture, especially in relation to soil properties and crop yield declines under cultivation.

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With the Division he took part in several land resource surveys and other research programs in Papua New Guinea.

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Jacket design by Denis French,
ANU Press

Printed in Australia

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The Commonwealth Scientific and Industrial Research Organization,
Australia

in association with

Australian National University Press
Canberra, Australia, London, England and Miami,
Fla., USA, 1983

First published in Australia 1983

Printed in Australia by Macarthur Press for the Australian National University Press, Canberra

National Library of Australia
Cataloguing-in-Publication entry

Bleeker, P. (Pieter).
Soils of Papua New Guinea.

Bibliography.
Includes index.
ISBN 0 7081 1104 1.
1. Soils - Papua New Guinea. I. Commonwealth Scientific and Industrial Organization (Australia). II. Title.

631.4′955′3

Library of Congress No. 82-72950

United Kingdom, Europe, Middle East, and Africa: Eurospan
3 Henrietta St, London WC2E 8LU, England
North America: Books Australia, 15601 SW 83rd Avenue, Miami, Florida 33157 USA
Japan: United Publishers Services Ltd, Tokyo
South-east Asia: Information Publications Pte Ltd, 24 Industrial Road, Singapore 1953

Acknowledgments

This book could not have been produced without the information collected by CSIRO soil scientists and the logistic support received from many Papua New Guineans during the land resources surveys. Of these, I particularly wish to thank Mr H.A. Haantjens, who took part in many of these surveys and first introduced me to this truly spectacular country and Mr R.M. Scott and Dr G.K. Rutherford.

Throughout the drafting of the manuscript I have greatly benefited from discussions, suggestions and criticisms, but above all the moral support that I received from colleagues, both within and outside CSIRO.

I am particularly indebted to Dr F.R. Moormann, professor in soils at the University of Utrecht, the Netherlands, who spent a great amount of time and effort on reading through the manuscript and suggested many improvements. The valuable suggestions and criticisms of Dr J.J. Reijnders and Mr M.F.W. Zijsvelt on the manuscript, and of Mrs J.A. Bellamy and Messrs G.S. Humphreys and A.W. Wood who read parts of it or made available hitherto unpublished information, are also gratefully acknowledged. Discussions with Dr B.G. Williams and Mr J.R. Sleeman, especially on the aspects of soil chemistry and mineralogy, are very much appreciated.

I am very grateful to Messrs D.F. Freyne, P.A. Healy and J.R. McAlpine for their personal interest and help to make this publication possible, and the Papua New Guinea Department of Primary Industry for its financial support.

Finally, I also wish to thank the staff of the Division of Land Use Research, particularly Mrs M.J. Lowe, Mrs N. Geier, Miss J.L.G. Sheaffe and Mrs A. Reece for their assistance with the editing, typing and the drafting of the figures, and the Australian National University Press for publishing this book.

Note on the use of 'New Guinea'

In accordance with the normal scientific practice 'New Guinea' has been used throughout this book to mean the whole island of which Papua New Guinea and Irian Jaya are political divisions. When Papua New Guinea is used, it refers specifically to the political entity that bears that name. The 'highlands' refer to a succession of intermontane plains, broad upland valleys and a number of large extinct volcanoes occurring in the central cordillera of Papua New Guinea.

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* Indicates a colour plate found between pp.32 and 33

Introduction

Much of the information presented in this book has been collected by soil scientists of the Division of Land Use Research, CSIRO, which between 1953 and 1972 carried out land resources surveys in Papua New Guinea at the request of the then Australian Administration. Prior to these surveys, very little was known about the country which is characterised by large areas of inhospitable terrain difficult of access. Although accessibility is still a major problem, much research has been carried out during the last three decades, not only by CSIRO workers, but also by researchers from many other institutions notably the Papua New Guinea Department of Primary Industry (formerly Agriculture, Stock and Fisheries), and the University of Papua New Guinea.

This publication began originally with the compilation of soils for which laboratory analyses were available. These data, derived from samples collected by CSIRO pedologists in many often remote parts of the country, were thought to represent a wide variety of Papua New Guinea's soils. However, because several classification systems had previously been used, it became necessary to reclassify the soils and for this purpose the Soil Taxonomy (US Dept of Agriculture 1975) was selected. This system, which is now internationally widely accepted, makes the data more accessible to scientists working in other parts of the tropics, but at the same time is very reliant on laboratory analyses which, due to other priorities, may unfortunately not always be readily available in developing countries.

The (re)classification of the soil according to the Soil Taxonomy resulted in the identification of eight orders, twenty-six suborders and sixty-one great soil groups. With this information and the data available from the land resource reports and outside sources it was decided to produce a book on Papua New Guinea soils even though, in the absence of sufficient analyses, many soils could only be tentatively identified.

Following an introductory section on the environment (chapter 1), and a discussion on soil classification and mapping (chapter 2), the next chapters (3-10) describe the soils at great soil group level according to the eight orders identified (Entisols, Histosols, Inceptisols, Vertisols, Mollisols, Alfisols, Ultisols, and Oxisols). For each great group separate sections on morphology, genesis, occurrence, association, fertility, and land use are given. Although this method of presentation is somewhat monotonous and inevitably leads to repetition, it was selected to give the information in a systematic and easily accessible way.

Upon completion of the soil sections it seemed desirable to widen the scope of the book by including chapters on soil related subjects, attempting as far as possible to synthesise the available information. Accordingly, a review of the various land inventory methods, including land system surveys, is given in chapter 11, while chapter 12 discusses soil erosion and conservation, and the possible application of the Universal Soil Loss Equation (USLE) to Papua New Guinea conditions. Type, depth, rate and the assessment of the degree of weathering are dealt with in chapter 13 together with some examples from Papua New Guinea. Chapter 14 examines the contents of primary nutrients (N, P, and K) in some typical great soil groups and trace element deficiencies in tree crops. A review of soil microrelief features at various locations in New Guinea is given in chapter 15, while the last chapter (16) briefly examines traditional food and crop agriculture, especially in relation to soil properties and crop yield declines.

After three decades of soil research there are still many gaps remaining in our knowledge. It is hoped that this publication will provide an impetus to soil research, which is essential to Papua New Guinea's agricultural development.

1 The Environment

LANDFORMS

The mainland of Papua New Guinea and its associated islands (Figure 1.1) form part of a highly mobile zone of the earth's crust, usually called the circum-Pacific mobile zone, surrounding the Pacific Ocean. its rugged and faulted mountain chains, which reach heights in excess of 4500 m in Papua New Guinea, are characterised by steeply sloping, narrow ridges separated by deeply incised V-shaped valleys. This uplift and faulting occurred during the late Oligocene to early Miocene period and is still in progress. Seismic and volcanic activity have resulted in large areas being covered by volcanic deposits, while weathering and denudation of the rugged, steeply sloping mountains has caused the deposition of extensive alluvial plains.

Löffler (1977, 1979) has subdivided Papua New Guinea into five major landscape regions and their fourteen associated landforms (Figure 1.2). A summary of this is given below.

The Southern Plains and Lowlands Region extends from the south coast to the foothills of the Central Ranges. In the far west it is more than 400 km wide, and is drained by the Fly River, which is more than 800 km in length and over 50 km wide at its mouth. The region gradually narrows towards the east (Figure 1.2), where the foothills of the Central Mountain Ranges divide it into several embayments. This area is mainly a relict alluvial plain, dissected in varying degree and largely lying above the present flood level of its river system. South of the Fly River this surface is mostly flat to very slightly undulating and generally less than 30 m above sea level. Extensive low lying areas of this plain are inundated during the wet season. The plain extends westward to the Digoel River, Irian Jaya, and is known as the Oriomo Plateau (Carey 1938). North of the Fly River is another plain, which is intricately dissected in relief by narrow ridges and valleys and ranges from 10 m in the south to over 60 m in the north. Here the even summit level of the ridges indicates a former depositional plain surface. This area has been referred to as the Fly-Digoel Shelf (Glaessner 1950; Smith 1965) and Fly-Digoel Depression (van Bemmelen 1949; Montgomery *et al.* 1950). The remainder of the region is dominated by very poorly drained or swampy alluvial plains. These are traversed by rivers having sinuous meandering channels with floodplains made up of scroll or point bar

Fig. 1.1 Papua New Guinea; provincial boundaries, major towns, cities and rivers

complexes, oxbow lakes and swamps, which in turn merge into extensive back-swamps (Plate 1.1). Near the coast there are also extensive tidal flats, which are interspersed with narrow bands of beach ridges and swales. Very large mangrove swamps built up from recent marine and estuarine sediments form parts of these tidal flats.

The Central Ranges Region extends throughout the mainland island of New Guinea, the highest peak in Papua New Guinea being Mount Wilhelm (4509 m). This region occupies nearly half of the island and forms a complex system of narrow ridges, V-shaped upland valleys and volcanoes. It varies in width from approximately 50 km near the Irian Jaya border and in eastern Papua New Guinea, to almost 200 km in its centre. The principal units of this major region are the Star Mountains in the west, through the Hindenburg, Muller, Kubor, Schrader, Bismarck and Owen Stanley Ranges, in the east. Each of these units reaches altitudes exceeding 3000 m. The highest peaks, around 4000 m, were covered by glaciers during the Pleistocene (Löffler 1972). The region as a whole has a high relief, and on some of its margins, where there is an abrupt break with the flanking lowlands, this relief may be over 300 m. Most of the Central Ranges have irregular branching, structureless ridges with

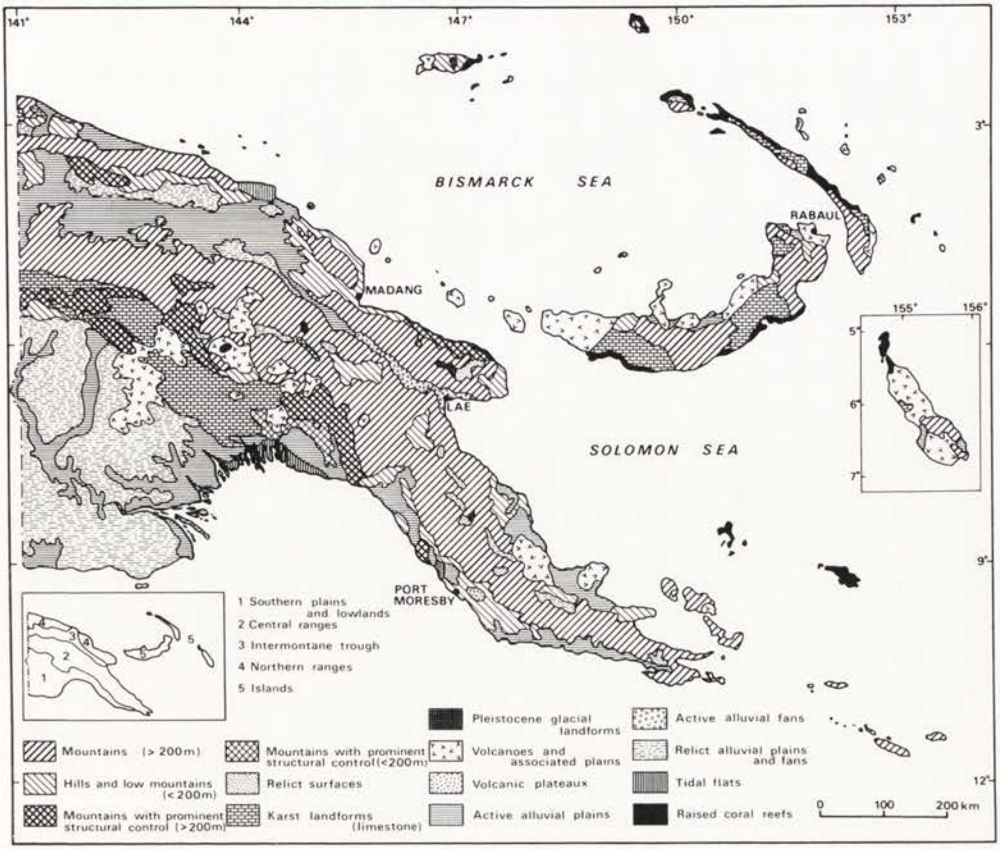


Fig. 1.2 Landforms and major landscape regions of Papua New Guinea (after Löffler 1979). Figures in brackets refer to relief.

narrow crests, long steep slopes and V-shaped valleys. They are usually located on igneous and/or sedimentary rocks. Very prominent, though less extensive are the structural homoclinal ridges (Löffler 1977) which have formed in areas where limestone or resistant sandstone alternate with soft sedimentary rocks. Also in the Central Ranges is the largest area of karst in Papua New Guinea (Figure 1.2), covering approximately 15 000 km^2. In the centre of the region the relief is generally much lower than at the margins. This area, referred to in the text as the *highlands*, is a succession of intermontane plains, broad upland valleys and a number of large extinct volcanoes. The eruption products of these volcanoes, which include Mount Hagen and Mount Giluwe, have covered extensive areas, particularly in the western part of the highlands. Volcanoes are also found in eastern Papua New Guinea where Mount Lamington, when it erupted in 1951, devastated some 240 km^2, killing some 3000 people (Taylor 1958).

The Intermontane Trough Region is a huge structural depression extending across New Guinea. The depression is made up of plains, lowlands and swamps, in most parts flanked by steep mountains. The Sepik plains, the most

Plate 1.1 Swampy or very poorly drained floodplains subject to frequent flooding are very common along major rivers such as the Fly and Sepik. This aerial photograph shows the fan-shaped scroll complexes made up of interlocking groups of meander scrolls and abandoned meanders along the Strickland River, a tributary of the Fly. Extensive backswamps, partly shown in the top left and bottom right corners, flank the scroll complexes. (Photograph is Crown Copyright and has been made available by courtesy of the Director of National Mapping Bureau, Port Moresby.)

extensive in Papua New Guinea, are dominantly swamps, meandering floodplains and fans bordering the northern flanks of the trough. The Markham-Ramu Valley also has large swampy areas, but is characterised by moderately to steeply sloping fans made up of coarse material derived from the backing, steeply sloping mountains.

The Northern Ranges Region runs parallel to the Central Ranges from which they are separated by the trough. The terrain is often very rugged and steeply sloping, and on the Huon Peninsula these mountains rise in places to 4000 m. Mountain ridges and V-shaped valleys bordered by foothills, and underlain by sedimentary rocks, are the dominating landscape. At the coast the mountains descend steeply into a narrow, discontinuous coastal plain. The north coast is actively rising with a maximum rate of uplift of 3 m per 1000 years (Chappell 1974).

The Islands Region can be subdivided into four major groups of islands (Löffler 1977). The Southern Bismarck Island Arc is a belt of active volcanoes running along the coast north of the mainland into New Britain. Numerous active volcanoes are to be found along the north coast of New Britain, large areas having been covered by ash deposits. The central and southern parts of

New Britain are dominated by rugged mountains formed on sedimentary rocks, particularly limestones which have prominent karst features.

The Northern Bismark Island Arc includes Bougainville, Buka Island, New Ireland, New Hannover and the Admiralty Islands. Bougainville, the largest island of the Solomons Group, has a massive central mountain chain dominated by three large, active volcanoes surrounded by volcano-alluvial footslopes and fans. New Ireland is a long, narrow island, which in its southern part contains mountain ridges and V-shaped valleys underlain by igneous rocks, while the central and northern parts are dominated by limestone with well developed karst landforms. Along the north coast the island is fringed by a narrow strip of raised coral, and along the south coast by a narrower, discontinuous strip of alluvium. To the west of New Ireland lie the Admiralty Islands of which Manus is the largest. It is mainly volcanic, consisting of hilly terrain and is surrounded by coral reefs.

The islands near the eastern tip of the mainland form an extension of the Central Ranges Region. Both the D'Entrecasteaux Islands and the Louisiade Archipelago have rugged mountains composed mainly of metamorphic rocks and fringed by coral reefs.

The Trobriand Islands lie to the north of the D'Entrecasteaux Islands. They are four islands and several small islets, all of raised coral limestone. Kiriwina, the main island, has a central ridge rising to 30 m with many sharp, ragged limestone pinnacles and has a high proportion of swamps. Woodlark Island, further to the east, also has much raised coral and a core of metamorphic rocks, in places over 400 m in height.

GEOLOGY

Although complex in nature, the geology of Papua New Guinea is now relatively well documented as a result of an active exploration program undertaken during the last three decades. The information has been summarised by the Bureau of Mineral Resources (1972) in a 1:1 million geological map and in a paper by Bain (1973). A more generalised account, summarised below, is that given by Ollier and Bain (1972) and Löffler (1977, 1982). The principal geological features and a generalised geological map are illustrated in Figures 1.3 and 1.4.

The mountain chain running through the centre of the mainland and the islands to the south-east are dominated by metamorphic and intrusive igneous rocks. Ollier and Bain (1972) have subdivided this central chain into three units namely, the Central Highlands, the Owen Stanley Ranges and a line of islands stretching from Goodenough Island to Rossel Island (Figure 1.3). The metamorphic rocks found in these units are composed mainly of altered sedimentary and volcanic rocks of Jurassic and Cretaceous age, while the intrusive rocks are predominantly of Miocene age.

In the West Papuan shelf, Palaoezoic rocks form the basement, outcropping in only one isolated location on the mainland. The overlying Mesozoic and Tertiary rocks show very little folding, indicating that the area has been relatively stable. These rocks, in turn, are overlain by Quaternary deposits derived from the Central Mountain Range.

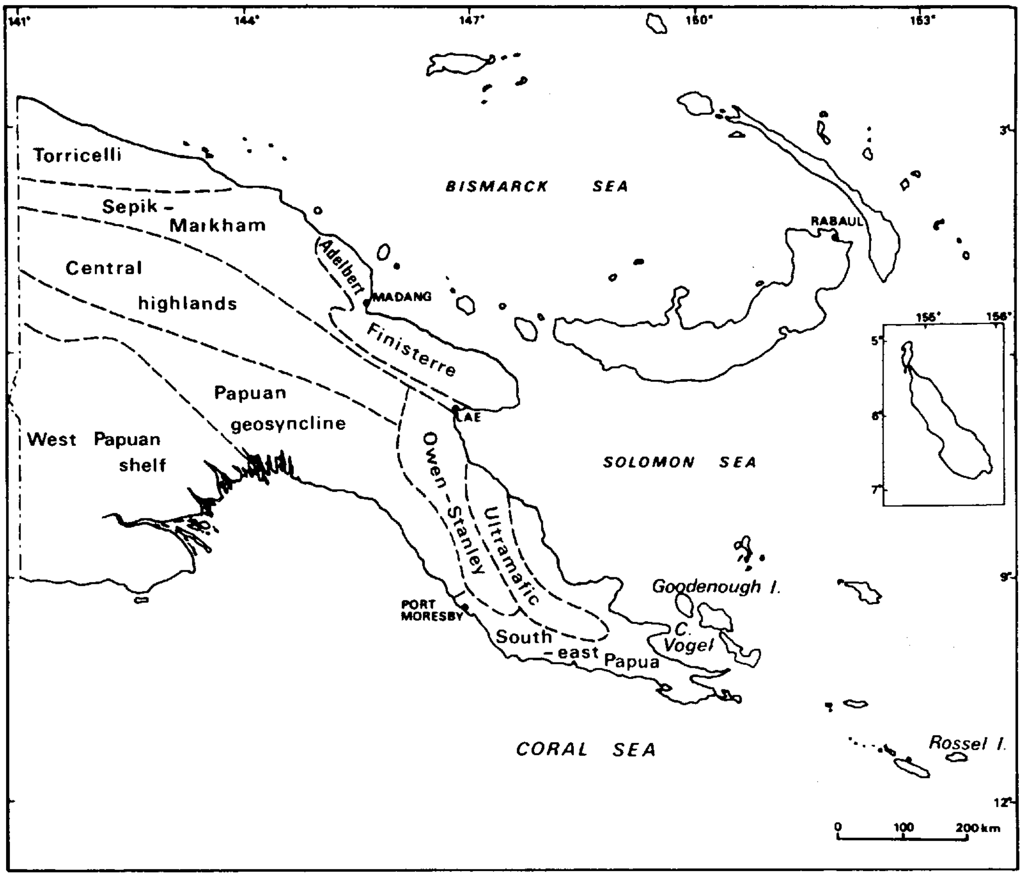


Fig. 1.3 Principal geological features of Papua New Guinea (modified after Ollier and Bain 1972)

In the Papuan geosyncline, located to the east, are thick sedimentary beds which have been subjected to tectonic movements. These beds were accumulated during the Mesozoic and Tertiary ages.

South-east Papua is perhaps the most geologically complicated area of Papua New Guinea, containing not only metamorphosed sedimentary rocks of Cretaceous and Jurassic age, but also many basic igneous Tertiary rocks.

North of the Owen Stanley Ranges is the Papuan ultramafic belt which is considered to be part of an old sea floor and mantle thrust over the continental rocks of the Owen Stanley Ranges (Ollier and Bain 1972). The Tertiary sediments and volcanics flanking the ultramafic belt in the Cape Vogel area are largely covered by Quaternary deposits of volcanic origin.

The Toricelli, Adelbert and Finisterre Ranges are considered to be geologically different from the rest of the mainland. Pliocene fine grained marine and terrestrial sediments on a basement of metamorphic rocks are mainly exposed in the Torricelli Mountains, while the Adelbert Range consists of folded Miocene siltstone, conglomerate and volcanics overlying unmetamorphosed lower Tertiary sediments and volcanics. Further to the

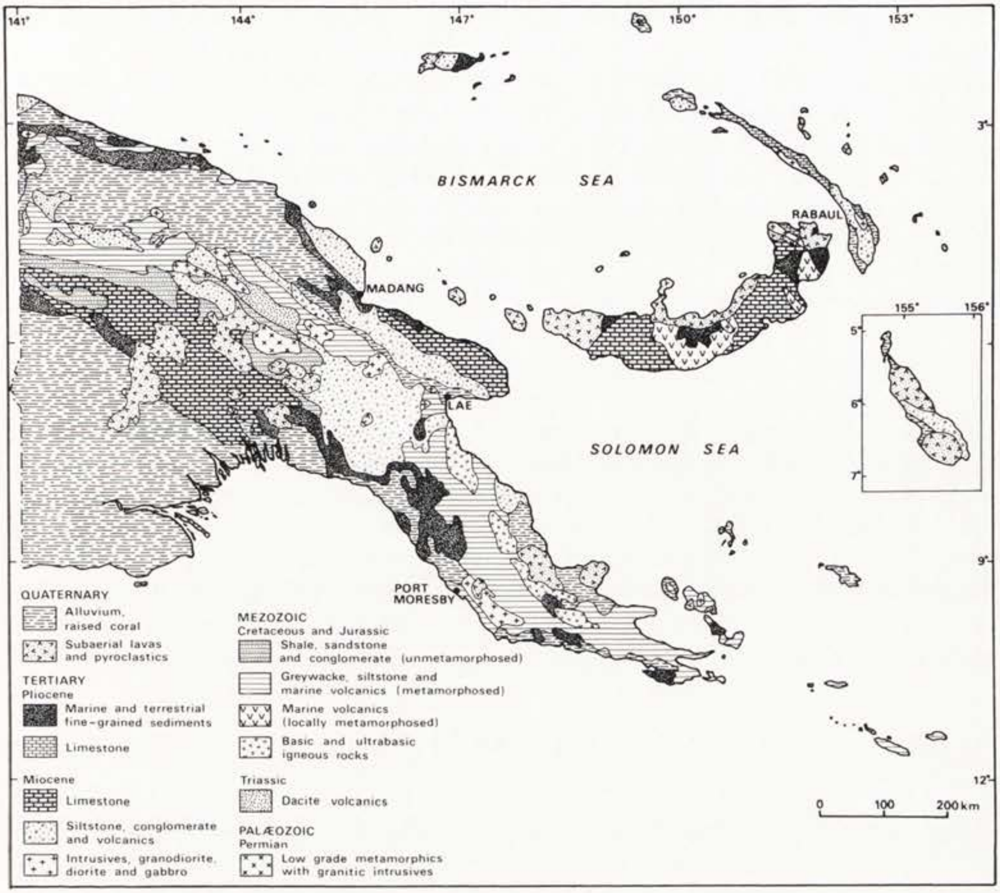


Fig. 1.4 Generalised geology (after Löffler 1979)

south-east, the Finisterre Range is mainly of Miocene limestone on a lower Tertiary volcanic basement.

Apart from a few areas of Mesozoic marine volcanics in New Britain, and the metamorphic islands of the south-east Papuan coast, the major Papua New Guinea Islands are dominantly composed of Tertiary rocks. Bougainville and the north coast of New Britain, however, have extensive areas covered by Quaternary deposits from active volcanoes.

The structural history of Papua New Guinea is explained as being caused by the interaction between and collision of the Australian Continental Plate and the Pacific Plate.* Since the late Palaeozoic period the Australian plate has been moving slowly northwards from its position near the South Pole, with southern New Guinea forming its northern rim. During most of the Mesozoic and continuing well into the early Tertiary extensive terrestrial deposition took

* These two large plates do not meet along a single boundary in Papua New Guinea. In reality there are several small rigid plates all moving in relation to the others and typically having zones of earthquake activity along their boundaries.

place on the southern part of the Pacific block. On the northern margin of the Australian Plate, however, a large geosyncline developed during the late Triassic, in which thick beds of marine sediments were deposited. Several periods of volcanism occurred during this deposition.

The landmass of Papua New Guinea started to take shape during the Miocene period, but it was not until the Pliocene that it became firmly established when large vertical movements along major fault lines created most of the present day landforms. This uplift is continuing in the Northern Ranges. Widespread volcanic activity occurring in the highlands as a result of the movements formed large volcanoes such as Mount Hagen and Mount Giluwe. These have been dated at 1.27 and 0.86 million years respectively (Löffler *et al.* 1980). While large scale volcanic activity ceased in the highlands about 200 000 years BP, some deposition of ash took place until about 50 000 years ago (Pain and Blong 1976). While on the mountain ranges above 3600 m glacial erosion took place, extensive denudation occurred at lower altitudes resulting in a strongly dissected landscape. Elsewhere, in limestone areas, typical karst features developed. Changes in the coastline, particularly in the south of Papua New Guinea, were brought about by glaciation in the northern hemisphere, causing lowering of the sea level by approximately 130 m. The Papua New Guinea landscape is still subject to rapid changes due to volcanism, landslides induced by seismic activity and various active denudation processes.

CLIMATE

Being located in the tropics Papua New Guinea is often assumed to have a climate characterised by constant high temperatures, a high rainfall and a high degree of humidity. Although this applies to most of the country which, using Köppen's classification (Köppen 1931), has a tropical rainforest climate (Af) there are nevertheless areas with open savanna (Aw), or mild temperate, rainy climates with or without distinct dry seasons (Cw and Cf), which both occur in highland areas above 1500 m.

The climate of Papua New Guinea has been described by McAlpine *et al.* (1982). That for the whole island of New Guinea, with particular reference being given to rainfall, has been described by Brookfield and Hart (1966). McAlpine *et al.* (1982) have developed a climatic classification applicable to Papua New Guinea conditions, which is based on altitudinal range and mean annual rainfall (Figure 1.5). A seasonality index, which is based on the difference between the highest and lowest mean monthly rainfall, divided by the mean annual rainfall is shown in Figure 1.6.

Although the local climate is strongly related to topography, the major climatic controls are influenced by seasonal latitudinal movements of two air masses separated by a low pressure belt, the *Intertropical Convergence Zone* (ITCZ). North-west winds prevail from late December through to mid April when the ITCZ is situated over, or to the south of Papua New Guinea. Because the heaviest and most frequent rainfalls are associated with these winds they are frequently called monsoons. Between May and October, when the ITCZ lies to the north of Papua New Guinea it causes dominantly south-easterly winds also known as trade winds, which blow with great regularity over the

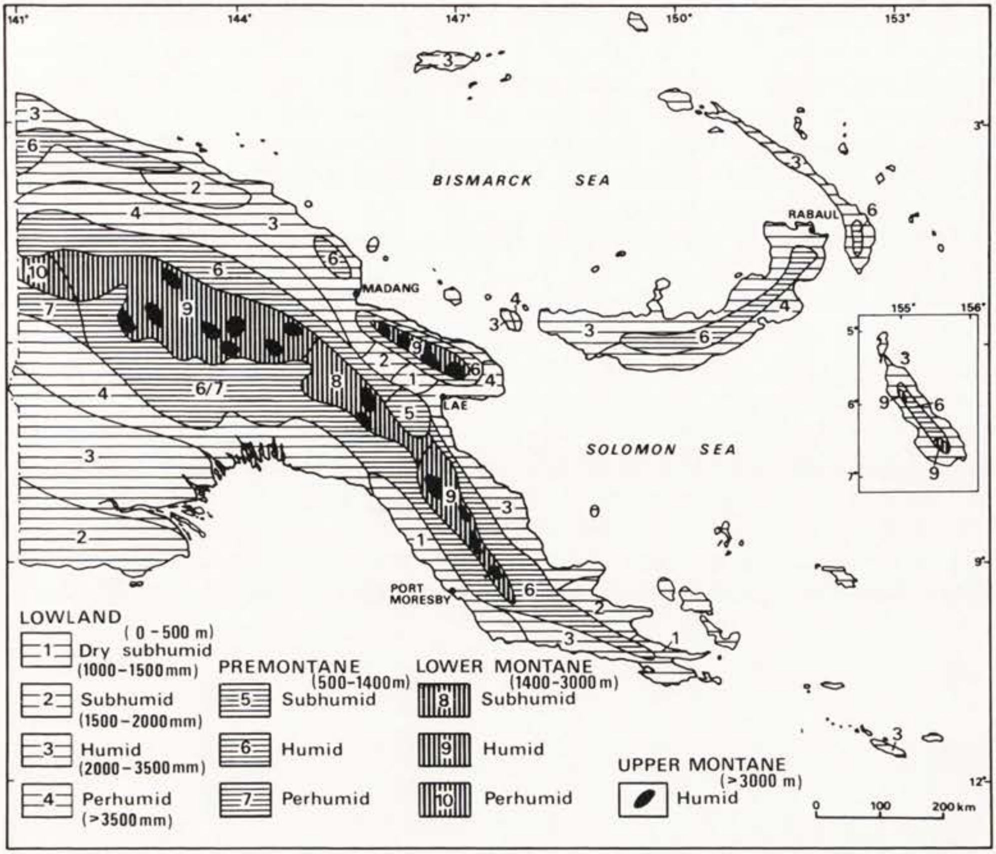


Fig. 1.5 Climate classification for Papua New Guinea based on altitude and mean annual rainfall (after McAlpine *et al.* 1982)

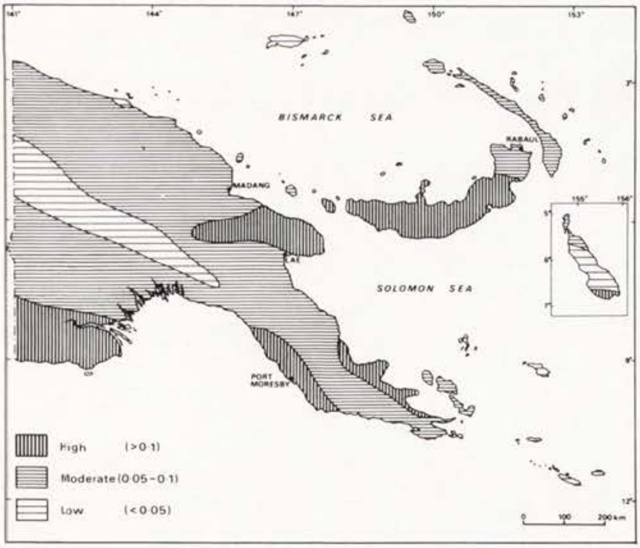


Fig. 1.6 Seasonality index (after McAlpine *et al.* 1982)

Coral Sea. Except in areas affected by strong orographical influences these trade winds do not produce frequent, heavy rainfalls. The short transitional periods between the two 'seasons' are characterised by flukey winds called 'doldrums'. These periods occur during late October and November and again during late April and May. In highland areas the seasonality in rainfall is still present, particularly in the east, but is much less marked due to local variations mainly related to topography.

The mean annual rainfall distribution map (Figure 1.7) indicates that the areas having an annual rainfall of less than 2000 mm are restricted to parts of the Markham Valley, the Bulolo Valley, the Maprik-Angoram area, the Eastern Highlands, and the coastal areas near Cape Vogel, Port Moresby and Daru. Large areas receive over 4000 mm a year, particularly the northern and southern flanks of the highlands and the south coast of New Britain. A few small centres in the Star Mountains, at the Irian Jaya border, and to the north-east of Kikori have an annual rainfall in excess of 8000 mm, while more than 10 000 mm has been recorded in the Ok Tedi area of the Star Mountains (McAlpine personal communication 1981).

The lowland areas are characterised by constantly high temperatures with only slight variations throughout the year (1-4°C for the mean daily

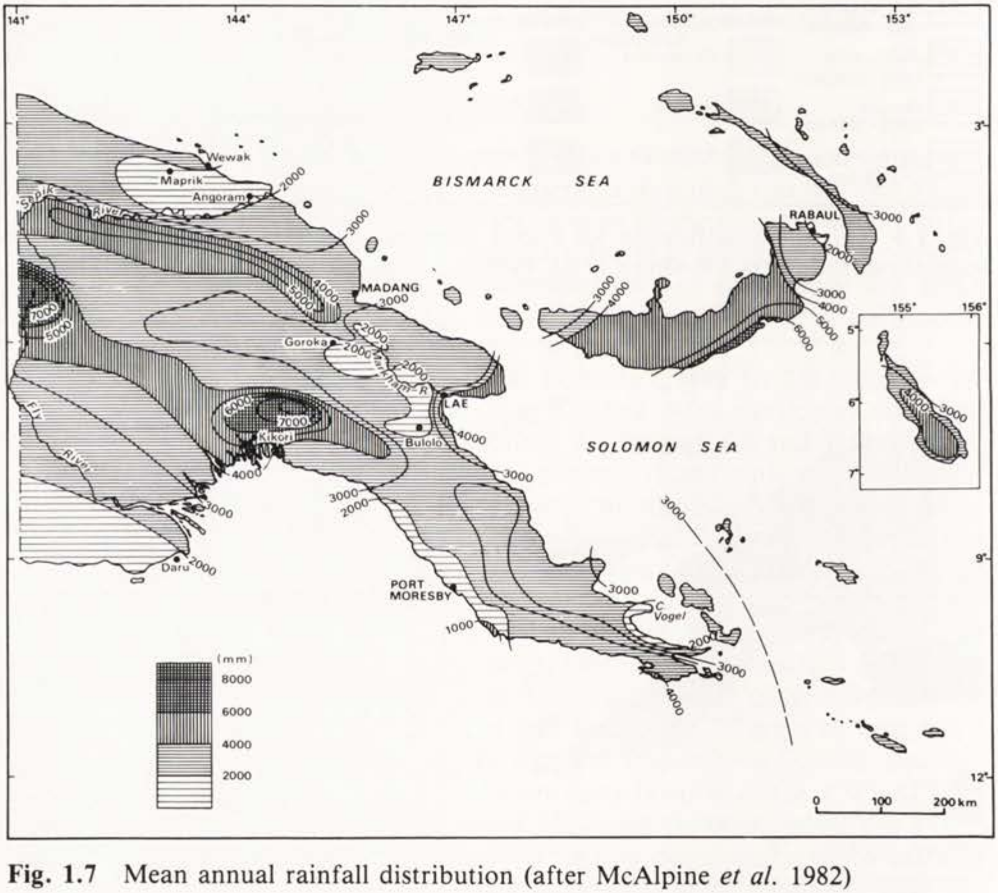


Fig. 1.7 Mean annual rainfall distribution (after McAlpine *et al.* 1982)

temperature). Mean maximum readings of 28-34°C and mean minimum readings of 20-25°C are usual with a daily fluctuation of about 7°C (Ford 1974). Generally with every 100 m increase in altitude the lapse rate is about 0.5°C, resulting in overall mean maximum temperatures of 20-29°C and mean minimum temperatures of 10-18°C in most of the highland valleys. In these areas the annual temperature ranges are about 11-13°C.

CLIMATIC EFFECTS ON SOIL

One of the most important factors in agriculture is the effect that rainfall has on the soil. Precipitation, evaporation, surface runoff, seepage or subsurface flow all have a direct bearing on the capacity of the soil to store moisture, which in turn depends on the available water holding capacity (AWC) of the soil. The AWC will vary from one soil to another, depending on such factors as soil depth, soil texture, organic matter content and clay mineralogy. Excess water can result in flooding and poorly drained conditions, while water shortage may cause drought, depending on the length of time and the available water holding capacity of the soil.

In order to study these soil-water relationships simple water balance techniques have been developed to investigate moisture requirements for plant growth (Fitzpatrick 1963; McAlpine 1973). These assist in drainage studies for agricultural suitability in the Markham Valley, Morobe Province (Holloway 1973). The water balance model employed has been described by McAlpine (1970) and detailed results for various stations in Papua New Guinea have been reported by him. A summary of the results and a description of the model follow.

The purpose of the water balance model is to estimate any changes in the level of moisture stored in a soil and also to assess any seasonal or annual water surplus and runoff. The model is applied to rainfall data from climate stations having a minimum of 15 years standard periods of records, and operates on a one week time interval. Changes in the storage of moisture in the soil are approximated by using actual weekly rainfall as input to the store and estimated weekly evaporation as withdrawal from it.

For land classification purposes a soil is assigned six water holding capacity ratings which are obtained by summation of separate estimates for the various textural horizons in the soil profile, taking into account organic matter contents, and by using the empirical figures of the US Soil Conservation Service (1951) (inches/feet converted into millimetres). Ratings may vary from >250 mm for soils with a very high, to <50 mm for soils with a very low water holding capacity. As yet, the model has been applied only to soils assumed to have an AWC of 150 mm, which is considered to be an 'average' rating. However, various other ratings can be applied to the model as more detailed soils data become available.

Assuming an AWC value of 150 mm, the model calculates the estimated water surplus, if present, by taking into account the amount by which weekly rainfall exceeds that required to recharge the soil moisture to its maximum capacity, after taking into account the evapotranspiration factor. This factor is calculated as 0.8 times mean weekly evaporation from a standard tank evaporimeter, when the AWC in the preceding week is above 75 mm (= 50 per cent of the maximum storage), and 0.4 times evaporation when the soil moisture falls below this level. Water balances have been calculated for various climate stations in Papua New Guinea, using rainfall and evaporation data, and estimates of runoff and soil moisture. These findings have been discussed by McAlpine *et al.* (1982). Figure 1.8, which shows the weekly soil moisture storage for a number of selected stations, indicates the range of soil moisture regimes in Papua New Guinea. Marked differences are apparent especially in the case of the 'drier' stations (Port Moresby, Erap and Kaiapit) where water stress occurs for varying periods in the dry season. These drier moisture regimes are, however, limited in extent as shown in Figure 1.9 where the soil moisture regimes have been classified by McAlpine *et al.* (1982) according to the degree and frequency of soil moisture depletion levels. Some of these drier areas (e.g. Western Province and the area south-east of Madang) appear to have soils with lower than 'average' (150 mm) water holding capacities, making the intensity and occurrence of soil moisture depletion even more likely. A large proportion of the country appears, however, to have low and infrequent incidences of soil water deficits.

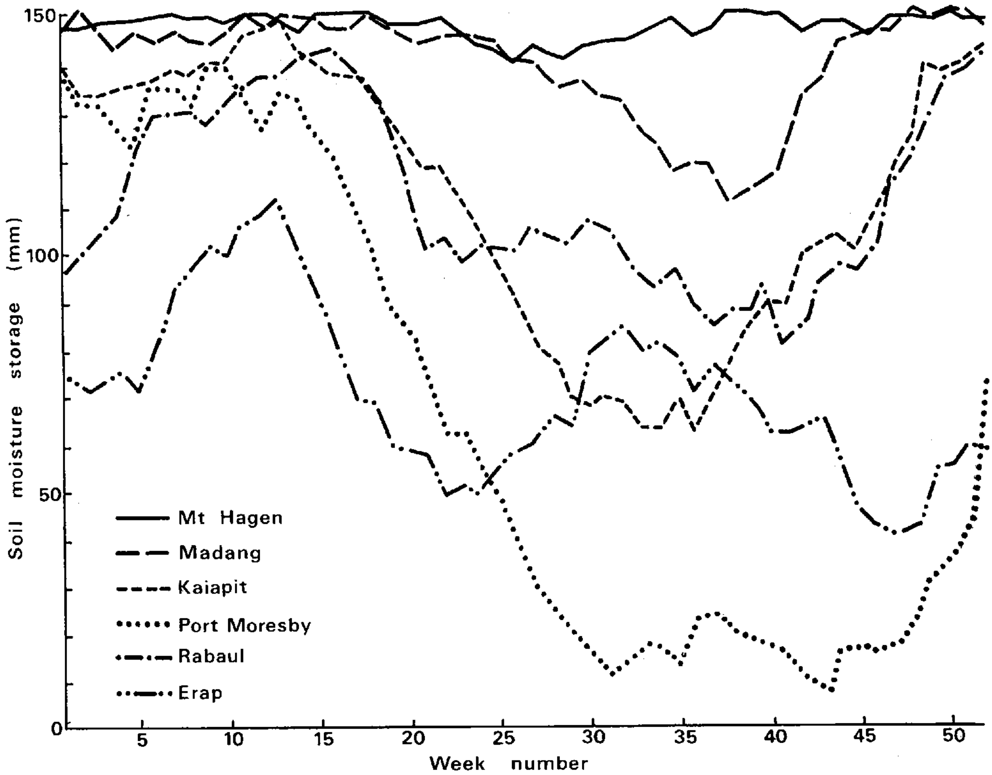


Fig. 1.8 Mean weekly soil moisture storage for a range of stations (after McAlpine *et al.* 1982)

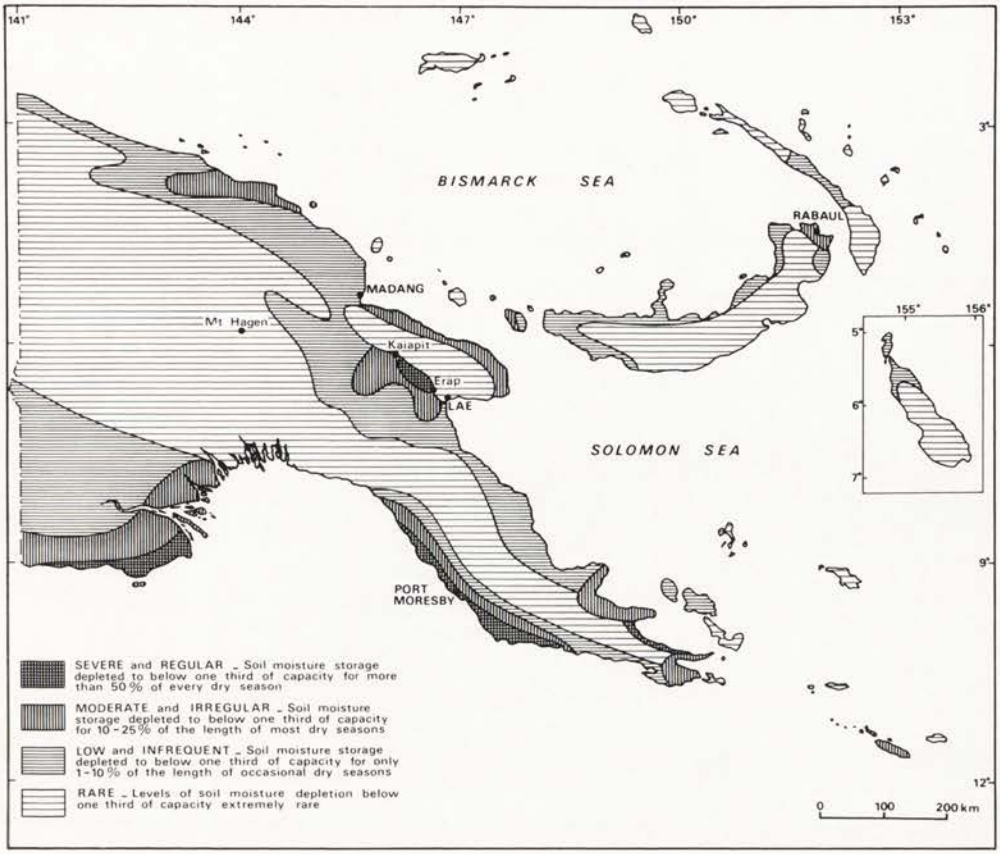


Fig. 1.9 Intensity and frequency of soil moisture depletion (after McAlpine *et al.* 1982)

VEGETATION

Papua New Guinea has a richly diverse flora, with extensive areas still being covered with primary forest. This diversity is largely attributable to the altitude range (sea level to over 4500 m) and to its geographical position. Papua New Guinea is considered to be the interchange of the Indo-Malesian and Australian zones of flora.

The vegetation has been described by Paijmans (1976, 1982). The major vegetation types distinguished by him are outlined here and their distribution is given in Figure 1.10.

Lowland Forest is predominant and extends to approximately 1400 m in areas where rainfall exceeds 1800 mm per annum. It is structurally and floristically the richest forest type and typically contains numerous palms, vines and climbers. Lowland forest develops best on relatively well drained alluvial plains, where its canopy height is 35 to 40 m. Impeded drainage will cause the canopy to be more open and irregular in height. In very poorly drained to swampy conditions, sago and pandans are found in the understorey.

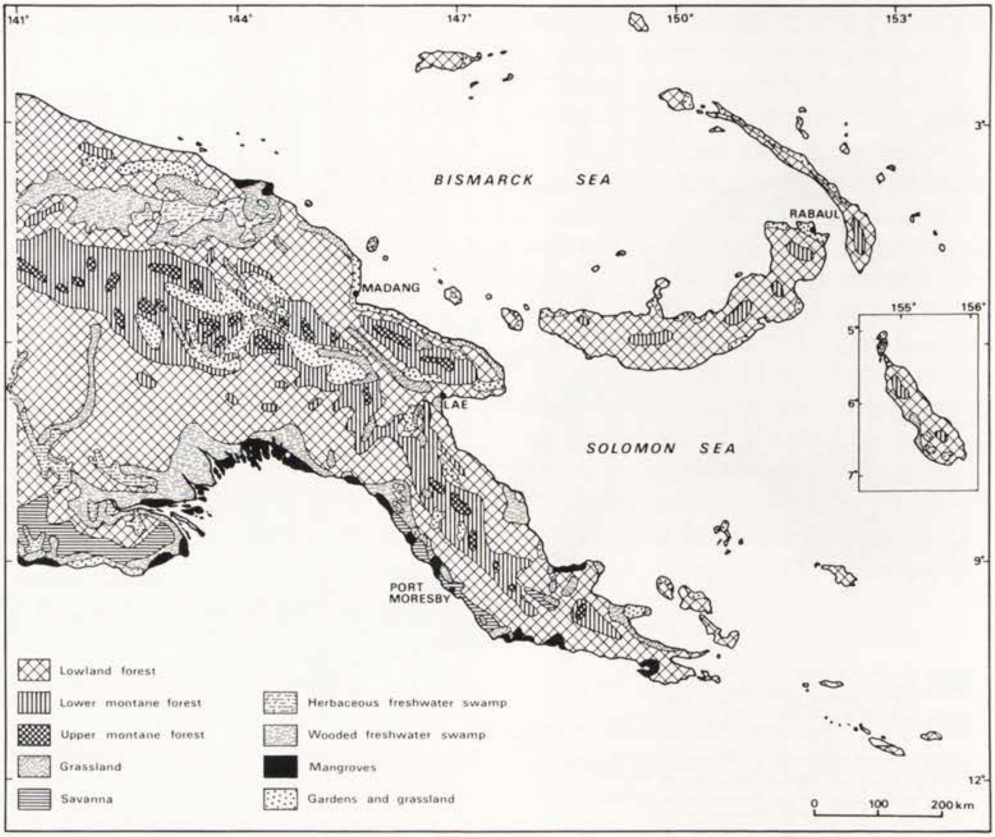


Fig. 1.10 Major vegetation types (after Paijmans 1982)

On hills and low mountains and in areas with a relatively low rainfall of high seasonality, the lowland forest is generally smaller and not as well developed.

At higher altitudes and with decreasing temperature, the lowland forest merges gradually into *Lower Montane Forest* (*c* 1500-3000 m). Low cloud cover, common to this environment, gives an impression of wetness, and vegetation reflects damp conditions with mosses covering trees and fallen branches. The forestry canopy is lower (20-30 m generally), more regular and denser than the average rainforest. The number of tree species is relatively small, oaks (*Castanopsis*, *Lithocarpus*), beech (*Nothofagus*) and species of laurel being the most common, together with conifers and trees of the myrtle family above 2000 m.

Around 3000 m, under increasingly cold conditions, there is a quite abrupt change to *Upper Montane Forest*. This is characterised by stunted, often gnarled trees, approximately 10-15 m in height, belonging to the conifer, myrtle, heath and rose families. Mosses and epiphytes are very common. Usually this forest forms a mosaic with areas of grassland (often called Alpine Grasslands), becoming more frequent with increasing altitude. Near the limit of the tree line (3800-3900 m) the forest degrades into scrub and grasses.

Open *Grassland* is common at altitudes from sea level to more than 4000 m. Tussock grasses, alpine herbs and mosses are found only above 4000 m. Because of the cold climate and frequent frosts these include many southern temperate species. The tussock grasses *Danthonia* and *Poa* are dominant, together with ferns, lichens and mosses, the latter two being found in conjunction with bare rock exposures at the highest altitudes. Between 2500 and 4000 m the grasslands are dominated by *Danthonia* together with *Deschampsia* which may grow up to 1 m in height and width. These grasses are mainly found on relatively well drained slopes, often in association with tree ferns. There is intensive sweet potato cultivation at lower altitudes (1500 and 2500 m) and many disused garden sites have been overgrown by dense, pure stands of up to 5 m tall sword grass (*Miscanthus floridulus*). In the lowlands, in hilly and low mountainous terrains that have a moderate to high rainfall seasonality, kangaroo grass (*Themeda australis*), kunai (*Imperata cylindrica*) and speargrass (*Heteropogon contortus*), between 0.5-1.0 m tall, are the most abundant species. In the lowland plains, however, pit-pit (*Saccharum spontaneum*) and kunai are dominant. Most of the grasslands below 2500 m are thought to have developed as a result of shifting cultivation and the practice of burning (Paijmans 1976; Manner 1969, 1976).

Savanna are grasslands with scattered trees of variable density which are found in areas having highly seasonal rainfall generally less than 1800 mm. They are restricted to a few areas, but occur mainly in the Port Moresby region where the dominant trees are eucalypts, and in the southern part of the Western Province where *Melaleuca*, *Tristania* and *Acacia* are the major trees. Kunai and kangaroo grass are the dominant grassland species. Savanna, like grassland vegetation, is considered to have developed largely because of clearing and burning.

Herbaceous freshwater swamps and *Wooded freshwater swamps* are commonly developed along the floodplains of major rivers. Usually the vegetation type is strongly related to the depth and seasonality of flooding. In areas subject to very deep flooding 'floating' swamp grasses are extensive, while in less deeply flooded situations tall cane grasses, such as *Saccharum robustum* and *Phragmites karka* are most common. Permanent herbaceous swamps are dominated by herbs, sedges and ferns and wooded freshwater swamps by *Campnosperma*. In areas having seasonal swamps where the water table remains close to the surface during the dry season sago palm (*Metroxylon sagu*) groves are found. Along the south-west coast *Melaleuca* occurs extensively in seasonally dry swamps.

Mangroves are found extensively along the south coast in relatively sheltered positions on tidal flats in the estuaries of the main rivers. They tolerate constant flooding and saline conditions, and are commonly zoned according to species composition with *Avicennia*, *Sonneratia* and *Rhizophora* occurring on the seaward side, and *Bruguiera* and *Rhizophora* forming tall forest inland. Nipa palms occur in the transition zone between the saltwater and freshwater environments.

Areas of *Gardens and grassland* are found between sea level and 2700 m, but dominate in the highlands.

2 Soil Classification and Mapping

Before 1963, CSIRO reconnaissance surveys in Papua New Guinea adopted a soil classification system based on morphogenetic similarities broadly corresponding to the great soil groups as defined in other parts of the world. However, difficulties in applying this method soon became apparent. Individual surveyor bias, resulting from the use by different pedologists, of the less than precise great soil group criteria was reflected in the incompatibility of soil data when applied from one survey area to another. Moreover up to this stage any more precise and systematic classification was precluded by lack of sufficiently detailed soil information. It was therefore decided, subsequent to the publication of the 7th Approximation of the comprehensive system of soil classification developed by the US Soil Conservation Service (1960), to adopt a modified form of this system for Papua New Guinea surveys and, as such, this was first implemented by Haantjens (1967b) in his report on the Safia-Pongani Survey which took place in 1963. Haantjens stressed in his report that the 7th Approximation names used were only tentative because many of the soils could not be positively identified, largely because of restrictions in analytical data. These limitations, together with other fundamental objections to the use of the 7th Approximation, have been discussed in detail by Webster (1968) and Stephens (1963). Nevertheless this classification proved useful in correlating soils and in later surveys by Bleeker (1969, 1971) and Haantjens (1972a,b).

Because this book is basically a discussion of Papua New Guinea soils for which analytical data are available and since it may also be of interest outside Papua New Guinea itself, the author has opted to use as its format the latest version of the USDA scheme of Soil Taxonomy (US Dept of Agric. 1975). As with its earlier version, the 7th Approximation, a major drawback of this system is its excessive reliance on soil analytical data. As will be discussed in the next section the identification of the argillic horizon, one of the major differentiae at the highest classification level (the order), has been particularly difficult because depositional phenomena (ash admixtures, colluviation and sheet wash) appear to be very common in Papua New Guinea and clay skins (argillans) are very difficult to identify in the field or by standard laboratory techniques. Many other problems have arisen at various other classification levels. For instance, in the Entisols, the alluvial soils belonging to the suborder Fluvents require by definition an organic carbon content 'that decreases irregularly with depth or remains above 0.2% to a depth of 125 cm', while many of the soil analyses are limited to a topsoil and subsoil sample only. The methods of analyses used have also never been spelled out in any detail. Most were carried out in overseas laboratories, such as the Royal Tropical Institute, Amsterdam, the Netherlands. Because they cover a period of approximately seventeen years of surveys some of the analytical methods used may have changed during such a long time interval. A complete adherence to many of the precisely defined differentiae of the soil taxonomy is therefore almost impossible for the 'classifier', necessitating whenever possible a substitution by other criteria, or use of his own 'judgment' based on field experience.

Another major inclusion in the soil taxonomy are parameters related to soil moisture data and temperature regimes. Apart from being difficult to obtain in developing countries, these often have, in the Papua New Guinea context, a very low information content. For instance, there appears little point in placing soils in 'tropical' great soil groups in an equatorial country.

On the other hand it should be stated that the soil taxonomy is now internationally widely accepted and has greatly facilitated communication between soil scientists in various countries. With all its limitations the scheme provides a convenient and meaningful framework for the classification of a broad range of soils found in widely variable and complex terrain such as Papua New Guinea. Moreover this system is presently commonly used by the Department of Primary Industry in Papua New Guinea (D.F. Freyne, personal communication) and has also been extensively applied in the neighbouring Solomon Islands (Wall *et al.* 1979).

As a first step towards facilitating the discussion, the 430 relevant soil profiles were reclassified according to the USDA classification system. In addition information on climate, landform, vegetation and parent material was included for each profile. The results have been published as a separate paper by Bleeker and Healy (1980). In Table 2.1 the great soil groups tentatively identified in Papua New Guinea are given together with their distribution and correlation with previously named soil groups. There is little doubt that as soil research continues additional great soil groups will be identified.

SOIL MAPPING

The first general soil map, at scale 1:2.5 million, covering the whole island of New Guinea was produced by Haantjens *et al.* (1967) in co-operation with Dutch soil scientists and shows a total of twenty-seven 'major soil groups'. The mapping units are arranged into soil associations of the high mountains, low mountains and hills, and plains and valleys. Although this map must be considered a first approximation it demonstrated, as pointed out by Haantjens (1970b) the great complexity and soil variability in comparison to other countries. This soil map was updated by Bleeker (1974) for the eastern part of the island as part of the FAO World Soil Map Project, using the FAO soil units (FAO 1974).

Table 2.1
Great soil groups identified in Papua New Guinea, their distribution and correlation with previously named soil groups

Order	Suborder	Great group	Distribution	Major previously named soil group
Entisols	Aquents	Sulfaquents	Very common	Saline peats and muds; Mangrove soils.
		Hydraquents	Very common	Young alluvial soils; Very poorly drained alluvial soils.
		Fluvaquents/ Tropaquents	Very common	Alluvial soils; Young alluvial soils; Recent alluvial soils.
		Psammaquents	Common	Recent alluvial soils.
	Psamments	Tropopsamments	Common	(coarse textured) Beach soils.
	Fluvents	Tropofluvents	Common	Young alluvial soils; Recent alluvial soils.
	Orthents	Troporthents Cryorthents Ustorthents	Very common Very local Very local	Lithosols; Skeletal soils; Slope soils; Colluvial soils.
Histosols	Folists Hemists	Cryofolists Cryohemists	Very local Very local	Alpine peat and humus soils.
		Tropohemists	Common	Peaty soils; Organic soils.
	Fibrists	Cryofibrists	Very local	Alpine peat and humus soils.
		Tropofibrists	Common	Peaty soils; Organic soils.
	Saprists	Troposaprists	Common	
Inceptisols	Aquepts	Halaquepts	Very local	—
		Cryaquepts	Very local	Skeletal soils; Peaty soils.
		Andaquepts	Local	Humic olive ash soils; Unweathered sandy volcanic soils with black topsoils.
		Tropaquepts	Common	Gleyed plastic heavy clay soils; Meadow soils; Dark soils of heavy texture.
	Andepts	Hydrandepts	Very common	Humic brown clay soils (on volcanic ash).
		Durandepts	Local?	—

Table 2.1 cont'd

Order	Suborder	Great group	Distribution	Major previously named soil group
		Vitrandepts	Very common	Unweathered sandy volcanic soils with black topsoils.
		Eutrandepts Dystrandepts	Very common	Moderately weathered brown ash soils; Moderately to little weathered brown ash soils.
Inceptisols	Tropepts	Humitropepts	Very common	Humic brown clay soils.
		Ustropepts	Local	Brown clay soils.
		Eutropepts	Very common	Brown forest soils; Dark colluvial soils; Shallow dark clay soils; Reddish clay soils.
		Dystropepts	Very common	Strongly weathered red and brown clay soils; Acid red to brown clay soils; Acid brown forest soils; Uniform red and yellow clays; Reddish clay soils.
	Ochrepts	Cryochrepts	Very local	Alpine peat and humus soils; Skeletal soils.
		Cryumbrepts	Very local	Alpine peat and humus soils; Skeletal soils.
Vertisols	Uderts	Pelluderts	Local	Alluvial black clay soils; Black earths.
	Usterts	Pellusterts	Very local	Dark cracking clay soils.
Mollisols	Aquolls	Argiaquolls	Local	Dull meadow podzolic soils; Meadow podzolic soils.
		Haplaquolls	Common	As above, but also including poorly drained old alluvial soils.
	Rendolls	n.a.	Very common	Rendzinas; Limestone soils.

Table 2.1 cont'd

Order	Suborder	Great group	Distribution	Major previously named soil group
	Ustolls	Natrustolls	Very local	Shallow black earths; Texture contrast soils.
		Calciustolls Argiustolls	Very local	Texture contrast soils; Brown clay soils.
		Haplustolls	Very local	Dark cracking clay soils; Beach soils.
	Udolls	Argiudolls	Common	Well drained old alluvial soils; Immature brown soils on sedimentary rocks; Dull meadow podzolic soils; Meadow podzolic soils.
		Hapludolls	Very common	Young alluvial soils; Well drained old alluvial soils; Old alluvial soils; Alluvial black clay soils.
Alfisols	Aqualfs	Plinthaqualfs	Common	Meadow podzolic soils; Meadow soils.
		Tropaqualfs	Common	As above, but also including gleyed plastic heavy clay soils and weathered gleyed soils.
	Ustalfs	Natrustalfs	Very local	Texture contrast soils.
		Rhodustalfs	Very local	Alkaline reddish clay soils.
		Haplustalfs	Local	Texture contrast soils; Brown clay soils.
	Udalfs	Natrudalfs	Very local	Brown forest soils.
		Rhodudalfs	Local	Terra rossas.
		Tropudalfs	Very common	Dull meadow podzolic soils; Brown forest soils; Immature brown soils on sedimentary rocks.
Ultisols	Aquults	Plinthaquults	Common	Meadow podzolic soils; Podzolised gley laterites.

Table 2.1 cont'd

Order	Suborder	Great group	Distribution	Major previously named soil group
		Albaquults	Local	Meadow podzolic soils; Lateritic and gleyed latosols.
		Tropaquults	Common	Meadow soils; Meadow podzolic soils; Gleyed plastic heavy clay soils; Lateritic and gleyed latosols.
	Humults	Plinthohumults	Local	Lateritic and gleyed latosols.
		Tropohumults	Common	Humic brown clay soils; Humic brown and red latosols; Strongly weathered red and brown clay soils.
	Udults	Plinthudults	Common	Red and yellow earths; Meadow podzolic soils.
		Rhodudults	Local	Acid red to brown clay soils.
		Tropudults	Common	As above, but also including dull meadow podzolic soils.
Oxisols	Humox	Haplohumox Acrohumox	Very local	Strongly weathered red and brown clay soils.
	Orthox	Haplorthox	Very local	Acid red to brown clay soils.
		Eutrorthox	Very local	Granular dark red uniform heavy clay soils.

THE USDA CLASSIFICATION SYSTEM

For readers unfamiliar with the USDA Scheme of Soil Taxonomy (US Dept of Agric. 1975) a brief summary is given.

The highest categories of the system are called *orders* which are recognisable by the suffix *sol*. There are ten orders each of which contains a formative element which in turn becomes the suffix for the names of suborders and great groups, the second and third categories of the system respectively. Names of suborders have two syllables, the first indicating the diagnostic properties of the soil and the second being the formative element of the order. Similarly the great group consists of the name of the suborder and a prefix that comprises one (or occasionally two) formative elements giving information on the diagnostic properties. Thus great groups have three syllables* and end with the name of the suborder. As an example the formative element of the order Entisols is *ent*. Wet, poorly drained Entisols are called at suborder level Aquents whilst those formed on very young sediments but lacking the characteristics associated with wetness belong to the suborder Fluvents. Aquents that are very wet (e.g. swampy soils) and 'soft underfoot' belong to the great group of Hydraquents, while Fluvents found in tropical climates characterised by little variation in mean summer and winter temperatures belong to the great group of Tropofluvents. Orders are identified by *diagnostic horizons*, or the lack thereof, but also by *diagnostic properties* referring to soil moisture and soil temperature regimes.† When diagnostic horizons occur at the surface they are called epipedons; at subsurface level they retain the term horizon. The important diagnostic horizons mentioned here are the *mollic*, *umbric* and *histic* epipedons and the *argillic*, *cambric* and *oxic* horizons. Briefly, the major criteria for the *mollic epipedon* are the presence of a thick dark surface horizon‡ containing at least 0.6 per cent organic carbon and having a base saturation of 50 per cent or more by the NH_4OAc method at pH 7. Similar criteria apply to the *umbric epipedon* but its base saturation is less than 50 per cent. The *histic epipedon* is usually more than 20 cm thick and normally occurs at the surface but may sometimes be buried at shallow depth. By definition it is saturated for more than 30 days in most years and contains between 12 and 18 per cent organic carbon depending on the clay content of the mineral fraction. The *argillic horizon* is normally a subsurface horizon that contains illuviated clay derived from the overlying eluvial horizon. However, in Papua New Guinea it does not seem logical to assume that all clay rich subsoils of soils formed on other than alluvial or colluvial deposits are entirely formed by illuviation of clay (see next section). The *cambic horizon* constitutes what has been called a colour or structure B horizon. Its identification is often somewhat intuitive, particularly in strongly gleyed soils. Cambic horizons should show evidence of sufficient alteration in the original rock structure, have textures finer than very fine sand, and colours which have a stronger chroma or redder hue than the underlying horizon. The *oxic horizon* is at least 30 cm thick and exhibits extreme weathering (commonly indicated by its occurrence on mature landforms). It has dominantly red colours and a high friability in relation to clay content. Like the argillic horizon, the oxic horizon

* Except for the Rendolls (Rendzinas) which are not further subdivided at suborder level.

† These refer to hot and dry (aridic/torric) moisture regimes for the Aridisols not found in Papua New Guinea and mesic, isomesic or warmer soil temperature regimes (mean annual temperature $\geqslant$ 8°C) for the vertisols having a limited distribution.

‡ Colour (Munsell) values darker than 3.5 when moist and 5.5 when dry and chroma less than 3.5 when moist. Thickness must be at least 10 cm if directly underlain by 'rock', $\geqslant$ 18 cm in soils with loamy and clayey epipedons and which have underlying diagnostic horizons plus a number of other requirements, and $>$ 25 cm if the texture is as coarse as or coarser than loamy sand *or* if no other diagnostic horizons are present and the organic carbon content of the underlying materials decreases irregularly with increasing depth.

is also very difficult to identify positively in the field, its identification being almost completely reliant on laboratory analyses.* Analytical data have shown that these soils are very rare in Papua New Guinea.

The identification of the argillic horizon

An argillic horizon as defined in the USDA scheme (*Soil Taxonomy*, pages 19-27) is often very difficult to identify in the field or by standard laboratory procedures.

The process of clay illuviation is not yet fully understood. Until about ten years ago it was generally assumed that profiles with heavier textured subsoils formed on non alluvial or colluvial materials, resulted from clay movement. Recent research, especially in micropedology, has challenged this concept, mainly on the basis that clay skins (argillans) are not always present in the subsurface horizon which otherwise fulfils the textural requirements for an argillic horizon or which, if present, are so weakly expressed that their positive identification is doubtful. Also, this horizon does not always show the increase expected in bulk density when clay illuviation takes place (Brewer 1968; Oertel 1968). To further complicate the issue there is also micropedological evidence that the (illuvial) clay skins can sometimes be destroyed after formation (Bennema *et al.* 1970) or, with time and age, move to greater depth in the soil profile (J. Sleeman personal communication).

Recent studies by McKeague *et al.* (1981) of a variety of Canadian soils showed that of the fifty-four pedons considered by pedologists to have argillic horizons only thirty-two had at least 1 per cent oriented illuvial clays as estimated by point counting of thin sections, which is the main accessory property of the argillic horizon.

Because the problems arising with the identification of the argillic horizon appear to be particularly confined to soils dominated by low activity clay (LAC)† they have been subjected to numerous discussions during international soil classification workshops and the result has been the proposal to introduce a *kandic horizon* as a diagnostic subsurface horizon (Moormann and Buol in press).

According to this proposal, a kandic horizon is a subsurface horizon with a significantly finer texture than the overlying horizon(s) and in which the higher clay content cannot be traced to subsurface accumulation by illuviation of layer-lattice clays. In pedons having a kandic horizon, this textural differentiation may be the result of one, or more, processes acting simultaneously or sequentially. The most important of these processes are differential weathering, causing clay destruction in the epipedon where weathering is most intense, and differential illuviation, both resulting in a greater loss of clay from the surface horizon(s); selective erosion, causing removal of the clay particles (and

* Cation exchange capacity of the fine earth fraction of less than 16 meq per 100 g clay by NH_4OAc at pH 7 and a fine earth fraction (< 2 mm) that retains 10 meq or less ammonium ions per 100 g clay from an unbuffered 1 N NH_4Cl solution.

† 1:1 lattice layer silicates, mainly kaolinites with varying amounts of oxy-hydroxides of Fe and Al.

humus) downslope; and sedimentation by coarser textured surface materials. The last process in particular seems relevant to Papua New Guinea conditions, where many fine textured subsurface horizons appear to fulfil the requirement of the kandic horizon as defined by Moormann and Buol (in press). In such situations, however, the overlying coarser textured surface horizon(s), which lack microstratification, may have been formed by one or a combination of processes, including lithological discontinuities of the parent material, colluvial slope wash* or slight contamination by coarser textured volcanic ash.

For these reasons the term argillic horizon, as used here, has been given a broader application than that of the USDA scheme and, much like the kandic horizon concept, connotes an horizon containing appreciably more clay than the overlying horizon(s). However, it is not necessarily formed by clay illuviation alone. Exceptions are soils formed on stratified alluvial or colluvial deposits, and those found in the vicinity of volcanoes where rejuvenation by volcanic ash has taken place as shown by microstratification.

That clay illuviation activity takes place in Papua New Guinea is evidenced in Plates 2.1 and 2.2 (colour section), showing channel ferriargillans with strong continuous orientation occurring in the B_{22} horizon of a Tropudalf located in the Northern Province.

LOCAL SOIL KNOWLEDGE

Being agriculturalist, the local population obviously has a comprehensive knowledge of soils, especially in relation to their suitability for crops. Unfortunately, with few exceptions, little information has been collected on this subject.

Soil knowledge amongst the Baruya people belonging to the Kukukuku group of highlanders has been reported by Ollier *et al.* (1971). The Baruyas, known as 'saltmakers', live at approximately 2000 m in the Wonenera and Marawaka valleys in the Eastern Highlands Province. The authors noted that the people have an extensive knowledge of their soils which, according to 'our' system, consist mainly of Rendzinas (Rendolls), Terra Rossas (Rhodudalfs?) and Alluvial soils (Tropofluvents). The Baruya, however, have no names for the soil profile as a whole. Their 'classification' embraces some twenty names for soils and also includes at least ten names for rocks and related materials (e.g. stone used for stone clubs). The soils are further subdivided according to their use as pigments or for agriculture. Pigments play a very important role in the society, and may be used for colouring string, war paints, or ceremonial purposes, such as initiation. The 'agricultural' soils are subdivided by the people into four major groups, which refer to dark coloured soils, reddish coloured soils, alluvial soils and saltgrass soils. The first three, in turn, are further subdivided on the basis of colour, thickness and their suitability for a particular crop, or group of crops. The fourth, saltgrass soils are those suited to the growth of a special reed used to produce salt, which is widely traded

* By coarser textured material derived from upslope, which has lost part of its clay according to one of the processes outlined above.

throughout the area. Chemical analyses of this salt showed very high potassium contents, dangerous for human consumption if used in large quantities.

Of the other research carried out on local soil knowledge (Brookfield and Brown 1963; Landsberg and Gillieson 1980; Wood in press) all authors agree that the people do not have a collective term for the whole profile, but describe individual horizons. According to Brookfield and Brown (1963) in their study of the Chimbu people, the terminology used, although often described in more general terms, is very similar to that used by soil surveyors, the major characteristics referring to colour, texture, soil depth, water holding capacity, organic matter content and workability. Wood (in press) states that the Huli people living in the Tari Basin distinguish individual horizons mainly by colour and texture criteria, the most fertile soils being those with the thickest, dark topsoil. Obviously the grouping or 'classification' is closely related to which soil produces the most abundant yields or the largest sweet potatoes, this being the staple crop in highland areas.

3 Entisols

Entisols have no profile development with the possible exception of a thin, dark or light coloured A horizon. They are very young soils occurring mainly on recently deposited alluvium, or are found in hilly or mountainous terrain where soil erosion has kept pace with soil formation.

Entisols have five suborders, four of which have been identified in Papua New Guinea. *Aquents* are the wet Entisols which are characterised by strong gleying at or close to the surface. Long periods of high water tables cause reduced conditions owing to a lack of oxygen, which is reflected in their grey and blue colours. *Fluvents* are basically the better drained counterparts of the Aquents occurring on recently deposited river sediments. They are mostly olive, olive brown, or brownish coloured (mostly in 2.5Y hues) and are well drained although some indication of gleying and/or mottling below 50 cm depth may be present. By definition the organic carbon content of the Fluvents decreases irregularly with depth or remains above 0.2 per cent to a depth of 125 cm. This is caused by stratification. Fluvents must have a texture finer than loamy sand to distinguish them from the *Psamments* which are coarse textured soils occurring commonly along the coast on beach sands or, less commonly, further inland on coarse sedimentary deposits such as sandstone. Entisols developed primarily on recent erosional surfaces are called *Orthents*. They are very common in mountainous terrain having slopes of more than 30°, but may also be found on alluvial deposits.

SULFAQUENTS

Morphology

Because these soils only become strongly acidified upon aeration, they have never been positively identified in Papua New Guinea. Nevertheless they can be expected to occur extensively in natural conditions in coastal areas on marine and estuarine deposits, which have specific type(s) of mangrove vegetation (Plates 3.1 and 3.2). Sulfaquents are continuously waterlogged soils, consisting of thick mostly silt or clay rich sedimentary layers with a high content of finely dispersed organic matter commonly intermixed with thin organic layers. They have a neutral to alkaline soil reaction. Upon drying,

Plate 3.1 Rhizophora Mangrove – a typical environment for the Sulfaquents and various Histosols

Plate 3.2 Knee shaped pneumatophores of *Bruguiera* in *Rhizophora/Bruguiera* mid-height evergreen forest.
Pneumatophores' special function is to provide oxygen to the trees. In addition, these roots stabilise the environment by trapping sediments.

whether by natural processes or drainage, these soils are expected to become strongly acidified (pH 3.5 or less) due to oxidation of sulphides present in the sediment. They have been called acid sulphate soils (Chenery 1954) or cat clays (van der Spek 1950) and have been known to exist in the Netherlands since the eighteenth century (Pons 1973). In Papua New Guinea they were previously referred to as saline peats and muds (Haantjens *et al.* 1967). An extensive review of these soils is given in the 1972 Symposium on Acid Sulphate Soils (Dost 1973).

Genesis

Being young soils formed of recently deposited sediments found under permanently reduced, waterlogged conditions, they show in their natural state little or no profile development. However, as shown by the extensive research carried out on these soils (Dost 1973; van Breemen 1976; Moormann and Pons 1974; Pons and van der Kevie 1969) this does not imply that some pedogenetic processes have not taken place.

According to Moormann and Pons (1974) soil genesis has already occurred during the establishment of the mangrove vegetation. These mangroves promote the accumulation of sediments, particularly where a dense rootmat of pneumatophores is exposed (Plate 3.2). These roots retard the flow of seawater, while the dense vegetation and roots add organic matter to the soil. The amount of organic matter formed is largely dependent on the rates of decomposition and the type of mangrove species, *Rhizophora* with its fibrous roots showing the highest organic matter contents (Hesse 1961). For decomposition and mineralisation under the prevailing anaerobic conditions the organic matter requires oxygen which is provided by iron oxides present in sediments and sulphates brought in by saline or brackish water. The ferrous hydroxide reacts with the sulphur to form iron sulphides; the energy required for this process being provided by the decomposition of the organic matter. The major source of potential acidity in these soils is, however, secondary pyrite (FeS_2) which accumulates when FeS reacts with S under reduced conditions (Moormann and Pons 1974). The amounts formed depend on the organic matter and iron oxide contents of the sediments and the quantities of sulphates supplied by seawater. Values of 1-4 per cent pyrite are, according to Moormann and Pons (1974) most common, but may reach more than 5 per cent. The calcium carbonate present in sediments in the humid tropics is most commonly dissolved by river water containing organic acids.

A second phase of soil genesis, dealing with 'real' soil formation, starts when the sediment becomes subject to aeration. This process, called *ripening* (Pons and Zonneveld 1965; Pons 1973), largely involves the dehydration of the soil causing an increase in consistency, shrinking, cracking, structure formation, oxidation, weathering and biological activity. In sediments rich in sulphides, pyrites are oxidised resulting in acidification of the environment. The large amounts of acids formed in turn attack the clay minerals causing the liberation of aluminium in amounts toxic to plants (Pons 1973). If these acids and soluble Al^{3+} ions are not leached out quickly, the end products are Sulfaquepts characterised by yellowish mottles and streaks of ferric sulphates (e.g. jarosite)

Plate 3.3 Crab mounds in the Purari River estuary under a mangrove community

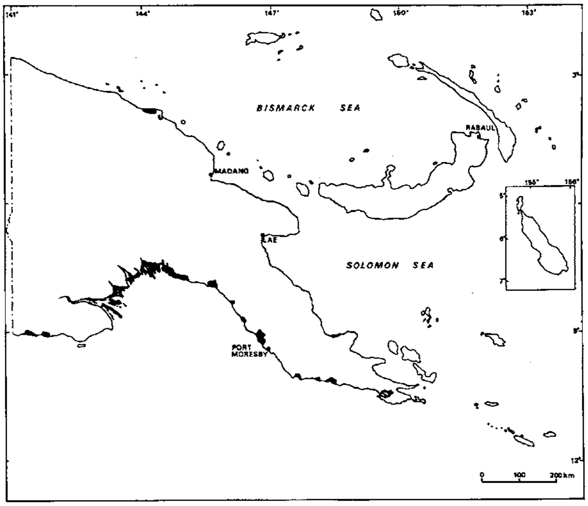
and which have very low exchangeable bases, and high exchangeable and free aluminium contents.

Generally Sulfaquents and other mangrove soils show little evidence of stratification. This may be attributed to intense crab activity which is very common in the mangrove environment, particularly in sediments rich in clay and/or silt. Here crabs (*Scylla serrata?*) may build mounds of up to 150 cm high and 250 cm across (Plate 3.3). These mounds are continuously subject to tidal erosion resulting in a constant mixing of the soil material. Very similar mounds, built by the mud lobster (*Thalassina anomala*) have been reported by Andriesse *et al.* (1973) along the west coast of Sarawak.

Occurrence

Sulfaquents can be expected to occur extensively under mangroves along large inlets and estuaries of major rivers which carry large quantities of sediments (Figure 3.1). These situations are particularly common on the south coast, along the Fly, Kikori and Purari Rivers. The occurrence of Sulfaquents appears to be related to particular types of mangroves or individual species. As has been discussed in the previous section, sediments with a *Rhizophora* vegetation, which is characterised by fibrous roots, have the highest organic matter contents, an essential requirement for the formation of these soils. For this reason work carried out by Jordan (1963) in West Africa has shown that Sulfaquents develop more commonly under *Rhizophora* than *Avicennia* species. Unfortunately, as yet, no research has been done on the mangrove soils

Fig. 3.1 Major distribution of swampy alluvial deposits covered by mangrove vegetation and characterised by Sulfaquents, Hydraquents and various Histosols



in Papua New Guinea but since *Rhizophora* appears to be the dominant mangrove species (Paijmans 1976) these soils are likely to cover extensive areas.

Association

On the coast these soils are closely associated with the Tropofibrists or raw peat soils and probably also with the as yet unidentified Sulfihemists. Inland Sulfaquents grade mainly into Hydraquents and Fluvaquents. Figure 3.2, giving a schematic cross-section of a coastal plain, Gulf Province, shows the relationship of some of these soils with landforms, vegetation, and land use.

Fertility

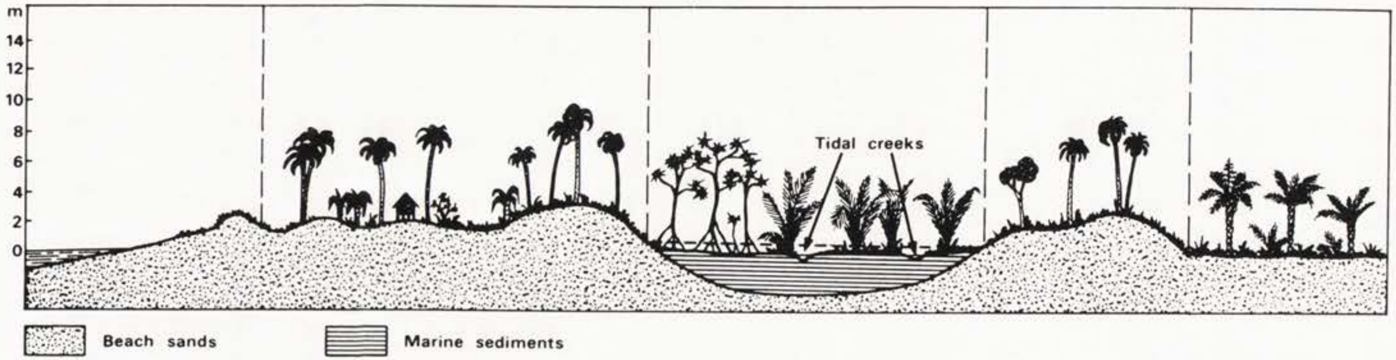
No analytical data are available but these soils are expected to have a moderately high chemical fertility under natural conditions.

Land Use

In general these soils can be considered unsuitable for agriculture although deepwater rice cultivation is a possibility, and in West Africa these soils have been used for this purpose. Better than average rice yields have been obtained from these soils in Sierra Leone where one crop per annum is produced during the wet season after rains have 'flushed out' the excess salts from the soil. If used for agriculture, these potentially acid sulphate soils should not be drained or only superficially drained to avoid acidification. Except for having only locally small gardens planted with yams and taro to supplement the staple diet of fish and sago, Sulfaquents are not cultivated in Papua New Guinea. Previously some tannin has been extracted from the bark of mangrove trees growing on these soils. However, because of the economic importance of the mangrove environment as a habitat for molluscs, fish, crabs and prawns it appears best left undisturbed.

Fig. 3.2 Schematic cross-section through a coastal plain, Gulf Province

Landform	Present beach and active beach ridge	Present stable beach ridge	Tidal flat	Inland beach ridge	Swale
Vegetation	Bare and colonizing	Coconut groves and gardens	Nypa palms; near coast mangroves	Coconut groves	Sedge grassland sago



Soils	Tropopsamments		Sulfaquents Hydraquents Tropofibrist (and other Histosols)	Tropopsamments Hapludolls or Eutropepts on inland ridges	Psammaquents
	Well drained undifferentiated sandy soils formed by wave and wind action; on beach ridges having weakly developed A_1 horizons; alkaline to weakly acid		Swampy undifferentiated soils often with interbedded thin peat layers; strongly gleyed, soft underfoot; under mangroves (*Rhizophora*) containing sulphites - Sulfaquents, elsewhere Hydraquents. Also thick mainly raw peat soils - Tropofibrist; neutral to alkaline	As other Tropopsamments but weakly acid; further inland commonly thick dark A_1 horizons - Hapludolls or Eutropepts	Very poorly drained to swampy sandy soils; weakly acid to neutral often weakly developed A_1 horizons or interbedded thin peaty layers; strong gleying
Present and/or potential land use	Unsuited for agriculture. Present use: fishing and recreation	Mainly suited for coconuts. Low fertility somewhat limits arable cropping. Present use: coconut groves and gardens	Unsuited for agriculture. Present use: gathering and light timber sources	As stable beach ridges	Unsuited for agriculture. Present use: sago collecting

HYDRAQUENTS

Morphology

Hydraquents like the Sulfaquents are permanently saturated and their high water content causes them to be characteristically soft underfoot. They lack the sulfidic materials typical of the Sulfaquents and are commonest in freshwater environments. They mostly have fine to medium textured, strongly gleyed, stratified alluvial layers occasionally interbedded with thin organic strata. The soil reaction varies between acid and neutral. Hydraquents are mainly found under swamp grassland (e.g. *Hanguana* and *Phragmites*), sago and less commonly, swamp forest. These soils were previously referred to as young alluvial soils or very poorly drained alluvial soils and in some cases also peaty or organic soils.

Genesis

Hydraquents are entirely formed by fluvial deposition, and their textures are largely dependent on the velocity of the water and nature of the material being eroded from the hinterland. A reduced sediment supply can give rise to an accumulation of organic material with minimal sedimentation of inorganic material. Whenever these soils occur in swampy backplains they are much clayier due to the reduced floodwater velocity. For this reason Hydraquents often comprise uniformly textured clays in which stratification is less obvious.

Occurrence

These soils are frequently found on scroll complexes, backplains and backswamps of major rivers such as the Sepik, Fly, Purari and Lakekamu (Plates 1.1 and 3.4, Figures 3.1 and 3.3).

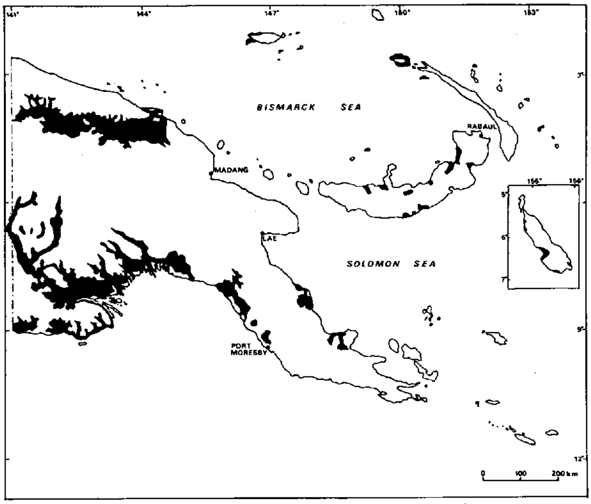


Fig. 3.3 Major distribution of poorly drained and swampy alluvial areas characterised by Fluvaquents, Hydraquents and various Histosols

PLATE 2.1

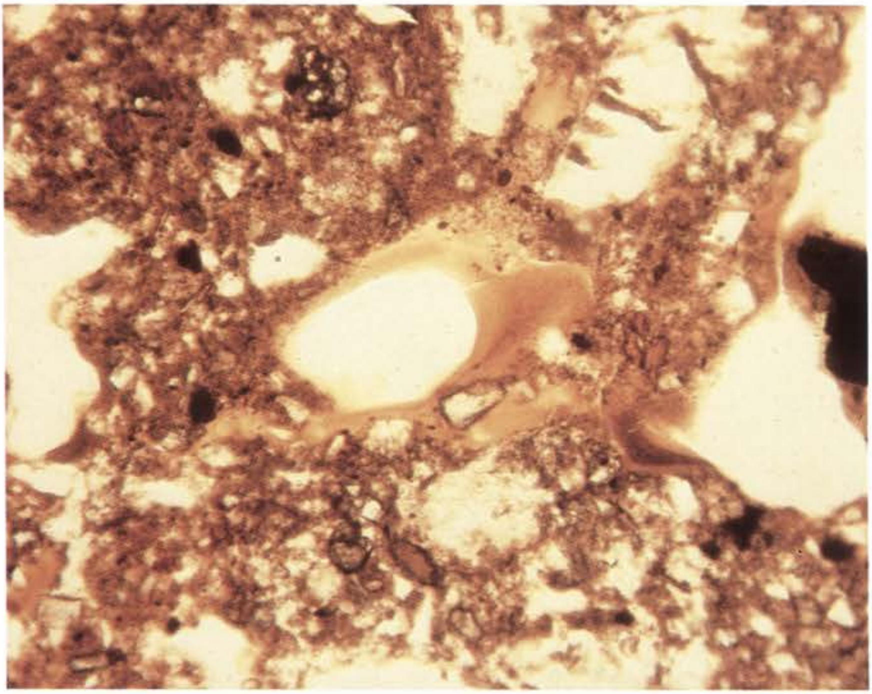
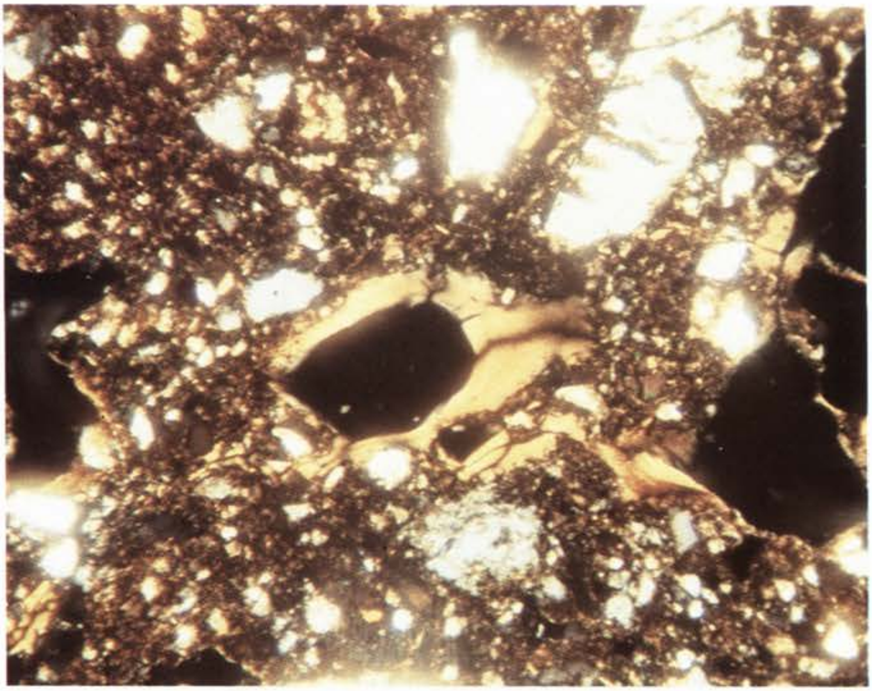


PLATE 2.2

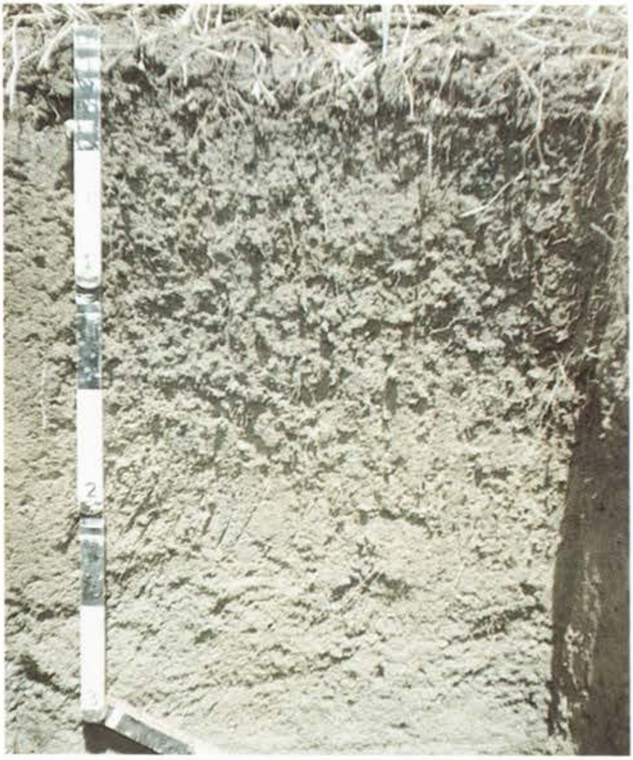


Channel ferriargillans with strong continuous orientation at a depth of 25 cm in a B_{22} horizon of a Tropudalf. Frame length 0.9 mm. (2.1) Plain light, (2.2) crossed polarisers. For a detailed description and analytical data, see Appendix 1. Plate 8.6 shows a colour photograph of this soil profile.

PLATE 3.7

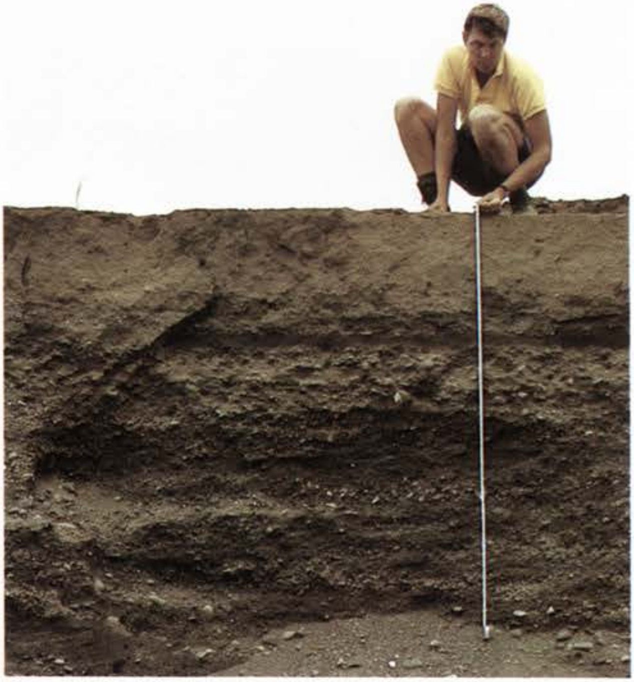
Fluvaquent developed on volcanic derived alluvium. A detailed description and analytical data are given in Appendix 1. Tape measurements indicate 6 in (15 cm) intervals.

PLATE 3.10



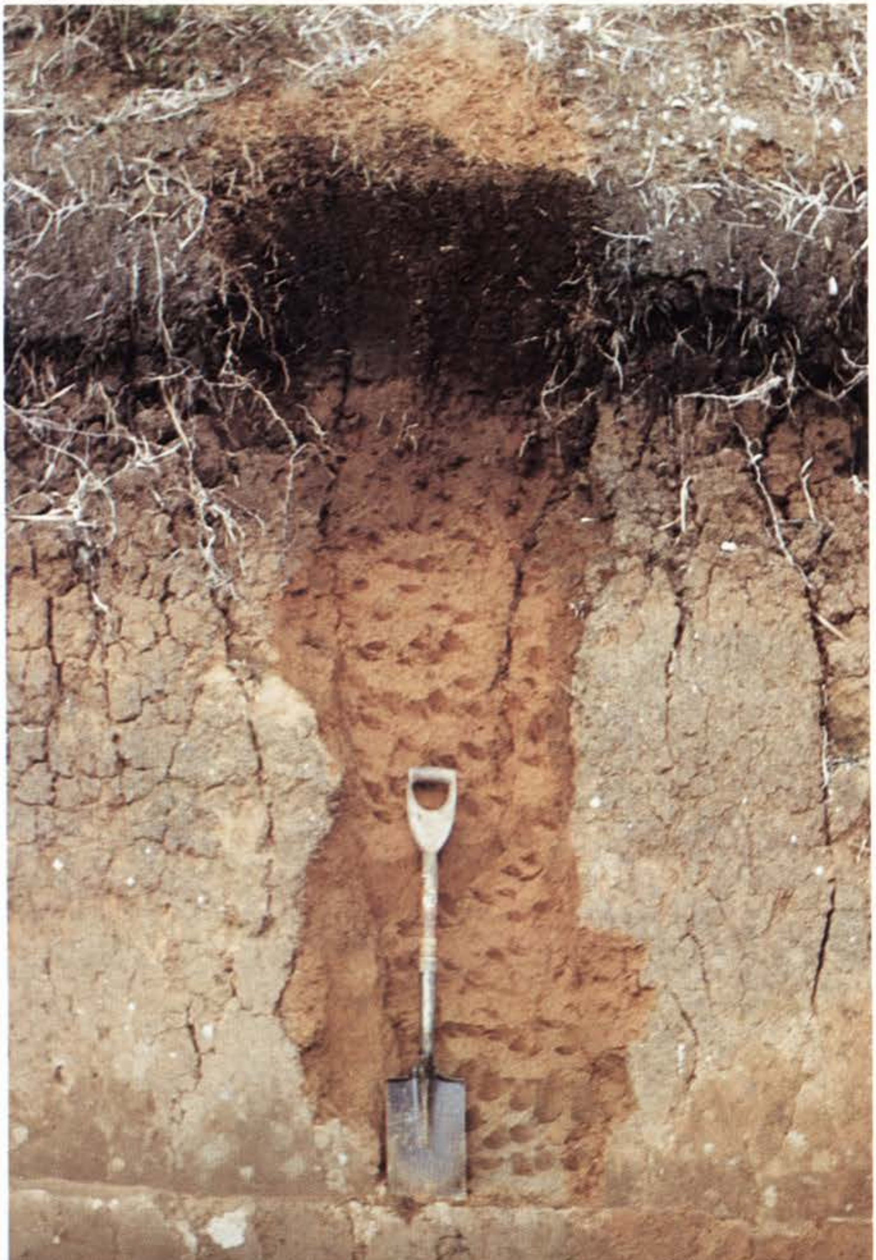
Tropofluvent developed on alluvial floodplain deposits. Detailed description and analytical data are given in Appendix 1. Tape measurements are given in 6 in (15 cm) intervals.

PLATE 3.13



Troporthent developed on coarse fan deposits in the Markham Valley. Soil consists of 40 cm of fine sand overlying coarse gravel. This soil shows a tendency to grade into a Tropopsamment but could not be classified as such because of the large volume of gravel below 40 cm.

PLATE 5.1

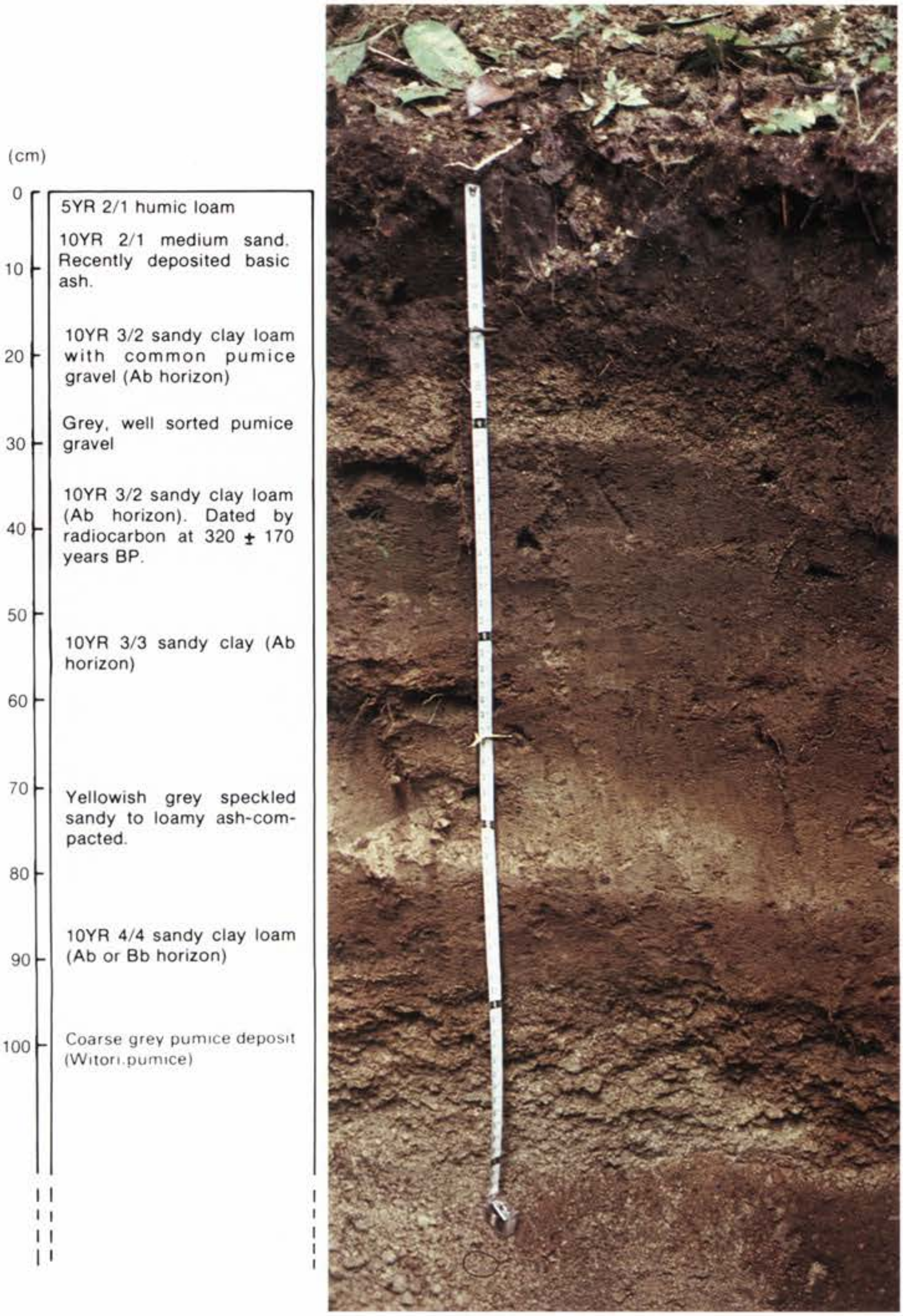


Hydrandept (humic brown clay soil) developed on volcanic ash overlying weathered, coarse textured tuff near Mount Hagen. Altitude 1700 m and rainfall 2500-3000 mm per annum. A detailed description together with analytical data is given in Appendix 1.

PLATE 5.5

Dystrandept located near Popondetta on the slightly dissected volcanic plains north-east of Mount Lamington. The soil consists of 30 cm of very friable loam with a crumbly structure and abruptly overlying yellowish grey speckled sand. These soils were formerly classified as unweathered sandy volcanic soils with black topsoils. Tape measurements are indicated by 6 in (15 cm) intervals.

PLATE 5.6

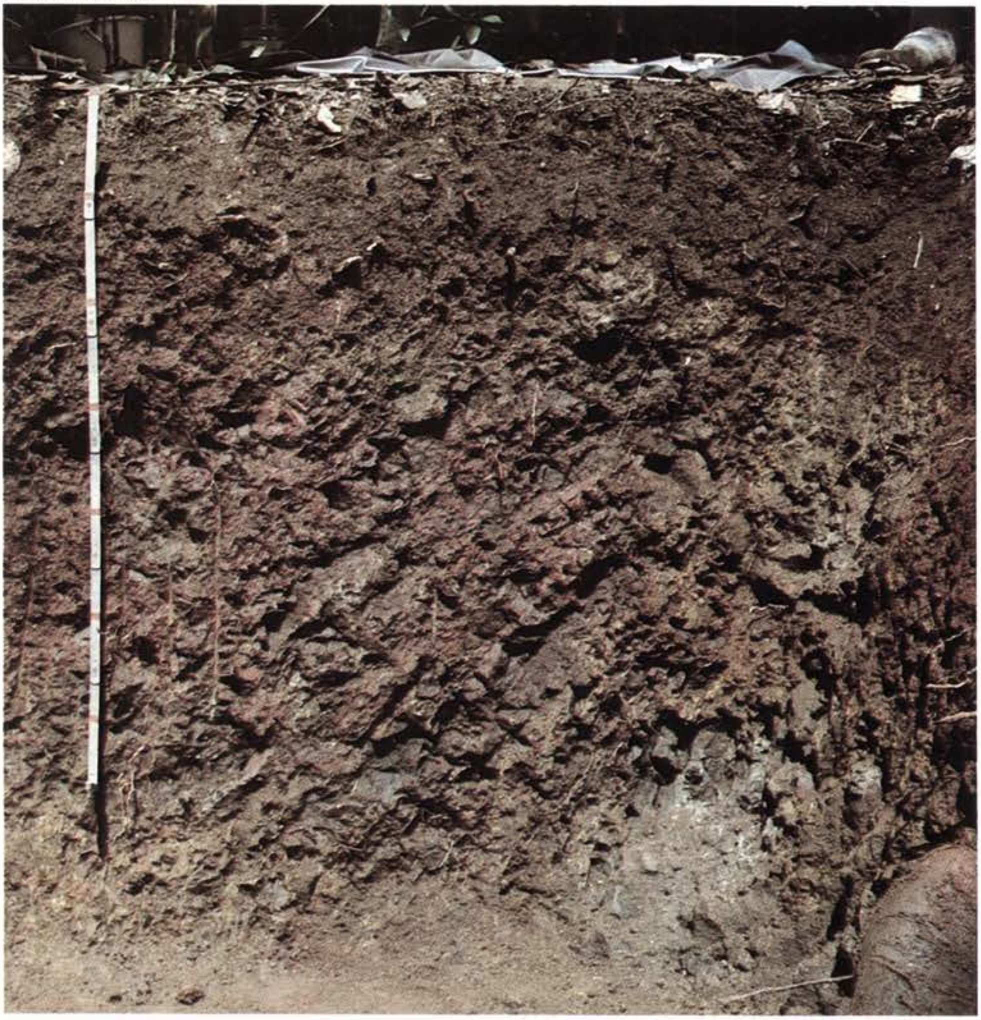


Eutrandept located near Hoskins, New Britain on the footslope of Witori volcano. This soil shows bedded airfall deposits with buried A and B horizons.

PLATE 5.11

Eutropept developed on siltstone approximately 20 km south-east of Wewak on a hillslope in the Prince Alexander Mountains. A detailed description and analytical data are given in Appendix 1.

PLATE 5.12

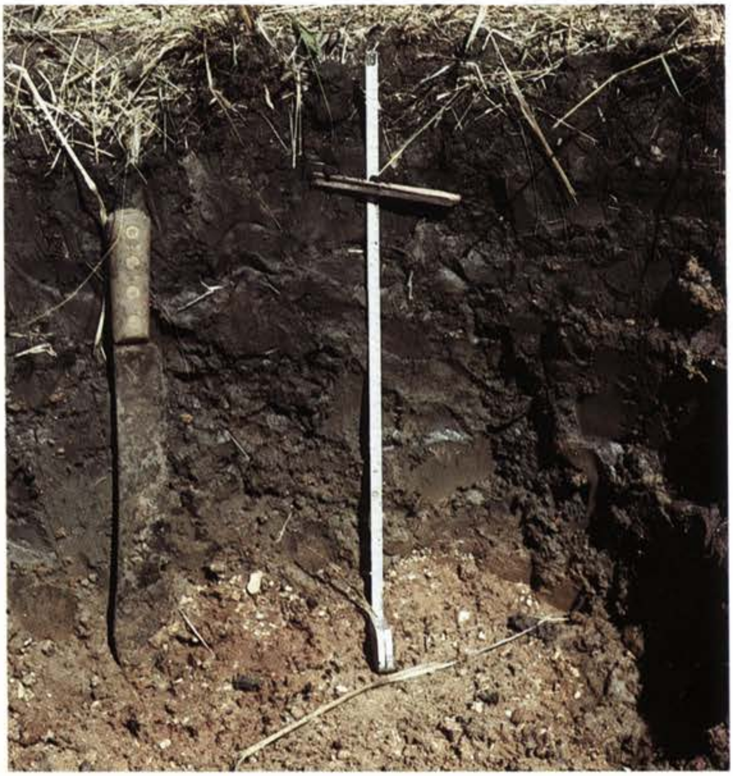


A shallow Eutropept developed on basic igneous rocks on a long hill ridge approximately 30 km north of Safia in the Northern Province. A detailed description and analytical data are given in Appendix 1. Tape measurement indicates 6 in (15 cm) intervals.

PLATE 6.2

Large slickenside with embedded root print and black vertical root channel cross-section with topsoil infill. These features occur typically in Vertisols.

PLATE 6.3



Shallow (60 cm) Pelludert developed on uplifted coral terrace dated at 220 000 years BP (Chappell, 1973) on the north coast of the Huon Peninsula. Annual rainfall 1500-2000 mm. A detailed description and analytical data are given in Appendix 1.

PLATE 7.1

Haplaquoll developed on alluvium in a tributary of the Sepik River. The soil consists of a very dark grey (10YR3/1) firm to plastic A_1 horizon merging gradually into a grey (5Y 4/1-5/1) prominently yellowish brown mottled subsoil. The texture is clay throughout the soil profile.

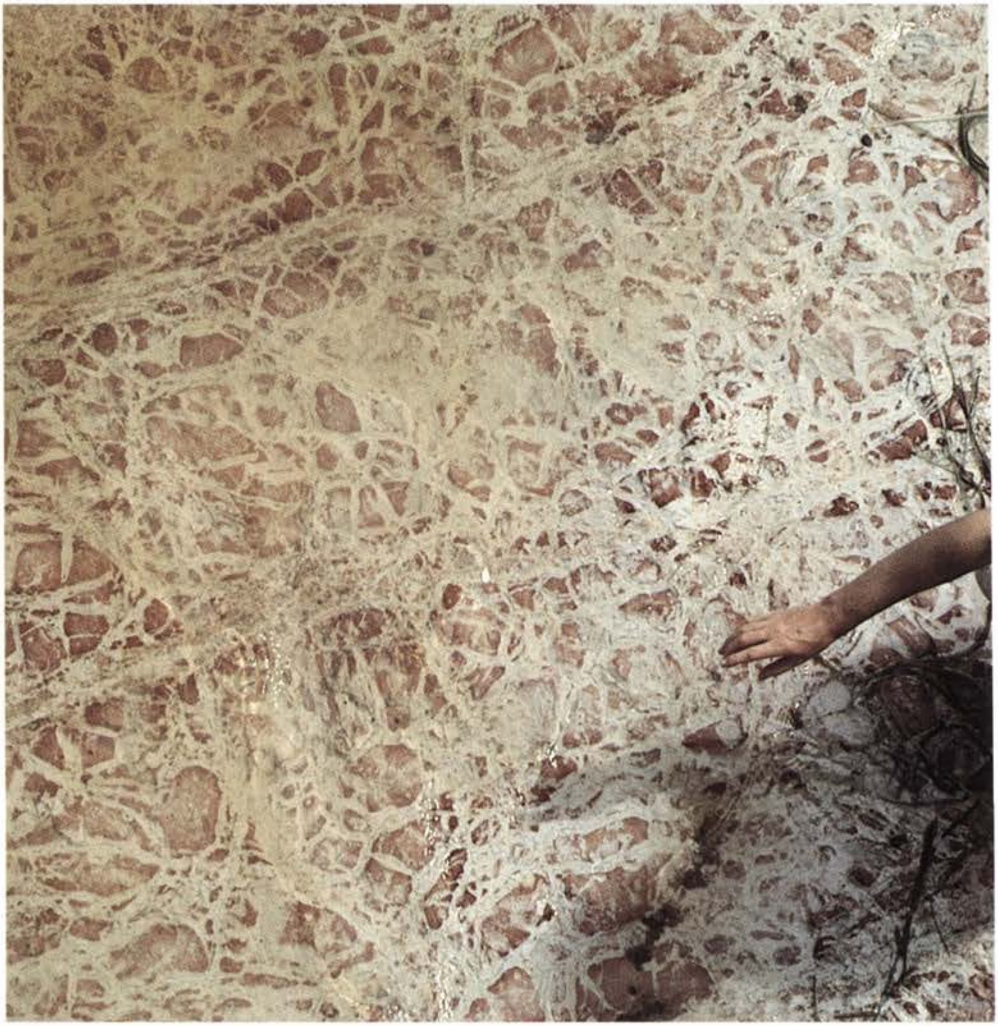
PLATE 7.2

Rendoll developed near Passam in the East Sepik Province. The profile comprises a 50 cm thick A_1 horizon abruptly overlying coral limestone. A detailed description and analytical data are given in Appendix 1.

PLATE 7.4

Hapludoll developed on colluvio-alluvium in slightly undulating terrain along the Upper Ramu River west of Usino. A detailed description and analytical data are given in Appendix 1.

PLATE 8.1

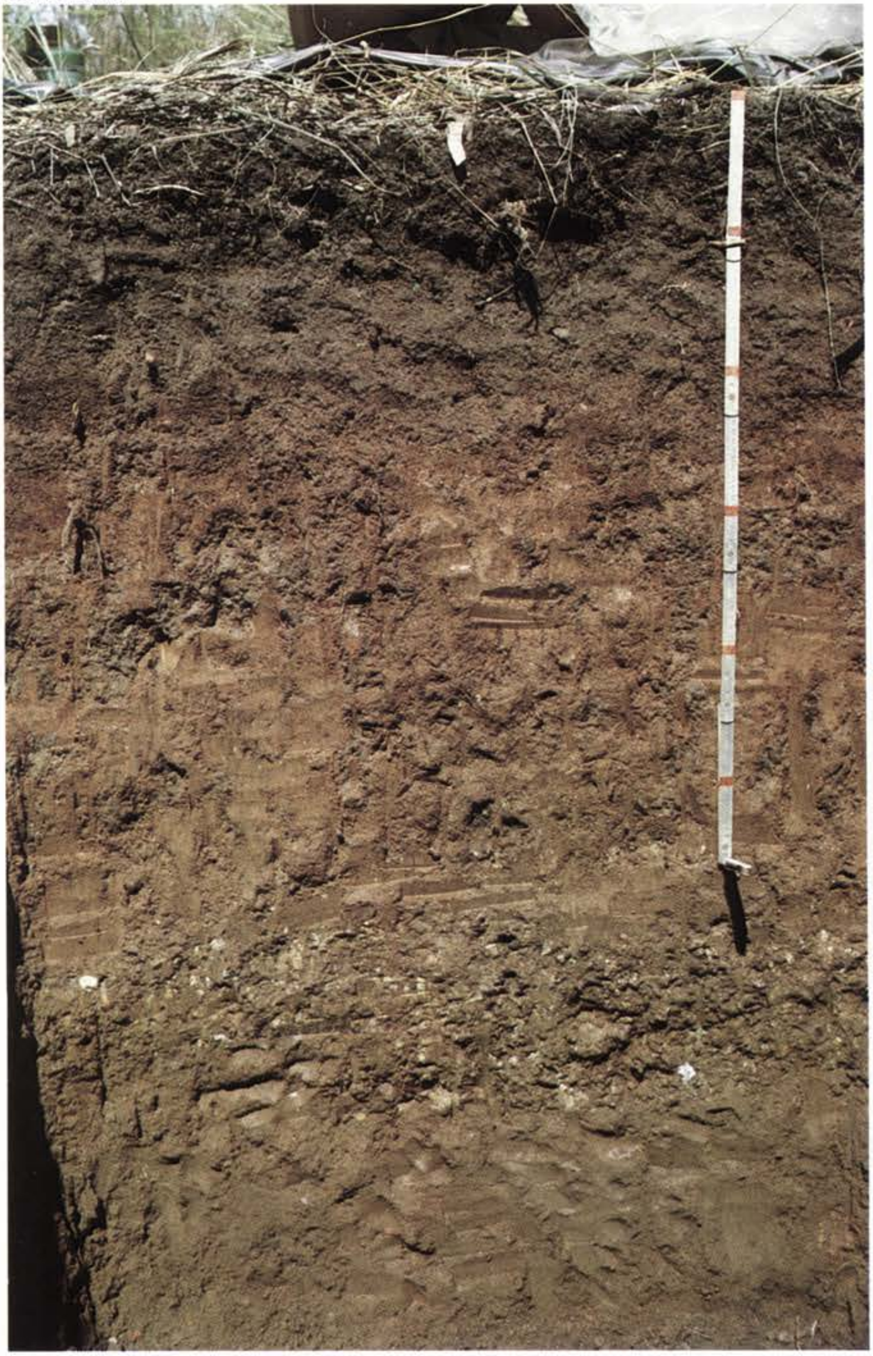


Plinthite occurring as reticulate mottling (red mottles in a grey matrix) in the B_2 horizon of a Plinthaquult developed on deeply weathered Pleistocene sediments near Lake Murray in the Western Province. This iron-rich, humus-poor material composed of clay with quartz and other diluents hardens irreversibly into an ironstone hard pan or irregular aggregates when exposed to repeated wetting and drying (Plate 8.2).

PLATE 8.4

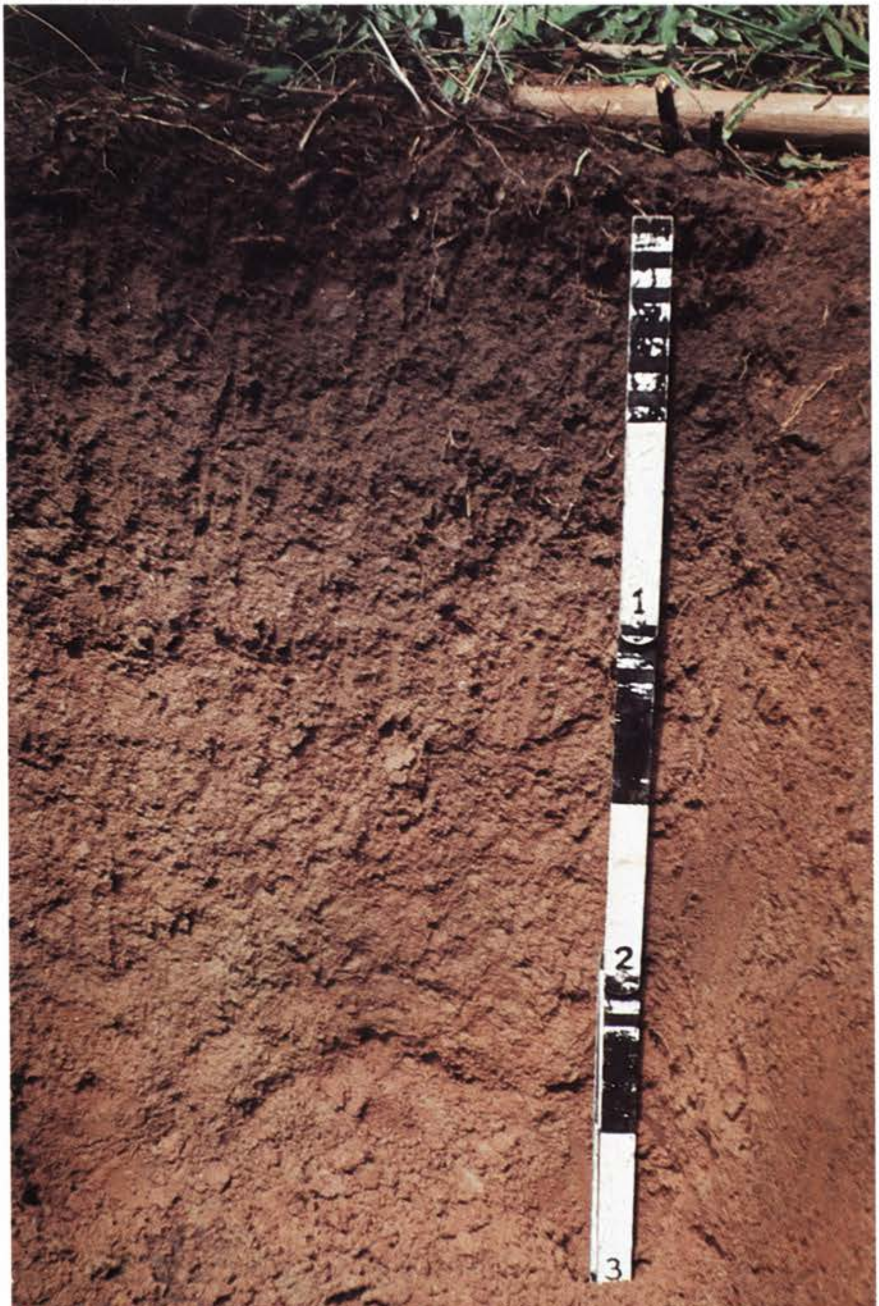
Rhodudalf developed on an uplifted coral terrace dated at 40 000 years BP (Chappell 1973) along the north coast of the Huon Peninsula. Vertical distance along tape is approximately 50 cm. A detailed description and analytical data are given in Appendix 1.

PLATE 8.6



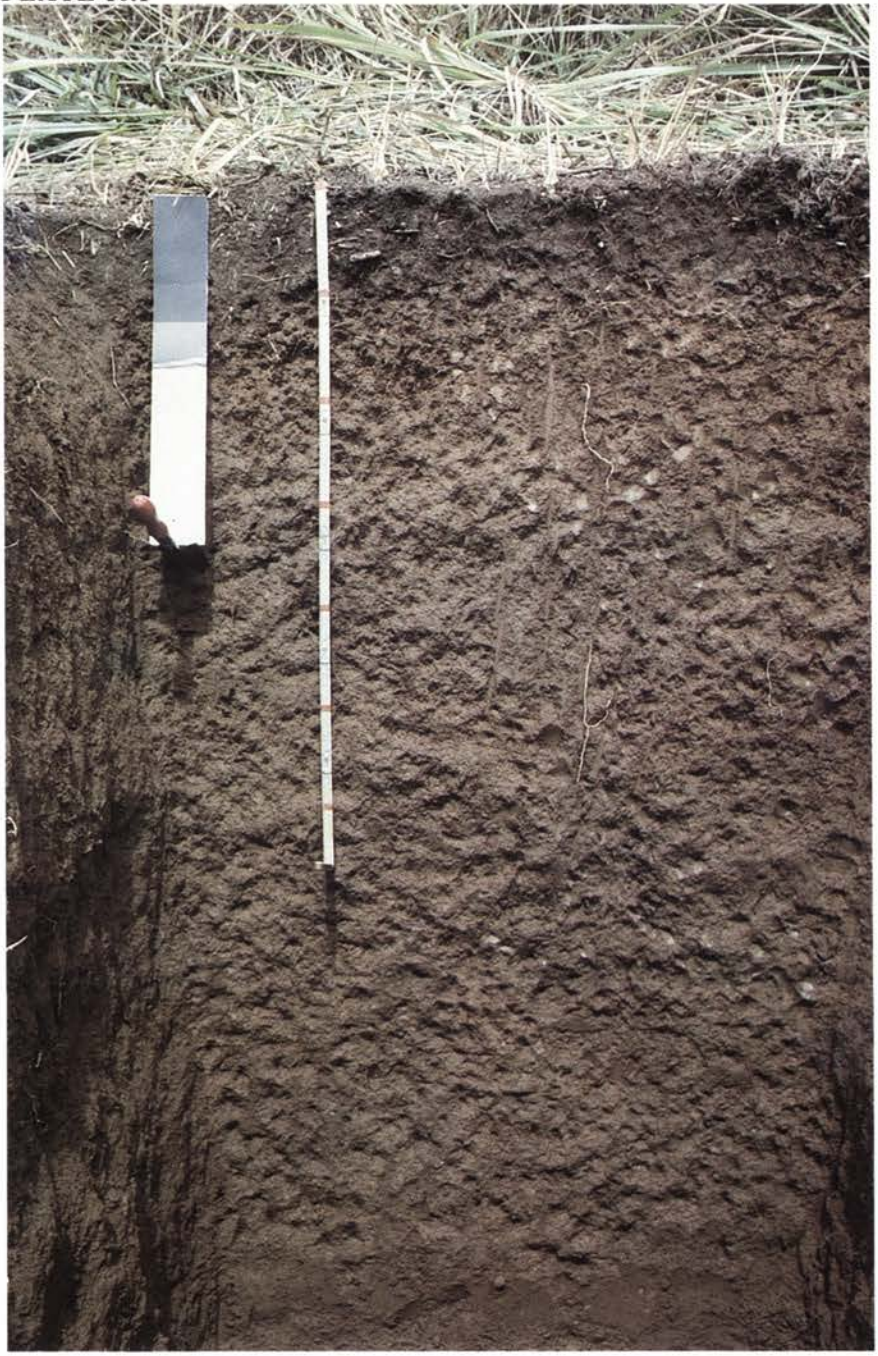
Tropudalf developed on sedimentary rocks on a very gently sloping plain. This profile is located approximately 10 km east of Safia in the Northern Province. The red tape markings indicate 6 in (15 cm) intervals. A detailed description and analytical data are given in Appendix 1.

PLATE 9.3



Tropohumult occurring on a gently sloping ridge with steep side slopes approximately 15 km south-east of Kokoda in the Northern Province. The parent material consists of metamorphic rocks. Annual rainfall 3500 - 4000 mm. Tape measurements are given in 6 in (15 cm) intervals. Detailed description and analytical data are given in Appendix 1.

PLATE 10.1



Acrohumox occurring on a broad crest with a 2-5° slope approximately 50 km north-north-west of Safia in the Northern Province. The parent material consists of fanglomerate derived from Miocene basalt. Annual rainfall 1500-2000 mm. Tape measurements indicate 6 in (15 cm) intervals. Detailed description and analytical data are given in Appendix 1.

Plate 3.4 Aramia River (Western Province) in flood with submerged levees, planted bamboo (feathery) and grassland swamp. This is a typical environment for the Hydraquents.

Association

Hydraquents are closely associated with Tropofibrists, Tropohemists and Troposaprists (organic or peaty soils). In better drained positions they grade into Fluvaquents and Tropofluvents. This association is shown in Figures 3.2 and 3.4 along with their relationship to Hydraquents, and to vegetation, landform, and present land use.

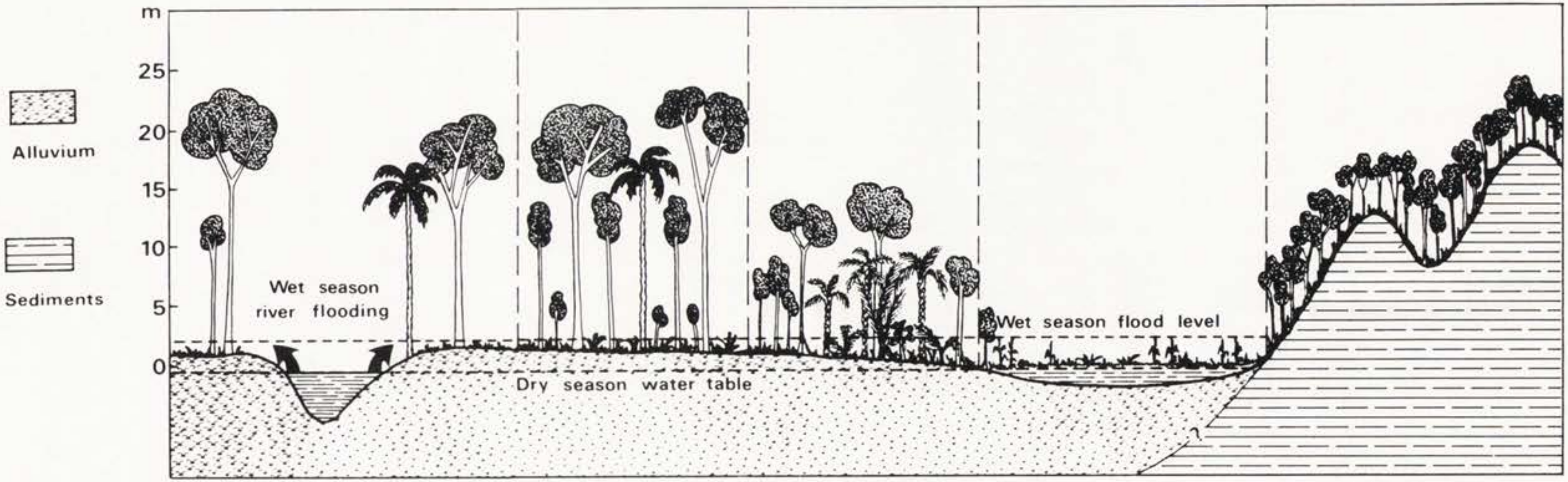
Fertility

Limited data from seven samples indicate a moderate to high fertility level. Cation exchange capacities, total exchangeable bases and base saturation are generally all high. Nitrogen and potassium values range between moderate and high while available phosphorus values from five samples vary between low and very high.

Land Use

Like the Sulfaquents, Hydraquents may have some potential for floating rice cultivation. Land reclamation for agriculture is only possible by expensive large scale projects which are uneconomic at present. Sago (*Metroxylon* spp.) (Plates 3.5 and 3.6), however, is an important food crop grown on these soils and if cultivated more extensively and intensively by using selected varieties,

Fig. 3.4 Schematic cross-section through freshwater environment including hilly terrain



	Levee and river / Floodplain	Backplain	Back swamp	Hills (on sedimentary rocks)
Landform	Levee and river; Floodplain	Backplain	Back swamp	Hills (on sedimentary rocks)
Vegetation	Tall, rather open alluvial forest (easy to walk through)	Poor alluvial forest, common sago and rattan; dense undergrowth	Herbaceous or phragmites swamps	Lowland hill forest
Soils	Tropofluvents Well to imperfectly drained stratified alluvial soils; olive brown or yellowish brown with possibly some mottling in subsoil (C horizon); textures mainly silty to fine sandy; weakly acid to neutral; commonly thin, weakly developed A_1 horizon; occasional wet season flooding for short periods	Fluvaquents Tropaquents Poorly to very poorly drained alluvial soils; stratification less obvious; strong gleying in subsoil, brownish mottling in topsoil; textures medium to fine; weakly acid to neutral Well suited for wetland rice cultivation. At present used mainly for sago collecting, hunting and gathering	Hydraquents Tropofibrist Swampy alluvial or peat soils; grey soils permanently waterlogged and 'soft' underfoot; mainly fine textured with thin interbedded peat layers or thick mainly poorly decomposed peats; weakly acid to neutral; peat soils often acid	Eutropepts and Dystropepts Well drained slightly to moderately weathered soils with brown or yellowish brown B horizons (cambric horizons); acid to neutral; thick dark topsoils may be present or absent
Present and/or potential land use	Well suited for arable cropping and if subject to short flooding only, also tree crops. At present occasionally used for gardening, hunting and fishing		Limited to deepwater rice cultivation and fish farming	Gentle to moderate slopes suitable for tree crops and to a lesser extent also arable crops. Present land use: gardening, hunting and gathering

Plate 3.5 Sago palms (*Metroxylon* spp.) in swampy patch of rainforest 3 km east of Malalaua (Gulf Province). This is a typical environment for Hydraquents, Fluvaquents and various Histosols (organic soils).

has a cash crop potential. Sago cultivation has also been proposed as a possible source of power alcohol in Papua New Guinea (Holmes and Newcombe 1980). It has been conservatively estimated that there are at least 300 000 ha of harvestable sago (Newcombe 1979).

FLUVAQUENTS (INCLUDING TROPAQUENTS)

Morphology

Tropaquents are discussed along with the Fluvaquents as they are indistinguishable without analytical data. Fluvaquents by definition have an organic carbon content that decreases irregularly with depth or remains above 0.2 per cent to a depth of 125 cm. Tropaquents do not have to fulfil this requirement but are simply Aquents found in areas where the mean soil temperature difference between 'summer' and 'winter' is less than 5°C. Both have stratified alluvial layers, mostly of variable texture, deposited by river flooding. However, unlike the Hydraquents their lower water content makes them firmer

Plate 3.6 Hollowing out the pith of a sago palm to obtain sago starch. Sago is the major subsistence crop in poorly drained lowland areas.

to walk on. They are generally poorly to very poorly drained but their water tables are below the surface during most of the year. Strong gleying is evident in these soils but fluctuations of the water table also result in the presence of brown or yellowish brown mottles in the topsoil or throughout the soil, which has a grey matrix. The soil reaction varies between strongly acid and alkaline which is most commonly related to whether the profile is found in a fresh, brackish or saltwater environment. Plate 3.7 (colour section) shows a Fluvaquent developed on volcanic derived alluvium (approximately 20 km north-east of Popondetta, Northern Province) for which a detailed description with analytical data is given in Appendix 1. Fluvaquents were previously referred to as alluvial soils, young alluvial soils and recent alluvial soils.

Genesis
Like the Sulfaquents and Hydraquents the profile genesis of these soils is almost entirely due to sedimentary depositions but is possibly modified by organic matter.

Improved drainage conditions in comparison to the Hydraquents are the result of a process called 'soil ripening' (Pons and Zonneveld 1965) which is restricted mainly to fine textured soils and may take place under natural conditions. Soil ripening can be caused by sediment build up, decreased flooding or by a relative land movement resulting from a regression of the sea or tectonic uplift. As a result, draining and evaporation of excess water takes place. This is greatly enhanced by the suction of penetrating plant roots and causes the loss of part of the organic matter by oxidation. The process leads to consolidation and subsidence of the soil increasing its bearing strength. The soil thus gradually becomes better suited for a greater variety of plants which in turn are more efficient in regulating the drainage and moisture regime. Oxidation of the ferrous iron compounds to ferric forms results in the development of brown mottling in the soil, which in the Fluvaquents is related to seasonal fluctuations in the depth of the groundwater table.

Occurrence
Fluvaquents and Tropaquents are, together with the Hydraquents, very common on floodplains, low terraces and weakly developed, low levees of major rivers, such as the Sepik, Fly and Purari Rivers (Figure 3.3). They also occur extensively, together with the Tropofluvents, on the more stable alluvial plains.

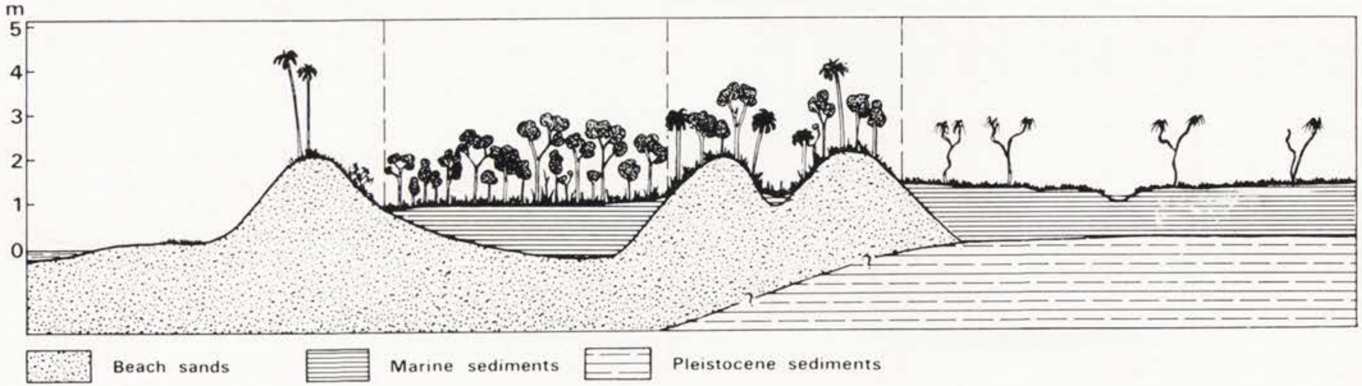
Associations
These soils occur almost always with Hydraquents and Tropofibrists, Tropohemists and Troposaprists in the backswamps, while on well developed levees, terraces and better drained, stable alluvial plains they may grade into Tropofluvents. Figures 3.4 and 3.5 show the relationship of these soils with landform and vegetation and their association with other soils.

Fertility
The analytical parameters used for assessing chemical fertility are given in Table 3.1. Table 3.2 lists the data of twenty-five soil profiles* giving number of samples and percentages for both topsoils (0-50 cm) and subsoils (50-120 cm). Where analytical data for more than one sample were available from

* It should be mentioned that, unless stated otherwise, this information is restricted to analyses obtained from areas surveyed by CSIRO and may thus not be representative of Papua New Guinea as a whole.

Fig. 3.5 Schematic cross-section through a coastal plain, Western Province

Landform	Beach and present beach ridge	Non-tidal flats; flooded in wet season	Inland beach ridges and swales	Plain with semi-permanent swamps; wet season flooding
Vegetation	Bare and mixed herbaceous vegetation, beach ridge commonly planted to coconuts	Littoral forest and woodland	Littoral forest and woodland (often converted to coconuts), grassland with sedges in swales	Low grassland with scattered pandanus trees



Soils	Tropopsamments and Psammaquents	Fluvaquents, Tropaquents and Pelluderts	Rendolls and Eutropepts on ridges; Tropaquepts in swales	Fluvaquents, Tropaquents, Pelluderts and Plinthaqualfs
	Alkaline sandy soils without any profile development. Wet and poorly drained in flat low lying areas. Well drained on ridges	Silty clay soils containing on sea side shell fragments in topsoil and inland calcium carbonates in subsoil. Cracks up to 50 cm deep and very hard surface in dry season; neutral over alkaline or weakly acid over alkaline further inland; very poorly drained	Ridges: sandy soils commonly with dark topsoils and calcareous cemented subsoils with concretions and shell fragments; alkaline; well drained swales; silty clays overlying beach sand at variable depth; neutral or alkaline; poorly drained	Clay soils, decalcified particularly on rises and furthest inland; locally sandy clay loam topsoil, bleached A_2 horizon and pronounced grey and red mottled subsoil; acid to weakly acid over neutral to alkaline; cracking in dry season and very hard surface layer; very poorly drained

Table 3.1
Analytical parameters used for assessment of chemical fertility

Fertility Class	Total N (% Kjeldahl)	Available P (ppm Truog)	Exchangeable K	Cation exchange capacity (meq/100 g – NH_4OAc)	Total exchangeable bases	Base saturation (%)
High (H)	>0.50	>50	>0.6	>25	>15	>60
Moderate (M)	0.10-0.50	10-50	0.2-0.6	6-25	3-15	20-60
Low (L)	<0.10	<10	<0.2	<6	<3	<20

Table 3.2
Chemical fertility data – Fluvaquents (25 soils)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	—	—	12	57	8	47	17	68	6	30	21	84	14	70	18	72	15	75	12	48	14	70
Moderate	24	96	7	33	6	35	7	28	10	50	4	16	6	30	7	28	5	25	11	44	6	30
Low	1	4	2	10	3	18	1	4	4	20	—	0	—	0	—	0	—	0	2	8	—	0
Total samples and percentage	25	100	21	100	17	100	25	100	20	100	25	100	20	100	25	100	20	100	25	100	20	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

topsoil or subsoil the mean value is given in the table. Available phosphorus data are less common than the other parameters because in many instances analyses of total phosphorus only were carried out.

The table indicates overall moderate nitrogen contents. Available phosphorus and exchangeable potassium contents in more than 80 per cent of the samples from both topsoil and subsoil vary between high and moderate, high values being more common in the topsoils. Cation exchange capacity (CEC) and total exchangeable bases (TEB) in more than 70 per cent of the samples have high values while base saturation (BS) figures vary between high and moderate. In general the Fluvaquents may be assessed as having a high to moderate fertility.

Clay mineral data (DTA analyses) from seven sites located in the Wewak-Lower Sepik and Ramu-Madang survey areas show montmorillonite and montmorillonite plus illite to be the dominant clay minerals with minor contents of hydrous iron oxide (Bleeker and Healy 1980).

Land Use

Serious flood hazards causing deposition of material and/or scouring of the land surface (Plates 3.8 and 3.9) together with poor drainage greatly reduce the suitability of the soils for agriculture. Land reclamation would involve high capital investment. Limited grazing and wetland rice cultivation appear to offer some possibilities in selected areas. Since areas with seasonal climates are

Plate 3.8 Close-up of silty material deposited by flooding and eroded subsequently by rain. The steep sided raised parts are protected by leaves.

Plate 3.9 *Melaleuca* tree with adventitious roots up to 120 cm high around its trunk. These presumably indicate the height of wet season flooding. Also shown are the scouring around its base and on the land surface in the background.

favourable for mechanical rice cultivation, the coastal plain of the Western Province would appear to be suitable for this purpose. Soils occurring here are very similar to those found near Merauke, Irian Jaya, which have been cultivated for rice during many years (Reijnders 1961; Schroo 1961, 1964). Because the results of the rice experiments may be applicable to Papua New Guinea a brief outline will be given in this section.

An experimental pilot scheme comprising two polders, each measuring 100 ha, was started west of the Koembe River in 1955. Each polder was characterised by one of the following major soil types occuring in the area: (1) decalcified marine silty clays (Fluvaquents or Tropaquents) derived from young marine deposits, and (2) very leached, decalcified quartzitic soils with loamy sand, sandy loam or silt loam topsoils and clayey, mottled subsoils (Plinthaquults). The extremely low fertility of these soils makes them unsuitable for cropping and their unsuccessful use for mechanical rice cultivation is discussed in the land use section of the Plinthaquults.

Rice cultivation on the partly decalcified marine silty clays occurring in the second polder has been more successful. This soil consists of a dark grey, rusty mottled silty clay A_1 horizon with a high organic matter content merging into a light grey, yellowish-stained, stiff clay which has proved to be somewhat toxic to wetland rice when ploughed to the surface. The topsoil, according to Schroo (1964), has a CEC of 33 meq/100 grams clay and a BS of 52 per cent. It becomes very hard and shrinks when dried, the clay fraction consisting of

30 per cent montmorillonite, 50 per cent (swelling) illite, 15 per cent kaolinite and 5 per cent quartzite. In accordance with slight undulations of the terrain, the decalcification of the surface soil and the formation of gypsum ($CaSO_4.2H_2O$) in the subsoil is more advanced in the rises than depressions. Outside the polder the depressions also contained harmful concentrations of chloride and magnesia during the wet season. These results are very similar to those obtained by Reijnders (1961) in the neighbouring Maro-Koembe area, in which he also comments on the 'fairly high' concentrations of sulphates (600-1000 ppm) throughout soils developed on the most recently deposited marine clays.

Later studies of the partly decalcified silty clay soils in a nearby area by van Es and van Schuylenborg (1967) have shown that their profile is in an initial stage of soil formation which will finally lead to the formation of a Natraqualf. Studies of the cation exchange characteristics and the soil solution indicated that the Ca ions are removed more intensively from the surface horizon than Mg ions which give rise to high, and possibly harmful magnesium concentrations. Before being cultivated, similar research work will have to be carried out on the coastal plain soils in the Western Province which are likely to have closely analogous characteristics.

Specific tree crops adaptable to the environment, such as sago and rattan, could probably be commercially cultivated. Local land use is at present limited to sago collecting, hunting and gathering.

PSAMMAQUENTS

Morphology

These are very poorly drained or swampy soils characterised by sandy textures and features related to wetness. They have high water tables which vary from slightly above to slightly below the surface during most of the year. Owing to their sandy nature gleying and mottling are generally much less pronounced than in the finer textured Fluvaquents. Psammaquents commonly show a slight darkening caused by organic matter in the A horizon which merges gradually into undifferentiated, structureless sand. The soil reaction varies between weakly acid and alkaline. Soils having thin salt crusts have been observed in areas with a high seasonality. Psammaquents were previously called beach soils and coarse textured alluvial soils.

Genesis

Except for the solution of some of the calcium carbonate present in the soil as shell fragments or derived from carbonate rich parent materials and possible formation of a thin A_1 horizon these soils have been subject to little pedogenesis. They are almost entirely confined to sandy deposits accumulated by wave and wind action along the coast.

Occurrence
Psammaquents are relatively rare in Papua New Guinea, their occurrence being limited to swales between beach ridges and degraded beach plains.They have also been found on drowned beach ridges in the mangrove zone behind the coastline and at the base of coarse textured alluvial fans in the Markham Valley.

Association
Psammaquents are most commonly associated with their better drained counterparts the Tropopsamments, also found on beach ridges.

Fertility
No data are available on these soils but the fertility is expected to be mostly low owing to their sandy textures and low organic matter content.

Land Use
Flooding, high water tables and the apparent low fertility of these soils render them unsuitable for agriculture. In areas of high population they are commonly used for sago collecting.

TROPOPSAMMENTS

Morphology
Tropopsamments are the well drained counterparts of the Psammaquents occurring in humid tropical areas. They usually have water tables below 50 cm depth and comprise thick, poorly graded, sands containing shell fragments and moderate amounts of weatherable materials. Their water holding capacity is very low. Tropopsamments commonly have a thin dark topsoil, particularly on the older more stabilised land surfaces. Their soil reaction varies between weakly acid to alkaline depending on their distance from the coast. Tropopsamments were previously called beach soils and coarse textured alluvial soils.

Genesis
As with Psammaquents, except for the possible formation of a thin A_1 horizon and some decalcification in soils containing calcium carbonate they have been subject to little pedogenesis.

Occurrence
Tropopsamments are mostly confined to beach ridges and degraded beach plains found along the coast, but they are also found on sandstones, coarse fan deposits (e.g. Markham Valley) or floodplain deposits of fast flowing rivers.

Association
These soils are closely associated with the Psammaquents found in poorly drained swales, while inland on older beach ridges they often grade into Rendolls and Eutropepts. Figures 3.2 and 3.5 show a cross-section of the coastal environment illustrating this association and the relationship of these soils with landform and vegetation.

Fertility
No data are available for these soils but the fertility is expected to be mostly low and almost entirely dependent on the organic matter content of the surface horizon.

Land Use
Being coarse textured, well drained and well aerated, these soils are excellently suited to coconut cultivation particularly close to the coast where water tables are kept in continuous movement by tidal influence. The expected low fertility limits arable cropping which can however be increased by green manuring. Present land use is mostly confined to coconut groves and gardening on beach ridges in coastal areas.

TROPOFLUVENTS

Morphology
These soils are the well to imperfectly drained counterparts of the Fluvaquents. Like them their organic carbon content must decrease irregularly with depth or remain above 0.2 per cent to a depth of 125 cm. Young alluvial soils that do not fulfil this requirement are, by definition, classified as Troporthents. Lack of sufficient analytical data has made it difficult to apply these criteria in Papua New Guinea. Therefore most well drained alluvial soils with little or no profile development are considered to belong to the Tropofluvents while the Troporthents are, with few exceptions, confined to recent erosional surfaces. It should be noted that some of the soils found in areas with a strong seasonal climate could also belong to the Ustifluvents but, as yet, these have not been positively identified.

Tropofluvents are stratified soils with marked texture variations. Their dominant form is a weakly developed (very) dark greyish brown or brown A_1 horizon merging into a (light) olive brown, yellowish brown or greyish brown, structureless C horizon. Mottling and/or gleying may be fairly common in the deep subsoil below 50 cm depth. Their soil reaction varies between weakly acid and alkaline, most soils being within the weakly acid to neutral (pH 5.6-7.5) range. pH values show a tendency to increase with depth or, alternatively, remain constant. Tropofluvents are commonly found under tall, open forest. Plate 3.10 (colour section) shows a typical example of a Tropofluvent developed on floodplain deposits. Tropofluvents were previously referred to as alluvial soils, young alluvial soils, recent alluvial soils and moderately well drained alluvial soils.

Genesis

The formation of Tropofluvents is very similar to that of the previously described Fluvaquents. Improved drainage conditions, reflected in a general lowering of the groundwater table, have resulted in the oxidation of iron compounds in the soil as evidenced by the brownish colours. Tropofluvents are the most developed of the Entisols so far described.

Occurrence

Tropofluvents occur most commonly on stable alluvial plains, levees and terraces along rivers, particularly in the Central, Northern and Madang Provinces (Figure 3.6).

Association

They are closely related to the Fluvaquents, Hapludolls and Halplaquolls. Figure 3.4 shows their relationship with landform and vegetation and their association with other soils.

Fertility

Table 3.3 lists the chemical fertility data for twenty-five Tropofluvents. Data show dominantly high CEC, TEB and BS values while both nitrogen and potassium contents are mostly moderate. Data on available phosphorus, although restricted, show marked variations, with actual values ranging between 0 and 580 ppm. These strong variations remain unexplained and do not appear to be related to organic matter content as might be expected. The 'real' exchangeable potassium values also range widely, 0.13-6.25 meq/100 g, but these strong variations are thought to be related to the parent material from which the alluvium has been derived. For instance, high values can be expected in alluvium derived from rocks rich in biotite, muscovite or orthoclase.

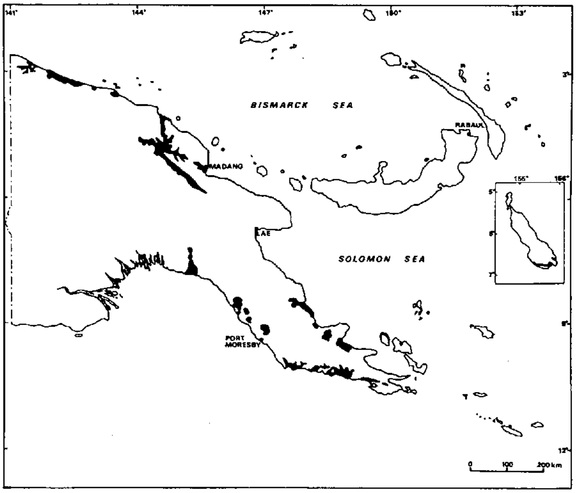


Fig. 3.6 Major distribution of the poorly to well drained alluvium characterised by Tropaquents, Tropofluvents and Hapludolls

Table 3.3
Chemical fertility data – Tropofluvents (25 soils)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	5	20	5	36	3	30	7	28	1	6	17	68	8	50	21	84	11	69	17	68	12	75
Moderate	19	76	4	28	4	40	16	64	10	63	8	32	8	50	4	16	4	25	7	28	3	19
Low	1	4	5	36	3	30	2	8	5	31	—	—	—	—	—	—	1	6	1	4	1	6
Total samples and percentage	25	100	14	100	10	100	25	100	16	100	25	100	16	100	25	100	16	100	25	100	16	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

Clay mineral data (DTA analyses) from four subsoils (C horizons) indicate that montmorillonite, or montmorillonite with illite or kaolinite (in a highland valley) are dominant with minor contents of hydrous iron oxides and/or gibbsite.

Land Use

Being relatively well drained soils subject to little or no flooding, and generally of moderate to high fertility, Tropofluvents are ideally suited to agriculture and offer excellent prospects for the more soil selective arable and tree crops such as maize, cocoa or lowland coffee. As yet, little of this land is used for farming by the local population.

TROPORTHENTS, CRYORTHENTS and USTORTHENTS

Morphology

The soils belonging to these three great groups in Papua New Guinea are all very shallow and lack diagnostic horizons. Typically found on erosional surfaces they have either heavily truncated profiles or bare rock at very shallow depth. However, they sometimes occur on coarse textured, gravelly or stony, depositional surfaces such as floodplains and fans (Plate 3.11).

Their subdivision criteria are based entirely on differences in climate regimes. The Cryorthents, typically of the highest mountains (Plate 3.12), have characteristically cold climates with mean annual soil temperatures of 8°C or less. The Troporthents, on the other hand, occurring in the humid climates with a more or less evenly distributed rainfall, require mean annual soil temperatures of more than 8°C with mean annual 'summer' and 'winter' soil temperatures differing by less than 5°C, whereas Ustorthents are typical of relatively dry, strongly seasonal climates where part of the soil dries out for at least 90 days in most years.

Cryorthents mostly comprise thin (less than 10 cm), dark, acid to weakly acid surface horizons with high organic matter content and abruptly overlying rock. Above 4300 m, however, where there is no vegetation, they consist of thin layers of unconsolidated material overlying rock. Ustorthents normally consist of black, dark grey or greyish brown, sandy loam to clay A_1 horizons, up to 15 cm thick, changing abruptly or gradually into parent rock. They have a neutral to alkaline reaction. Troporthents are by far the most common of these three great soil groups and have thin dark, or thick lighter coloured surface horizons grading into rock or coarse textured unconsolidated material (Plate 3.13, colour section). They are mostly weakly acid to neutral. All three great groups were referred to previously as lithosols, skeletal soils and outcrops, and slope soils.

Genesis

Except for slight weathering of the underlying rocks and the possible incorporation of organic matter and the formation of soil structure in the surface horizon, the profile development of these soils is minimal.

Plate 3.11 Maze of flood channels of Markham River (near Kaiapit) comprising coarse textured gravels and sandy deposits. At its widest point the river is about 1.2 km.

Plate 3.12 Cryorthents (mostly Lithosols) and bare rock exposures on the summit and steep side slopes of Mount Wilhelm, the highest mountain of Papua New Guinea (4509 m).

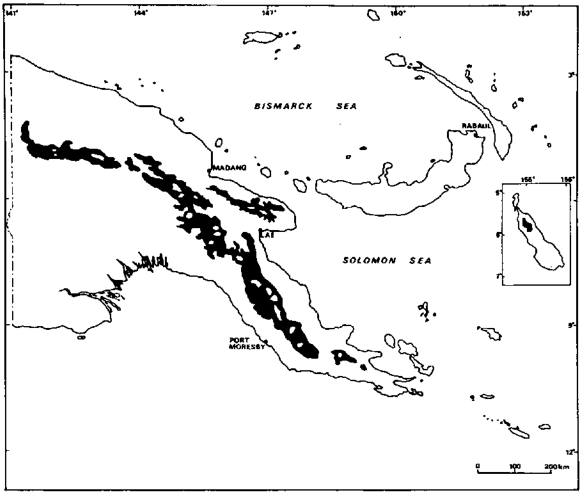


Fig. 3.7 Major distribution of Troporthents and Humitropepts

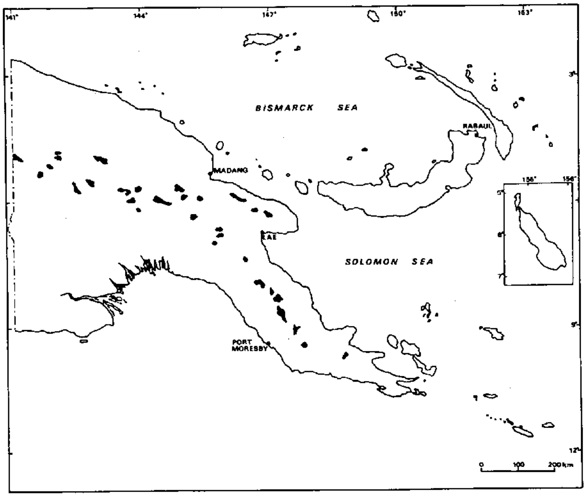


Fig. 3.8 Major distribution of Cryorthents and Cryofolists

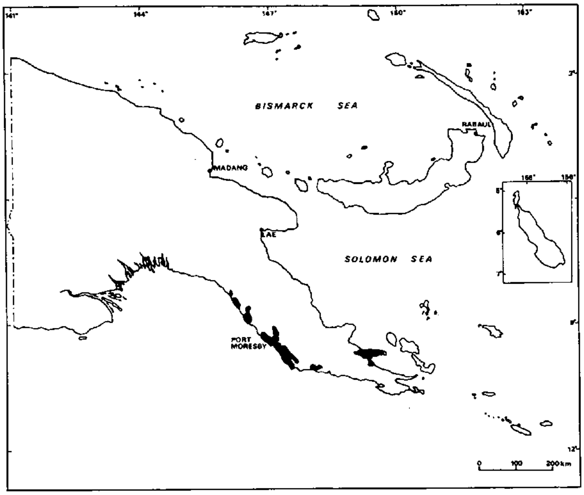
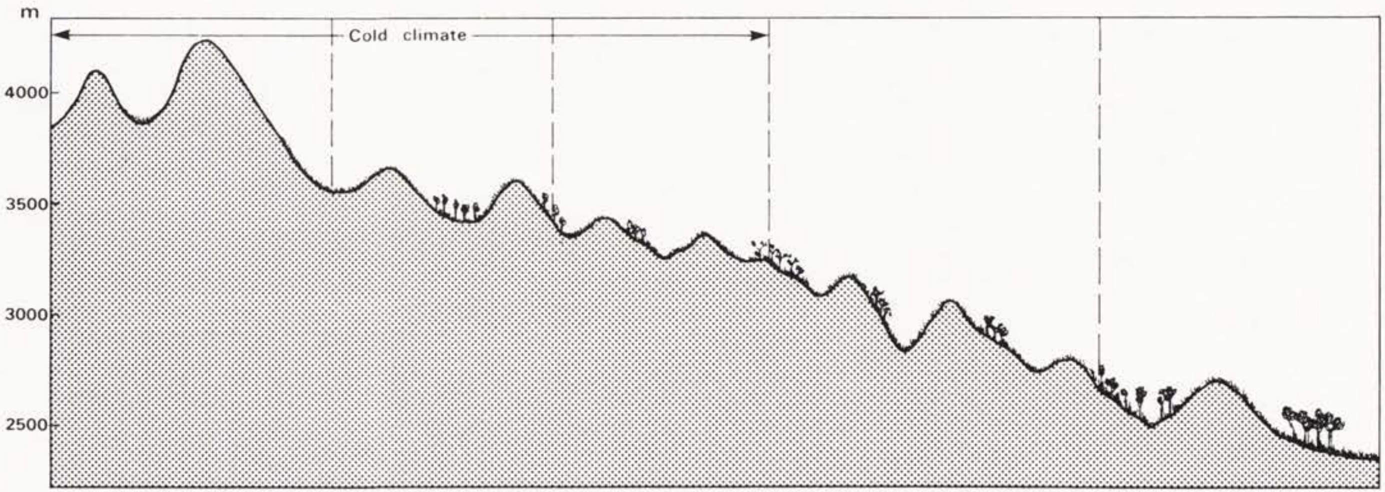


Fig. 3.9 Major distribution of Ustorthents and Eutropepts

Fig. 3.10 Schematic cross-section through high mountains

Landform	Mainly steep to precipitous slopes	Ridges with moderate slopes		Moderately to steeply sloping terrain below 3000 m	Long gentle to moderate slopes of extinct volcanoes
Vegetation	Above 4300 m bare rock, herbs and ferns; below 4300 m grassland	Alpine grassland with occasional patches of subalpine scrub and forest		Alpine grassland with patches of scrub and montane forest	



Soils	Cryorthents, Cryohemist, Cryfolist and Cryofibrist	Cryaquepts and Cryofolist	Cryumbrepts and Cryochrepts	Troporthents and Humitropepts	Hydrandepts
	Above 4300 m mainly rock outcrop and very shallow soils; below 4300 m mainly peat soils overlying rock or rubble	Poorly drained soils with gleyed B horizons and thick acid topsoils high in organic matter. Peat soils overlying rock or rubble	Imperfectly to well drained soils with yellowish brown B horizons with or without thick dark topsoils	Shallow soils with thin dark or thick lighter coloured surface horizons; well to imperfectly drained soils with yellowish brown B horizons and high organic matter contents	Continuously wet brown to strong brown soils with fine textured B horizons and thick dark topsoils rich in organic matter
Land use	Hunting			Hunting and gathering	Hunting and gathering; extensive cultivation below 2500 m

Occurrence

Troporthents occur from almost sea level to approximately 3400 m in steeply sloping mountainous or hilly terrain and occasionally also on fan and flood-plain deposits. However, they are commonest between 2700 and 3400 m (Figure 3.7). Cryorthents are most numerous in areas above 3400 m* where soil formation is minimal (Figure 3.8), while Ustorthents (Figure 3.9) are very common in areas with pronounced seasonal climates having a low rainfall and where soil erosion outstrips soil formation.

Association

Troporthents are associated with the more developed Humitropepts; Cryorthents mostly with peaty soils such as the Cryofolist. Figure 3.10 is a schematic cross-section of the high mountains showing these associations as well as landform and vegetation relationships. Ustorthents are mostly associated with Ustropepts and Pellusterts.

Fertility

Data from a few profiles belonging to the Troporthents indicate a moderate to high chemical fertility level.

Land Use

These soils are unsuitable for agriculture but some grazing may be possible in the lowlands and at lower altitudes in the highlands. Some pyrethrum is grown on the deeper Troporthents between 1800 and 2700 m, although present land use is mainly confined to hunting and gathering.

* Humphreys (pers. comm. 1982) considers that the 3600 m altitude boundary is the best estimate for the 8°C soil isotherm.

4 Histosols

Histosols are characterised by a strong accumulation of organic matter which gives rise to very dark brown, dark brown or black horizons occurring at or close to the surface. They are nearly always saturated with water for most of the year and, by definition, must contain at least 12-18 per cent organic carbon depending on the clay content of the mineral fraction and kind of underlying material. In general the organic horizons must have a combined thickness of at least 40 cm, unless immediately overlying parent material, when they may be thinner.

The division of the Histosols into suborders is largely based on the degree of decomposition of the organic matter. Hence, *Fibrists* contain slightly decomposed, *Hemists* half decomposed, and *Saprists* highly decomposed organic matter. Where soils contain various admixtures of little, half, or highly decomposed horizons they are classified according to the dominant material. The fourth suborder of the Histosols, the *Folists*, are defined as having better, relatively freely, drained conditions. They consist primarily of organic horizons resting directly on rock, or fragmented gravel, or stones or boulders such as morainic materials. These Histosols suborders are all found in Papua New Guinea under climate regimes ranging from cold upper montane humid to the warm lowland humid.

CRYOFOLISTS, CRYOHEMISTS and CRYOFIBRISTS

Morphology

These are typically zonal* soils being found in mountains above 3400 m with characteristically low mean annual temperatures (8°C or less). They commonly have 40-80 cm thick, black, dark reddish brown, very dark brown or very dark grey organic or peaty horizons. These in turn directly overlie consolidated or unconsolidated rocks or, less commonly, grade into a weakly developed thin B horizon. Their soil reaction varies from weakly to strongly acid. Cryofolists (Plate 4.1) are more or less freely drained soils occurring on gently to steeply

* Zonal referring to vertical zonality.

Plate 4.1 Soil exposure showing Cryofolists and Cryorthents on a river terrace on the western flank of Mount Giluwe. Two buried soil profiles dated 1800 and 1400 years BP are also present, the lower one being pointed at in the photograph.

sloping terrain covered by alpine grassland and herbs, or mossy forest (Plate 4.2). Cryohemists and Cryofibrists are the poorly drained to swampy counterparts of the Cryofolists, and are found mainly in flatter terrain and in drainage depressions under sedge grassland (Plate 4.3). These soils were formerly called alpine peat and humus soils, and bog soils.

Genesis

Because of the relatively cool climate the chemical weathering of the mineral fraction is at a minimum and the formation of these soils is largely determined by a build up of organic matter which cannot be broken down sufficiently by soil organisms. At high altitudes in tropical areas the soil organisms responsible for mineralisation are mainly fungi which, according to Mohr *et al.* (1972) are relatively inactive under the prevailing low temperatures, and thus allow the organic matter to accumulate. It is interesting to note, however, that some soil formation has been reported by both Hope (unpublished data) and Rutherford (1964) from these areas. Hope (unpublished data) noted slight increases in clay content with depth in mineral horizons of Cryofolists found on Mount Giluwe and Mount Albert Edward, while analyses of similar soils collected from summit areas of Mount Giluwe by Rutherford (1964) showed a pronounced increase in organic matter content with depth, suggesting that some humus illuviation may have taken place. Although considered unlikely by Rutherford

Plate 4.2 Mossy forest on Mount Wilhelm, a typical environment for Cryofolists

Plate 4.3 Tarn or depression carved by glacial erosion on Mount Giluwe. These depressions are typically filling up with peat bog vegetation, forming Cryofibrists and Cryohemists.

(1964), admixture by volcanic ash could possibly also explain the increases in clay or organic matter content with depth. As will be discussed in the Hydrandept section (Chapter 5), recent work by Pain and Blong (1979) indicates that young volcanic ash deposits are much more widespread in highland areas than originally thought.

Occurrence

These soils are scattered throughout the wet mountainous terrain between 3400 to more than 4000 m (Figure 3.8). Being typically zonal soils they have a great variety of parent materials and landforms. They are estimated to cover less than 1 per cent of the total land area of Papua New Guinea.

Association

Their main association is with Cryorthents and, to a lesser extent at somewhat lower altitudes, associations also form with Cryaquepts, Cryumbrepts and Cryochrepts. Figure 3.10 shows these soil associations and related landform and vegetation.

Fertility

Very few analytical data are available, but fertility appears to be moderate to high.

Land Use

The prevailing wet, cloudy conditions, occasional light frosts and inaccessibility greatly restrict agricultural activity. Limited grazing is a possibility at the lowest altitudes in the better drained areas but the land is probably best left in its natural state for watershed protection and occasional hunting.

TROPOFIBRISTS, TROPOHEMISTS and TROPOSAPRISTS

Morphology

These soils are found up to 3400 m, but mainly occur in the lowlands, under very poorly drained and swampy conditions. They are very young soils characterised by little or no soil formation. Thick layers of brown to dark brown, raw to well decomposed peat, loamy peat or clayey peat with very low bulk densities, alternating with one or more mineral horizon(s) of variable thickness are most typical. Within one soil profile these peaty horizons often comprise individual layers in various stages of decomposition, the deepest layer commonly being the most decomposed. Soil reaction varies between strongly acid and alkaline with the alkaline soils occurring under mangroves in coastal areas. Most of these soils were previously described as organic soils, peat soils and bog soils with some few as alpine peat and humus soils. An example of a Tropohemist profile is given in Appendix I.

Genesis

Tropofibrists, Tropohemsits and Troposaprists are saturated with water either permanently or during most of the year. This causes a lack of oxygen, militating against the breakdown of organic matter by bacterial activity. Although some mineralisation is caused by anaerobic bacteria this is much less than under dryland conditions and an accumulation of organic matter results. In coastal areas the mangrove vegetation sometimes plays a specific role in the formation of peats, the tree roots forming a dense mat that gives rise to an undecomposed peat layer below the soil surface (Jordan 1963).

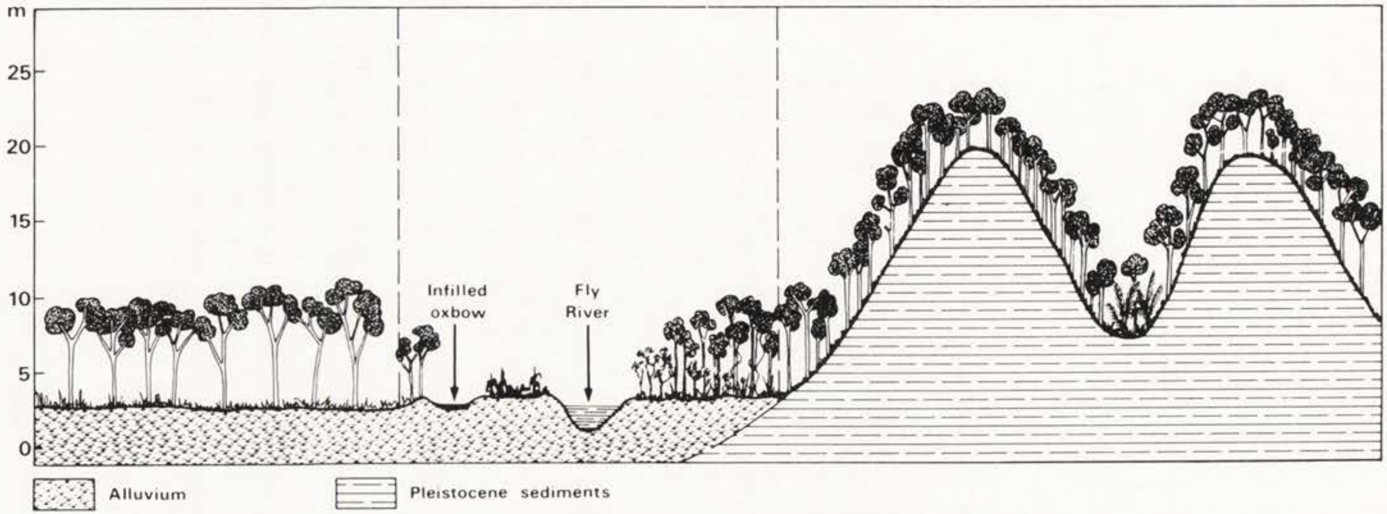
Occurrence

These soils are found most frequently in relatively sheltered positions along river floodplains where little active sedimentary deposition takes place. They are especially common in backplains of major rivers covered by sedge grassland (Plate 4.4), swamp forest, often with *Campnosperma* as the dominant tree, and sago. Other relatively extensive occurrences include mangrove areas dominated by *Rhizophora* and *Bruguiera* spp. They are also found in flat to moderately sloping terrain in the highlands up to 3400 m. Figures 3.1 and 3.3 show the major distribution of these soils in Papua New Guinea.

Plate 4.4 Back plain of the Sepik River covered by swamp grassland. These swamps are subject to deep flooding with little sediment deposition giving rise to mainly Tropohemists (well decomposed black peat soils) but also Tropofibrists and Troposaprists.

Fig. 4.1 Schematic cross-section through floodplains of the Fly River and dissected plateau of the Fly-Digoel shelf

Landform	Backswamps of major rivers	Scroll complexes	Intricate pattern of low rises and narrow valleys (hillslopes 3–15°)
Vegetation	*Melaleuca* swamp savanna, swamp grassland and swamp woodland	Open rainforest climber thicket and tall swamp grassland	Ridges: closed rainforest, locally very dense and thin stemmed. Valleys: sago *Campnosperma* swamp woodland and swamp forest



Soils	Tropofibrist, Tropohemist and Hydraquents	Hydraquents and Fluvaquents	Tropudults and Tropohumults
	Organic soils; alternate layers of raw or partly decomposed peat and mineral horizons weakly acid to acid; swampy alluvial soils; silty clay loams to clays; soft underfoot; weakly acid to neutral; swampy	Alluvial soils; silt loams becoming silty clay loams to silty clays with increasing distance away from river; often soft underfoot; weakly acid to neutral; very poorly drained to swampy	In valleys: Haplaquents and Hydraquents. Ridges: well drained strongly acid soils with loam to sandy clay loam A horizons overlying reddish brown clay to heavy clay B_2 horizons; moderate amounts of iron concretions common; high organic carbon contents throughout the soil locally common. Valleys; very poorly drained to swampy strongly acid alluvial soils.

Association

Closest associated with these soils are the Fluvaquents, Hydraquents and Sulfaquents. Figures 3.2 and 4.1 show the association of these soils with other soils and their relationship with landform and vegetation.

Fertility

Chemical fertility data for these soils are mainly limited to organic carbon and nitrogen determinations of peaty horizons. Their high organic matter content is reflected in the high levels of nitrogen and cation exchange capacities. Values for exchangeable potassium appear mostly moderate but, while limited samples indicate high total phosphorus contents, the available phosphorus levels are mostly low to moderate. The peaty layers of these soils are characterised by high C/N ratios (usually between 20 and 40) indicating a low rate of nitrification.

The chemical and physical properties of five drained Tropofibrists (raw peats overlying clays), which are cultivated for tea, have been investigated by Drover (1973). These soils, located at Olgoboli research station in the Wahgi Valley, are, under natural conditions, covered by *Phragmites* and generally considered to have a high chemical fertility when cleared and drained (Hartley 1967). The data given in Table 4.1 appear to support this, although total nitrogen, and exchangeable potassium and exchangeable magnesium contents are all lower under tea than under *Phragmites* regrowth. According to Drover (1973) this is caused by element losses during the tea harvest, these elements being recycled under regrowth conditions. The marked differences in exchangeable potassium values, however, also appear to indicate that the peat potassium reserves are variable and that deficiencies may occur in the soils under tea after a period of cropping. The relatively low CEC values of the peats are attributed by Drover (1973) to the poorly decomposed state of the plant material in which the exchange sites are not fully developed.

Table 4.2 shows the soil moisture data of the peat layers which are characterised by a high water retaining ability. For comparison, Drover (1973) has included a sample taken from an adjacent, virgin swamp which was under water. A comparison of the moisture contents (at 0.3 and 15 atmospheres) of the surface peats indicates, according to Drover, that clearing and drainage have a considerable effect on reducing the range of water available for uptake by plants. He stresses that when drained, the peat should not be allowed to become air dry, since it does not wet again easily and shows a considerable amount of shrinkage well before the 15 atmospheres moisture content is reached.*

* For instance, the *potential* shrinkage of the virgin soil at 0.1 atm, assuming no air space remains, can be calculated as follows: 826 ml of H_2O is present for each 100 g of solid. Assuming a particle size density of raw peat of 1.25,
the volume equals 80 g ($V = {}^{M}/D \rightarrow V = \frac{100}{1.25} \rightarrow V = 80$) or the shrinkage potential equals 826 + 80 = 906 ml. Similarly the bulk density of the same soil may be calculated at $BD = \frac{100}{906}$ or 0.11 (at 0.1 atm) and $BD = \frac{100}{178}$ or 0.56 (at 15 atm).

Table 4.1
Chemical fertility data (5 obs) of peat layers in drained Tropofibrist (raw peat soils) at Olgoboli Research Station, Wahgi Valley, about 18 km NE of Mount Hagen (after Drover 1973)

Vegetation	pH*	%N	Exchangeable cations (meq/100 g)				CEC
			Na	K	Ca	Mg	
Regrowth (mainly *Phragmites*)							
mean	4.2	2.02	0.20	1.14	12.8	7.2	24.4
range	(4.1-4.5)	(1.59-2.51)	(0.14-0.34)	(0.43-2.40)	(11.4-19.9)	(3.2-14.5)	(15.1-29.9)
Tea							
mean	3.9	1.63	0.23	0.32	12.3	3.9	32.6
range	(3.8-4.2)	(1.09-1.94)	(0.10-0.33)	(0.03-0.12)	(8.6-24.6)	(1.9-10.0)	(23.7-45.5)

* Methods used; pH measured by inserting a glass electrode into a paste made from the moist peat CEC by a 1 molar ammonium chlorite extraction and exchangeable cations by atomic absorption. Soil N was estimated by a Kjeldahl method.

Table 4.2
Soil moisture data (% oven dry weight) of peat layers in five drained and one virgin Tropofibrist (raw peat soils) at Olgoboli Research Station, Wahgi Valley, about 18 km NE of Mount Hagen (after Drover 1973)

Vegetation	0.1 atm	0.3 atm	3 atm	15 atm
Regrowth (mainly *Phragmites*)				
mean	314	274	204	135
range	(221-455)	(197-414)	(146-334)	(94-262)
Tea				
mean	310	246	188	146
range	(228-377)	(192-302)	(152-235)	(110-184)
Virgin swamp (one sample only)	826	464	176	98

It would thus appear that the general fertility of these soils is moderate to high. Appendix I gives a typical example of a lowland Tropofibrist.

Land Use

These soils are unsuitable for agriculture unless major land reclamation measures are undertaken, although some swamp rice cultivation is a possibility in lowland areas. In the Wahgi Valley some areas with these soils have been

Plate 4.5 Local farmers completing a channel dug to drain a *Phragmites* swamp in the Wahgi Valley for cultivation

reclaimed and are now successfully used for tea cultivation and farming (Plate 4.5). Some of the mangrove peat soils with a neutral to alkaline reaction in saturated condition are likely to develop into acid sulphate soils when reclaimed (see Chapter 3, Sulfaquents section). Present land use is mainly confined to fishing and sago collecting in lowland areas.

5 Inceptisols

Inceptisols are soils with minor to moderate profile development typified by thick dark A_1 horizons ($\geq$ 25 cm) and/or B horizons (Cambic horizons) in which no clay illuviation has taken place. Together with the Entisols and Alfisols they are the commonest soils in Papua New Guinea and are estimated to cover approximately 40 per cent of the total land mass.

Inceptisols occur in diverse climatic environments ranging from the hot, humid lowlands to the cool, wet highlands and they have parent materials ranging from volcanic ash to unconsolidated sediments and hard rocks. Soils belonging to this order may be found in association with either the very slightly or unweathered soils such as the Entisols or the very strongly weathered Oxisols.

The Inceptisols are subdivided into six suborders, five of which are found in Papua New Guinea. Their subdivision into suborders is based on criteria relating to wetness (drainage), parent material, climate and organic matter content. *Aquepts* are Inceptisols showing strong gleying often with pronounced mottling and they commonly have thick dark A horizons and grey, strongly yellowish brown mottled subsoils. *Andepts** are Inceptisols formed on ash, pumice or other pyroclastic materials which may be fresh or reworked. They are well drained, very permeable soils and by definition are characterised by their low bulk densities and appreciable amounts of an amorphous clay mineral called allophane. These properties are difficult to ascertain when no analytical data are available and in some instances clay mineral analyses obtained from various sources have yielded somewhat conflicting data. This will be discussed in more detail for each of the great groups belonging to the Andepts. *Tropepts* are mainly well drained soils with yellowish brown, brown or reddish brown B horizons. They are found in areas where the mean annual soil temperature is 8°C or higher and the difference between mean 'summer' and 'winter' temperature (at 50 cm depth) is less than 5°C. *Ochrepts* and *Umbrepts* are confined to high altitudes (approximately 3400 m) where the mean annual soil temperature is 8°C or less and thus very rarely occur in Papua New Guinea.

* It has been proposed to elevate the Andepts to an order called Andisols because these soils have several important properties in common. These will be discussed in more detail in the Hydrandept section.

Umbrepts have thick dark coloured A_1 horizons, *Ochrepts* do not have these properties.

HALAQUEPTS

Morphology

Halaquepts are alkaline soils characterised by very high exchangeable sodium contents.* Because the morphology of these soils offers no specific field characteristics, columnar structure being only rarely present, they are very difficult to identify without laboratory analyses. For this reason little is presently known about their occurrence, their positive identification being limited to the Markham Valley where they are locally found on fan deposits (Zijsvelt 1973).

Halaquepts have a black to very dark greyish brown, friable to very friable, sandy loam to clay loam A_1 horizon, between 10 and 25 cm thick, and having a fine to medium crumb or strong, fine subangular blocky structure. This horizon merges into a 10-20 cm thick, friable to very friable, (very) dark greyish brown to olive brown, silt loam to silty clay loam transitional horizon, or directly overlies a variable textured, gleyed and/or mottled subsoil with a dominantly subangular blocky structure.

Halaquepts are moderately to strongly calcareous, calcic horizons being commonly present, and always have pH values above 8.0. Their water tables, which are high during the wet season, are subject to significant movements.

Genesis

Halaquepts are clima-hydromorphic soils developed on recent alluvial fan surfaces. Apart from the prerequisite of having relatively high sodium contents in the soil system, their formation depends strongly on the high bicarbonate (HCO_3^-) levels found locally in the seasonally fluctuating groundwater table. While calcium and magnesium ions present in the soil solution will under normal circumstances replace the sodium on the exchange complex, they combine with the bicarbonate anions, precipitating as carbonates. This causes high levels of sodium absorption on the exchange complex resulting in high pH values ($\geqslant 8.0$). Zijsvelt (1973) has suggested that the Halaquepts may be only 'seasonal soils', being formed at the beginning of the dry season by capillary enrichment of part of the soil with sodium, which is again leached out of the soil during the early wet season.

The seasonally fluctuating groundwater table, in addition, causes gleying and reduction processes in the soil, as shown by the greyish colours and mottling.

* By definition they have a SAR (sodium absorption ratio) of > 13 (or sodium saturation that is 15 per cent or more) in half or more of the upper 50 cm of the soil and which decreases with depth below 50 cm.

Occurrence
Halaquepts have been positively identified at a few localities in the drier parts of the Markham Valley (Rumu and Rumu-Wawin fans) and in the vicinity of Port Moresby. They may also occur in isolated pockets and other dry areas with a high seasonal rainfall.

Association
Halaquepts are mainly found in association with Tropaquepts, Eutropepts, Tropaquents, Haplaquolls and Hapludolls.

Fertility
Data given by Zijsvelt (1973) indicate moderate to low nitrogen, low available phosphorus and high exchangeable potassium contents. The percentage exchangeable sodium (ESP) in these soils may reach values of up to 68.

Land Use
Very high exchangeable sodium contents and seasonally wet conditions render these soils unsuitable for agriculture, except limited grazing.

CRYAQUEPTS

Morphology
Cryaquepts have a 30-55 cm black, very dark brown or reddish brown, fine to medium textured A horizon which abruptly overlies stony and/or bouldery material mixed with soil or hard rock. These soils are strongly acid and have high organic matter contents. They were previously named peaty soils but analytical data have since indicated that their organic matter contents are not high enough to qualify them as Histosols.

Genesis
Apart from their lower organic matter content, the genesis of these soils is basically similar to that of the Cryofolist, Cryohemist and Cryofibrist great groups discussed previously. Cryaquepts are young soils, being limited to the building up of organic matter and the formation of a thick, acid topsoil.

Occurrence
Cryaquepts are found scattered on ridges and moderate slopes throughout the high mountains above 3400 m. They are zonal soils found on a wide variety of parent materials. Their vegetation consists of alpine tussock grassland and occasional scrub and forest remnants.

Association
Cryaquepts are most closely associated with the Cryofolists, Cryorthents, Cryohemists and Cryofibrists. Figure 3.10 shows this association in combination with landforms and vegetation.

Fertility
Limited data from three soils examined indicate that they generally have a moderate to high chemical fertility. The organic matter content varies between 9 and 15 per cent. Nitrogen values are closely related to this high organic matter content. While cation exchange capacities are high, total exchangeable cations and base saturation figures are mostly low, which is probably indirectly related to the high acidity. Both exchangeable potassium and available phosphorus values are moderate, but phosphorus, in all three profiles examined, shows a pronounced decrease with depth which appears to be related to a similar decrease in organic matter content.

Land Use
Occurring as they do at high altitudes under wet, cool climatic conditions, these soils are unsuitable for agriculture, although limited grazing might be possible. Present land use is mainly confined to hunting.

ANDAQUEPTS

Morphology
These are poorly drained soils consisting of volcanic ash deposited *in situ* or reworked. They have 30-100 cm thick A_1 horizons rich in organic matter merging into grey, light brownish grey or olive brown B or C horizons which are often mottled. Textures vary, the highland soils formed on older ash having mainly clayey horizons whereas the recent lowland ash soils are mainly medium to coarse textured. They were previously classified as unweathered sandy volcanic soils with black topsoils (lowlands) and humic olive ash soils (highlands). Their vegetation consists of grassland.

Genesis
The formation of these soils is largely governed by poor drainage conditions which in turn are closely related to the topography. Because of the moderate to rapid permeability of the ash even in the fine-textured soils, their occurrence is limited to terrain depressions or broad flat surfaces where seepage from upslope takes place. Fluctuations of the water table cause oxidation and reduction processes in the soil and this is reflected in gleying and/or mottling. Reduced conditions will also enhance the accumulation of organic material. The other important properties typical of volcanic ash soils, such as pH dependent surface charge and phosphate fixation, will be discussed in Chapter 14.

Occurrence
Although these soils are relatively rare, occurring only in small, isolated areas, they are found in a wide variety of climates and at altitudes from sea level to 2000 m. They have been recorded on both Recent and Pleistocene ash deposits on the mainland but are likely to be present also in other active volcanic areas such as the islands of Bougainville and New Britain.

Association

At the higher altitudes these soils are associated mainly with the Hydrandepts, while in the lowlands they may grade into both Eutrandepts and Dystrandepts.

Fertility

Insufficient analytical data are available but in general chemical fertility levels are expected to be high. Possible phosphate fixation problems in these soils are discussed in Chapter 14.

Land Use

Because of poor drainage these soils are generally unsuitable for agriculture apart from some grazing and in the lowlands possibly some wetland rice cultivation.

TROPAQUEPTS

Morphology

Tropaquepts are by far the most common great group belonging to the suborder Aquepts. Their main classification criterion is based on a difference of $< 5°$ between 'mean summer' and 'mean winter' soil temperature at 50 cm depth. Tropaquepts encompass soils with A-C and A-B-C profiles. These include young alluvial soils with thick ($\geqslant$ 25 cm) dark topsoils having a low base saturation as well as the more mature soils with well developed cambic horizons. Because of this, Tropaquepts include soils previously named dark soils of heavy texture, gleyed plastic heavy clay soils and meadow soils.

Soils with A-C profiles developed on recently deposited alluvium have very dark grey or black, locally organic, A_1 horizons between 30 and 50 cm thick, merging into grey or bluish grey C horizons. Occasionally small, prominent yellowish brown mottles are present. Soils with A-B-C profiles mostly have very dark greyish brown to dark grey A_1 horizons between 10 and 40 cm thick which overlie a 20 to 50 cm thick prominently brownish mottled dark grey or light grey B horizon. Locally this B horizon contains small concretions. The B horizon in turn overlies weathered fine grained sedimentary rocks such as siltstone or mudstone or fine textured colluvium and alluvium derived from these rocks. Tropaquepts are weakly to strongly acid and are found dominantly under grassland with sedges.

Genesis

Like the other soils belonging to the Aquept suborder the formation of these soils is strongly influenced by poor drainage conditions. These conditions, in turn, are caused by the very slowly permeable fine grained parent material and the weathering products derived from it. Their presence under grassland with sedges which have a fine dense rootmat in combination with relatively wet conditions, serves to promote the accumulation of organic matter, as is evidenced by the very common presence of dark topsoil.

Occurrence
Tropaquepts are found in level depressions and on flat to very gently undulating terrain. However, they are also common on undulating ridges, crests and upper slopes underlain by siltstones and mudstones, particularly in the highlands. Tropaquepts occur at altitudes from sea level to 3000 m but are not very widespread.

Association
Soils characterised by A-C profiles developed on recent alluvium are found in close association with Fluvaquents and, to a lesser extent, also Haplaquolls. More mature soils developed on old alluvium and sedimentary rocks with A-B-C profiles are most commonly associated with the better drained Dystropepts, Eutropepts and Tropudalfs.

Fertility
Table 5.1 shows the chemical fertility data of sixteen Tropaquepts. Data presented in Table 5.1 indicate dominantly high CEC and moderate to high TEB, BS, percentage nitrogen and exchangeable potassium figures. Nitrogen values are always high at approximate altitudes of 2000 m or more, but also appear commonly high under very poorly drained or swampy lowland conditions. Data on available phosphorous indicate low to moderate values, only two subsoil samples collected from tuffaceous sandstone and Pleistocene sediments showing values above 100 ppm. Limited clay mineral data from four profiles indicate the presence of montmorillonite plus illite with common gibbsite and goethite in two soils and kaolinite plus metahalloysite with some goethite in the other soils.

Land Use
Tropaquepts are best suited for grazing provided they are not too wet and, in the lowlands, also for rice cultivation. In the highlands they are at present commonly used for sweet potato cultivation. When drained by simple ditches as in the highlands they can also be planted with tree crops such as coffee.

HYDRANDEPTS

Morphology
Hydrandepts are soils formed on andesitic volcanic ash deposited mainly during the Pleistocene and typically occur between 1500 and 3000 m in the highlands under a continuously wet climate and rarely, if ever, have a moisture content below field capacity. (This refers to the amount of water a freely drained soil can hold.) Their relative age, in comparison to the recently deposited volcanic ash soils found in the lowlands, has resulted in the ash weathering into mature soils with well developed dark coloured A_1 horizons and fine textured, mainly clayey, subsoils (Plate 5.1, colour section). For this reason these soils were formerly termed humic brown clay soils* (Haantjens 1970a) and latosolic Andosols (Haantjens *et al.* 1967).

* This soil group also included soils developed on sedimentary rocks.

Table 5.1
Chemical fertility data - Tropoquepts (16 soils)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	5	31	—	—	2	14	6	43	1	7	12	86	9	64	6	43	5	36	3	22	5	36
Moderate	10	63	7	47	4	29	7	50	9	64	2	14	5	36	8	57	6	43	9	64	6	43
Low	1	6	8	53	8	57	1	7	4	29	—	—	—	—	—	—	3	21	2	14	3	21
Total samples and percentage	16	100	15	100	14	100	14	100	14	100	14	100	14	100	14	100	14	100	14	100	14	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

Hydrandepts are deep soils having medium to fine textured A_1 horizons with a granular or fine crumb structure and a high organic matter content. These A_1 horizons are normally 20-65 cm thick, but may be as thin as 5 cm or as thick as 100 cm depending on the type of terrain in which they occur. The A_1 horizon overlies with a clear boundary a yellowish brown, strong brown or yellowish red B_2 horizon 30 to more than 150 cm thick. Because of the continual moist to wet conditions of the soils these horizons have been described as being structureless. However, when artificially dried they often develop a strong subangular blocky structure. Drying also results in an irreversible dehydration of the clays into aggregates of silt and sand size, which is the major characteristic of these soils. B horizons are always very porous giving the soils a rapid permeability. The B horizon in turn merges into a thick (light) yellowish brown to olive brown C horizon frequently speckled with dark minerals. This horizon is massive and porous, becoming more sandy with depth. Hydrandepts are generally strongly acid with a pH commonly within the 4.5-5.5 range.

Genesis

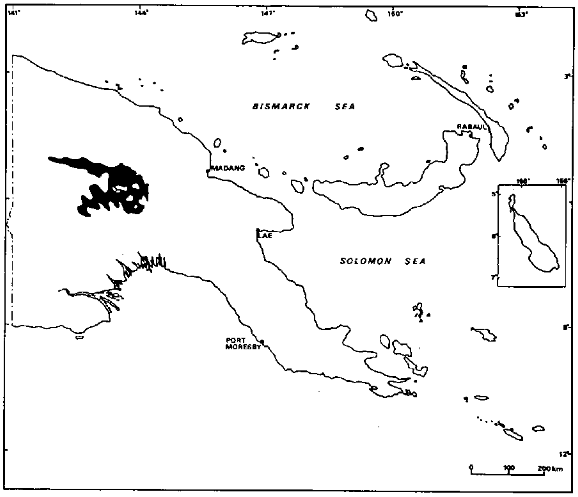
Hydrandepts are typical clima-lithomorphic soils developed on rapidly permeable volcanic ash of extinct Pleistocene volcanoes in a relatively cool, wet climate (mean annual temperatures 10-20°C and mean annual precipitation 2500-4000 mm) with low to moderate seasonality. The major features of these soils are the rapid weathering of the ash into clay and the accumulation of organic matter in the surface horizons.* Because of the high rainfall and rapid permeability bases are quickly lost, the soils becoming acid and unsaturated. Base saturation figures obtained from these soils generally show values of less than 10 per cent. However, the presence of the clay mineral allophane, found in various amounts in these soils together with gibbsite (see fertility section) is responsible for a variable charge and cation exchange capacity dependent on the state of hydration of the soil and the pH. These properties together with phosphate retention are not only typical for Hydrandepts but apply to all volcanic ash soils (Andepts and Andaquepts or 'Andisols') and are therefore discussed in detail in Chapter 14 (see Phosphorus section).

The generally high CEC and low BS values obtained by Haantjens and Rutherford (1965) for these soils are explained by the fact that measurement of the CEC for variable charge soils gives an overestimate when using a conventional determination (at pH 7.0). Although the base saturation figures could therefore be significantly higher when the effective CEC is used in the calculation, effective referring to the net-charge determined at the prevailing field pH, these soils should still be considered highly leached profiles which have been subject to rapid weathering.

Hydrandepts commonly have thick dark topsoils with a high organic matter content. An examination of twenty-two A_1 horizons showed an average thickness of almost 30 cm and a mean organic matter content of 17.2 per cent. The formation of these topsoils appears to be related to the permanently wet climate and low temperatures. These conditions greatly enhance the accumulation of plant waste which cannot be broken down sufficiently by soil organisms. This is discussed in more detail in the sections dealing with the

* This process is discussed in detail in the genesis section of the Eutrandepts/Dystrandepts.

Fig. 5.1 Major distribution of the Hydrandepts



genesis of the Cryofolist, Cryohemist and Cryofibrist. However, the notably high organic matter is also attributed to the presence of gibbsite and allophane with which it forms stable compounds ('complexation'), thus reducing the rate of mineralisation of the organic matter by soil micro-organisms. This also accounts for the high C/N ratios which are mostly 15 or more.

It is interesting to note that these soils, although consisting of layered ash deposits, may also contain illuviated clay as has been shown by a micro-morphological study by Rutherford (1964). Rutherford found clay cutans* in the deep B horizon of a Hydrandept, their position on channels, and joint and skew planes together with their discrete nature and lack of adhesion indicating a probable illuvial origin.

Data given by Wood (in press) indicate that the Hydrandepts have topsoil bulk density values of less than 0.85 g/cm^3 (at 1/3 bar water retention).

Occurrence

Hydrandepts are found on dissected slopes and ash plains (Plates 5.2 and 5.3) of extinct Pleistocene volcanoes. They have developed on both ash and redistributed volcano-alluvial deposits but are also to be found on hills, mountains and plateau areas having a thick ash cover overlying sedimentary rocks. They are mostly under grassland and gardens, but also under lower montane forest. Figure 5.1 shows the major distribution of the Hydrandepts in Papua New Guinea.

Recent work by Pain and Blong (1979) has shown that volcanic ash is much more widespread in the highlands than originally thought. Although volcanic activity virtually ceased more than 50 000 years ago, in the highlands numerous additional young volcanic ash layers derived from other sources have occurred. Figure 5.2 taken from Pain and Blong (1979) shows the distribution of these thin volcanic ash layers (or tephra beds), fourteen of which have been identified. These beds have a total thickness of more than 40 cm in some locations. The sources of the ash have not been positively identified, except for

* A detailed analysis (X-ray diffraction) of a cutan indicated that it consisted mainly of gibbsite, moderate amounts of amorphous material, assumed to be allophane, and minor magnetite.

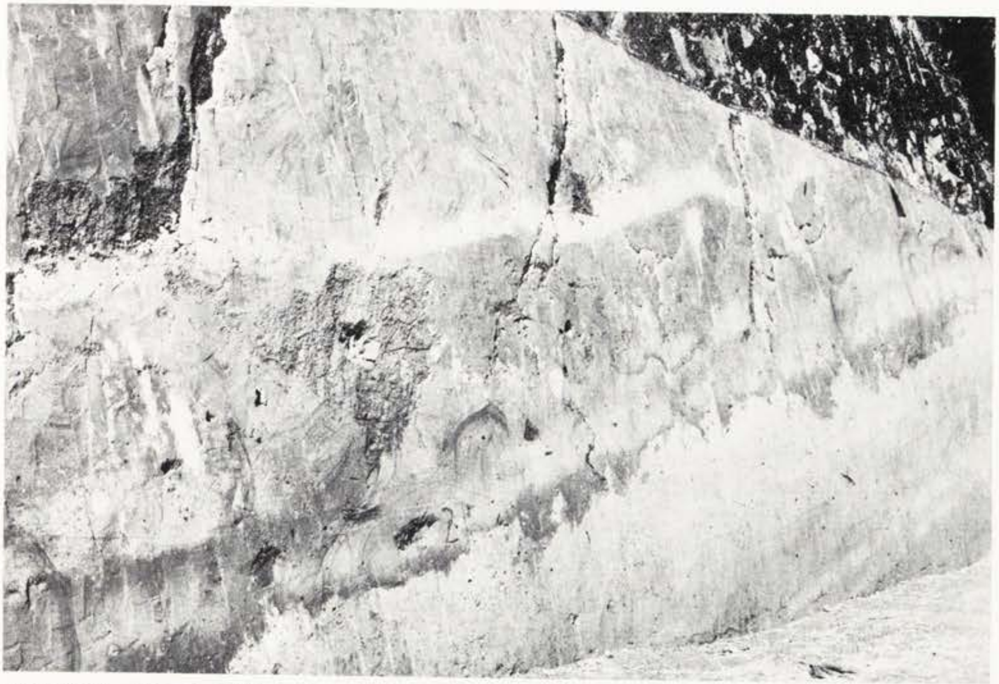


Plate 5.2 Road cutting in ash deposits near the mouth of the Tale River, Tschak Valley in Wabag area (Enga Province)

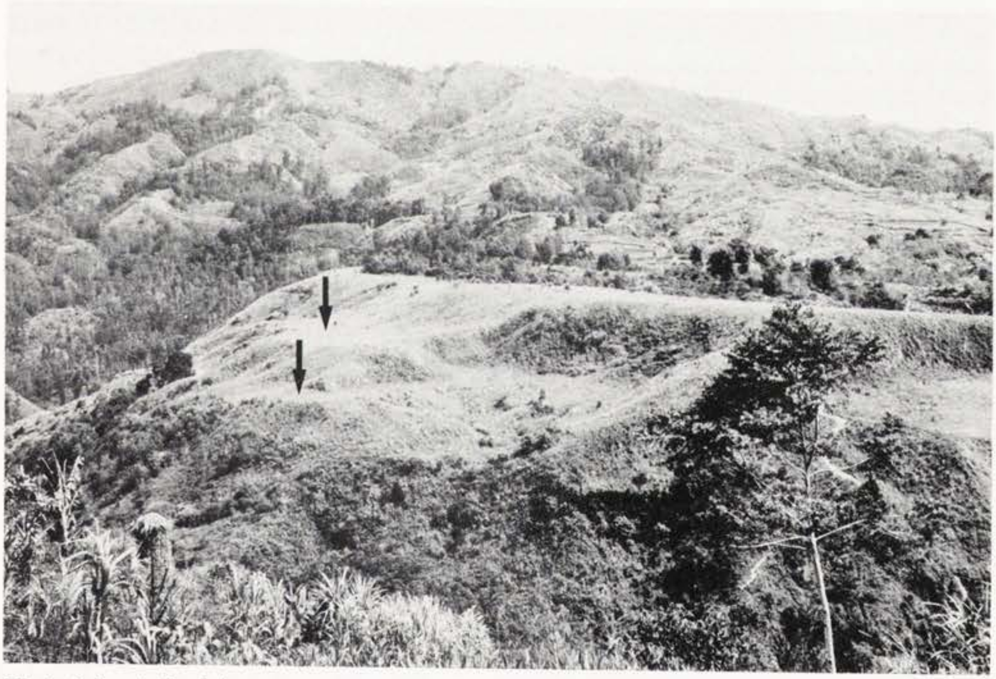


Plate 5.3 Ash plain on western side of the Minamp River with two terrace remnants on the left (arrows) and earth flow alcoves in centre and right hand side of picture. These ash plains are typically covered by Hydrandepts.

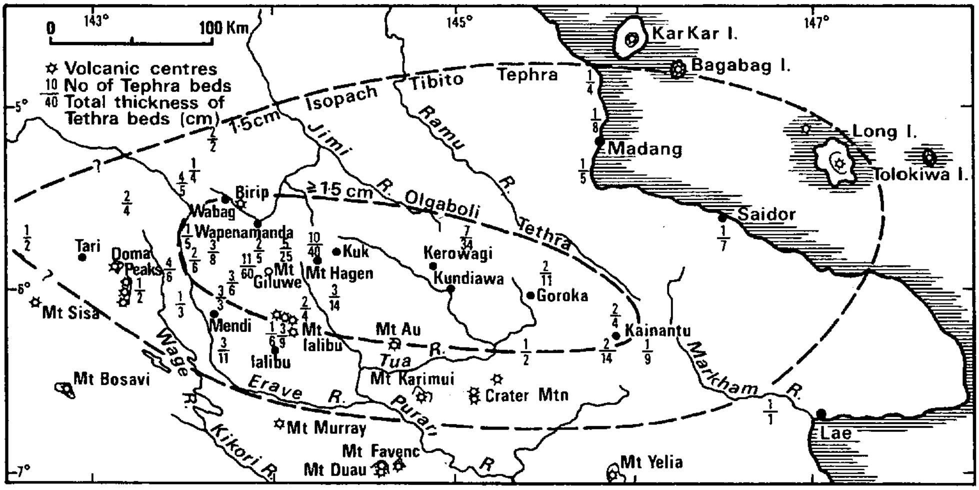


Fig. 5.2 Distribution of 'young' volcanic ash in the highlands (deposited <50 000 years ago) derived from other than highland sources (after Pain and Blong, 1979)

the youngest which erupted on Long Island more than 300 years ago. The other sources of ash are thought to lie in the Bismarck Sea. Rejuvenation by recently deposited volcanic ash could well explain the tendency of many topsoils of Hydrandepts, and many other soils developed on non-ash deposits, to be somewhat coarser textured than the subsoils, especially those developed on more stable surfaces. On the other hand, however, mixing by soil organisms and cultivation have reduced some of these effects. Also, on moderate to steep slopes, much of this recently deposited volcanic ash could have been removed by erosion, particularly in areas where farming is common.

Association

These soils are closely associated with the Humitropepts developed on sedimentary rocks and the Tropaquepts and Andaquepts found in flat areas and drainage depressions with impeded drainage. At high altitudes and on steep slopes they may also occur in association with both the Cryofolists and Troporthents. Figure 3.10, a schematic cross-section of the high mountains, shows the relationships of Hydrandepts to other soil groups and to landform and vegetation.

Fertility

General chemical fertility data for twenty-three soils are given in Table 5.2. While CEC values are dominantly high, both TEB and BS figures are almost always low. These low values are most likely due to the pH dependent surface charge (see genesis section) and generally high acidity of the soils, pH values being mostly within the 4.5-5.5 range. The high organic matter contents, in contrast, appear largely responsible for the dominantly high CEC and nitrogen values. Exchangeable potassium values vary between low and high, but only four of eighteen topsoil samples show low values, the rest being equally divided between high and moderate. However, subsoil values are only low to moderate throughout. Available phosphorus contents also vary between low and high,

Table 5.2
Chemical fertility data - Hydrandepts (23 soils)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	17	77	2	9	—	—	7	39	—	—	19	95	9	53	—	—	—	—	—	—	—	—
Moderate	5	23	6	27	5	38	7	39	8	47	1	5	8	47	5	26	2	12	1	5	2	12
Low	—	—	14	64	8	62	4	22	9	53	—	—	—	—	14	74	15	88	18	95	15	88
Total samples and percentage	22	100	22	100	13	100	18	100	17	100	20	100	17	100	19	100	17	100	19	100	17	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

but more than 60 per cent of the soils contain less than 10 ppm, indicating that deficiency in this nutrient is widespread. This suggests a strong fixation of phosphorus to organic matter and possibly also iron-aluminium compounds (see Chapter 14). However, Birch (1960) has suggested that the widespread practice of topsoil mounding under traditional agriculture in the highlands (Plate 5.4) leads to rather pronounced cycles of drying and wetting which might cause the liberation of phosphorus as well as nitrogen.

Clay mineral data from twelve soils analysed using X-ray diffraction and differential thermal analyses (DTA) and carried out by various institutions are given in Table 5.3. The table clearly shows somewhat conflicting information, not only between the X-ray and DTA determinations but also between X-ray analyses carried out by institutions in Norway and Australia. According to Rutherford and Haantjens (1965) this appears to be mainly due to the poorly crystallised nature of the clay minerals, the presence of mineral complexes, and the intimate bonding of the clay minerals with finely dispersed organic matter which give generally diffuse patterns difficult to identify using X-ray equipment. Allophane in particular seems to be difficult to identify by X-ray diffraction, its possible presence as amorphous material being indicated in only

Plate 5.4 Sweet potato, the basic food crop of the highlands, is cultivated in mounds of earth containing compost. In the western highlands these mounds are up to 1 m high and 2 m across and much larger in comparison to the eastern highlands (Plate 12.5). Using composting techniques, these gardens have been cultivated almost permanently for 50 years. This garden is found at 2700 m, where sweet potato takes approximately 12 months to mature and frost can be a serious hazard. As shown, every garden has groups of mounds at different stages of maturity. Cash crops grown at this altitude include Irish potatoes, cabbages and pyrethrum (shown mainly in the foreground and right hand side of the photograph).

Table 5.3
Clay mineralogy of the Hydrandepts

Soil profile and horizon		Depth (cm)	Minerals of the clay fraction: DTA analyses (Netherlands)	X-ray analyses: Australia	X-ray analyses: Norway
W5	A_1	10-15	—	M4,K4	I3,V3,ML3, (all very diffuse), K1
	$-B_2$	30-40	M4,A3,Go1,Gi1	—	I3,ML3,V3,M2,F1,Gi1
	$-B_2$	80-90	Gi4,A4,M1	Gi5,M2	—
	$-C_2$	160-175	A5,Go1	Gi4,M4	V5 plus diffuse reflections
W366[a]	$-A_{12}$	20-30	Gi5	M4,K4,Q2	—
	$-B_{21}$	75-85	Gi5,Go2	—	—
	$-B_{22}$	200-210	Gi4,A4	M4,K4,Q2	V3,ML3,I3,M2?
W33	$-B_2$	50-60	—	K5	—
	$-C_1$	100-115	—	K5	—
W70	$-B_{21}$	30-40	Gi4,A4,Go1,M1	—	—
	$-B_{22}$	65-75	Gi4,A4	—	—
	$-C_1$	120-140	Gi4,A4	—	—
MT-P2	$-A_{12}$	10-20	—	Gi4,M4	—
	$-B_2$	30-50	—	Gi5	—
	-BC	65-80	—	Gi5,Q3	—
MT-P5	$-A_b$	35-50	—	Gi4,M4,Q3,K2	—
	$-C_1$	75-90	—	Gi5,M3,Q3	—
MT-P11	-A/B	20-33	—	Gi4,M4	—
	$-A_{1b}$	35-45	—	M5,Gi3,Q3	—
	$-B_{21}$	70-90	—	Gi4,M4	—
MT-P19	$-B_{21}$	70-90	—	Gi5,14A° mineral 2	—
MT-P21	$-B_{23}$	95-120	—	Gi5,M2,K2	—
	$-B_{24}$	180-200	—	Gi5,amorphous material?	—
MT-P30	$-B_2$	30-40	—	Gi4,M4,K2	—
	$-IIC_1$	90-100	—	K5	—
MT-P36	$-B_2$	80-90	—	K4,M4,Q3	—
GMH-P5	$-B_3$	75-100	K5	—	—

Explanation of symbols:

K	=	kaolinite	A	=	allophane
M	=	montmorillonite	Go	=	goethite
I	=	illite	Gi	=	gibbsite
V	=	vermiculite	F	=	feldspar
ML	=	mixed layer	Q	=	quartz

Clay minerals are indicated as follows:
5 = more than half
4 = one-third to half
3 = one-fifth to one-third
2 = one-twentieth to one-fifth
1 = less than one-twentieth

W = Wabag survey
MT = Mendi-Tari survey
GMH = Goroka-Mount Hagen survey

For detailed profile descriptions, see Bleeker and Healy (1980) one of the twenty-six samples (MT, P21-B24 horizon). In comparison, by using DTA the presence of allophane is indicated in three of the four profiles analysed, the profile lacking allophane unfortunately being represented by only one sample. By carefully analysing Table 5.3 the following general conclusions can be made about the clay minerals of the Hydrandepts. Gibbsite ($Al_2O_3 . 3H_2O$) is the dominant clay mineral as shown by both X-ray (Australian Mineral Development Laboratories, Australia) and DTA analyses. DTA results also show a tendency for the amounts of allophane to increase with depth. Montmorillonite and vermiculite, illite and various mixed layer minerals are commonly also present, particularly in surface horizons. Kaolinite appears to be dominant in some profiles, while quartz is rarely present in significant amounts. Recent other and more detailed research (Brigatti 1975; Pain 1973; Parfitt 1975; Rutherford and Watanabe 1966; Wallace 1971; Wood in press) in general shows similar trends although the previously encountered difficulties with the identification of allophane become apparent, this clay mineral being present in larger quantities than originally thought.

Data given by Rutherford and Watanabe (1966) on the clay mineralogy of two Hydrandepts, one located at the footslope, and the other approximately 80 (air) km from Mount Giluwe indicated that amorphous materials, mostly allophane and kaolinite and gibbsite, are common in the soils. Because of the different clay mineral composition, the profile nearest Mount Giluwe containing no gibbsite, the authors conclude that the soils appear to have developed in materials from ash showers of different ages. However, a similar soil developed near Tambul, also at the footslope of Mount Giluwe, and investigated by Pain (1973) and Parfitt (1975) showed a quite different clay mineral composition. Their data showed that allophane and gibbsite are the dominant clay minerals in surface beds (about 2 m thick) dated at 30 000 years, while halloysite is present only in older beds, dated at more than 50 000 years BP.

Wood (in press) in his study of the Tari Basin soils states that X-ray diffraction data of clay minerals of the Hydrandepts indicate that gibbsite is the dominant crystalline mineral, quartz also being important, but the presence of large amounts of amorphous minerals was indicated in the field using the Fieldes and Perrott (1966) test,* and in the laboratory by pH sodium fluoride values above 9.4.

The clay mineralogy of samples collected at various highland locations by Brigatti (1975) (see Table 14.2.) from presumably Hydrandepts and Andaquepts indicate the dominant presence of allophane and halloysite. The dominance of allophane in soils found under poorly drained to swampy conditions (Andaquepts) has been attributed by Pain and Blong (1979) to absence of weathering under reduced conditions.

The physical and engineering properties of these soils have been studied by Wallace (1971) who noted that they contain the clay minerals gibbsite,

* This test was not available when the CSIRO surveys were carried out in the highlands. It is based on the fact that aqueous solutions of fluorides (at pH > 7) react with the hydroxy-aluminium sites of allophane which releases hydroxyl ions and causes the pH to increase. This increase in pH is measured and gives an indication of the amounts of allophane present.

Table 5.4a
Mineralogy of the sand fraction of Hydrandepts

Profile	W5			W33		W366[a]		MT,P6		MT,P15	MT,P19	MT,P21		MT,P30	
Horizon	A_1	B_2	C_2	B_2	C_1	A_{12}	B_{22}	B_2	C_1	B_{21}	B_{22}	B_{23}	B_{24}	B_2	$11C_{11}$
Heavy fraction															
% of total	7	15	46	12	17	58	34	64	55	32	10	11	88	74	11
Opaque	37	41	—	79	21	40	17	33	15	17	68	72	100	21	75
Goethite	—	—	—	—	—	—	—	3	—	5	8	21	—	—	—
Amphibole	37	56	97	17	78	58	83	59	81	75	21	5	—	77	22
Pyroxene	—	—	—	—	—	—	—	5	3	1	—	1	—	—	—
Olivine	16	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Tourmaline	4	1	1	1	—	1	—	—	—	—	—	—	—	—	1
Epidote	—	—	—	—	—	—	—	—	1	—	—	—	—	1	1
Rutile	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—
Zircon	6	2	2	3	1	1	—	—	—	—	3	1	—	1	1
Garnet	—	—	—	—	—	—	—	1	—	1	—	—	—	—	—
Light fraction															
% of total	93	85	54	88	83	42	66	36	45	68	90	89	12	26	89
Quartz	2	8	3	8	3	n.d.	4	43	21	11	13	8	n.d.	n.d.	n.d.
Feldspars	98	92	97	92	97	n.d.	96	57	79	89	87	92	n.d.	n.d.	n.d.

Table 5.4b
Mineralogy of the sand fraction of Hydrandepts

Profile	GMH P3	GMH P5	GMH P7
Horizon	B_{22}	A_2	A_{12}
Heavy fraction			
Rock fragments	5	5	15
Ferrous concretions	—	3	—
Ore	12	2	2
Amphibole	43	64	—
Pyroxene	—	1	2
Light fraction			
Acid plagioclase	2	—	—
Acid-Intermediate plagioclase	—	4	—
Intermediate plagioclase	—	6	—
Sanidine	—	—	2
Volcanic glass	—	—	28
Quartz	36	15	45
Organic silica	2	—	6

W = Wabag survey area GMH = Goroka-Mount Hagen survey area
MT = Mendi-Tari survey area

allophane and hydrated halloysite and when dried, lose their plasticity irreversibly. They are also a very distinctive group of engineering soils which, although characterised by an 'extreme' porosity and very high field moisture content, have a considerable shear strength and structural stability.

Data on the sand mineralogy of eleven soils are given in Tables 5.4a and b.* These show a generally rich mineral reserve, amphiboles dominating the heavy fraction and feldspars the light fraction.

Land Use

Although chemically less fertile than generally thought, Hydrandepts are well suited for agricultural production. Soils found on steeper sloping terrain are best used for higher altitude tree crops such as coffee and tea while, because of greater erosion risks, arable cropping is to be preferred on the flatter land. Pastures also offer considerable potential, particularly at higher altitudes. Frost is a serious hazard in terrain above 2000 m. Severe frosts occurred in 1972 when almost all subsistence food gardens were destroyed (Brown and Powell 1974). Subsistence cropping is almost entirely confined to sweet potato cultivation, although European vegetables are also grown successfully.

* Because of the more detailed investigations carried out on the light sand fraction of soils from the Goroka-Mount Hagen area two tables are given.

VITRANDEPTS (INCLUDING DURANDEPTS)

Morphology

These are typically lowland soils found near active volcanoes. They are the least weathered great group belonging to the Andepts, showing little, if any, evidence of leaching and being characterised by coarse textures and relatively high amounts of gravel, although their moisture content is higher than might be expected in such coarse textured soils.

They have a generally thin (3-15 cm), friable to very friable, very dark greyish brown to dark brown (10 YR 3/2–3/3), sandy loam A_1 horizon with a weakly developed fine subangular blocky structure which either merges into a dark brown, about 10 cm thick, transitional B_1 horizon, or directly overlies a weakly developed (dark) yellowish brown (10 YR 4/4–5/6) friable sandy loam B_2 horizon containing pumice gravel and between 10 and 25 cm thick. This B_2 horizon, in turn, abruptly overlies a number of dull yellowish brown and (light) olive brown, structureless, sandy loam, loamy sand, sand or gravel beds, typical of depositional stratification, and which are commonly interbedded with buried A or B horizons. Thin (< 10 cm), hard, cemented pans have also occasionally been found at between 50 and 100 cm depth in these soils (Zijsvelt and Torlach 1975), indicating that some of these profiles grade into Durandepts. Since these authors mention the local presence of even thicker (> 10 cm) hardpans in the area between Mount Pago and the Kapiura River, in the West New Britain Province, Durandepts are also likely to occur on the Papua New Guinea mainland and have been included in this section. Vitrandepts are weakly acid to neutral and have bulk densities between 0.47 and 0.64 g/cm^3 in weathered ash, and 0.94 g/cm^3 in the unweathered volcanic ash beds (Zijsvelt and Torlach 1975).

Genesis

Because in most soils derived from volcanic ash the genesis is closely related to the weathering of volcanic glass, discussed in the Eutrandepts/ Dystrandepts, the reader is referred to this section. The formation of hard pans in some of these soils, most commonly observed in profiles found on flat to almost level terrain, is attributed to the solution of silica (Zijsvelt and Torlach 1975). During the initial stages of weathering SiO_2 is rather soluble, but as under continual leaching by rainwater calcium and magnesium are dissolved, the environment acidifies, decreasing the solubility of silica which is precipitated lower down the profile in the zone subject to a fluctuating groundwater table, thereby cementing the loose ash and pumice gravel.

Occurrence

Vitrandepts appear to occur most commonly along the north coast of New Britain and locally also in the Mount Lamington area and in the Northern Province. They may also be present on Bougainville Island (Figure 5.3). They are found on a wide variety of landforms associated with active or dormant volcanoes. Durandepts seem to occur in much more localised areas on the flat to very gently sloping terrain, such as footslopes of volcanoes.

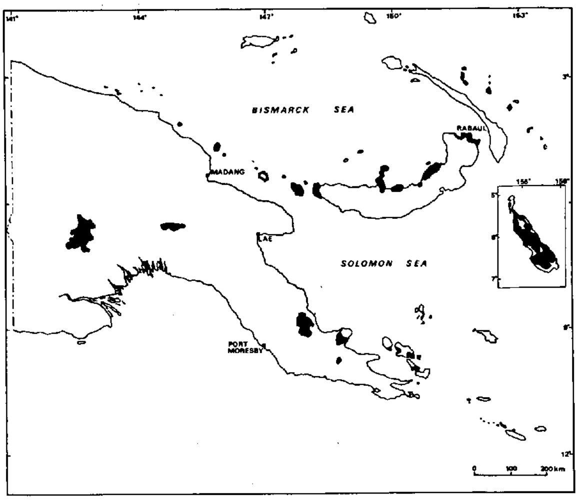


Fig. 5.3 Major distribution of the Dystrandepts, Eutrandepts and Vitrandepts

Association

Apart from the close association between the Vitrandepts and Durandepts, both these great groups are intimately associated with the Eutrandepts and to a lesser extent also with the more mature Dystrandepts.

Fertility

Data given by Zijsvelt and Torlach (1975) from the Vitrandepts located in the Ala-Kapiura area, West New Britain Province, indicate that these soils generally have high nitrogen, low available phosphorus and high exchangeable potassium contents. As with other volcanic ash soils the authors noted the remarkable accumulation of organic matter in the surface horizon, particularly in the top 5 cm, with values ranging between a minimum of 9.3, and a maximum of 33.1 per cent. Some of these data together with the clay mineralogy and pH dependent charge properties typical for these soils are discussed in Chapter 14.

Land Use

Except for the soils containing hardpans, for which the suitability should be downgraded, particularly for deep rooting tree crops, similar conditions apply to those discussed in the next (Eutrandept/Dystrandept) section.

EUTRANDEPTS and DYSTRANDEPTS

Morphology

These are most typically lowland soils although they may occur at altitudes up to 1500 m. They are found near both active and extinct volcanoes and are discussed together because of their very similar profile morphology. Dystrandepts and Eutrandepts are distinguished from each other by a base saturation (by NH_4OAc) value which must be $\geqslant 50$ per cent in some subhorizon between a depth of 25 and 75 cm for the Eutrandepts and < 50 per cent for the Dystrandepts. They are generally less gravelly than the Vitrandepts and often characterised by a property called thixotropy* which is an essential classification requirement for the Dystrandepts, but not necessarily so for the Eutrandepts.

Eutrandepts and Dystrandepts are characterised by well developed, dark, humic, very friable A_1 horizons with a fine crumb or granular structure and are generally 10-30 cm thick. The A_1 horizon overlies with a clear boundary a yellowish brown to dark brown B horizon with a weak fine blocky structure. Alternatively the A_1 horizon may directly overlie a greyish brown, olive brown or grey coloured coarser textured C horizon (Plate 5.5, colour section). These C horizons are commonly compacted and contain pumice gravel. Like the Vitrandepts, cementation into a hard pan by what appears to be secondary silica has occasionally been observed in C horizons, particularly those found near Cape Hoskins in the West New Britain Province. Buried A and B horizons frequently found in these soils are indicative of several major volcanic eruptions separated from each other by periods of relative tranquility (Plate 5.6, colour section). Soils with buried A horizons are especially common in New Britain (Bleeker and Parfitt 1974; Hartley *et al.* 1967) and Bougainville (Scott 1967). Owing to their different stages of weathering there is often a marked difference in texture. For instance, the very young ash soils found in Bougainville and New Britain commonly have loamy topsoils merging into sandy loam or loamy sand subsoils, while the buried horizons often have sandy clay-loam textures. Soils near Mount Lamington and Mount Victory in the Northern Province and described by Haantjens (1964a, b) as 'moderately to little weathered brown ash soils' commonly have sandy clay-loam to sandy clay, friable and porous subsoils. They are overlain by a slightly coarser textured topsoil which appears to have been caused mainly by rejuvenation of recent coarser textured ash deposits. Most of these soils appear to belong to the Dystrandepts. Other soils in the same area described by Haantjens (1964a, b) as 'unweathered volcanic ash soils' have mainly sandy textures but are confined to gently sloping plains covered by redistributed ash deposits. These too appear to belong mainly to the Dystrandepts.

Other Dystrandepts and Eutrandepts developed on both andesitic and dacitic ash have been described by Haantjens (1967a) near Mount Suckling, also in the Northern Province. The majority of these soils have thick dark topsoils, while the few without occur mainly on steep slopes where colluvial slope wash is common. Even in these profiles with thin A_1 horizons, organic carbon contents

* Thixotropy – according to the USDA scheme of soil taxonomy (US Dept of Agric., 1975) thixotropic means 'change by touch'. Thixotropy apparently is the result of a type of structure occurring in some soil materials, that if broken down, can rebuild itself. Soils having this property are often described by soil scientists as 'smeary'. Thixotropy can be recognised in the field by pressing a bit of wet soil between thumb and forefinger: the material at first resists deformation but under increasing pressure can be moulded and deformed; under greater pressure the soil changes suddenly from a plastic solid to a liquid, the fingers skid (smeary consistency) and free water can often be seen on the fingers. After a few seconds the soil will set again in its original condition.

appear to be high owing to the presence of the amorphous clay mineral allophane (see genesis section), and probably also because the samples were collected in high rainfall areas at or above 1000 m. Six of the seven soil profile samples by Haantjens show very low base saturation figures caused by the acid soil reaction and belong therefore to the Dystrandepts. It should be remembered, however, that the CEC was determined at pH 7.0 (NH_4OAc) and is therefore an over estimate of the net negative charge that would be operative at the lower field pH. Hence the base saturation figures are lower than the actual field situation (see Chapter 14). Their texture varies between sandy loam and sandy clay, texture differences being related to age differences as well as composition of the parent material.

There are several other areas in the country covered by extensive volcanic ash deposits but unfortunately little or no information is available for them. These include the active volcanic areas on Kar Kar, Long and Umboi Islands as well as extinct volcanic terrain surrounding Mount Karimui, Mount Soaru and Mount Bosavi. The Mount Karimui and Mount Soaru soils have been briefly described by Bleeker (1975) and more recently by Wood (1979) and are characterised by dark brown, friable A_1 horizons between 15 and 35 cm thick overlying yellowish brown B horizons. These soils are really intergrades between the lowland ash soils and the Hydrandepts occurring at higher altitudes.

The organic topsoil is generally thinner and the organic matter contents lower due to the warmer temperatures promoting a more rapid breakdown of organic matter than occurs at higher altitudes. While the soils of the Karimui area are mainly uniform loam to sandy loam soils frequently having buried horizons below 40 cm, the Soaru soils are mainly composed of highly leached very deep friable dark brown clay soils. These differing textures are likely to be caused by differences in parent material and age. The Mount Soaru soils seem to be older and, according to Wood (1979), may have been derived from reworked ash mudflow deposits, while the Mount Karimui soils have been formed largely in airfall volcanic ash.

No published data are available on the soils in the Mount Bosavi area. However, the author briefly visited the area in 1971. Auger hole observations indicated brown to very dark brown (10 YR 4/3) topsoils overlying very thick dark yellowish brown to yellowish red clay subsoils. Very deep weathering was apparent and two holes blasted previously by a geophysical party on the footslope at approximately 1000 m altitude showed brown clay exposed to a depth of 15-20 m. One of the two potassium-argon dates given by Löffler *et al.* (1980) indicates that Mount Bosavi could be the oldest known Papua New Guinea volcano (1.93 million years). Soil samples analysed for clay minerals are discussed in the next section.

A typical example of a Dystrandept profile is given in Appendix I.

Genesis

The formation of these soils is largely governed by the rapidly permeable parent material and a climate characterised by an annual rainfall between 2000 and 4000 mm, which has a moderate to high seasonality and mean annual temperatures between 20 and 26°C. Typically these soils contain the amorphous clay mineral allophane which forms during an early stage of weathering by aluminium combining with silicic acid. During the formation of these secondary minerals the soluble components (e.g. Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) are leached by rainwater with the aid of carbonic acid while sesquioxides accumulate as a residue. Fieldes (1955) has proposed the following weathering sequence from glass and feldspar with increasing age advancing through the stages (1) volcanic glass and feldspar, (2) amorphous silica (allophane B), (3) silica rich allophane (allophane AB), (4) alumina rich allophane (allophane A), and (5) halloysite. Detailed clay mineral analyses of five soils (Eutrandepts and Vitrandepts) located near Hoskins, New Britain as given in Table 5.5 appear to confirm that this weathering sequence also operates in lowland tropical

Table 5.5
Clay mineralogy and radiocarbon data from Eutrandepts and Vitrandepts located near Hoskins, New Britain (after Bleeker and Parfitt 1974)

Soil pit and sample	Depth (cm)	Minerals of the clay fraction: allophane B	allophane AB	allophane A	halloysite	other minerals	Radiocarbon data (BP)
Lavege							
P1-1a	0-10	****	0	0	0	(Q),(C)	—
1b	20-30	**	**	0	0	(Q),(C)	<830 ± 110
2	70-75	0	**	0	**	0	>830 ± 110
P4-1	0-10	****	0	0	0	(Q),(C)	—
2	30-40	*	**	*	0	(Q),(C)	—
3	50-60	0	**	0	**	0	—
4	75-85	0	*	0	***	(Q),(C)	Presumably as P1, sample 2
5	100-110	0	*	0	***	0	—
Rikau							
P28-1	0-3	***	*	0	0	0	<320 ± 170
2	65-70	0	**	0	**	0	>320 ± 170
P27-1	130-135	0	*	0	***	0	—
2	250-260	0	*	0	***	0	Probably >2500 years
Silopy Road							
P16-1	0-10	0	**	**	0	(Q)	—
2	76-84	0	0	***	0	(C)	—
3	140-170	0	**	0	**	(K),(M),(V)	—
4	220-240	0	**	0	**	(K),(V)	—
5	370-390	0	*	0	***	(K),(V)	<1990 ± 90
6	730-760	0	*	0	***	(K),(V)	>1990 ± 90

Key to clay minerals: * = little; ** = moderate; *** = high; **** = very high.
0 = not detectable; ( ) indicates trace amounts; Q = quartz; C = cristobalite; K = kaolinite; M = montmorillonite; V = vermiculite.

Table 5.6
Clay mineralogy* of Dystrandepts and Eutrandepts of the Safia-Pongani area

Soil profile and horizon	Depth (cm)	X-ray analyses	DTA analyses	EM analyses	IRA-analyses a† 2.0-0.5u	IRA-analyses a† <0.5u	IRA-analyses b† <2u	% Allophane (esti-mated)	Extrac Al_2O_3 (%)	Approx age estimate (C14)
P17-A_{11}	0-20	I4,Ib4,F2	H5	H4,Mi4	K5A1	K5	K5	2	0.32	
-A_{12}	30-40	Ib5,F3	n.d.	H4,Mi4	K5	K5	K5	2	0.36	—
-A_{13}	60-80	Ib5,F3	n.d.	H4,Mi4	K5	K5	K5	5	0.29	
P8 -A_1	0-20	V5,H3	A3,K3,MO3, Gi1	A5,Ag3	A5	A5	A5	2	2.60	
-B_{22}	45-90	V5,H3	A3,K3,MO3 Gi1	A5,Ag3	A5	n.d.	A5	9	3.52	3000 years
-C_1	125-150	V5,Ib2	n.d.	A5,Ag3	n.d.	n.d.	A5	11	3.92	
P10-A_{11}	0-18	V5	A4,MO4,Gi1	Ag5	A5	A5	A5	4	3.88	
-A_{12}	20-40	V5,Ib2	A4,MO4,Gi1	Ag5	A5	A5	A5	8	2.98	5000 years
-B_2	60-90	V5	n.d.	Ag5,Mi3	n.d.	n.d.	A5	10	3.35	
-C_1	120-150	V5,Ib2	n.d.	Ag5	n.d.	n.d.	A5	8	1.64	
P12-A_1	0-20	Ib4,V4,F2	H5	H5	K5	K5	K5	3	0.63	
-B_{21}	30-50	Ib5,V4	H or K5	H5,A3	K5	K5	K5	7	0.79	—
-B_3	90-115	Ib5	n.d.	H5,A3	K5	K5	K5	8	0.70	
P41-BC	45-60	V5	A3,H3,HO3 Gi2	Ag5,A4,H2	n.d.	n.d.	A5	13	3.33	—
-IIB_1	110-135	V5,Gi3?	A4,H3,Gi3	A4,H4	K3,A3 Gi3	K3,A3 Gi3	K3,A3 Gi3	25	3.69	
P45-A_{11}	0-10	V5	A4,MO4,Gi1	Ag5,A3,Mi3	A5	A5	A5	4	3.09	
-AC	40-60	V5	n.d.	Ag5	A5	n.d.	A5	8	2.74	
-C_1	90-105	V5	n.d.	Ag5,A5	n.d.	n.d.	A5	15	1.78	

* Analyses by Soil Bureau DSIR, Wellington, NZ under supervision of Dr M. Fieldes.
† a = clays separated by the bicarbonate dispersion technique
bb = clays separated by 'standard technique' used at Soil Bureau

I = illite; Ib = interlayered hydrous micas; V = vermiculite; Mi = micaceous minerals; A = allophane; Ag = allophane gel; H = halloysite; K = kaolinite; Gi = gibbsite; F = feldspar; MO = mineral organic complex

Clay minerals are indicated as follows: 5 = more than half; 4 = one-third to one half; 3 = one-fifth to one-third; 2 = one-twentieth to one-fifth; 1 = less than one-twentieth areas. Radiocarbon data indicate that halloysite can be formed under these conditions within a time span of 300-2000 years BP (Bleeker and Parfitt 1974). Clay mineral data from Dystrandepts and Eutrandepts sampled in the Safia-Pongani area (Haantjens 1967a) are given in Table 5.6 but show a much more complex clay mineral composition. The six profiles were examined by the Soil Bureau, Dept of Scientific and Industrial Research (DSIR), New Zealand (unpublished data) using X-ray diffraction, differential thermal analyses (DTA), electron microscopy (EM) and infrared absorption (IRA) techniques. In addition the allophane content was estimated using a moisture-regain method where the soil is heated to 300°C to destroy some of the organic matter and a measurement is then made of the amount of water taken up in an atmosphere of 56.5 per cent relative humidity. As shown in the table, the various techniques in some cases give quite different interpretations of the clay mineral content. However, many of these discrepancies can be explained. For instance, crystalline minerals are detectable only by X-ray diffraction. It is not yet possible using this method to make any reliable estimate of the amorphous mineral content or of the absolute concentration of any of the crystalline clay minerals. The figures given in the table are therefore only quoted as proportions of each crystalline constituent to the total crystalline mineral content. The X-ray diffraction data indicate the dominance of the clay minerals vermiculite, interlayered hydrous micas and illite. When using differential thermal analyses (DTA) techniques the soil samples show the presence of halloysite and/or kaolinite, allophane and gibbsite. A rough estimate of the gibbsite content made by the Soil Bureau DSIR, New Zealand indicates that this is low. DTA analysis also revealed the presence of a mineral organic complex which is difficult to destroy by hydrogen peroxide treatment and is not completely decomposed by heat until about 700°C. Electron microscopy showed that the kaolinite type mineral revealed by using the DTA technique is really tabular halloysite, confirmed the presence of micaceous clay minerals revealed when using X-ray techniques, and indicated the presence of two types of allophane. Allophane normally appears as a fluffy formless powder when using electron microscopy but in many of the samples another allophane type resembling a gel which shrinks upon drying is also present. According to the DSIR Soil Bureau, this type could be allophane B similar to that found in the previously discussed New Britain soils (Table 5.5, Plate 5.7), indicating a very early stage of weathering. Radiocarbon dates obtained from two soils confirm ages of 3000 to 5000 years BP for samples in which allophane gel is present. All samples shown in Table 5.6 were also analysed using infrared absorption patterns according to a standard method used by the Soil Bureau and a bicarbonate dispersion technique. These two methods were used in order to obtain information on the effects of the dithionite/citrate reagents, used to extract free and bound iron and alumina. These effects appear, however, to be only slight. Overall results show that the soils can be separated into two quite distinct groups, namely soils containing dominantly halloysite and soils containing dominantly allophane or allophane gel. This distinction is best shown in the electron microscope data, but is also clearly indicated by the figures for extractable alumina in the table. Soils containing halloysite have extractable Al_2O_3 values of less than 0.8 per cent, but when allophane gel was

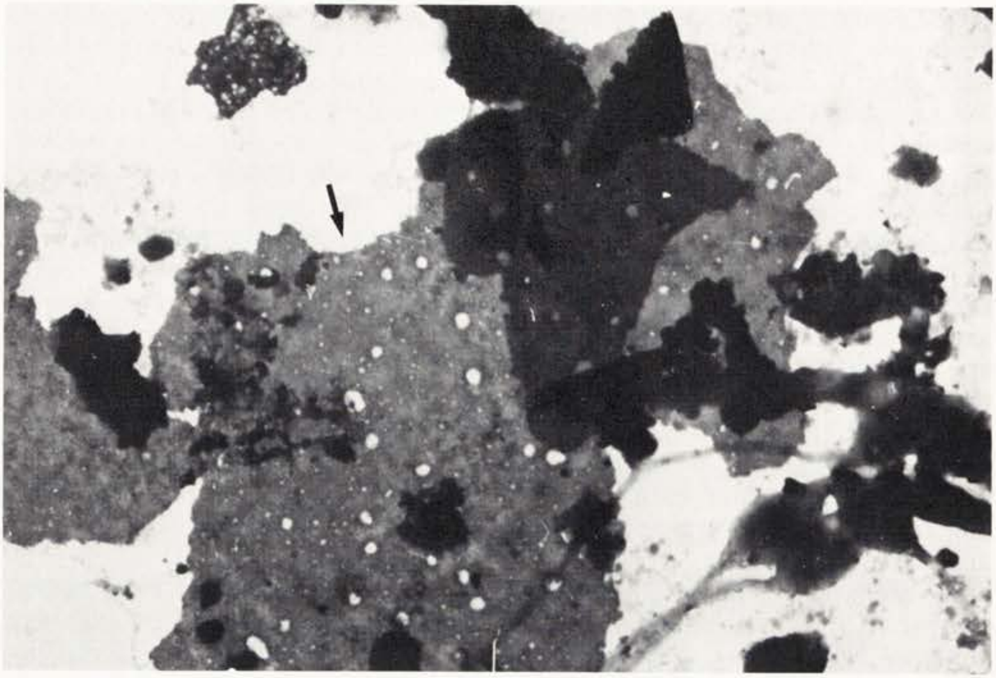


Plate 5.7 Electron micrograph of the 2μ fraction (×12 000) showing amorphous silica (= allophane B) in a recent volcanic ash soil (Vitrandept) near Hoskins, West New Britain Province (after Bleeker and Parfitt 1974)

visible in the electron micrograph the extractable alumina value was approximately 3 per cent in nine out of eleven samples. It appears that the allophane gel, being very amorphous, was readily soluble in the extractant, although sufficient material was left to appear as the dominant constituent in the electron micrograph. According to the Soil Bureau, DSIR, the presence of allophane gel (allophane B) appears to indicate an early stage in the formation of clay minerals and probably younger soils in comparison to those containing halloysite. However, Haantjens (1966) considers that there is very little evidence from field data that this is the case. The presence of small amounts of gibbsite in the soils may be related to a much higher rate of release of alumina than silica during weathering thereby causing the alumina to crystallise into gibbsite before it can combine with silica to form allophane. This fits in with the supposition that allophane gel, which is often present together with gibbsite in the soils, is an early stage of weathering and may be an impure alumina gel rather than allophane. According to Haantjens (1966) this is also supported by field data because gibbsite concretions were found in upper parts of weathering profiles located at the bottom of dissection slopes in the dissected ash covered mudflow landscape where these soils were sampled.

Clay mineral data using X-ray diffraction techniques of soils from the Buna-Kokoda area (Haantjens 1964a) are given in Table 5.7. Here again reliable estimates of the amounts of amorphous material present could not be made but amorphous material, not positively identified as allophane, was found in three

Table 5.7
Clay mineralogy* of Dystrandepts and Eutrandepts of the Buna-Kokoda area

Soil profile and horizon	Depth (cm)	X-ray diffraction data
P3-A_{12}	10-30	H4,Hb4,V1,F1?
-B_2	65-85	H5,Hb2,V2
P7-C_1	25-41	V5,K2,AM?
P8-B_1	20-35	V4,K1,Q1,F1,AM?
-IIC	75-100	V5,Ho1,K1,Q1,AM?
P9-A_{12}	10-20	Hh5,V4,Ho1,AM5?
-C_{11}	45-50	V5,Hh4,Gi4,Ho2,AM5?
-C_2	115-120	V5,H1,Gi1,F1,Ho1,AM5?

* Analyses by CSIRO, Division of Soils, Adelaide

H	= halloysite	Gi	= gibbsite
Hh	= hydrated halloysite	Ho	= hornblende
K	= kaolinite	F	= feldspar
V	= vermiculite	Q	= quartz
Hb	= hydrobiotite	AM	= amorphous material

Clay minerals are indicated as follows:

5	= more than half	2	= one-twentieth to one-fifth
4	= one-third to half	1	= less than one-twentieth
3	= one-fifth to one-third		

of the four soil profiles analysed with considerable quantities likely to be present in P9. Vermiculite, halloysite and hydrated halloysite are shown in the table to be the major crystalline clay minerals. In addition kaolinite, hydrobiotite, gibbsite, hornblende, feldspar and quartz are present in small quantities in some horizons emphasising the complex clay mineral composition of these soils. Of the other minor clay minerals found in these soils (or Andepts in general) imogolite, consisting of very long, extremely narrow fibres was, using various identification-techniques, first recognised by Greenland *et al.* (1969) in a Eutrandept (?) located near Mount Lamington in the Northern Province. The authors had difficulty in obtaining a complete dispersion of the clay fraction, although part was found to disperse at pH 3.5. Since its first positive identification traces of imogolite have been observed under the electron microscope in nearly all volcanic ash soils, regardless of their age (Parfitt and McHardy 1974).

Other minor clay minerals include opal found in topsoils (0-30 cm) of very recently deposited volcanic ash, it being present in large quantities, together with volcanic glass in some of the uppermost surface horizons (Parfitt 1975). According to Parfitt these opals occur mainly in the silt fraction and consist of both plant (silica diatoms) and biogenic opals.

Another typical feature of these soils is the very high organic matter content of the topsoil as reflected in the dark, humic A horizon(s). Data from twenty-two sites show a mean organic matter content of 11.5 per cent in the topsoils while nitrogen also reaches a high mean value of 0.6 per cent. In this instance, the high organic matter content, in comparison to other lowland soils, is attributable to complexation with allophane. Allophane appears to limit the decomposition of organic matter in the soil, either by the formation of stable humus-clay complexes (Kobe and Fujisawa 1963) or by controlling the decomposition of organic matter by micro-organisms (Aomine and Kodama 1956; Harada 1959). (See Chapter 14.)

Occurrence
Dystrandepts and Eutrandepts are fairly widespread in Papua New Guinea but are found mainly on the islands Bougainville and New Britain and on the mainland in the Northern, Southern Highlands and Chimbu Provinces (Figure 5.3). They occur on a wide variety of landforms. These include not only volcanic slopes, domes and outwash plains, but also ash blanketed hilly and mountainous areas in the vicinity of volcanoes (Plate 5.8).

Association
Apart from being closely associated with the Vitrandepts, these soils are associated with the Troporthents and bare rock exposures on very steep slopes, domes and lava flows. On steeply sloping terrain where the ash cover has been removed by erosion they may grade into Dystropepts and Eutropepts, while at altitudes above 1500 m they grade into Hydrandepts.

Plate 5.8 Eutrandepts, Dystrandepts and Vitrandepts typically occur on volcanic slopes and volcano-alluvial fans. The fan shown here below Lake Loloru in Bougainville has a slope of 6° and is cut by valleys 100 m deep. The vegetation consists of mid-height and tall forest.

Fertility

Table 5.8 shows the chemical fertility data of twenty-three soils forming thirteen Dystrandept and ten Eutrandept profiles. It indicates generally moderate to high fertility levels, the percentage nitrogen, exchangeable potassium, cation exchange capacity and base saturation values all being dominantly within the moderate to high range. Base saturation values for twenty-one topsoils and seventeen subsoils are almost evenly divided between the high, moderate and low classes, with the more acid Dystrandepts predictably having the lowest values. Information on available phosphorus is too limited to allow for a reliable assessment, but deficiencies are expected to be widespread due to phosphate fixation (see Chapter 14).

In summary, it can be said that, apart from many nutrients being present in the vegetation itself, the chemical fertility is generally lower than one would normally expect in view of the luxuriant vegetation usually found on these soils. Nutrient levels are almost solely confined to the top 25 cm of the soil profile and are largely due to the high organic matter content. It appears likely, however, that the lush vegetation also obtains some of its nutrients from the rapidly weathering, rich mineral reserve, particularly volcanic glass (Bleeker 1975), while good physical soil conditions, especially the high friability which promotes rooting, is also an important factor.

Land Use

Gently to moderately sloping terrain covered by these soils is very suitable for tree crops, pastures and commonly also arable crops. Although the general deficiency of available phosphorus is unlikely to affect tree crops seriously, it will depress yields of garden crops, and fruits such as bananas and paw paw. Therefore small applications of fertilisers or mulching to maintain fertility would be advantageous. Much of the present cocoa and palm oil in Papua New Guinea is produced on these soils. The Eutrandepts/Dystrandepts together with Vitrandepts (without hardpans) are, however, best suited to the more demanding tree crops such as cocoa and robusta coffee, while oil palm and rubber can also grow well on less fertile soils not developed on volcanic ash, such as the Dystropepts.

In the late 1960s pastures were sown on these soils in the Karimui area and elephant grass (*Pennisetum macrostachium*) was thriving there when the area was briefly visited by the author in 1971. It had been planted under ringbarked vegetation and in places had reached heights of more than 2 m, indicating that it was undergrazed, the cattle preferring grass below 1 m in height. Paragrass and green leaf *Desmodium* also grow well in this area. By comparison, cattle grazing areas in the Gazelle Peninsula, New Britian have done poorly (E. Hugh, personal communication). Whereas this was originally attributed to overgrazing, it now appears that the poor condition of the cattle may be due to trace element deficiencies in the soils. Analyses of seven grass, legume and tree leaf samples from pastures frequently grazed by the cattle showed zinc, cobalt and molybdenum deficiencies. Severe cobalt deficiencies have been reported in rhyolitic ash soils occurring on the Central Plateau of North Island, New Zealand (Wells 1968). However, zinc and molybdenum levels are generally high in both plant and soil samples collected from volcanic ash.

Table 5.8
Chemical fertility data - Dystrandepts and Eutrandepts (23 soils)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	15	65	—	—	—	—	5	23	1	6	10	50	6	35	3	14	2	12	8	38	6	35
Moderate	8	35	—	—	—	—	13	59	9	50	10	50	10	59	13	59	8	50	5	24	5	30
Low	—	—	3	n/a	1	n/a	4	18	8	44	—	—	1	6	6	27	6	38	8	38	6	35
Total samples and percentage	23	100	3	n/a	1	n/a	22	100	18	100	20	100	17	100	22	100	16	100	21	100	17	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

Another promising cash crop in the Karimui area is cardamon which grows well in areas at altitudes of 800-1300 m, where mean annual temperatures are around 22°C.

Present land use is mainly based on bush-fallow cultivation, the main crops being sweet potato, yam and taro. While gardens are shifted regularly (approximately every seven to fifteen years after successive crops) in most areas their rotation is normally restricted to clearly defined areas, since individual social groups tend to confine their land use to particular landforms within the area they cultivate (McAlpine 1967). This practice causes few problems where cultivable land is readily available. However, large population increases and conversions of land to cash cropping combined with a recent trend to more communal grouping rather than scattered houses has resulted in an intense cultivation cycle. This is exemplified in the East New Britain Province where 65 per cent of cultivable land is estimated to be under cocoa and other cash crops (Bleeker and Freyne 1981) while figures in the densely populated Gazelle Peninsula, forming a large part of this province, are even higher. Consequently the remaining land is almost permanently cultivated, causing reduced fertility levels and soil erosion.

HUMITROPEPTS

Morphology

Humitropepts have a profile morphology very similar to the Hydrandepts and like these soils mostly occur in the highlands, mainly between 1500-3000 m under a continuously wet climate. For this reason they were previously grouped with the Hydrandepts into one great soil group called humic brown clay soils (Haantjens 1970a). However, unlike the Hydrandepts, they have not developed on pyroclastic materials but typically are to be found on moderately to steeply sloping terrain away from volcanoes, underlain by both consolidated and unconsolidated rocks (except mudstone) of which most, if not all the volcanic ash has been removed by erosion. Because soil samples tested by granulometric analysis show ready dispersion through part or the whole profile, this appears to indicate that most of the ash cover has been stripped. Humitropepts are characteristically leached acid to strongly acid soils with well developed black to very dark greyish brown A_1 horizons. These A_1 horizons, normally between 25 and 50 cm thick, have a friable consistency and a fine blocky to crumb structure. This horizon overlies, with a clear or abrupt boundary, a dark brown, strong brown or yellowish brown, fine textured, friable to firm B horizon with a weakly developed blocky structure. The B horizon in turn gradually merges into weathered rock. Pedons of Humitropepts are normally more than 1 m thick. They are commonest under grassland but may also occur under forest.

Genesis

Humitropepts are predominantly found in the wet highlands with moderate temperatures. As discussed in more detail in Chapter 4 (Histosols) these relatively low temperatures considerably retard the breakdown of the organic matter leading to the formation of mostly thick, dark topsoils. In addition, these soils have relatively high organic matter contents in the B horizons probably caused by downward movement of organic compounds such as chelates or humus protected sols and/or contamination by volcanic ash. High precipitation also causes severe leaching of bases giving rise to an acid to strongly acid soil reaction and clayey textures. In most soils there appears to be a slight increase in clay content with depth.

Occurrence

Humitropepts are soils common throughout the central cordillera at altitudes between 1500-3000 m, occurring on virtually every consolidated and unconsolidated rock type except pyroclastics and mudstone. They probably also cover small areas on Bougainville Island. Figure 3.7 shows their major distribution. They are mostly found on well drained, moderately to steeply sloping, but relatively stable mountainous terrain (Plate 5.9) but occur also on well drained colluvio-alluvial valley-fill material. Occasionally, however, Humitropepts are also found at lower altitudes under grassland on very gently sloping terrain.

Plate 5.9 Humitropepts typically occur in the highlands at altitudes of 1500-3000 m on dissected mountain and hill ridges. This picture, taken from a hill near Watabung, shows the road climbing to Daulo Pass. The parent material is mainly schist intruded by granodiorite.

Association

At higher altitudes these soils grade into Troporthents, Cryochrepts, Cryumbrepts and various Histosols, such as the Cryofolist. Humitropepts can be distinguished in the field from the Hydrandepts by the absence of dark speckled minerals in the subsoils. On slowly permeable soft sedimentary rocks, such as mudstones, Humitropepts may grade into the poorly drained Tropaquepts. Figure 3.10 shows the association of these soils with other soils as well as their relationship with landform and vegetation.

Fertility

Chemical fertility data are given in Table 5.9 for twenty-two soils. Generally the fertility level appears to be moderate. CEC and percentage nitrogen values are dominantly high but the CEC contents decrease quite markedly with depth in the subsoil. This could be partly caused by an intermixing with volcanic ash in the topsoil as many of the samples were collected in the Western Highlands where a thick ash cover is common and not all the ash may have been stripped by erosion. As discussed previously, lower temperatures and the presence of allophane both inhibit the breakdown of organic matter which largely accounts for the high CEC and percentage nitrogen values. The mean organic carbon and percentage nitrogen values for the Humitropepts are 8.5 and 0.66 per cent respectively (twenty-two samples). In comparison mean values for the Hydrandepts are 10.0 and 0.8 per cent (twenty-three samples), while values for the lowland Dystrandepts, Eutrandepts and Vitrandepts are respectively 6.7 and 0.6 per cent for organic carbon and percentage nitrogen.

Exchangeable potassium and total exchangeable base values evince similar trends with mainly moderate values in the topsoil and low values in the subsoil. Base saturation figures, as with the Hydrandepts, are dominantly low and can be attributed to the acid soil reaction. Available phosphorus values range between low and moderate, again suggesting a strong fixation of phosphorus by organic matter.

The clay mineral data for seven soils belonging to the Humitropepts are given in Table 5.10. This table shows a great variety of clay minerals, but kaolinite and metahalloysite appear to be most common together with gibbsite. The presence of gibbsite could be due to influence of volcanic ash (see Hydrandepts). However, illite and montmorillonite have also been recorded in two profiles developed on sedimentary rocks.

Land Use

The gentle to moderately sloping frost free terrain below 2000 m is best suited for tree crops and arable crops and above 2000 m is best used for pastures. Many of these soils are presently under sweet potato cultivation and coffee. It is expected that fertiliser applications will show a good crop response and, rather surprisingly, best results have been obtained with nitrogen fertilisers (Bourke personal communication). A further lessening of the bush-fallow period due to high population densities and conversion of land to cash cropping could well result in the destruction of the organic topsoil and green manuring techniques are advisable.

Another high altitude cash crop grown on these soils is pyrethrum.

Table 5.9
Chemical fertility data - Humitropepts (22 profiles)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	16	73	—	—	—	—	2	10	2	13	19	95	8	57	—	—	—	—	—	—	1	7
Moderate	6	27	10	45	4	31	15	75	4	27	1	5	5	36	10	50	5	36	7	35	2	14
Low	—	—	12	55	9	69	3	15	9	60	—	—	1	7	10	50	9	64	13	65	11	79
Total samples and percentage	22	100	22	100	13	100	20	100	15	100	20	100	14	100	20	100	14	100	20	100	14	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

Table 5.10
Clay mineralogy of the Humitropepts

Soil profile and horizon		Depth (cm)	Minerals of the clay fraction	
			DTA-analyses (Netherlands)	X-ray analyses (Australia)
GMH-P11	-C	75-95	K4,MH4,Go2	—
GMH-P22	-B_{21}	50-75	Gi5,V2	—
GMH-P30	-B_{22}	145-170	I5,K2,M2	—
GMH-P32	-B_1	30-55	K4,MH4,Gi2	—
	-B_{22}	85-115	K5,Go2	—
GMH-P37	-B_{21}	30-50	K4,MH4,Go2	—
	-B_{22}	75-100	MH4,K4,Go2	—
MT-P3	-AC	55-70	—	Gi4,Q4 and 14A° mineral 2
MT-P38	-B_2	15-25	—	M4,Q4,I2
	-C_1	50-55	—	M5,Q4
	-C_1	100-110	—	Q5,I2

Explanation of symbols: K = kaolinite; MH = metahalloysite*; M = montmorillonite; I = illite; V = vermiculite; Go = goethite; Gi = gibbsite; Q = quartz

GMH = Goroka-Mount Hagen survey
MT = Mendi-Tari survey

Clay minerals are indicated as follows:
5 = more than half
4 = one-third to half
3 = one-fifth to one-third
2 = one-twentieth to one-fifth
1 = less than one-twentieth

* Metahalloysite is dehydrated halloysite.

USTROPEPTS

Morphology

Ustropepts are relatively shallow soils rich in bases and are typical of low rainfall areas with a pronounced dry season and a vegetation of eucalypt savanna (Plate 5.10). Since this type of climate is rare in Papua New Guinea these soils cover only small areas and are mainly confined to a narrow coastal strip in the Central Province.

Ustropepts are mainly fine textured soils with A-B-C profiles, occasionally showing stratification due to colluvial slope wash. The A_1 horizon is 10-30 cm thick with a black, dark brown or dark reddish brown colour and, when dry, has a hard to very hard consistency. This horizon overlies with a clear boundary a thick brown or yellowish brown B horizon containing calcium carbonate concretions but occasionally it merges into a red B horizon often

Plate 5.10 Eucalypt savanna near Port Moresby with a dense undergrowth of mainly *Themeda* grassland. Much of this land is covered by Ustropepts.

containing ironstone gravel. Ustropepts have a neutral to alkaline soil reaction and were previously classified as brown clay soils and red gravelly clay soils (Scott 1965). An example of an Ustropept with analytical data is given in Appendix I.

Genesis

Ustropepts are climamorphic soils derived from fine textured sedimentary rocks rich in calcium and magnesium. They are only slightly leached and commonly contain fairly high amounts of exchangeable sodium in the subsoil. Mabbutt and Scott (1966) have attributed this to cyclic salt blown in by south-easterly ocean winds under past drier climatic conditions and subsequent leaching under the presently prevailing higher rainfall. It would appear that the slow permeability and high water holding capacity of the soils together with dominance of smectites in the clay fraction would preclude the leaching of sodium and other cations into the deeper subsoil and consequently moderate amounts of soluble salts are retained in the soils. Alternatively the salt could have derived from the parent rocks being brought up by capillary movement of groundwater during the dry season. However, the occurrence of these soils on various sedimentary rocks of different ages and the presence of high amounts of exchangeable sodium in profiles developed on alluvium (Halaquepts) in the same area would support Mabbutt and Scott's theory that the common high amounts of exchangeable sodium are due to cyclic salt. In soils containing calcium carbonate concretions there is some leaching from the surface horizon down the profile while the base saturation of the deeper subsoil is maintained and some calcium carbonate is precipitated.

Occurrence
Ustropepts are limited in their occurrence to a long narrow coastal strip stretching from approximately Hisui in the north-west to Hood Point in the south-east of the Central Province. The annual precipitation is 1500 mm or less. They are found mainly on footslopes and gently to moderately sloping hillslopes.

Association
These soils are found in close association with Argiustolls, Calciustolls and Troporthents or rock outcrops.

Fertility
Data on the chemical fertility of these soils are limited to a few sites but the levels generally appear to be moderate. As can be expected the CEC, TEB and BS values are generally high in these slightly leached soils and exchangeable potassium contents moderate to high. Values of nitrogen and available phosphorus, however, appear to be low.

Land Use
The relatively dry climate with its pronounced dry season rather limits the selection of tree crops and to a lesser extent arable crops. Erosion hazards on moderately sloping terrain further limit arable cropping. Pastures therefore appear to offer the best potential. Present land use is limited to some subsistence gardening.

EUTROPEPTS and DYSTROPEPTS

Morphology
Since the Eutropepts and Dystropepts are very similar in profile morphology and are found in close proximity to each other they are discussed together. They are either with or without a high base saturation and are very common in Papua New Guinea, as they occur throughout the humid areas at low to mid altitudes (approximately sea level to 1500 m). Because of their widespread occurrence on varying landforms and parent materials, they show a large variation in profile thickness and colour. By definition, Eutropepts and Dystropepts must have an altered or colour B horizon (cambic horizon) and/or a thick (≥ 25 cm) dark topsoil with a base saturation level of less than 50 per cent (umbric epipedon). Their A horizons are usually (dark) brown, (very) dark greyish brown or dark reddish to yellowish brown in colour and between 5 and

35 cm thick. This A horizon merges gradually into, or clearly overlies, a 25 to 100 cm thick B horizon having various shades of brown (brown, strong brown, yellowish brown, etc.) or yellowish red colours and commonly contains weathered rock fragments. This horizon in turn overlies a brown, yellowish or reddish brown, greyish or olive coloured C horizon of variable thickness. They are fine to medium textured but whereas the soil reaction of the Dystropepts is largely weakly to strongly acid that of the Eutropepts is usually weakly acid to neutral. They have formed mainly on sedimentary rocks, colluvium and Recent to Pleistocene alluvial deposits, but may also occur on igneous and metamorphic rocks. They are found in almost any type of terrain under either forest or grassland. Plates 5.11 and 5.12 (colour section) show two examples of Eutropepts, one developed on mudstone, the other on basic igneous rocks. Analytical data for both these soils are given in Appendix I. The Eutropept profile shown in Plate 5.12 and tabulated in the appendix (Safia Soil Project II, 152) has been contaminated by volcanic ash as indicated in the mineralogy sand fraction by the presence of groundmass (volcanic glass).

Genesis

The development of the Eutropepts and Dystropepts is largely governed by the formation of a B horizon (cambic horizon) which lacks the accumulation of translocated silicate clays. This B horizon consists of weathered material having structural properties such as blocky structure and/or more pronounced colours in comparison to the underlying and overlying horizons. These stronger colours are mainly caused by residual concentrations of iron oxides released by weathering of primary minerals. A cambic B horizon as it is often called is commonly developed in gently to moderately sloping terrain where soil formation and erosion are in near equilibrium. Eutropepts and Dystropepts therefore are dominantly slightly to moderately weathered and are widely distributed on hilly to mountainous terrain throughout Papua New Guinea.

Soils with or without a cambic B horizon but having a thick ($\geq$ 25 cm) dark topsoil* with a base saturation of less than 50 per cent are also included in the Dystropepts. These soils are commonly found in the more stable, flat to gently undulating terrain of the lowlands where organic matter can accumulate sufficiently to form a topsoil, or at higher altitudes where, owing to cooler temperatures, the breakdown of organic matter is slower.

Occurrence

Dystropepts and Eutropepts are probably the commonest soils in Papua New Guinea since they mainly occur in hilly (Plate 5.13) and mountainous terrain from sea level to approximately 1500 m, as well as on stable alluvial plains and river terraces where active deposition has ceased. Figure 5.4 shows the major distribution of these soils.

* With less than 12 kg organic carbon per square metre in the soil between depth of 25 cm and 1 m.

Plate 5.13 Dissected moderately to steeply sloping hill country west of Madang recently cleared for gardening. This type of terrain is typical for Dystropepts and Eutropepts.

Association

Because of their widespread occurrence Dystropepts and Eutropepts are found in association with many other soils. These include Troporthents, Tropofluvents, Hapludolls, Humitropepts and Tropudalfs. Figure 3.4 is a schematic cross-section of the lowland freshwater environment backed by hilly terrain in which Dystropepts and Eutropepts occur commonly.

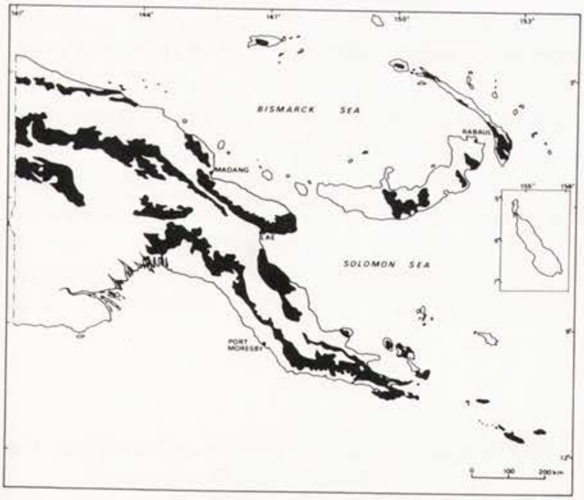


Fig. 5.4 Major distribution of Dystropepts and Eutropepts

Fertility

Data on the chemical fertility of twenty-two Dystropept and Eutropept profiles are given in Table 5.11. Overall fertility levels appear to be moderate but, except for percentagte nitrogen and CEC contents which are respectively dominantly high and moderate in the topsoils, there is a quite marked variation in individual nutrients. Available phosphorous and exchangeable potassium values are mainly moderate to low, while TEB contents are dominantly high to moderate in the topsoils and moderate to low in the subsoils. Base saturation levels predictably* vary widely between these two great groups, Eutropepts having high to moderate and Dystropepts dominantly moderate to low values.

The clay mineralogy of these soils is given in Tables 5.12a and 5.12b and shows that kaolinite is by far the dominant clay mineral in these soils. DTA analyses of the soils occurring in the Lower Ramu-Atitau area also show high contents of gibbsite.

Land Use

Since they occur on a wide variety of terrain and parent materials these soils have a wide range of land use. The gentler sloping hilly terrain offers some prospects for tree crops, particularly oil palm and rubber while areas with steeper terrain are more suited to grazing. At present much of the hilly and mountainous areas are used for traditional agriculture (bush/fallow cultivation).

CRYOCHREPTS and CRYUMBREPTS

Morphology

These soils are rare in Papua New Guinea and are only found at altitudes above 3400 m under cool, wet climates. Cryumbrepts by definition have thick dark A_1 horizons which may overlie a colour or structure B horizon (cambic horizon) while Cryochrepts have a thin or light coloured A_1 horizon but must have a cambic B horizon. The A_1 horizons are commonly between 20 and 50 cm thick and have black, very dark greyish brown or dark brown colours. This topsoil merges into an up to 80 cm thick, weakly developed B horizon or directly overlies rock rubble or consolidated parent material. Cryochrepts and Cryumbrepts are weakly to strongly acid in their topsoils becoming weakly acid to neutral with depth. Because of their commonly high organic matter content Cryumbrepts are commoner than Cyrochrepts. These soils were previously called alpine peat and humus soils (Haantjens 1970a; Rutherford and Haantjens 1965).

* These are by definition ⩾ 50 per cent in all subhorizons between depths of 25 cm and 1 m in the Eutropepts, and < 50 per cent in a similar depth zone for the Dystropepts.

Table 5.11
Chemical fertility data – Dystropepts (22 profiles) and Eutropepts (10 profiles)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	2	6	3	15	1	10	4	14	—	—	21	72	7	41	11	38	4	24	6	21	4*	24
Moderate	26	81	6	30	4	40	17	59	7	41	8	28	10	59	12	41	6	35	14	48	5†	29
Low	4	13	11	55	5	50	8	27	10	59	—	—	—	—	6	21	7	41	9†	31	8†	47
Total samples and percentage	32	100	20	100	10	100	29	100	17	100	29	100	17	100	29	100	17	100	29	100	17	100

*T = Topsoil, normally sampled with 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

* All samples Eutropepts.
† All samples Dystropepts.

Table 5.12a
Clay mineralogy of Dystropepts

Soil profile and horizon		Depth (cm)	Minerals of the clay fraction: X-ray analyses (Australia)	DTA-analyses (Netherlands)
W*-398	$-B_2$	15-25	K5,I3	—
	$-C_1$	55-65	K4,I4,Q3	—
	$-C_2$	110-120	I5,Q3	—
BK-P11	$-B_1$	5-15	H5,Gi2,Q1,Gi1	—
	$-B_{21}$	15-30	H5,Gi2,Go1	—
	$-B_{23}$	65-95	H5,Gi3,Go2	—
SP-P11	$-A_1$	0-7	K5,Sm1	—
	$-B_2$	35-70	K5	—
	$-C_1$	90-120	K5	—
SP-P26	$-A_1$	0-20	K2†,Ch and/or V2,M2	—
	$-B_2$	60-80	K2	—
	$-B_3$	150-165	K2	—
SP-P33	-AB	0-25	K5,Ch and/or V3,Sm1,I1	—
	$-B_{22}$	95-115	K5,Ch and/or V2,M2	—
SP-P42	$-B_2$	10-30	K5	—
SP-P43	$-B_1$	35-50	Ch and/or V5,K2	—
	$-B_3$	90-110	K5, Ch and/or V3,Sm1	—
WLS-P14	$-B_2$	30-45	—	K4,M4,Gi3
LRA-P1	$-B_{23}$	60-75	—	K4,Gi4
LRA-P3	$-B_2$	30-50	—	Gi4,K4
LRA-P7	$-B_{21}$	50-80	—	Gi4,K4
LRA-P13	$-B_2$	60-80	—	K4,Gi4
LRA-P52	$-B_1$	50-75	—	K4,Gi4,I2

* Refers to survey area: W = Wabag, BK = Buna-Kokoda, SP = Safia-Pongani, WLS = Wewak-Lower Sepik and LRA = Lower Ramu-Atitau.
† Soil apparently contains very little crystalline clay. For explanation of symbols see Table 5.12b.

Genesis

The formation of these soils is basically very similar to the previously described high altitude peat soils (Cryofolist, Cryohemist and Cryofibrist) with which they were grouped originally. Their genesis is largely determined by the build-up of organic matter. However, analytical data have shown that the organic matter contents are too low or their peaty surface horizons too thin to qualify them as Histosols. Where present, cambic B horizons are only slightly weathered as shown by their weakly acid to neutral soil reaction and weak structure development.

Table 5.12b
Clay mineralogy of Eutropepts

Soil profile and horizon		Depth (cm)	Minerals of the clay fraction: X-ray analyses (Australia)	Minerals of the clay fraction: DTA-analyses (Netherlands)
WLS-P10	-B_2	30-50	—	M and I5,Gi3,Go3
LRA-P21	-B_2	12-45	—	M5,Go2
Safia II 152	-B_1	5-20	K5,V3,Go2	—
	-B_2	25-45	K or H5, Go or He2, V or Ch1	—
	-C_{12}	60-75	K4, V or Ch4, Go or He1	—

Explanation of symbols:
K = kaolinite
H = halloysite
V = vermiculite
Ch = chlorite
I = illite
M = montmorillonite
Sm = smectite
Gi = gibbsite
Go = goethite
He = haematite
Q = quartz

Clay minerals are indicated as follows:
5 = more than half
4 = one-third to half
3 = one-fifth to one-third
2 = one-twentieth to one-fifth
1 = less than one-twentieth

Occurrence
These soils occur widely scattered above 3400 m throughout mountainous terrain such as Mount Giluwe, Mount Wilhelm, Mount Kubor and Mount Hagen. They are found on a great variety of parent materials.

Association
Cryochrepts and Cryumbrepts are found in close association with the high altitude Histosols (Cryofolist, Cryohemist and Cryofibrist), Cryaquepts and Cryorthents. Figure 3.10 shows this association together with data on landform and vegetation.

Fertility
Data on the chemical fertility of these soils are limited to two profiles which indicate generally high fertility levels due to high nitrogen contents and cation exchange capacities. However, owing to fixation by organic matter available phosphorus contents are expected to be low.

Land Use
Their occurrence only at altitudes at or above 3400 m in cool, wet climates make these soils unsuitable for agriculture except possibly grazing. Present land use is confined to hunting and gathering.

6 Vertisols

Vertisols are clima-lithomorphic soils typical of areas having a low and highly seasonal rainfall, where they are almost always found on calcareous rocks such as limestone and shale, and alluvial or colluvial deposits. They are uniformly textured soils with a high clay content and very slow permeability, which shrink and crack, and swell from one season to another (Plate 6.1). Vertisols generally have topsoils with a fine granular structure and subsoils characterised by a very plastic consistency. Expansion of these subsoils upon wetting, due to the presence of smectite clays, creates slickensides which are very common (Plate 6.2, colour section). Vertisols normally have black to dark grey colours, a

Plate 6.1 Vertisol (Pelludert) showing deep cracks. This soil occurs in the dry coastal area of the Western Province.

neutral to alkaline soil reaction, and commonly contain calcium carbonate concretions in their subsoils.

Vertisols have four suborders, two of which, namely the Uderts and Usterts, have been recorded in Papua New Guinea. *Uderts* require a more humid climate than the Usterts, are more widespread in occurrence and, by definition, have cracks that remain open for less than 90 cumulative days. The *Usterts*, by comparison, are confined to a narrow coastal strip in the central Papuan region where the annual rainfall drops to 1000 mm or less and the dry season is more pronounced and of relatively long duration. It is therefore expected that in this environment the cracks remain open for 90 or more cumulative days. Both Usterts and Uderts are further subdivided on the basis of their dominantly grey or black colours into Pelluderts and Pellusterts. Because of their very similar profile morphology these two great groups will be discussed together.

Vertisols were previously classified as alluvial black clay soils (Haantjens 1976), black earths (Haantjens 1970a) and dark cracking clay soils (Scott 1965).

PELLUDERTS and PELLUSTERTS

Morphology

These soils have A-C profiles. They have a 20 cm to over 100 cm thick, black to very dark grey A_1 horizon with a clay texture. This horizon gradually merges into a similarly textured dark grey, grey or greyish brown, mostly structureless C horizon with common brownish mottles and many slickensides or shearing faces. The C horizon is very to extremely plastic and sticky when wet, and very hard when dry. It often contains soft or hard calcium carbonate or iron/manganese concretions. Occasionally a transitional AC horizon may be present. Soil reaction is weakly acid in the topsoils, and increases gradually to neutral and alkaline in the subsoils. Plate 6.3 (colour section) shows an example of a Pelludert while detailed descriptions and analytical data for two profiles are given in Appendix I.

Genesis

The formation, nature and distribution of these soils are strongly related to climate, parent material and topography. These specific conditions favour the formation of expanding clays (montmorillonites) which, in a climate regime characterised by marked changes in moisture content, causes the typical swelling, shrinking and churning features of these soils.

Apart from being present in the original parent material, which appears to be restricted to lacustrine sediments deposited in alkaline and magnesium rich environments (Dudal 1965), montmorillonite may be formed during rock weathering, or by alkaline earths imported by seepage from adjacent uplands. It requires for its formation an ample supply of magnesium and calcium, the first playing an important role in the synthesis of montmorillonite, and the second maintaining a favourable pH for its formation (Dudal 1965). The stability of the clays formed depends, however, on the absence of substantial leaching which may be due to a relatively low rainfall combined with a slow permeability and poor drainage conditions in a material rich in clay. If these conditions are not fulfilled the montmorillonite can only remain in the soil if a continuous supply of alkaline earths is maintained, either from rock weathering or outside sources.

In Papua New Guinea, Pelluderts and Pellusterts are mostly formed on base rich parent materials (e.g. basic/ultrabasic rocks and calcareous sediments also containing magnesium) restricting the acidification of the soil profile. They are also predominantly found in the driest areas (1000-2000 mm precipitation); where they often occur in relatively wet, low lying positions (e.g. footslopes). The limited leaching of cations from the surface horizons, which is largely restricted to the wet season, is reflected in higher subsoils base saturation values. Some calcium carbonate may also be precipitated as soft segregations and/or hard nodules.

The effects of swelling, shrinking and self mulching are largely responsible for the deep and irregular penetration of organic matter into the soil, lack of horizon differentiation, absence of clay migration, and local microrelief formation.

The general dark colour of these soils does not appear to be solely due to organic matter, since this is not particularly high (see Figure 12.4). It was previously thought to be influenced by the presence of metallic oxides or other mineral constituents, but research by Singh (1956) has indicated that the colour is largely caused by the formation of a clay/organic matter complex. According to Dudal (1965) the organic matter may be adsorbed in the clay surface or even possibly be chemically bound to the clay. It has been suggested that the formation of the clay organic complexes is favoured by anaerobic conditions during the wet season, the organic matter fixed to the clay becoming resistent to decomposition and its stability being enhanced by the presence of calcium.

Occurrence

Pellusterts are confined to a dry coastal hill zone in the vicinity of Port Moresby, where they are found on small, flat plains and in drainage depressions, where accumulation of bases from seepage and run-on takes place. Scott (1965) estimated that they cover approximately 150 km^2 in the Port Moresby-Kairuku area. Pelluderts have been recorded very locally in small, isolated, slightly wetter areas. These include the far western part of the coastal plain of the Western Province, uplifted coral terraces along the north coast of the Huon Peninsula, flat to gently undulating slightly uplifted marine deposits and small alluvial flats in the Madang Province, and very gently sloping terrain composed of colluvium derived from volcanic rocks in the Eastern Highlands Province.

Association

In undulating to hilly terrain Pellusterts are associated with Haplustalfs, Ustropepts and Ustorthents. Pelluderts commonly occur with Tropudalfs and Eutropepts. In floodplain environments both Pellusterts and Pelluderts may also be associated with Fluvaquents and Tropaquents (Figure 3.5).

Table 6.1
Chemical fertility data - Pelluderts and Pellusterts (11 profiles)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	—	—	—	—	—	—	2	18	1	10	11	100	10	100	11	100	10	100	8	73	10	100
Moderate	7	88	2	n/a	1	n/a	6	55	5	50	—	—	—	—	—	—	—	—	3	27	—	—
Low	1	12	3	n/a	1	n/a	3	27	4	40	—	—	—	—	—	—	—	—	—	—	—	—
Total samples and percentage	8	100	5	n/a	2	n/a	11	100	10	100	11	100	10	100	11	100	10	100	11	100	10	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

Fertility

Data on the chemical fertility of eleven Pellustert and Pelludert profiles are listed in Table 6.1 and appear to indicate a generally moderate to high fertility level. As can be expected, CEC, TEB and BS values are all high. Nitrogen levels are dominantly moderate, and exchangeable potassium moderate to low. Data on available phosphorus are insufficient to draw any firm conclusions, three of the five topsoil samples showing low and two moderate values. Vertisols often have fairly high exchangeable sodium contents.

Land Use

Although having only a limited distribution, these soils appear to offer good agricultural possibilities, particularly for wetland rice and grazing.

With irrigation the Pellusterts and Pelluderts could probably support arable cropping such as cotton but tillage would be very difficult without suitable machinery, the soils becoming hard as concrete, shrinking and cracking deeply when dried. These tillage difficulties could also explain why these soils are at present not cultivated by the Papua New Guinea farmer. The upper terraces along the north coast of the Huon Peninsula are being successfully grazed, the pastures being mainly *Themeda australis* grasslands. However, many injuries, sometimes resulting in cattle losses, have been caused by the jagged limestone outcrops which are common in the vicinity of these soils.

7 Mollisols

Mollisols are slightly to moderately weathered soils which are found in environments ranging from the hot, dry subhumid lowlands to the cold wet highlands. Since they also form on many kinds of parent materials,* they are widely distributed throughout Papua New Guinea. They are characterised by the accumulation and decomposition of relatively large amounts of organic matter in a base rich environment. This is evidenced by their generally thick (≥ 25 cm), well developed, dark topsoils (mollic epipedons). The high content of bases is reflected in high base saturation values which, by definition, must be > 50 per cent, not only in the dark topsoil, but also in the B horizon if present. This B horizon may be a colour or structure horizon (cambic horizon) or a horizon containing presumably illuviated clay (argillic horizon). However, the A horizon may sometimes directly overlie unconsolidated deposits (e.g. alluvium), or weathered or hard rock (A-C profiles).

Mollisols have seven suborders, four of which have been found in Papua New Guinea. Their subdivision is mainly based on criteria related to wetness, parent material and climate. *Aquolls* are the poorly drained to swampy Mollisols showing strong gleying immediately below the dark topsoil. *Rendolls* are Mollisols formed in a wet, humid climate of low to moderate seasonality, on very highly calcareous materials, such as limestone. They are normally shallow soils and, for this reason, can have an A_1 horizon ≥ 10 cm thick if it directly overlies hard or broken rock.

Ustolls are well to imperfectly drained Mollisols occurring in areas with a relatively low rainfall and pronounced dry season. As a result they have soil moisture deficiencies during part of the year. Typically Ustolls are found under savanna vegetation. *Udolls* are the commonest of the Mollisols and occur throughout Papua New Guinea in a wet, humid climate of low to moderate seasonality and they are unlikely to have seasonal soil moisture deficiencies.

* Including volcanic ash deposits (or other pyroclastic materials) if the fine earth fraction, within a depth of 35 cm, has a bulk density of 0.85 or more or contains < 60% vitric volcanic ash. Presently Mollisols developed on ash have not been identified in Papua New Guinea.

ARGIAQUOLLS

Morphology

These are poorly to very poorly drained soils having finer textured subsoils (argillic horizons). Argiaquolls have a black, (very) dark grey, very dark greyish brown, or very dark brown, firm to friable A_1 horizon which is frequently mottled, and is between 25 and 60 cm thick. Its texture varies between sandy loam and clay loam. The A_1 horizon merges gradually into a thick, uniform, grey coloured or prominently grey, white, yellowish brown and/or brown mottled, B_2 horizon with a very plastic and sticky consistency. Small to moderate amounts of iron/manganese concretions are frequently present in both the horizons. Argiaquolls generally have a weakly acid to neutral soil reaction. They belong to soil groups previously described as dull meadow podzolic, and meadow podzolic soils (Haantjens 1968b).

Genesis

Argiaquolls are litho-hydromorphic soils formed on fine grained rocks with moderate to high clay contents. They are often found in low lying, level to very gently sloping terrain where water seepage and runoff can accumulate. In many profiles weathering of the parent material and clay illuviation have created perched water tables on the slowly permeable clay subsoil. This causes intermittent saturation as shown by the grey matrix colours and pronounced brown or yellowish brown mottling of the subsoil. Temporary wet conditions also restrict the breakdown of organic matter contributing to the formation of thick dark topsoils. Seepage from upslope adds bases, silica and other soluble materials which tend to accumulate in the soils following evapotranspiration during dry periods. The coarser textured surface horizons appear to have been formed by a combination of soil processes including clay illuviation, differential weathering, and possibly colluvial slope wash (see Chapter 2).

Occurrence

Argiaquolls occur only in small, widely scattered localities between sea level and 1500 m. Here they are restricted to low lying positions and are mainly developed on slowly permeable parent materials such as Pleistocene sediments, mudstones and siltstones.

Association

Their main association is with Tropaquepts, Haplaquolls and Tropaqualfs.

Fertility

Argiaquolls have not been extensively sampled and analytical data are restricted to five profiles. CEC, TEB and BS values range from high to moderate, high values being more common. Nitrogen contents appear to be moderate and exchangeable potassium and available phosphorus values mostly low.

Land Use
This is possibly restricted to wetland rice cultivation at low altitudes, and to limited grazing. Their patchy distribution, however, makes them unsuitable for any large scale development, and at present they are not cultivated.

HAPLAQUOLLS

Morphology
Haplaquolls are the commonest great group of the Aquoll suborder. They have mainly developed on Recent or older, alluvial or colluvial deposits and show little profile development. B horizons are rarely present.

The soils have a black to very dark greyish brown, plastic or firm clay A_1 horizon between 25 and 50 cm thick. This horizon merges into a grey, olive grey or greyish brown coloured subsoil, with common to many brown or yellowish brown mottles. Texture is mostly silty clay or clay, but may vary between silt loam and clay loam. Small amounts of firm to soft concretions, or in colluvial derived soils weathered rock fragments, are common. Haplaquolls have an alkaline soil reaction when found near the coast but are weakly acid inland. They belong to soil groups formerly called poorly drained old alluvial soils, alluvial soils and meadow soils (Haantjens 1970a, 1976). Plate 7.1 (colour section) shows a typical example of a Haplaquoll developed on alluvium.

Genesis
The main genetic process has been the development of a thick, dark A_1 horizon. Because these soils are wet during part of the year, their organic matter is much more slowly mineralised than in well aerated soils and, consequently, the organic matter content of the A horizon is relatively high. Although the subsoil may have undergone some weathering, leaching and biological activity this, with a few exceptions, has not altered the parent material significantly enough to form a B horizon.

Occurrence
Haplaquolls are found throughout Papua New Guinea mainly on flat to very gently undulating terrain such as floodplains, low terraces, and tidal flats.

Association
These soils are most closely associated with other poorly drained alluvial soils such as Fluvaquents and Hydraquents, and sometimes locally with various Histosols (organic soils).

Fertility
Data limited to four sites indicate a generally moderate level of chemical fertility. TEB and BS values are high, while CEC and exchangeable potassium contents range between moderate and high. Nitrogen values are moderate and

available phosphorus contents (three samples) are moderate or low. Locally, near the coast these soils may have high exchangeable sodium contents.

Land Use

Like the Argiaquolls these soils have a limited, rather patchy distribution. Poor drainage and occasional flooding greatly restrict their use for arable and tree crops but grazing and, in the lowlands, some wetland rice cultivation should be possible. In coastal areas, some of these soils may have high exchangeable sodium contents and excess salts need first to be flushed from the soil by wet season rains. They are not cultivated at present.

RENDOLLS

Morphology

Rendolls are shallow to very shallow lithomorphic soils formed on highly calcareous parent materials such as limestone. They are widely distributed throughout the wetter parts of Papua New Guinea. Typically they have black and, less frequently, very dark brown or very dark greyish brown, clay loam, or clay A_1 horizons with a strong fine crumb or granular structure and a very friable to firm consistency. This A_1 horizon is between 10 and 50 cm thick. Its structure may grade from granular or crumb in its upper part to a medium to strong subangular blocky or blocky lower down. Weathered rock fragments or calcium carbonate concretions are present and the amount increases with depth. Normally this horizon abruptly overlies massive limestone. Rendolls have a weakly acid to neutral soil reaction, the pH increasing gradually with depth. They belong to great groups formerly described as rendzinas, limestone soils and shallow black structured clay soils (Haantjens 1964b, 1968b, 1976). Plate 7.2 (colour section) is a typical example of a Rendoll developed on a steep hillslope near Passam in the East Sepik Province.

Genesis

Rendolls are relatively young soils formed by the gradual dissolving and removal of calcium carbonate under the influence of carbonic acid (H_2CO_3) formed by the solution of atmospheric carbon dioxide. H-ions from carbonic acid assist the dissolution of $CaCO_3$ and the free Ca^{2+} so formed may then be retained on the exchange complex or leached downwards through the profile, together with HCO_3^- ions. This process results in the formation of a highly calcium saturated clay residue in which the clays remain flocculated as evidenced by the generally well developed structure of these soils. The high calcium ion content also appears to create favourable conditions for the rapid mineralisation of the organic matter. However, the fact that soils high in exchangeable calcium often have higher organic matter contents than soils low in exchangeable calcium, as reflected in their dark topsoil colour, has led to the conclusion that calcium helps to preserve humic substances. Stevenson (1965) has suggested that either calcium humates and organic-mineral compounds are formed which are less available to micro-organisms, or that calcium coagulates humic substances and prevents their dispersion and subsequent removal. In many locations these soils appear to have been intermixed with small amounts of volcanic ash.

Occurrence

Rendolls are widespread throughout Papua New Guinea in moderately to steeply sloping limestone terrain (Plate 7.3), and on recent or uplifted coral terraces. Locally they also occur on beach ridges rich in shell fragments (see Figure 3.5). Their altitudinal range varies between sea level and 3000 m. Figure 7.1 shows the major distribution of these soils.

Association

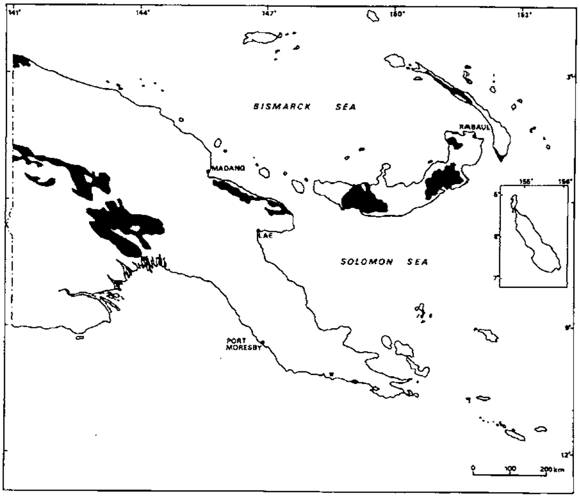
Rendolls are closely associated with Troporthents, Eutropepts and bare rock exposures in hilly or mountainous terrain. On coral terraces they grade at higher altitudes (with age) into Rhodudalfs and Rhodustalfs.

Fertility

Data are restricted to seven profiles developed on coral terraces and indicate generally moderate to high fertility levels. CEC, TEB and BS figures are all dominantly high, while nitrogen and available phosphorus levels range between moderate and high. Exchangeable potassium varies from low to high, with moderate values being the most common.

Plate 7.3 Karst landscape with limestone towers south of Nenja in the Southern Highlands Province. These areas are characterised by Rendolls, Troporthents and bare rock outcrops.

Fig. 7.1 Major distribution of Rendolls and Troporthents



Land Use

Although they have good physical properties and a moderate to high general fertility level, these shallow soils mostly occur in rugged terrain with moderate to steep slopes and, consequently, are unsuitable for agriculture. Exceptions are the deeper soils found on the coral terraces near the coast which are suitable for arable cropping and grazing. However, the common occurrence of rock outcrops and stones prevents any large scale cultivation. Many of the soils on the coral terraces are cultivated.

NATRUSTOLLS

Morphology

Natrustolls are well drained soils characterised by very high exchangeable sodium contents (> 15 per cent), and occur in relatively dry, highly seasonal climates. They have a black, very dark grey or very dark greyish brown, medium to fine textured A_1 horizon which has a friable to firm consistency, a fine to coarse angular blocky structure and are between 25 and 35 cm thick. When dry this horizon often becomes massive, very hard, and appears to have a rapid runoff. It grades into a 10 to 20 cm thick dark brown or black transitional horizon containing weathered rock fragments or chert gravel which, in turn, grades into a greyish brown, massive, mottled clay, B_2 horizon. Natrustolls most commonly show a pronounced increase in clay content with depth. Soil reaction is weakly acid at the surface increasing to neutral or alkaline in the deep subsoil. Natrustolls belong to a great soil group formerly called texture contrast soils (Scott 1965).

Genesis

Natrustolls are slightly to moderately weathered soils characterised by moderate to high levels of exchangeable sodium and magnesium in their exchange complex. These levels are probably largely the result of groundwater rich in sodium and magnesium rising seasonally to a shallow depth. Clay dispersion is facilitated by the high amounts of sodium and magnesium ions resulting in the formation of B_2 horizons containing illuviated clay. Clay illuviation is further enhanced by the strongly seasonal climate (see Chapter 8). Their common occurrence in low topographic positions suggests, however, that their development may also have been influenced by colluvial material derived from upslope.

Occurrence
Natrustolls have a very limited distribution, being restricted to a few, small, low rainfall areas found south-east of Maprik in the East Sepik Province, and in the narrow coastal belt centred around Port Moresby in the Central Province. They occur mostly on gently sloping footslopes and moderately sloping side slopes of low hill ridges.

Association
Natrustolls with finer textured subsoils occur mainly in association with Haplustalfs and Natrustalfs, while the uniform textured Natrustolls are mostly found in association with Haplustolls and Eutropepts.

Fertility
Analytical data are restricted to two profiles which indicate high to moderate CEC, TEB and BS values and moderate to low nitrogen and exchangeable potassium levels. The one topsoil sample analysis for available phosphorus has a low value.

Land Use
High exchangeable sodium contents, and massive, hard setting topsoils with a high runoff propensity during the wet season render these soils generally unsuitable for agriculture apart from grazing. They are not at present cultivated.

CALCIUSTOLLS

Morphology
Calciustolls are found in relatively dry, highly seasonal climates and are characterised by the high amounts of calcium carbonate concretions in their B_2 horizon. They have a black to very dark brown A_1 horizon with a fine crumb or fine subangular blocky structure, are friable when moist, and very hard when dry and have a clayey texture. This A_1 horizon is between 25 and 30 cm thick and merges gradually into a massive, (dark) brown, olive brown or yellowish brown, sandy clay or silty clay B_2 horizon. Consistency is friable to firm when moist and plastic and sticky when wet. Calciustolls have a weakly acid soil reaction, gradually becoming alkaline with depth. To date they have

been found only on sedimentary rocks. They belong to soils formerly called brown clay soils (Scott 1965).

Genesis

Calciustolls are clima-lithomorphic soils typical of low rainfall areas with sedimentary rocks of high calcium content. These sediments are relatively young and have been subjected to only mild leaching, resulting in sufficient bases being retained in the subsoil to form segregations of calcium carbonate.

Occurrence

These soils are restricted to very small occurrences in the dry narrow southern part of the coastal belt of the Central Province where their total area is less than 100 km^2 (Scott 1965). However, they may occur in other relatively dry areas. They are found in footslopes and gently undulating terrain of low relief slopes which are generally less than 4°.

Association

Calciustolls are found mainly in association with Argiustolls and Ustropepts.

Fertility

Analytical data are restricted to two profiles. CEC, TEB, BS and exchangeable potassium values are all high, while nitrogen values are barely moderate. Available phosphate contents, in the absence of any data, are thought to be low due to the presence of free calcium carbonate which reduces the solubility of calcium phosphates.

Land Use

Although of very limited distribution, these soils appear generally well suited for arable crops, tree crops and grazing. Soil moisture stress during part of the year is the most serious limitation and careful crop selection, particularly with tree crops, is essential. Little, if any, of this land is cultivated at present.

ARGIUSTOLLS

Morphology

Argiustolls are well to imperfectly drained soils found in low rainfall areas and have heavy textured brown subsoils. The A_1 horizon is black, very dark brown, or very dark greyish brown, with a sandy clay loam or clay texture, a fine crumb structure, and friable consistency. This horizon is mostly between 20 and 40 cm thick, but may be thinner if the very dark colours and relatively high organic matter content continue in the B horizon. The A_1 horizon merges gradually into a (very) dark brown to brown, or yellowish brown, sandy clay to heavy clay B_2 horizon with a subangular blocky structure, and a consistency which is hard to very hard when dry and plastic and sticky when wet. Small amounts of gravel and weathered rock fragments may be present. With depth, rock fragments become more numerous and the clay content decreases as the B_2 horizon gradually merges into weathered parent material composed of sedimentary or volcanic rocks. Some mottling may be present in the deeper subsoil. Argiustolls have a neutral soil reaction, with pH values increasing slightly with depth. These soils were previously classified as brown clay soils (Scott 1965).

Genesis

Argiustolls are clima-lithomorphic soils which are formed from fine grained rocks with only moderate clay contents. Upon weathering these rocks become relatively permeable, giving rise to well aerated conditions which are reflected in the dominantly brown to dark brown subsoil colours. Argiustolls have a high base saturation status, largely attributable to their basic parent materials, although seepage and runoff from upslope could also have an influence on this. The higher clay content of the subsoil appears to have been caused by leaching and clay movement, the latter process being enhanced by favourable climatic conditions. However, differential weathering and soil layering should also be taken into account when considering the formation of the heavier textured subsoil.

Occurrence

Argiustolls are fairly common in the small dry coastal belt of the Central Province, particularly on the very broad gentle footslopes of low ridges to the north-east of Port Moresby. There are also localised occurrences in valley heads and re-entrants of branching and low rounded ridges in the same area. These soils are somewhat more common in occurrence than the previously discussed Natrustolls.

Association

Argiustolls are found mainly in association with Haplustolls, Calciustolls, Ustropepts and Haplustalfs.

Fertility

Data are available for four profiles (Bleeker and Healy 1980). These indicate high CEC, TEB and BS levels. Percentage nitrogen ranges between low and high while exchangeable potassium has high to very high values in three samples, and a moderate level in the fourth. There is no information on available phosphorus.

Land Use

Being mainly well drained and possessing apparently moderate to high fertility, these soils seem well suited for arable crops, tree crops and pastures. Seasonal moisture deficits, which could have constituted a major limitation to their use, are somewhat offset by the greater than normal soil depth and rooting range. Little of this land is cultivated.

HAPLUSTOLLS

Morphology

These are young, slightly weathered soils with A-C profiles and have been developed on recently deposited materials such as alluvium and beach sands. These Ustolls also are restricted to relatively dry, highly seasonal climates. They have black, very dark greyish brown or dark brown A_1 horizons generally between 40 and 60 cm thick. Both texture and consistency vary with the parent material. Haplustolls developed on beach sands consist of loose, single grain fine sands or loamy sands. Those developed on alluvium are mainly clays, very hard when dry, firm to very firm when moist, and plastic and sticky when wet. These soils often have a fine subangular blocky A_1 horizon while the subsoils are dominantly massive. Those developed on fine textured alluvium are closely related to the Vertisols. However, they do not have shearing faces or sufficiently deep cracks and, accordingly, have been grouped with the Mollisols. Haplustolls, whether developed on beach sands or alluvium, have brown to greyish brown C horizons with sandy and clayey textures respectively. Shell fragments or secondary calcium carbonate concretions are present in the subsoil. Haplustolls have a neutral over alkaline soil reaction. They belong to soil groups previously called dark cracking clay soils and beach soils (Scott 1965).

Genesis

Having been formed on recently deposited littoral or fluvial materials, Haplustolls have been subjected to little soil development, except for the incorporation of organic matter in the surface horizon and some leaching of carbonates which have been redeposited lower down the profile as calcium carbonate segregations. All Haplustolls have calcium rich parent materials such as coral reef limestone, beach sands rich in shell fragments, or other calcareous sediments.

Occurrence

Haplustolls are confined to small, isolated occurrences in the narrow dry coastal belt of the Central Province. The sandy Haplustolls are mainly found on the inland side of the beach ridges, whilst the fine textured soils are confined to the raised coral platforms covered by alluvium and to low lying alluvial plains.

Association

Haplustolls are found along with other young soils developed on littoral and alluvial deposits such as the Fluvaquents, Tropofluvents, Tropopsamments and Psammaquents.

Fertility

Chemical fertility data are available for only three profiles, two of which have been developed on alluvium and the other on beach sand (Bleeker and Healy 1980). CEC, TEB and BS values are all high, but this is to be expected from the last two values, owing to the presence of free calcium carbonate in the soils. Percentage nitrogen varies between moderate and high, and exchangeable potassium between low and high, with one very high value occurring in the beach sand topsoil. There are no data for available phosphorus.

Land Use

Haplustolls appear suited to arable crops, tree crops and grazing although seasonal soil moisture deficiencies could prove the most serious limitation, particularly with those soils developed on beach sands. The dominantly fine textured alluvial soils are difficult to cultivate by hand. Only some of the sandy soils are cultivated.

ARGIUDOLLS

Morphology

Argiudolls, along with the Hapludolls, are the most common Mollisols, being widespread throughout the wetter parts of Papua New Guinea. Although they can have a wide variety of parent materials, they are to be found mostly on fine grained sedimentary rocks or old fine textured alluvial deposits. This is responsible for their often imperfect drainage which is reflected in some mottling of the subsoil, the mottling increasing gradually with depth. Argiudolls are found up to 2000 m but occur mainly below 1000 m. Their wide distribution and formation on a great variety of parent materials is reflected in their variable profile morphology, as shown by differences in colour and texture.

Their A_1 horizon is usually very dark greyish brown to very dark brown, but may also be black or dark reddish brown. This horizon is between 25 and 55 cm thick and has textures ranging between sandy loam and clay with the coarse textures being most common in soils developed on the old alluvial deposits such as those found in the East and West Sepik Provinces. Soil consistency reflects the many texture differences which vary from slightly hard to very hard when dry, very friable to very firm when moist, or slightly plastic to very plastic and sticky when wet. The A_1 horizon, in turn, gradually merges into a very plastic or very firm, fine textured, silty clay to (sandy) clay B_2 horizon. Slow permeability in this horizon is evident from the mainly yellowish brown or (dark) brown matrix colours and the greyish brown, brownish grey or grey mottles which become more pronounced and more frequent with depth. This subsoil occasionally has numerous iron/manganese concretions. A uniformly coloured reddish brown, or yellowish red, B_2 horizon is sometimes present, particularly in the well drained and more mature Argiudolls. The B_2 horizon is normally so thick that the underlying weathered parent material is rarely encountered. Argiudolls are weakly acid. They were previously variously grouped as moderately weathered well drained old alluvial soils, immature mottled residual soils, immature brown soils on sedimentary rocks, and the more mature uniform red and yellow clays and red and yellow earths (Haantjens 1968b, 1976).

Genesis

As discussed in the previous section, Argiudolls comprise soils which have quite marked differences in profile morphology. They include both immature and more mature soil profiles, as shown by their variable soil colours and the wide range of landforms and parent materials on which they occur. Their weakly acid soil reaction, combined with a high to moderate base saturation in the subsoils, suggests that only moderate leaching has taken place. The main soil forming processes, therefore, appear to stem from the accumulation of organic matter in the A_1 horizon, some translocation of iron from the A to B horizon, together with clay transport. Although increase in their clay content with depth is generally less marked in comparison to the Argiustolls, it nevertheless seems likely that this increase has not resulted from clay illuviation alone. It appears more likely that the finer textured B_2 horizons have formed by a variety of processes including clay illuviation, soil layering due to colluvial action, and clay destruction in the A horizon followed by the removal of the weathering products (mainly silica and alumina) by leaching. Iron and manganese have been largely removed. In the freely drained more mature soils, this is presumably caused by leaching but, in the imperfectly drained soils, seems more likely to result from periodic waterlogging above the impermeable clay subsoil.

Occurrence

Argiudolls are commonly found in gently sloping undulating terrain underlain by sedimentary rocks, river terraces, or colluvio-alluvial fans. Occasionally they occur on moderate slopes of hills and mountains which have volcanic rocks for parent material.

Association

Argiudolls are found in association with many other soils because of their wisespread, if somewhat patchy, distribution. However, they are mostly found together with Hapludolls, Tropofluvents, Tropudalfs, Eutropepts, Dystropepts and Tropaquepts.

Fertility

Data on the chemical fertility of seventeen Argiudolls are given in Table 7.1. The influence the differing parent materials and landforms have on these soils is reflected in their variable fertility levels. From the analytical data available, it appears that the lowest values are for the soils developed on Pleistocene sediments. However, in more than 75 per cent of the samples, CEC, TEB, BS and topsoil exchangeable potassium values range between moderate and high, whereas subsoil exchangeable potassium ranges between moderate and low.

Table 7.1
Chemical fertility data - Argiudolls (17 profiles)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	—	—	2	15	2	15	7	41	—	—	7	41	11	65	12	71	11	65	13	76	10	59
Moderate	15	88	1	8	1	8	6	35	10	59	9	53	5	29	5	29	6	35	4	24	7	41
Low	2	12	10	77	10	77	4	24	7	41	1	6	1	6	—	—	—	—	—	—	—	—
Total samples and percentage	17	100	13	100	13	100	17	100	17	100	17	100	17	100	17	100	17	100	17	100	17	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

Similarly, percentage nitrogen values are moderate and available phosphorus values low.

Land Use

These soils have no serious limitations for agriculture apart from their rather patchy distribution. Arable crops and grazing in particular offer good prospects, but applications of phosphate fertilisers will be necessary, particularly on the soils developed on Pleistocene sediments. Tree crops are slightly less suitable as the slowly permeable heavy textured subsoils can cause waterlogging over short periods. Many Argiudolls are used for bush-fallow cultivation.

HAPLUDOLLS

Morphology

Hapludolls are widely distributed throughout the wetter region, but are commonest in the lowlands below 1000 m. They are young soils characterised by high (> 50 per cent) base saturation figures throughout the soil. Typically they have A-C profiles, although in some cases, in more developed soils, they have A-B-C profiles.

Hapludolls have well developed black, (very) dark brown, or very dark greyish brown, A_1 horizons generally between 25 and 60 cm thick. Locally this A_1 horizon is less than 25 cm thick in shallow soils such as those found in moderately to steeply sloping terrain. Normally this A_1 horizon overlies an olive brown, brown or dark greyish brown, C horizon which commonly is faintly mottled. This C horizon is often fine textured, structureless, of firm consistency when moist, and plastic and sticky when wet. On colluvium or alluvium, however, the C horizon may overlie a buried profile. Occasionally, the A_1 horizon merges into a dark brown, olive grey or dark grey fine textured B_2 horizon between 25 and 40 cm thick. Since Hapludolls mostly occur on stratified unconsolidated materials such as alluvium, colluvium or fan deposits, the soils may show a considerable variation in texture, both within and between soil profiles. Hapludolls are dominantly neutral or weakly acid in reaction but subsoils or whole profiles may locally also be alkaline, particularly in slightly drier areas. They are well to imperfectly drained. Hapludolls were previously grouped as young alluvial soils, well drained old alluvial soils, moderately well drained alluvial soils, brown forest soils and immature soils on sedimentary rocks (Haantjens 1968b, 1976; Scott 1965). Plate 7.4 (colour section) shows a Hapludoll developed on colluvio-alluvium along the Upper Ramu River.

Genesis

Apart from the differentiation of a well developed thick A_1 horizon due to organic matter accumulation and structural development, there is little other evidence of soil formation. The A_1 horizon is largely caused by the reduction

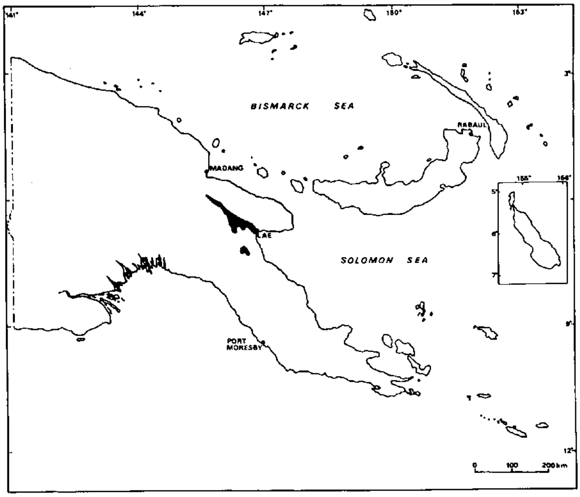


Fig. 7.2 Major distribution of Hapludolls and Tropopsamments

or cessation in the deposition of sedimentary material and melanisation of the soil.* Although the subsoil may have been subjected to some leaching and biological activity, these processes have not, except in a few cases, sufficiently altered the character of the parent material to form a cambic B horizon.

Occurrence

Hapludolls are most common in flat to very gently undulating terrain such as plains, fans and ridge crests throughout the lowlands below 1000 m, but occasionally are also found at higher altitudes. Their parent materials vary from volcanic to metamorphic or sedimentary rocks but Hapludolls dominate on colluvial and alluvial deposits. Their single largest occurrence is on the more stable surfaces of the Markham Valley (Figure 7.2), where they are found mainly in association with Tropopsamments and have been described by Zijsvelt (1973). They are probably also widespread on the Bulolo fans.

Association

On alluvial or colluvial parent materials, Hapludolls are usually found in association with Tropopsamments, Tropofluvents, Troporthents, Tropaquents and Haplaquolls. On consolidated rocks, however, they are mostly associated with Eutropepts, Dystropepts and Tropudalfs.

Fertility

Chemical fertility data for thirty-five soil profiles are given in Table 7.2. CEC, TEB and BS values are dominantly high, while nitrogen values are all moderate. However, both exchangeable potassium and available phosphorus values vary markedly, which appears to be related to both parent materials and mineral reserve. For instance, although data are limited, values obtained from

* Melanisation (Buol *et al.* 1973) refers to changes in colour value in the soil caused by an increase in organic matter content.

Table 7.2
Chemical fertility data - Hapludolls (35 profiles)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	—	—	7	32	6	40	10	29	3	12	30	88	19	76	31	89	21	87	25	71	22	92
Moderate	35	100	9	41	3	20	19	56	11	44	4	12	6	24	4	11	3	13	10	29	2	8
Low	—	—	6	27	6	40	5	15	11	44	—	—	—	—	—	—	—	—	—	—	—	—
Total samples and percentage	35	100	22	100	15	100	34	100	25	100	34	100	25	100	35	100	24	100	35	100	24	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

Table 7.3
Chemical fertility data (NPK) of Hapludolls in the Markham Valley (modified after Zijsvelt 1973)

	%N		Available P (ppm) (Olson)		Exchangeable K (meq %)	
Nutrient Level	topsoil only*	%	'whole' soil†	%	'whole' soil†	%
High	—	—	—	—	56	98
Moderate	60	92	50	83	1	2
Low	5	8	10	17	—	—
Total samples and percentage	65	100	60	100	57	100

* Refers to topsoil only (0-25 cm)
† Refers to topsoil (0-25 cm) and subsoil (50-75 cm) and obtained as follows:
If subsoil figures are higher than topsoil figures, use mean value.
If subsoil figures are one class lower than topsoil figures, use topsoil figures only.
If subsoil figures are more than one class lower than topsoil figures, use mean value.

recent alluvial soils (Madang Province) are higher than those for the weathered Pleistocene sediments (East and West Sepik Provinces). Nitrogen, phosphorus and potassium data collected by Zijsvelt (1973) from Hapludolls occurring in the Markham Valley are given in Table 7.3. This information clearly shows high exchangeable potassium, and moderate nitrogen and available phosphorus contents. Zijsvelt (1973) noted that the highest nitrogen and available phosphorus values occurred in the western part of the survey area. Presence of nitrogen is related to the annual precipitation, highest values commonly being found in soils of the higher rainfall areas. Highest available phosphorus values generally occur in soils where the pH value is lowest. The lowest pH values are found in the western part of the area where, because of higher annual rainfall, leaching is greatest. According to the author, the pH of the Markham Valley soils is mostly within the 6-9 range. Alkaline soils appear to be partly responsible for deficiencies in trace elements such as zinc.

Land Use

Hapludolls seem well suited for arable crops, tree crops, pastures and, on the medium to fine textured colluvio-alluvial deposits, also wetland rice cultivation. In the Markham Valley they are being extensively used for grazing. A sugar estate has recently been established at Gusap in the far western part of the valley. By 1983 this estate is expected to produce 330 000 tonnes of cane and about 32 000 tonnes of sugar, making Papua New Guinea self sufficient.

Few of these soils are at present cultivated by the local population.

8 Alfisols

Alfisols are moderately weathered soils which, by definition, have horizons containing translocated clay (argillic horizon) with a moderate to high base saturation.* Since an argillic horizon, as defined in the USDA scheme, is difficult to identify in the field or by standard laboratory procedures, different criteria have been set for its identification in Papua New Guinea (see Chapter 2).

Like the Entisol, Inceptisol and Mollisol orders, Alfisols are common throughout Papua New Guinea and have a wide variety of parent materials and climate regimes. There are five suborders, three of which have been recorded in Papua New Guinea. *Aqualfs* are the poorly to very poorly drained Alfisols which have seasonally high water tables and which are subjected occasionally to wet season flooding. *Ustalfs* are the well drained Alfisols which occur in relatively low rainfall areas with a pronounced dry season resulting in soil moisture deficiencies. *Udalfs* are also well drained soils but occur in wet, humid climates with a low to moderate seasonality and have little or no soil moisture deficiencies.

PLINTHAQUALFS

Morphology

Plinthaqualfs have moderately developed very dark grey, grey or very dark greyish brown A_1 horizons between 15 and 45 cm thick. Commonly this A_1 horizon overlies, with an abrupt or clear boundary, a dark grey to grey A_2 horizon between 15 and 30 cm thick, commonly containing a low amount of small hard concretions and/or bleached fine sand or silt grains. When present, this A_2 horizon abruptly overlies a prominently grey, red, and brown mottled, very plastic, impermeable clay B_2 horizon with low to high amounts of iron concretions and which is 50-100 cm thick. This iron-rich, humus-poor material

* Normally more than 35 per cent at 125 cm below the argillic horizon or 180 cm below the surface.

occurring in the B_2 horizon is composed of clay with quartz and other diluents and is called plinthite (Plate 8.1, colour section). Plinthite changes irreversibly into an ironstone hardpan or irregular aggregates when exposed to repeated wetting and drying (Plate 8.2). With increasing depth the red and brown mottling decreases gradually, the deep subsoil becoming light grey and white coloured within the zone of the permanent water table. The texture of the surface horizons (A_1 and A_2) may vary between loamy sands and clays giving rise to either abrupt or gradual increases in clay content with depth. Plinthaqualfs have a strongly acid soil reaction, their pH increasing slightly with depth. They belong mostly to great groups previously described as meadow podzolic soils, dull meadow podzolic soils and meadow soils (Haantjens 1968b, 1970a).

Genesis

The formation of the Plinthaqualfs is very similar to that of the associated Plinthaquults (Chapter 9). Weathering, however, has not been strong enough to completely remove the bases by leaching as reflected in the higher base saturation in the deep subsoil. Strong gleying has, however, developed in both Plinthaqualfs and Plinthaquults, due to a rising groundwater table, as well as rainwater ponding on the very slowly permeable subsoil during the wet season. Iron and manganese have largely been lost from the A horizon(s) under influence of acid leaching and waterlogging but some remain concentrated as concretions in the lower A_2 and/or B_2 horizon. Oxidation and reduction processes and concentration of iron as hydrated oxides have produced the characteristic grey, brown and red mottling patterns.

Plate 8.2 Plinthite, hardened irreversibly into massive blocks of lateritic ironstone. This exposure is located on a footslope near Port Moresby in the Central Province.

Occurrence
Plinthaqualfs are found locally in the East and West Sepik Provinces on flat to very gently sloping parts of broad depressions of undulating to rolling country consisting of Pleistocene sediments and other fine textured sedimentary rocks. They also occur very locally on gently sloping fan surfaces in the Highland Provinces.

Association
They are mostly associated with both the Plinthaquults and their better drained counterparts the Plinthudults which have slightly lower base saturation figures.

Fertility
Analytical data on fertility are available for five profiles. CEC, BS and percentage nitrogen values are dominantly moderate while TEB, available phosphorous and exchangeable potassium values vary between moderate and low. These soils may also have trace element deficiencies similar to the Plinthaquults (see Chapter 9).

Land Use
Poor drainage conditions and seasonal flooding render these soils unsuitable for arable and tree crops. Wetland rice cultivation appears to offer some potential although it would require flood control measures and considerable fertiliser input. Grazing therefore appears to be the best type of land use. Plinthaqualfs are largely uncultivated.

TROPAQUALFS

Morphology
Tropaqualfs are poorly to very poorly drained soils having moderately developed, very dark grey or very dark greyish brown, friable to firm A_1 horizons, generally between 10 and 30 cm thick, but up to 80 cm thick in localised areas. Texture varies between medium and fine, sandy loam, clay loam and clay being most common. This A_1 horizon has a clear boundary overlying a slowly permeable, very plastic and sticky, grey to light grey, brown and yellowish brown mottled, clay B_2 horizon between 20 and 100 cm thick. Occasionally a thin, dark grey, transitional horizon may be present between the A_1 and B_2 horizon. The B_2 horizon in turn merges gradually into a variable coloured, but less clayey, C_1 horizon containing a few weathered rock fragments which become more numerous with depth. Tropaqualfs are mostly weakly acid in the surface horizon gradually becoming neutral or alkaline in the deep subsoil. In those soils developed on calcareous sedimentary rocks, calcium carbonate concretions may be present in the subsoil. Tropaqualfs were formerly mainly called meadow podzolic soils,

Table 8.1
Chemical fertility data - Tropaqualfs (11 profiles)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	2	18	1	11	2	22	2	20	2	18	6	60	6	55	3	33	5	46	3	33	8	73
Moderate	6	55	3	33	1	11	5	50	5	46	4	40	5	45	6	67	6	54	6	67	3	27
Low	3	27	5	56	6	67	3	30	4	36	—	—	—	—	—	—	—	—	—	—	—	—
Total samples and percentage	11	100	9	100	9	100	10	100	11	100	10	100	11	100	9	100	11	100	9	100	11	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

meadow soils, gleyed plastic heavy clay soils and weathered gleyed soils (Haantjens 1964b, 1968b, 1970a; Rutherford and Haantjens 1965).

Genesis

This is almost identical to the Plinthaqualfs except that weathering and leaching have been less pronounced. The Tropaqualfs are younger soils with higher base saturation levels than the Plinthaqualfs and lack the pronounced red mottling often characteristic for plinthite. Occasionally, on calcareous parent materials, some of the excess leachates may be precipitated as calcium carbonate segregations in the deep subsoil. Since the subsoil is usually saturated for most of the year, the soil turns grey owing to reduction and partial removal of iron. Part of this iron may then become concentrated and form brown and yellowish brown mottles when exposed to air during dry periods.

Occurrence

Tropaqualfs are found throughout Papua New Guinea on flat to gently sloping terrain comprising fine textured sedimentary rocks or their colluvio-alluvial derivatives. Typical associated landforms include drainage depressions, broad ridges, fan surfaces and gentle slopes.

Association

Their main association is with their better drained counterparts the Tropudalfs although in neighbouring terrain with steeper slopes they may grade into Eutropepts and Dystropepts.

Fertility

Data for eleven profiles are listed in Table 8.1. Predictably, CEC, TEB and BS values are high or moderate in both topsoils and subsoils of all profiles. On the other hand, nitrogen, potassium and phosphorus values vary considerably, which appears to be caused largely by the wide range of altitudes and parent materials. Data indicate a higher fertility level in highland soils which is probably related to the higher organic matter content. In contrast, lowland soils developed on Pleistocene sediments appear to have the lowest fertility levels. Clay mineral data for eight samples representing five profiles are given in Table 8.2 and indicate a somewhat mixed composition; montmorillonite with kaolinite, or kaolinite with illite being commonest.

Land Use

Poor drainage conditions together with flooding on low-lying sites render Tropaqualfs unsuitable for most types of agriculture. Possible exceptions are grazing and wetland rice cultivation on flat to very gently sloping terrain at low altitudes.

Table 8.2
Clay mineralogy of Tropaqualfs

Soil profile and horizon		Depth (cm)	Minerals of the clay fraction: X-ray analyses (Australia)	Minerals of the clay fraction: DTA-analyses (Netherlands)
SP*-P19	-A_1	0-10	M5,K2	—
	-B_{21}	30-50	M5,K2	—
WLS-P15	-B_{23}	50-75	—	K4,M4,Gi3
LRA-P17	-B_{22}	35-45	—	M5,HI3
MT-P4	-B_2	40-60	K4,I4,Q3	—
	-C	85-105	K4,I4,Q3	—
GMH-P14	-B_2	100-120	—	K5
GMH-P20	-B_2	75-100	—	MH5,K2

Explanation of symbols: K = kaolinite; MH = metahalloysite†; M = montmorillonite; I = illite; HI = hydrous iron oxides; Gi = gibbsite; Q = quartz

Clay minerals are indicated as follows:
5 = more than half
4 = one-third to half
3 = one-fifth to one-third
2 = one-twentieth to one-fifth
1 = less than one-twentieth

* Refers to survey area:
SP = Safia-Pongani
WLS = Wewak-Lower Sepik
LRA = Lower Ramu-Atitau
MT = Mendi-Tari
GMH = Goroka-Mount Hagen

† metahalloysite is dehydrated halloysite.

NATRUSTALFS

Morphology

Natrustalfs are typically found in low rainfall areas having a pronounced dry season and a vegetation of eucalypt savanna. They consist of an often compacted, massive, dark greyish brown to black loam or clay loam A_1 horizon, usually 15-30 cm thick. This horizon is hard to very hard when dry and sometimes contains quartz and chert gravel, and/or stones. The A_1 horizon overlies either a massive bleached A_2 horizon or merges gradually into a (very) dark greyish brown clay to sandy clay B_2 horizon which is plastic and sticky when wet, and 40-100 cm thick. The B_2 horizon is characterised by very high (greater than 15 per cent) exchangeable sodium content often evidenced by a columnar structure (Plate 8.3). Some profiles contain low to moderate amounts of calcium carbonate concretions while in others magnesium may be the dominant exchangeable cation. Natrustalfs have a weakly acid to neutral soil reaction in the topsoil increasing gradually to alkaline in the subsoil. Most of these soils were previously described as texture contrast soils (Scott 1965).

Plate 8.3 Columnar structure in the B_2 horizon of a Natrustalf located in the vicinity of Port Moresby. (Notebook size 18 × 12 cm.)

Genesis

Natrustalfs are climamorphic soils, the pronounced seasonal climate facilitating the translocation of clay from the A to B_2 horizon. This process, favouring clay dispersion, is greatly enhanced by the presence of sodium and magnesium ions in colloidal form. These soils appear to have formed mainly on sedimentary rocks rich in calcium, magnesium, and possibly sodium. Their occurrence in generally low topographic positions (e.g. footslopes, interfluves) appears to indicate that the high sodium content may have been derived from rock weathering and through flow from upslope locations. Mabbutt and Scott (1966) have, however, attributed the high percentage of exchangeable sodium in these soils to cyclic salts blown in by south-easterly ocean winds under dryer climate conditions and subsequently leached down the profile under the present wetter climate.

Occurrence

Natrustalfs are found mainly in small areas on very gently sloping interfluves and footslopes underlain by sedimentary rocks. They are confined to a long, narrow coastal strip near Port Moresby where the annual precipitation varies between 1000 and 1500 mm.

Association

Natrustalfs occur in close association with the Haplustalfs. In low-lying positions they grade into Fluvaquents and Tropofluvents, while on slopes they may be associated with Ustropepts and Troporthents.

Fertility
Data for only two soil profiles analysed indicate low nitrogen and moderate exchangeable potassium contents. Predictably, CEC, TEB and BS values are high. There are no data on available phosphorous, but levels are probably low.

Land Use
High exchangeable sodium contents, a massive hard compacted A horizon and impermeable subsoil, coupled with unfavourable climatic conditions, all render these soils unsuitable for most tree crops, arable crops and also, but to a lesser extent, wetland rice. Grazing under natural conditions appears to offer the best prospects. At present Natrustalfs are not cultivated.

RHODUSTALFS

Morphology
Rhodustalfs are clima-lithomorphic soils occurring mainly on limestone in areas having a pronounced dry season. They are rather shallow soils characterised by their very dark red coloured subsoils in which the increase in clay content with depth is only gradual. The moderately developed A_1 horizon consists of dark reddish brown, very friable to friable, clay loam to clay, usually with a crumb structure, and between 10 and 25 cm thick. This horizon gradually merges into a clay B_2 horizon with a moderately to strongly developed fine blocky or subangular blocky structure and friable consistency. Shiny coatings are often observed on the peds, indicating the likely presence of clay skins. The B_2 horizon is normally 20-50 cm thick and directly overlies hard rock or merges gradually into a red clay C horizon containing high amounts of calcium carbonate concretions or limestone fragments. Rhodustalfs have a neutral soil reaction in the topsoil, becoming alkaline with depth. They were formerly called alkaline reddish clay soils (Scott 1965) and terra rossas (Haantjens *et al.* 1967).

Genesis
The formation of the Rhodustalfs will be discussed in the section dealing with the Rhodudalfs which have a very similar genesis and profile morphology but are found in wetter climates with less pronounced dry seasons.

Occurrence
These soils are found at low altitudes on level surfaces which have calcareous rocks as parent materials, such as uplifted coral terraces. They are restricted to areas with pronounced seasonal climates and a relatively low rainfall.

Association
Rhodustalfs are found in close association with the other limestone soils occurring in relatively dry areas, such as Calciustolls and Haplustolls. Rock outcrops are also common.

Fertility

Although data are limited, these soils are expected to have generally moderate to high fertility levels. CEC, TEB, BS and exchangeable potassium levels are high and the percentage nitrogen values moderate. No data are given for available phosphorous, but total phosphorus levels are high.

Land Use

Although Rhodustalfs are rather shallow soils, frequently found in rocky or stony terrain, they have excellent physical properties and appear to be well suited for arable cropping, grazing and, to a lesser extent, coconuts. Soil moisture stress, however, could be a serious limitation to tree crops. Present land use is limited to local subsistence farming.

HAPLUSTALFS

Morphology

Haplustalfs are the commonest of the great soil groups belonging to the Ustalf suborder but, like the Natrustalfs and Rhodustalfs, have a very limited distribution. Their definition is largely based on negative properties, for example absence of high exchangeable sodium and lack of a pronounced red colour.

They have well developed, black, brown to dark brown or reddish brown, friable, loam to sandy clay loam A_1 horizons, 20-40 cm thick, with a fine crumb structure. This horizon overlies a massive, thick, brown to dark brown or brownish grey, clay B_2 horizon which is plastic and sticky when wet. It occasionally contains reddish mottles, manganese concretions or calcium carbonate. Bleached A_2 horizons are present in some profiles. Haplustalfs either have a weakly acid soil reaction throughout, or become increasingly alkaline with depth. They were previously described as texture contrast soils and brown clay soils (Scott 1965). Haplustalfs are commonly found on old volcanic and sedimentary rocks. Their vegetation is eucalypt savanna.

Genesis

Haplustalfs are still relatively young soils as shown by their moderate to high CEC, TEB and BS figures and weakly acid to alkaline soil reaction. However, they have undergone sufficient leaching to remove many of the bases from the upper part of the profile, and some from the lower part as shown by their almost fully saturated subsoils. Although leaching has also caused some clay illuviation, this does not appear to be strong enough to account fully for the rather marked increase in clay content with depth (see argillic horizon discussion in Chapter 2). Haplustalfs show little evidence of movement of iron compounds. Locally there has been a slight segregation of manganese in the B horizon. This has probably been caused by manganese mobilisation in the topsoil when it is partly saturated, this process being aided by the weakly acid soil reaction. Although the Haplustalfs generally have well developed A_1 horizons, their lower organic carbon contents reflect an apparent rapid breakdown due to the prevailing climatic conditions.

Occurrence
Haplustalfs are confined to a relatively dry, narrow coastal strip in the vicinity of Port Moresby where they are found typically on gently sloping footslopes.

Association
These soils are closely associated with the Natrustalfs located in similar conditions closer to the coast. They are also likely to occur in association with Ustropepts, Troporthents and Pellusterts.

Fertility
Chemical fertility data are available for four profiles. CEC, TEB and BS levels are moderate to high and increase markedly with depth. Percentage nitrogen levels appear to be mostly low (three samples) while the exchangeable potassium varies between low and moderate. No data are given on available phosphorous.

Land Use
These soils, which are of restricted distribution, are best suited for arable cropping and grazing, soil moisture stress limiting most tree crops. Present land use is confined to some bush-fallow cultivation.

NATRUDALFS

Morphology
Natrudalfs are the wetter counterparts of the Natrustalfs occurring in areas with an annual rainfall of 2000-3000 mm and low to moderate seasonality. Like the Natrustalfs, they have B_2 horizons characterised by high exchangeable sodium contents (greater than 15 per cent). They have a generally moderately to well developed, dark greyish brown, clay loam or clay A_1 horizon between 15 and 30 cm thick, a very hard consistency and a moderate coarse blocky structure. This A_1 horizon either merges gradually into an olive brown and/or dark greyish brown, firm to very firm, (sandy) clay transitional horizon or directly overlies an olive brown to dark brown, very firm clay B_2 horizon. The B_2 horizon is usually over 50 cm thick and overlies with a clear boundary, weathered rock. The lower part of the B_2 horizon may contain few to moderate amounts of calcium carbonate concretions. They have a weakly acid to neutral soil reaction. Natrudalfs were previously included in the brown forest soils (Haantjens 1968b).

Genesis
Their formation is basically very similar to the Natrustalfs. Since these soils occur in areas characterised by a less pronounced seasonal climate, which is less favourable for clay movement, other factors may also have influenced the formation of the finer textured subsurface horizons (see argillic horizon discussion in Chapter 2). The high exchangeable sodium content in these soils is most likely derived from the sediments on which these soils have been formed.

Occurrence
Natrudalfs have only been found near Wewak on broad crestal surfaces underlain by coarse textured sedimentary rocks such as sandstone. They are likely to occur also in other areas with similar rainfall regimes.

Association
Natrudalfs are found in association with Tropudalfs, Eutropepts and Dystropepts.

Fertility
Information on fertility is limited to one site which indicates a moderate to high fertility level.

Land Use
The high exchangeable sodium content of the subsoil severely limits the agricultural potential of these soils, particularly for tree crops. Pastures and arable cropping offer the best prospects for agriculture.

RHODUDALFS

Morphology
Rhodudalfs are the wetter counterparts of the Rhodustalfs and are found in areas having an annual rainfall greater than 1500 mm with a moderate to low seasonality. Like the Rhodustalfs, they have very dark red or dark reddish brown coloured subsoils and are typically found on limestone, particularly on uplifted coral reefs. The increase in clay content with depth is generally only very gradual, and hence difficult to determine by field textures only. Rhodudalfs vary greatly in thickness, which is largely attributable to their age, and they may range from as little as 30 cm to over 2 m on the oldest terraces. They have moderately to well developed black to very dark reddish brown, friable to very friable, clay loam to clay, A_1 horizon with a granular or fine crumb structure and is 5 to 30 cm thick. This A_1 horizon merges into a dark reddish brown or dark red clay B_2 horizon which is friable when moist and plastic and sticky when wet. It most commonly has a moderately developed medium subangular blocky structure. The B_2 horizon directly overlies coral limestone or merges into a yellowish red or strong brown horizon. Rhodudalfs are weakly acid to neutral. They were formerly called terra rossas (Scott 1967; Haantjens *et al.* 1967). Plate 8.4 (colour section) shows an example of a typical Rhodudalf developed on an uplifted coral reef along the north coast of the Huon Peninsula.

Genesis

Rhodudalfs can be formed within a relatively short time span as exemplified by a profile (Plate 8.4) found on an uplifted coral terrace which has been dated by Chappell (1973) at 40 000 years BP. Formation is essentially brought about by the solution and leaching of carbonates due to hydrolysis which, under free drainage conditions, result in the accumulation of weathered limestone residues. Although the solum (A + B horizon) is virtually free of carbonates, calcium is the predominant cation of the exchange complex. The high amounts of exchangeable calcium and high organic matter contents have resulted in a well developed structure. Except for the local presence in some profiles of small iron concretions in the subsoil, sesquioxides remain evenly distributed throughout as is reflected in the pronounced red colours. Because granulometric analyses have shown that there is a gradual increase in clay content with depth, and clay skins are occasionally present in some soils, they have been grouped in the Alfisol order. Nevertheless there is other evidence to suggest that at least some of these soils are not solely formed by *in situ* weathering of limestone. Because limestone weathering residues normally make up only very small quantities (1-3 per cent) of the total, very large amounts of limestone are needed to form soils like the Rhodudalfs and Rhodustalfs. For instance, geomorphological research into uplifted coral terraces in Buka Island in the North Solomons Province suggests, on the basis of their state of preservation, a downgrading of less than 3 m, while at least 70 m of coral from relatively pure limestone would have been required to form the deepest soil (Scott 1967). Similarly, data from a Rhodudalf located on an uplifted coral reef along the north coast of the Huon Peninsula (Plate 8.4) indicate that approximately 50 cm of soil has been formed in 40 000 years (on average, 1 cm every 800 years). This too would require very large amounts of limestone and extreme weathering rates. It therefore seems likely that material derived from outside sources must have been added to these soils. Since many Rhodudalfs and Rhodustalfs are found in close proximity to active volcanoes, contamination by volcanic ash seems the most likely source.

Occurrence

Rhodudalfs are found at low altitudes (mostly below 300 m) on rather level surfaces. They are mostly associated with coral limestone, but may occasionally be found in small pockets in sedimentary limestone such as dolines. Their distribution is very limited.

Association

On the youngest terraces and on steep slopes in sedimentary limestone country, Rhodudalfs are closely associated with Rendolls, Troporthents and with rock outcrops (Plate 8.5). Occasionally they may also grade, on older, higher terraces, into Pelluderts.

Fertility

The fertility of these soils is expected to be moderate to high but only limited analytical data are available. The samples analysed are expected to have been contaminated by recently deposited volcanic ash, causing higher than average

Plate 8.5 Uplifted coral terraces located along the north coast of the Huon Peninsula. At present these terraces are extensively grazed. Rock outcrops and stepped rocky surfaces are clearly shown in the foreground of the photograph. The youngest (lower) terraces are characterised by Rhodudalfs and Rendolls.

fertility values. The relatively high organic matter content gives rise to relatively high nitrogen, CEC, TEB and BS values. The limited data show moderate to high exchangeable potassium contents. Available phosphorus contents are expected to be low due to fixation by organic matter.

Land Use

Because Rhodudalfs are often found in close association with shallow soils such as Rendolls, Troporthents and rock outcrops, their potential for large scale agricultural development is limited. Grazing may be possible, but the jagged limestone outcrops and small sink holes can cause serious damage to cattle. On the other hand, the deeper soils with their moderate to high fertility and good physical properties offer considerable potential for small scale arable cropping and, on the deepest soils, tree crops such as coconuts. Rhodudalfs are easily cultivated and are intensively farmed in populated areas.

TROPUDALFS

Morphology

This is the commonest great group of the Alfisols. They are moderately weathered, well to imperfectly drained soils with finer textured subsoils (argillic horizons). Tropudalfs are found throughout Papua New Guinea under relatively wet, humid climates with a moderate to strong seasonality. They have various parent materials, but are commonly found on sedimentary rocks. They are largely defined on negative properties, for example absence of high exchangeable sodium and lack of a pronounced dark reddish brown colour. Tropudalfs have a moderately developed A_1 horizon with a mostly (very) dark greyish brown, (very) dark grey or (dark) brown colour and a loam or clay loam texture. This horizon is 10 to 35 cm thick, has a very friable to firm consistency and compound blocky to subangular blocky structure breaking into granular or fine crumbs. The A_1 horizon overlies a clay B_2 horizon, 25 to more than 150 cm thick, with a moist, firm to very firm, and wet, plastic to very plastic consistency. This horizon contains illuviated clay as shown in Plates 2.1 and 2.2 (colour section). Depending on the drainage condition and degree of weathering, it may be yellowish brown, reddish brown or yellowish red in colour when well drained, or may show brown, greyish brown, or grey mottles when imperfectly drained. Structural deveiopment, when it occurs, is generally weak subangular blocky. Low to moderate amounts of concretions are common and may also occur in the overlying A_1 horizon. Occasionally a thin (10-20 cm) transitional horizon is present. The B_2 horizon gradually merges into a yellowish brown, brown, or olive brown C horizon. This is mostly slightly less clayey than the overlying horizon and contains weathered rock fragments. Grey and white mottles may occasionally be present in this horizon.

Tropudalfs are acid to weakly acid throughout the soil or have a gradual increase in pH with depth, varying from weakly acid in the topsoil to neutral or alkaline in the deep subsoil. Because of their wide distribution, Tropudalfs were formerly identified with many great groups. These include brown forest soils and gleyed brown forest soils (Haantjens 1968b), immature brown soils and immature brown residual soils (Haantjens 1976), acid red to brown clay soils (Scott 1965), red and yellow earths (Haantjens 1968b) and strongly weathered red and brown clay soils (Haantjens 1976). Plate 8.6 (colour secton) shows a typical example of a Tropudalf.

Genesis

The formation of these soils is basically similar to that of the previously described Haplustalfs. However, they have been subjected to stronger leaching as shown by their mostly lower CEC, TEB and BS values and more pronounced colours. The presence of Tropudalfs in wetter climates probably accounts for the gradual increase in their clay content. Because some of these soils are found in the vicinity of active volcanoes, they have been contaminated by ash which could be partly responsible for the coarser textured topsoils, as shown in the sand mineralogy by the presence of volcanic glass (Bleeker 1972).

Occurrence

Tropudalfs occur throughout the country on gently to moderately sloping crests, plains and hillslopes. They have developed dominantly on sedimentary rocks, such as siltstone, mudstone and Pleistocene sediments. Although widespread, they do not dominate in any one area.

Table 8.3
Chemical fertility data - Tropudalfs (31 profiles)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	—	—	1	6	1	7	5	16	3	10	10	32	16	53	10	32	17	57	12	39	14	47
Moderate	28	90	5	31	1	7	17	55	14	47	21	68	14	47	21	68	13	43	19	61	16	53
Low	3	10	10	63	13	86	9	29	13	43	—	—	—	—	—	—	—	—	—	—	—	—
Total samples and percentage	31	100	16	100	15	100	31	100	30	100	31	100	30	100	31	100	30	100	31	100	30	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

Association

Because of their wide distribution, these soils are found in association with many other great groups of which the most important are Eutropepts, Dystropepts, Hapludolls and Tropudults.

Fertility

Data for thirty-one soil profiles are listed in Table 8.3. This table shows moderate to high CEC, TEB and BS contents throughout the soils. Nitrogen contents are dominantly moderate, while exchangeable potassium values vary widely and are probably related to the parent materials, soils developed on Pleistocene sediments having the lowest values. Data on available phosphorus are limited to sixteen topsoil and fifteen subsoil samples and show dominantly low values.

Land Use

Difficult terrain conditions and the rather scattered occurrence of these soils appear to be the greatest limitation for large scale agricultural development. Nevertheless tree crops, such as cocoa, coffee and coconuts and, on gently sloping terrain, also arable crops such as maize, peanuts and tobacco, offer potential for cash cropping particularly in the more populated lowland areas. The soils are also suitable for cattle grazing. At present these soils are only locally used for subsistence agriculture.

9 Ultisols

Ultisols are strongly weathered soils which, by definition, have a horizon containing translocated clay (argillic horizon) and a low base saturation.* The process causing the movement of clay from one horizon to another is known as clay illuviation and is often more pronounced in climates with a high seasonality.† Argillic horizons are often difficult to identify positively (see Chapter 2).

Being found on land surfaces of widely variable age and composition Ultisols are relatively commonplace in Papua New Guinea. They occur under continual wet or seasonal climates from sea level to 3000 m.

Ultisols have five suborders, three of which have been recorded in Papua New Guinea. *Aquults* are the poorly to very poorly drained Ultisols with seasonally high water tables. They are often subjected to seasonal flooding. *Humults* are characterised by a high organic matter content throughout the soils. They are commonest in highland areas where climatic conditions are relatively cold, but also occur occasionally in the lowlands. *Udults* are typical of humid lowland areas without pronounced dry seasons and characteristically lack the properties ascribed to the Aquults and Humults.

PLINTHAQUULTS

Morphology

Most Plinthaquults have a poorly developed, dark grey to dark greyish brown A_1 horizon between 10 and 40 cm thick. This horizon commonly merges with a clear boundary into a grey, or greyish brown A_2 horizon. Occasionally, however, this distinctly lighter coloured A_2 horizon may be absent. When present it overlies, with an abrupt boundary, a grey to light grey, strongly red and brown mottled B_2 horizon in which clay skins are often only faintly discernible. This generally massive, thick (normally >100 cm), B_2 horizon has

* Normally less than 35 per cent at 125 cm below the upper part of the argillic horizon.

† See Genesis section of Plinthaquults.

a clay texture, a very plastic consistency and often contains low to moderate amounts of pisolitic iron concretions. When exposed to repeated wetting and drying, this iron-rich humus-poor mixture of clay and quartz hardens irreversibly into irregular aggregates, which is called *plinthite* (see Plate 8.1, colour section). The texture of the overlying topsoil (A_1 and A_2 horizons) can vary greatly, depending on locality. In the East Sepik Province the surface horizons commonly have a clay loam to clay texture, with the clay content increasing gradually with depth, whilst in the Western Province there is an abrupt textural change with depth, the surface horizon here consisting mostly of loam, silt loam, sandy loam or loamy sand. Plinthaquults have a strongly acid soil reaction and are confined to relatively low rainfall areas (1500-2000 mm) with a moderate to high seasonality. Locally these soils have a strong microrelief (see Chapter 15). They were formerly called meadow podzolic soils (Haantjens 1698b) and podzolic laterites (Haantjens *et al.* 1967).

Genesis

The genesis of the Plinthaquults is the result of deep, strong weathering on stable, but low lying and seasonally inundated, mostly Pleistocene colluvio-alluvial deposits. Under the influence of acid, leaching bases and silica* are removed resulting in the formation of a thick zone of dominantly kaolinitic clay. Oxidation and reduction processes, caused by seasonal wetting and drying, and concentration of iron as hydrated oxides lower down the profile produce the characteristically grey, brown and red mottling patterns in the subsoil (plinthisation) (see Plate 8.1, colour section). Some of the iron (and manganese), lost from the A horizon(s) or brought in laterally by throughflow from upslope locations, may also be precipitated as concretions in the lower A_2 and/or B_2 horizon. Evaporation at the capillary fringe, above the water table, considerably enhances this process.

The mostly thick, coarser textured, A horizons are formed by strong weathering, causing leaching and/or destruction and removal of the clay minerals. Since clay illuviation is facilitated by seasonal wetting and drying (United States Soil Conservation Service, 1967), optimal conditions exist for this process under the prevailing highly seasonal climate. Clay movement and redeposition take place in three main phases. First, the wetting of a dry soil induces clay dispersion and transport; second, as the soil dries, cracks are developed through which gravitational water or water held at low tension percolates and clay particles are adsorbed to the surface; third, as dry soil takes up moisture and reaches saturation, the process of percolating water carrying clay particles will be reduced. Repetition of this process over long periods, particularly in areas with a high seasonality, can lead to the formation of soils with higher clay content in the subsoil. Schroo (1964) has likewise concluded that in Plinthaquults and related soils located in the coastal area between the Bian and Koembe Rivers in Irian Jaya, the light textured surface horizons and heavy textured subsoils are induced by pedogenesis. However, he also remarked that 'one gets the impression that the primary textural differences are

* Discussed in more detail in the Genesis section of the Haplorthox and Eutrorthox.

characteristic for transported soils'. Similar conditions apply to these soils occurring in the Western Province. Hence the pronounced textural differences found in these soils in both Irian Jaya and the Western Province could have been caused by both pedogenesis and sedimentary sorting.

Occurrence

These soils cover extensive flat to very gently sloping areas, and broad drainage depressions in the Western Province south of the Fly River, as well as in both the East and West Sepik Provinces north of the Sepik River. Figure 9.1 shows their major distribution.

Association

Plinthaquults are usually found in close association with their slightly better drained counterparts the Plinthudults and Tropudults. In the West and East Sepik Provinces they may also grade into Plinthaqualfs and Tropaqualfs. Figure 9.2 gives a schematic cross-section of the undissected plateau of the Western Province, showing the relationship of Plinthaquults to landform and vegetation. Plate 9.1 typifies this landscape at ground level.

Fertility

Plinthaquults, where they occur in the Western Province (Figure 9.1) have a very low fertility level. Their percentage nitrogen, exchangeable potassium, available phosphorus, CEC, TEB and BS values are all low. They are very leached, strongly acid (pH $\leqslant$4.5 throughout) soils, the mineral content of the surface horizons being comprised predominantly of quartz. Their exchange complex is almost completely dependent on the organic matter content of the A_1 horizon. Base saturation values are lower than 5 per cent; calcium and magnesium appear only in traces below the surface horizons, having been replaced by hydrogen and aluminium ions.

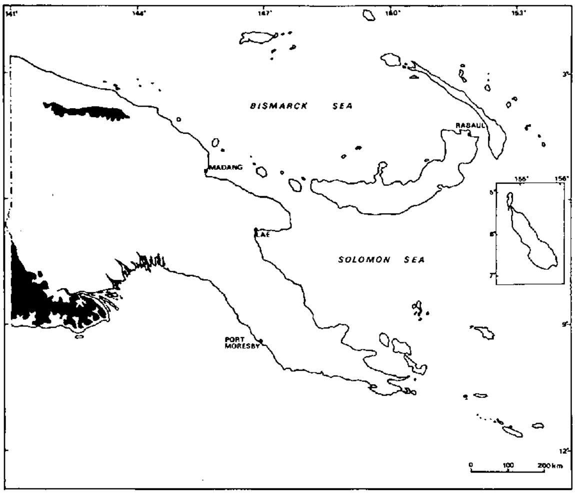
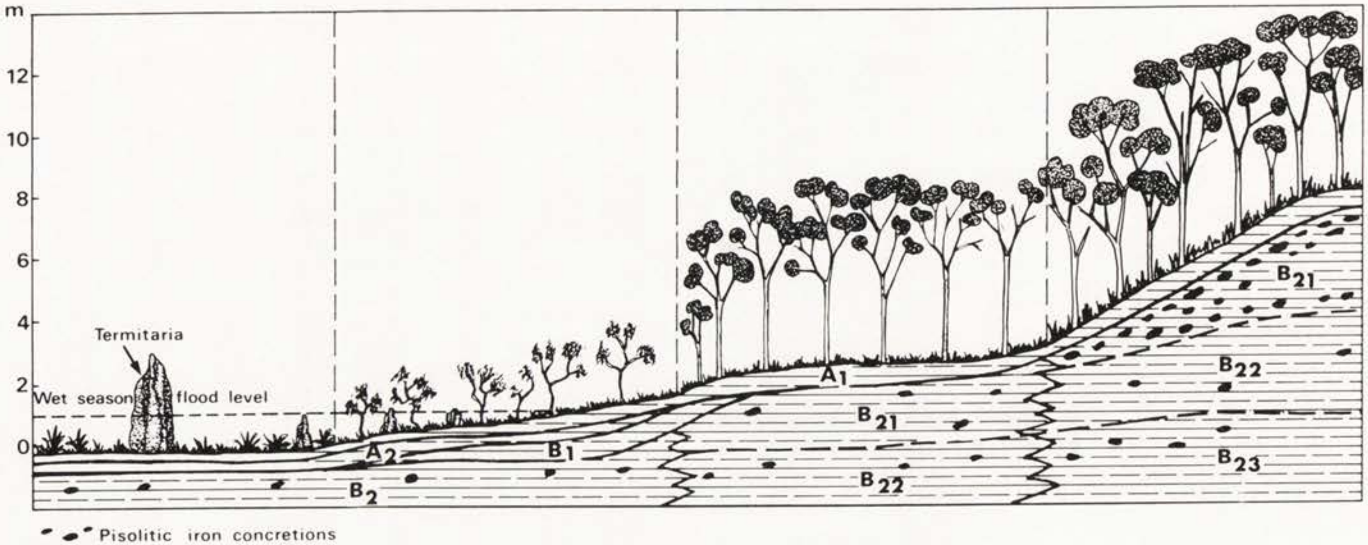


Fig. 9.1 Major distribution of Plinthaquults, Plinthudults, and Tropudults

Fig. 9.2 Schematic cross-section through undissected plateau, Western Province (see also Plate 9.1)

Landform	Broad depression	Very gentle slopes	Low rises	Broad low rise
Vegetation	Sedge grassland	Low thin-stemmed stunted *Banksia, Melaleuca* and *Grevillea*	Tall mixed savanna	Monsoon forest



Soils	Plinthaquults	Plinthudults	Tropudults	Acrorthox
	Poorly drained strongly acid soils with sandy loam to silt loam A_1 and A_2 horizons overlying a very plastic, impermeable grey red and brown mottled clay to heavy clay B_2 horizon. Pisolitic iron concretions commonly present. Long wet season flooding and rapid drying out in dry season	As previous soil but imperfectly drained, the mottled B_2 horizon occurring below 50 cm depth. A transition B_1 horizon is commonly present. Short wet season flooding and rapid drying out in dry season	Well drained strongly acid soils with loamy sand to sandy loam A_1 horizons overlying a brown to reddish brown loam to sandy clay loam B_2 horizon which in turn merges into an impermeable red and grey mottled clay to heavy clay horizon at depth $\geqslant$125 cm. No flooding, but topsoil rapidly drying out in dry season	Well drained strongly acid soils with sandy loam to loam A_1 horizons merging into red gravelly loam to gravelly clay loam B_{21} and B_{22} horizons. The impermeable mottled subsoil occurs normally below 3 m depth

Plate 9.1 Termitaria up to 5 m high and most probably built by the termite *Nasutitermes triodiae* (Froggatt) are a typical feature on poorly drained sedge grassland depressions characterised by Plinthaquults. This flat terrain commonly merges into a very gently sloping rim of low *Melaleuca-Banksia-Grevillea* savanna with Plinthudults. Tall mixed savanna and monsoon forest in turn occurs on low rises surrounding the depressions and very gentle slopes. These rises are typified by Tropudults and Acrorthox. A schematic cross-section is given in Figure 9.2.

The general fertility of Plinthaquults in the East and West Sepik Provinces is slightly higher than in the Western Province. These soils are less leached as reflected in the slightly higher BS values (generally 20-30 per cent). CEC and TEB figures are mostly moderate, while nitrogen and exchangeable potassium vary between low and moderate. When present, available phosphorus is always very low.

Land Use

Because of the very low fertility, poor drainage, and common seasonal flooding, nearly all of these soils are unsuitable for arable and tree crops. Wetland rice may offer some possibilities but would require a large input of fertilisers. Wetland rice mechanically cultivated on these soils near Merauke, Irian Jaya has, however, proved unsuccessful (Schroo 1964). In Irian Jaya these Plinthaquults were originally selected for mechanical rice cultivation because of their wide distribution, 'ideal' conditions for mechanisation, and their impermeable subsoil considered favourable for water control. On the other hand, the necessity for large fertiliser inputs was recognised. Schroo (1964) considers that crop failures resulted because of problems related to soil induced toxicity (aluminium) and physiological diseases of susceptible rice varieties. It was also noted, in several localities, that the topsoils formed very loose structures which, when wet, collapse easily under the pressure of heavy machinery. The critical upper limit of plasticity proved to be 35 per cent (Schroo 1964). Wetland rice experiments on Plinthaquults in the East and West Sepik Provinces have also yielded poor results which have been attributed to the low soil fertility and trace element deficiencies. Grazing of water buffaloes and deer appears to be the most suitable type of land use. Deer are presently found in large numbers on these soil areas in the Western Province.

ALBAQUULTS

Morphology

Albaquults to date have only been found in a few areas in the highlands. They are characterised by a marked increase in clay content in the argillic horizon which underlies a bleached A_2 horizon containing in its lower part large amounts of reddish brown concretions. Albaquults lack the pronounced grey, red and brown subsoil mottling which is characteristic for the Plinthaquults. The A_1 horizon is 20-40 cm thick, and is divided into a black, organic clay upper section, and a very dark grey, clayey gravel lower part. This horizon abruptly overlies a thick, brownish grey, very plastic, clay B horizon, which has a grey matrix colour and contains small red mottles. With depth, this horizon changes gradually to yellowish brown or strong brown in colour, indicating that the gleying in the upper part is largely due to rainwater ponding on the compacted impermeable subsoil. Albaquults are strongly acid. They were previously classified as lateritic and gleyed latosols (Haantjens 1970a).

Genesis

This is basically very similar to that of the Plinthaquults, except that the strong gleying is caused by rainwater ponding rather than by a rising groundwater table. The extensive iron segregation which causes the numerous iron concretions found in the lower part of the A horizon can be attributed to the continual wetting and drying of this horizon. This cycle results from stagnating rainwater on the massive, compacted, heavy textured subsoil.

Occurrence

These soils are locally found in slight depressions on flat to gently undulating surfaces, and surface remnants, of Pleistocene fans in the highlands below 2000 m. Localised occurrences can be expected also in the southern parts of the Western Province.

Association

Albaquults are found in close association with other poorly drained soils also having argillic horizons, namely Tropaquults, Tropaqualfs and Plinthaqualfs.

Plate 9.2 *Crotalaria* roots showing acute surface bending caused by high amounts of iron concretions in the lower part of the A horizon of an Albaquult located near Minj in the Western Highlands Province

Fertility

Although no analytical data are available, the fertility level is expected to be generally low.

Land Use

Waterlogging during wet periods, possible water stress during dry periods, low fertility, and poor root penetration on the concretionary compact horizon (Plate 9.2) seriously restrict the agricultural suitability of these soils. Limited grazing therefore appears to offer the best prospects for land use. In the highlands, some of these soils are presently being cultivated in areas where more suitable land is not readily available.

TROPAQUULTS

Morphology

Tropaquults, by definition, have little or no plinthite at less than 125 cm depth. Because they are found at altitudes varying from sea level to almost 3000 m, the A_1 horizon can vary greatly in thickness. In the lowlands the A_1 horizon is commonly between 5 and 20 cm thick, whereas in the highlands, where the cooler climatic conditions are less conducive to the breakdown of organic matter, it may be up to 50 cm thick. The A_1 horizon mostly has a loam to clay loam texture, black to very dark grey colours, and merges into a very plastic, light grey, grey or greyish brown, clay B_2 horizon. This horizon in turn remains grey, becomes yellowish brown or pale brown with depth, or has a pronounced red and brown mottling pattern below 125 cm. Occasionally a thin, greyish coloured transitional horizon is present between the A_1 and B_2 horizons. Reddish brown concretions occur locally in the subsoil. These soils are strongly acid, the pH increasing slightly with depth. Tropaquults were previously grouped as gleyed plastic heavy clay soils (Rutherford and Haantjens 1965) while some were classified as meadow soils and meadow podzolic soils (Haantjens 1970a).

Genesis
Tropaquults are hydro-lithomorphic soils formed on fine textured sedimentary rocks such as siltstone, mudstone and Pleistocene colluvio-alluvial deposits. The slowly permeable parent materials lead to intermittent waterlogging which causes gleying of these soils. Weathering and leaching which have been strong enough to remove most of the bases and some silica have resulted in the dominance of the clay mineral kaolinite in most soils. However, small quantities of illite and/or montmorillonite can often be found, indicating that these soils are somewhat less weathered than the Plinthaquults. Although significant clay illuviation is assumed to have taken place, part of the clay increase with depth could have been caused by other processes (see Chapter 2). Iron and manganese lost from the surface horizon due to acid leaching and waterlogging have not as yet been concentrated by reduction processes in sufficient quantities in the B_2 horizon to produce the red and grey mottling patterns characteristic of the Plinthaquults.

Occurrence
Tropaquults are restricted to occurrences on terraces, fans, colluvial depressions and slump alcoves, as well as irregularly slumped moderate slopes in the highlands. They also occur locally on old, poorly drained plains in lowland areas, particularly in the Western and East and West Sepik Provinces. Their parent materials are mainly fine textured sedimentary rocks or alluvial and colluvial deposits derived from these rocks.

Association
These soils are mostly found in association with their better drained counterparts the Tropudults, but also with other morphologically very similar soils having a higher base saturation, namely the Tropaqualfs and Tropudalfs.

Fertility
Data indicate, rather surprisingly, that these soils have a generally moderate fertility. However, of the seven profiles sampled, six are located in the highlands and are characterised by relatively high organic matter contents. This

is reflected in the high CEC and percentage nitrogen values in the surface horizons of these soils. TEB, BS and available phosphorus are mainly moderate to low, with values decreasing with depth, while exchangeable potassium has moderate contents in five of the seven profiles analysed. The chemical fertility of the lowland soils is expected to be generally low.

Land Use

Poor physical soil conditions and poor drainage render these soils unsuitable for tree crops and, to a lesser extent, arable crops. Locally in wet lowland depressions wetland rice cultivation may be possible, although grazing appears the most suitable type of land use. In the highlands, owing to the high population densities combined with a general land shortage, most of these soils are cultivated although only after drainage ditches have been dug.

PLINTHOHUMULTS

Morphology

Plinthohumults are soils having a high organic carbon content, either throughout or in the upper part of the finer textured subsurface horizon.* This horizon has, in addition, a pronounced grey, red, and brown mottling pattern which, in comparison to the Plinthaquults, does not occur immediately below the A_1 horizon but at greater depth.

Plinthohumults have a well developed very dark greyish brown, 20-40 cm thick, clay loam to clay A_1 horizon, merging into a distinctly red and yellowish brown mottled very firm to very plastic, clay B_2 horizon. Below 50 cm this horizon becomes increasingly greyish brown, very light grey mottled, and normally has, between 80 and 125 cm, the prominent red, white and yellowish brown mottled pattern characteristic of plinthite. Few to moderate amounts of small iron concretions are common in the subsoil. Plinthohumults are strongly acid throughout, and are imperfectly drained due to the heavy textured, impermeable subsoil. They were previously grouped as lateritic and gleyed latosols (Haantjens 1970a).

Genesis

This will be discussed in the next section dealing with the Tropohumults. The formation of plinthite has previously been discussed under the Plinthaquults.

Association

Plinthohumults are found mainly in association with the Tropohumults and Plinthaquults.

* >12 kg organic carbon in 1 m^2 to a depth of 1 m or $\geq$0.9 per cent organic carbon in the upper 15 cm of the argillic horizon.

Occurrence
Plinthohumults are not common in Papua New Guinea. Up until now these soils have only been found in the highlands where they are irregularly distributed between 1500 and 2500 m. They have developed mainly on fine textured sedimentary rocks and occur on crests and on moderately sloping hilly to low mountainous terrain.

Fertility
Analytical data, restricted to one site, indicate generally moderate values, which appear largely due to the relatively high nitrogen and organic carbon contents.

Land Use
Imperfect drainage and slow permeability, combined with a high runoff, and their common occurrence on moderately sloping terrain, restrict the suitability of these soils for agriculture. Grazing offers the best potential. Present land use is confined to sweet potato cultivation.

TROPOHUMULTS

Morphology
Like the Plinthohumults, Tropohumults are characterised by their high organic carbon content found either throughout the soil or in the upper part of the argillic horizon. In comparison to the Plinthohumults, they are well drained and lack the prominent mottling characteristic of plinthite. They are mostly found in the Highlands, but also occur in lowland areas and, therefore, their profile morphology also varies widely. The A_1 horizon is mostly 10-30 cm thick, but may range between 2 and 60 cm. At the highest altitudes this horizon tends to be at its thickest and obtains its highest organic carbon content. In undisturbed areas at high altitudes the A_1 horizon is also often covered by a dark brown to black, 10-20 cm thick, root mat and leaf litter horizon. The A_1 horizon colour ranges between (very) dark brown to brown, (very) dark greyish brown or occasionally black, dark yellowish brown or reddish brown. It is medium to fine textured, with a friable to very friable consistency, and a granular to very fine blocky structure. The A_1 horizon merges into a thick (>50 cm) clay B_2 horizon which also has a wide colour range but is mainly yellowish brown to strong brown in the upper part, and reddish to reddish brown in the lower part. This B_2 horizon has a dominantly friable consistency and a weakly developed structure. Tropohumults are mostly strongly acid. Plate 9.3 (colour section) shows a typical example of a Tropohumult. They were formerly classed as humic brown clay soils on sedimentary rocks (Haantjens 1970a; Rutherford and Haantjens 1965), reddish clay soils (Rutherford and Haantjens 1965), strongly weathered red and brown clay soils (Haantjens 1964a, b) and acid brown clay soils (Scott 1965).

Genesis

Tropohumults are basically climamorphic soils. The main soil forming processes are strong leaching, accumulation of acid organic matter in the surface horizon, and the downward movement and deposition of some organic matter, iron oxides, alumina and clay. These processes, which are enhanced when these soils occur on acid and/or permeable rocks, may take place in several different ways. Following the initial loss of bases during the weathering process, the accumulating organic matter in the surface soils is unsaturated and acid. With continued strong leaching under high rainfall conditions, the clay may be partly destroyed by weathering, removed from the topsoil, or partly carried downward as a negatively charged humus protected sol. Organic compounds are also capable of mobilising and translocating iron and aluminium oxides and many other metal ions upon weathering. This process is called chelation and involves the holding of an ion within a ring structure of organic origin. Humus may also be translocated independently of sesquioxides in colloidal form. Because these processes are very similar to those taking place in Spodosols (Podzols), these soils previously were often described as being 'podzolised', for example, podzolised latosols (Reijnders 1964).

Occurrence

Tropohumults occur on a very large variety of parent materials including sedimentary, igneous, as well as metamorphic rocks which usually have a moderate to rapid permeability. They are found in mostly rugged, hilly and mountainous terrain, from sea level to 3000 m, but are commonest at higher altitudes with lower temperatures. Their vegetation ranges from forest to man-made grassland.

Association

Tropohumults are associated with a great many soils including Tropodults, Tropudalfs, Humitropepts, Dystropepts and, at the highest altitudes, with Hydrandepts, Troporthents, Cryumbrepts and Cryochrepts.

Fertility

Table 9.1 gives the chemical fertility data for thirty-two profiles. CEC values are high to moderate in the topsoils and this is reflected in the dominantly moderate nitrogen contents, which show a tendency to increase with altitude, high values being common in samples taken above 2000 m. Subsoil CEC values are also moderate, while TEB and BS contents vary between moderate and low in the topsoil, and are dominantly low in the subsoils. Exchangeable potassium figures range between low and high in the topsoil and moderate to low in the subsoil. This appears to be related to the parent material since the highest values most often occur in soils derived from igneous rocks. Data on available phosphorus are, with few exceptions, restricted to soils occurring in the Highland Provinces and these indicate low to moderate values. Clay mineral data listed in Table 9.2 clearly show the advanced stage of weathering of these soils. Kaolinite, gibbsite and occasionally quartz are the dominant clay

Table 9.1
Chemical fertility data – Tropohumults (32 profiles)

Fertility Class	Total N		Available P				Exchangeable K				Cation exchange capacity (CEC)				Total exchangeable bases (TEB)				Base saturation (BS)			
	T*	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%	T	%	S	%
High	7	22	1	6	2	12	9	30	—	—	18	60	6	20	1	3	—	—	—	—	—	—
Moderate	25	78	8	44	5	29	11	37	13	43	12	40	21	70	19	64	7	23	12	43	5	18
Low	—	—	9	50	10	59	10	33	17	57	—	—	3	10	10	33	23	77	16	57	23	82
Total samples and percentage	32	100	18	100	17	100	30	100	30	100	30	100	30	100	30	100	30	100	28	100	28	100

*T = Topsoil, normally sampled within 0-50 cm layer.
S = Subsoil, normally sampled within 50-120 cm layer.

Table 9.2
Clay mineralogy of Tropohumults

Soil profile and horizon		Depth (cm)	Minerals of the clay fraction: X-ray analyses (Australia & Norway)	Minerals of the clay fraction: DTA-analyses (Netherlands)
MT*-P1	$-B_1$	15-30	K5,M4,I2	—
	$-B_2$	35-60	K5	—
	$-B_3$	65-85	K4,I4,Q3	—
	$-C_2$	95-200	I4,K4	—
MT-P16	$-B_{21}$	15-30	M4,Q4	—
	$-B_{22}$	50-75	Q5,K3,I3	—
	$-C_1$	155-170	Q5,I4	—
MT-P18	$-B_{21}$	30-50	Q4,M4	—
	$-B_{22}$	80-90	Q4,K4,M3	—
MT-P20	$-B_{21}$	50-65	Gi4,Q3,K3,M3	—
	$-B_{22}$	90-105	Gi4,I4,Q2	—
	$-B_{23}$	125-150	I4,M2,K2	—
MT-P23	$-B_{21}$	20-45	K4,Gi4,Q2	—
	$-IIA_1$	90-110	K5,Gi3	—
W-129	-AB	40-60	K5	—
	$-B_{22}$	90-120	K5,I2	—
W473	$-A_1$	5-15	Ch3,ML3,I2,K2,Q2†	—
	$-B_{11}$	20-30	Ch3,I3,K3,ML2,Q2	—
GMH-P4	$-B_{21}$	45-60	—	MH4‡,K4,Go2
	$-C_1$	180-210	—	K5,Go2
GMH-P27	$-B_2$	45-75	—	K5
MK-P21	$-A_1$	0-12	K5	—
	$-B_{21}$	15-30	K5	—
	$-B_{22}$	40-55	K5	—
	$-B_3$	135-150	K5	—
MK-P55	$-A_{11}$	0-15	K5,Ch3	—
	$-A_{12}$	40-50	K5,Ch3	—
	$-B_{21}$	75-90	K5,Ch3	—
	$-B_{22}$	125-140	K5,Ch3	—
	$-B_{31}$	150-165	K5,Ch4	—
BK-P5	$-B_1$	5-27	K5,Go2	—
	$-B_{21}$	30-105	K5,Go2	—
	$-B_3$	190-200	K5,Go1	—
BK-P18	$-A_3$	2-10	Gi5,K2,Go or He2,Q2,Ch2	—
	$-B_{21}$	15-65	Gi5,Ch3,H2,Go2,Q2	—
	$-B_{22}$	75-115	Gi5,H3,Go2,Ch2,Q1	—

* Refers to survey area: MT = Mendi-Tari; W = Wabag; GMH = Goroka-Mount Hagen; MK = Morehead-Kiunga; BK = Buna-Kokoda

† Refers to <20μ fraction

‡ Metahalloysite is dehydrated halloysite

Explanation of symbols: K = kaolinite; H = halloysite; MH = metahalloysite; M = montmorillonite; Ch = chlorite; ML = mixed layer; Q = quartz; Gi = gibbsite; Go = goethite; He = haematite

Clay minerals are indicated as follows:
5 = more than half
4 = one-third to half
3 = one-fifth to one-third
2 = one-twentieth to one fifth
1 = less than one-twentieth

minerals. The presence of gibbsite, particularly in the surface horizons, could have been caused partly through contamination by volcanic ash (see Chapter 13).

Land Use

The dominantly rugged hilly to mountainous terrain with moderate to steep slopes is the major factor limiting agricultural suitability of these soils. Although the fertility is generally moderate, largely due to the relatively high organic matter content, it may be difficult to maintain under continuous cropping. These soils therefore appear better suited for grazing, with tree crops being restricted to the gentler sloping terrain. Present land use is mainly confined to subsistence agriculture.

PLINTHUDULTS

Morphology

Plinthudults are imperfectly drained, strongly acid soils, with prominently mottled, fine textured subsoils at depths of 50 cm or more. Their very dark greyish brown, to very dark brown A_1 horizon is between 15 and 50 cm thick, with loam to sandy clay loam texture, and a friable to very friable consistency. Commonly this horizon contains low to moderate amounts of quartz gravel, and/or a few bleached sand grains. The A_1 horizon commonly overlies, with a clear boundary, a 10-30 cm thick, greyish brown A_2 horizon, having a sandy loam to sandy clay loam texture and containing low to high amounts of gravel. However, when this A_2 horizon is absent, the A_1 horizon merges into a brown to reddish brown, transitional B_1 horizon of variable texture. The A_2 or B_1 horizon, in its turn, abruptly overlies a very thick (>100 cm) B_2 horizon consisting of prominently grey, red, and yellowish brown mottled, very plastic, impermeable clay to sandy clay, containing low to moderate amounts of purple, red, and reddish brown iron concretions. Plinthudults occur commonly under low scrub or grassland vegetation. Previously most of these soils were grouped as meadow podzolic soils and gleyed red and yellow earths (Haantjens 1968b).

Genesis

Plinthudults are hydro-lithomorphic soils formed on fine textured, impermeable, Pleistocene sediments, their genesis being basically very similar to the Plinthaquults. Since they occur at relatively higher topographic positions compared to the Plinthaquults, they have slightly better drainage, as indicated by the prominently mottled deep subsoil. Clay content increases gradually to abruptly as soil depth increases and this is probably mainly related to the varying amounts of coarse particles present when the sediments are deposited.

Occurrence

Plinthudults are typically found in very gently sloping terrain, and on broad rises of undulating plains. Their parent materials consist of Pleistocene sediments. Figure 9.1 shows the major distribution of these soils, as well as the Plinthaquults and Tropudults.

Association

Plinthudults are found in close association with the Plinthaquults in broad depressions, and with Tropudults on broad low rises. Figure 9.2 shows the catenary relationship of these soils.

Fertility

Chemical fertility data for four soil profiles collected in the East and West Sepik Provinces indicate, as expected, a generally low level of fertility. CEC and BS values of these soils are moderate in the topsoil and moderate to low in the subsoil, while TEB values (three samples) are low. Nitrogen, potassium and available phosphorus contents are also low. It is interesting to note that two out of the four samples had relatively high exchangeable sodium contents. Since these soils are located at a considerable distance inland (>60 km) the sodium appears to have been derived from weathering of the parent rocks. Samples of Plinthudults collected by Zijsvelt (unpublished data) in the Western Province indicated even lower general fertility levels, particularly for available phosphorus. Zijsvelt states that the non-availability of this important nutrient is caused by very favourable conditions for phosphate retention; the very high clay fraction is composed mostly of kaolinite and hydrous oxides of iron and aluminium. Zijsvelt has also shown that removal of the natural vegetation followed by cropping causes a rapid decline in fertility of the A_1 horizon.

Land Use

The inherent low fertility and strong acidity of these soils seriously limit their agricultural suitability. Short, wet season flooding further limits cultivation, particularly of tree and arable crops. Experimental rice cultivation on similar soils at Yambi, in the East Sepik Province, has yielded only poor results. These were attributed not only to the low soil fertility and trace element deficiencies but also to other factors related to cargo cults and an unusually wet dry season, preventing the burning of bush for rice gardens (Hale 1978). Serious problems with mechanical rice cultivation on the Plinthaquults in the Merauke area of Irian Jaya have been discussed previously. Similar difficulties can be expected with the Plinthudults in the Western Province. Grazing, therefore, is the only suitable alternative. At present these soils are cultivated very little.

RHODUDULTS

Morphology

Rhodudults are deep, well drained, strongly acid soils which do not contain plinthite in the upper 125 cm of the profile, and which are characterised by their dark colour values.* In addition, they lack the relatively high organic matter content in the subsoils characteristic of the Humult suborder. The very dark, reddish to greyish brown, friable, clay A_1 horizon is 10-30 cm thick, and merges, with a clear boundary, into a friable to firm, clay B_2 horizon, 75 cm or more thick. This permeable horizon usually has a weakly to moderately developed blocky structure.

Rhodudults have been found on relatively permeable volcanic rocks and sediments. They were previously grouped as acid red to brown clay soils (Scott 1965), uniform red and yellow clays (Haantjens 1968b) and red and yellow latosols (Haantjens *et al.* 1967).

Genesis

Rhodudults are clima-lithomorphic soils found mostly on ferro-magnesium rich rocks at low altitudes in savanna climates, characterised by a relatively low precipitation (1500-2500 mm per annum) and a moderate to low seasonality. Free drainage conditions are a prerequisite for keeping the iron-hydroxides, released by weathering, completely oxidised. This leads to the formation of the red to dark red colours typical of these soils. In other aspects the formation of these soils is very similar to the other better drained Ultisols.

Occurrence

Rhodudults are found in the relatively dry coastal areas of the East Sepik and Central Provinces. They have a patchy distribution, being restricted to freely drained upper slopes and crests, between sea level and 1000 m.

Association

These soils are closely associated with the less freely drained Tropudults, which are distinguishable from the Rhodudults mainly by their yellowish red to yellowish brown coloured subsoils. On steep sideslopes adjacent to crests, Dystropepts and Troporthents may also be found with these soils.

Fertility

Data for three sites indicate generally low to moderate fertility levels. CEC contents are moderate, and both TEB and BS values range from moderate in the topsoil to low in the subsoil. Nitrogen levels are also moderate, and exchangeable potassium varies between high and low in the topsoil while

* The surface horizon has, by definition, a colour value moist of less than 4 in all parts, while the subsoil has a colour value dry of less than 5 and no more than 1 unit higher than the value moist.

subsoil values are low throughout. Data on available phosphorus (one profile) show zero values, conditions being favourable for phosphate retention in these soils (see Chapter 14). Clay mineral data (one profile) indicate much kaolinite, together with a little goethite and a trace of gibbsite.

Land Use

Slight erosion hazards and the low to moderate fertility somewhat limit agriculture. Because of their occurrence on crests and upper slopes, their distribution is localised thereby restricting large scale agricultural development. Good physical conditions and free drainage favour tree crops, particularly the less soil selective, such as rubber and oil palm. On the Sogeri plateau near Port Moresby, Rhodudults and Tropudults are cultivated for rubber at altitudes of approximately 500 m.

TROPUDULTS

Morphology

Tropohumults and Tropudults are the commonest great groups of the Ultisols. However, while the Tropohumults are mostly found in the cool highlands, Tropudults typically occur in the hot, humid lowlands below 1000 m on a wide variety of parent materials. They are very closely associated with the Rhodudults but lack the dark colour values typical of these freely drained soils.

Tropudults have a dark reddish brown, dark greyish brown or dark brown, friable to firm, A_1 horizon, normally 15-40 cm thick. Occasionally, however, this horizon is much thinner or even eroded away. The A_1 horizon commonly grades into a reddish to yellowish brown B_1 horizon, 20-50 cm thick, sometimes showing weak, greyish brown mottling. This B_1 horizon, when present, merges gradually into a yellowish red, red, or reddish brown, friable, B_2 horizon, between 50 and 100 cm thick. With depth the soil colour gradually changes into brown or yellowish brown, or becomes prominently red and grey mottled. Soil texture varies but soils having clayey textures throughout the profile are the most common, particularly on igneous rocks. Soils formed on Pleistocene sediments show, however, a great variety of textures. These differences appear to be related to the amount of coarse particles in the sediment, which varies with locality. This is reflected in the change of texture which, with depth, may be either abrupt (loamy sand to loam overlying clay), or gradual (sandy clay loam or clay loam overlying clay). Tropudults are strongly acid soils. They were previously described as acid red to brown clay soils (Scott 1965), uniform red and yellow clays (Haantjens 1968b) and red and yellow latosols (Haantjens *et al.* 1967).

Genesis

The formation of these soils is basically very similar to that of the other Ultisols already discussed in previous sections. Strong weathering has resulted in the loss of most bases and some silica. This process has led to the formation of kaolinitic clays which have a very low base saturation. Although clay skins are evident in the B_2 horizons of soil pits, part of the textural changes with depth could also have been caused by primary textural differences or clay destruction and lateral removal from the upper part of the soil profile. The colour of these soils is more yellowish than that of the Rhodudults. This appears to be related to more prolonged moist conditions in the soil profile and is probably caused by seepage from upslope.

Occurrence

Tropudults are found on gently undulating surfaces, crests, and rounded upper slopes throughout lowland areas where there are high temperatures, and a rainfall between 1500 and 4000 mm with a moderate to high seasonality. They occur under both grassland and forest vegetation.

Association

Tropudults are mainly found in association with Plinthudults, Rhodudults, Tropohumults, Tropudalfs and Dystropepts. Figure 9.2 is a typical cross-section of a lowland and shows the relationship of these soils to the Plinthudults and Plinthaquults.

Fertility

Data from six soils indicate moderate to low fertility levels. CEC values are moderate, while both TEB and BS figures are dominantly low. Nitrogen values (five samples) are moderate and exchangeable potassium varies between low and moderate. Data on available phosphorus (three samples) indicate low to moderate values. However, these values are expected to be generally low.

Land Use

Erosion hazards, in the moderately sloping terrain especially, and the moderate to low fertility are the major factors limiting cultivation. In particular, the subsoil nutrient reserve is very low and fertiliser requirements will be high. Pastures and the less selective tree crops, such as rubber and oil palm, appear to offer the best prospects in the more accessible areas. At present this land is only very locally cultivated, hunting and gathering being the major types of land use.

10 Oxisols

Oxisols are very weathered soils typically found on old land surfaces in both tropical and subtropical areas. Old, stable landforms are rare in Papua New Guinea and these soils occur only in a few, small, widely scattered locations below 1000 m. Some of the soils previously classified as latosols, red and yellow latosols and laterites (Haantjens *et al.* 1967), which are widespread in the Western Province, were considered to belong to the Oxisols. Analytical data, however, suggest that, because of the stringent criteria in the definition of the oxic horizon, only very few of these soils belong to this order. With Oxisols the weathering has been so extreme that virtually the only remaining minerals in the oxic horizon, which, by definition, must be >30 cm thick, are quartz, free oxides and 1:1 lattice clay minerals, such as kaolinite. This strong weathering is reflected in the fine earth fraction which, by definition, must have a CEC of 16 meq or less per 100 g clay using the ammonium acetate determination. Several other criteria apply to the definition of the oxic horizon and these are outlined in detail in *Soil Taxonomy* (US Dept of Agric. 1975).

Two suborders of the Oxisols, namely the Humox and Orthox, have been identified in Papua New Guinea, while a third, the Aquox, comprising poorly drained soils, may also occur locally. *Humox* are characterised by a high organic matter content to a depth of 1 m,* excluding the organic surface litter.† *Orthox* are soils lacking the poor drainage, or high organic matter contents, characteristic of the Aquox or Humox.

HAPLOHUMOX and ACROHUMOX

Morphology

Haplohumox and Acrohumox being very similar are discussed together. They are separated from each other, at great group level, by a cation retention capacity value‡ in some subhorizon(s) of the oxic horizon. Both great groups

* The absence of bulk density data and % organic carbon contents to a depth of 1 m has often made it impossible to identify these soils positively.

† Humox also require an isothermic, thermic or cooler temperature regime. However, since a definite proposal has been made to waive this requirement it has not been applied (F.R. Moorman personal communication 1981).

‡ For the Haplohumox >1.5 meq per 100 g clay, and for the Acrohumox ⩽1.5 meq per 100 g clay (by NH_4Cl determination).

are characterised by a thick (>50 cm), dominantly reddish brown, occasionally red or yellowish red, B_2 horizon which has a relatively high organic matter content, a very low supply of bases, and a high friability in relation to clay content. The overlying A_1 horizon may vary in thickness from less than 5 cm to over 20 cm, has dark brown, brown or very dark greyish brown colours, and a fine to medium subangular blocky structure. The B_2 horizon commonly has a weakly developed blocky structure, and usually grades into a thick brown to reddish brown transitional horizon. Alternatively, it overlies a brown, or yellowish red C horizon with or without mottles, containing weathered rock fragments. These strongly acid soils consist mostly of clay loams or clays, with a high permeability in relation to clay content. Both the Haplohumox and Acrohumox are usually confined to gently sloping surfaces comprising old colluvio-alluvial deposits derived from igneous rocks (Plate 10.1, colour section). In the vicinity of active volcanoes their topsoils are often slightly coarser in texture than the subsoils due to contamination by volcanic ash. They were formerly called strongly weathered red and brown clay soils (Haantjens 1964b).

Genesis

These soils are typical end products of prolonged weathering under hot, wet and humid conditions on relatively stable landforms. This has resulted in the selective removal of silica and bases and in the formation of poorly crystallised kaolinitic clays that are acid and unsaturated with bases (see next Genesis section). Their relatively high organic matter content, in comparison to that of other Oxisols found in very similar environments, remains unexplained, although they appear to occur at slightly higher altitudes. In other tropical countries these soils are mainly found at higher altitudes in cool, humid climates.

Occurrence

Both the Acrohumox and Haplohumox have a very restricted distribution. They have been recorded in isolated, small areas in the Northern and Milne Bay Provinces and on the Sogeri plateau near Port Moresby. Isolated occurrences are likely on stable landforms throughout Papua New Guinea, particularly in areas underlain by ultrabasic rocks.

Association

These soils are closely associated with Dystropepts, Tropohumults, Rhodudults and Tropudults.

Fertility

Data are very limited but the fertility level is expected to be generally low. Fertility of these soils is largely governed by the above average organic matter content in the topsoil, which results in moderate nitrogen levels and cation exchange capacities. Both exchangeable potassium and available phosphorus values are expected to be low, and BS and TEB contents low to moderate.

Some clay mineral data given in Table 10.1 clearly indicate the strongly weathered nature of these soils; kaolinite/halloysite and/or goethite being always the dominant clay minerals.

Land Use

Although their physical properties are generally good, low fertility, high acidity, and possible aluminium, iron, or trace element toxicity seriously limit the agricultural potential of these soils. Some of these soils found on ultrabasic rocks have very high nickel and chromium contents. They are best left in their natural state and, at present, are not being cultivated.

HAPLORTHOX and EUTRORTHOX

Morphology

These soils are very similar to the Haplohumox and Acrohumox. However, the lower organic matter content of their B_2 horizon is reflected in their dominantly red and yellowish red colours. Differences in classification between the Eutrorthox and Haplorthox are based on analytical data. Eutrorthox have a base saturation of 35 per cent or more throughout the soil. Haplorthox lack this but have a 'modest' cation exchange capacity. When an A_1 horizon is present, it is thin (<25 cm) and overlies, with a clear boundary, a generally thick (>50 cm) B_2 horizon which is fine textured, strongly acid, and has a high friability in relation to clay content. Haplorthox and Eutrorthox have been found on ultrabasic rocks, volcanics and uplifted coral limestone. In contrast to soils of the Humox suborder, they appear to occur mainly at lower altitudes in areas with high mean annual temperatures. They were previously classified as acid red to brown clay soils (Scott 1965) and granular dark red uniform heavy clay soils (Haantjens 1964b).

Genesis

Like the other, previously discussed, Oxisols these soils are typical end products of deep, strong weathering on relatively stable landforms and under free drainage conditions.

The process by which silica is leached leaving iron and/or aluminium in the soil is called ferrallitisation.* It is considered the most common soil-forming process in the humid tropics and ultimately leads to the formation of Oxisols. The solubility of alumina, iron and silica in soils is strongly dependent on the pH of the soil solution. At pH values of 5-8, for instance, the solubility of alumina is very low and silica does not hydrolyse† until the pH of the soil

* Formerly also referred to as laterisation or lateritisation.

† Hydrolyses refers to the chemical reaction between the H or OH ions of water and the ions of the mineral ultimately leading to formation of clay minerals.

solution is 7 or more. As a result, only very small amounts of SiO_2 and Al_2O_3 are released under these conditions. These small amounts are not very mobile and form colloidal suspensions which, at a later stage, combine to form a relatively insoluble aluminium silicate such as kaolinite. During the first stage of weathering, dissolution and leaching of the basic elements Na, K, Ca and Mg takes place, the metal ions combining with the OH ions. This leaching of alkaline elements and their subsequent replacement by H ions will slowly lead to acidification of the remaining materials. However, when the acidification is not strong, as is the case with basic rocks, the environment remains alkaline for a relatively long time, and leaching of silica together with bases continues as they are more mobile under these conditions. This enables the precipitation of alumina which, under favourable circumstances, crystallises into gibbsite. As the environment gradually acidifies owing to a decrease in the supply of bases under continual leaching, minerals containing iron, for example biotite, are attacked by hydrolyses and iron hydroxides are formed. These iron hydroxides do not migrate very far because of their low solubility under all but extremely acid conditions. The increase in iron oxide contents leads to a gradual rubrification (red colouring) of the profile. On relatively stable, free draining surfaces the continuation of these processes over long periods will ultimately lead to the formation of strongly weathered, highly leached, poorly differentiated, reddish or yellowish soils rich in kaolinite, sesquioxides and quartz.

Occurrence

Only isolated occurrences of these soils have so far been recorded on stable landforms in areas most commonly underlain by ultrabasic rocks. These were found near Cape Vogel and Safia in the Milne Bay and North Provinces, and on the Sogeri Plateau near Port Moresby.

Association

Haplorthox and Eutrorthox are associated mainly with Dystropepts, Tropudults and Rhodudults.

Fertility

Chemical fertility data from three profiles indicate that a generally low fertility level can be expected from these soils. Clay mineral data for one profile are given in Table 10.1.

Land Use

In Papua New Guinea these soils are not cultivated at present, and are considered unsuitable for agriculture due to their low fertility, high acidity, and possible aluminium, iron or trace element toxicity. With heavy fertiliser applications some of these soils have, however, become highly productive in other countries.

Table 10.1
Clay mineralogy of some Oxisols found in the Northern Province

Soil profile and horizon	Depth (cm)	Minerals of the clay fraction (X-ray analyses)
142* $-A_{11}$	0-5	K >80%; Go 10-20%
$-A_{12}$	5-15	K/Hh 65-80%; Go 10-20%; Gi 1-5% and Q <1%
$-B_{22}$	60-85	K/Hh >80%; Go/He 10-20%
$-C_{12}$	365-395	K/Hh >80%; Go 10-20%
196* $-B_{1}$	2-22	Go 65-80%; K 10-20%; T 10-20%; V/Ch 5-10% and Gi 1-5%
$-B_{21}$	22-42	Go 65-80%; K 10-20%; T 10-20% and Gi 1-5%
$-B_{22}$	50-72	Go >80%; T 5-10%; Gi?
$-B_{23}$	110-140	Go >80%
$-B_{24}$	170-190	Go >80%
229* $-A_{1}$	0-2	K/H >80%; V/Ch 5-10%; Gi 5-10% and Q <1%
$-B_{1}$	2-10	K/H >80%; V/Ch 5-10%; Go/He 5-10%; Gi 5-10% and T 1-5%
$-B_{22}$	20-40	K/H >80%; Ch 5-10%; Go/He 5-10% and Gi 5-10%
$-B_{23}$	70-95	K/H >80%; Ch 5-10%; Gi 5-10% and Go/He 1-5%
$-C_{11}$	260-285	K/H 50-65%; Gi 10-20%; Go/He 10-20%; Ch 5-10% and Mu 5-10%
370* $-A_{11}$	0-4	K/H >80%; Ch 5-10%; Go 5-10% and Q <1%
$-A_{12}$	5-15	K/H >80%; Ch 5-10%; Go 5-10% and Q <1%
$-B_{22}$	60-80	K/H >80%; Ch 5-10% and Go 5-10%
$-C_{1}$	260-290	K/H >80%; Ch 5-10% and Go 5-10%
P36† $-A_{1}$	0-5	Go 65-80%; K 20-30%; Gi 5-10% and Q <10%
$-B_{21}$	5-20	Go 40-50%; K/H 20-30%; Gi 10-20%; Ch/V 10-20% and Q <1%
$-B_{23}$	55-65	Go 50-65%; K/H 20-30%; V/Ch 5-10% and Q <1%
$-C_{1}$	130-170	An/Cr 50-65% and M 40-50%

* Acrohumox
† Haplorthox

Legend:

K = kaolinite	V = vermiculite	Cr = chrisotile
Hh = hydrated halloysite	Ch = chlorite	Q = quartz
	Mu = muscovite	Go = goethite
H = halloysite	T = talc	He = haematite
M = montmorillonite	An = antigorite	Gi = gibbsite

11 Land Inventory

Much of the data given in the previous chapters has been obtained from land resource surveys. A discussion of the soils would therefore not be complete without some mention of the resource inventory methods used previously in Papua New Guinea and the land suitability assessment.

LAND SYSTEM SURVEYS

A land system is defined as an area, or group of areas, throughout which there is a recurring pattern of topography, soils and vegetation (Christian and Stewart 1953). The land system concept originated in 1947 with a survey in northern Australia and was first implemented in Papua New Guinea in 1953. By 1969 fourteen land system surveys had been carried out in Papua New Guinea; areas ranged in size from 4000 to 20 000 km^2, and covered in total nearly half of the 470 000 km^2 landmass (Figure 11.1).

An essential feature of these surveys is the preliminary mapping, definition and description of the land systems by all scientists concerned, from aerial photography mostly at scales of 1:40 000 to 1:50 000. A basic survey team consists of a geomorphologist, soil scientist and plant ecologist, and logistics officer. The mapping, which takes 3-4 months, is followed by a 2-3 month period of field work, during which scientists together examine commonly preselected sites. This collective examination has been found to greatly facilitate the interpretation of data. The land survey is followed by data analyses, discussion and report writing, usually taking another 1-1½ years. The finalised report incorporates a land system map, usually at scale 1:250 000.

The utility of land system mapping depends on the recognition of distinct airphoto patterns (Plate 11.1) and the ability of the team to describe the individual patterns and distinguish between them. In comparison to Australia, Papua New Guinea has a much more complex terrain, large areas of which are covered by a dense vegetation obscuring the landforms and inhibiting access to many areas. For these reasons, the areas surveyed were kept relatively small. To overcome the inherent problems attempts have been made to clarify the land system mapping procedure (Haantjens *et al.* 1967; Scott *et al.* 1967; Haantjens 1965a, 1968a) and to devise different methodologies of mapping (Blake and Paijmans 1973a, b; Speight 1974).

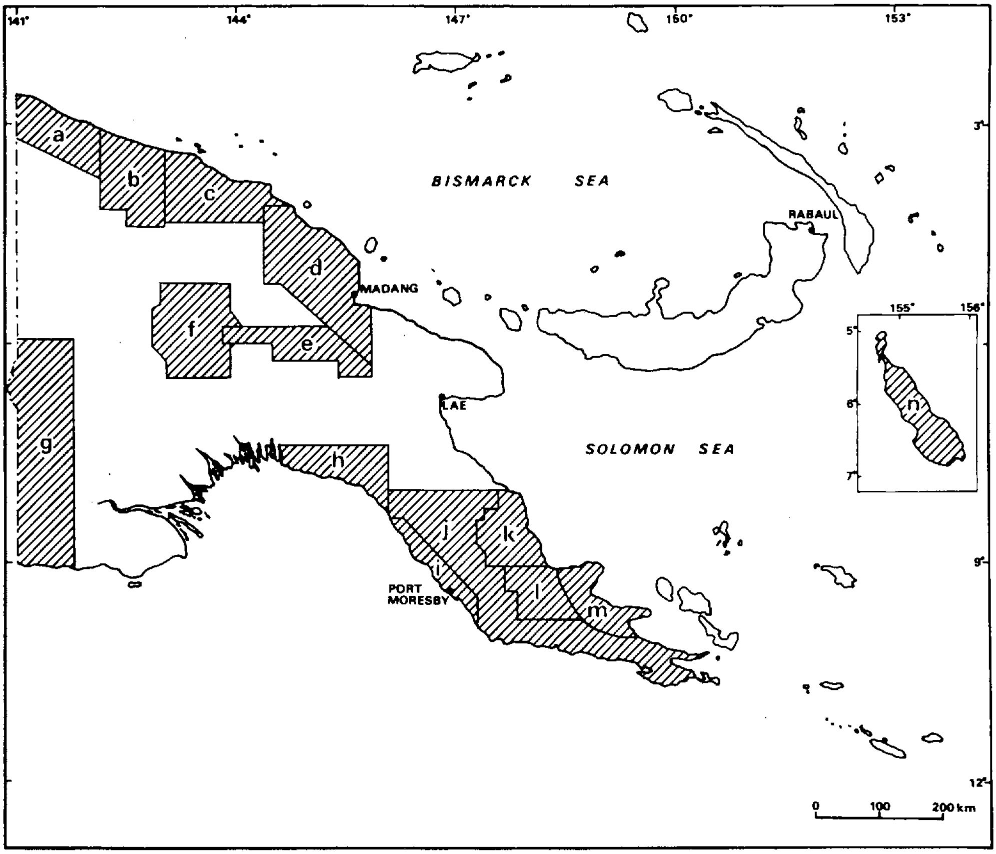


Fig. 11.1 Areas covered by surveys of Division of Land Use Research, CSIRO; a, Vanimo; b, Aitape-Ambunti; c, Wewak-Lower Sepik; d, Ramu-Madang; e, Goroka-Mount Hagen; f, Wabag-Tari; g, Morehead-Kiunga; h, Kerema-Vailala; i, Port Moresby-Kairuku; j, Eastern Papua; k, Buna-Kokoda; i, Safia-Pongani; m, Wanigela-Cape Vogel; n, Bougainville-Buka Islands.

Similar problems apply to the recognition of land units, which are components or 'building blocks' of the land system and have been variously defined (Mabbutt and Stewart 1963; Christian and Stewart 1968; Brink *et al.* 1966). According to Haantjens (1968a) attempts to define the concept of a land unit 'have wavered between requirements of uniformity in characteristics, of mapability in relation to map scale, and of simplicity of description and utility for land use purposes'. In the initial survey report (Christian and Stewart 1953), the land unit concept does not appear, the land system *per se* providing an excellent picture of the terrain configuration and its complexity. A very similar format, with added, more refined descriptions, has been used in two of the latest Papua New Guinea reports (Haantjens *et al.* 1972; Löffler *et al.* 1972). In the majority of reports, however, land units form an integral part of the land system description and are presented in a tabular form under separate headings for landforms, soils, vegetation and often land classes or (land)

Plate 11.1 Oblique aerial photograph of the Andabare River, Southern Highlands Province. The photograph, taken in south-west direction, shows the swampy alluviated upland valleys of Kandep land system (Ka), surrounded by the dissected slopes and fans on sedimentary rocks and colluvium of Andabare land system (An) which are covered by natural grassland. Andabare land system, in turn, is surrounded by mountains and escarpments on limestone, covered by lower montane forest and called Kaijende land system (Kj).

limitations. Examples of the two land system description methods are given in Appendix II, Examples 1 and 2.

LANDFORM TYPES

Another approach was adopted to map the results of a rapid (6 weeks field work) survey, covering 61 000 km^2 of eastern Papua New Guinea. It included the whole, or parts, of five previously surveyed areas which, although accounting for half the landmass, involved some 150 different land systems described in varying detail. With the components (land systems) distinguishable in the remainder of the area, this would have brought the total to above 200 (Blake and Paijmans 1973a). Therefore, after taking into account the broad nature of the survey and the very few ground observations made in the area, it was decided to remap the area. By identifying only those landforms and relief classes that could be observed and interpreted by using airphotos and on available geological information the area was divided into 58 landform types. The mapping method has been outlined in detail by Blake and Paijmans

(1973a, b). In Appendix II, Example 3 an example of a landform type description is given.

The weakness of this approach, which also applies to land system surveys or any other extrapolative soil survey, is that they assume the soils to be sufficiently closely associated with landform or vegetation to allow reliable correlations. From the tabulated land unit descriptions of land systems the reader may get an exaggerated impression of the precision and reliability of the data, particularly for soils, which are extrapolated from a limited number of soil sites.* By using the even broader landform type method this situation is even further compounded.

Results of a study by Bleeker and Speight (1978) on soil-landform relationships in two test areas in Papua New Guinea have indicated that the current techniques and sampling densities used in land resource surveys can produce only very generalised information on soil distribution. To obtain reliable predictions of soil formation at the level commonly implied in such surveys, further intensive studies are required. Nevertheless, there is little doubt that land system surveys have been very useful for the collection of basic data for little known areas. They are still being used in developing countries by international agencies (e.g. Birchall *et al.* 1979) where they offer a practical alternative to intensive, high cost surveys.

LAND SUITABILITY ASSESSMENT

A resource inventory would be incomplete without an assesement of the most suitable land use for the areas which have been mapped. This land classification may accord with its present use, its suitability for a specific crop, or, in a wider context, for a combination of crops. The amount of detailed information forthcoming will naturally depend on the data collected and scale of mapping.

All but one of the resource reports published by CSIRO, Division of Land Use Research, contain information on the suitability of the land for agriculture. In the early reports, small scale maps (mostly 1:1 million) were produced in the form of generalised groupings of land systems with suitability classes varying from very high to very low in potential. These ratings were assessed on the suitability class of the dominant land unit(s), minor units being ignored. For this assessment an early version of the land capability classification, developed by the US Department of Agriculture (Klingebiel and Montgomery 1961) was used as a basis. In this scheme land is grouped into eight classes, denoted by Roman figures, which indicate the level of suitability of the land for different types of crop production. Each class, excepting class I, is divided into a number of subclasses, denoted by letter symbols indicating the nature of the limiting factors (e.g. d = drainage improvements and st = stoniness), because of which the land is placed in a particular land class. This system was slightly modified for tropical environments by Haantjens (1963) to incorporate tree crops and wetland rice cultivation.

* Densities vary between 29 and 72 sites per 1000 km^2 in areas surveyed in Papua New Guinea.

The latest reports, however, incorporated a new system developed by Haantjens (1969a), the most important features of which are:

(1) the land is specifically classified into four distinct types of agricultural use (arable crops, tree crops, improved pastures and wetland rice)
(2) each mapping unit as a whole is assessed according to a sliding scale of suitability, by which,
(3) more than one limitation or hazard lowers its overall capability class more than one single factor.*

This system gives a much better indication of the 'mean' capability of each mapping unit. It has been successfully applied to surveys, and is also presently used by the Papua New Guinea Department of Primary Industry. With some modifications, this scheme has been used by Bleeker (1975) to produce a large scale (1:1 million) land limitation and agricultural land use potential map of Papua New Guinea. As shown in Table 11.1 the mapping units have been assigned factor ratings. These are arranged from left to right in a somewhat arbitrary order of importance. The map reference is arranged similarly. It starts with the 'least' important factor and lowest rating (the 'best' land), with the ratings denoting progressively more serious or limiting factors for agriculture. As many as four ratings are given by letters making up a map symbol with the initial (capital) letter indicating the highest and/or most important factor rating of the mapping unit. Map colours (or hatchings) have been accorded to the most important (first) factor of a similar rating. An example of this system is given in Figure 11.2 for the North Solomons Province. It should be noted that the legend here refers only to the mapping units for the North Solomons Province, the original map having many more subdivisions under the major headings.†

The overall suitability for arable crops (C), tree crops (T), improved pastures (P), and flooded or wetland rice (I) is also given in the map reference. This assessment is based on such general assumptions as that tree cropping leads to less erosion than arable cropping on the same kind of land, or that arable crops require less well drained soils than do tree crops. Suitability levels are indicated in letter symbols from VH (very high) to N (nil). Since there is such a variety of environmental conditions for both arable and tree crops these have been further subdivided into four altitudinal classes; 1 = lowland (0-600 m), 2 = mid altitude (600-1200 m), 3 = highland (1200-1800 m) and 4 = high altitude (1800-2400 m). The assessment of the suitability levels according to the factor ratings is given in Table 11.2, while Table 11.3 shows how the *overall* suitability of the mapping units is determined for units having more than one factor rating. The map produced by Bleeker (1975) should be considered a preliminary inventory only, assessing as it does the suitability of the mapping units according to four very broadly defined land use types. It was not possible, taking into account the number of mapping units involved and the limitations of scale, to represent individual crops effectively. However, as shown in Figure 11.3, the map can be used to produce generalised suitability maps for

* In other words two hazards in class 2 and one in class 3 might give an overall assessment in class 4, while in the USDA system the land would still be in class 3.

† Bleeker (1975) originally distinguished sixty different units.

Table 11.1

Explanation of factor ratings (after Bleeker 1975)

Factors are rather arbitrarily arranged from the most to the least important (left to right)

Rating	Slope steepness (erodibility) E or e	Flooding and/or inundation hazards F or f	Drainage status D or d	Drought risks M or m	Factor Altitude (m) L or l	Surface rocks and/or stones (%) R or r	Fertility N or n	Salinity S or s	Soil Reaction A or a
0	Level or sloping <2°	No flooding and/or inundation	Well drained	No drought risks	<1200	<1	Apparently relatively fertile	No salinity	Weakly acid to neutral (field pH 6.0-7.0)
1	Slope 2-6°	Occasional seasonal flooding	Imperfectly drained	Possible drying out of upper horizon of profile for short periods	1200-2400	1-2	Appears to have low fertility	Saline (conductivity <6 mmhos/cm)	Acid or weakly alkaline (field pH 5.0-6.0 or 7.0-7.5)
2	Slope 6-9°	Occasional irregular flooding or inundated for up to 1 month	Poorly drained; easily improved	Profile dries out for indefinite periods	2400-3000	3-7			Alkaline (field pH 7.6-8.5)
3	Slope 9-17°	Inundated for 1-3 months	Very poorly drained; relatively easily improved		>3000	8-30			Strongly acid (field pH <5.0)
4	Slope 17-30°	Frequent irregular flooding, or occasional deep devastating flooding, or inundated for 3-6 months	Poorly to very poorly drained; difficult to improve			>30			Strongly alkaline (field pH >8.5)
5	Slope >30°	Permanently or semi-permanently inundated, or subject to very frequent or tidal flooding	Swampy						

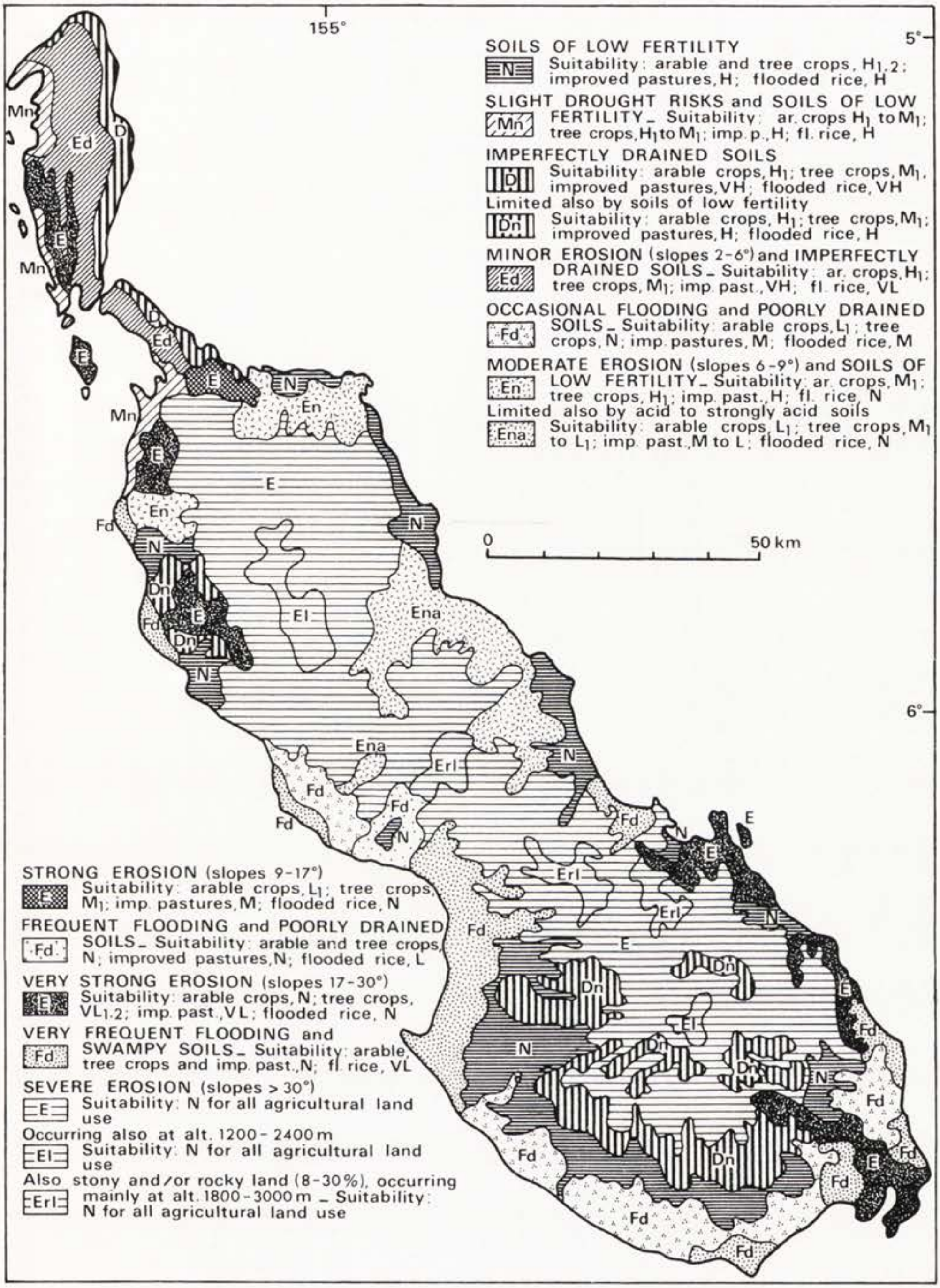


Fig. 11.2 Land limitations and agricultural land use potential of the North Solomons Province* (after Bleeker 1975)

* Suitability levels are indicated as follows: VH, very high; H, high; M, moderate; L, low; VL, very low; N, nil. Subscripts indicate the suitability levels for arable and tree crops, according to altitudinal zones broadly subdivided into 1, lowland (0-600 m); 2, mid altitude (600-1200 m); 3, high land (1200-1800 m); 4, high altitude (1800-2400 m) zones. Suitability levels for flooded rice are considered at least one level lower in soils with rapid permeabilities

Table 11.2

Assessment of suitability levels* for arable crops (C), tree crops (T), improved pastures (P) and flooded rice (I)† according to factor ratings (after Bleeker 1975)

Rating	Erodibility E or e	Flooding and/or inundation F or f	Drainage status D or d	Drought risks‡ M or m	Factor Altitude (m)‡ L or l		Surface rocks and/or stones (%) R or r	Fertility N or n	Salinity S or s	Soil reaction A or a
0	$C_1T_1P_1I_1$	$C_1T_1P_1I_1$	$C_1T_1P_1I_1$	P_1I_1	0-600	P_1I_1	$C_1T_1P_1I_1$	$C_1T_1P_1I_1$	$C_1T_1P_1I_1$	$C_1T_1P_1I_1$
					600-1200	P_1I_1				
1	$C_2T_1P_1I_5$	$C_2T_2P_2I_2$	$C_2T_3P_1I_1$	P_2I_1	1200-1800	P_1—	$C_2T_1P_1I_3$	$C_2T_2P_2I_2$	$C_3T_4P_3I_2$	$C_2T_2P_2I_2$
					1800-2400	—T_5P_2				
2	$C_3T_2P_2$—	$C_3T_4P_3I_3$	$C_3T_4P_2I_1$	$C_3T_3P_3I_5$		——P_3—	$C_3T_2P_2I_5$			$C_3T_3P_2I_2$
3	$C_4T_3P_3$—	C_4—P_4I_3	$C_4T_5P_3I_1$			——P_4—	$C_4T_3P_3$—			$C_3T_3P_3I_3$
4	—T_5P_5—	Flooded C_5—P_4I_4 Inundated C_5—P_5I_4	C_4—P_4I_1				—T_5P_5—			$C_4T_5P_3I_3$
5	————	———I_5	——P_5I_2							

* Suitability levels are indicated as 1, very high (VH); 2, high (H); 3, moderate (M); 4, low (L); 5, very low (VL); —, nil (N).

† In the assessment of the suitability for flooded rice, problems related to getting the irrigation water onto the land and difficulties in the construction of rice bays are *not* taken into account.

‡ Ratings 0 and 1 for factors M and L are not given for arable and tree crops because these depend strongly on the choice of crop.

Table 11.3
Determination of overall suitability of mapping units for arable crops (C), tree crops (T), improved pastures (P) or flooded rice (I) from suitability levels of individual factor ratings as determined in table 11.2 (after Bleeker 1975)

Individual suitability	Overall suitability	Individual suitability	Overall suitability
All	1	Three 3, two 2, rest 1	Nil
One 2, rest 1	2	One 4, rest 1	4
Two 2, rest 1	2	One 4, one 2, rest 1	4
Three 2, rest 1	3	One 4, two 2, rest 1	5
Four 2, rest 1	3	One 4, three 2, rest 1	5
Five 2, rest 1	4	One 4, one 3, rest 1	5
One 3, rest 1	3	One 4, one 3, one 2, rest 1	5
One 3, one 2, rest 1	3	One 4, one 3, two 2, rest 1	Nil
One 3, two 2, rest 1	4	One 4, two 3, rest 1	Nil
One 3, three 2, rest 1	4	Two 4, rest 1	Nil
One 3, four 2, rest 1	5	One 5, rest 1	5
Two 3, rest 1	4	One 5, one 2, rest 1	5
Two 3, one 2, rest 1	4	One 5, two 2, rest 1	Nil
Two 3, two 2, rest 1	5	One 5, one 3, rest 1	Nil
Two 3, three 2, rest 1	5	One 5, one 4, rest 1	Nil
Three 3, rest 1	5	Two 5, rest 1	Nil
Three 3, one 2, rest 1	5		

individual crops. By refining the original scheme, with definitions for the specific requirements of crops, it is proposed to later produce individual crop suitability tables for both cash and subsistence crops. These refinements together with the inclusion of management levels* will also bring the system into closer conformity with the FAO (1976) 'Framework for Land Evaluation'. This system is basically intended as a 'framework' around which national or local systems can be developed. One of the fundamental principles embodied in its methodology is that land suitability can only be properly assessed when related to specific land use which must be of a sustained nature. This implies the cultivation of a nominated crop (or group of crops with very similar requirements), which is grown at a required level of management, without causing environmental degradation.

An excellent summary of the FAO system is given by Young (1976). A major criticism of this system is, however, that 'the framework does not specify how

* Intensive, improved traditional and traditional management levels. Intensive agriculture referring in this context to mechanised, dominantly cash cropping with high management levels and major capital inputs. Traditional agriculture on the other hand, refers to shifting cultivation, with variable rotation periods and involving practices such as manual labour with simple implements, no chemical fertiliser use or pest control and the minimum amount of agriculture extension. Improved traditional agriculture refers to the usage of improved seeds, some fertilisers, more sophisticated tools and/or light machinery etc. It implies the likely ability of the land to produce at least one crop each year with sustained yields over a period of continuous cultivation.

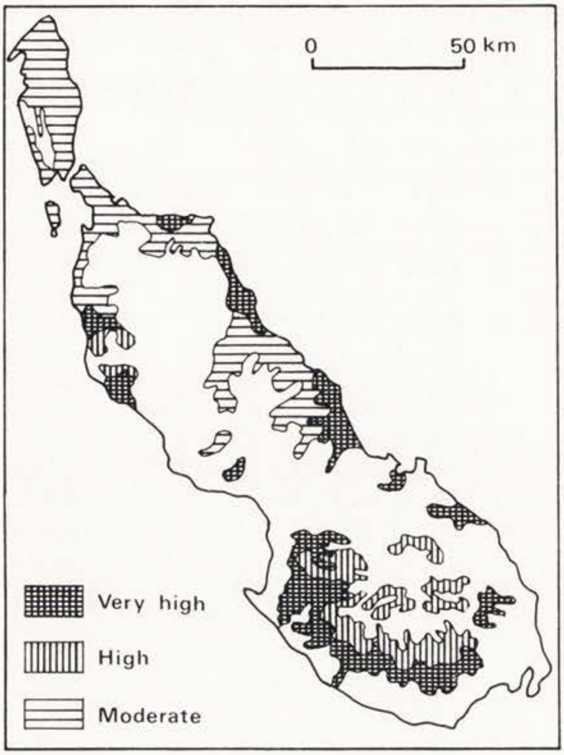


Fig. 11.3 Areas suitable for growing cocoa in the North Solomons Province

suitability is to be determined, but in practice systems based upon it are likely to use conversion tables which employ, in whole or in part, the concepts of limitations'.

Perhaps even more important is the emphasis placed in the framework on economic considerations. Although there is little doubt that economics are vital in any land use decisions, a land classification scheme incorporating these considerations is likely to be subject to sudden changes, particularly in a rapidly developing country such as Papua New Guinea. Market price fluctuations in cash crops, road building etc., would necessitate an almost continuous reappraisal of the evaluation systems calling for highly qualified staff and possible computer facilities. Although such a system may be well suited to industrialised countries it seems hardly applicable to a developing country. Using a simpler scheme based solely on biophysical land characteristics an agricultural economist or land planner can make decisions as the land becomes more accessible or market prices rise.

12 Soil Erosion

Soil erosion, in the forms of sheet, rill or gully erosion, constitutes a serious threat to soil productivity and environmental quality and, as such, appears to pose some problems in parts of Papua New Guinea. These are mainly in relatively densely populated areas where rapid population growth, combined with the introduction and continuing expansion of cash cropping, has resulted in land, previously considered unsuitable for cultivation, being brought into production. Cash crops, such as coffee and cocoa, are now often being grown on the best agricultural land, which, being less susceptible to erosion, is better suited to arable farming. Consequently the 'poorer' terrain is being subjected to erosion hazards.

With few exceptions very little research into soil erosion has been carried out until recently in tropical countries including Papua New Guinea. One such experiment is now being conducted by the Department of Primary Industry near Kundiawa, in the Chimbu Province, while another has been carried out in the Tari Basin in the Southern Highlands Province (A. Wood personal communication 1981). To date, preliminary results of these experiments appear to indicate that, if taken in a world wide context, soil erosion losses are much less serious than generally thought. Nevertheless there are indications that erosion could become a serious problem in some areas, unless preventive measures are implemented. This is particularly the case on the Gazelle Peninsula, East New Britain, where the danger of erosion is perhaps most acute.

In contrast to tropical areas, soil erosion has been extensively studied in temperate regions especially in the United States of America where the principal method for predicting soil erosion losses is the Universal Soil Loss Equation (USLE). This was specifically developed over the years from 1940 as a means of predicting soil losses in the Corn Belt (Wischmeier and Smith 1978). It has been applied since then, sometimes in a modified form and with varying degrees of success, to various tropical areas (Dangler *et al.* 1976; Roose 1975; Elwell and Stocking 1974, 1976). A possible application of the USLE to Papua New Guinea conditions is discussed in this chapter. Results of erosion experiments in the Chimbu Province by Humphreys (personal communication 1982) indicate that this seems warranted.

Papua New Guinea has extensive wet, mountainous areas prone to earthquakes and volcanic activity and undoubtedly incurs large soil losses due to landslides and mudflows. Research into denudation rates caused by natural agencies thus has an important application to Papua New Guinea and is therefore also briefly reviewed in this chapter.

THE UNIVERSAL SOIL LOSS EQUATION

The USLE is equated as $A = R \times K \times L \times S \times C \times P$ where A represents the computed soil loss per unit area, R the rainfall and runoff, K the soil erodibility, L the slope length, S the slope steepness, C the cover and management factor and P the support practice factor.

Rainfall and Runoff Factor (R)

Research undertaken by the United States Department of Agriculture has shown that soil losses are directly proportional to a rainstorm parameter called the rainfall erosion index (EI). This index represents the product of the total kinetic energy of the rainfall (E) and the maximum rainfall intensity for a given 30-minute period within a storm (I_{30}). This is the greatest average intensity experienced in any 30-minute period during the storm, computed from recording rain gauge charts by locating the greatest amount of rain which falls in any 30 minutes and doubling the amount to obtain mm/hour. However, research into the suitability of this index for tropical areas (Hudson and Jackson, 1959; Lal 1976) established only poor correlations between it and soil erosion, which in the tropics appears to be related more to the much higher kinetic energy of the rainstorms than is the case in temperate regions. Lal (1976) therefore introduced the AI_m index which is the product of the maximum intensity I_m, for a given period, and the total rainfall amount (A). According to Lal this index provides a more accurate indication of rainfall erosivity than other indices developed for tropical areas. Moreover it is easier to calculate than the EI_{30} index. Hudson (1971), carrying out research in Zimbabwe-Rhodesia, found that there is a threshold value of intensity of 1 inch or 25 mm per hour at which rain starts to become erosive. By using this value, usually termed the KE>1 or KE>25 index, and leaving out the energy of the non-erosive rain an excellent correlation was obtained by Hudson (1971) between splash erosion and the total energy of the rest of the rain. The KE index can be incorporated into the EI or AI index and would appear much better suited to regions with a tropical rainfall.

Like Lal's (1976) work, recent research by Osuji *et al.* (1980) in Nigeria has shown high correlation coefficients of the AI_m index with soil losses, but the results were only marginally higher than those obtained for the KE>25 and EI_{30} indexes.

It would appear, from the above, that much more research work is needed in tropical areas in order to determine the most comprehensive rainfall parameter.

Unfortunately in Papua New Guinea pluviometer data (clock hour data taken at 6-minute intervals) are only available from some ten stations. Apart from this data often being incomplete, little consideration was given to whether the site was representative of a typical climate regime. It is therefore not possible at present to make a reliable assessment of the erosivity using either the EI_{30} or AI_m index. However, the country has a good network of approximately 525 rainfall stations for which the monthly precipitation has been summarised by McAlpine *et al.* (1975). This makes it possible to calculate a modified Fournier index, defined as

$$\sum_{i=1}^{12} \frac{p_i^2}{P}$$

where p equals the maximum monthly precipitation and P equals the annual precipitation. This index has been used by FAO (1977) in its World Soil Degradation Project and a correlation with the rainfall and runoff factor (R) of the USLE has been established. However, since the precise relationship between the R factor of the USLE and the modified Fournier index changes from one zone to another the relationship should be fitted to known values for some stations in a zone (see Annex IV by H.M.J. Arnoldus in FAO 1977). Figure 12.1 shows the rainfall erosivity in Papua New Guinea, simplified into

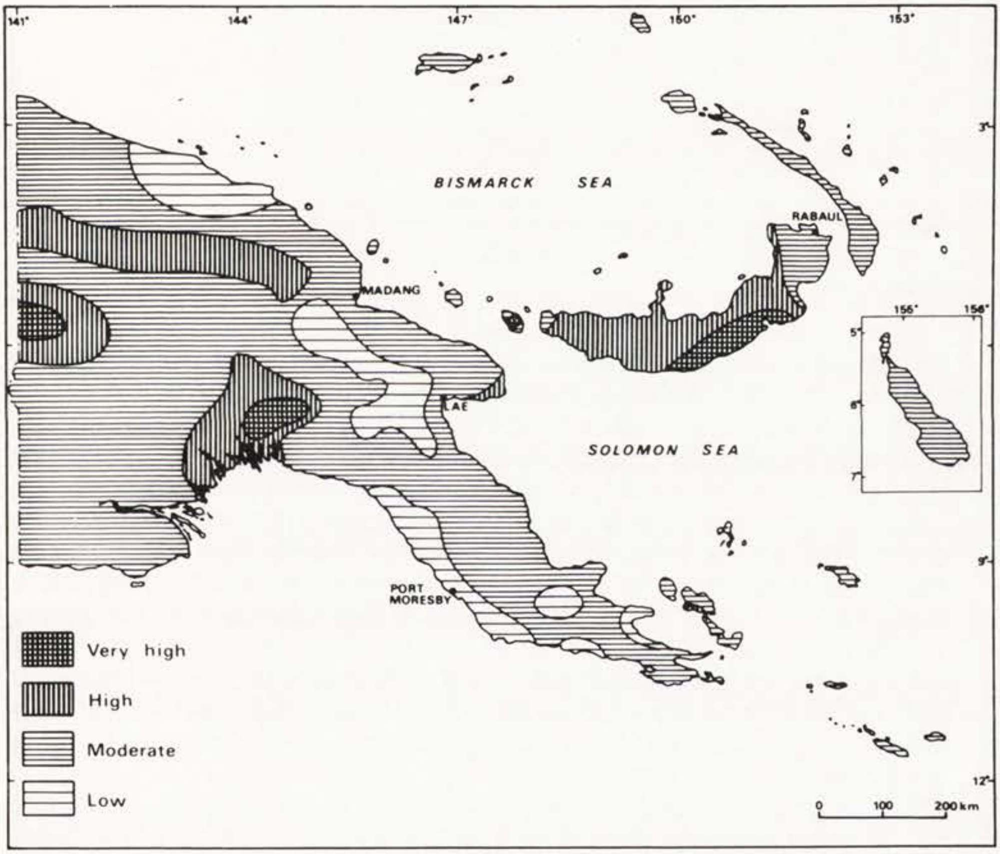


Fig. 12.1 Rainfall erosivity in Papua New Guinea, simplified into four classes and calculated based on the modified Fournier index

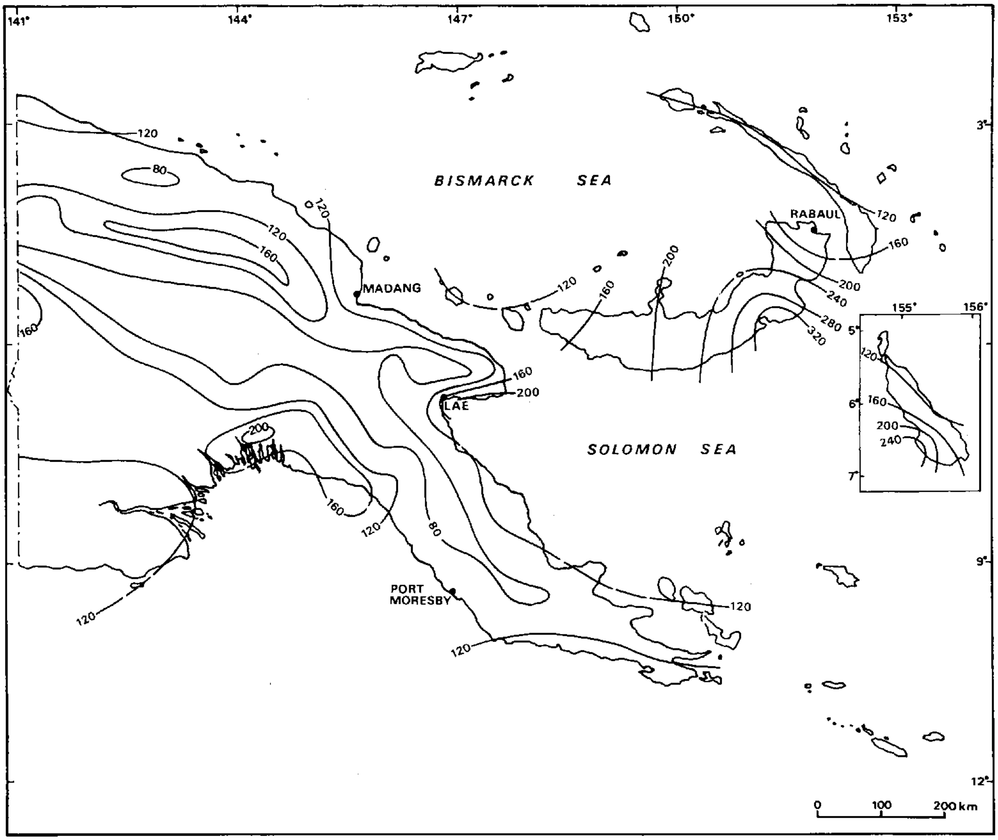


Fig. 12.2 Map of maximum daily rainfalls likely to occur every 2 years (after McAlpine *et al.* 1982)

four classes and calculated on the modified Fournier index. As can be expected the potential erosion risks are highest in the very wet, and lowest in the relatively dry areas with a high seasonality. In Figure 12.2 the maximum daily rainfall likely to occur every two years is shown. Based on this map a few generalisations have been made by McAlpine *et al.* (1982) namely:

(1) Falls of more than 100 mm per day do not occur in the main body of the Central Ranges, but may occur on coastal or island ranges. It should be stressed that although these storms are not persistent enough to produce high 24-hour totals, this does not necessarily mean that they are not intense for short periods (McAlpine *et al.* 1982). However, clock hour data (pluviometer) recorded over seven years at Kainantu (annual rainfall 2000 mm with a pronounced dry season) in the Eastern Highlands indicate, on average, only three days each year as having rainfall intensities of more than 25 mm (1 inch/hour).

(2) The heaviest daily falls (>150 mm) occurred in nearly all lowland stations, but were considerably less frequent in the drier areas and on the islands near to the equator. Except for these latter areas such falls can be expected on average once in a 1-3 year period (McAlpine *et al.* 1982). Rainfall

intensities greater than 25 mm per hour in dry lowland areas appear to follow a very similar pattern to those recorded in the highlands. Pluviometer data from Port Moresby (annual rainfall 1000 mm with a high seasonality), Central Province, taken over a 15-year period indicate an average 3-4 days each year with intensities of more than 25 mm (1 inch) per hour. However, in the wet lowland areas the pattern differs considerably. For example Madang (annual rainfall 3500 mm with north-west season maxima) over an eight-year period, had 23 days each year with intensities of more than 25 mm per hour and short term intensities (<6 minutes) occurred at a rate of 140 mm/hour every two years, rising to 180 mm/hour over a 10-year period.

(3) Heavy falls are most frequent in the wettest areas of Papua New Guinea, particularly in those areas subject to south-east season maxima, where they occur at least once a year. Taking Lae (annual rainfall 4600 mm with south-east season maxima) as a representative station, 6-minute short term intensities occurred at a rate of 170 mm/hour for the 2-year return period, and 200 mm/hour every ten years (McAlpine *et al.* 1982). Clock hour pluviometer data of intensities of >25 mm per hour from the same station (eight year period) show, however, very similar figures to Madang, the average being 22½ days each year.

Soil Erodibility Factor (K)

The K factor in the USLE is a quantitative value experimentally determined on a 72.6 ft (22 m) long plot with a uniform lengthwise slope of 9 per cent. In the United States it has been measured for twenty-three major soils and is now usually calculated from a nomograph developed by Wischmeier, Johnson and Cross (1971) which is shown in Figure 12.3. As demonstrated in the nomograph the soil erodibility factor is dependent on the texture (percentage silt plus very fine sand and percentage sand [100-2000μ fraction]), the organic matter content, the structure and the permeability of the soil. The K values obtained by using this nomograph have shown high correlations with those measured experimentally (Wischmeier and Smith 1978).

Whereas soil erodibility measurements have only just begun in Papua New Guinea, in Hawaii the K factor has been determined on ten benchmark soils (El Swaify and Dangler 1976) and data from eight of these soils, which are very similar to those occurring in Papua New Guinea, are given in Table 12.1. Although these data are rather limited, the table clearly shows that low K values are generally obtained from soils having high organic matter contents in combination with favourable physical conditions (e.g. Hydrandepts, Tropohumults, Dystrandepts).

These good physical properties would appear to be indicated also in the case of the Eutrustox, the high friability in relation to clay content of these soils permitting a relatively rapid permeability. However, the table also shows that there can be marked differences within great soil groups, as demonstrated by the Eutrandepts.

The relatively high organic matter content common to many Papua New Guinea soils seems to indicate that relatively little soil erosion has occurred during the last few decades, particularly in the densely populated highlands.

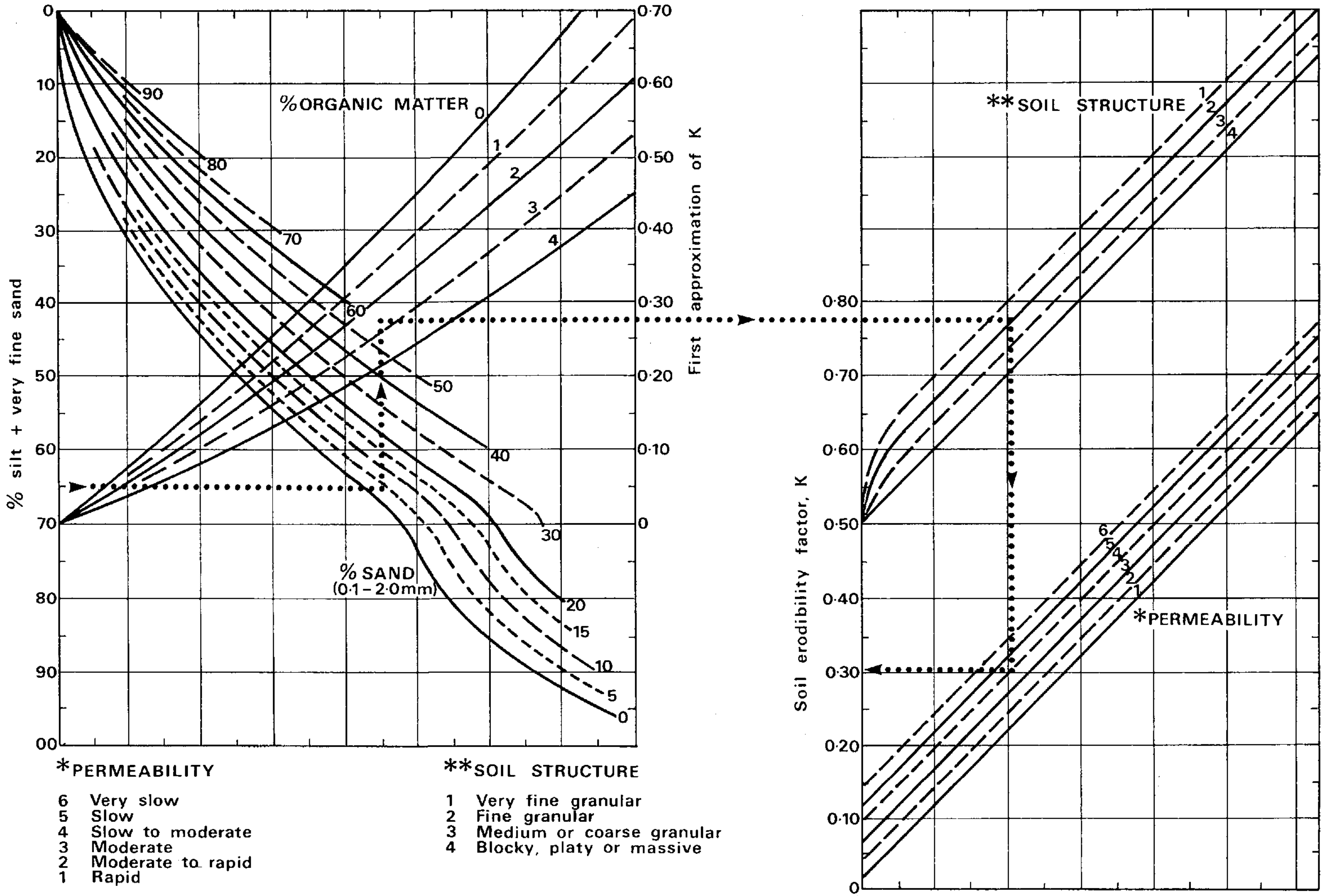


Fig. 12.3 Soil erodability nomograph* (after Wischmeier, Johnson and Cross 1971)

**Procedure:* with appropriate data, enter scale at left and proceed to points representing the soil's % sand (0.1–2.0 mm), % organic matter, structure

Table 12.1
Approximate values of the soil erodibility factor (K) for benchmark soils in Hawaii (after Dangler *et al.* 1976)

Great soil group	K factor
Tropohumults	0.10
Eutrustox	0.17
Chromusterts	0.28
Dystrandepts	0.17
Eutrandepts (typic)	0.20
Eutrandepts (entic)	0.49
Hydrandepts	0.10
Ustropepts	0.20

Data on lake sediments collected in the Mendi area (Oldfield *et al.* 1980), however, do indicate that there were two phases of increased erosion and sedimentation in the highlands; one between 150-300 years ago and possibly related to the introduction of the sweet potato and the other about 30 years ago and probably associated with changes in land use caused by European influences. Figure 12.4 gives the mean organic matter content of topsoils (0-25 cm) of some of the major great soil groups. These data show marked variations between the great groups, but all *mean* values exceed 3 per cent organic matter. High levels of organic matter characterise several soil groups, principally those soils developed on volcanic ash, and those occurring mainly at high altitudes (Hydrandepts, Eutrandepts/Dystrandepts, Humitropepts and Tropohumults). The reasons for these high levels have been given in the earlier chapters on the individual soil groups. Although the number of Rendoll samples is rather limited, their relatively high organic matter content in comparison to the other Mollisols (Hapludolls and Argiudolls) is somewhat surprising, as normally one would expect a rapid breakdown of organic matter in these limestone derived soils which are characterised by high pH values and free drainage conditions. However, similar high organic matter (and nitrogen) contents have been reported from soils (such as the Rendolls) found in other parts of the world which are characterised by high levels of exchangeable calcium. Stevenson (1965) suggests that either calcium humates and organic mineral compounds are formed which are less available to micro-organisms, or that calcium coagulates humic substances and prevents their dispersion and subsequent removal.

Very similar mean organic matter content values have been obtained from Solomon Island soils (Wall *et al.* 1979). Here the Hydrandepts, Ustropepts,* Humults and Humox in particular show high organic matter content, with the Hydrandept topsoils containing an average 16 per cent organic matter, compared to 17.1 per cent for the same soils in Papua New Guinea.

As regards the other soil properties used in the nomograph to determine the K factor, it is again difficult to make precise statements for great groups.

* Ustropepts with vertic properties, the high organic matter contents referring to the whole soil.

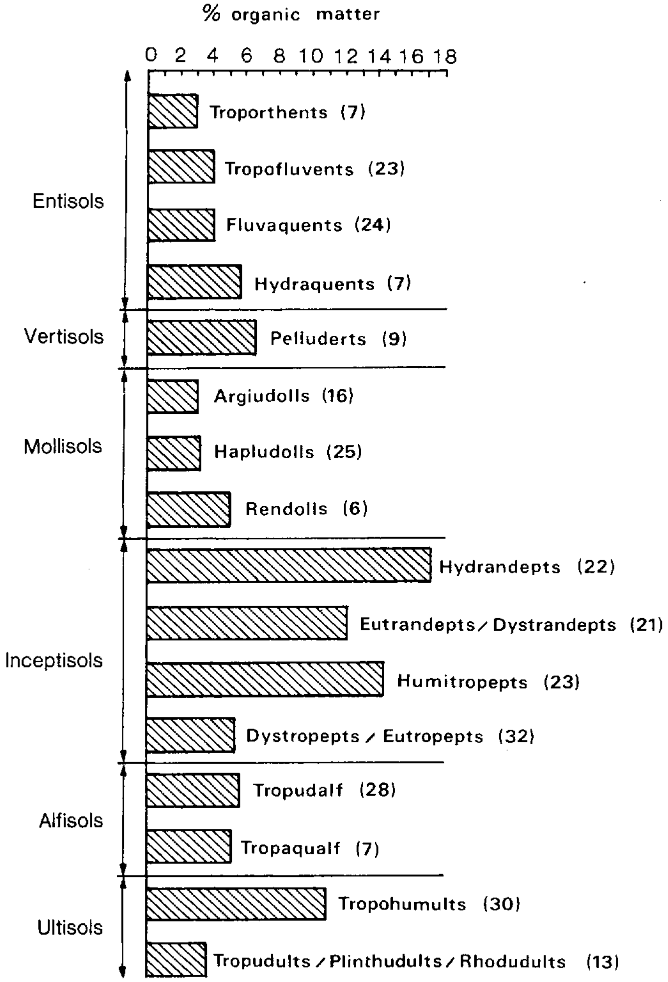


Fig. 12.4 Mean topsoil organic matter contents of major great soil groups in Papua New Guinea (number of samples in brackets)

However, a few generalisations on the textural properties of some great soil groups can be made which may prove helpful in assessing the soil erodibility factor. Charts showing these general groupings are given in Figure 12.5a, b and c.

Of the undeveloped Entisols, Psammaquents and Tropopsamments are, by definition, always within the sand to loamy sand texture range. Of the others, Tropaquents, Fluvaquents, Hydraquents and Tropofluvents characteristically have high silt contents, the dominant textures being silty clay, silty clay loam and silt loam. However, soils occurring at some distance from rivers (e.g. backswamps or abandoned oxbows), and those found near the mouths of rivers will in general have a very high clay content. Other exceptions are the alluvial soils derived from redistributed volcanic ash deposits, such as those that occur very commonly in the Northern Province and which have mainly

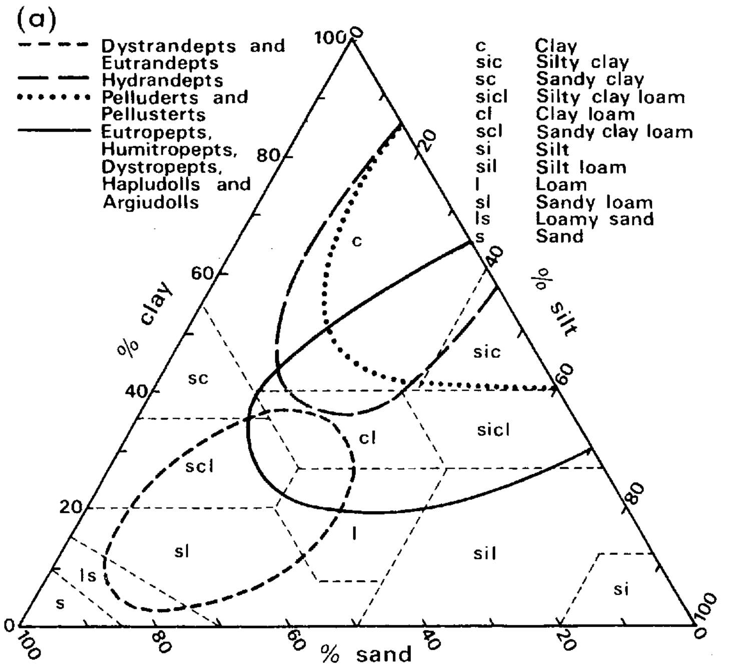


Fig. 12.5a Dominant textures of some major great soil groups in Papua New Guinea

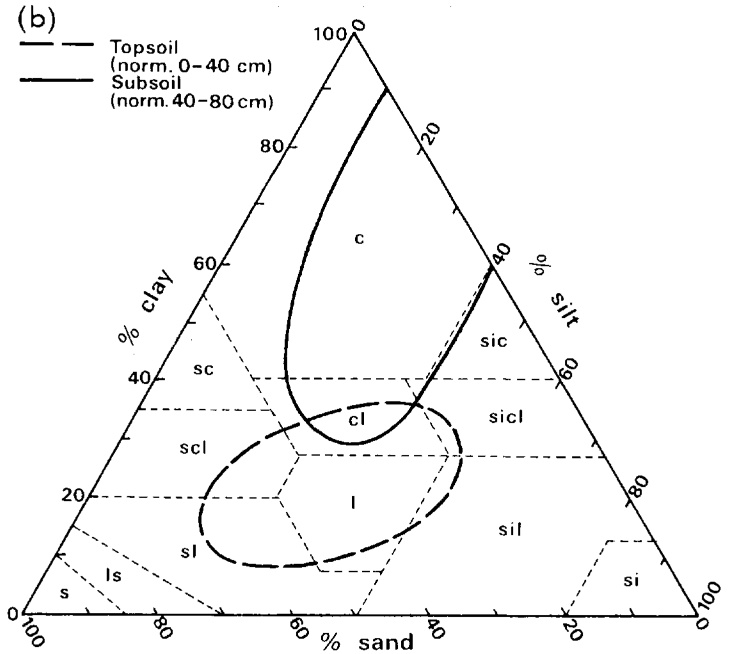


Fig. 12.5b Dominant topsoil and subsoil textures of Alfisols and Ultisols

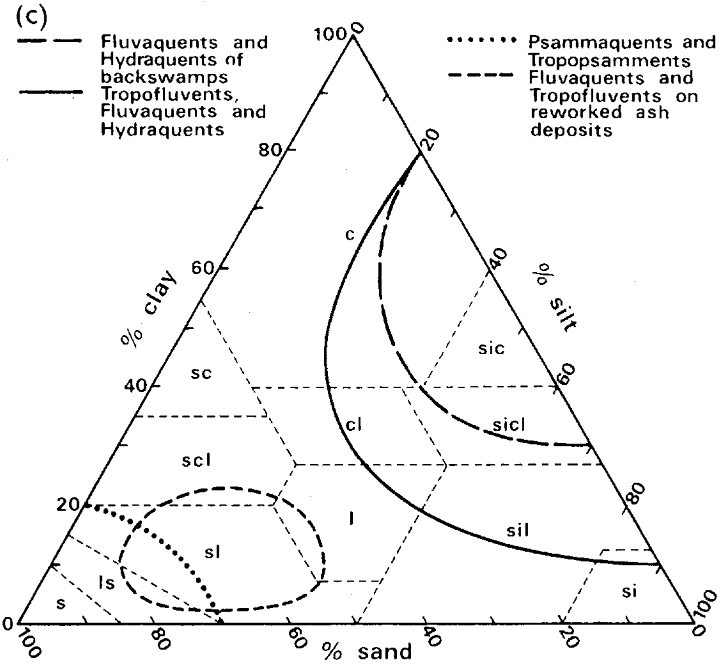


Fig. 12.5c Dominant textures of young alluvial soils in Papua New Guinea

sandy loam or loamy sand textures. The typical lowland volcanic ash soils (Dystrandepts, Eutrandepts, Vitrandepts) characteristically have high sand contents, their main textures being loamy sand, sandy loam, loam or sandy clay loam. Highland ash soils (Hydrandepts) on the other hand have high clay contents, even though this is often not borne out in granulometric analysis because of dispersion difficulties. Vertisols (Pelluderts and Pellusterts) always have high clay (>40 per cent) and low sand (<30 per cent) contents, the dominant textures being silty clay or clay.

Those Inceptisols that have not developed on pyroclastic materials together with the Mollisols encompass a predictably wide range of textures. However, their sand content rarely exceeds 50 per cent, while the silt and clay content mostly falls within the 20-70 per cent range. Soils with higher subsoil clay contents (Alfisols and Ultisols) are dominantly medium textured (sandy loam, loam or clay loam) in their surface horizons and fine textured in their subsoils. But surface horizons of these soils, which cover large areas south of the Fly River in the Western Province, typically have a high very fine sand content.

Little information is available on soil structure, particularly of subsoils, since most soils have been described from auger borings. For the most part moist to wet conditions make it impossible to recognise structural properties but soil samples collected have shown that many soils become well structured upon drying.

The soil erodibility nomograph only uses four major soil structure types, three of which are subdivisions of granular, (1) very fine, (2) fine and (3) medium to coarse granular while the other refers to blocky, platy or massive.

Fine to very fine granular or crumb structures appear to be most common in the topsoils of Hydrandepts, Humitropepts, and Tropohumults, all of which are characterised by high organic matter contents. Similarly the lowland ash soils (Dystrandepts, Eutrandepts and Vitrandepts) and most Mollisols are also well structured because of their relatively high organic matter content and have fine to medium granular or crumb, but also very fine blocky structures. Weakly to moderately developed fine (angular) blocky structures appear to be the most common type in the Tropepts, whereas the Entisols have normally no structural development.

Although no measurements are available on soil permeability this parameter is assessed for land classification purposes by using field textures in combination with other soil properties such as clay mineralogy, porosity and structure. Based on these characteristics, assumptions as to permeability can be made for each great soil group as has been done in Table 12.2.

Finally, by applying each of the parameters discussed above, namely organic matter content, texture, structure and permeability, the soils have been provisionally grouped into four soil erodibility classes which are listed in Table 12.3.

Table 12.2
Generalised assessment of soil permeability for various great soil groups

Permeability	Texture	Structural properties	Great soil group
Very rapid (>20 cm/h)	coarse sand and gravel	single grain (structureless)	Psammaquents Tropopsamments Vitrandepts*
Rapid (6-20 cm/h)	fine sand to sandy loam sandy clay loam to clay	single grain, granular or crumb non-swelling clays with high macroporosity or strong granular or crumb structure	Eutrandepts* Dystrandepts* Hydrandepts Humitropepts Tropohumults
Moderate (1-6 cm/h)	sandy clay loam to clay loam silty clay to heavy clay	moderate porosity and structure above average porosity	Hapludolls Rendolls Haplaquolls Rhodudalfs Rhodustals and various Oxisols
Slow (0.25-1 cm/h)	silty clay to heavy clay	non swelling clays of moderate porosity and structure	Tropofluvents Fluvaquents/ Tropaquents Dystropepts Eutropepts Tropudalfs
Very slow (<0.25 cm/h)	sandy clay to heavy clay	dense, structureless, no visible pores; often swelling clays	Plinthaquults Plinthaqualfs Pelluderts Pellusterts

* Lacking any cemented horizons resembling duripans.

Table 12.3

Provisional grouping of some major soil groups according to their soil erodibility risk

Great Soil Group	Hydrandepts Humitropepts Dystrandepts Eutrandepts Vitrandepts	Rendolls Hapludolls Argiudolls Rhodudalfs Rhodustalfs Psammaquents Tropopsamments Tropohumults Plinthohumults	Tropudalfs Dystropepts Eutropepts Troporthents Fluvaquents Tropofluvents Hydraquents Tropaquepts Tropaqualfs	Pelluderts Pellusterts Plinthaquults Plinthaqualfs Albaquults Plinthudults
Soil Erodibility Risk	Very low	Low	Moderate	High
	Soils with very high to high organic matter contents and moderate to rapid permeabilities. Granular to fine crumby surface horizons; some lowland Andepts may have moderate very fine sand plus silt contents.	Except for sandy Entisols these soils have moderate organic matter contents and moderate permeabilities. Sandy Entisols have generally low organic matter contents, are rapidly permeable and structureless (single grain). Entisols often have moderate very fine sand plus silt contents.	Generally slowly permeable soils with moderate organic matter contents. The alluvial Entisols have low to moderate organic matter contents, are massive and may have moderate very fine sand plus silt contents.	Vertisols: Very slowly permeable, often subject to surface scaling and having prismatic or coarse blocky structures, but moderate organic matter contents. Ultisols and Alfisols: generally relatively low organic matter contents and relatively high very fine sand plus silt contents. Poorly structured surface horizons.

Topographic Factor (LS)

Length and steepness of slope both substantially affect the rate of soil erosion by water. Both factors have been evaluated separately in research projects and are represented in the soil loss equation by L and S respectively. A table and chart have been developed by the US Department of Agriculture to determine the values of the topographic factor for specific combinations of slope length and steepness. These criteria were derived from the equation:

$$LS = (\lambda/72.6)^m \times (65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065)$$

where λ = slope length in feet
θ = angle of slope
m = 0.5 if the percentage slope is 5 or more, 0.4 on slopes of 3.5 to 4.5 per cent, 0.3 on slopes on 1-3 per cent and 0.2 on uniform gradients less than 1 per cent.

The table produced by Wischmeier and Smith (1978) relates to 'normal' cropping situations with slope lengths ranging between 25 and 1000 m and percentage slope varying between 0.2 and 20 per cent (0°10′ and 11°20′). Presumably it has been extensively tested for these conditions and the LS values range between 0.06 (0.2 per cent slope with a length of 25 feet) and 12.9 (on a 20 per cent slope with a length of 1000 feet).

In Papua New Guinea traditional farming methods may be employed on slopes of more than 30 per cent (17°) particularly in the densely populated highlands (Plate 12.1) where there is a serious shortage of arable land.

Plate 12.1 Subsistence farming on a more than 30° limestone dipslope near Kundiawa, Chimbu Province

Cultivation on these slopes can be expected to result in much higher LS values, because of related increases in both the velocity and volume of surface runoff.

Wischmeier and Smith (1978) have also included in their publication an LS chart converted to metric units with the percentage slope ranging between 0.5 and 50 per cent (<1° to >26°) and slope length varying between 5 and 300 m. This chart is shown in Figure 12.6 and, although unlikely to have been extensively tested for the steeper slope categories and tropical rainfall regimes, is still the best available. Excellent 1:100 000 scale maps of Papua New Guinea with 40 m contour intervals have recently become available. By using these maps it is envisaged that both the percentage slope and slope length will be estimated and, by using the LS chart (Figure 12.6), that relevant, if somewhat rough values will be obtained.

In this context it is important to mention the experiment of Ahmad and Breckner (1974), one of the few that have been carried out on very steep slopes in a tropical environment. Nine cleared plots, involving three Tobago soils developed on volcanic rocks, diorite and schist respectively, were established on slopes of 10, 20 and 30°. Table 12.4 shows the total soil losses recorded at eight of the nine sites during the experiment, and the calculated soil losses over a one-year period under average rainfall conditions. On two of the three soils the losses recorded on the 30° plots were considerably less than on the 10° plots while, on the other hand, the third soil showed a slightly higher soil loss on the 30° plot than on the 10° plot. According to Ahmad and Breckner (1974) these

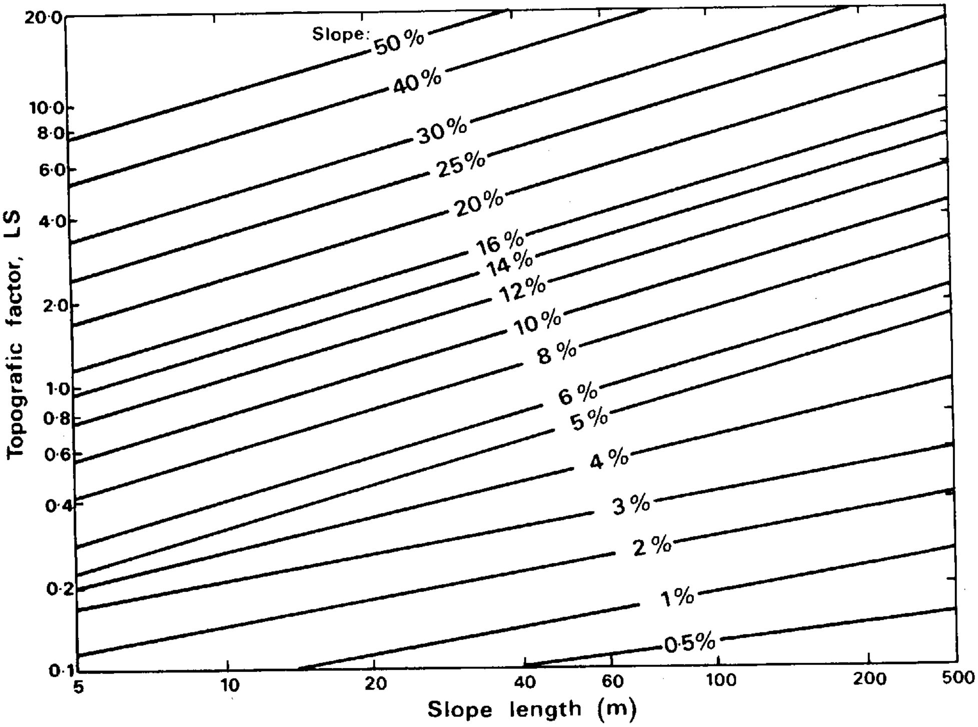


Fig. 12.6 Slope effect chart for metric system (after Wischmeier and Smith 1978)

Table 12.4
Total soil losses and amount of rainfall measured for three Tobago soils covering a period between mid July to the end of December and the computed total losses over a one-year period under normal rainfall conditions (after Ahmad and Breckner 1974)

Soil type	Slope (degrees)	Rainfall (mm)	Soil loss (t/ha)	Depth of soil (cm)	Depth of soil that would have been lost over one year (cm)
Goldsborough clay	10	780.8	121.6	0.89	2.16
(volcanic rocks)	20	780.8	170.4	1.22	2.95
	30	780.8	15.2	0.10	0.22
Concordia sandy	10	694.4	103.9	0.76	2.06
clay loam (diorite)	30	694.4	114.0	0.84	2.26
Bloody Bay	10	957.6	212.8	1.52	3.81
clay loam (schist)	20	957.6	160.8	1.14	3.18
	30	957.6	180.8	0.76	1.91

differences could not be wholly attributed to the soil properties. Furthermore, the losses sustained by the soil developed on diorite, although considered to be highly erodible, were actually the lowest. The authors therefore attribute the marked variations to a reduction in effective slope length with increasing slope angle, combined with exposure to wind during rainstorms which, depending whether the wind direction is away from or towards the slopes will further counteract or enhance this process. Because no data on the speed, direction and frequencies of the winds are given this argument is not wholly convincing. The data provided in the table on the Goldsborough clay show that a larger than tenfold loss in soil was sustained over a one-year period on the 20° plot exposed to the sea than on the 30° plot located in a sheltered position. Although the wind exposure factor must have significantly influenced this loss, it would appear to be too large to be attributed to this process only. The study clearly indicates, however, that the relationship established between the topographic factor LS and soil loss is not always as straightforward as one might be led to expect.

With the possible exclusion of some coastal areas, wind exposure is not likely to affect soil losses in Papua New Guinea significantly. However, Ahmad's and Breckner's argument that the effective slope length will be reduced on steeply sloping terrain under vertically falling rain seems valuable in that it may to some degree result in lower LS values.

Cover and Management Factor (C)

The cover and management factor, by definition, is the ratio of soil loss from land cropped under specific conditions to the corresponding loss from clean-tilled continuous fallow.* Because soil losses from land cropped under specific

* Soil losses from a continuously fallow area are calculated by the product of the factors R, K, L and S.

conditions are dependent on many variables, including climate, crop canopy, surface litter and cultivation practices, this factor is generally very difficult to assess. In order to deal with these many variables elaborate tables have been evolved which are based on long term, expensive field measurements. Since these tables, understandably, only take into account monocropping systems under temperate climates, they will be of little use under Papua New Guinea conditions.

Research by Hudson (1957) and Elwell and Stocking (1974, 1976) in Zimbabwe-Rhodesia has shown that the percentage vegetal cover is an effective index for quantitively estimating soil losses and is particularly well suited to developing countries. Their experiments were carried out on a sandy loam soil on a 4.5 per cent slope which was covered at a height of 15 cm above the soil surface by a mosquito-gauze in order to simulate a full vegetal canopy. This destroys the raindrop energy but allows most of the rainfall to reach the soil surface. The results showed the soil loss from the unprotected surface to be 127 times that of the protected plot on which there was 13 times less runoff. Very similar results were obtained from a plot under grass cover. Previous experiments carried out on a grazing land, having a wide range of vegetal cover conditions, further showed this parameter to be a good indicator of soil losses. Using their findings Elwell and Stocking developed curves for each of the percentage vegetal cover values by calculating the cumulative value of erosive rain falling on bare soil and plotting this against the measured soil losses. Results of 8-year average values of soil loss plotted against percent vegetal cover are shown in Figure 12.7. The most important conclusion to be drawn from these results is that, under the prevailing conditions, rapid increases in soil loss and runoff did not occur until the vegetal cover (plant leaves + basal cover + litter) fell below 30 per cent.

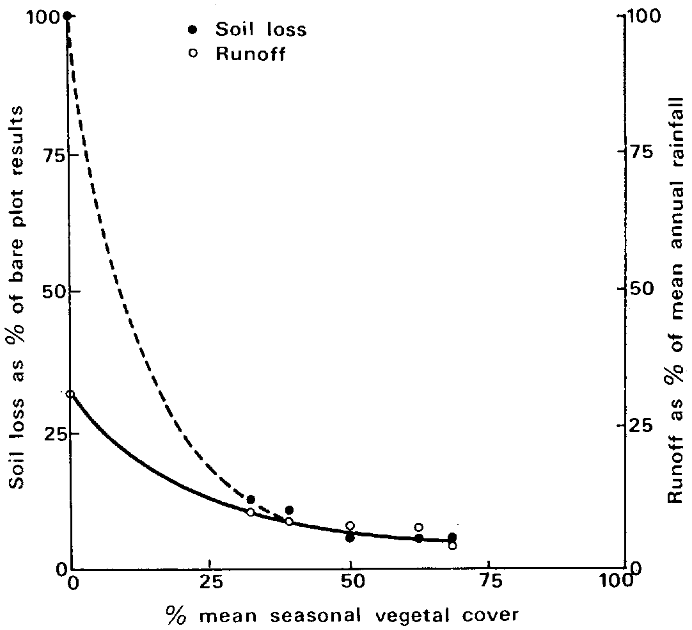


Fig. 12.7 Mean annual soil loss and runoff variations with estimated mean per cent vegetal cover on grazing land (after Elwell & Stocking 1976)

Since most of Papua New Guinea has a dense vegetation, the cover and management factor is only likely to play a significant role in areas under intense cultivation. Yet even in these areas, a vegetal cover of less than 30 per cent is likely to occur only during relatively short periods. Preliminary results from soil erosion plots growing sweet potato in the highlands (J. Humphreys personal communication 1981) have shown that the vegetation cover following garden preparation was 0 per cent, after planting 5 per cent and reached 25-30 per cent some four months later. Based on a shifting cultivation cycle of four years (in reality this is more likely to be 6-12 years), and assuming the soil loss figures from Zimbabwe-Rhodesia to apply also to Papua New Guinea conditions, this would indicate that serious soil erosion may only occur on average during one month each year. Under lowland conditions where there is a more rapid vegetation growth, and where longer shifting cultivation cycles apply, the erosion risks are even further reduced. From this it would appear that in Papua New Guinea, given the present traditional cultivation system and with the prevailing climates providing optimum conditions for plant growth, the cover and management factor is not expected to greatly affect soil losses as calculated by the USLE equation.

Very generalised cover and management factors (called land use factors), have been used by FAO in its methodology for assessing soil degradation (FAO 1978). These are shown in Table 12.5, and range from 0.8 for arable land to zero for rice fields.

It may be argued that, owing to the often high upper storey in rainforest, raindrops may regain an appreciable velocity before reaching the soil surface. However, because of the generally dense understorey (Plate 12.2) and a generally high percentage of leaf litter coverage on the soil surface, this is unlikely to happen. Estimates of the amount of rainfall reaching the soil surface under a rainforest canopy vary widely. Freise (1936) has estimated that approximately one-third of the total rainfall reaches the ground as throughfall, while another third streams down the tree trunks. Lundgren and Lundgren (1979) consider this stemflow value very high, their data from rainforest sites in Tanzania indicating that stemflow was unimportant, being only about 1 per cent of the gross rainfall in the present forest. An estimate by Turvey (1974) for a rainforest site east of Port Moresby has 80 per cent of the rainfall reaching the ground. Very similar figures (78 per cent) have been obtained from a rainforest site in Tanzania (Lundgren and Lundgren 1979). Although

Table 12.5
Land use factors used by FAO (1978) for the assessment of water erosion

Land use type	Factor
Arable land	0.8
Fruit trees, vineyards and plantations	0.6
Rough grazing	0.5
Meadows	0.1
Woods and forest	0.05
Virgin forest and jungle	0.001
Rice fields	0.0

Plate 12.2 Lowland forest on well drained alluvium in Madang Province. Note the dense understorey, restricting waterdrops in regaining energy from the upper canopy

a very wide range of figures (3-57 per cent) are given in the literature according to these authors, they conclude that the normal range of total rainfall interception in a mixed, closed, tropical rainforest is 15-35 per cent.

From the discussions above it should not be concluded that there is no soil erosion under rainforest. Ruxton (1967) has described slopewash taking place in hilly and mountainous terrain covered by mature, primary rainforest in the Northern Province. Here, especially on steep slopes, canopy openings are fairly common due to tree fall, the scrub layer is often sparse and leaf litter thin, and cause waterdrop erosion. Bik (1967), however, considered that slopewash did not occur in forested areas in the Western Highlands. The subject of slopewash in forest has been extensively reviewed by Löffler (1977) and seems to be related to variations in altitude and vegetation.

Support Practice Factor (P)

This factor incorporates practices that are employed to slow down the runoff rate and thus reduce soil erosion. In Papua New Guinea it applies mainly to

Plate 12.3 Terraced gardens on moderate slopes near Goroka, Eastern Highlands Province. Gardens are fenced mainly to prevent pigs and other animals from entering. Other low fences about 25 cm high and consisting of closely planted upright sticks, are erected within the garden to counteract soil erosion.

farming in areas of the highlands where extensive measures are often taken to prevent erosion, e.g. the building of low soil retaining fences across the slopes (Plate 12.3). However, this preventive measure is not included in the support practice of the universal soil loss equation, in which it is regarded as part of the LS factor by using the terrace intervals as slope length.

TRADITIONAL SOIL CONSERVATION

Local farmers are obviously aware that serious soil erosion may occur unless preventive measures are taken, particularly in highland areas. This is illustrated in a discourse given by a local farmer* who lives in the Upper Chimbu Valley just below Mount Wilhelm and who farms between 2400 and 2600 m. A summary of this talk is given below. The described farming methods and erosion preventive measures are common to the valley.

Whenever it is decided to start a new garden, trees, scrubs and pit-pit are cut.† If no fence is present, special trees‡ are selected for fencing, otherwise

* Michael Paglau - Traditional soil conservation in the Upper Chimbu Valley. Talk given on 12 September 1980 and translated by Anton Goie.

† Pit-pit in this context is used as a general term for tall reed-like grasses.

‡ Mostly *Cordyline terminalis* called *tanket* and *Casuarina*. Cuttings from *Cordyline* strike easily and the trees are long lived.

the old fence is patched. These fences are mainly erected to prevent pigs and other animals from entering the garden but also mark individual land ownership and reduce soil erosion. Upon completion of the fencing soil preparation starts, but the method used is dependent on the steepness of the slope. If the slope is not too steep grass tussocks are dug up before the dry grasses and rubbish are burnt. This is then followed by erection of a low soil retaining device about 25 cm high, called a *giu* (Plate 12.3), which consists of a large number of short sticks, planted close together, upright in the soil. However, on steep slopes more susceptible to erosion a *giu* is erected before the grass tussocks are dug up, to prevent these and other heavy material, such as rocks, from rolling downslope and destroying other gardens and fences. If cultivation takes place on a very steep slope a slightly bigger and stronger soil retaining device is erected before the garden preparation begins. After the grass tussocks are dug, they are dried and burnt together with other large vegetable material. Whatever is too large to burn, or left after the burn, is removed from the garden and an ordinary *giu* is erected to prevent soil erosion. After construction of all necessary retaining fences the soil is broken up and all fine vegetable matter gathered in heaps for burning. The ashes are particularly used when Irish potatoes, cabbages and other greens are planted. Then finally downslope ditches are dug whenever needed (Plate 12.4). Some Chimbu farmers prefer not to make ditches on very steep slopes because they realise these may develop into gullies after heavy rain. However, grid-iron ditches are

Plate 12.4 Sweet potato garden on a steep slope in the Bena-Bena area, near Goroka, Eastern Highlands. Note the shallow drains at right angles to the contours. These drains not only ensure adequate drainage, but also provide some protection against erosion during the short cropping period.

always dug for drainage purposes on land ranging from nearly level to moderately steep and vary according to the needs of the site. They also assist in reducing rill or gullying erosion by dividing the slope into shorter segments. In very poorly drained areas they are not only deeper, but also closer together. Apart from preventing soil erosion and improving drainage *giu* and ditches are also used to delineate boundaries within a garden, where specific beds are often set aside for special purposes.

In lowland areas erosion prevention methods are also occasionally used. Burnett (1963), for instance, describes the construction of rough terraces made from *Casuarina* trunks in the Simbai River area, Madang Province.

SOME PRELIMINARY RESULTS OF SOIL EROSION EXPERIMENTS IN THE HIGHLANDS

To date, only two soil erosion experiments have been carried out in Papua New Guinea, both being located in the densely populated highlands.

The first is presently being conducted by the Department of Primary Industry near Kundiawa in the Chimbu Province (G.S. Humphreys personal communication 1981), while the second one was carried out in the Tari Basin in the Southern Highlands Province (A. Wood personal communication 1981). The results of these experiments are given in Tables 12.6 and 12.7. Although

Table 12.6

Soil losses (tonnes/ha/yr) with slope and vegetation cover near Kundiawa, Chimbu Province (after Humphreys unpublished data)

Plot size (m^2)	% Veg. cover	Number of plots	Average slope (degrees)	Soil losses (tonnes/ha/year)
Bare plots				
2	0	4	9.9	9.7
2	0	3	15.7	12.6
2	0	6	20.3	17.3
2	0	2	29.0	47.7
2	0	2	35.0	64.7
2	0	3	42.0	62.0
Fallow plots				
2	>50	3	8.0	1.8
2	>50	3	13.2	2.2
2	>50	3	17.2	3.6
2	>50	5	20.8	3.2
2	>50	4	34.3	3.1
2	>50	2	44.0	4.6
Garden plots				
244	variable	1	11.0	15.3
135	(see text)	1	11.9	5.4
104		1	12.1	8.8
169		1	12.7	5.5
95		1	14.1	8.7
1375		1	20.0	28.4

Table 12.7
Soil losses (tonnes/ha/yr) on mounded sweet potato gardens with slope in the Tari Basin, Southern Highlands Province (after Wood unpublished data)

Drainage area (m^2)	Approx % vegetation cover	Average slope (degrees)	Soil losses (tonnes/ha/year)
663	5	1	0.1
580	10	3	0.4
468	25	5	0.7
592	30	7	1.2
304	10	10	1.8
600	30	13	5.1
400	20	18	9.1
304	20	23	11.9
176	15	25	13.6

the data presented are very limited and should be interpreted with great care, they nevertheless show very similar and interesting results.

The calculations given in Table 12.6 for the Kundiawa area (average rainfall (13 years' records) 2249 mm), are based on twelve to sixteen months' data collection, while, in addition, the relatively small plot size (2 m^2) has been converted to one hectare. The soil loss estimates are averages only and were made on a number of soil types (mainly Humitropepts and Hydrandepts), with clay loam to clay topsoils, and include soils developed on mixed sedimentary rocks, which in some localities are covered by volcanic ash layers of variable thickness. A comparison between soil type and soil loss has to date not been attempted by Humphreys and also the soil losses have not been adjusted to rainfall differences between sites nor with rainfall intensity.

Data given in the table for the 2 m^2 bare plots (no vegetation) show only slight losses (almost 10 tonnes/ha/year) on the 10° slope, increasing gradually to slightly more than 17 tonnes/ha/year on the 20° slope, followed by an abrupt increase on the 29° and 35° slope and a levelling off (or decrease ?) to a loss of about 60-65 tonnes/ha/year on the 42° slope. Although these losses are significant, particularly on the higher slope categories, they are nevertheless relatively low by international standards and it may be questionable if such losses would seriously effect soil degradation. This is borne out by a comparison with Table 12.4 and with Table 12.8 which shows the soil

Table 12.8
Soil degradation classes by water erosion (FAO 1978)

	Soil loss (tonnes/ha/year)
None to slight	<10
Moderate	10-50
High	50-200
Very high	>200

degradation classes used by FAO (1978) and its World Soil Degradation Project.

The figures presented in the lower half of Table 12.6 represent plots with a fallow vegetation of grasses exceeding 50 per cent and garden plots (95 to 1375 m^2) of sweet potato in which the garden was prepared and dug over at the beginning of measurement. In the latter (six) sweet potato plots the vegetation cover after garden preparation was 0 per cent, after planting about 5 per cent, and after four months about 25-30 per cent. As can be expected, it is during this initial period that the soil losses were substantially greater than the remaining period, when the vegetation cover is mostly >50 per cent and which involves the major period of maturation. These situations are considered to be much more indicative of Papua New Guinea conditions under traditional agriculture. Although the table shows some unexpected variations in soil losses with slope, which may be related to differences in soil type, the calculated soil losses are again low to very low by international standards. Very similar results are given in Table 12.7 for soil losses recorded in the Tari Basin by Wood (unpublished data), the highest rate of 13.6 tonnes/ha/year being found on a 25° slope. Wood's experiments were carried out on Hydrandepts, which occupy over 70 per cent of the Basin. The erosion plots were set out in mounded sweet potato gardens, with variable vegetal cover, sites being selected where there were obvious first order catchments forming saucer-shaped areas. The erosion was measured using tin erosion traps sunk into the ground to catch the runoff and suspended sediment. According to Wood (personal communication 1981) some sediment may have been lost through overflow during heavy rain.

Wood's experiments formed part of an extensive agriculture and land use survey involving a study of soil deterioration, which is a serious problem in some highland areas. Local farmers interviewed by Wood have attributed this to several factors including decrease in fertility (the soil losing its 'grease'), moisture deficiencies (the soil has gone dry) and soil erosion. According to Wood most farmers considered that this process began at about the time when the first Europeans visited the Tari area (late 1930s, early 1950s). He investigated the problems of declining soil fertility in detail by analysing soil samples from different environments including volcanic ash soils located at lower and higher altitudes, alluvial soils and peat or organic soils. Of these soils the lower altitude ash soils are cultivated for up to 60 years with only short fallows while similar soils at higher altitudes are rarely cultivated for more than 10 years. In contrast the very productive alluvial and organic soils have in some cases been cultivated for more than eight generations!

Results given by Wood (unpublished data) indicate that of the major elements in the volcanic ash soils (Hydrandepts), phosphorus increases during the first few years of cultivation, declining rapidly after about 10 years, presumably caused by iron and aluminium fixation. Organic matter and total nitrogen levels are high in these soils but also show a steady decline as cultivation continues over the years, the depletion being most pronounced in areas with steeper slopes and a higher rainfall. On the alluvial and peaty soils there is, according to Wood, little depletion of bases or phosphorus with cultivation, the fertility levels also being higher overall than in the volcanic ash soils. Wood thus clearly shows, as can be expected, that the soil fertility declines with the length of cultivation which was also shown in a decrease in sweet potato tuber yields.

He attributes this process of soil deterioration in most part to soil erosion which has accelerated with increasing population necessitating more forest clearing for cropping. This process was further accelerated by the arrival of Europeans and the introduction of new crops, and tools such as steel axes. Wood's arguments are logical and sound. Nevertheless one cannot expect a soil to continue producing high yields by only practising simple composting techniques without the application of chemical fertilisers. However, it would appear that by a more widespread implementation of more sophisticated composting methods such as the incorporation of other waste materials in the soil, along with a more extensive application of traditional methods of soil erosion control (see previous section) the rate of soil erosion could be reduced. In addition tree crops such as arabica coffee should preferably be planted on the steeper (but not too steep) slopes and not, as is presently fairly common, on the flatter land better suited for arable cropping.

Although the data given above on soil erosion are only preliminary, they do indicate clearly that soil losses by water erosion are less serious than expected in the highlands. As discussed in the previous sections this is thought to be related to several factors, the most important being the rapid re-establishment of the vegetation cover, relatively low rainfall intensities and the high soil organic matter content. Organic matter is the key to the fertility decline because it is intimately related to the major elements nitrogen and phosphorus and greatly improves the soil structure. Data gathered from local inhabitants in the highlands by Hamilton (unpublished data) appear to indicate that, under the prevailing relatively cool and wet climatic conditions, a humic topsoil nearly 15 cm thick can form within a time span of 25-30 years if the soil is left undisturbed.

Finally it may also be relevant to mention results of runoff and soil loss obtained by Lundgren (1980) from forest and agricultural plots located

Table 12.9

Runoff and soil losses recorded (two-year period) from sites located in the Mazumbai Mountains, Tanzania (modified after Lundgren 1980)

Land use	Plot size (m^2)	Slope (degrees)	Annual rainfall (mm)	% runoff by rainfall	Soil loss (tonnes/ha/year)
Intermediate Evergreen	12	12	1115	0.4	0.0
Forest	,,	24	,,	1.0	0.1
Small-scale agriculture	12	11	635	0.1	0.0
land	,,	19	,,	0.1	0.0
Highland Evergreen	12	14	820	0.8	0.0
Forest	,,	22	,,	1.3	0.1

between 1450 and 1600 m in the Usambara Mountains, Tanzania. On each of the three sites selected, which were covered by soils classified as humic Nitosols (Tropohumults ?) according to the legend of the FAO World Soil Map (FAO 1974), four runoff plots of 12 m^2 each were installed, two on gentle and two on steep slopes. The results (Table 12.9) clearly show that the values obtained for both surface runoff and soil loss are very low. This is especially the case with the plot located on small scale agricultural land which according to the author can be attributed to differences in climate and, probably more importantly, to proper land management. Land management is in many respects different from that used by the average farmer in the area. This indicates that by applying appropriate soil conservation measures, arable cropping may be carried out in some locations, even on moderately to steeply sloping terrain, without causing serious erosion.

EROSION CAUSED BY NATURAL PROCESSES

Because of the complete stripping of the vegetation, one of the most readily observed features of erosion in Papua New Guinea are landslides.* These mass movements of soil and rock take place under the influence of gravity when shearing stress exceeds shearing resistance. The resulting earth movement may vary in size from small slumps,† involving displacements of a few tens to a few thousand cubic metres (Plates 12.5 and 12.6) to enormous slides with associated mudflows involving a million or more cubic metres of rock and soil (Plates 12.7 and 12.8). There is little doubt that many landslides are triggered off by earthquake activity, often after periods of heavy rain, and resulting in movement of water saturated mudflows downslope. Because of their fairly common occurrence in the landscape, and because they provide a relatively easy way to calculate denudation rates, landslides have received much attention by geomorphologists (Simonett 1967; Pain 1972, 1975; Pain and Bowler 1973).

Using airphoto interpretation Simonett (1967) studied the distribution of landslides in the Bewani and Torricelli Mountains. Landslides were grouped into size classes and their distribution checked against topography, vegetation and geology. The resulting pattern of distribution clearly showed that landslides are absent in Recent alluvial plains, while in hilly areas the differences in distribution appeared to be related to parent material, relief, slope steepness and earthquake activity. In mountainous areas extensive landslides occurred on both granite and sedimentary rocks, but distinct differences in number, type and size were noted by Simonett (1967). While on sedimentary rocks major movements are massive rotational slumps, those in granite areas, apart from being characterised by higher volumes of earth moved, have both single debris avalanche movements and complexes of deep and shallow avalanches combined with extensive gullying of weathered bedrock.

Pain (1975) has described a major mudflow, consisting of tephra, which occurred 20 000-30 000 years ago near Mount Hagen in the Western Highlands

* In this context used as a general term including mudflows and slumps.

† Slumps or rotational sliding are caused by the downward slipping of earth along curved slip planes over short distances, usually resulting in backwards tilting of the surface.

Plate 12.5 Small slump in sweet potato garden near Kundiawa, Chimbu Province on soils developed on siltstones and mudstones. Note the small sweet potato mounds in comparison to those found in the western parts of the highlands (Plate 5.4). Small mounding, presumably mainly to preserve moisture, is typical of the drier eastern highland areas with a high seasonality. In the wetter western highland areas, however, which lack a dry season, but where there is a greater risk of frost, large mounds dominate.

Plate 12.6 Slumping in volcanic ash and greywacke sandstone near Lagiap River, Enga Province

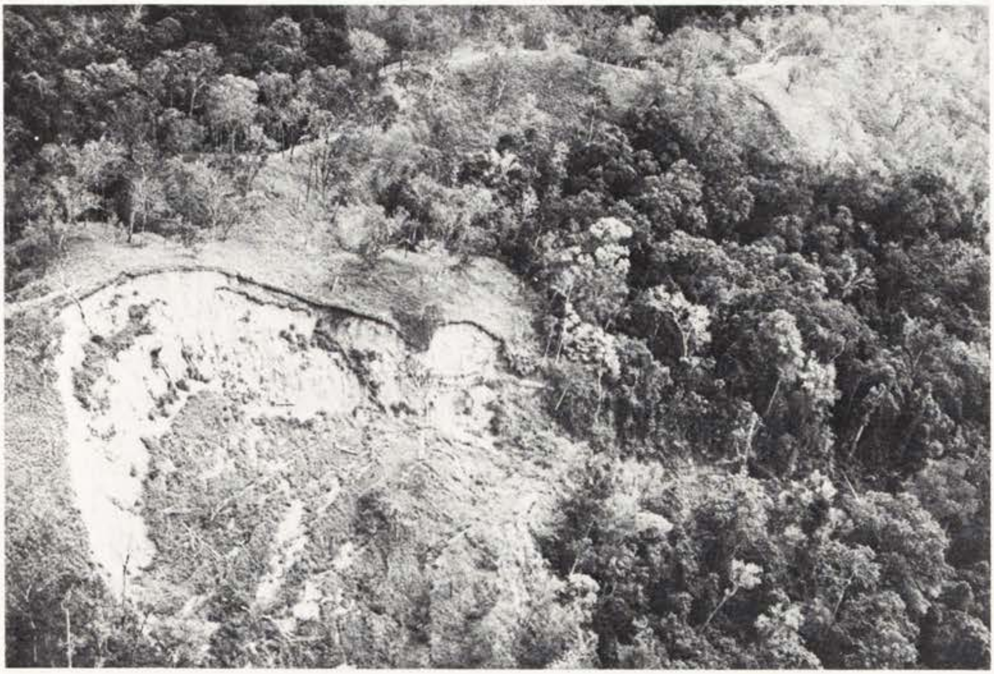


Plate 12.7 Landslide on hilly terrain approximately 15 km north-north-west of Safia airstrip, Northern Province. The parent material consists of fine grained sedimentary rocks (Domara River Beds).

Plate 12.8 Recent landslide on fine grained sedimentary rocks in Chimbu Province

Table 12.10
Rates of surface lowering measured in Papua New Guinea
(after Blong and Humphreys, 1982)

Location	Parent material	Rate (cm 1000 yr^{-1})	Source
Hydrographers Range	volcanic	8-75	Ruxton & McDougall (1967)
Kaugel Basin	volcanic and Tertiary	27	Pain (1973)
Mt Giluwe	volcanic	50	Löffler (1977)
Torricelli and Bewani Mtns	granite and mixed sedimentary	100-143	Simonett (1967)
Vulcan, Rabaul	volcanic	1800	Ollier & Brown (1971)
Aure River	mixed geology including mudrocks	419	Pickup (1977)
Purari at Wabi	mixed geology including mudrocks	79	SMEC (cited in Pickup (1981)
Ok Ningi	mixed geology including mudrocks	298-405	Pickup (1981)
Fly River	mixed geology including mudrocks	26-35	Pickup (1981)
Chim shale	mixed geology including mudrocks	4600-9100	Blong & Humphreys (1982)

and has also been attributed to earthquake activity. Similarly Pickup *et al.* (1981) have attributed the sediment yields from basins on the headwaters of the Fly River, which have annual runoffs in the range of 5300-7200 mm/year, to landslide and slope wash activated under tropical rainforest. Although many of the landslides are small, occasionally massive landslides occur from the limestone escarpment. Byrne *et al.* (1978) have estimated that two to three landslides per year occur in the upper Ok Tedi catchment with an average slide volume of about 30 000 m^3. It would thus appear that landslides occur on a wide variety of parent materials. However, small slumps seem to be most common on sedimentary rocks and low grade metamorphics. Particularly in seismic active areas these natural processes must have a profound effect on the soils.

Data available on denudation rates in PNG, obtained by various methods, have been summarised by Blong and Humphreys (1982) and are shown in Table 12.10. This table clearly indicates very large variations in denudation rates between, but also within, various parent materials. The erosion rates recorded by Blong and Humphreys (1982) from road batters cut in mudstones and siltstones, called Chim shale, are among the highest in the world.

13 Weathering

Weathering is the breakdown and alteration of rocks *in situ* under the influence of physico-chemical processes. It has been defined by Reiche (1945) as 'the response of materials that were in equilibrium with the lithosphere, to conditions at or near their contact with the atmosphere, the hydrosphere and perhaps more importantly the biosphere'.

Because soils comprise the disintegrated, finely divided residual material of rock weathering, mixed with organic remains, weathering is intimately related to soils. Apart from work done by Humbert (1948), Ruxton (1968a) and Haantjens and Bleeker (1970) there has been very little research on weathering in Papua New Guinea.

TYPES OF WEATHERING

Weathering can be either *physical* or *physico-chemical*. Physical or mechanical weathering, defined as alteration without chemical change, is rarely encountered in Papua New Guinea. This can largely be explained by the small range in temperature and because the bedrock is usually covered by a thick protective weathering mantle. Even above 4000 m, where bare rock exposures are very common, rock shattering caused by temperature fluctuations or frost are seldom evident. Other processes occasionally observed in Papua New Guinea are fracturing of stones or rocks by grass fires, tree roots and comminution by fast flowing streams. Little is known about the effects of wetting and drying and moisture swelling which are included by Ollier (1969) in mechanical weathering processes. However, these may be of some significance, particularly in areas with highly seasonal climates.

Chemical weathering is the alteration of rocks in terms of compounds and contents of chemical elements. Because it always results in physical changes in the subject material it is more commonly referred to as physico-chemical weathering and is prevalent in Papua New Guinea where high mean annual temperatures, humidity and rainfall are very conducive to this type of weathering. The alterations induced by it are mainly related to hydrolyses of minerals, which are the chemical reactions between H^+ or OH^- ions of water and the ions of primary minerals. Ultimately, this leads to the formation of secondary minerals frequently involving considerable losses of constituents of the parent material. Mineral analyses of the weathering profile and the underlying parent material may provide an insight into the type and amount of mineral weathering that has taken place. To evaluate the degree of weathering precisely is a very complex and lengthy process, but in broad terms weathering may be expressed as being either *mature*, *immature* or *skeletal weathering* (Haantjens and Bleeker 1970; Bleeker in press) (Figure 13.1). When, in time, the mineral composition of a material reaches a point of negligible further change, the weathering may be termed *mature*. Maturely weathered material contains very high amounts of secondary clay minerals and very low amounts of rock fragments and weatherable minerals in comparison to fresh rock. Ultisols and Oxisols occurring on dissected Pleistocene piedmont plains, alluvial fans, terrace benches and occasionally also on uplifted coral terraces are typical of maturely weathered materials. Despite the generally favourable climatic and lithological conditions mature weathering is not very common in Papua New Guinea (Figure 13.1).

In contrast to mature weathering, *skeletal* weathered materials contain low amounts of secondary clay minerals and high amounts of rock fragments and weatherable minerals. *Immature* weathering refers to materials containing

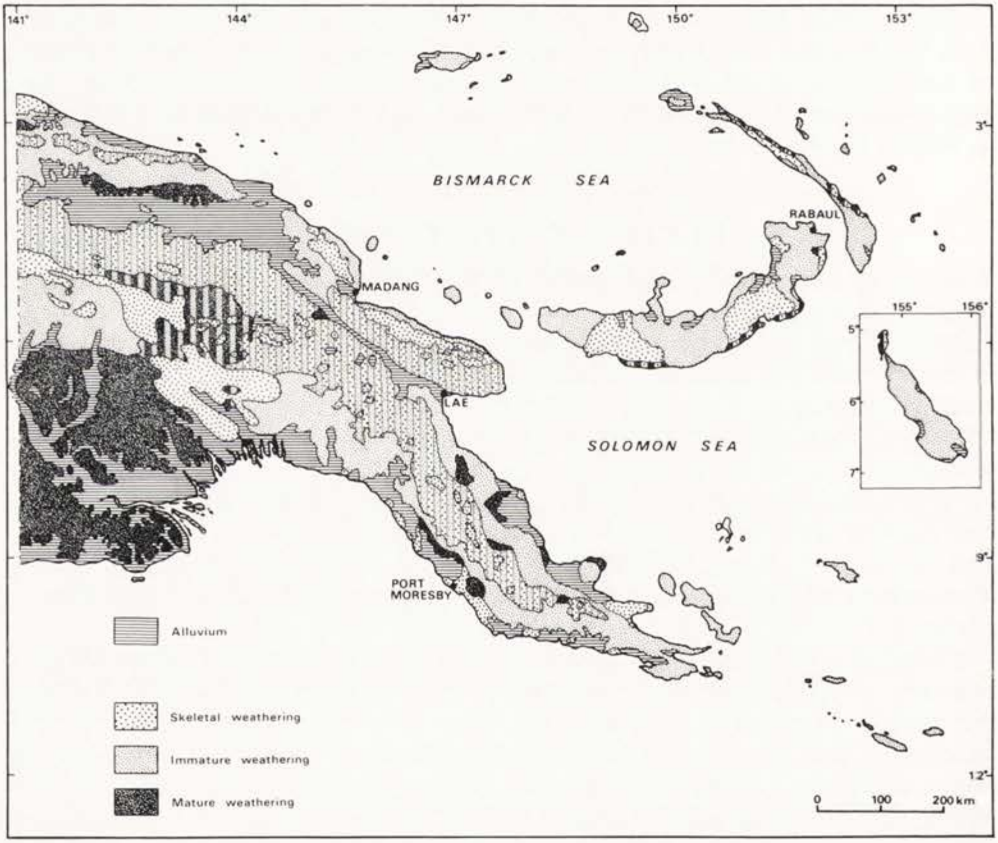


Fig. 13.1 Types of weathering in Papua New Guinea

intermediate amounts of secondary clay minerals, rock fragments and weatherable minerals. Because of the preponderance of recently formed unstable landscapes both these two weathering types are very common. Most skeletal weathering occurs on finer grained, thinly bedded, hard sedimentary (e.g. limestone) and volcanic rocks. It is commonest on steep to very steep slopes at high altitudes with a cool climate, where the equilibrium between rapid weathering and rapid erosion precludes either a complete removal or strong accumulation of weathering products. Skeletal weathering is also to be found in more gently sloping lowland areas in the vicinity of active volcanoes. Typical soils in skeletally weathered areas are Troporthents or Cryorthents, Rendolls, various high altitude Histosols (Cryofolist) or recent volcanic ash soils, such as the Vitrandepts or Eutrandepts. Immature weathering dominates on more stable, moderately to gently sloping terrain, particularly at lower altitudes with high mean annual temperatures. Characteristic soils found there are certain Inceptisols (Eutropepts and Dystropepts), Alfisols (Tropudalfs) or the more developed Mollisols (Argiudolls).

Because of the active formation of clay minerals associated with both mature and immature weathering, the last may be subdivided according to the dominant type of clay minerals formed into *smectite*, *kandite** and *sesquox* weathering, although mixtures of two or all three types are not uncommon (Ruxton 1968a; Haantjens and Bleeker 1970).

Smectite weathering is characterised by the clay minerals montmorillonite, illite and vermiculite. It is mostly associated with immaturely weathered material in relatively shallow profiles developed on hilly uplands underlain by calcareous sedimentary rocks, basic/ultrabasic rocks or derived sediments, uplifted coral terraces or on alluvium rich in calcium or magnesium. Montmorillonite is formed mainly in environments rich in silica and bases (Barshad 1964). Because it is mostly unstable under wet tropical conditions with high mean annual temperatures (e.g. Keller 1957; Grim 1968), soils rich in it are uncommon in Papua New Guinea. Its development is therefore largely restricted to the dry coastal zone in the vicinity of Port Moresby and a few other low rainfall areas (1500-2000 mm) with pronounced dry seasons. Under these conditions the leaching of bases is largely impeded or, alternatively, the acidification of the soil profile hampered.

Vermiculite, a magnesium rich smectite, is found in many soils. Here it occurs in two types† formed either by the alteration of biotite or muscovite (Douglas 1977). In Papua New Guinea vermiculite, commonly in association with montmorillonite, is often found in weathering products derived from basic and ultrabasic rocks, but it has also been reported in volcanic ash deposits in the wetter regions (Haantjens and Bleeker 1970).

Illites (or hydrous micas), are rich in potassium (commonly >4% K_2O), and in Papua New Guinea are the main clay minerals of sediments such as shales and mudstones. According to van Olphen (1963) illites may form through the

* The term kandite is commonly used as an alternative group name for clay minerals belonging to the kaolin group (e.g. Marshall 1975).

† Namely trioctahedral and dioctahedral vermiculite, the last being found only in particles too small for single X-ray examination.

weathering of muscovite and phlogopite. Because of the disagreement over exactly what illite is or should be, the use of the name is now avoided by some clay mineralogists (Fanning and Keramidas 1977).

Kandite weathering is characterised by the clay minerals kaolinite and halloysite. The amorphous clay mineral allophane has also been included in this weathering type, as has been done by Kerr (1959). Kandite weathering is by far the commonest type in Papua New Guinea and is to be found in immature and mature weathered materials and often, although in small amounts, in skeletal weathering. For the most part kandite clay minerals are found in wet areas with high mean annual temperatures where they are formed by the alteration of aluminium silicates and an almost complete leaching of bases. Since the solubility of alumina and silica is relatively low in soils having pH values between 5 and 8, and since the small amounts of Al_2O_3 and SiO_2 released are not very mobile, these combine to form relatively insoluble secondary aluminium silicates. One of these secondary aluminium silicates, namely allophane, is found extensively in young volcanic ash deposits where, as the weathering of the ash increases under continual leaching, the proportion of allophane decreases while that of kaolinite/halloysite or gibbsite increases (Haantjens 1964a, b; Haantjens and Rutherford (1964). Radiocarbon data relating to Andepts in New Britain have indicated that halloysite can form in minor quantities within a time span of 300-2000 years under hot humid lowland conditions in otherwise skeletally weathered materials (Bleeker and Parfitt 1974). The rate of halloysite formations under cooler highland conditions appears to be similar to those in Japan and New Zealand, halloysite having been recorded in large quantities in Hydrandepts developed on ash dated 50 000 years BP, while younger ashes (30 000 years) were composed of a mixture of allophane and gibbsite (Pain 1973; Parfitt 1975).

Since halloysite appears to have been incorrectly identified previously, as poorly crystallised kaolinite, its distribution and importance remain uncertain. Halloysite (or poorly crystallised kaolinite?) appears to be commoner than kaolinite under impeded drainage conditions (Haantjens and Bleeker 1970). However, detailed clay mineral analyses have shown that both halloysite and kaolinite are present in large quantities in many well drained reddish clay soils (Acrohumox, Tropudults and Tropudalfs) in high rainfall areas (Bleeker 1972).

Sesquox weathering is characterised by the crystalline hydroxides such as goethite, haematite and gibbsite. Normally these clay minerals are only present in small amounts in both kandite and smectite weathering products. Soils dominated by goethite or haematite appear to be restricted to ultrabasic rocks or sediments derived from those which have a very low aluminium content and have also been almost entirely leached of bases. Since such conditions are seldom met with in Papua New Guinea, soils rich in goethite or haematite rarely occur. Gibbsite, in contrast, is more often found as a dominant clay mineral. In Papua New Guinea the most essential requirements for its formation appear to be the presence of sufficient aluminium in the parent material, a high rainfall with low seasonality and free drainage conditions. Gibbsite often dominates in highland volcanic ash soils (Hydrandepts) (30 000-50 000 years old?), where it appears to have been formed by an appreciable loss of silica due to leaching which has resulted in insufficient quantities being available to form the secondary aluminium silicates required for kandite weathering. Small quantities of gibbsite are also common in recent lowland ash soils (Eutrandepts and Vitrandepts) in which allophane is the dominant clay mineral. However, in older ash soils at lower altitudes (mainly Dystrandepts?) gibbsite appears to have been replaced by kaolinite and halloysite, as borne out by clay mineral data from Mount Bosavi in the Southern Highlands Province. One of the potassium-argon dates given by Löffler *et al.* (1980) indicates that Mount Bosavi could be the oldest known Papua New Guinea volcano, dated at 1.93 million years. In soils developed on sedimentary rocks gibbsite has been recorded in significant amounts only above 3000 m in Papua New Guinea (Haantjens and Bleeker 1970) and in similar locations in Irian Jaya (Reijnders 1964).

THE ASSESSMENT OF THE DEGREE OF WEATHERING AND CHEMICAL CHANGES

Estimating the degree of weathering is very complicated since many factors have a bearing on it. Brewer (1964) considers the measurements of the amount of weathering of the constituent minerals, and the estimation of the weathering severity of the micro environment to be the most important. He stresses also the importance of leaching in the weathering processes, particularly in tropical and subtropical environments, and advocates the use of two indexes. These are the *absolute weathering* index, which measures the loss of each mineral species during soil formation, and the *intensity of weathering* index. Preferably measurements of mineral losses should be applied to various size fractions including the clay fraction; the loss estimations should be quoted as absolute amounts rather than percentages (if percentages are used certain minerals may be completely weathered while in absolute amounts the material may only be very little weathered). The *intensity of weathering* refers to the amount of weathering of primary minerals of known relative resistance and the effectiveness of leaching as shown by the kind of secondary minerals formed. The determination of the *absolute weathering* index requires numerous mineral analyses, preferably of various size fractions, and is only practicable in very detailed weathering studies. Simpler techniques have been proposed, such as those based on the percentage of a particular mineral species that has been weathered, on ratios of certain mineral species occurring in the light and heavy sand fraction (e.g. Ruhe 1956) or, more recently, on the zirconium to calcium oxide ratios of the silt and fine sand fractions (Chittleborough and Oates 1980). However, as pointed out by Brewer (1964), all these methods are only applicable to *single* profiles on *uniform* parent materials or to *separate* profiles on *common* parent material with the same mineral ratios and the same size frequency distribution of the mineral species used to calculate the ratios. Only by calculating the amounts of losses of each mineral species during soil formation can a comparison be made between the *absolute weathering* on different parent materials. However, careful checking to ensure that the parent material is uniform, and has not already been altered by soil forming processes, is essential. It is equally important to ensure that the weathering profile has been formed *in situ* and has not been contaminated by volcanic ash or colluvial material.

The *intensity of weathering* is reflected in the kind of secondary minerals formed and a table listing secondary clay size minerals* in order of their mineral weathering sequence has been drawn up by Jackson and Sherman (1953). Because this table was basically formulated by taking into account the weathering intensity factors, it has sometimes been applied directly as a measure of weathering intensity. Mohr *et al.* (1972) object to such use on the grounds that not enough emphasis is placed on whether the minerals are of secondary or primary origin. They stress the importance in the weathering process of whether the mineral is still an 'original rock building component' or simply the result of secondary crystallisation. The authors instance an example of two Indonesian soils, one containing quartz and muscovite, and the other cristobalite and illite, which have according to the table similar weathering stages (6 and 7). The weathering of the second soil is obviously much more advanced. Brewer (1964) too, has cautioned that Jackson and Sherman's (1953) table has a general application only and should always be used with discretion. He uses as an example an alpine humus soil (Histosol) occurring in a wet, high altitude environment in which little weathering of primary minerals has taken place. The clay fraction of this soil (11 per cent) is nevertheless dominated by gibbsite and hydrobiotite which, if measured against the table, are indicative of high and moderate weathered material respectively. Such circumstances also apply to Papua New Guinea. In one such instance, a Eutrandept located in New Britain was found to contain only about 5 per cent clay, yet this fraction was dominated by allophane and some halloysite, while the primary minerals were practically unweathered. Similarly, in very wet highland areas the rapid leaching of the very permeable volcanic ash may remove most constitutents leading thereby to the almost direct formation of primary minerals into gibbsite.

Some of these difficulties may be overcome by using the *weathering mean* developed by Jackson and Sherman (1953), which takes into account both the residual minerals and the solids formed from solution. This weathering mean is calculated from the equation: $m = \frac{\Sigma\,(ps)}{\Sigma\,(p)}$, where p equals the percentage of a mineral in the soil, and s equals the weathering stage of that mineral according to the weathering sequence table of Jackson and Sherman (1953). In soils unsaturated with bases, which are typical in Papua New Guinea, the weathering mean may be calculated on the clay fraction alone, while in soils where the silt fraction has been weathered appreciably it may also be applied to that fraction.

Various improvements to the weathering mean calculations have been suggested. By taking into account the percentage of clay size minerals in the soil, expressed as a fraction (percentage clay divided by 100), and multiplying it by the weathering mean, the *new weathering mean* is obtained, denoted as m_1 (Brewer 1964). A disadvantage of this index is that it does not account for

* The table includes some primary minerals, such as biotite and hornblende, which may also be found in the clay fraction.

clay movement (clay illuviation), which is common in many Papua New Guinea soils. Further refinements proposed by Brewer (1964) take into account the primary minerals still present in the soil material, as well as adjustments for any clay size material which may have been originally present in the parent material.

Most other methods of measuring weathering intensity are based on the molecular ratios of rocks and their weathering products, as determined by elemental analyses. Because rock weathering in the tropics often has loss of silica as its main effect* and aluminium or aluminium plus iron are known to be relatively stable the Si/Al and Si/R† ratios have often been used as an indication of weathering intensity. In soils these ratios are generally calculated on the composition of the clay fraction, but analyses of the fine earth (<2 mm) have also been used. Dudal and Moormann (1964) give Si/R ratios of generally less than 1.5 for the clay fraction of red-yellow Latosols, and values between 1.2-2.0 for dark red and reddish brown Latosols found in south-east Asia. Ratios of less than 2.0 and 1.5 for Si/Al and Si/R respectively, for analyses of the fine earth, are considered typical of Brazilian Latosols (Bennema *et al.* 1959). Ruxton (1968b) reporting on a weathering study of volcanic rocks found in the Northern Province and from other parts of the world states that these ratios provide an easy way to quantify the degree of rock weathering (for kandite weathering alone). It should be noted, however, that these ratios have a number of restrictions in their application. For instance, as has been pointed out by both Marshall (1935) and Hseung and Jackson (1952) they are of little significance for soils having 2:1 clay minerals and must remain constant during the weathering process. These limitations have led Parker (1970) to propose an alternative and more widely applicable weathering index for silicate rocks which takes into account the individual mobilities of the most mobile major elements‡ using bond strength considerations.

Probably the best known weathering indexes based on molar ratios are Reiche's (1943, 1950) weathering potential index (WPI) and his weathering direction or product index (WD).§ The WPI represents the molecular ratios between groups of various oxides. Because it expresses the relative abundance of 'unstable' compounds it can also be used as a weathering intensity index. WPI values are, however, very dependent on hydroxyl water content (water of hydration above 112°C denoted as H_2O^+) which was intended by Reiche (1943) to indicate the energy content of the materials during the process of weathering. The WD for its part essentially shows the relative abundance of

* This process, which is often called laterisation or lateritisation, should be referred to as ferralutisation.

† SiO_2/Al_2O_3 and $SiO_2/Al_2O_3 + Fe_2O_3$.

‡ Based on the proportions of the alkali (Na, K) and alkaline (Ca, Mg) earth metals present.

§ $$WPI = \frac{100 \times \text{mole } (K_2O + Na_2O + CaO + MgO - H_2O^+)}{\text{mole } (SiO_2 + Al_2O_3 + Fe_2O_3 + FeO + TiO_2 + CaO + MgO + Na_2O + K_2O)}$$

$$WD = \frac{100 \times \text{mole } SiO_2}{\text{mole } (SiO_2 + Al_2O_3 + Fe_2O_3 + FeO + TiO_2}$$

silica so it can also be used as a weathering index. This index is, however, basically very similar to the silica to sesquioxide ratio.

Other methods have since been developed to trace chemical changes in soils and rocks during weathering and soil formation. In 1970 van der Plas and van Schuylenborgh advocated a slightly modified version of Niggli's (1936) petro-chemical calculation methods, which may also be applied to soils. The Niggli method is discussed at length by Mohr *et al.* (1972). Briefly, it involves the conversion of total analyses data into molecular percentages which are then grouped into *al* (Al_2O_3), *alk* ($Na_2O + K_2O$), *fm* ($FeO + Fe_2O_3 + MgO + MnO$) and *ca* ($CaO$) on the basis of mutual percentages (the total should be 100 per cent).

Si (SiO_2) is then converted into a percentage by using the same conversion factor applied to the other fractions. The groups thus obtained were used by Niggli for petro-chemical calculations of different igneous rocks by computing the amount of silica bound to other elements and the amount of free silica (quartz). Van der Plas and van Schuylenborgh's modification applied to soils involved constructing assemblages of standard minerals for each horizon from chemical data and then comparing the individual soil horizons. However, this is a lengthy and complex process and Beckman (1975) opts for the simpler system of Barth (1948) which uses as its base a 'standard cell', a rock unit containing 160 oxygen ions. This method has also been recommended by Keller (1957) to calculate gains and losses during soil formation on the assumption that aluminium remains constant. To facilitate the calculations Barth (1948) adopted a standard cell of 160 oxygen anions because in many rocks 100 cations are associated with it. He stressed the importance of oxygen in rock studies related to volumes because it comprises about 92 per cent of the volume and concluded that, although many profound chemical and mineralogical changes may occur during the weathering process, many of these take place without changes in volume.

The method of calculation involves three steps in order to obtain the *cation proportions* (Cp), the *oxygen proportions* (Op) and the number of each of the *cations in the standard cell* (Cs). These steps are:

(a) To obtain Cp, the weight percentage of each oxide is divided by the molecular weight and multiplied by the number of cations in the oxide formula (e.g. SiO_2 contains 1 cation, and Al_2O_3 contains 2 cations).

(b) To obtain Op the Cp values are multiplied by the number of oxygens per cation in each oxide (e.g. for SiO_2 multiply by 2 and for Al_2O_3 multiply by 1.5).

(c) To obtain Cs the proportion of each cation is divided by Σ Op and multiplied by 160.*

As has been pointed out by Beckman (1975) this method affords a *direct* comparison between the number of cations in different materials without having to calculate artificial assemblages of minerals as has been advocated by van der Plas and van Schuylenborgh (1970).

* Thus $\frac{Cp(SiO_2)}{\Sigma\ Op} \times 160 = Cs(SiO_2)$ and $\frac{Cp(Al_2O_3)}{\Sigma\ Op} \times 160 = Cs(Al_2O_3)$.

SOME EXAMPLES OF WEATHERING IN PAPUA NEW GUINEA

In the examples given in Figures 13.2 and 13.3 the weathering mean, new weathering mean and silica to sesquioxide ratios for three Oxisols, a Tropudalf and Hapludoll profile have been related to profile depth. Deep mature weathering is evident in two of the Oxisol profiles, whereas the third shows only very shallow, mature weathering (Figure 13.2a). In all profiles weathering mean values for the solum (A + B horizons) are very close to 10, although in soils characterised by deep sesquox weathering it is somewhat higher, reaching a value of 12 in B_{23} horizon. Very similar patterns emerge for almost all the other curves given in Figures 13.2b and c for the new weathering mean and silica to sesquioxide ratios, except for the inverse relationship for the Si/R curves. Only the new weathering mean curve for the profile characterised by deep kandite weathering forms an exception, which is due to the marked decrease in clay content with depth below the B_3 horizon. Most curves are slightly slanted in the surface (0-20 cm) layer, caused by volcanic ash contamination (Bleeker 1972) probably largely derived from the 1951 Mount Lamington eruption. The low to very low silica to sesquioxide ratios for the Oxodols are in agreement with the figures quoted by Dudal and Moormann (1964) for typical Latosols found in south-east Asia.

In example 13.3a, b and c the patterns for the immaturely weathered Hapludoll are much alike, but this does not apply to the immaturely weathered Tropudalf. The highest/lowest values for the Tropudalf occur, as can be expected, in the B_{21} horizon (Figure 13.3b and c). Its weathering mean (Figure 13.3a), however, shows a marked increase in the A_2 horizon which appears to indicate that this horizon is the most intensely weathered.This can be put down to its relatively high goethite content, resulting from a secondary iron formation caused by seasonal waterlogging above the impermeable heavy clay subsoil by iron-rich seepage water derived from higher up the crest. In contrast Figure 13.3b shows a very pronounced increase in value between the A_2 and B_{21} horizon attributed to the abrupt texture contrast (12 versus 79 per cent clay). In Figure 13.3c this increase is much more gradual. Here the B_{21} horizon is clearly the more intensely weathered as evidenced by the dominance of kaolinite in the clay fraction, which in itself constitutes 79 per cent of the total soil. The high Si/R value of the A_1 horizon of this profile stems from the silica rich residue in the surface horizon, caused by the contamination by recently deposited andesitic ash combined with some clay illuviation. This is particularly evident when the Si/R ratios are calculated on the fine earth (<2 mm fraction). However, this effect is largely masked in the A_2 horizon by the secondary enrichment by iron oxides. These examples clearly show that great care must be taken when interpreting weathering indexes.

Using Reiche's (1943) methods chemical changes taking place in four different types of rocks weathering into soils are plotted in Figures 13.4 and 13.5. Figure 13.4 is a triangular diagram in which the molecular ratios between SiO_2, (Al_2O_3 + Fe_2O_3) and (K_2O + Na_2O + CaO + MgO) are plotted on a percentage basis and show smectite, kandite and sesquox weathering plus a combination of the three. The distance between and the direction of the plotted

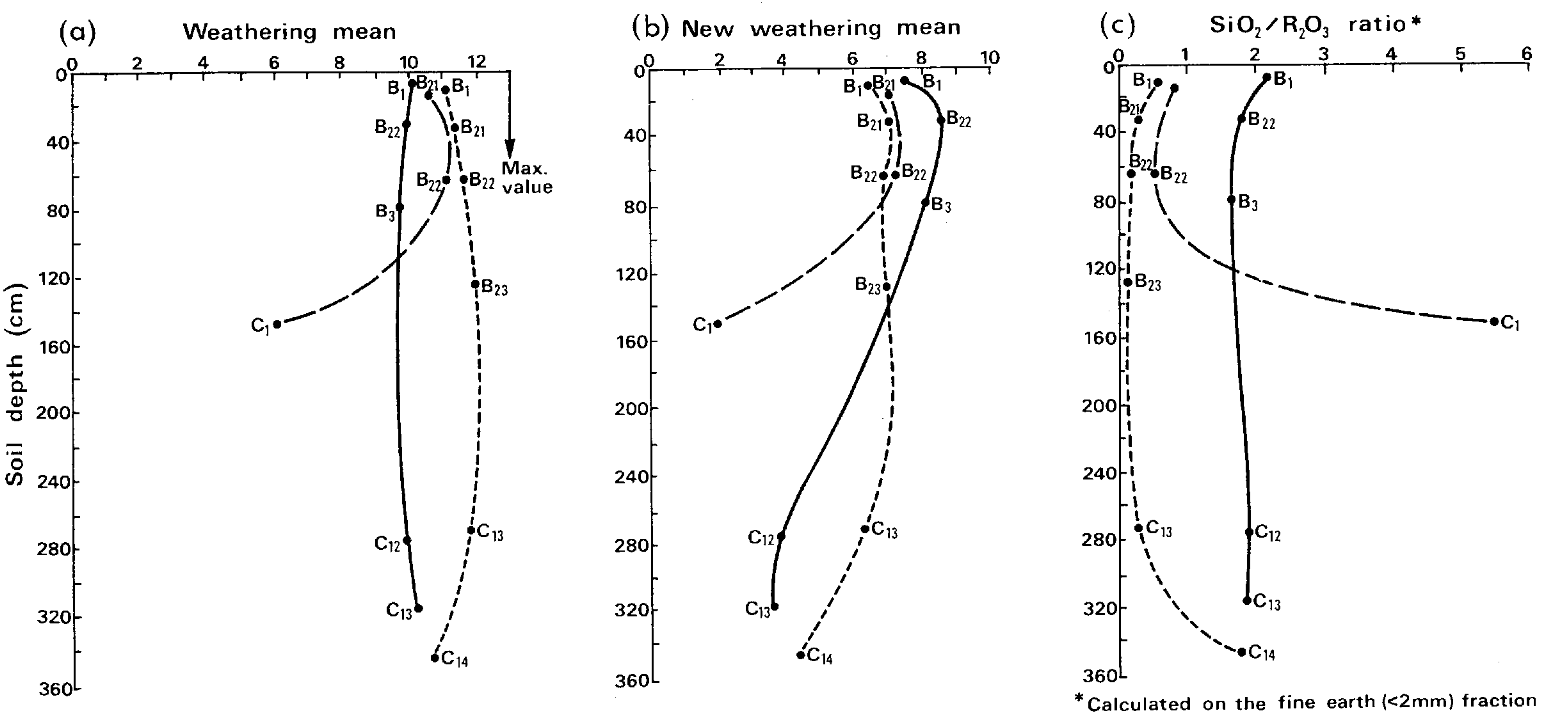


Fig. 13.2 Weathering mean, new weathering mean and silica to sesquioxide ratios for three Oxisol profiles, located near Musa in the Northern Province (see Fig. 14.8). --- Deep sesquox (goethite) weathering in an Acrohumox developed on fan deposits derived from ultrabasic breccia. — Deep kandite (kaolinite/halloysite) weathering in an Acrohumox developed on a narrow crest consisting of mudflow fanglomerates derived from basic igneous rocks. –– Shallow sesquox/kandite (goethite and kaolinite) weathering in a Haplorthox developed on a spur crest consisting of ultrabasic igneous rocks.

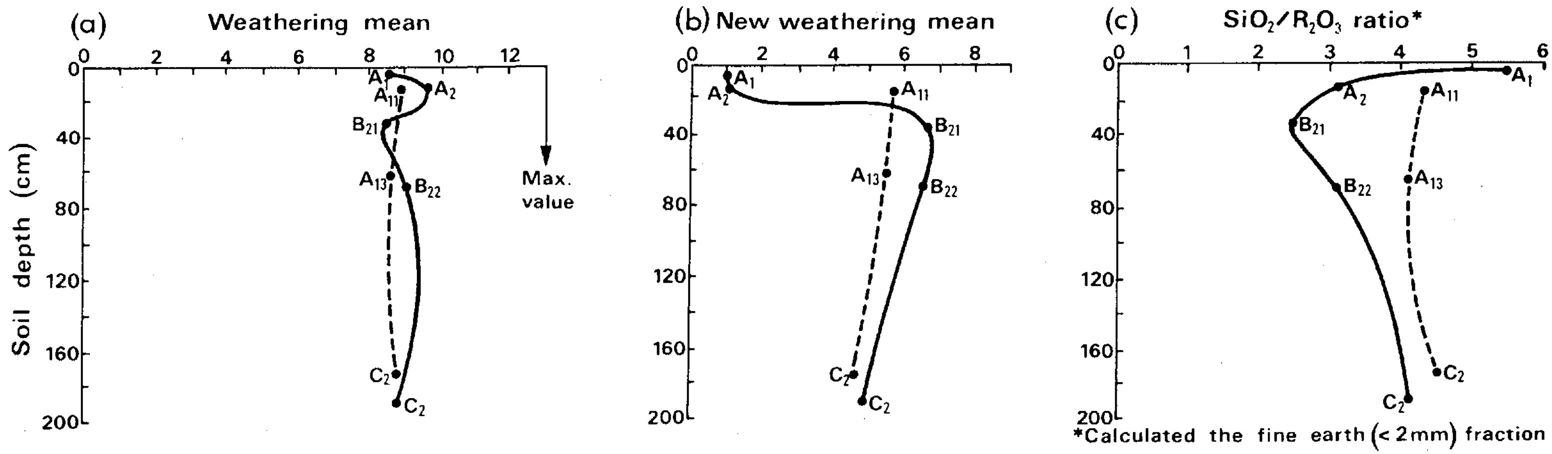


Fig. 13.3 Weathering mean, new weathering mean and silica to sesquioxide ratios for a Tropudalf and Hapludoll profile, located near Musa in the Northern Province (see Fig. 14.8). — kandite/smectite weathering in a Tropudalf developed on a broad crest consisting of sedimentary rocks. --- smectite weathering in a Hapludoll developed on a crest consisting of sedimentary rocks.

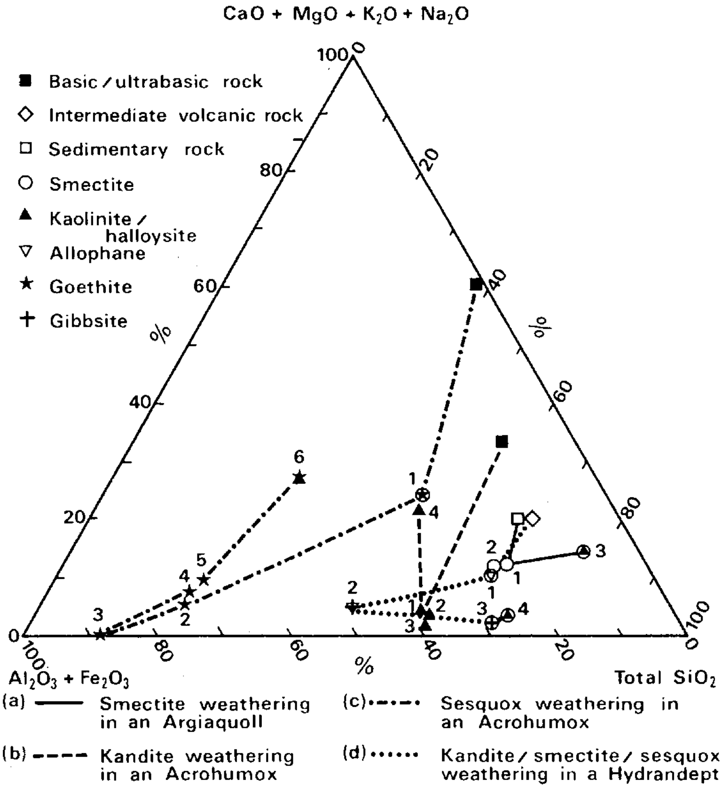


Fig. 13.4 Examples of four different kinds of weathering plotted on Reiche's (1943) triangular molar percentage diagram. The weathered materials (soil horizons) are numbered upwards to the surface of each profile. Profiles a, b and c are located near Musa in the Northern Province (see Figure 14.8) while (d) is found near Wabag in the Western Highland Province (after Haantjens and Bleeker 1970)

points represents the amount and direction of the chemical changes and indicates relative gains and losses, as well as weathering intensities. The Argiaquoll profile (Figure 13.4a), a typical example of smectite weathering, is from a poorly drained site in a relatively low (1000-1500 mm), highly seasonal rainfall area, on a stable Pleistocene surface underlain by impervious sediments. Leaching is impeded and total element losses are small as shown in the diagram by the closeness between the points and by the high silica and base contents. The large gain in SiO_2 of sample 3 (an A_1 horizon) is thought to have been caused by substantial loss of clay by illuviation, resulting in a gain of siliceous skeleton grains, and possibly also ash contamination. The fact that this surface sample also contains kaolinite, estimated between 15 and 40 per cent by X-ray diffraction, indicates that, even in circumstances considered ideal for the formation of montmorillonite, some of this clay mineral has been transformed.

Although kandite weathering sometimes passes through an intermediate stage of smectite weathering, for the most part rocks appear to change directly into kandite materials as demonstrated by one of the Acrohumox profiles

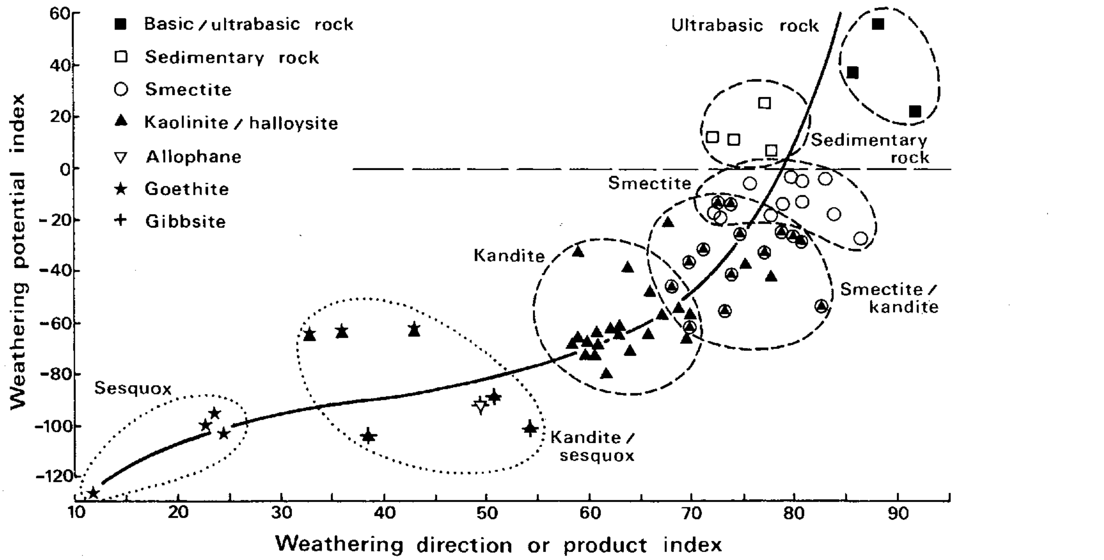


Fig. 13.5 Progressive weathering of different rocks into their weathering products as shown by Reiche's (1943) weathering potential index (WPI) and weathering direction (WD) (modified after Haantjens and Bleeker 1970)

(Figure 13.4b). This freely drained profile occurring on a 20-50 m wide, slightly rounded crest underlain by fanglomerates derived from Miocene basalt, is characterised by a rapid, heavy loss of bases and a moderate gain in sesquioxides, mainly as Al_2O_3. The increase in bases in sample 4 (an A_{11} horizon) stems again from its rejuvenation by airborne volcanic ash (mostly volcanic glass).

So far only a few cases have been reported in Papua New Guinea where sesquox weathering dominates the weathering material. One of the profiles, given in the diagram (Figure 13.4c), is an Acrohumox which contains more than 80 per cent goethite in the deep subsoil (at more than 2 m) and has a negligible cation exchange capacity. The soil occurs on a freely drained, undulating fan surface consisting of mudflow deposits derived from ultrabasic rocks, and possibly also from calcareous schists. Weathering of these rocks into goethite has been possible only because of their very low aluminium content (0.40 per cent Al_2O_3 in the rock sample). Some montmorillonite (estimated at 20-30 per cent) (sample 1) has been formed during the initial stage of weathering, which involved large losses of bases from the base-rich parent material. During further weathering this montmorillonite was completely lost along with most of the bases. The high percentage of bases in the surface sample (a B_1 horizon 2 to 22 cm thick) is again caused by volcanic ash contamination. The clay mineral data also show the presence of small amounts of kaolinite and talc in the upper part of the profile (samples 4, 5 and 6). According to Haantjens and Bleeker (1970) this could possibly be caused by a minor change in the composition of the mudflow deposits. Very strong leaching, reflecting intense weathering, has occurred. This is clearly depicted in the diagram by the length of line separating the parent material and sample points 1 and 2.

The fourth profile (Figure 13.4d) included in the diagram is descriptive of the complex weathering process leading to the formation of allophane and many other clay minerals. This soil is a freely drained Hydrandept, occurring at an altitude of 1750 m on a gently undulating ash plain with a lower montane humid climate (2500-3000 mm) of moderate seasonality. In sample 1, the volcanic ash is shown initially to lose bases and to gain sesquioxides by weathering into vermiculite and allophane. With continued weathering, more silica is lost and sesquioxides are increased. The total analyses data show this increase to consist largely of Al_2O_3, resulting in a mixture of allophane, gibbsite and some halloysite. The large gains in silica in samples 3 and 4 (an A_1 and B_2 horizon) indicate the presence of a discontinuity in the profile, unrecognised in the field, which owing to the presence of illite and kaolinite has been attributed by Haantjens and Bleeker (1970) to contamination by derivatives from sedimentary rocks. At the same time the presence of small amounts of vermiculite, gibbsite and allophane also present in the samples are indicative of rejuvenation by airborne volcanic ash. As has been shown by Pain and Blong (1979) recent ash deposition is much more widespread in the highlands than was originally thought (see Figure 5.2).

In Figure 13.5 the weathering potential index (WPI) values and weathering direction (WD) values of some fifty soil and rock samples from a variety of Papua New Guinea soils have been plotted in relation to their dominant clay mineral composition. The figure clearly illustrates a progressive weathering sequence from smectite clays (right hand corner of the diagram, just below the zero line) to sesquox clays (in the lower left hand corner). The intermediate position of the kandite weathering products in the diagram is indicative of low WPI values, reflected in large losses of bases, and relatively high WD values, reflected in only moderate losses of silica. This confirms their status as potential end products of weathering (Haantjens and Bleeker 1970).

Table 13.1 lists the total analyses data for an Acrohumox developed on mudflow fanglomerates derived from basic igneous rocks, while Table 13.2 lists that for an Haplorthox formed on basic igneous rocks. In the right hand section of the tables the oxides have been individually recalculated to show the ratio of ions (elements) present in the standard rock cells (160 oxygens) following Barth's (1948) method, as outlined earlier. As demonstrated in the tables there is a marked difference between the two sets of figures, clearly indicating that weight percentages can give a distorted pattern of chemical changes in element content of weathering profiles, which is basically concerned with numbers of ions. The samples, which are representative of two 'very weathered' Oxisol profiles clearly show the number of oxygen and hydrogen ions contained in silicate clays and in hydrated oxides. Particularly the water plus (H_2O^+) and iron (Fe_2O_3 + FeO) values of the standard cell differ noticeably from the total analyses data. Beckman (1975) has used the standard cell approach to soil formation studies by comparing its results with results obtained from employing sand and/or clay mineral analyses, micromorphology and other techniques.

Surface contamination by volcanic ash of the B_1 horizon (sampled at 6 cm depth) of the Acrohumox profile, clearly evident in the sand mineralogy (Bleeker 1975), is also demonstrated by its standard cell composition. As

Table 13.1
Total analyses data and compositions of standard cells of an Acrohumox developed on mudflow fanglomerates derived from basic igneous rocks

	Total analyses data							Number of cations in 160-oxygen standard cell					
		Horizons							Horizons				
	Parent material (400 cm)	C_{13} (315 cm)	C_{12} (275 cm)	B_3 (82 cm)	B_{22} (30 cm)	B_1 (6 cm)		Parent material (400 cm)	C_{13} (315 cm)	C_{12} (275 cm)	B_3 (82 cm)	B_{22} (30 cm)	B_1 (6 cm)
SiO_2	48.56	39.84	39.33	40.12	38.59	39.16	Si	43.93	33.25	32.48	31.34	30.63	31.99
Al_2O_3	14.70	23.50	25.85	32.99	31.90	28.03	Al	15.66	23.12	25.15	30.36	29.87	26.99
Fe_2O_3	6.35	19.61	15.73	9.31	8.34	6.08	Fe	8.32	12.54	10.06	5.87	5.87	5.54
FeO	5.28	0.27	0.41	0.57	1.34	2.68							
MgO	9.76	0.34	0.64	0.19	2.03	5.63	Mg	13.16	0.40	0.79	0.23	2.39	6.87
CaO	7.31	0.26	0.55	tr	1.07	3.78	Ca	7.07	0.25	0.50	—	0.91	3.29
K_2O	0.28	0.59	1.35	0.07	0.09	0.26	K	0.33	0.65	1.44	0.05	0.10	0.27
H_2O^+	4.83	12.77	13.18	15.82	15.23	13.19	H*	29.14	71.07	72.54	82.39	80.64	71.83
MnO	0.20	0.15	0.10	0.04	0.05	0.08	Mn	0.16	0.10	0.05	–	0.05	0.05
TiO_2	1.91	2.40	2.66	1.34	1.32	1.26	Ti	1.30	1.50	1.63	0.80	0.81	0.78
P_2O_5	0.24	0.22	0.25	0.08	0.11	0.16	P	0.16	0.15	0.17	0.05	0.07	0.10
C_2O_3	0.03	0.08	0.04	0.03	0.03	0.03	Cr	—	0.05	0.02	0.02	0.02	0.02
NiO	0.02	0.08	0.03	0.02	0.02	0.02	Ni	—	0.05	—	—	—	—
Totals	99.47	100.11	100.12	100.58	100.12	100.36	0	160	160	160	160	160	160

* Beckman (1975) has adopted the practice of recording H_2O^+ as OH^+ and of subtracting the oxygens involved from 160 to give a 'residual' oxygen figure.

Table 13.2
Total analyses data and composition of standard cells of a Haplorthox developed on ultrabasic igneous rocks

	Total analyses data					Number of cations in 160-oxygen standard cell			
		Horizon					Horizons		
	Parent material (270 cm)	C_1 (150 cm)	B_{33} (62 cm)	B_2 (12 cm)		Parent material (270 cm)	C_1 (150 cm)	B_{33} (62 cm)	B_2 (12 cm)
SiO_2	41.98	38.49	15.17	21.67	Si	35.54	34.14	15.27	20.19
Al_2O_3	0.36	2.02	15.07	19.91	Al	0.36	2.13	17.94	21.87
Fe_2O_3	5.76	15.31	47.90	33.64	Fe	5.03	12.52	40.73	27.18
FeO	1.94	3.10	5.16	4.64					
MgO	36.03	28.00	2.52	4.00	Mg	45.40	39.96	3.76	5.54
CaO	0.51	0.41	tr	0.20	Ca	0.46	0.37	—	0.22
K_2O	<0.01	0.01	0.05	0.06	K	—	—	—	0.06
H_2O^+	12.33	10.86	10.79	12.38	H*	69.55	64.18	72.61	76.84
MnO	0.12	0.24	0.62	0.22	Mn	0.10	0.16	0.55	0.17
TiO_2	0.03	<0.01	<0.01	0.07	Ti	—	—	—	0.06
P_2O_5	<0.01	<0.01	0.03	0.05	P	—	—	—	0.04
Cr_2O_3	0.46	0.94	2.01	2.84	Cr	0.31	0.64	1.58	2.07
NiO	0.51	0.57	0.72	0.31	Ni	0.36	0.43	0.61	0.22
Totals	100.05	99.97	100.05	99.99	0	160	160	160	160

* See footnote to Table 13.1.

Table 13.3

Calculations on gains and losses, assuming that aluminium has remained constant in an Acrohumox. Total analyses data have been recalculated to show the ratio of elements present in reference rock cells containing 160-oxygens

	Parent material	C_{13} horizon	Recalculated assuming Al-constant	Gains or losses	C_{12} horizon	Recalculated assuming Al-constant	Gains or losses	B_3 horizon	Recalculated assuming Al-constant	Gains or losses
Si	43.93	33.25	22.51	−21.42	32.48	20.23	−23.70	31.34	16.17	−27.76
Al	15.66	23.12	15.66	—	25.15	15.66	—	30.36	15.66	—
Fe	8.32	12.54	8.49	+0.17	10.06	6.27	−2.05	5.87	3.03	−5.29
Mg	13.16	0.40	0.27	−12.89	0.79	0.49	−12.67	0.23	0.12	−13.04
Ca	7.07	0.25	0.17	−6.90	0.50	0.31	−6.76	—	—	−7.07
K	0.33	0.65	0.44	+0.11	1.44	0.90	+0.57	0.05	0.03	−0.30
H	29.14	71.07	48.11	+18.97	72.54	45.19	+16.05	82.39	42.50	+13.36
Mn	0.16	0.10	0.07	−0.09	0.05	0.03	−0.13	—	—	−0.16
Ti	1.30	1.50	1.02	−0.28	1.63	1.02	−0.28	0.80	0.41	−0.89
P	0.16	0.15	0.10	−0.06	0.17	0.11	−0.05	0.05	0.03	−0.13
Cr	—	0.05	0.03	+0.03	0.02	0.01	+0.01	0.02	0.01	+0.01
Ni	—	0.05	0.03	+0.03	—	—	—	—	—	—
O	160	160	108.32	−51.68	160	99.68	−60.32	160	82.53	−77.47

shown in Table 13.1 calcium and magnesium ions are markedly higher in the B_1 horizon than in the B_{22} horizon.

Calculations on gains and losses taking place as the parent material alters into soil may be made in cases where the profiles, from prior investigations, can reasonably be assumed to have formed *in situ* on parent materials in which the variability has been minimal. For this reason the results forthcoming from Tables 13.3 and 13.4, which exclude the contaminated surface horizons, are indicative only. The calculations on gains and losses are based on the assumption that aluminium has remained constant, as has been done by Keller (1957). Moreover, in the C_{12} and B_3 horizons of the Acrohumox the very low amounts of calcium and magnesium ions may be insufficient to act as flocculants for aluminium (Keller 1957).

Both tables illustrate the large losses of metal ions that can be expected to take place during the formation of an Oxisol. In Table 13.3 the weathering of the parent material into an Acrohumox is shown to have resulted in a replacement of these metal ions by hydrogen. In the Haplorthox profile (Table 13.4), even larger losses of ions have occurred, this time including hydrogen. In large part this is due to the very high molecular water content (H_2O^+) of the parent material consisting of serpentine (antigorite/chrysolite). It is unlikely that in this set of circumstances the original rock structure could be maintained, large losses being highly likely to cause fabric collapse and decreases in volume. It should be noted, however, that there have also been several instances of isovolumetric rock weathering recorded in Papua New Guinea (Haantjens and Bleeker 1970).

Because of the relatively high chromium contents present in the Haplorthox profile, calculations on gains and losses have also been made using the hypothesis that the chromium content has remained constant (Table 13.5). Although the losses are less pronounced the profile evinces very similar trends to those in Table 13.4. It should be realised, however, that the chromium ion content is still relatively small in comparison to aluminium and that slight variations in the determined values may therefore lead to significant variations in gains and losses.

DEPTH AND RATES OF WEATHERING

Deep weathering of 40 m or more, which is common in many tropical countries (Ollier 1969) is infrequent in Papua New Guinea where the landforms are relatively youthful and unstable. Most of the data available lack information relating depth to type of weathering. A maximum of 32 m of strong (mature?) weathering has been reported on the Sogeri Plateau, east of Port Moresby on consolidated rocks (volcanic agglomerates) (Thompson, quoted by Haantjens and Bleeker 1970). Other examples given by these authors for areas underlain by consolidated rocks indicate maximum depths ranging from 15 to 30 m, but include mature, immature as well as skeletal weathering. Mature weathering profiles on consolidated rocks are commonly 1-3 m thick and either overlie a thicker zone of less weathered material, or directly rest with an abrupt boundary on little altered rocks. On steeper slopes, in hilly or mountainous terrain, immature and skeletal type weathering is most in evidence, mature

Table 13.4

Calculations on gains and losses, assuming that aluminium has remained constant in a Haplorthox. Total analyses data have been recalculated to show the ratio of elements present in reference rock cells containing 160-oxygens

	Parent material	C_1 horizon	Recalculated assuming Al-constant	Gains or losses	B_{33} horizon	Recalculated assuming Al-constant	Gains or losses
Si	35.54	34.14	5.77	−29.77	15.27	0.31	−35.23
Al	0.36	2.13	0.36	—	17.94	0.36	—
Fe	5.03	12.52	2.12	−2.91	40.73	0.81	−4.22
Mg	45.40	36.96	6.25	−39.15	3.76	0.08	−45.32
Ca	0.46	0.37	0.06	−0.40	—	—	−0.46
K	—	—	—	—	—	—	—
H	69.55	64.18	10.85	−58.70	72.61	1.45	−68.10
Mn	0.10	0.16	0.03	−0.07	0.55	0.01	−0.09
Ti	—	—	—	—	—	—	—
P	—	—	—	—	—	—	—
Cr	0.31	0.64	0.11	−0.20	1.58	0.03	−0.28
Ni	0.36	0.43	0.07	−0.29	0.61	0.01	−0.35
O	160	160	27.04	−132.96	160	3.20	−156.80

Table 13.5

Calculations on gains and losses, assuming that chromium remained constant in a Haplorthox. Total analyses data have been recalculated to show the ratio of elements present in reference rock cells containing 160-oxygens

	Parent material	C_1 horizon	Recalculated assuming Cr-constant	Gains or losses	B_{33} horizon	Recalculated assuming Cr-constant	Gains or losses
Si	35.54	34.14	16.52	−19.02	15.27	2.99	−32.55
Al	0.36	2.13	1.03	+0.64	17.94	3.52	+3.16
Fe	5.03	12.52	6.06	+1.03	40.73	7.98	+2.95
Mg	45.40	36.96	17.89	−27.51	3.76	0.74	−44.66
Ca	0.46	0.37	0.18	−0.28	—	—	−0.46
K	—	—	—	—	—	—	—
H	69.55	64.18	31.06	−38.49	72.61	14.23	−55.32
Mn	0.10	0.16	0.08	−0.02	0.55	0.11	+0.01
Ti	—	—	—	—	—	—	—
P	—	—	—	—	—	—	—
Cr	0.31	0.64	0.31	—	1.58	0.31	—
Ni	0.36	0.43	0.21	−0.15	0.61	0.12	−0.24
O	160	160	77.44	−82.56	160	31.36	−128.64

weathering, where it appears, being only very thin. Here the deepest weathering is found on crests and upper slopes. The limited records also appear to indicate that both mature and immature weathering profiles are generally deeper on igneous than on sedimentary material and that the proportion of mature weathering decreases gradually with increasing altitude. According to Löffler (1977) this zonation is often upset, many deep, mature weathering profiles occurring in highland areas.

When dealing with unconsolidated rocks it is often difficult to identify the lower boundary of the weathered material. Mature weathering more than 4 m deep has been found on mudflow deposits derived from ultrabasic rocks east of Musa in the Northern Province (see Fig. 14.8). Pleistocene sediments which cover very extensive areas in the Western Province are maturely weathered to depth of 10-15 m (Bleeker 1971).

Observations on rapidly permeable volcanic ash deposits in the highlands have shown that immature weathering as deep as 15 m develops rapidly, but that mature weathering is mostly restricted to about 2-3 m in the oldest ashes.

The depth of weathering in unconsolidated materials appears to be mainly related to permeability and drainage, shallow weathering being dominant on impervious sediments or on poorly drained plains where bases are only very slowly leached.

Because of the favourable climatic conditions, rates of weathering are generally considered to be rapid in the tropics. However, as shown below, these rates are strongly influenced by other environmental factors, such as parent material and elevation. Studies by Ruxton (1968a) of volcanic ash deposits from Mount Lamington, Northern Province have shown that, at altitudes of 1000-1400 m, volcanic glass can be expected to weather almost completely into allophane in 8000-27 000 years. In comparison only slight etching of hornblende was apparent in ashes less than 20 000 years old. Radiocarbon data from lowland volcanic ash soils found near Cape Hoskins, West New Britain Province indicate that small amounts of halloysite can form within a time span of 300-2000 years in profiles considered to be only skeletally weathered (Bleeker and Parfitt 1974). The rate of halloysite formation under cooler, wet highland conditions appears to be much slower as shown by a date of 50 000 years BP in a Hydrandept located near Tambul (Pain 1973; Parfitt 1975). It can be seen, therefore, that in volcanic ash deposits in particular the relationship of age to degree of weathering is not always readily apparent owing to the thickness of the beds, depth of burial below younger ash layers and drainage conditions.

Using radiocarbon methods, peaty horizons in an unweathered alluvial deposit have been dated at 3500 years BP in the East Sepik, 5800 years BP in the Western Highlands (3000 m) and 3780 and 1800 years BP and on Mount Giluwe (3100 m) in the Southern Highlands Province (Haantjens and Bleeker 1970; Blake and Löffler 1971). In the Kaugel Valley samples of slightly weathered alluvium collected at altitudes of 2300 m near Tambul in the Western Highlands Province are older than 40 000 years (Löffler 1972; Pain 1973). A wood sample found by Blake (1971) in maturely weathered sediments on a cliff exposure along the Fly River in the Western Province has been dated at 27 000 years, while shallow immature weathering (up to 1 m) found in uplifted coral limestone soils was dated by Chappell (1973) at 40 000 to 80 000 years.

14 Primary Nutrients in Soils and Trace Element Deficiencies in Tree Crops

Of the elements essential for plant growth nitrogen, phosphorus and potassium are often required in large quantities and are therefore commonly referred to as primary nutrients. This chapter discusses the contents and distribution of primary nutrients in Papua New Guinea soils. It also gives a summary of the present knowledge of trace element deficiencies found in major tree crops.

NITROGEN

The primary source of nitrogen is the atmosphere where N_2 is the predominant gas and from which it is obtained by biological agents and, less importantly, also by rainwater charged with ammonia and nitrates percolating through the soil.

The four most important biological agents responsible for fixing nitrogen have been listed by Stevenson (1965) and are: (1) blue-green algae, which have persisted during very long periods of the earth's history and occur in almost every environment where sufficient sunlight is available for photosynthesis; (2) free living (non symbiotic) bacteria of which *Clostridium*, *Beyerinckia* and to a lesser extent also *Azotobacter* are most widely distributed in tropical soils, their individual occurrence being mainly dependent on the soil reaction; (3) bacteria living in symbiosis with leguminous plants. This process is thought to be particularly important in the tropics (R. Wetselaar personal communication 1981) where the symbiotic genus *Rhizobium*, which is commonly associated with Leguminosae, contributes to the nitrogen fertility of the soils; and (4) bacteria living in symbiosis with non-leguminous plants. As with the third biological agent, nitrogen is fixed, but in this case by plants belonging to the non-leguminous families of which the Casuarinaceae are the most important in tropical areas.

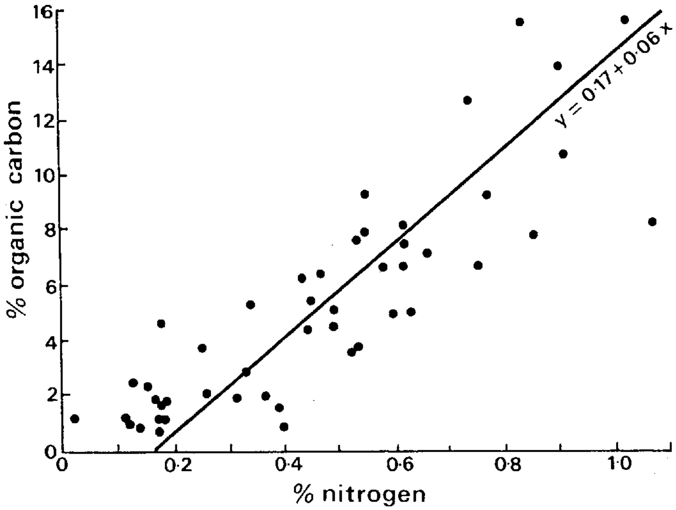


Fig. 14.1 Relationship of organic carbon to nitrogen in 48 topsoil samples representing Dystropepts, Eutropepts and Humitropepts. The relationship is significantly correlated (R^2 = 0.87) at the 0.001 level

Soil Nitrogen

Nitrogen content in soils normally ranges between 0.02 and 0.4 per cent (Corbett 1969). It is found in soil usually in combination with organic matter and consequently is concentrated mainly in the A_1 horizon. This close relationship is apparent in Figure 14.1, where soil nitrogen and organic carbon* contents of A_1 horizons of Papua New Guinea soils belonging to the Dystropepts, Eutropepts and Humitropepts great groups have been plotted against each other.

Most plants obtain their nitrogen directly from the soil solution.† Here nitrogen is provided by micro-organisms attacking plant residues and forming ammonium (NH_4^+) ions (ammonification) which, in well aerated, acid to neutral soils, are then transformed into nitrate (NO_3^-) ions (nitrification) (Corbett 1969). The rate of nitrification, which largely controls the quantity of nitrogen available to plants, is itself dependent on the carbon-nitrogen (C/N) ratio of the soil. In soils of agricultural importance in temperate regions a ratio of 10-12 is considered to be typical of the organic matter in the surface horizon (Stevenson 1965). Analytical data (Wall *et al.* 1979) from the Solomon Islands show a modal C/N ratio of 9 (mean 10.2) for all samples analysed, the range being from 7-13. For Papua New Guinea soils the ratio is usually within the 8-14 range, but may show marked variations depending on the decomposition stage of the plant materials. For instance C/N ratios of 20-40 are common in Histosols. Usually soil nitrogen content appears to be slightly higher in tropical than temperate soils. This has been attributed by Jenny (1941) to the more

* Organic carbon obtained from chemical analyses is usually multiplied by 1.72 to obtain the organic matter content.

† The soil solution refers to the water in the soil containing cations (e.g. Ca^{2+}, Mg^{2+}, K^+), and anions (e.g. HCO_3^-, Cl^-, No_3^-).

favourable conditions for plant growth and the more frequent occurrence of species of Leguminosae in tropical forests.

Stevenson (1965) considers that the major factors affecting the nitrogen content of soils are climate, vegetation, topography, physical soil characteristics and activities of the microflora and microfauna. Although these factors are all closely related the major influences on soil nitrogen distribution in Papua New Guinea appear to be climate (temperature, as a function of altitude, and rainfall) and parent material (presence or absence of volcanic ash deposits). This is clearly shown in Figure 14.2, where the mean soil nitrogen

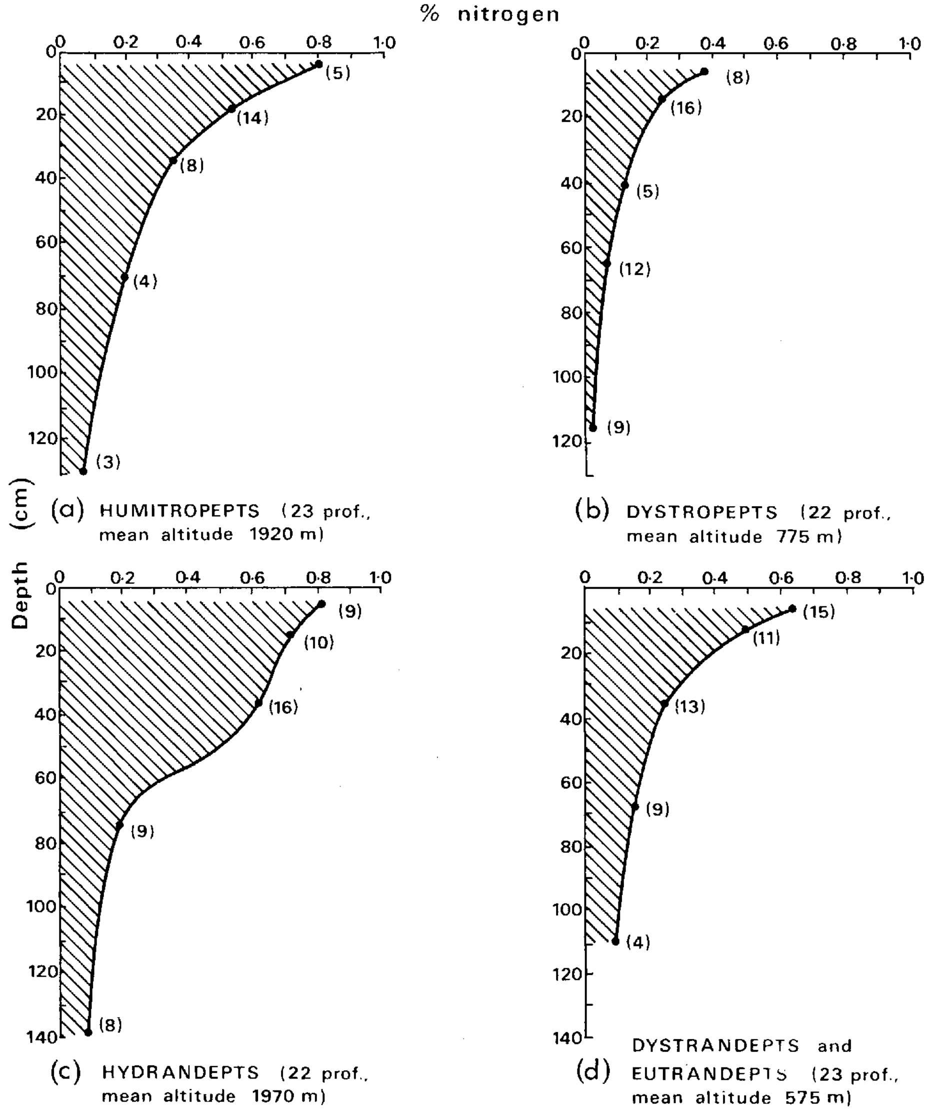


Fig. 14.2 Mean nitrogen distribution with depth* for typical great soil groups in Papua New Guinea

* Mean nitrogen content has been calculated according to five depth zones 0-10, 10-25, 25-50, 50-100 and 100-200 cm. Number of samples is given in figure in brackets

has been plotted against depth for some typical highland (14.2a, c) and lowland (14.2b, d) great soil groups developed on volcanic ash or other parent material. Because of the limited number of samples mean nitrogen contents were calculated according to five depth zones. Although individual samples within depth zones commonly show variations caused by other factors such as degree of slope and sampling techniques, they nevertheless clearly indicate that there are a number of great soil groups having distinctly different nitrogen contents. The Humitropepts (14.2a) and Hydrandepts (14.2c) occurring in relatively cool climates at mean altitudes between 1900 and 2000 m are characterised by a very high nitrogen content, particularly in the A_1 horizon. This is largely attributable to the much slower rate at which organic matter decomposes with increasing altitude because of reduced microbiological activity. In comparison, the Dystropepts (14.2b) and Eutrandepts/Dystrandepts (14.2d) are more often found at lower altitudes with higher temperatures and this is reflected in their much lower nitrogen content. However, a pronounced difference in soil nitrogen content is also apparent when comparing soils developed on volcanic ash and non ash within roughly similar mean altitudinal zones (14.2a with c and b with d). This appears to be related to the clay mineral allophane and aluminium oxides, very common in both lowland and highland volcanic ash soils. As discussed in the relevant genesis sections of Chapter 5 these form stable complexes retarding the decomposition of organic matter and consequently nitrogen. Similar trends emerge when the mean nitrogen distribution in the surface 25 cm of Vitrandepts (six profiles, Figure 14.3a) and Eutropepts (five profiles, Figure 14.3b) are compared, using data collected by Zijsvelt and Torlach (1975) in the Ala-Kapiura area, West New Britain Province. These figures also show a very pronounced accummulation of nitrogen in the top 5 cm of the soils.

Figure 14.4 relates nitrogen content to soil depth for other typical great soil groups and other lowland soils for which there is sufficient sampling data.

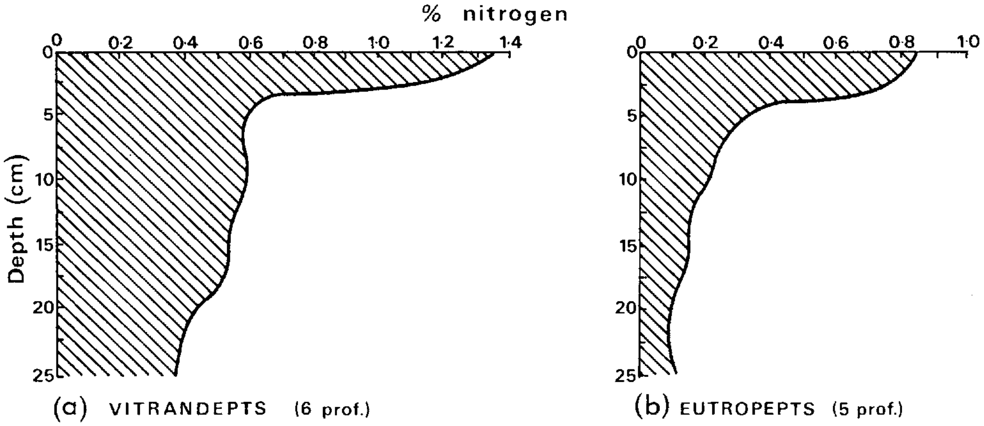


Fig. 14.3 Mean nitrogen distribution in the surface 25 cm* of two typical soils, occurring in the Ala-Kapiura area West New Britain Province

*Samples taken at 2.5 cm intervals. Data source Zijsvelt and Torlach 1975.

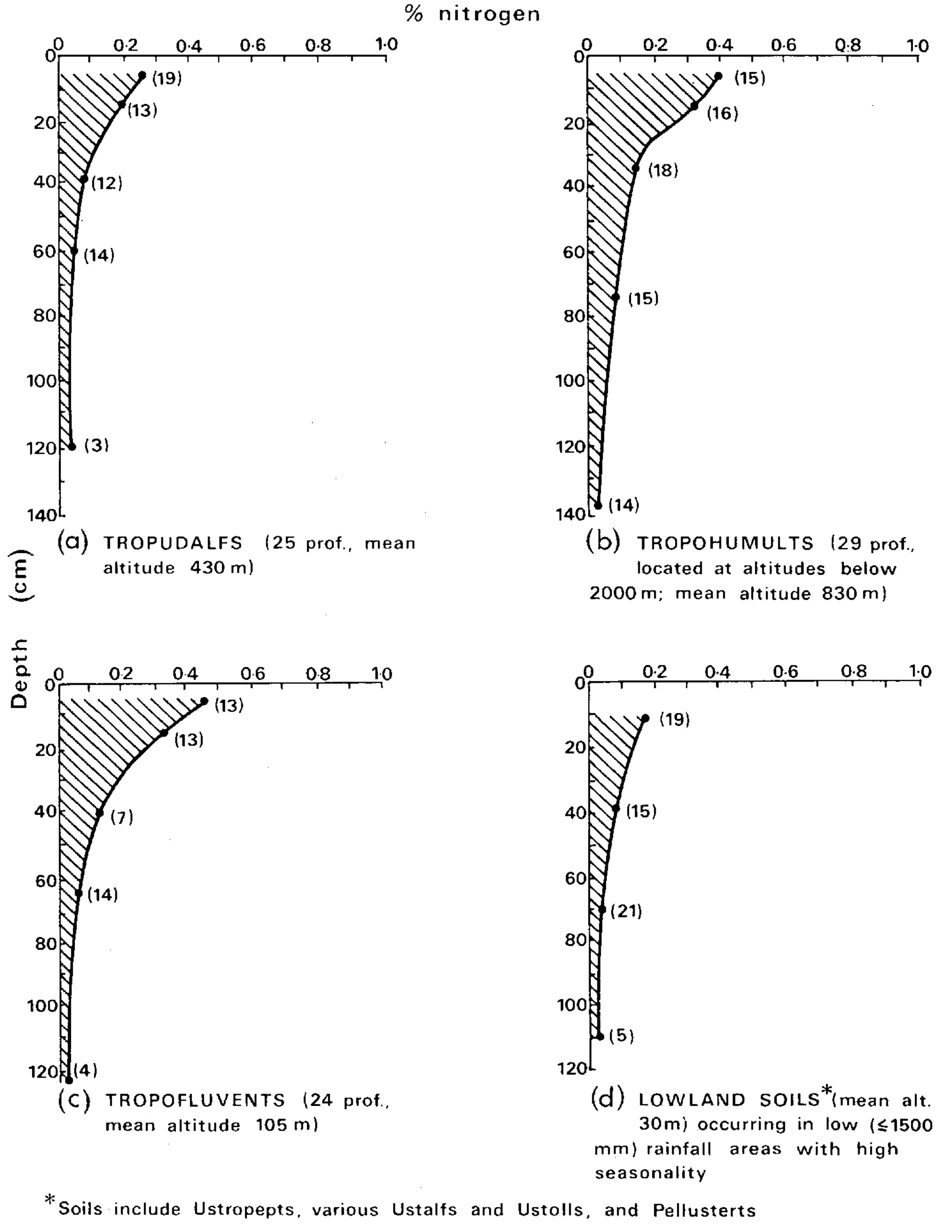


Fig. 14.4 Mean nitrogen distribution with depth* for typical great soil groups and other lowland soils of low rainfall areas in Papua New Guinea

* Mean nitrogen content has been calculated according to five depth zones 0-10, 10-25, 25-50, 50-100 and 100-200 cm. For soils occurring in dry lowland areas the 0-10 and 10-25 cm zones have been combined due to insufficient sampling in the top 10 cm. Number of samples is given in brackets on figure

Values for the Tropofluvents (14.4c) appear to be high considering that these soils were developed on recent alluvial deposits and that average topsoil (0-25 cm) nitrogen contents for similar soils in the Markham Valley show average values of only 0.13 per cent (Zijsvelt 1973). However, most of these latter samples are from areas with significantly lower mean annual rainfall which may partly account for the marked difference in mean soil nitrogen content. Zijsvelt's (1973) data is interesting in that it clearly shows that the highest nitrogen content occurs in soils located in the western part of the Markham Valley, suggesting a correlation with annual rainfall, which increases in a westerly direction. The effects of low annual rainfall on soil nitrogen contents are also demonstrated in Figure 14.4d. Here data for various great soil groups found in dry areas (annual rainfall 1000-1500 mm, high seasonality) had to be combined because of the limited number of samples. In comparison to the other 'lowland' soils, occurring in higher rainfall areas, mean soil nitrogen values are low. Limited data on Ultisols (mainly Plinthaquults and Plinthudults), which are widespread on Pleistocene sediments in relatively dry areas (1500-2000 mm annual rainfall) in the Western and Sepik Provinces, also indicate low soil nitrogen levels. Similar relationships between climate and nitrogen have been observed by Jenny and Raychandhuri (1960) in Indian soils.

Zijsvelt (1973) also noted that the coarse textured Tropopsamments found throughout the Markham Valley had consistently lower nitrogen contents than other soils sampled, while nitrogen values for various Mollisols were significantly higher than the Entisols.

Of the other factors affecting the soil nitrogen, restricted drainage conditions, often related to topography, are also important. This is shown by the very high (mostly above 1.5 per cent) nitrogen contents of peaty layers (tiers) found in various Histosols and to some extent also in some Hydraquents (at high altitudes the formation of Histosols is also strongly influenced by the low temperature).

It would appear then that nitrogen levels of lowland soils found in higher rainfall areas are generally moderate, whilst in the cooler, wetter highlands nitrogen levels are generally high, and that the nitrogen in the soil is nearly all in the form of organic matter. Nevertheless, nutritional studies of cocoa, coffee, tea and coconuts have shown nitrogen deficiencies (Carne and Charles 1966; Southern 1966, 1969c; Southern and Hart 1969). According to Murty and Dick (unpublished data)* it is the most common nutrient deficiency found in cocoa, even when the soil nitrogen status is high. The deficiency appears generally associated with high light intensity conditions and, according to the authors, is rarely encountered when the cocoa is well shaded. Similarly, Holloway (1978), summarising the research findings of work carried out on coffee nutrition in the Eastern Highlands Province, states that nitrogen deficiencies are common in both young and mature coffee but that no significant yield increases have yet resulted from fertiliser applications. This claim appears rather surprising, but as mentioned by Holloway (1978), the nitrogen uptake can be inversely related to sulphur levels and hence additions

* D.W.P. Murty and Kay Dick - Plant nutrition diagnosis in the Territory of Papua New Guinea. Paper presented at 1970 ANZAAS Congress, Port Moresby.

of either nutrient could induce deficiencies of the other. Nitrogen deficiencies may be disclosed by high C/N ratios in the soils, since this ratio indicates the degree of nitrification.

PHOSPHORUS

Phosphorus is one of the major nutrients required for plant growth. Like nitrogen, readily available soil phosphorus is mostly located in the organic matter, which can account for 15 to 80 per cent of the total phosphorus in the soil (Corbett 1969). However, it also occurs in the mineral fraction of the soil where it is released by the weathering of primary minerals and is usually found in combination with calcium, magnesium, iron and aluminium. Phosphorus ions (available to plants in three forms, namely $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-}) present in the soil solution are the major source directly available to plants, their concentration depending on many factors (including redox potential, organic matter and clay content) of which the soil reaction is one of the most important. The solubility is highest in soils with a pH of 6.0-6.5 (Corbett 1969), but with increasing pH, especially in the presence of free $CaCO_3$, the solubility of calcium phosphates is impeded. As will be discussed in the next section, a similar problem occurs not only in very acid, strongly weathered soils but also in soils developed on volcanic ash deposits. Thus, although many soils may contain relatively large amounts of *total* phosphorus, little may be present in a form *available* to plants.

Another difficulty encountered with soils is that analytical data on available phosphorus normally only give a rough approximation of what is available to plants in real terms. Moreover the most commonly used methods (Olson, Bray and Truog) often give varying results, as exemplified in Table 14.1. As

Table 14.1
Phosphate extracted from Markham Valley soils* using the Olson and Bray methods (modified after Parfitt and Thomas 1975)

Locality	Rainfall (mm/year)	pH	P extracted (Olson) mg kg^{-1}	P extracted (Bray) mg kg^{-1}
Munum	2600	7.6	30	60
Leron	1400	6.9	8	19
Wawin	1400	8.1	11	65
Mara Lumi	1400	7.9	27	172
Rumion	1400	7.9	33	130
Markham farming	1400	7.8	16	74
Atzera	1400	7.5	27	30
Umi	2000	6.8	ND†	8

* Described as often calcareous, recent alluvial soils, mostly containing large amounts of montmorillonite. Subsequent analyses showed that the Umi site soil was almost entirely composed of volcanic glass and allophane, probably derived from volcanoes located along the north coast. The soil at Leron, closest to Umi, contained montmorillonite and halloysite with some allophane. Based on Zijsvelts' (1973) Markham Valley survey the majority of these soils appear to belong to the Hapludoll and Tropofluvent great soil groups.

† Not detectable.

discussed by Parfitt and Thomas (1975) the data from the Bray method (Table 14.1) are too variable, as is to be expected when using an acid solution on mostly calcareous soils. The Olson extraction method, by comparison, usually gives best predictions on neutral or calcareous soils. However, the results given for the weakly acid ash derived Umi soil (Table 14.1), containing allophane, would seem to indicate that in this case the Bray method is more suitable. Young (1976) and Parfitt and Thomas (1975) both mention the difficulties encountered when one extraction method alone is used on a variety of soils and this applies particularly to Papua New Guinea with its wide climatic range and its great variety of parent materials and consequently soils.

Phosphorus data obtained from samples collected by CSIRO, although covering many different environments, are in most cases too limited to allow for general conclusions and are for the most part also restricted to the Truog extraction method and/or total phosphorus content. These determinations have already been discussed in the relevant great soil group fertility sections and the following material deals almost solely with research data available from sources other than CSIRO.

Research in Papua New Guinea

Phosphorus deficiencies have been identified in many strongly weathered, acid to strongly acid soils and volcanic ash soils throughout the world (Andriesse *et al.* 1976; Aomine and Yoshinaga 1955; Fieldes and Schofield 1960; Fox *et al.* 1968), including Papua New Guinea (Brigatti 1975; Parfitt 1975; Parfitt and Thomas 1975; Parfitt and Mavo 1975).

In the strongly weathered soils, comprising mostly Oxisols and Ultisols rich in iron and aluminium, the phosphorus combines with these elements forming compounds having a very low solubility. This results in *fixation*, whereby not enough phosphorus is available to plants, causing a stunted growth, but fortunately, except in the Western Province, these soils are not very common in Papua New Guinea. More importantly, however, phosphorous fixation is widespread in the productive volcanic ash or ash derived alluvial soils covering extensive areas in the densely populated highlands, the Northern Province and on the islands of New Britain and Bougainville, where it has only recently been recognised. This can be attributed to the fact that field trials on these soils were initially only conducted with mature tree crops having low phosphate requirements which showed no response to fertiliser applications. Holloway (1978), for instance, summarising the studies carried out on coffee nutrition in the highlands, states that phosphorus applications appear essential only to young plants to promote root growth.

Since the mid-1970s, however, extensive research has been carried out in Papua New Guinea on the clay mineralogy, pH dependent surface charge and phosphate retention of 'Andisols', and their phosphate requirements for cropping. Because these properties are all indirectly related and of particular importance to these soils, some further elaboration is warranted. pH dependent surface charge characteristics have been discussed in detail by Greenland and Mott (1978) and Russell (1973) and are related to the negative charges carried on the surfaces of layers forming a clay particle. The surfaces of clay particles can be divided in broad terms into two groups, namely the siloxene types and the hydrous oxide types (Greenland and Mott 1978). While the siloxene types are typical for the micas and 2:1 clay minerals, the hydrous oxide types are found at all broken edges of clay particles and on all surfaces of crystalline and amorphous oxides. It is these hydroxide types which carry a charge dependent on the pH and the electrolyte concentration of the soil solution. Under acid conditions the charge associates with hydrogen ions, but under alkaline conditions the hydrogen ions dissociate, which, according to Greenland and Mott (1978) may be represented by

$$M - OH_2^+ \rightleftharpoons M - OH \rightleftharpoons M - O^- + H_2O$$

more acid   more alkaline

and where M represents a co-ordinated metal or silicon ion in the clay surface. The pH at which the surface is uncharged is known as the point of zero charge (pzc) and depends largely on the affinity of the ion M^{n+} for electrons.

Thus, allophanic soils have a large pH charge dependency and adsorb phosphate strongly at low soil pH.*

In Papua New Guinea Brigatti (1975) studied in detail the chemical properties of samples collected from topsoils (A_1 horizons) covering both highland and lowland environments. Although no detailed soil descriptions or classification are given, his samples from Pleistocene highland volcanic ash soils located at Tambul, Kuk, Rairong, Kindeng and Aiyura† appear to belong to the Hydrandepts and Andaquepts.‡ Samples collected from lowland sites at Higatura, Kerevat and Mosa§ consist of soils developed on recent volcanic ash deposits and are thought to belong to the Vitrandepts and Eutrandepts. Clay mineral analyses of the samples showed that three of the soil clays (Tambul, Higatura and Kerevat) consisted predominantly of allophane,¶ the Mosa sample of a mixture of allophane and halloysite, while the remaining samples were found to contain mostly halloysite. The clay mineralogy and pH dependent surface charge, shown in Table 14.2, were found by Brigatti (1975) to correlate closely with the phosphate requirements of the soils, the last being estimated using adsorption isotherms. Soils dominated by allophane, which is characterised by a large surface area and has many surface aluminium hydroxide groups, adsorbed phosphate more strongly and had a greater pH dependent surface charge than halloysitic soils (Table 14.2). However, Brigatti (1975) found that phosphate adsorption occurred also in soils dominated by halloysite, a clay mineral probably formed by the weathering of allophane (Parfitt and Mavo 1975). Like the allophanic soils, he attributes this largely to

* As shown in the formula, under more alkaline conditions the charge becomes negative and adsorption of the (negative) P ions disappears.

† Annual rainfalls about 2600-2700 mm, except for Aiyura which is located in the drier eastern part of the highlands and has an annual rainfall of about 2100 mm.

‡ Soils collected at Rairong, Kindeng and Aiyura have formed on alluvium of mixed composition but are dominated by Pleistocene volcanic ash.

§ Annual rainfall approximately 2500, 2800 and 3600 mm respectively.

¶ The dominance of allophane and volcanic glass (in the coarser fractions) in the Tambul soil has been attributed by Pain and Blong to preservation under swampy conditions.

Table 14.2
pH dependent charge properties and clay mineralogy of topsoils of volcanic ash or ash derived soils (modified after Brigatti 1975)

Location	Net charge (-ve) me/100 g		Major clay mineral composition	
	pH 5.0	pH 7.5	fine clay (<0.2 μ)	coarse clay (0.2-2 μ)
Tambul* (WHP)	5.0	29.3	Ah	Ah,Hh
Kuk* (WHP)	13.8	28.5	Hh,A	Hh,MH,A
Rairong* (WHP)	9.5	23.8	Hh,A,MH	MH,G
Kindeng* (WHP)	8.3	20.5	Hh,A	Hh,A,MH
Aiyura* (EHP)	15.0	27.5	Hh,MH,Go	MH,Go
Higature† (NP)	5.0	22.5	A	V
Mosa† (WNBP)	12.7	19.2	Ah,Hh	Hh,A
Kerevat† (ENBP)	5.5	14.0	Ah	Ah

WHP = Western Highlands Province
EHP = Eastern Highlands Province
NP = Northern Province
WNBP = West New Britain Province
ENBP = East New Britain Province

A = allophane
Ah = hisingerite (ferri-allophane)
Hh = hydrated halloysite
MH = meta-halloysite (dehydrated halloysite)
G = gibbsite
Go = goethite
V = vermiculite

* Presumably Hydrandepts and Andaquepts
† Presumably Vitrandepts and Eutrandepts

surface aluminium hydroxide groups, but these are presumbly present in much smaller quantities. It has also been reported (e.g. Syers *et al.* 1971) that iron oxides have a lower affinity for phosphate in comparison to aluminium oxides. However, although the clay fractions of soils rich in halloysite contained higher amounts of iron (particularly the Aiyura soil) than those rich in allophane, Brigatti does not consider this a significant contributory factor. Adsorption measurements carried out by Brigatti (1975) on the clay fraction, pretreated to remove the amorphous coatings of aluminium, iron or organic matter, showed a markedly increased level of phosphate retention in the halloysitic samples when the organic matter was removed, while that of the soils rich in allophane was only slightly affected. This appears to indicate that the maintenance of organic matter, a widespread practice in the highlands, is beneficial in reducing phosphate fixation by halloysitic soils.

The phosphate fixing properties of a much greater number of soils, including those formed on volcanic ash and alluvium, and strongly weathered soils rich in iron or aluminium oxides have been investigated by Parfitt and Mavo (1975). Their results are given in Table 14.3. In general, data presented for the soils developed on volcanic ash follow similar trends to those given by Brigatti (1975), the highest adsorption rates in most cases being recorded in soils rich in allophane. An exception is the soil located at the Kerevat site (Table 14.3), which has a very low phosphate requirement. This soil, found less than 400 m from the Kerevat PRT site, apparently did not receive any fertiliser

Table 14.3
Soil location, classification, phosphate requirements, pH and clay minerals (modified after Parfitt and Mavo 1975)

Site	Province	Soil*	mg per kg P sorbed at 0.2 mg per litre equilibrium concentration† (phosphate requirement)	pH	Components present in clay fraction
Tambul (0-15 cm)	WH	Humic andosol	1200	5.1	allophane, volcanic glass, >> imogolite, halloysite
Aiyura D10‡ (0-15 cm)	EH	Humic andosol	660	5.0	allophane, volcanic glass, >> imogolite
Kuk A2 (0-15 cm)	WH	Humic andosol	480	5.2	halloysite
Kuk C4 (0-15 cm)	WH	Humic andosol	380	5.2	halloysite, metahalloysite, allophane >> imogolite
Kerevat PRT (0-15 cm)	ENB	Andosol	400	5.7	allophane, volcanic glass
Kerevat KSF (0-15 cm)	ENB	Andosol	30	5.6	allophane, volcanic glass
Kabiufa (0-15 cm)	EH	Humic latosol	300	5.4	halloysite, kaolinite
Aiyura J7 (0-15 cm)	EH	Meadow soil	120	6.0	kaolinite > chlorite > amorphous material

Table 14.3 cont'd

Sogeri (0-7 cm)	Central	Red latosol	300	4.8	kaolinite >> goethite, hematite
Sogeri (24-28 cm)	Central	Red latosol	600	4.6	kaolinite >> goethite, hematite
Subitana (0–7 cm)	Central	Red latosol	600	4.4	kaolinite, metahalloysite, lepidocrocite, goethite, gibbsite, chlorite
Subitana (50-54 cm)	Central	Red latosol	1000	4.3	kaolinite
Subitana (140-144 cm)	Central	Red latosol	1500	4.2	kaolinite
Umi	Morobe	Andosol	340	6.8	allophane, amorphous material, imogolite, silicate
Leron	Morobe	Alluvial soil	150	7.7	montmorillonite, halloysite, allophane
Maralumi	Morobe	Alluvial soil	50	7.9	montmorillonite

* Closest equivalent according to Soil Taxonomy: Humic Andosol-Hydrandept; Andosol-Eutrandept; Humic Latosol-Humitropept; Meadow Soil-Tropaquept; Red Latosol-Rhodudult or Haplorthox and Alluvial Soil-Tropofluvent.

† The P application in kg per ha required to give this concentration may be calculated approximately assuming the top 10 cm of one ha of soil weighs 1.5×10^6 kg for non ash and 1.0×10^6 kg for ash soils.

‡ Refers to local block numbers.

applications, the strong difference in adsorption rates being attributed by the authors to soil variability. Likewise, different results may occur when data from similar locations are compared, such as those collected by Parfitt and Mavo (1975) and Brigatti (1975). These differences appear to be due to local soil variability. Inconsistent results clearly emphasise the necessity for detailed and accurate soil and site descriptions.

Parfitt and Mavo's (1975) data (Table 14.3) for the volcanic soils show that the Tambul site requires the most phosphate (approximately 1200 kg P/ha, assuming a bulk density of 1.0 for the top 10 cm of the soil) which is in agreement with field trials which were carried out subsequently. Similar, but much less serious problems with phosphate fixation occur in the other ash soils (Andepts).

Data for the strongly weathered soils (Oxisols?) found in the Central Province (Subitana and Sogeri) also have very high rates of phosphate adsorption, which, as indicated in the electron micrographs, are caused by iron oxides cementing the kaolinite particles. Values for the Subitana clay are highest because these are less well crystallised and thus have a larger surface area than the Sogeri clays (see Table 14.3). According to Parfitt and Mavo (1975) this is caused by the pronounced difference in rainfall (3500 mm at Subitana versus 2000 mm at Sogeri).

Ultisols found widespread in the Western Province and to a lesser extent those in the East and West Sepik Provinces, are likely to show similar symptoms. Data, although limited, give strong indications of very low available phosphate contents (generally less than 10 ppm based on the Truog extraction method) and a clay fraction dominated by poorly crystallised kaolinite.

It is widely accepted that fertiliser applications may do little to rectify phosphorus fixation problems, and that liming, to increase the soil pH and phosphorus availability, is usually not effective. Since fertiliser spread on the soil surface will often remain fixed, Parfitt and Mavo (1975) have suggested that to get the best possible results it should be placed in bands 2-3 cm below the seeds. No conclusive results supporting the application of lime have been obtained from Papua New Guinea (Brigatti 1975). However, although having little effect on halloysitic soils, significant reductions in phosphate requirements were obtained from soils rich in allophane after lime was applied. This can be expected, since liming will result in an increase in the soil pH. Because organic phosphates appear to be less readily fixed than inorganic forms, the maintenance of organic levels in halloysitic soils is considered to give the best results in controlling the phosphate availability.

Research into inorganic phosphorus, carried out in Irian Jaya, should be mentioned since the findings may be relevant to Papua New Guinea. Schroo (1963) has reported available phosphate contents ranging between 50 and 1000 ppm (Truog extraction) in soils developed on limestone in the karst region of the Ajamaroe plateau in the Bird's Head, an area which is estimated to cover about 100 000 ha. Determinations of the total phosphorus content* of the soils similarly showed very high (1-25 per cent) values, but no clear correlation with

* Extraction with Fleishman acid consisting of 50% conc. H_2SO_4 plus 50% conc. HNO_3.

available phosphorus. Limestone samples analysed proved that the rock was not a phosphorite, mean phosphate content being fairly normal at 0.20 per cent P_2O_5. Total analyses carried out on a representative sample, a deep reddish brown (5YR 4/3) silty clay having 18.6 per cent total and 650 ppm available phosphorus, showed that the soil contained remarkably low silica content, but high amounts of sesquioxides. Calcium contents were, moreover, too low to allow the formation of calcium phosphates, while examinations of the sand fractions confirmed the absence of phosphate bearing minerals, such as apatite and collophane. The sand fraction did, however, contain isotropic greyish grains consisting of an iron coated secondary mineral called *Crandallite*. According to Schroo (1963) these highly phosphate soils have been formed by weathering and accumulation of compounds originally present in the limestone. A survey of the uplifted Pleistocene coral reefs, found in the south of the island of Biak, subsequently confirmed that these soils also occur in other large areas with a young karst topography. Twenty-four samples collected at depths of 0-75 cm from yellowish brown (10YR 5/6-5/8) and dark reddish brown (5YR 3/3) silty clay horizons (pH 5.5-6.5) had average Truog values of 450 ppm. Although considered unsuitable for fertiliser manufacture (because of their high iron and aluminium contents and too low average P_2O_5 contents) Schroo (1963) suggested that this material could possibly be used as a slow acting, low grade fertiliser. This was later confirmed in pot trials. Since the Irian Jaya deposits were found at widely separated locations and limestone covers very large areas in Papua New Guinea, similar deposits are likely to occur there also. At present very little information has been collected from these areas, because of their inaccessibility and generally low suitability for agriculture. However, a few very high available phosphorus values (up to 965 ppm Truog) have been recorded from limestone soils sampled near Lake Kutubu, and also south-west of Mendi in the Southern Highlands Province (see Bleeker and Healy 1980). It is interesting to note that Rutherford and Haantjens (1965), when discussing the analytical data (Wabag-Tari area), state that 'for unknown reasons some individual samples of many soil families show high available phosphorus values' and add that these families include soils developed on limestone and calcareous rocks. Surprisingly, limited samples collected from soils on uplifted coral terraces have not shown these very high values. Nevertheless the Irian Jaya results warrant a further investigation into the possible existence of high inorganic phosphorus deposits in Papua New Guinea.

POTASSIUM

Unlike nitrogen, and to a lesser extent phosphorus, potassium is not mainly found in the soil organic matter, but is a constituent of many minerals, such as K-feldspars and micas (e.g. orthoclase, microcline, muscovite and biotite). Thus its distribution generally follows a pattern that is related to rock type and the degree of weathering of the soil. For instance, the potassium content of strongly weathered Ultisols and Oxisols is mostly very low, while soils rich in the clay minerals montmorillonite and illite, which contain potassium in their structure, usually evince no signs of potassium deficiency.

The total potassium content in mineral soils (K_2O) ranges between 0.05 and 3.5 per cent (Bear 1964), only a small percentage of which is usually directly available to plants. Arnold (1960) subdivided the soil potassium contents into readily-exchangeable and non-exchangeable categories. Although plants may sometimes obtain their potassium from non-exchangeable forms, the exchangeable potassium is generally considered a good index of potassium available to plants.

Since nutrients are transferred from the soil to the plants via the soil solution, the potassium availability depends to a large extent on its relation to other cations. Experiments in which calcium has been added to the soil by applying limestone in order to increase the pH and improve soil structure have indicated a depressed potassium availability (Rajokovic 1966, quoted by Best 1977). Likewise, a high magnesium content in the exchange complex causes similar problems, affected crops showing potassium deficiency symptoms. Potassium fixation also takes place when increased rates of fertiliser are applied to the soil. Previously this fixation was thought to be caused mainly by wetting and drying of the soil (Corbett 1969), but recent research by Barber (1979) has shown that, although this process causes slight increases in fixation, it is much more closely related to the type of clay mineral present. Barber's (1979) experiments in Kenya clearly indicated that amorphous and montmorillonitic clays have a much greater capacity to fix potassium than kaolinitic clays. Compared to phosphorus, potassium fixation is considered to be a less serious problem. This is because potassium available to plants is a cation (K^+) found permanently in the exchange complex. On the other hand it is also more readily leached than is phosphorus.

Potassium in the Soil

Because potassium is present in most soils in larger quantities than phosphorus, deficiency symptoms have been reported less frequently, and the soil analytical data indicate mainly moderate to high exchangeable potassium levels in Papua New Guinea soils. Nevertheless deficiencies are known to occur. Unfortunately, however, as with nitrogen and phosphorus, the information enabling a correlation of the soil with plant nutrient problems is scarce.

In Figures 14.5 and 14.6 the mean exchangeable potassium distribution with depth for some typical Papua New Guinea soils is given. Here a pronounced increase in potassium levels in the top 10 cm of most soils is evident, which is apparently related to a relatively high potassium mobility, rapid leaching of plant material causing surface accumulation. As shown in Figure 14.5c and d, Hydrandepts and Dystrandepts/Eutrandepts have significantly higher average potassium levels than do Humitropepts and Dystropepts (Figure 14.5a and b). This is doubtless linked to their formation on volcanic deposits, the ash contributing a supply of easily weatherable minerals. The sand mineralogy of the Hydrandepts clearly shows that considerable amounts of weatherable minerals, particularly feldspars, are still present in these soils (see Chapter 5, Tables 5.4a and b). Deep weathering of the Hydrandepts is evidenced in Figure 14.5c by the very gradual decrease in potassium content with depth below the

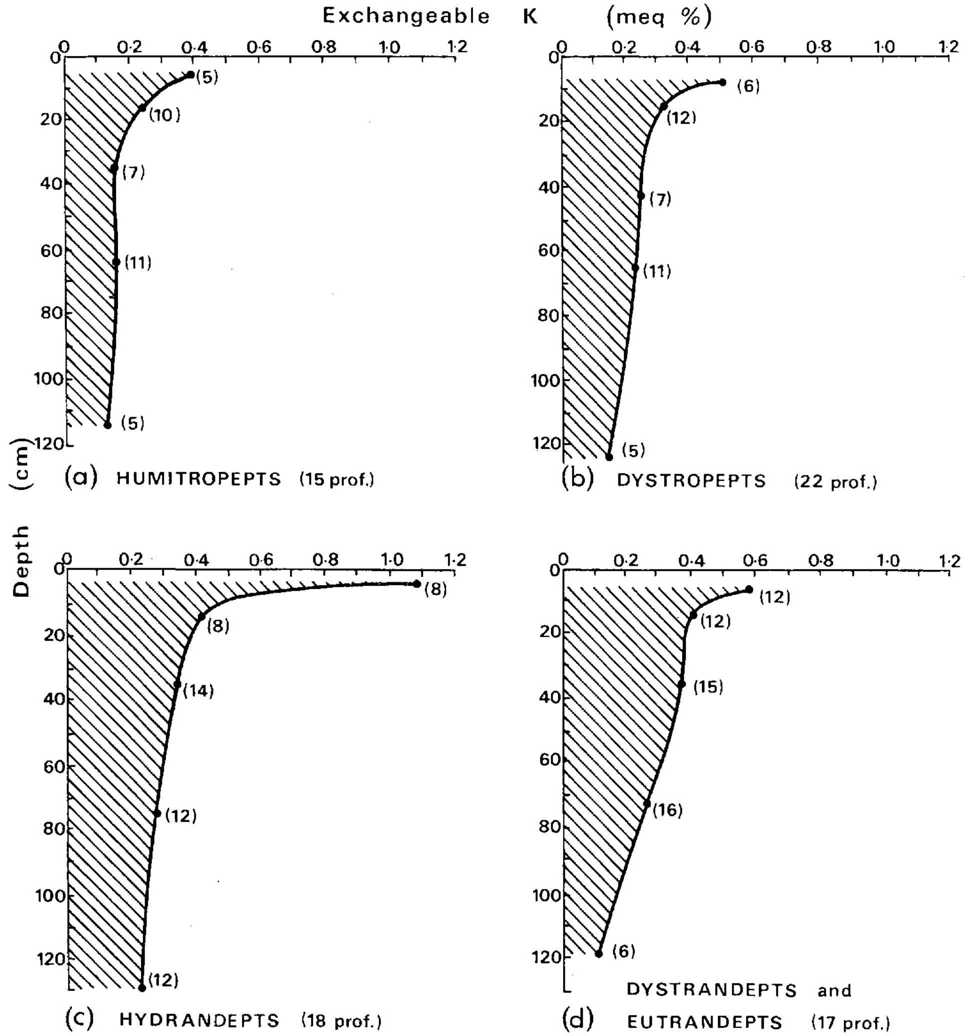


Fig. 14.5 Mean potassium distribution with depth* for typical great soil groups in Papua New Guinea

* Mean potassium contents have been calculated according to five depth zones; 0-10, 10-25, 25-50, 50-100 and 100-200 cm. Number of samples is given in brackets on figure

surface accumulation. When comparing the Humitropepts and Dystropepts (Figure 14.5a and b), the first show the lowest values with mean potassium contents falling below 0.2 meq at about 20 cm depth. The differences between the two great soil groups appear to be mainly related to the parent materials, the samples collected from the Humitropepts having a larger component of rocks with inherently low potassium content. It is expected that with increased, more representative sampling these levels will more closely approximate those of the Dystropepts.

Data given in Figure 14.6a for the Oxisols, although only represented by a limited number of profiles, closely follow a pattern which could be anticipated.

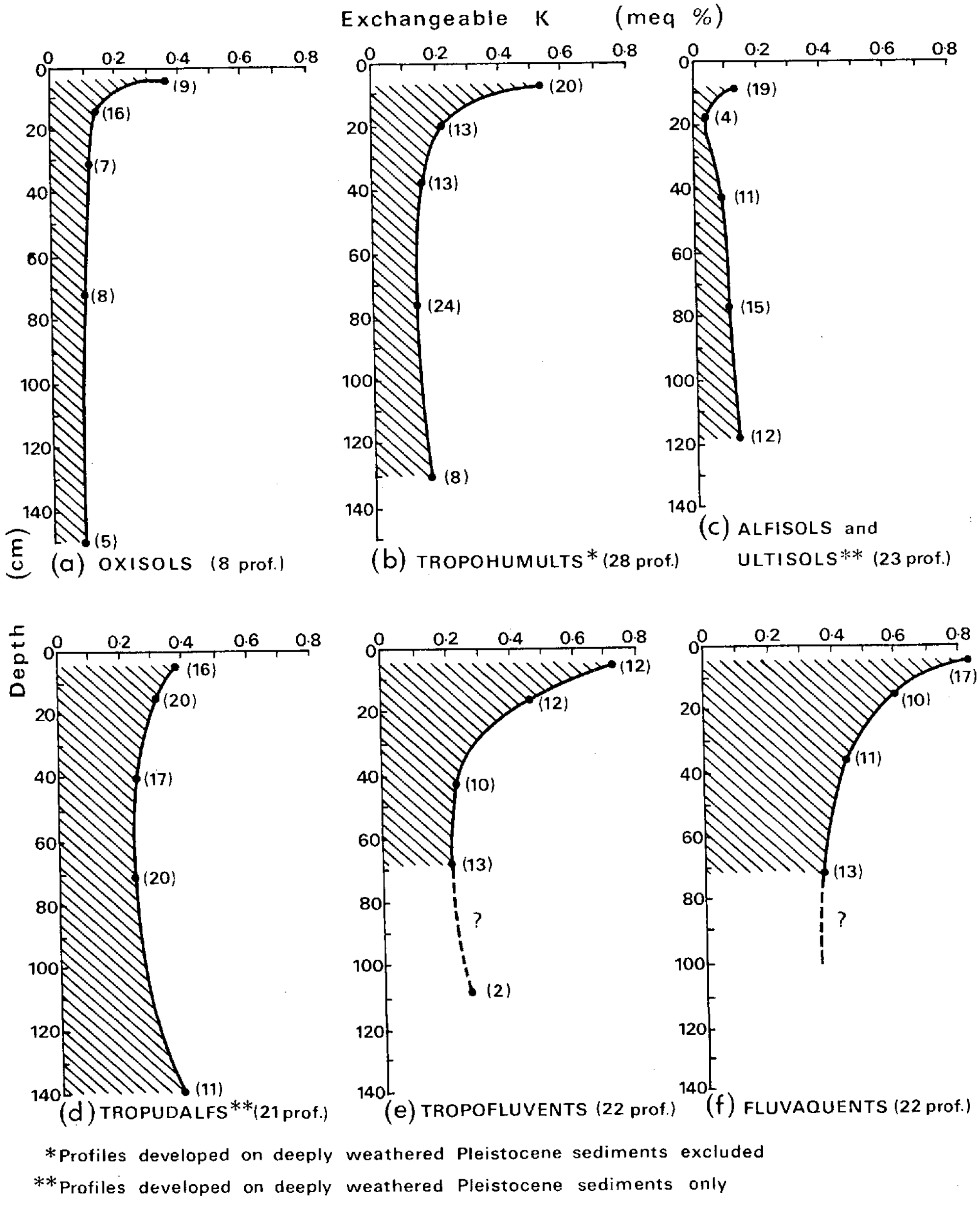


Fig. 14.6 Mean potassium distribution with depth* for typical great soil groups and soil orders in Papua New Guinea

* Calculated according to five depth zones; 0-10, 10-25, 25-50, 50-100 and 100-200 cm. Number of samples is given in brackets on figure

Deep strong weathering has resulted in very low exchangeable potassium values, except for a slight surface accumulation. Very low exchangeable potassium contents are also indicated in the Ultisols and Alfisols developed on strongly weathered Pleistocene sediments (Figure 14.6c). These have soils characterised by pronounced increases in clay content with depth. Apart from the slight surface accumulation, potassium reaches extremely low values in the leached sandy subsurface horizon (A_2), in turn followed by a very slight increase with depth in the clayey subsoil. Further variances in weathering pattern are shown by comparing the mean potassium distribution of the Tropohumults and Tropudalfs (14.6b and d), the last and least weathered group exhibiting markedly higher potassium levels. In the Tropudalfs particularly the zone between 30-70 cm depth is manifested by a lower potassium content, which appears to be related to the more advanced stage of weathering of this horizon (a B_2) in comparison to both underlying and overlying horizons. A similar, but much less pronounced trend, is indicated for the Tropohumults. Data presented in Figure 14.6e and f for the alluvial soils (Tropofluvents and Fluvaquents) show quite marked differences between the two great groups. This is to be expected since the mineral composition of the alluvium is strongly influenced by its source material and may therefore vary considerably from one area to another, depending on the rock type(s). This is also clearly indicated in Table 14.4 which shows the exchangeable potassium levels of typical great groups in the Markham Valley, where the soils have developed on alluvial and fan deposits. Here values of more than 0.40 meq per cent have been recorded for all great groups with over 65 per cent of the samples (topsoils and subsoils) having values of more than 1.5 meq per cent.

In Figure 14.7 the mean exchangeable potassium distribution in the surface 25 cm (2.5 cm intervals), is given for some Vitrandepts (a) and Eutropepts (b) occurring in the Ala-Kapiura area of West New Britain Province, using data collected by Zijsvelt and Torlach (1975). The strong potassium accumulation

Table 14.4
Potassium contents of Markham Valley soils*
(modified after Zijsvelt 1973)

	Exchangeable K (meq %)		
Great soil group	>1.5	1.5-0.76	0.75-0.41
Tropaquents	2	—	—
Tropopsamments	3	2	—
Tropofluvents	10	3	1
Troporthents	4	—	1
Halaquepts	3	9	1
Eutropepts	1	—	—
Haplaquolls	3	1	—
Hapludolls	41	15	2
Totals	67	30	5

* Based on values for both topsoil (0-25 cm) and subsoil (50-75 cm)

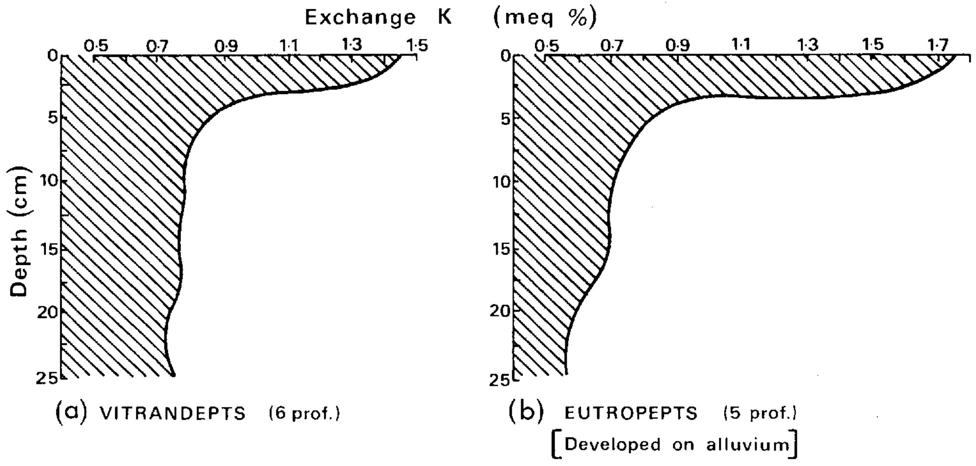


Fig. 14.7 Mean potassium distribution in the surface 25 cm* of two typical soils, occurring in the Ala-Kapiura area,† West New Britain Province
* Samples taken at 2.5 cm intervals
† Data source Zijsvelt and Torlach 1975.

in the surface (2.5 cm) layer is again very clear, as is the high potassium content in both soils, although the Vitrandepts seem somewhat better supplied with potassium with increasing depth than the Eutropepts. The data would appear to indicate also that the exchangeable potassium levels for the Vitrandepts are higher than those for the other previously discussed lowland volcanic ash soils (Figure 14.5d Dystrandepts/Eutrandepts). This may well have been caused by differences in age and composition of the volcanic ashes coming as they do from different areas. (The Dystrandepts/Eutrandepts samples were mostly collected in the Northern Province.) Moreover it should be noted that different sampling techniques have been applied, the data, in the case of Figure 14.7, representing samples taken at specific depths (2.5 cm intervals) while, on the other hand, those shown in Figures 14.5 and 14.6 apply to composite samples. However, data (Hartley *et al.* 1967) from the nearby Balima-Tiaru area tend to confirm that the volcanic deposits in this part of West New Britain do have high exchangeable potassium contents, average values (16 profiles) being 0.98, 0.70 and 0.42 meq% within depth zones of 0-4, 5-10 and 10-25 cm respectively.

As has been mentioned in the previous section, potassium available to plants depends on its relation to other cations, particularly calcium and magnesium. While Zijsvelt and Torlach (1975) consider that an exchangeable potassium content of 0.2 meq% is adequate, providing it forms at least 2 per cent of the total exchangeable bases, they state that Ca/K and Mg/K ratios of more than 20 and 10 respectively are unfavourable and may reduce the uptake by plants. Similarly research by Best (1977) and Sumbak and Best (1976) has shown that a high exchangeable magnesium content in soils, coupled with a very low exchangeable potassium content, may give rise to serious deficiency symptoms in coconut palms. Studies by these authors of the soils, described as 150 cm deep sandy clay loams overlying sand on the ridges (Tropofluvents?) and clay soils in the swales (Fluvaquents?), found on the (degraded?) littoral plains near

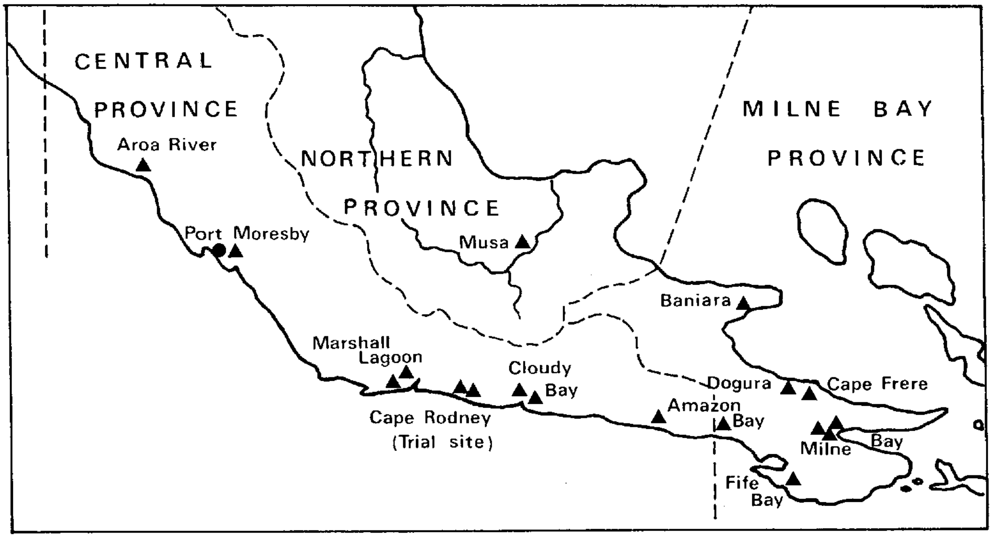


Fig. 14.8 Location of sites exhibiting high soil exchangeable magnesium/ exchangeable potassium ratios (after Best 1977)

Cape Rodney, about 160 km south-east of Port Moresby (see Figure 14.8), clearly indicate very high Mg/K ratios, especially in the fine textured, frequently flooded, inland swales. Here Best (1977) recorded average values of 11.7 and 0.1 meq% respectively for exchangeable magnesium and potassium, resulting in very pronounced deficiency symptoms in the coconut palms. Although fertiliser trials carried out by Sumbak and Best (1976) have shown good responses to potassium, large initial applications of fertilisers were necessary. For this reason Best (1977) has suggested that other crops may be a better commercial proposition. As shown in Figure 14.8, Best (1977) concluded from his study that there may be other, quite large areas in the south-eastern part of Papua New Guinea with similar problems.

Data given by Zijsvelt and Torlach (1975) for the Vitrandepts and Eutrandepts in the Ala-Kapiura area, West New Britain Province, indicate that deficiencies are unlikely to occur in either of these soils, but potassium seems more readily available in the ash soils (Vitrandepts). Similar conditions may be expected to apply to most of the other lowland volcanic ash soils (Dystrandepts/Eutrandepts). Analytical data from the highlands also indicate very low (generally less than 10) Ca/K and Mg/K ratios for the Hydrandepts (16 profiles). On the other hand, potassium deficiencies have been reported in coffee growing areas (Murty and Kay Dick unpublished data). In the Markham Valley, where the soils have a generally high to very high potassium content, Zijsvelt (1973) concludes that deficiencies may still occur, due again to unfavourable Mg/K and possibly Ca/K ratios. He states, however, that this probably only applies to the Halaquepts and the poorly drained, fine textured soils found along the Ramu River.

Potassium deficiencies have also been reported by Baseden and Southern (1959) in coconut palms growing on coral-derived soils along the east coast of

New Ireland. Most of the deficiencies noted occurred on the more inland, deeper, and very acid soils, described as having yellowish or reddish yellow colours. The authors conclude that soils containing less than 0.6 meq% potassium are unlikely to produce optimum coconut yields, and have inadequate reserves for continued healthy growth, without fertiliser applications. From the information given by Baseden and Southern (1959) on productivity (nuts/palm) and exchangeable cations, there does not appear to be any clear relationship between the productivity and Ca/K or Mg/K ratios.

While it is evident that information is inadequate to allow a correlation of soil types with plant nutrients the available data are also very difficult to interpret. This is largely due to variations in nutrient requirements from one crop to another, but also to other factors, such as management, shading and drainage, and draws attention to the need for closer co-operation between pedologists and agronomists.

MINOR ELEMENTS

Parent materials richest in micro elements are those derived from intermediate, basic and ultra basic rocks. Little is yet known about the trace element content of Papua New Guinea soils. Bleeker and Austin (1970) studied the trace element content of six profiles* located near Musa (Safia) in the Northern Province, about 160 km east of Port Moresby (see Figure 14.8). They found a significant relationship between the trace elements and other variables, including percentage clay (nickel, zinc and copper), sand fractions (chromium), parent material concentration (copper) and drainage conditions (manganese and cobalt). Although mean values for copper, zinc and manganese in the soil were in line with the world average specified by Vinogradov (1959) and Swaine (1955), nickel, chromium and cobalt had markedly higher levels, indicating a strong influence of ultrabasic rocks in the sedimentary derived soils. Very high chromium and nickel values (up to 3.5% Cr_2O_3 and 1.45% NiO) have also been recorded in the very strongly weathered Acrohumox, developed on mudflow deposits and ultrabasic breccias found in a nearby area. Most Ultisols and Oxisols developed on ultrabasic rocks, or sediments derived from these, can therefore be expected to contain high amounts of minor elements, which may possibly be toxic to crops.

More is known about trace element deficiencies in tree crops. In a study embracing the whole of Papua New Guinea, Southern and Kay Dick (1969) diagnosed the characteristic leaf symptoms produced by deficiencies through the medium of foliar analyses. Although almost entirely confined to major tree crops, some of their results may also be applicable to important subsistence crops. Table 14.5 shows the critical levels for trace elements in major tree crops, obtained by foliar analyses, as proposed by Southern and Kay Dick (1969). Their results are discussed below along with other relevant research material.

Studies of *coconuts* have for the most part concentrated on iron (Fe) and manganese (Mn) deficiency problems, which are commonly found on coral

* Tropudalfs (3 profiles), Argiudolls (2 profiles) and an Argiaquoll (1 profile).

Table 14.5
Proposed critical levels for trace elements in major tree crops in Papua New Guinea (after Southern and Kay Dick 1969)

		ppm Manganese		ppm Iron		ppm Zinc		ppm Copper		ppm Boron	
Crop	Sample used	A	B	A	B	A	B	A	B	A	B
Coconuts	14th leaves	20	30	20	40		10		2.5		10
Cocoa	3rd mature leaves	15	30	30	50	20	30	4	6	15	25
Arabica coffee	3rd leaves	25	50	40	70	6	8	5	9	25	40
Robusta coffee	3rd leaves	20	35	40	70	7	10		7		30
Rubber	Top storey (whorl) leaflets	30	50	60	80	15	20		8		20
Tea	Mature leaves from plucking table	50	100	60	120	9	12	3	5	8	12

A = level below which symptoms occur or deficiency is marked.
B = level below which responses are likely.

atolls in the South Pacific but, as yet, are unobserved in Papua New Guinea. Research by Southern (1967) has, however, indicated the widespread occurrence of sulphur deficiencies which cause chlorosis,* low yields and poor quality ('rubbery') copra. Southern obtained excellent field responses to sulphur applications on his experimental sites (Figure 14.9). They cover not only recent alluvial soils (sites 1, 2, 3, 7, 8 and 9) (Tropofluvents?) but also volcanic ash soils (sites 4, 5 and 6) (Andepts).† The field trials carried out on alluvial soils and soils developed on fan deposits‡ (alluvial 'outwash' plains) which entailed twice yearly application of sulphur and, in some areas, sulphur with nitrogen fertilisers, also produced a marked increase in nut production.

In *cocoa*, symptoms of iron, zinc, boron and manganese deficiences have all been recorded. Low manganese values were found by Southern and Kay Dick (1969) in neutral to alkaline soils, presumably of alluvial origin. Iron deficiencies are very common in cocoa, but are seldom serious. Low iron contents are often associated with high manganese contents. In cocoa, as with coconuts, iron deficiencies are quite common when grown on soils found on uplifted coral reefs (Rendolls and Tropudalfs?). They are also found in the alkaline alluvial soils of the Markham Valley. Here the symptoms have been considerably reduced by using ferrous sulphate foliar applications. Zinc

* Yellow colouring of the leaf, resulting from partial failure to develop chlorophyll.

† Responses to sulphur in these soils are rather surprising, since most of the supply of this element lies in the organic matter which is mostly high.

‡ Described as medium over fine textured, slightly alkaline, alluvial soils, subject to water logging and occasional flooding (Tropaquents or Haplaquolls?) and loams overlying gravel beds at shallow depth (Troporthents?).

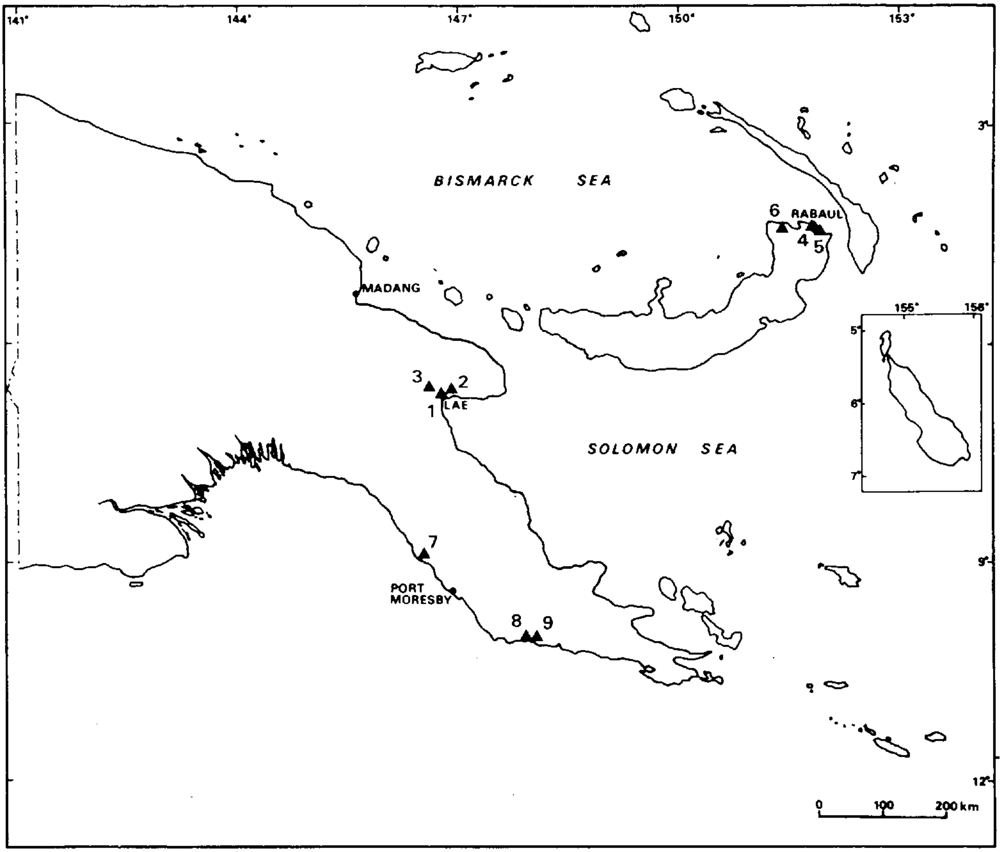


Fig. 14.9 Location of sites* at which sulphur deficiencies have been recorded in coconuts by Southern 1967

* Site locations: 1, Lae; 2, approx. 30 km east of Lae; 3, approx 30 km west-north-west of Lae in the Markham Valley; 4 & 5, Kopopo area, south-east of Rabaul; 6, Bainings District west of Rabaul, 7-80 km north-west of Port Moresby, presumably the Aroa River Area; and 8 & 9, 160 km south-east of Port Moresby in the Cape Rodney area.

deficiencies also occur in cocoa grown in the same area. They have also been reported in Irian Jaya by Schroo (1959) as occurring in young trees growing on highly leached, acid, infertile soils (Oxisols and Ultisols?) in the Mappi District in the south, and on alluvial silt loams found on alluvial fans derived from the Cyclops Mountains in the north. As yet, no copper deficiency symptoms have been observed in cocoa in Papua New Guinea, although Southern and Kay Dick suggest that copper responses could arise in cocoa cultivated on volcanic ash soils (Andepts). Boron deficiencies, on the other hand, are not expected to pose any problems in cocoa grown in Papua New Guinea.

Foliar analyses of trace element nutrition in *Arabica coffee* indicate that no serious manganese and copper deficiencies are likely to be encountered (Southern and Hart 1969). Throughout the highlands slight iron deficiency symptoms have been found in isolated trees where they may often be ascribed to periods of stress. Deficiencies of zinc are, however, much more widespread, particularly in the Eastern Highlands Province. Southern (1969a, 1969b) and Southern and Kay Dick (1969) nevertheless suggest that serious deficiencies could result where heavy fertiliser applications are made without additional trace elements. Boron deficiencies are common, but appear to be confined to a number of well defined areas including the Banz area in the Western Highlands, and the Kainantu area in the Eastern Highlands Province. Bourke (1980) also describes the widespread occurrence of boron deficiencies throughout the highlands with particular reference to the Southern Highlands Province, where they affect not only coffee, but also root crops and vegetables. Experiments have shown that this deficiency is easy to remedy by applying coffee pulp or boron fertiliser (Bourke 1980).

Robusta coffee, not being a major cash crop, has not been researched so intensively. Manganese deficiencies are common on the neutral or alkaline alluvial soils found in the Markham Valley and along the coast of the Central Province, in the New Britain volcanic ash soils, and on the coral limestone derived soils found along the coast of the Huon Peninsula in the Morobe Province. Zinc deficiencies often found in conjunction with manganese deficiencies are very common in the Cape Rodney area, Central Province. Iron, copper, and boron deficiencies have not been positively identified, as yet, in robusta coffee. Symptoms, previously attributed to iron, have since been identified as manganese deficiencies.

Trace element requirements for *rubber* are likely to be low, and to date only manganese has been identified as being commonly deficient in major rubber producing areas. Along the coast in the Central Province, suspected manganese deficiencies have been observed in young rubber trees growing on weakly acid to slightly alkaline alluvial soils with a high base saturation (Tropofluvents and Fluvaquents?), but according to Southern and Kay Dick (1969), are likely to be confined to these soils. Iron, copper and boron deficiencies are not expected to occur in rubber, while zinc deficiencies have been noted only in two rubber nurseries located at Cape Rodney and are not considered to be a problem in established plantings.

In *tea*, zinc and manganese deficiencies have been reported by Southern (1969c). Southern and Kay Dick (1969) suggest that zinc deficiencies may cause some problems in the future, and that copper, boron and iron require a further investigation.

On the Gazelle Peninsula, East New Britain Province it has been noted that cattle, in general perform poorly. Although originally this was attributed to overstocking, a more likely alternative explanation is trace element deficiencies, such as cobalt or zinc.

15 Soil Microrelief

This interesting soil feature has received little attention in the soil literature of New Guinea, it being reported in any detail in only two locations. Microrelief patterns in the Sepik River Area, East Sepik Province, have been described comprehensively by Haantjens (1965b, 1969b) and Lee (1967) although the authors disagree as to its causes. Other occurrences found in the coastal plain of the Western Province and the Merauke area of Irian Jaya, the latter having been reported briefly by Schroo (1964), are also described in this chapter and some mention is also made of other more common types, e.g. soil disturbance by the fauna. The effects of animals on the soil have, according to Hole (1981) received too little attention from pedologists.

Microrelief related to swelling and shrinking of the soil is often referred to as 'gilgai', a term derived from an Australian Aboriginal word meaning 'a small waterhole'. This microrelief type has been extensively researched in Australia (Hallsworth 1968; Paton 1974; Knight 1980) and other tropical areas (Dudal 1965) where it is mostly attributed to the expansion of clays occurring in soils formed in relatively dry climates with a high seasonality. Although typical gilgai has not been found in similar environments in Papua New Guinea, microrelief resembling Hallsworth's (1968) 'melon hole' gilgai was noted by the author during a reconnaissance survey of the coastal plain in the Western Province, Papua New Guinea, in 1967.

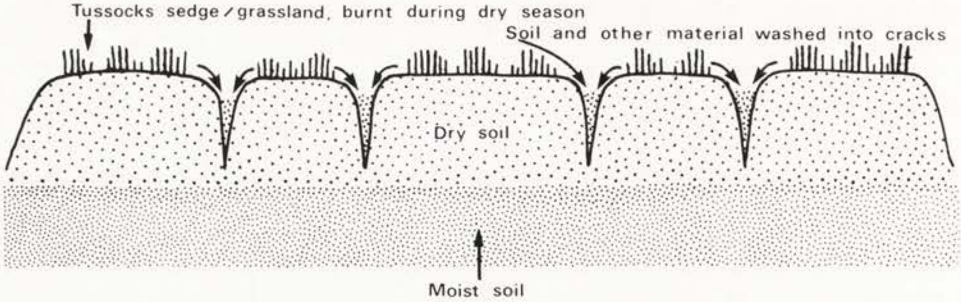
SOIL MICRORELIEF IN THE COASTAL PLAIN OF THE WESTERN PROVINCE, PAPUA NEW GUINEA, AND THE MERAUKE AREA OF IRIAN JAYA

Both these areas have a dominantly savanna type vegetation. They also have relatively low rainfall, pronounced dry seasons, are subject to flooding in the wet, and to drought conditions in the dry seasons. Morehead, the closest climate station to the microrelief in the Western Province, receives an annual rainfall of approximately 1900 mm (McAlpine *et al.* 1975). Further south in the drier coastal plain the rainfall is estimated to be between 1600-1700 mm, while the mean annual rainfall at Merauke is approximately 1500 mm (Brookfield and Hart 1966). Although the soils in both areas consist dominantly of Plinthaquults and Tropaquents/Fluvaquents, the microrelief near Merauke has only been observed on the first, and that occurring in the Western Province on the second great soil group. Schroo (1964) describes these soils as commonly consisting of fine sandy loam to loamy sand topsoils abruptly overlying red and grey mottled clay to heavy clay subsoils. He refers to the microrelief there as being 'a sort of gilgai' and attributes its formation to the high exchange acidity of the soil which causes a rapid decomposition of the organic absorption complex resulting in the release of aluminium which is partly leached into the B horizon. This process is accentuated in the bare, shallower depressions between grass clumps where accumulated rainwater continues to percolate through the soil for long periods thereby causing clay removal to be accelerated and the soil to subside gradually. On the other hand, the grass mounds are less leached, with their root systems also helping to keep the soil in its original volumetric state. In these circumstances, this continuing process results, in time, in the gradual formation of a microrelief consisting of pits and mounds. Unfortunately Schroo's (1964) description of the microrelief does not include more detailed information on the size, shape, depth and height of the hollows and ridges, and on its relationship to the terrain. He also does not explain the initial formation of the bare patches between the tussock grassland (burning?) or the possibility of rainfall splash erosion and the removal of fine soil particles between the grass clumps by overland flow.

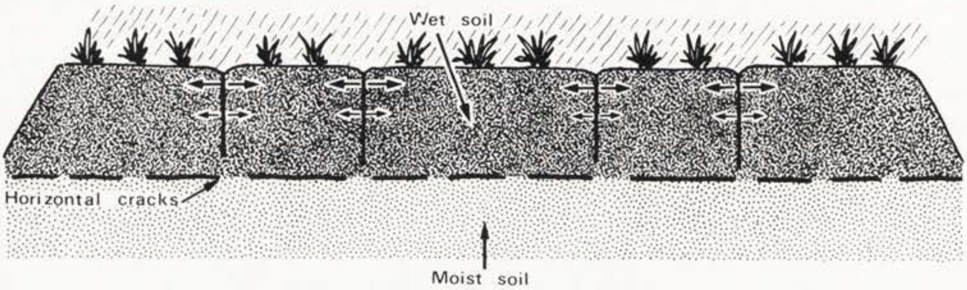
Though unrecorded as yet, this form of microrelief can be expected to occur in the Western Province where extensive areas of Plinthaquults are found in conjunction with vegetative and climatic conditions similar to those found in the Merauke area. It is incorrect, however, to refer to this microrelief as being 'a sort of gilgai', since typical gilgai is formed by the forcing upwards of large blocks of soil, rich in swelling clays (Hallsworth 1968).

Such a process, though, could possibly account for the very pronounced microrelief found in tussocky grassland in the almost flat (slopes less than 1°) coastal plain of the Western Province and noted by the author during a brief visit as being 'irregular islands' approximately 80-120 cm in width, which have been dissected by gullies 20-30 cm wide and 20-40 cm deep. Although resembling the 'melon hole gilgai' occurring in the higher rainfall areas of tropical and subtropical Australia in many respects (Hallsworth 1981), here again it is incorrect to type it as such, since it has clearly defined interconnecting gullies, absent in 'melon hole' gilgai. The soil consists of a grey to dark grey silty clay which gradually merges into a grey to light grey, slightly finer textured, clay subsoil with common to many yellowish-brown mottles. It has a wet, plastic, slightly sticky to sticky consistency in the A horizon. When dry this soil is very hard at the surface. The field pH is 5.5 in the A_1 horizon increasing gradually to 7.0-7.5 in the subsoil. It is a typical coastal plain soil derived from marine sediments and classified as a Tropaquent with vertic properties which are apparent from the pronounced cracking of the soil during the dry season.

Although this soil was not sampled and analysed for its clay mineralogy it appears to be much the same as the Tropaquents that are to be found on the coastal plain near Merauke, Irian Jaya, and which have been described by

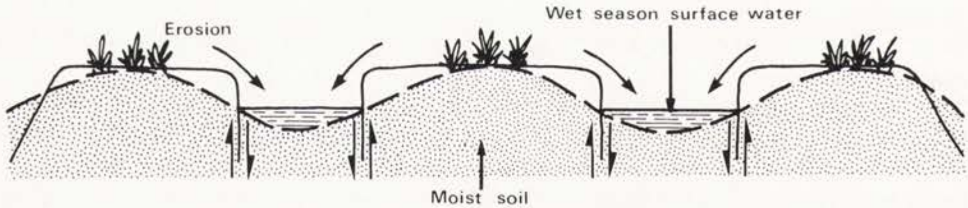


I *Dry season:* soils containing large amounts of swelling clays dry out resulting in the development of cracks. While the dry season continues soil and other material fall into these cracks. The upper soil layer dries out, while the layer below remains moist.



II *Wet season:* swelling of soil material fallen into cracks. Surface layer becomes wet and saturated as the rain continues, while the subsurface layer remains moist. This results in the formation of more or less horizontal cracks.

Expansion of the surface material fallen in the cracks and the formation of horizontal cracks at the boundary between the now wet, saturated topsoil and most subsurface layer results in the uplift of soil blocks.



III *Final shape of microrelief:* Erosion of material from the hummocks into the depressions and its subsequent removal will, over a period of time, result in the formation of a gently undulating microrelief in which the subsurface horizon is exposed on the upper soil block.

Fig. 15.1 The formation of soil microrelief on Tropaquents (with vertic properties) in the coastal plain of the Western province (based on Hallsworth 1968)

Schroo (1964) and van Es and van Schuylenborgh (1967). According to Schroo (1964) the clay mineral composition of these soils is 30 per cent montmorillonite, 50 per cent swelling illite, 15 per cent kaolinite and 5 per cent quartzite, a composition which remains uniform throughout practically all of the young marine coastal plain. Assuming that the Western Province Tropaquents also have a similar content of swelling clay minerals, a possible formation process of the microrelief is outlined in Figure 15.1. However, much more detailed research will need to be carried out to provide a definite explanation on the formation of this microrelief. The possible occurrence of rain splash erosion and overland flow will have to be investigated, because high intensity rains are likely to fall during the onset of the wet season, after burning of the grassland during the dry season.

THE SOIL MICRORELIEF OCCURRING ON THE UNDULATING PLAINS NORTH OF THE SEPIK RIVER, EAST SEPIK PROVINCE

This microrelief is common in the rolling to undulating plains which consist of moderately to strongly weathered Pleistocene sediments. The area has a mean annual rainfall of 1600-2000 mm with a generally well defined dry season (McAlpine *et al.* 1975). As described in detail by Haantjens (1965b, 1969b) and Lee (1967) it consists of two distinctly different types of microrelief. *Pitted soils* occur on gentle slopes and are characterised by sharply defined holes or unconnected trenches (Plate 15.1). *Sorted stripes*, which never occur in association with the pitted soils, are found locally on moderate slopes (generally above 5°) and consist of a network of gravel and stone strips separated from each other by moulded soil ridges from 15 cm high (Plate 15.2).

The various patterns of microrelief of the pitted soils are shown in Figure 15.2a. According to Haantjens (1965b) the depth of the depressions usually increases with the width while, as can be seen in the figure, varying greatly in shape and size. The vegetation in the depressions is very sparse, being limited to a few sedges, ferns and occasional grass tussocks. The rises, however, carry a generally dense cover of trees, shrubs and herbs or grasses (mainly *Themeda australis* and *Ischaemum barbatum*) depending on the location of the site. Haantjens' (1965b) study has shown that the pitted microrelief is commonest in the Plinthaquults, Plinthudults and Plinthaqualfs, but occurs as well on Tropaqualfs and Tropaquepts (previously described as meadow podzolic and meadow soils, gleyed forest soils and black alluvial clays). Except for the last, all other soils show a pronounced increase in clay content with depth.

The sorted stripe patterns (Figure 15.2b) are covered with short grassland (mainly *Themeda australis*), which is sparsest on the gravel strips. The gravel is locally sorted, the narrowest strips generally having the coarsest gravel or stones. The moulded soil ridges rise normally 15-30 cm above the gravel strips and contain large wormcasts, whereas there is no soil material at all on the gravel strips. According to Haantjens (1965b) the stripe patterns are aligned at a 20-30° angle with the maximum slope. This has been refuted by Löffler (1977) who found that the preferential orientation is downslope at maximum

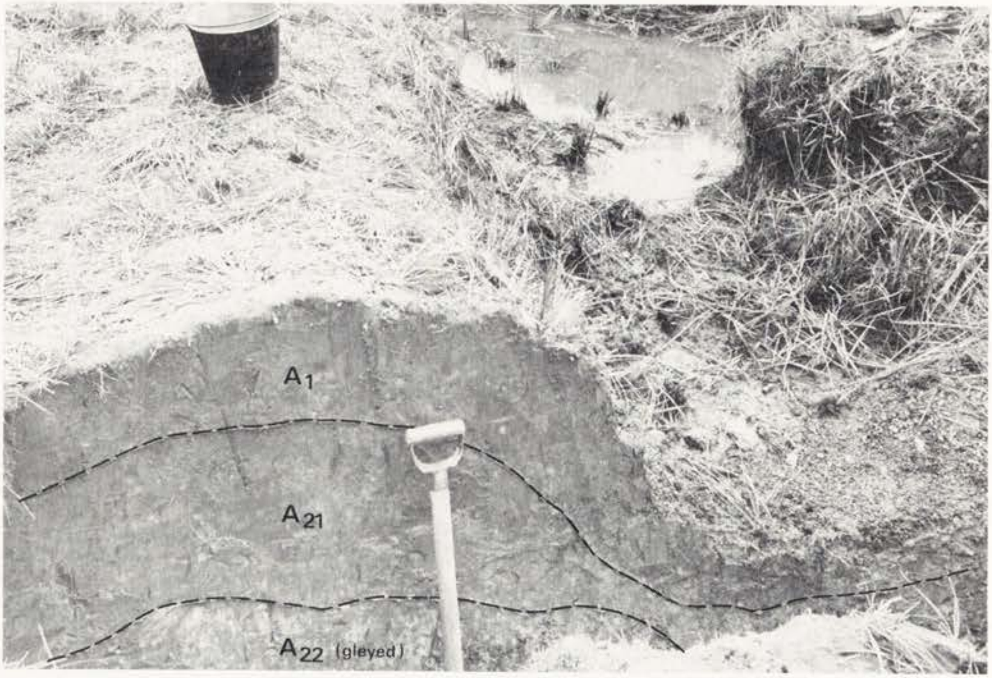


Plate 15.1 Soil microrelief of pitted soil in the Sepik plain. Note the concave-convex slope and the water standing in the depression, which is caused by the very slowly permeable subsoil.

Plate 15.2 Stone stripes revealed by a recent burn on a 7° slope of rolling to undulating plains north of the Lower Sepik River. The densely packed quartz gravel layers (up to 1 m wide) alternate with moulded soil ridges (1-3 m wide and about 15-30 cm high).

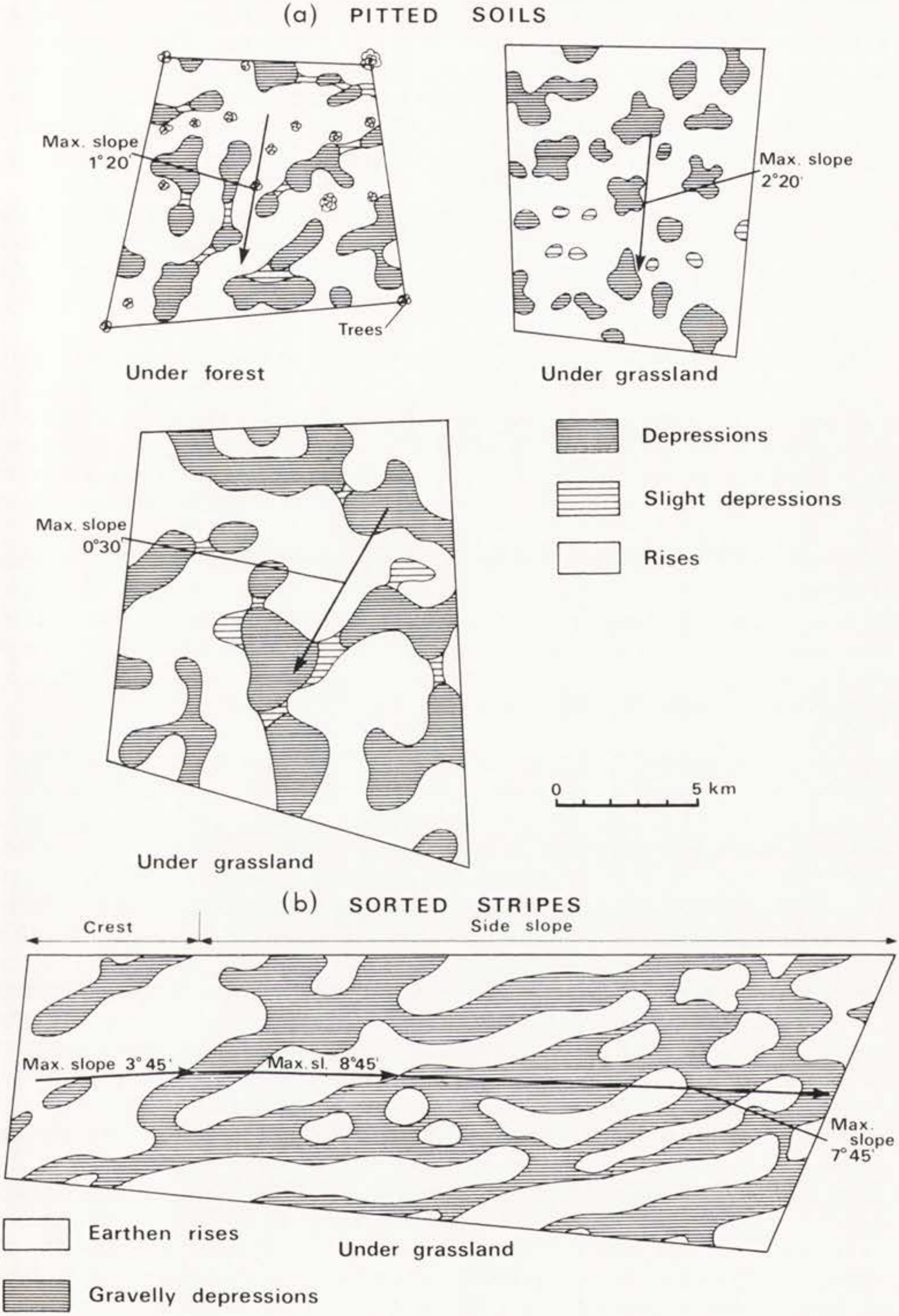


Fig. 15.2 Various microrelief patterns (modified after Haantjens 1965b)

slope angle and considers that surface or rill wash must also have played an important role in the differentiation of the stone stripes. This argument is strengthened by the absence of the stone stripes on flat to gently sloping ridge crests. This microrelief pattern has only been observed in Plinthaquults and Plinthudults that have a lot of gravel close to the surface. They are generally slightly better drained and have a less pronounced texture contrast than do similar soils having a pitted microrelief.

Haantjens' detailed investigation based on analytical data indicates that the microrelief of the *pitted soils* is caused by the transportation of soil from depressions onto rises by large earthworms. This improves the habitat of the earthworms, the rises providing a greater depth of well aerated soil during wet periods.

Haantjens (1965b) discards soil deformation due to volume changes (gilgai), and water and wind erosion as factors leading to the formation of the pitted microrelief. His reasons for this are: absence of swelling clays (deformation); occurrence of the microrelief on gentle slopes and absence of interconnected depressions (water erosion); and the wet climate, dense vegetation, coherent nature of the soil material and undirectional pattern of the depressions (wind erosion).

The *sorted stripes* on the other hand, he considers to be the result of several processes, including weathering and erosion which lead to the initial concentration of gravel in surface horizons and the formation of shallow rills. Subsequent processes including mechanical disturbances, some swelling and shrinkings of the soil material, along with earthworm activity are seen as furthering the accumulation of gravel.

Later research by Lee (1967) has rejected the hypotheses that the pitted microrelief is mainly caused by earthworm activity based on considerations related to differences in shape between the pitted soils and sorted stripes, concentration of burrows, lack of soil disturbance and the apparent absence of any degree of social behaviour of earthworms assumed by Haantjens (1965b). Lee (1967) suggests that the microrelief is primarily the result of differential burning of grass followed by wind and water erosion and that, once the microrelief is established, the better drained rises naturally provide the most suitable habitat for the soil fauna. He applies the same reasoning to the rises of the sorted stripes with the grasses which are concentrated on the mounds and ridges, here once again providing the principal source of food for the earthworms. These, Lee argues, have ecologically adapted from previous forest to the present man induced grassland conditions (Reiner and Robbins 1961).

While Lee does not question the association of earthworms with the microrelief, it seems hard to understand why they should not be actively involved in its formation. Although correct in assessing the climate of the area to be much more seasonal (Arnold 1968; McAlpine *et al.* 1975) than did Haantjens (1965b), his argument that the microrelief is due to deflation still appears unconvincing. Haantjens (1969b) reiterates that, because of the absence of strong winds, lack of any directional pattern in the pitted microrelief, and its occurrence also in forested areas, this process is most unlikely.

The author considers that destruction of the vegetation by recurring, though infrequent, severe grass fires together with surface or rill wash, particularly on steeper sloping land bearing the stone stripes, may also have influenced the formation of the microrelief. However, Lee's (1967) observations related to the concentration of burrows and lack of disturbance in the ridge material of pitted soils require a more detailed investigation.

MICRORELIEF CAUSED BY TERMITE ACTIVITY

In savanna areas termite mounds (Plates 9.1 and 15.3) are prominent features of the landscape. In Papua New Guinea these mounds are numerous and widespread on the flat to very slightly undulating plains south of the Fly River and on the fluvial plains in the vicinity of Port Moresby. The climate in both these areas is characterised by a low rainfall and a pronounced dry season. Present also, but less striking and less common, are the small domed or conical mounds to be found in forested areas throughout lowlands (Plate 15.4).

As yet, none of these features have been studied in detail in Papua New Guinea. However, extensive work has been carried out in Australia (Lee and

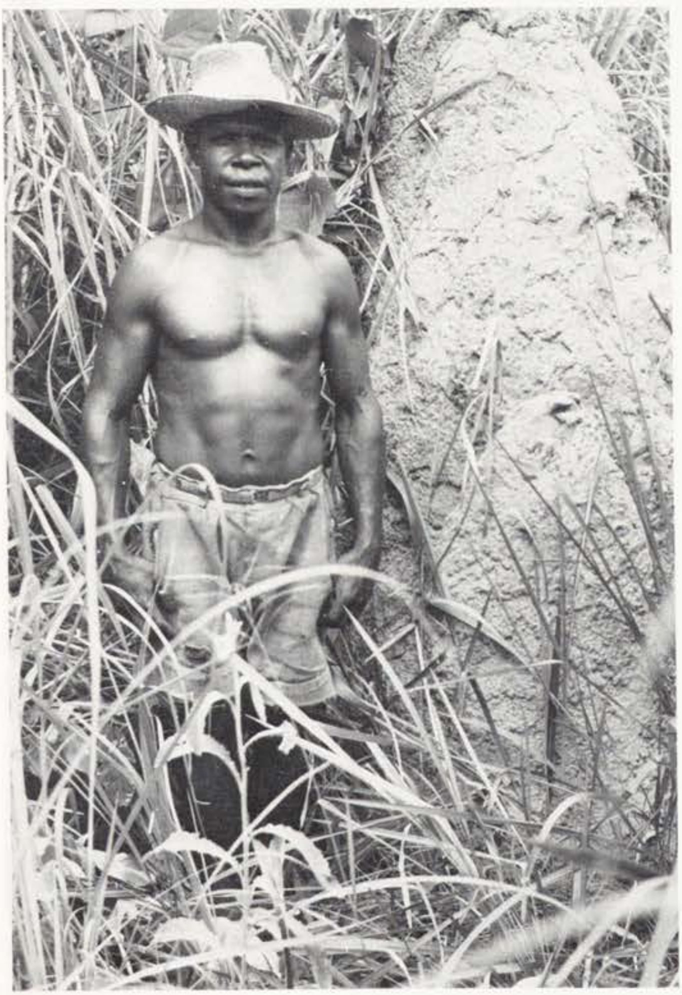


Plate 15.3 Termite mound occurring in the periodically flooded alluvial plains of the Port Moresby area. The vegetation consists of tall *Saccharum-Imperata* grassland and the soil of alkaline silty clay (Tropaquent).

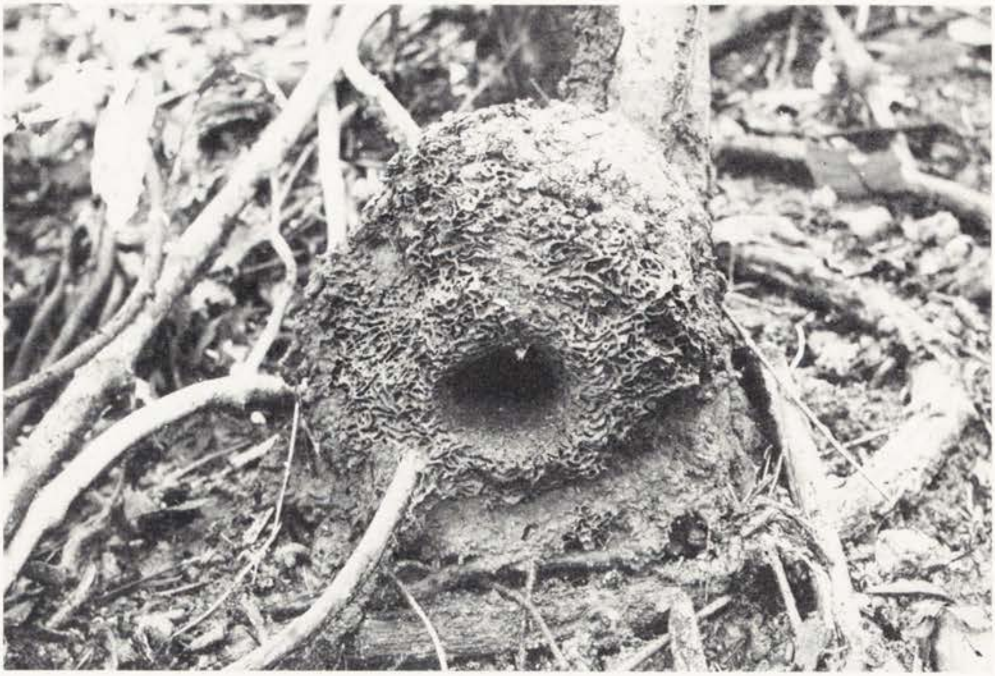


Plate 15.4 Abandoned mound, approximately 40 cm high, belonging originally to the termite *Microcerotermes biroi*. This mound occurs at approximately 130 m altitude near Putei, Gulf Province in hilly terrain covered by primary forest. The mound is now being used by the bird *Micropsitta pisio*.

Wood 1971; Williams 1968) and Africa (Harris 1971; Nye 1954, 1955; Sys 1955; Hesse 1955).

In view of the significance of termites in pedogenesis some of this work is briefly reviewed here, particularly that which relates to Northern Australia where conditions closely resemble those found in the Western Province of Papua New Guinea.

Large fluted or columnar mounds, up to 4 m in height, and most probably built by *Nasutitermes troidiae* (Froggatt) occur mostly in seasonally flooded areas of the West Province (Plate 9.1) covered with monsoon scrub and low mixed savanna. The soils are Plinthaquults with loamy sand to sandy loam topsoil overlying a prominently red and grey mottled clay subsoil.

Similar termites have been described near Brocks Creek in the Northern Territory by Williams (1968). Here on granite soils, *N. troidiae* mounds, with the mean volume of 3 m^3, occur at a density of about one per hectare, with two in every three mounds being defunct. Allowing a ten-year time lapse for a dead mound to disintegrate, Williams calculated that 0.2 m^3 of soil would be laid down per hectare each year, adding 2 cm to the topsoil every 1000 years.

Particle size analyses from mounds, in comparison to the surrounding soil, shows that *N. troidiae* selects clay and silt in preference to sand particles (Lee and Wood 1971). Thus it appears that in these areas the removal of clay and silt from the subsoil to the surface mounds, from where they are eventually eroded onto the surface, plays an important role in 'homogenising' the soil profile. However, there is little evidence of this occurring in the Western Province where the mounds are mostly to be found in soils which have a pronounced texture differentiation. A possible explanation for this is that clay illuviation keeps in balance with the amount of fine material being brought to the surface by termite activity. This could also possibly account for the relatively high silt contents often observed in the surface horizons and furthermore would support Schroo's (1964) impression that the primary textural differences are characteristic for transported soils. In addition to this physical disturbance and 'overturning' of the soil profile, termite activity has been reported as causing an increase in the fertility of the mounds in comparison to the surrounding soil (Hesse 1955; Sys 1955). According to Lee and Wood (1971) the practice of growing crops on land where termite mounds have been levelled is widespread in Africa and Asia, but this has not yet been observed in Papua New Guinea. Much of this increase in fertility appears attributable to higher organic matter contents of the mounds in comparison to the surrounding soil. This is not surprising since termites use organic materials to cement soil particles.

OTHER FORMS OF MICRORELIEF

Soil disturbance caused by the rooting of wild or domesticated pigs (Plate 15.5) is common throughout Papua New Guinea. The resulting microrelief is particularly prevalent in the densely populated highlands where pig numbers

Plate 15.5 Microrelief caused by uprooting of the soil by wild pigs near Safia in Northern Province

are markedly higher than in the lowlands. It has been estimated that there are sixty pigs for every hundred people in Papua New Guinea (McArthur 1972). Although pig droppings may add to the fertility of the soil and their grubbing help to break up soil there is also an increased risk of soil erosion. In the densely populated highland areas, marked soil losses appear to have occurred locally caused by rooting pigs in temporarily abandoned gardens, which consequently had to be left fallow for periods of 15-20 years (G. Humphreys personal communication 1981).

Other, more local forms of microrelief caused by animals are the large mounds, made of leaves and twigs, built in forested areas by bush turkeys belonging to the genus *Megapodius* and the burrows dug and used as nesting areas used by bush hens (*Amauroronis olioceus*) in warm ground surrounding thermal areas, as can be found in the vicinity of Cape Hoskins, East New Britain Province.

Terrain undulations described as 'channel' and 'corrugation' microrelief have been briefly reported by Knight (1973) in the Markham Valley. Channel microrelief, found on the gravel and sandy gravel surfaces of fans, consists of elongated mounds and depressions with smooth boundaries and is considered to be a remnant feature of the braided channels that deposited the fan sediments. Corrugation microrelief occurs only very locally and is characterised by elongated mounds and depressions which have sharp, step-like boundaries. According to Knight (1973) this microrelief may be the result of differential contraction or expansion of the soils rich in swelling clays (gilgai).

16 Traditional Food Crop Agriculture in Relation to Soil Properties

As in many other tropical areas of the world, the traditional system of agriculture in Papua New Guinea is based on shifting cultivation or bush fallow rotation, with 63 per cent of the working population being mainly engaged in subsistence production (Macewan 1978). The terms shifting cultivation and bush fallow rotation are used synonymously here. Strictly speaking, however, shifting cultivation implies the continual movement to new garden areas, whereas under bush fallow rotation, which is a common practice in the Papua New Guinea highlands, the gardens are rotated within a limited area.

The practice of shifting cultivation has been studied by many researchers, notably Barrau (1958), FAO (1974), Gourou (1956), Kellogg (1963), Newton (1960), Nye and Greenland (1960); and in New Guinea by Reijnders (1961), Brookfield and Brown (1963), Clarke and Street (1967), Manner (1969, 1976) and Wood (1979).

Preparation of a garden for shifting cultivation (Plate 5.13) involves clearing light brush and undergrowth, and cutting larger trees to about 1 m above ground level. In most cases, the chopped material and stems and branches of forest trees are then gathered in heaps and burned. The ash is spread over the new garden. The land is usually cropped for two to three years and then allowed to revert to bush. After a period of years the cultivator may return to the area and crop it again. Shifting cultivation is thus based on a practice in which the land is rotated rather than the crops as in most western farming systems. The fallow period varies from 3 to 15 years and is largely determined by the availability and quality of cultivable land. Jenny *et al.* (1949) have shown that it takes about ten years to restore the organic matter and nitrogen levels after cropping in Colombian and Costa Rican soils. Data given by Sanchez (1976) similarly indicate that the nutrient accumulation reaches a plateau after about eight years in an udic tropical forest on a Ultisol in Zaire, the author assuming that growth rates may be even faster in soils with a higher base status.

Where possible shifting cultivators are thought to prefer forested areas, mainly because of expected higher yields but also because of labour and time saved in contrast to that involved in working grassland areas. Most research workers confirm the expectation of higher yields in forested areas (e.g. Nye and Greenland 1960; Kellogg 1963), their results showing that organic carbon, total nitrogen, total exchangeable bases and pH values are all higher in forest soils than in grassland soils. These lower values in grassland soils have been attributed to the lower humus content of soils because of the reduced rates of grass and root production due to repeated burnings. Very similar results have been obtained in Papua New Guinea by Clarke and Street (1967), Manner (1969, 1976) and Wood (1979), although their studies have been almost entirely confined to highland areas.

The most important sources of food in Papua New Guinea are given in Figure 16.1. As shown in this figure cultivation is largely based on the tuberous root crops of sweet potato, taro and yams. Sweet potato is the main staple of the densely populated highlands, but is assuming importance also in coastal regions as a replacement for the more traditional crops, particularly taro. Sago is a major source of food in the poorly drained and swampy lowland alluvial

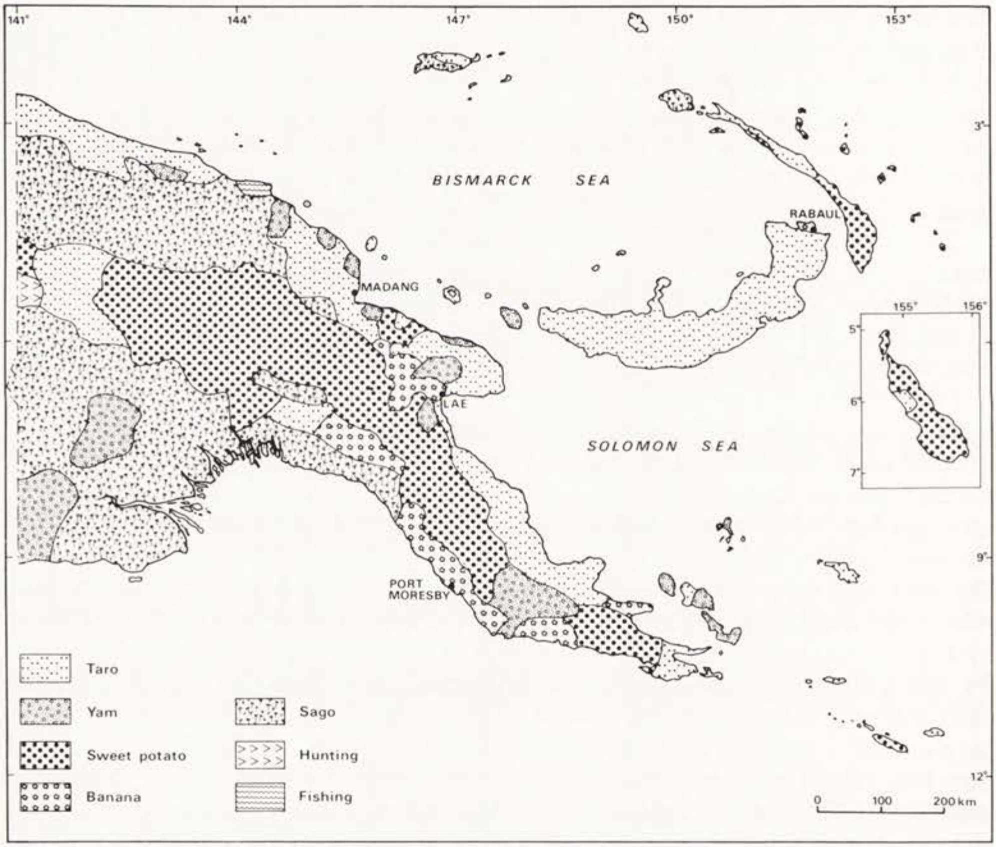


Fig. 16.1 Principal sources of food in Papua New Guinea (after Lea 1970)

plains, while bananas are especially important in the drier areas with seasonal climates such as the coastal zone of the Central Province and the Markham Valley. Rice, the staple food in neighbouring Indonesia, is not cultivated as a subsistence crop in Papua New Guinea. Although a matter of speculation, this may be largely attributable to the dominantly wet and humid climate lacking the pronounced dry season necessary for harvesting.

CHANGES IN SOIL PROPERTIES RESULTING FROM AGRICULTURAL PRACTICES

Although in similar environments grassland soils often have darker A_1 horizon colours than those under forest,* their organic matter content is generally lower. These dark colours are not only due to the higher humic acid content of grassland soils, (the humic acids being largely responsible for the black and brown colours (Corbett 1969)), but also to the presence of very slowly decomposing charcoal particles, following frequent burning. On the other hand, the significantly higher air and soil temperatures in grasslands and cleared areas considerably increase the rate of organic matter decomposition. Temperature differences between grassland and forest sites in the Bulolo area are given in Table 16.1, while soil and air temperature measurements recorded for bare and mulched sites at Port Moresby are shown in Table 16.2. Significant temperature differences between forest/grassland and bare/mulched sites are apparent. The very high 'bare soil' temperatures given in the figure for 2 and 4 cm depths must also seriously influence germination, emergence and seedling growth of crops.

Differences in mean organic carbon and nitrogen contents of Hydrandepts and Humitropepts under primary forest, gardens and grassland conditions are given in Figure 16.2. As expected the forest sites with the lowest temperatures show the highest mean organic carbon and nitrogen contents. Although the data are limited, and also no detailed information on the ages of the vegetation types are available,† it is interesting to note the different trends for sites under grassland and gardens for each great group. In the Hydrandepts, found mainly in the wetter parts of the highlands west of Mount Hagen, composting in large mounds (Plate 5.4) is extensively practised and results in the higher organic carbon and nitrogen contents attained from the garden soil. In the Humitropepts, however, which occur most commonly in the slightly drier areas to the east, composting is virtually absent, and mounds are small (Plate 12.5). Therefore significantly lower organic carbon and nitrogen contents for garden sites in comparison to those under forest result, while Humitropepts under grassland again show a build up of organic matter levels.

Similar trends are evident in the mean cation exchange capacity values for both these great groups under different vegetation types (Figure 16.3).

* For instance, in the highlands Hydrandepts under forest have A_1 horizons dominated by very dark grey and very dark greyish brown (10 YR 3/1-3/2) colours, while for those under grassland black and very dark brown (10 YR 2/1-2/2) colours predominate.

† Reijnders (1961) has shown in Irian Jaya that significant changes occured in exchangeable cation levels of topsoils within short time spans during the cultivation cycle.

Table 16.1
Temperature data (°C) recorded* during fine and wet days in forest/grassland transects near Manki Village (Bulolo area) at 1600 m altitude (modified after Gillison 1970)

	Transect	Fine day Max.	Fine day Min.	Wet day Max.	Wet day Min.
Grassland	1	29.4	11.7	20.6	15.6
	2	31.7	14.4	22.2	11.1
	3	25.0	13.9	21.1	15.6
Forest	1	18.9	12.8	13.3	12.2
	2	16.7	12.2	13.3	11.1
	3	15.6	11.1	14.4	11.7

* Recorded in shade 10 cm above ground by thermohygrograph.

Table 16.2
Soil temperatures (°C) under a bare soil and mulched soil on a clear day at Port Moresby (after Latu *et al.* 1975)

Depth (cm)	Time 7.20 a.m.		10.30 a.m.		1.20 p.m.		5.10 p.m.	
	Bare	Mulched	Bare	Mulched	Bare	Mulched	Bare	Mulched
2	24	27	42	35	49	38	36	34
4	25	27	40	33	47	35	38	34
6	24	27	35	31	42	34	38	34
8	26	27	32	31	37	33	37	34
10	27	28	31	30	37	32	38	33
Air temperature	18		28.5		29		26	

However, the pH values, although within a narrow range (5.1-5.5), show an opposite trend with soils under forest being slightly more acid. This is related to the higher organic matter contents and the higher proportion of fulvic acids to be found in the forest sites (Corbett 1969). These fulvic acids, being mobile, assist the movement of mineral constituents through the soil and thereby acidify the upper part of the profile.

The chemical properties of lowland (0-600 m) Hapludolls under various vegetation formations are shown in Figure 16.4. Apart from having much lower nutrient levels, these soils follow similar trends to the Humitropepts.

Limited chemical fertility data collected by Wood (1979) from topsoils of Andepts in the Karimui and Bomai Plateau areas under different vegetation types are given in Table 16.3. Fertility levels are high, except for available phosphorus which at the relatively low soil pH is likely to be adsorbed by allophane, but there also appears to be a marked decline of available

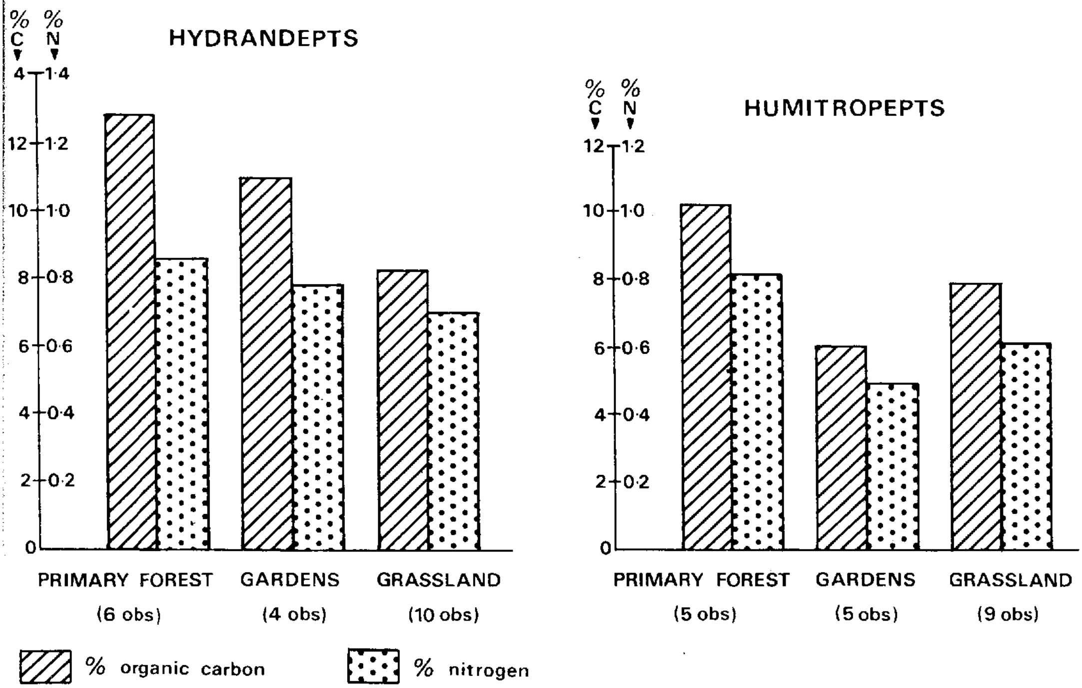


Fig. 16.2 Mean organic carbon and nitrogen content of A_1 horizons (0-40 cm) of Hydrandepts and Humitropepts under various vegetation formations (altitudinal range 1700-2400 m)

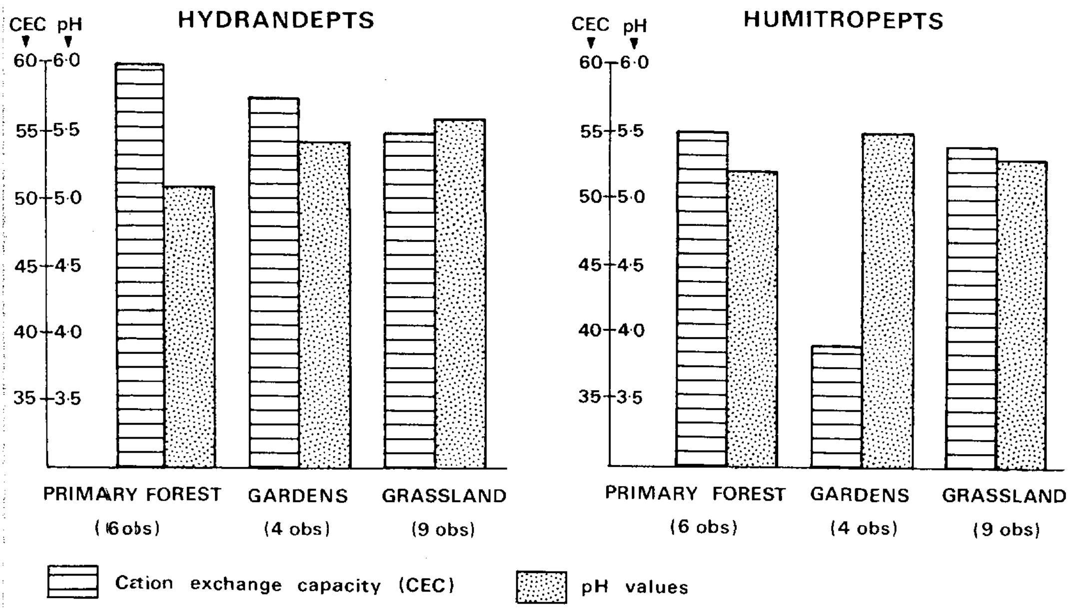


Fig. 16.3 Mean cation exchange capacities and pH values of A_1 horizons (0-40 cm) of Hydrandepts and Humitropepts under various vegetation formations (altitudinal range 1700-2400 m)

Table 16.3
Chemical analyses for topsoils from the Karimui and Bomai Plateaux areas under different types of vegetation (after Wood 1979)

Vegetation types	Number of soil samples	pH	Available P (Olsen) ppm	Exchangeable cations me% Ca	Mg	K	Na	Cation exchange capacty me%	Base saturation %	% C	% N
Rainforest	3	5.8 (5.4-6.4)	11.7 (8.8-15.6)	35.2 (29.1-43.3)	7.3 (6.2-9.6)	0.9 (0.5-1.4)	0.5 (0.4-0.6)	41.1 (34.3-53.5)	97 (91-100)	10.8 (9.9-11.7)	1.0 (0.9-1.1)
Cultivated gardens	6	5.8 (5.2-6.1)	7.2 (4.3-9.8)	20.7 (12.0-28.6)	3.9 (1.6-6.8)	1.2 (0.5-2.4)	0.5 (0.2-0.9)	29.4 (25.4-32.5)	81 (53-90)	8.5 (5.8-10.1)	0.9 (0.6-1.0)
Fallow gardens	1	5.4	2.8	15.0	2.4	0.8	0.3	19.2	96	6.8	0.7

Mean values are shown and the range is given in brackets.

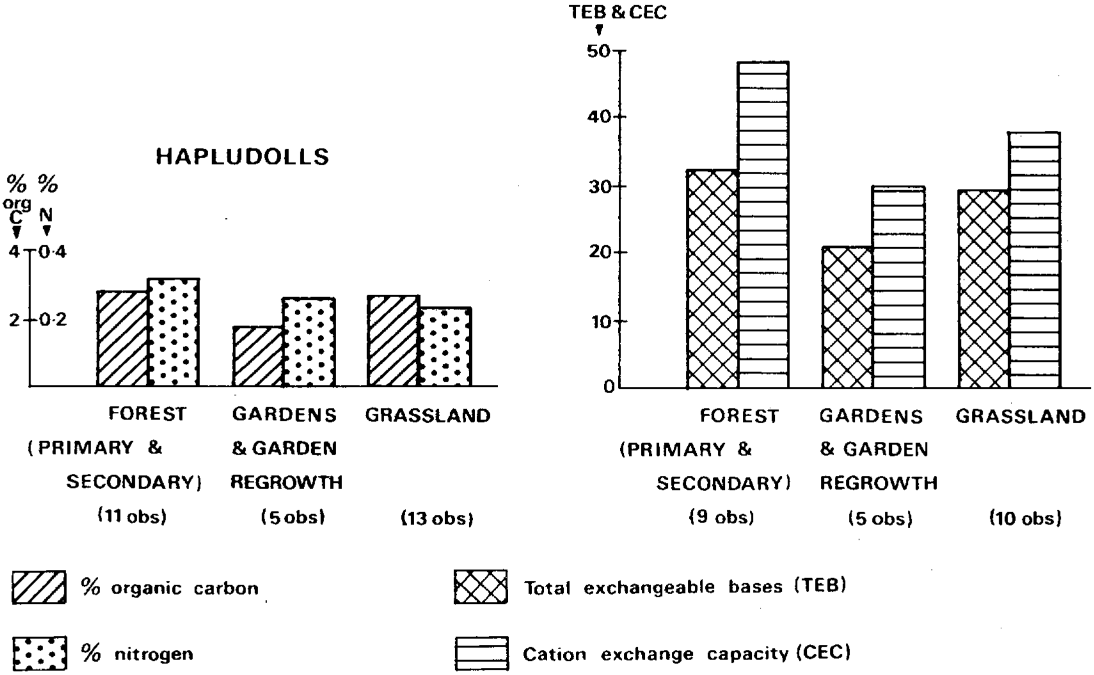


Fig. 16.4 Chemical properties of A_1 horizons (0-40 cm) of Hapludolls under various vegetation formations

phosphorus resulting from a lowering of the organic matter content through cultivation. Less pronounced reductions were noted by Wood in exchangeable calcium and magnesium, cation exchange capacity and percentage nitrogen levels. Much of the same conditions have been observed in the densely populated Gazelle Peninsula, New Britain, where Graham and Baseden (1956) calculated the organic matter represented over 65 per cent of the exchange complex of soils. They have stressed the need for its preservation in the interest of long term fertility but there are indications that a shortage of land for subsistence cropping has since caused serious soil degradation problems (Bleeker and Freyne 1981).

CROP YIELD DECLINES UNDER TRADITIONAL AGRICULTURAL SYSTEMS

In many tropical countries declines in yields have been recorded when a number of consecutive crops are grown (e.g. Sanchez 1976). In Papua New Guinea Clarke and Street (1967) studied a community of Maring people living between 600-1400 m, on the northern slopes of the Bismarck Mountains. They established an experiment to measure the decline in fertility of soils by comparing sweet potato yields of four sites previously under forest, grassland and in old or producing gardens. For each site the cultivation history was known. At each site one-third of the plots had NPK fertiliser applied, one-third received applications of ash collected from local houses, while the remaining control plots were left untreated.

In the trial, which lasted six months, all plots treated responded to fertiliser applications, the greatest percentage increases in yields being recorded at sites which prior to the experiment consisted of the producing and nearly abandoned garden. Clarke and Street (1967) take this to indicate a decline in nutrient availability during the growing period. However, an anomaly is apparent in that the yields of all plots established in the producing garden were unexpectedly and significantly lower than those found in the abandoned garden regardless of whether they were control plots, or plots which received ash or fertiliser application. This marked imbalance in the percentage yields of plots must be attributed to other factors and, according to the authors, could be due to competition of weeds and pest infestation, or a change in soil structure. Unfortunately only very limited site and soil descriptions are provided, and also the chemical analyses data of the soils are very generalised. These factors make it difficult to rule out soil variability as a cause.

That soils do change over short distances and that even within one soil series the soil can be very heterogeneous, has been demonstrated not only in Papua New Guinea (Bleeker and Speight 1978), but also in many other parts of the world (Ahn 1974). Results of chemical analyses may also show a marked variance, and it is preferable that when such detailed research is carried out, a great number of composite samples should be analysed.

Manner (1969, 1976) has carried out two investigations on the effects of shifting cultivation and fire on both vegetation and soils. His study areas were located near Kompiai (Jimi Valley) in the Western Highlands Province on the southern slopes of the Bismarck Mountains. Manner (1969) found that shifting cultivation and burning affect some of the chemical and physical properties of the soils, increasing the base saturation, total bases (TEB) and pH on the one hand, and decreasing organic matter and nitrogen on the other. However, when as a result of repeated burnings, secondary forest is converted to perpetual grassland, there is a decrease in exchangeable bases, organic carbon, total nitrogen and pH. Manner (1969) points out, however, that his results are substantiated by limited soil analyses and are based on the assumption that samples are representative of the study area. He further assumes that the soils have been formed under similar parent material, climate and topography. Of more importance perhaps is his conclusion that the protection of grassland from fire can result in succession by woody vegetation and an attendant increase in soil fertility. This fact, as stressed by Manner (1976), provides strong evidence that tropical grasslands may be of anthropogenic origin. During his later investigations Manner (1976) also carried out extensive regeneration studies, using floristic properties of forests and grasslands and biomass measurements. In reference to the soils, classified as typic or hydric Dystrandepts, the available phosphorus content for all surface samples tested within the 2-12 ppm range, appears to be an important factor in limiting the length of cropping to two years, but there are indications that this may also be affected by increased competition from weeds and other regrowth. His soil analytical data, while confirming his 1969 results, also include additional information on bulk density, CEC and C/N ratios, the first showing an increase, and the others decreased values when forest is converted to garden. Manner (1976) further concludes that soils found under *Themeda* grassland are the most degraded, both physically and chemically.

Although not directly related to shifting cultivation, some mention should be made here of the results of a 20-years rotation trial conducted on volcanic ash soils (Andepts) at the Lowland Experimental Station, Kerevat in the East New Britain Province (Bourke 1980). A comparison between continuous cropping of sweet potato, taro and peanuts or cowpeas (narrow rotations) and a half year period of food crops rotated with one and a half year green manure crops (wide rotations) showed that neither cropping pattern maintained yields for all crops at or near the original levels. Yields of sweet potato and peanuts, in particular, fluctuated widely and were attributed by Bourke (1980) to the high incidence of pests and disease, and to variations in the cultivars used. These problems should be much less severe under the shifting cultivation system.

The chemical fertility levels of all plots also showed a marked decline, probably mainly due to organic matter, which over the 16-year sampling period decreased from approximately 10 to almost 5 per cent.

The experiment also showed only very small differences in nitrogen content between the narrow and wide rotations, thereby indicating that the leguminous green manure crops used (*Mimosa* and *Pueraria*) did little to prevent the long term soil nitrogen decline. In this regard preliminary experiments with *Casuarina* in the highlands (Thiagalingam and Fahmy 1981) have shown that the soil nitrogen content increases with age of the trees and was higher than that under *Albizia* or *Crotalaria*.

ADVANTAGES AND DISADVANTAGES OF SHIFTING CULTIVATION

The advantages and disadvantages of shifting cultivation have been subject to numerous discussions. It is generally agreed that the most important advantages are:

(1) That it is basically a form of crop rotation in which regrowth and fallowing provide beneficial contributions by increasing the biological activity and by building up of the organic matter content. This results in an improved soil structure and increased chemical fertility. Particularly in highland areas abandoned gardens also provide supplementary food for foraging pigs (although this is likely to increase soil erosion risks) and where fallow periods are long enough may also provide firewood and building materials.

(2) That it prevents soil erosion. In Papua New Guinea many gardens are to be found on steep slopes (Plate 12.1), commonly because of land shortage, but sometimes also because they provide adequate drainage (Plate 12.4). Serious erosion hazards may result unless preventive measurements are taken (Plate 12.3, Chapter 14). Fallowing after short cropping periods and minimum tillage practice considerably reduce the erosion risks. For instance, experiments in Nigeria (unpublished data from Lal, quoted by Greenland 1975) have shown that on a 8-9° slope planted with maize under

a 780 mm annual rainfall, soil losses were reduced from 23.6 tons/ha when ploughed, to 0.14 tons/ha under zero tillage. The rapid rejuvenation of tree stumps and bushes in a garden may provide, in addition, some vegetative cover, decreasing the soil erosion risk and other soil degradation processes, such as leaching of nutrients or breaking up of the soil structure.

(3) That it is an effective method of pest control. This is probably the most advantageous aspect of shifting cultivation.

According to Charles (1976), the main reason in Papua New Guinea for the decline in yields when the same soil is cropped continuously was pest infestation. He correctly points out that humid tropical countries lack temperatures cold enough to eradicate insects, impede weed growth or eliminate crop disease organisms. Therefore without fallowing and minimum tillage and herbicides, the subsistence farmer has little hope of maintaining his yields. The threat of pest and disease infestation may also be one of the reasons why the Papua New Guinea farmer prefers to grow a variety of crops in a garden rather than take the risk of monocropping.

One of the main disadvantages in practising shifting cultivation is that it requires very large areas of land per head of population. Macewan (1978) estimated than in Papua New Guinea an average garden area of 1000 m^2 per person will normally be used by people who rely mainly on gardens, a little husbandry and some cash resource for their livelihood, while people for whom sago is the staple diet need an area of 1000-2500 m^2 per person. Obviously, there are very pronounced differences from one location to another which are related to factors such as soils, climate, topography, altitude and alternative food sources and for this reason it is extremely difficult to calculate accurately the land area needed per head of population (carrying capacity).

The rapid increases in population, common in many developing countries, cause land shortages and consequently a reduction in the fallow period, in turn increasing the risk of soil erosion. The tendency of people to live in larger communities closer to roads and the introduction of cash crops has in some instances further reduced the land available for shifting cultivation. Cash crops, too, are often planted on the better land closest to roads and villages, necessitating the carrying of garden produce over longer distances. In this regard shifting cultivation is an uneconomic system in terms of productivity and output.

Gourou (1956) argues that shifting cultivation is not the result of any inescapable physical constraint, nothing requiring it to be *the* agricultural technique practised in the tropical world. While admitting that there are many tropical areas with very poor soils, he points out examples of poor farming techniques which preclude the optimum use of the 'richest' soils. However, as stated by Gourou (1956), it is much easier to talk about means of improvement than to carry them out, which would involve major changes in agricultural practices. Throughout the world the subsistence cultivator, including the Papua New Guinea farmer, is often criticised for his reluctance to adopt new crops and adapt to new techniques. Harris (1978) in his work in the highlands has, however, demonstrated a readiness on the part of farmers to adapt new techniques and new crops to changing conditions, especially in those areas subjected to population pressures.

According to Greenland (1975) agricultural advancement should be oriented towards the use of better seeds, zero or minimum tillage, mixed cropping and the use of fertilisers. Charles (1976), although considering shifting cultivation an efficient method of subsistence agriculture in Papua New Guinea, advocates the development of more permanent farming systems. He lists various alternatives including the substitution of fallow periods by grazing, the use of human dung or compost for manure, crop rotation to reduce pest and diseases, fertilisers and other chemicals as well as the use of legumes as rotation crops or green manures, to improve soil nitrogen levels.

There is little doubt that Papua New Guinea is better endowed with soils suited for agriculture than many African countries and that more permanent farming systems could be developed. The author suggests, however, that the efficacy of any new techniques applied should first be thoroughly tested. Returns from fertiliser applications may not be economic. Moreover fertilisers are unavailable to many farmers. The use of grass or legume fallows as an alternative to commercial fertilisers has given variable results (e.g. Vine 1954; Bourke 1980). Vine (1954) carrying out field trials in Nigeria using grass-legume fallows found that 'fairly good' yields could be obtained over many years without the application of fertilisers. Similar results can be expected, at least in some areas, in Papua New Guinea. This is borne out by the mulching techniques extensively used in the Western Highland areas on soils which have been cultivated almost continuously for 50 years (Wood in press; B. Allen personal communication 1980). On the other hand, as previously mentioned, research by Bourke (1980) on Andepts in the lowlands of Papua New Guinea has indicated that the use of legumes as rotation crops or green manures fails to maintain production levels.

Although, except for taro blight, pests and diseases are not considered a serious problem in most areas (Macewan 1978) the introduction of high-yielding pest and disease resistant crops is advocated, particularly if more permanent systems of agriculture are to be developed in Papua New Guinea.

Appendix I

Profile Descriptions and Analytical Data

The following profiles are included in this section:

FLUVAQUENT

FAO soil unit: dystric Gleysol (Gd)

Previous soil group: alluvial soils - coarse textured, with fine-textured subsoils

Survey area: Buna - Kokoda, P 6

Airphoto/grid reference: RAAF '51, Mt Lamington, CAJ85, R2-5061; B.X13.Y6

Altitude: 30 m

Land form: almost level surface with a few steeply sloping small creeks, 3 m deep

Parent material: alluvium, volcanic derived

Climate: lowland humid; 3000 - 3500 mm p.a.; high seasonality

Vegetation/land use: tall regrowth (low secondary forest) regularly used for gardening

Drainage status: poorly drained

Remarks: water-table at 140 cm (dry season)

Horizon	Depth (cm)	Description
A11	0 - 8	Moist very dark brown (10YR 2/2) sandy loam to sandy clay loam; firm; moderate fine granular structure; clear even boundary
A12	8 - 33	Moist dark greyish brown (10YR 4/2) fine sandy loam with common small yellowish brown mottles; firm; structureless. Clear even boundary
C1	33 - 65	Wet dark grey (10YR 4/1) fine sand to loamy sand with many small distinct yellowish brown and brown mottles; friable to very friable; structureless. Abrupt boundary
C2	65 - 95	Wet light brownish grey (2,5Y 6/2) friable silty clay loam with common small distinct grey and dark brown mottles; lower part of this horizon contains many large and small pockets of grey loamy sand. Abrupt boundary
C3	95 - 100	Wet dark grey (10YR 4/1) sand; non plastic, non sticky; structureless

	Horizon (depth in cm)					
	A11	A12	C1	C2	C2	C3
	0 - 8	8 - 30	35 - 65	65 - 75	75 - 90	95-100
pH (1:5) H_2O	6.3	5.9	6.7	6.9	6.9	7.0
pH (1:5) KCl						
Total soluble salts (%)	0.033	0.022	0.013	0.019	0.017	0.010
Chloride (%)	0.008	0.009	0.006	0.010	0.008	0.003
$CaCO_3$ (%)						
Extractable bases						
Ca (m - equiv. %)	16.0	5.5		8.1		
Mg	6.7	3.6		9.8		
K	0.40	0.24		0.31		
Na	0.06	0.19		0.23		
TEB	23.16	9.53		18.44		
Exchange acidity (H)	10.8	10.6		4.2		
Cation exchange capacity	34.0*	20.1*		22.6*		
Base saturation (BS)	68	47		82		
% organic carbon	4.46	1.68				
% nitrogen	0.33	0.16				
C/N ratio	14	11				
Available P (Truog) (ppm)						
Total P (25% HCl) (ppm)						
Gravel %						
Granulometric composition						
2000 - 200 μ	3	1	1	1	1	16
200 - 50 μ 50 - 20 μ	62	65	84	30	44	76
20 - 2 μ	19	19	12	52	42	5
Less than 2 μ	16	15	3	17	13	3

* Sum of cations.

TROPOFLUVENT

FAO soil unit: dystric Fluvisol (Jd)

Previous soil group: alluvial soils (coarse textured)

Survey area: Buna - Kokoda, P 23

Airphoto/grid reference: LAL98, '42, Kokoda - Sirorata, 4V; C.X28.Y9

Altitude: 320 m

Land form: flat to very gently undulating floodplain with a few rounded gullies, 3 m deep

Parent material: alluvium

Climate: lowland humid; 3000 - 3500 mm p.a.; moderate seasonality

Vegetation/land use: recently cleared for gardening and rubber plantation

Drainage status: imperfectly drained

Horizon	Depth (cm)	Description
A11	0 - 6	Wet very dark brown (10YR 2/2) loam; non-plastic, non-sticky; moderate very fine crumb structure; rare bleached sand grains. Abrupt uneven boundary
A12	6 - 20	Moist very dark grey (10YR 3/1) loam; friable; moderate very fine crumb to subangular blocky structure. Gradual uneven boundary
C1	20 - 42	Moist olive-brown (2.5Y 3/4) friable silt loam; low content of small subangular gravel. Clear uneven boundary
C2	42 - 62	Wet light olive-brown (2.5Y 5/4) sandy loam; slightly plastic, slightly sticky; structureless; moderate content of subangular gravel. Gradual even boundary
C3	62 - 84	Wet greyish brown (2.5Y 5/2) sandy loam; slightly plastic, slightly sticky; structureless; high content of subangular gravel. Clear even boundary
C4	84 - 120+	Wet dark grey (5Y 4/1) gravelly loamy sand; non-plastic, non-sticky

	Horizon (depth in cm)					
	A11	A12	C1	C2	C3	C4
	0 - 5	10 - 20	20 - 40	45 - 60	65 - 80	90-105
pH (1:5) H_2O	6.4	6.0	5.8	5.8	5.9	6.0
pH (1:5) KCl						
Total soluble salts (%)	0.047	0.026	0.016	0.013	0.009	0.011
Chloride (%)	0.009	0.006	0.005	0.005	0.004	0.002
$CaCO_3$ (%)						
Extractable bases						
Ca (m - equiv. %)	19.2	5.0	0.35	0.21		
Mg	5.0	1.1	0.40	0.33		
K	1.8	1.0	0.53	0.36		
Na	0.11	0.08	0.09	0.05		
TEB	26.11	7.18	1.37	0.95		
Exchange acidity (H)	40.8	43.7	24.6	8.9		
Cation exchange capacity	66.9*	50.9*	25.9*	9.8*		
Base saturation (BS)	39	14	5	10		
% organic carbon	11.3	7.95				
% nitrogen	0.86	0.64				
C/N ratio	13	12				
Available P (Truog) (ppm)						
Total P (25% HCl) (ppm)						
Gravel %	7	2	7	17		33
Granulometric composition						
2000 - 200 µ	33	31	13	27		29
200 - 50 µ 50 - 20 µ	34	46	58	44		50
20 - 2 µ	16	14	23	23		19
Less than 2 µ	17	9	6	6		2

* Determined by summation of extractable bases and exchange acidity.

TROPOHEMIST

FAO soil unit: eutric Histosol (Oe)

Previous soil group: organic soils

Survey area: Lower Ramu - Atitau, P 40

Airphoto/grid reference: Adastra '57, Nubia, CAJ79, R2-5096; B.X15.Y20

Altitude: 3 m

Land form: flat swamp

Parent material: peat over alluvium

Climate: lowland humid; 2000 - 2500 mm p.a.; moderate seasonality

Vegetation/land use: sago clusters and Phragmites

Drainage status: swampy

Remarks: water-table at surface. Flooded at least 1.5 m in wet season

Horizon	Depth (cm)	Description
Oe1	0 - 30	Wet very dark greyish brown and very dark brown rather loosely packed and not completely decomposed loamy peat, in which mineral patches occur somewhat separated from peaty patches. Gradual boundary
Oe2	30 - 100	Wet very dark brown; dry black to dark grey (10YR 2/1 - 4/1) well decomposed loamy peat. Becomes gradually denser and more decomposed with depth. Contains many small to large firm and dense peaty pieces, which are dark brown inside. Non-plastic and very sticky (dry hard). Clear boundary
Oi1	100 - 107	Wet black dense well decomposed peat. Abrupt boundary
C1	107 - 120+	Wet grey and mottled very plastic and very sticky clay

	Horizon (depth in cm)
	Oe2
	35 - 90
pH (1:5) H_2O	5,5
pH (1:5) KCl	5,1
Total soluble salts (%)	
Chloride (%)	
$CaCO_3$ (%)	
Extractable bases	
Ca (m - equiv. %)	18,70
Mg	7,17
K	0,19
Na	1,08
TEB	27,14
Exchange acidity (H)	
Cation exchange capacity	80,04
Base saturation (BS)	34
% organic carbon	14,0
% nitrogen	0,90
C/N ratio	16
Available P (Truog) (ppm)	0
Total P (25% HCl) (ppm)	
Gravel %	
Granulometric composition	
2000 - 200 μ	3
200 - 50 μ	16
50 - 20 μ	61
20 - 2 μ	13
Less than 2 μ	7

HYDRANDEPT

FAO soil unit: humic Andosol (Th)

Previous soil group: humic brown clay soils

Survey area: Goroka - Mount Hagen, P 3

Airphoto/grid reference: Adastra '55, Mt Hagen, CAJ22, R2-5110; D.X17.Y12

Altitude: 1740 m

Land form: near gently undulating sloping edge on somewhat undulating broad low plateau

Parent material: volcanic ash overlying weathered, coarse-textured tuff

Climate: lower montane humid; 2500 - 3000 mm p.a.; moderate seasonality

Vegetation/land use: garden

Drainage status: well drained

Horizon	Depth (cm)	Description
A11	0 - 25	Moist very dark brown to black (10YR 2/1) very friable organic loam with a moderate very fine crumb and a strong fine to medium subangular blocky structure (compound structure). Clear even boundary
A12	25 - 52	Moist black (10YR 2/1) friable organic loam to clay loam with a moderate fine blocky structure. Clear irregular boundary
B21	52 - 85	Moist dark brown to dark reddish brown (7.5YR 3/4 to 5YR 3/3) firm clay with a weak coarse blocky structure. Gradual undulating boundary
B22	85 - 110	Moist strong brown (7.5YR 5/6) friable clay; structureless but finely porous. Gradual even boundary
B3	110 - 175	Moist yellowish brown (10YR 5/8) structureless, very friable (but brittle) clay loam with common fine to medium distinct very dark brown mottles; generally porous. Diffuse even boundary
IIC1	175 - 215	Moist yellowish brown (10YR 5/8) with black and white specks; very friable (brittle) structureless sandy clay loam. Clear but very irregular boundary
IIC2	215 - 250+	Yellowish grey, white speckled, dense weathered coarse-textured volcanic ash

	Horizon (depth in cm)				
	A11	A12	B21	B22	C1
	10 - 20	30 - 45	65 - 80	95 - 105	175 - 200
pH (1:5) H_2O	5.6	6.0	5.4	6.6	6.0
pH (1:5) KCl					
Total soluble salts (%)					
Chloride (%)					
$CaCO_3$ (%)					
Extractable bases					
Ca (m - equiv. %)			1.25	1.25	
Mg			0.57	0.30	
K			0.48	0.48	
Na			0.11	0.09	
TEB			2.41	2.12	
Exchange acidity (H)					
Cation exchange capacity			33.58	18.83	
Base saturation (BS)			7	11	
% organic carbon	13.8	14.8	4.1	1.6	
% nitrogen	0.98	0.92			
C/N ratio	14	16			
Available P (Truog) (ppm)		4	6		
Total P (25% HCl) (ppm)					
Gravel %					
Granulometric composition					
2000 - 200 μ		tr	tr	4	10
200 - 50 μ		1	1	13	12
50 - 20 μ		24	85	66	54
20 - 2 μ		74	14	15	16
Less than 2 μ		1*	tr*	2*	8*

Sand mineralogy B22 horizon†: carried out by Royal Tropical Institute, Netherlands

acid plagioclase	2%
quartz	36%
hornblende	43%
rock fragments	5%
ore	12%
organic SiO_2	2%

* Low value due to dispersion difficulties.

† Mineral reserve considered rich.

DYSTRANDEPT

FAO soil unit: ochric Andosol (To)

Previous soil group: Ochrandept

Survey area: Safia - Pongani, P 8

Airphoto/grid reference: Adastra '61, Kombari, CAJ150, R1-5043; C.X5.Y18

Altitude: 1525 m

Land form: rather wide (5 m) part of crest of steep ridge, 20^{o} slope

Parent material: andesitic volcanic ash

Climate: premontane humid; 2000 - 2500 mm p.a.; moderate seasonality

Vegetation/land use: lower montane rainforest

Drainage status: well drained

Horizon	Depth (cm)	Description
A0	5 - 0	Dark reddish brown (5YR 2/2) open structured root mat with organic matter; pH 3.5, Abrupt boundary
A1	0 - 23	Wet black (10YR 2/1) and with depth very dark greyish brown (10YR 3/2) very friable, slightly sticky, structureless clay loam; field pH 5, Clear boundary
A2	23 - 38	Wet dark greyish brown (10YR 4/2), black speckled wet very friable to slightly plastic and slightly sticky (rather smeary) sandy clay loam; field pH 5.5 - 6. Clear boundary
B21	38 - 45	Wet very dark greyish brown and very dark brown (10YR 3/2, 2/2) very friable, but smeary sandy clay loam. Clear boundary
B22	45 - 100	Wet dark brown to brown (10YR 4/3), black speckled, friable silt loam; field pH 6. Diffuse boundary
C1	100 - 150+	Wet dark yellowish brown to yellowish brown (10YR 4.5/4.5) strongly black and whitish speckled very friable loam; field pH 6

	Horizon (depth in cm)			
	A0	A1	B22	C1
	12 - 0	0 - 20	45 - 90	125 - 150
pH (1:5) H_2O	3,8	4,2	5,4	5,4
pH (1:5) KCl				
Total soluble salts (%)				
Chloride (%)				
$CaCO_3$ (%)				
Extractable bases				
Ca (m - equiv. %)	1,17	0,30	tr	tr
Mg	1,63	0,26	0.04	tr
K	0.70	0.08	0,04	0,02
Na	0,11	0.01	0.01	0.01
TEB	3.61	0.65	0,09	0,03
Exchange acidity (H)				
Cation exchange capacity	100,97	55.00	37,01	29,30
Base saturation (BS)	4	1	tr	tr
% organic carbon	19,6	8,7	2,4	1,6
% nitrogen	2,04	0,74	0,28	0,16
C/N ratio	10	12	8	10
Available P (Truog) (ppm)				
Total P (25% HCl) (ppm)	1540	720	100	170
Gravel %				
Granulometric composition				
2000 - 200 μ		17	20	26
200 - 50 μ		20	16	13
50 - 20 μ		36	37	39
20 - 2 μ		5	17	9
Less than 2 μ		22	10	13

Clay mineral analyses by Soil Bureau, D.S.I.R., New Zealand

A11 horizon — Allophane - much (EM analysis*); vermiculite - much (XR); allophane gel - common (IRA, EM); kaolinite/halloysite - little? (XR, DTA); gibbsite - little (DTA); mineral organic compounds - little? (DTA)

B22 horizon — Allophane gel - much (EM, IRA); vermiculite - much (XR); allophane - common (EM); kaolinite/halloysite - little? (XR, DTA); gibbsite - little (DTA); mineral organic compounds - little? (DTA)

C1 horizon — Allophane gel - much (IRA, EM); vermiculite - much (XR); illite - little (XR)

* XR = X-ray; DTA = differential thermal analyses; EM = electron microscope; IRA = infra-red absorption.

USTROPEPT

FAO soil unit: calcic Cambisol (Bc)

Previous soil group: brown clay soils

Survey area: Port Moresby - Kairuku, 189

Airphoto/grid reference: Adastra '56, Port Moresby, CAJ50, R2-5021

Altitude: approx. 50 m

Land form: upper slope, 2 - 10^{o}

Parent material: sedimentary rocks

Climate: lowland dry subhumid; 1000 - 1500 mm p.a.; high seasonality

Vegetation/land use: Eucalyptus confertiflora

Drainage status: well drained

Horizon	Depth (cm)	Description
A1	0 - 8	Very dark brown (10YR 2/2) very hard silty clay loam with a crumb structure and some grit
B21	8 - 45	Brown to dark brown (7,5YR 4/4) silty clay; plastic and sticky when wet; some grit
B22	45 - 75	As above, but loamy and contains $CaCO_3$ concretions
B23	75 - 120+	Dark yellowish brown (10YR 4/4) friable sandy clay loam; calcareous; wet plastic and sticky

	Horizon (depth in cm)		
	A1	B21	B22
	0 - 8	8 - 45	45 - 75
pH (1:5) H_2O	6.7	6.5	7.8
pH (1:5) KCl			
Total soluble salts (%)			
Chloride (%)			
$CaCO_3$ (%)	n.d.	n.d.	n.d.
Extractable bases			
Ca (m - equiv. %)	35.68	46.45	35.93
Mg	12.34	13.41	9.82
K	0.57	0.22	0.11
Na	0.32	0.93	1.00
TEB	48.91	61.01	46.86
Exchange acidity (H)			
Cation exchange capacity	53.71	59.77	51.08
Base saturation (BS)	91	>100	92
% organic carbon	1.0	0.3	0.1
% nitrogen	0.08	0.02	0.01
C/N ratio	13	15	10
Available P (Truog) (ppm)			
Total P (25% HCl) (ppm)	260	3010	3260
Gravel %			
Granulometric composition			
2000 - 200 μ	7	4	26
200 - 50 μ 50 - 20 μ	8	9	17
20 - 2 μ	47	42	35
Less than 2 μ	38	45	22

EUTROPEPT

FAO soil unit: eutric Cambisol (Be)

Previous soil group: brown forest soils

Survey area: Wewak - Lower Sepik, P 10

Airphoto/grid reference: Adastra '58, Wewak, CAJ94, R3-5044; A.X16.Y13

Altitude: 255 m

Land form: hillslope, 6^{o}, near steep descent to coast

Parent material: siltstone

Climate: lowland humid; 2000 - 2500 mm p.a.; low seasonality

Vegetation/land use: forest, at site replaced by low regrowth

Drainage status: well drained

Horizon	Depth (cm)	Description
A1	0 - 25	Moderately dry very dark greyish brown (2.5Y 3/2) extremely firm silty clay with a weakly developed fine blocky structure. Gradual boundary
B2	25 - 72	Moist yellowish brown (10YR 5/4) firm silty clay loam with a weak very fine blocky structure. Gradual boundary
C	72 - 90+	Light greyish brown fragmented angular siltstone, mixed with some brown clay

	Horizon (depth in cm)	
	A1	B2
	0 - 20	30 - 50
pH (1:5) H_2O	6,4	7.2
pH (1:5) KCl	5.0	5.2
Total soluble salts (%)		
Chloride (%)		
$CaCO_3$ (%)		
Extractable bases		
Ca (m - equiv. %)	21,23	24.50
Mg	7,08	6.07
K	0,39	0.28
Na	0,54	0.69
TEB	29.24	31.54
Exchange acidity (H)		
Cation exchange capacity	61.07	53,97
Base saturation (BS)	47	58
% organic carbon	2,9	0.5
% nitrogen	0.33	0.08
C/N ratio	9	6
Available P (Truog) (ppm)	10	60
Total P (25% HCl) (ppm)	1840	440
Gravel %		
Granulometric composition		
2000 - 200 μ	1	1
200 - 50 μ	3	1
50 - 20 μ	12	23
20 - 2 μ	34	47
Less than 2 μ	50	28

Clay minerals analysed by Royal Tropical Institute, Netherlands (differential thermal analyses)

B2 horizon montmorillonite plus illite - much, gibbsite - common, goethite - common

EUTROPEPT

FAO soil unit: eutric Cambisol (Be)

Previous soil group: no name

Survey area: Safia Soil Project II, 152

Airphoto/grid reference: Adastra '57, Moni River, CAJ82, R2-5043; A.X3.Y4

Altitude: 200 m

Land form: almost flat 20 m wide bench on stepped crest of long hill ridge with maximum crestal slope of 20°, local slope 4 - 6°

Parent material: basic igneous rock

Climate: lowland subhumid; 1500 - 2000 mm p.a.; high seasonality

Vegetation/land use: rainforest

Drainage status: well drained

Horizon	Depth (cm)	Description
A1	0 - 2	Moist (very) dark reddish brown (5YR 3,5/4 - 3/4) very friable clay loam; moderately fine to very fine blocky and some medium to fine crumb; very few small hard weathered rock fragments; abundant fine to very coarse roots; thin, but full, leaf litter cover. Abrupt even boundary
B1	2 - 22	Moist (very) dark reddish brown (5YR 3,5/4) very friable clay loam to clay; weak fine to medium blocky breaking up readily into medium crumb; common hard, weathered angular rock fragments; many fine to very coarse roots. Clear boundary
B2	22 - 45	Moist dark red (2.5YR 3/6) very friable silty clay loam; very weak medium to coarse subangular blocky, breaking into medium crumb; very few hard to slightly hard red strongly weathered rock fragments, 10-20 mm; many fine to coarse roots. Clear boundary
C11	45 - 75	Moist red (10R 4/6) with some black coatings, slightly hard totally weathered rock. Gradual to clear irregular boundary
C12	75 - 120+	Moist weathered rock, breaking up into small to medium angular fragments; slightly hard to hard; reddish brown (2.5YR 4/4) to red (2.5YR 4/8) and black; few fine to medium roots concentrated in cracks

	Horizon (depth in cm)				
	A1	B1	B2	C11	C12
	0 - 2	5 - 20	25 - 45	60 - 75	75 - 100
pH (1:5) H_2O	6.6	6.4	6.6	6.2	6.4
pH (1:5) KCl					
Total soluble salts (%)	0.121	0.039	0.012	0.004	0.005
Chloride (%)	0.002	0	0	0	0
$CaCO_3$ (%)					
Extractable bases					
Ca (m - equiv. %)	18.46	13.30	5.49	7.30	12.60
Mg	6.19	4.08	4.35	5.24	5.89
K	0.19	0.13	0.10	0.09	0.07
Na	0.29	0.27	0.18	0.11	0.20
TEB	25.13	17.78	10.12	12.74	18.76
Exchange acidity (H)					
Cation exchange capacity	25.5	19.5	16.3	17.5	19.8
Base saturation (BS)	99	91	62	73	95
% organic carbon	4.96	2.86	0.58	0.25	0.13
% nitrogen	0.49	0.32	0.09	0.02	0.01
C/N ratio	10	9	7	12	10
Available P (Truog) (ppm)					
Total P (25% HCl) (ppm)					
Gravel %	7	10	tr	11	34
Granulometric composition					
2000 - 200 μ	27	25	4	32	59
200 - 50 μ	19	18	10	15	17
50 - 20 μ	5	6	7	10	6
20 - 2 μ	15	15	40	25	10
Less than 2 μ	34	36	39	18	8

Clay minerals analysed by CSIRO, Division of Soils, Australia (X-ray diffraction)

B1 horizon kaolinite 50 - 60%; vermiculite 30 - 40%; goethite 10 - 20%

B2 horizon kaolinite/hydrated halloysite >80%; haematite/goethite 10 - 20%; vermiculite and chlorite 5 - 10%

C12 horizon kaolinite 40 - 50%; vermiculite and chlorite 40 - 50%; goethite/haematite 5 - 10%

Silt mineralogy analysed by CSIRO, Division of Soils, Australia

B1 kaolinite 50 - 65%; vermiculite 20 - 30%; goethite/haematite 5 - 10% and quartz 5 - 10%

B2 kaolinite >80%; haematite 10 - 20% and quartz 1%

C12 kaolinite 30 - 40%; vermiculite/chlorite 50 - 65%; goethite/haematite 5 - 10% and quartz 1 - 5%

Sand mineralogy carried out by CSIRO, Division of Land Use Research, Australia

B1 heavy fraction (5% of total); opaques 13%, magnetite/ilmenite 8%, ground mass 8% epitode 4% and amphibole 67%

light fraction (95% of total); alterites 82%, clay aggregates 4%, ground mass 1%, biotite/muscovite 1%, quartz 4% and feldspar 8%

B2 heavy fraction (1% of total); opaques 37%, magnetite/ilmenite 6%, ground mass 1%, epidote 1% and amphibole 55%

light fraction (99% of total); alterites 87%, rock fragments 10%, clay aggregates 2% and feldspar 1%

C12 heavy fraction (1% of total); opaques 79%, magnetite/ilmenite trace, epidote 10%, amphibole 9% and pyroxene 2%

light fraction (99% of total); alterites 88%, rock fragments 7%, clay aggregates 3%, quartz 2% and feldspar trace

Total analyses carried out by Australian Mineral Development Laboratory, Australia

B1 SiO_2 46.3%, Al_2O_3 16.0%, Fe_2O_3 9.9%, FeO 4.10%, MgO 0.93%, P_2O_5 0.19%, TiO_2 1.05%, K_2O 0.06%, MnO 0.70%, Cr_2O_3 0.03%, NiO 0.02%, H_2O^+ 9.35% and H_2O^- 2.55%

B2 SiO_2 44.3%, Al_2O_3 20.5%, Fe_2O_3 16.9%, FeO 0.55%, MgO 0.55%, P_2O_5 0.08%, TiO_2 1.05%, K_2O 0.02%, MnO 0.80%, Cr_2O_3 0.04%, NiO 0.02%, H_2O^+ 11.8% and H_2O^- 2.45%

C12 SiO_2 44.7%, Al_2O_3 18.1%, Fe_2O_3 14.7%, FeO 3.10%, MgO 2.75%, P_2O_5 0.08%, TiO_2 0.90%, K_2O 0.03%, MnO 0.95%, Cr_2O_3 0.06%, NiO 0.02%, H_2O^+ 10.3% and H_2O^- 2.05%

Trace elements carried out by Australian Mineral Development Laboratory, Australia

B1 vanadium 0.02%, cobalt 0.06%, copper 0.05% and zirconium 0.005%

B2 vanadium 0.04%, cobalt 0.005%, copper 0.03% and zirconium 0.005%

C12 vanadium 0.02%, cobalt 0.005%, copper 0.025% and zirconium 0.003%

PELLUSTERT

FAO soil unit: pellic Vertisol (Vp)

Previous soil group: dark cracking clay soils

Survey area: Port Moresby - Kairuku, 210

Airphoto/grid reference: Adastra '56, CAJ50, Port Moresby, R1-5031

Altitude: 30 m

Land form: plain

Parent material: alluvium

Climate: lowland dry subhumid; 500 - 1000 mm p.a.; high seasonality

Vegetation/land use: grassland

Drainage status: poorly drained

Remarks: note high exchangeable sodium in subsoil

Horizon	Depth (cm)	Description
A11	0 - 15	Moist very dark grey (N 3/0) hard fine blocky, silty clay, sticky and plastic when wet
A12	15 - 100	Moist very dark grey (N 3/0) clay, hard, massive and cracking when dry, sticky and plastic when wet. Some carbonate concretions
C	100 - 120+	Similar to horizon above, but silty clay with more carbonate concretions

	Horizon (depth in cm)		
	A11	A12	C
	0 - 15	15 - 90	90 - 120
pH (1:5) H_2O	6.8	7.2	7.2
pH (1:5) KCl			
Total soluble salts (%)			
Chloride (%)			
$CaCO_3$ (%)	n.d.	n.d,	n.d.
Extractable bases			
Ca (m - equiv. %)	23.72	30.83	36.85
Mg	13.75	16.50	20.60
K	2.52	0.46	0.52
Na	1.39	5.82	7.77
TEB	41.38	53.61	65.74
Exchange acidity (H)			
Cation exchange capacity	35.01	53.62	57.08
Base saturation (BS)	>100	100	>100
% organic carbon	1.9	0.6	0.3
% nitrogen	0.18	0.04	0.01
C/N ratio	11	15	30
Available P (Truog) (ppm)			
Total P (25% HCl) (ppm)	610	300	200
Gravel %			
Granulometric composition			
2000 - 200 μ	1	1	4
200 - 50 μ 50 - 20 μ	7	3	3
20 - 2 μ	47	25	51
Less than 2 μ	45	71	42

PELLUDERT

FAO soil unit: pellic Vertisol (Vp)

Previous soil group: no name

Survey area: Sialum, P 2

Airphoto/grid reference: Adastra '68, Kalasa, CAJ1252, Coast Key-2056; B.X7.Y25

Altitude: 360 m

Land form: uplifted coral terrace

Parent material: coral limestone

Climate: lowland subhumid; 1500 - 2000 mm p.a.; high seasonality

Vegetation/land use: mixed grassland, mainly Themeda and Imperata

Drainage status: imperfectly drained

Remarks: broad terrace surface underlain by coral limestone, dated at 220 000 years, but soil probably much younger: little or no sign of microrelief

Horizon	Depth (cm)	Description
A11	0 - 10	Moist black (N 2/0) friable clay with a moderate, medium, subangular blocky structure; many roots; common 1-2 mm quartz gravel. Gradual even boundary
A12	10 - 45	Wet black (20YR 2/1) plastic, slightly sticky, massive, structureless clay; many 0.5-1 mm quartz gravels; many slickensides. Clear even boundary
A13	45 - 58	Wet dark yellowish brown (10YR 3/4) plastic and sticky clay; massive; common limestone fragments. Clear even boundary
C	58 - 65	Wet reddish brown (5YR 4/4) to yellowish red (5YR 4/6) plastic, sticky gravelly clay; gravel consists of coral limestone; massive. Abrupt boundary to coral limestone at 65 cm

	Horizon (depth in cm)			
	A11	A12	AB	C
	0 - 10	20 - 40	45 - 55	55 - 65
pH (1:5) H_2O	5.7	6.0	7.6	8.0
pH (1:5) KCl				
Total soluble salts (%)	0.004	0.003	0.006	0.006
Chloride (%)	<0.002	<0.002	<0.002	<0.002
$CaCO_3$ (%)	—	—	—	62.4
Extractable bases				
Ca (m - equiv. %)	20.3	34.5	44.0	22.4
Mg	3.8	4.4	4.2	2.5
K	0.29	0.16	0.24	0.19
Na	0.33	0.41	0.51	0.32
TEB	24.72	39.47	48.95	25.41
Exchange acidity (H)				
Cation exchange capacity	58.5	60.0	55.5	26.5
Base saturation (BS)	42	66	88	96
% organic carbon	6.5	1.7	0.85	0.50
% nitrogen				
C/N ratio				
Available P (Truog) (ppm)				
Total P (25% HCl) (ppm)				
Gravel %	n.d.	n.d.	n.d.	n.d.
Granulometric composition				
2000 - 200 μ	0	1	1	0
200 - 50 μ 50 - 20 μ	17	9	2	0
20 - 2 μ	27	11	7	0
Less than 2 μ	56	79	90	100

RENDOLL

FAO soil unit: Rendzina (E)

Previous soil group: Rendzina

Survey area: Wewak - Lower Sepik, P 12

Airphoto/grid reference: Adastra '58, Wewak, CAJ94, R4-5062; D.X31.Y15

Altitude: 305 m

Land form: hill slope in low, but steeply sloping hilly country; slope at site 25^{o}

Parent material: coral limestone

Climate: lowland subhumid; 1500 - 2000 mm p.a.; high seasonality

Vegetation/land use: forest regrowth

Drainage status: well drained

Horizon	Depth (cm)	Description
A11	0 - 25	Moist very dark brown (10YR 2/2), dry black (10YR 2/1) very firm and slightly sticky (when moister probably very plastic) clay loam with irregular, weakly developed medium to coarse angular blocky structure, probably mainly due to cracking in roadcut exposure. Contains very few pieces of limestone. Diffuse boundary
A12	25 - 50	Moist very dark greyish brown (10YR 3/2) clay loam; very firm but falls apart into small blocky fragments that are very plastic. Abrupt boundary
C	50 - 90+	Irregular pieces of crystalline limestone of various sizes, which are light yellow outside. The space in between is filled up with moderately wet dark yellowish brown (10YR 3/4) plastic heavy clay

	Horizon (depth in cm)
	A11
	10 - 25
pH (1:5) H_2O	6,8
pH (1:5) KCl	5,3
Total soluble salts (%)	n.d.
Chloride (%)	n.d.
$CaCO_3$ (%)	n.d.
Extractable bases	
Ca (m - equiv. %)	36,81
Mg	0,70
K	0,17
Na	0,95
TEB	38,63
Exchange acidity (H)	
Cation exchange capacity	69,45
Base saturation (BS)	56
% organic carbon	2,6
% nitrogen	0,37
C/N ratio	8
Available P (Truog) (ppm)	20
Total P (25% HCl) (ppm)	1990
Gravel %	
Granulometric composition	
2000 - 200 μ	1
200 - 50 μ	3
50 - 20 μ	31
20 - 2 μ	43
Less than 2 μ	22

Clay minerals analysed by Royal Tropical Institute, Netherlands (differential thermal analyses)

A11 horizon Montmorillonite plus illite - much; gibbsite - common; goethite - common

HAPLUDOLL

FAO soil unit: haplic Phaeozem (Hh)

Previous soil group: well drained old alluvial soils

Survey area: Gogol - Upper Ramu, P 12

Airphoto/grid reference: Adastra '55, Urigina, CAJ24, R1-5010

Altitude: 170 m

Land form: slightly undulating terrain dissected by wide shallow channels and having some long low rises

Parent material: colluvio-alluvium

Climate: lowland perhumid; 4000 - 4500 mm p.a.; moderate seasonality

Vegetation/land use: rainforest with deciduous trees replaced by grassland

Drainage status: well drained

Horizon	Depth (cm)	Description
A11	0 - 18	Moist very dark brown (10YR 2/2) very friable organic loam with a medium granular and weak subangular blocky structure. Gradual even boundary
A12	18 - 35	Moist black (10YR 2/1) friable organic loam to clay loam with a medium subangular blocky structure. Clear even boundary
A13	35 - 50	Moist very dark brown (10YR 2/2) loose structureless loamy gravel: gravel ranges in size from 2-40 mm; large pieces are often yellow, weathered and easily broken by spade; most of the gravel is rounded but some is subangular. Clear even boundary
C1	50 - 65	Moist coarse sandy gravel; loose; structureless; gravel 2-40 mm in size, usually rounded and not strongly weathered. Abrupt even boundary
IIA1	65 - 98	Moist dark brown (10YR 3/3) friable structureless loam; contains in the top 10 cm small tubular wormcasts decreasing with depth. Clear even boundary
IIA3	98 - 105	Moist very dark greyish brown (10YR 3/2) very friable, structureless gravelly fine sandy clay loam: gravel is rounded, unweathered and usually 2-6 cm in diameter

	Horizon (depth in cm)			
	A11	A12	A13	IIA1
	0 - 15	20 - 35	35 - 50	65 - 95
pH (1:5) H_2O	7.0	6.8	7.5	7.5
pH (1:5) KCl				
Total soluble salts (%)	0.031	0.035	0.022	0.021
Chloride (%)	0.008	0.007		
$CaCO_3$ (%)				
Extractable bases				
Ca (m - equiv. %)		13.00		3.60
Mg		17.00		16.50
K		0.32		0.17
Na		0.03		0.09
TEB		30.35		20.36
Exchange acidity (H)				
Cation exchange capacity		33.00		21.00
Base saturation (BS)		92		97
% organic carbon	2.8	2.8		
% nitrogen	0.21	0.19		
C/N ratio	13	15		
Available P (Truog) (ppm)	23	<1		1
Total P (25% HCl) (ppm)				
Gravel %		4	43	
Granulometric composition				
2000 - 200 μ		14		2
200 - 50 μ 50 - 20 μ		25		54
20 - 2 μ		30		25
Less than 2 μ		31		19

RHODUDALF

FAO soil unit: chromic Luvisol (Lc)

Previous soil group: no name

Survey area: Sialum, P 6

Airphoto/grid reference: Adastra '68, Kalasa, CAJ1252, Coast Key-2056; A.X18.Y32

Altitude: 27 m

Land form: uplifted coral terrace

Parent material: coral limestone

Climate: lowland subhumid; 1500 - 2000 mm p.a.; high seasonality

Vegetation/land use: mixed Themeda - Imperata grassland

Drainage status: well drained

Remarks: terrace dated at 40 000 years

Horizon	Depth (cm)	Description
A1	0 - 8	Moist black (5YR 2/1) friable clay with a fine crumb structure. Clear even boundary
B21	8 - 25	Moist dark reddish brown (5YR 2/2) very friable clay with a medium subangular blocky structure. Gradual even boundary
B22	25 - 50	Moist dark reddish brown to dark red (2.5YR 3/4 - 3/6) very friable clay with a weak subangular blocky structure. Clear even boundary
?IIA1	50 - 55	Moist dark reddish brown (5YR 3/4) very friable clay with a weak subangular blocky structure. Abrupt boundary to large rock or coral limestone at 55 cm

	Horizon (depth in cm)			
	A1	B21	B22	IIA1
	0 - 5	10 - 20	30 - 40	50 - 55
pH (1:5) H_2O	6.5	6.2	6.2	7.0
pH (1:5) KCl				
Total soluble salts (%)	0.006	0.005	0.003	0.006
Chloride (%)	0.003	<0.002	<0.002	0.004
$CaCO_3$ (%)	—	—	—	—
Extractable bases				
Ca (m - equiv. %)	25.8	17.5	8.8	11.0
Mg	5.4	2.5	0.41	0.17
K	1.70	0.37	0.40	0.47
Na	0.34	0.42	0.23	0.35
TEB	33.24	20.79	9.84	11.99
Exchange acidity (H)				
Cation exchange capacity	56.5*	49.5*	36.5*	33.5*
Base saturation (BS)	59	42	27	36
% organic carbon	5.7	3.6	2.6	4.1
% nitrogen				
C/N ratio				
Available P (Truog) (ppm)				
Total P (25% HCl) (ppm)				
Gravel %				
Granulometric composition				
2000 - 200 μ	0	0	0	0
200 - 50 μ 50 - 20 μ	8	4	2	4
20 - 2 μ	22	17	18	21
Less than 2 μ	70	79	80	75

Clay minerals analysed by University of Papua New Guinea (differential thermal analyses, X-ray diffraction and electron microscope)

A1 horizon	kaolinite/halloysite†	- dominant, gibbsite trace
B21 horizon	kaolinite/halloysite†	- dominant, gibbsite - common, goethite trace
B22 horizon	kaolinite/halloysite†	- dominant, gibbsite - common, goethite trace
?IIA1 horizon	kaolinite/halloysite†	- dominant, gibbsite - common

Total analyses carried out by Australian Mineral Development Laboratory

	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	P_2O_5	CO_2	C	H_2O^+	H_2O^-
A1	34.9	20.6	12.7	0.74	1.66	0.17	0.30	0.93	0.27	0.14	0.20	6.2	9.29	7.23
B21	32.3	25.0	13.8	0.55	0.88	0.08	0.15	1.03	0.21	0.11	0.20	3.9	11.36	6.94
B22	25.6	30.1	16.5	0.40	0.48	0.05	0.15	1.29	0.18	0.13	0.15	2.8	14.49	5.65
IIA1	16.4	31.3	18.4	0.38	0.84	0.05	0.13	1.35	0.10	0.32	0.25	4.6	14.65	7.89

* These values appear high in relation to the clay mineral composition, and suggest halloysite rather than kaolinite. It should be noted, however, that the organic carbon contents are also relatively high.

† Not well crystallised.

TROPUDALF

FAO soil unit: ferric Luvisol (Lf)

Previous soil group: no name

Survey area: Safia Soil Project II, P 25

Airphoto/grid reference: Adastra '57, Ubo, CAJ83, R3-5045; A.X26.Y21

Altitude: 255 m

Land form: slightly dissected and stripped plain with local terrace formation, local slope 2^{o} near crest of broad (300 m) interfluve

Parent material: youngest Domara River beds

Climate: lowland subhumid; 1500 - 2000 mm p.a.; high seasonality

Vegetation/land use: eucalypt savanna with Themeda, Imperata and Ophiuros grass

Drainage status: well to imperfectly drained

Horizon	Depth (cm)	Description
A11	0 - 12	Moist very dark greyish brown (10YR 3/2) very friable loam; locally moderately, locally strongly fine to medium crumb, compound with much less subangular blocky; abundant fine roots. Clear even boundary
A12	12 - 22	Moist to wet dark brown (7,5YR 3/2), with depth dark brown (7.5YR 4/2) very friable sandy clay loam; massive in situ, but breaks up into weak medium to coarse subangular blocky; moderate very small gravel (concretions?); few to moderate medium to fine roots. Clear even boundary
B21	22 - 37	Moist dark reddish brown (5YR 3.5/4) very friable clay loam; massive, but breaks up into medium crumb and granular fragments; high very small firm to hard concretions; little strongly weathered subangular gravel up to 30 mm; few medium to fine roots. Clear even boundary
B22	37 - 87	Moist red (2,5YR 4/6) hard clay with common white and yellow specks of weathered minerals; massive, dense, but breaking into coarse very angular and few medium to small subangular to rounded fragments separated by 0.5-5 mm dark grey sheets and veins, apparently cutanic material; few worm or root holes; few hard, small gravels; very few small roots. Gradual wavy boundary
C1	87 - 107	Moist patchy dark brown (10YR 4/3), dark yellowish brown (10YR 4/4), dark brown (7,5YR 4/4) hard gravelly clay loam; massive, almost like concrete; gravel rounded, up to 40 mm and slightly to moderately weathered; no roots. Gradual wavy boundary
C2	107 - 180	Wet dark yellowish brown (10YR 4/4) friable, but slightly brittle, slightly sticky sandy clay loam; massive. Gradual boundary
C3	180 - 215	Wet olive-brown (2,5Y 4/4) friable to slightly plastic, slightly sticky sandy clay loam; moderate fresh to slightly weathered small gravel. Clear boundary
C4	215 - 260+	Moist olive-brown (2,5Y 4/4) friable to slightly plastic sandy clay loam

	Horizon (depth in cm)					
	A11	A12	B21	B22	C1	C2
	0 - 10	10 -20	20 - 35	50 - 75	90-105	115-140
pH (1:5) H_2O	6.6	6.1	6.0	6.0	6.8	6.8
pH (1:5) KCl						
Total soluble salts (%)	0.015	0.005	0.004	0.003	0.004	0.004
Chloride (%)	0	0	0	0	0	0
$CaCO_3$ (%)						
Extractable bases						
Ca (m - equiv. %)	6.49	2.06	1.72	2.08	5.48	4.98
Mg	2.74	1.94	2.67	5.80	12.25	12.54
K	0.18	0.10	0.10	0.10	0.16	0.15
Na	0.23	0.19	0.22	0.23	0.26	0.21
TEB	9.64	4.29	4.71	8.21	18.15	17.88
Exchange acidity (H)						
Cation exchange capacity	9.7	5.5	8.0	16.8	21.6	20.4
Base saturation (BS)	99	78	59	49	84	88
% organic carbon	2.43	0.70	0.61	0.37	0.16	0.14
% nitrogen	0.15	0.06	0.07	0.06	0.04	0.04
C/N ratio	16	12	9	6	4	4
Available P (Truog) (ppm)						
Total P (25% HCl) (ppm)						
Gravel %	tr	2	2	0	37	0
Granulometric composition						
2000 - 200 μ	23	35	11	11	26	6
200 - 50 μ	20	14	26	11	11	33
50 - 20 μ	16	11	9	7	9	10
20 - 2 μ	22	17	17	17	21	18
Less than 2 μ	19	23	37	54	33	33

Clay minerals analysed by CSIRO, Division of Soils, Australia (X-ray diffraction)

A11 horizon — kaolinite 30 - 40%; vermiculite and chlorite 20 - 30%; interstratified material 20 - 30%; goethite 5 - 10%; talc 5 - 10%; quartz <1%

B21 horizon — kaolinite 40 - 50%; vermiculite and chlorite 10 - 20%; goethite/haematite 10 - 20%; interstratified material 10 - 20%; talc 5 - 10%; quartz <1%

B22 horizon — kaolinite 40 - 50%; vermiculite and chlorite 20 - 30%; interstratified material 10 - 20%; goethite 5 - 10%; talc 5 - 10%

C2 horizon — montmorillonite 40 - 50%; vermiculite and chlorite 20 - 30%; kaolinite 10 - 20%; talc 5 - 10%; haematite/goethite 1 - 5%

Silt mineralogy (2 - 20 μ) analysed by CSIRO, Division of Soils, Australia (X-ray diffraction)

A11 quartz 65 - 80%, feldspar 10 - 20% and vermiculite/chlorite 5 - 10%

B21 quartz 40 - 50%, feldspar 10 - 20%, talc 5 - 10%, chlorite 5 - 10%, kaolinite 5 - 10%, goethite/haematite 5 - 10% and crystobalite 1 - 5%

B22 vermiculite/chlorite 40 - 50%, kaolinite 10 - 20%, talc 10 - 20%, feldspar 10 - 20% and quartz 5 - 10%

C2 vermiculite/chlorite 20 - 30%, montmorillonite 20 - 30%, feldspar 20 - 30%, kaolinite 10 - 20%, talc 5 - 10%, amphibole 5 - 10% and quartz 1 - 5%

Sand mineralogy carried out by CSIRO, Division of Land Use Research, Australia

B21 heavy fraction (9% of total); opaques 33%, magnetite/ilmenite 11%, epitode 14%, amphiboles 37% and pyroxenes 5%

light fraction (91% of total); alterites 14%, rock fragments 48%, biotite/muscovite 1%, quartz 27% and feldspar 10%

B22 heavy fraction (8% of total); opaques 35%, magnetite/ilmenite 43%, epidote 15%, amphiboles 5% and pyroxenes 2%

light fraction (92% of total); alterites 7%, rock fragments 55%, clay aggregates 3%, biotite/muscovite 2%, quartz 16% and feldspar 17%

C2 heavy fraction (11% of total); opaques 55%, magnetite/ilmenite 18%, epidote 6%, amphiboles 19% and pyroxenes 2%

light fraction (89% of total); alterites 33%, rock fragments 33%, clay aggregates 2%, quartz 11% and feldspar 21%

Total analyses carried out by Australian Mineral Development Laboratory

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	P_2O_5	TiO_2	K_2O	MnO	Cr_2O_3	NiO	H_2O^+	H_2O^-
A11	67.7	7.90	4.1	4.45	n.d.	0.11	0.80	0.45	0.15	0.60	0.05	4.35	1.60
B21	57.1	13.9	13.2	1.60	0.59	0.06	0.15	0.40	0.20	0.50	0.10	7.50	1.90
B22	50.3	17.7	13.0	0.95	1.11	0.05	1.05	0.70	0.14	0.35	0.20	8.65	3.20
C2	54.3	14.9	12.6	1.45	2.35	0.08	0.90	2.30	0.15	0.45	0.25	6.15	2.60

Trace elements carried out by Australian Mineral Development Laboratory

B21 vanadium 0.015%, cobalt 0.015%, copper 0.015% and zirconium 0.02%

B22 vanadium 0.015%, cobalt 0.01%, copper 0.005% and zirconium 0.01%

C2 vanadium 0.01%, cobalt 0.01%, copper 0.005% and zirconium 0.015%

TROPOHUMULT *

FAO soil unit: humic Acrisol (Af)

Previous soil group: strongly weathered red and brown clay soils

Survey area: Buna - Kokoda, P 20

Airphoto/grid reference: 1942, LAL98 (Kokoda to Sirorota), photo 9V; B.X13.Y3

Altitude: 425 m

Land form: gently sloping ridge with steep side slopes

Parent material: metamorphics (phyllite?)

Climate: lowland perhumid; 3500 - 4000 mm p.a.; moderate seasonality

Vegetation/land use: rainforest, locally a few gardens

Drainage status: well drained

Horizon	Depth (cm)	Description
A0	2 - 0	Decomposed leaves mixed with some recently deposited grey Mt Lamington ash
A1	0 - 17	Moist very dark greyish brown (10YR 3/2) clay; very friable; moderate crumb structure. Clear even boundary
B1	17 - 32	Moist brown to dark brown (7.5YR 4/4) clay; friable; weak subangular blocky structure. Gradual uneven boundary
B21	32 - 53	Moist yellowish red (5YR 4/6) clay; firm; medium subangular blocky; few greyish brown mottles. Gradual boundary
B22	53 - 180	Moist red (2.5YR 4/6) clay; very firm to very plastic; weak angular blocky structure; common, medium distinct strong brown mottles. Gradual boundary
B23	180 - 200+	Moist red (2.5YR 4/8) clay; very firm to very plastic; common, medium distinct yellowish brown and a few white mottles

*Depending on the amount of weatherable minerals this profile could also be classified as a Palehumult

	Horizon (depth in cm)				
	A1	B1	B21	B22	B23
	0 - 15	20 - 30	35 - 50	60 - 150	180 - 200
pH (1:5) H_2O	4.8	4.7	4.6	4.7	4.9
pH (1:5) KCl					
Total soluble salts (%)	0,023	0,015	0,012	0,008	0.006
Chloride (%)	0,005	0,004	0.002	<0.001	<0.001
$CaCO_3$ (%)					
Extractable bases					
Ca (m - equiv. %)	1,50	0,34		0,16	
Mg	1,00	0.95		0,71	
K	0,67	0,51		0.42	
Na	0.10	0,10		0,09	
TEB	3,27	1,90		1,38	
Exchange acidity (H)	30,00	22,60		16,00	
Cation exchange capacity	33,30*	24,50*		17,40*	
Base saturation (BS)	10	8		8	
% organic carbon	4,83	2,58	0,79		
% nitrogen	0.37	0,19			
C/N ratio	13	14			
Available P (Truog) (ppm)					
Total P (25% HCl) (ppm)	320	230	100	80	
Gravel %					
Granulometric composition					
2000 - 200 μ	5	7	7	1	3
200 - 50 μ 50 - 20 μ	14	11	6	6	11
20 - 2 μ	18	22	16	10	19
Less than 2 μ	63	60	71	83	67

* Determined by summation of extractable bases and exchange acidity.

ACROHUMOX*

FAO soil unit: acric Ferralsol (Fa)

Previous soil group: no name

Survey area: Safia Soil Project II, 142

Airphoto/grid reference: Adastra '57, Moni River, CAJ82, R1-5017; A.X17,Y6

Altitude: 430 m

Land form: 20 - 50 m wide slightly rounded ridge crest, local slope 2 - 5° and steep side slopes

Parent material: probably fanglomerate derived from Miocene basalt

Climate: lowland subhumid; 1500 - 2000 mm p.a.; high seasonality

Vegetation/land use: Imperata - Ophiuros grassland, 2 m high

Drainage status: well drained

Horizon	Depth (cm)	Description
A11	0 - 5	Moist dark brown (7,5YR 3/2) very friable clay; moderately very fine to fine crumb with little fine to medium subangular blocky; abundant fine to medium roots. Clear even boundary
A12	5 - 15	Moist dark reddish grey (5YR 4/2) very friable clay; weak medium subangular blocky; many fine to medium roots. Clear slightly wavy boundary
B21	15 - 60	Moist dark reddish brown (5YR 4/5) very friable clay; appears massive, but is very weakly very fine to fine blocky with slightly shiny ped faces which do not appear to be cutans; very few fine pores; very few quartz grains and red very small soft strongly weathered rock fragments; few fine roots. Gradual strongly wavy to irregular boundary
B22	60 - 137	Moist dark reddish brown (5YR 3,5/4) very friable clay; massive but breaking up into fine to very fine blocky and medium crumb; few reddish brown, thin coatings along fine cracks and trace of weathered rock fragments; very few fine roots. Diffuse, probably wavy boundary
B3	137 - 327	Moist dark reddish brown (5YR 3/4) very friable silty clay; massive, similar breakage as above, but with slightly more shiny crack faces and common reddish brown crack coatings; trace of small brown, whitish and red soft strongly weathered rock fragments; trace of fine roots. Diffuse boundary
C11	327 - 360	Moist very dark grey (10YR 3/1) and dark reddish brown (5YR 3/2) mottled or reticulate friable silty clay to silty clay loam; common reddish brown small soft weathered rock fragments; no roots. Clear boundary
C12	360 - 402+	Moist to wet patchy brown to dark brown (7,5YR 4/2) and reddish brown (5YR 3/2) friable to slightly plastic clay

* Classified as a humox assuming a bulk density of >1.3.

	A11	A12	B21	B22	B3	C12
	Horizon (depth in cm)					
	0 - 5	5 - 15	25 - 50	60 - 85	155-180	365-395
pH (1:5) H_2O	5.5	5.0	5.2	5.4	5.3	5.4
pH (1:5) KCl						
Total soluble salts (%)	0.017	0.007	0.003	0.002	0.002	0.002
Chloride (%)	0	0	0	0	0	0
$CaCO_3$ (%)						
Extractable bases						
Ca (m - equiv. %)	3.72	0.53	0.52	0.32	0.49	0.42
Mg	1.49	0.23	0.10	0.12	0.20	0.49
K	0.24	0.13	0.10	0.10	0.13	0.14
Na	0.34	0.25	0.22	0.22	0.28	0.30
TEB	5.79	1.14	0.94	0.76	1.10	1.35
Exchange acidity (H)						
Cation exchange capacity	18.9	11.7	11.3	10.6	13.5	17.0
Base saturation (BS)	31	10	8	7	8	8
% organic carbon	6.96	3.36	1.12	0.19	0.18	0.04
% nitrogen	0.44	0.25	0.09	0.03	0.02	0.02
C/N ratio	16	13	12	6	9	2
Available P (Truog) (ppm)						
Total P (25% HCl) (ppm)						
Gravel %	tr	0	0	0	0	0
Granulometric composition						
2000 - 200 μ	3	1	1	1	2	1
200 - 50 μ	12	5	1	2	2	2
50 - 20 μ	4	3	2	3	6	5
20 - 2 μ	26	18	18	16	34	27
Less than 2 μ	55	73	78	78	56	65

Clay minerals analysed by CSIRO, Division of Soils, Australia (X-ray diffraction)

A11 horizon	kaolinite >80%; goethite 10 - 20%
A12 horizon	kaolinite/hydrated halloysite 65 - 80%; goethite 10 - 20%; gibbsite 1 - 5%; quartz <1%
B22 horizon	kaolinite/hydrated halloysite >80%; goethite/haematite 10 - 20%
C12 horizon	kaolinite/hydrated halloysite >80%; goethite 10 - 20%

Silt mineralogy (2 - 20μ) analysed by CSIRO, Division of Soils, Australia (X-ray diffraction)

A12 kaolinite 40 - 50%, haematite 20 - 30%, magnetite 10 - 20%, gibbsite 5 - 10%, cristobalite 5 - 10% and quartz 5 - 10%

B22 kaolinite 40 - 50%, haematite 30 - 40%, magnetite 5 - 10%, cristobalite 5 - 10% and quartz 1 - 5%

C12 kaolinite/hydrated halloysite 40 - 50%, goethite/haematite 30 - 40% and magnetite 10 - 20%

Sand mineralogy carried out by CSIRO, Division of Land Use Research, Australia

A12 heavy fraction (26% of total); opaques 2%, magnetite/ilmenite 14%, ground mass tr, amphiboles 83% and pyroxenes 1%

light fraction (74% of total); alterites 5%, rock fragments 1%, clay aggregates 13%, ground mass 4%, quartz 28% and feldspars 49%

B22 heavy fraction (14% of total); opaques 33%, magnetite/ilmenite 64%, amphiboles 2% and zircon 1%

light fraction (86% of total); rock fragments 4%, clay aggregates 74%, quartz 16% and feldspars 6%

C12 heavy fraction (1% of total); opaques 29%, magnetite/ilmenite 50%, epidote tr, amphiboles 10%, pyroxenes 1% and zircon tr

light fraction (99% of total); alterites 1%, clay aggregates 96% and quartz 3%

Total analyses carried out by Australian Mineral Development Laboratory

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	P_2O_5	TiO_2	K_2O	MnO	Cr_2O_3	NiO	H_2O^+	H_2O^-
A12	33.0	24.6	11.4	3.25	0.84	0.22	1.95	0.07	0.07	0.07	0.02	12.1	2.90
B22	36.4	28.9	14.7	0.55	0.21	0.24	2.00	0.03	0.05	0.06	0.05	13.2	2.90
C12	35.6	28.4	15.3	0.60	0.35	0.28	1.80	0.03	0.13	0.08	0.02	13.3	3.10

Trace elements carried out by Australian Mineral Development Laboratory

A12 vanadium 0.02%, cobalt <0.005%, copper 0.01% and zirconium 0.025%

B22 vanadium 0.03%, cobalt <0.005%, copper 0.01% and zirconium 0.025%

C12 vanadium 0.03%, cobalt 0.005%, copper 0.01% and zirconium 0.02%

Appendix II

Example 1 - Land system description of the Aitape-Ambunti Survey area (after Haantjens *et al.* 1972)

Yindigo land system: convex or slumped broad very low hill ridges of dissected weathered surface on mudstone: tall forest with an irregular canopy with light-toned crowns, mid-height grassland, and secondary vegetation.

TABLE 1: Description of land system shown above

YINDIGO LAND SYSTEM (206 km²)

Landforms - Very low generally accordant hill ridges that tend to be branching or have an irregular pattern, but are locally subparallel. Ridges are broad, or very broad if poorly expressed wide short spurs are included. Altitude ranges from 60 to 210 m; 40% below 75 m. Relief is generally 30-60 m. Hill slopes range from gentle to moderately steep but are predominantly moderate. They are normally convex (probably 45% of area), but concave where slumped (probably 37%). Prominent small slump alcoves common in several areas; in other cases ridges have slump benches, which in rare cases lead to presence of emergent residual crestal ridges. Short steep slopes occur locally near incising rivers and very short precipitous slopes can be present above slumps. Ridge crests (probably 15%) are rounded or level and narrow to broad, rarely very broad; broad crests represent remnants of an old surface. Crests are somewhat peaked with very gentle to moderate crestal slopes. This locally results in individual very low hills. In some instances wide apparent valleys consist largely of ultra-low convex residual ridges with gentle slopes, probably remnants of younger surface cut below normal ridge crest surface. Southern and eastern parts include alluviated valley floors (probably 3% of area) 40-200 m wide, mostly inclusions unmappable as Pandago or Kabuk land systems.

Streams and Drainage - Moderately dense dendritic to subparallel pattern of long and predominantly north-south-flowing small first- to third- (rarely fourth) order streams with few very short tributaries. Most streams of local or near-local origin, and only one or two larger through-going rivers. Streams flow in shallow beds 2-15 m wide and mostly shallowly cut into narrow (10-30 m) strips of alluvium. Except for smallest headwaters they have low to very low gradients; lower courses disappear in wider swampy valleys without channels and blocked by the more vigorous aggradation in adjoining Screw, Nagam, or Misinki land systems. No gravel or sand in stream beds. Surface runoff probably moderate in relation to through drainage, so flood spates are fairly frequent and many small streams may cease to flow after long rainless periods.

Hill ridges appear more often imperfectly to poorly drained than well drained. Small valley floors are poorly drained to swampy and inundated for long periods in wet season.

Vegetation - More than 50% covered by secondary vegetation including grassland. Regrowth dominated by cane grass (*Saccharum*) (GtR) forms an important element in secondary vegetation, especially in north-east corner. Mid-height grassland (G) covers 12%; some tracts are dominated by *Imperata cylindrica*, others have a mixed composition in which *Themeda australis*, *Ophiuros exaltatus*, *Sorghum nitidum*, *Ischaemum barbatum* and *Imperata cylindrica* are the most important. Tall forest with an irregular canopy with light-toned crowns (Fid) covers hill ridges in the north. Towards the south is mid-height forest with a small-crowned canopy (Fms) on crests and still farther south it extends also over slopes. Tall forest with a rather closed canopy (F) occurs on valley floors, but mid-height forest with an irregular canopy and sago palms in the understorey (FmM) where valleys are swampy. Areas covered by these are 23%, 18%, 3% and 2% respectively.

Geology – Pliocene rocks, predominantly mudstone, some siltstone, and minor intercalated sandy beds, probably subhorizontal to very gently dipping. Slopes locally covered with veneer of colluvium derived from the rocks but in places including remnants of Pleistocene fanglomerate.

Weathering and Soils (22 obs.) – Weathering generally shallow immature, rarely shallow mature, on both slopes and crests. Slopes with slump benches and some crests have only shallow skeletal weathering. Underlying rocks softened by generally strong, locally moderate hydration which possibly extends several metres.

Probable soil composition is UOPB,* IODA1, AAU1, UAPB1 common; UOPT, UOPA1, UOTO1, AAOO, AUTQ, AUTA3, MUHO2, IODE4, EUHO6, EUHO7, EUHA7, EUHU1 minor. On crests and on slopes not obviously slumped commonly occur very strongly to strongly developed, acid (rarely strongly acid), moderately thick to thick (rarely moderate thin), very plastic to very firm heavy clay to silty heavy clay soils with prominent red, brown, and light grey mottling, with 15-45 cm thick coarser-textured friable to firm sandy clay loam, loam, clay loam, or clay surface horizons, and with thin to moderately thick dark topsoils. Some are moderately gleyed (UOPA1, UABP1), some slightly gleyed (UOPB), and some not gleyed (UOPT). Also present on convex slopes in approximately equal proportion are moderately developed, weakly acid to acid, moderately thick to moderately thin (rarely thick), very firm to very plastic heavy clay to silty heavy clay (rarely clay) soils, either uniformly textured (IODA1, IODE4, MUHO2) or with 15-45 cm thick coarser-textured, friable to plastic clay loam to clay surface horizons (AAOO, AAU1, AUTQ). Some are moderately gleyed (AAOO, AAU1), others slightly gleyed (IODA1, AUTQ). They commonly have thin to moderately thick or even thick (MUHO2, AAU1) dark topsoils. Although differences are not pronounced, soils on crests appear more often strongly developed and slightly more acid than those on slopes, whilst the latter, probably as a result of slight colluvial accumulation, have thicker coarser-textured surface horizons and more consistently dark topsoils. Soils on the lower-level hill ridges appear less developed than those on normal higher ridges.

Soils on slumped slopes and some foot slopes partly include moderately developed, weakly acid to acid, moderately thick to thick, very plastic to very firm heavy clay to silty heavy clay soils (rarely clay or sandy clay), generally slightly to moderately gleyed (IODA1, AUTA3, AAU1), generally with 15-45 cm thick coarser-textured friable to firm sandy loam, clay loam, or clay surface horizons (AAU1, AUTA3, UOTO1) and rarely thick dark topsoils (AAU1). Also common are undeveloped, weakly acid to acid, deep to moderately shallow, firm to very firm or very plastic, slightly stratified silty clay, clay or silty heavy clay colluvial soils (EUHO6, EUHO7) which are locally slightly gleyed (EUHA7) and commonly have thin dark topsoils. Only soil observed on narrow valley floor is an undeveloped, weakly acid, moderately shallow, moderately gleyed, very plastic heavy clay alluvial soil (EAHU1). In general, soils of alluvial valleys similar to those in Misinki and Pandago land systems.

* These are coded 7th Approximation (United States Soil Conservation Service 1960) terms, e.g. UOPB stands for an Umbraquultic Plintaquult.

Population and Land Use – Population of 6340 distributed over 26 villages. Present land use covers 118.3 km^2 (36% of area), 15% in land use intensity class 2, 30% in class 3, 5% in class 4, and 50% in class 5. More intensive land use restricted to eastern occurrences. Exploitation of sago important in subsistence. Some villages also use land in adjoining Screw land system.

Transitions to Other Land Systems – Pattern of Yindigo is in many places very similar to that of Kworo land system. Boundaries between the two are commonly arbitrary and located on the evidence of field sampling and 'intuition' rather than clear differences in photo pattern. As explained, both land systems commonly naturally grade into each other. Generally, however, Yindigo has a coarser ridge pattern, more convex and gentler slopes, and a slightly higher relief. In some cases Yindigo can be transitional to most-dissected parts of Burui land system. Transitional patterns and gradual boundaries also common with Kaugiak and Musendai, and to a lesser degree Sandri and Sengi land systems, Kaugiak having a higher relief and longer more regular ridges, Musendai a lower relief and gentler slopes, Sandri being much more finely dissected, and Sengi having a higher relief and more irregular shorter ridges, commonly with remnants of rock structure.

Forest Resources (7 obs.) – Forest covers 43%; low forest resources. Much forest has a moderate stocking rate (Fid/F 39 km^2, Fid 10 km^2, Fid/FR 3 km^2, Fid/FmM 2 km^2). Low stocking rate forests (Fms 16 km^2, Fms/FmM 16 km^2, Fms/F 3 km^2, Fms/Fid/F 3 km^2) also occur. Access category Iw.

Agricultural Assessment – Moderate capability for improved pastures, low capability for arable crops, and very low capability for tree crops. Unsuitable for tree crops mainly because of the poor physical condition and imperfect to poor drainage of the soils, while slump risks on slopes are a contributory factor. These factors are of less importance for arable crops and even less for improved pastures, although there might be some difficulties in pasture establishment. Erosion hazards are main limitation for these land uses. Capability for pastures is well up in the moderate class and this land use offers real possibilities also because stock water can be easily supplied from small dams erected in valleys and slope folds. Minor supporting cultivation of crops may be feasible. Narrow valley floors best used for sago production, pastures, and/or irrigated rice. Soil nitrogen contents mostly moderate, but occasionally low. Phosphate contents mostly very low to low, rarely high, but in undeveloped colluvial and alluvial soils commonly moderate, less frequently low to very low. Potash contents range from high to low, with a few very high and very low values; they are mostly high, locally moderate in undeveloped colluvial and alluvial soils. Rather frequent slight, and rather rare severe, soil water stress, mainly on ridge crests and convex slopes.

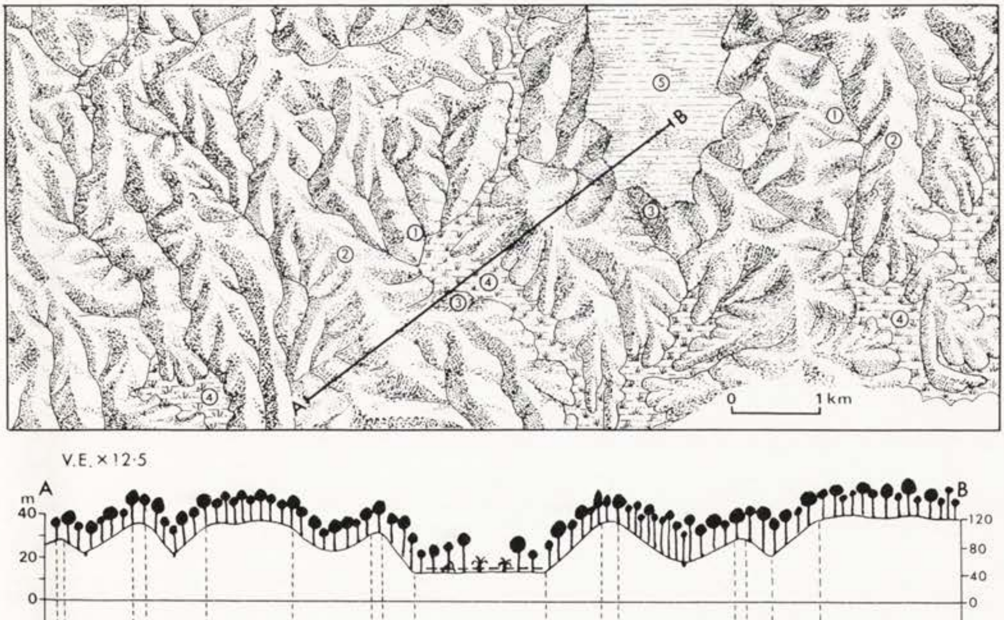
Engineering Assessment – Topography a minor limitation in road construction, although many small bridges and large culverts will be needed in E-W or SW-NE aligned roads. Road cuttings easily made in soils and underlying soft rocks, but may be liable to cave in. Major problems in road construction are: lack of road-surfacing materials, probably restricted to very small and thin surficial quartz gravel and iron concretion beds; low suitability of soils and upper rock strata for subgrade; difficulties in attaining good roadside drainage because of slow permeability; and a tendency to slumping on some slopes. Possible, but not likely, that some brightly mottled subsoils will harden irreversibly upon drying, and may be used as low-grade laterite for road surfacing. Unmade roads should utilise coarser-textured surface soils to reduce slipperiness and bogginess. Soils are CH, and CH with a thin veneer of MH, CL, ML; probably depths are moderately deep, deep, very deep subdominant, shallow minor. Several sites suitable for small airfields without undue earth movement, but surfacing and drainage problems are as for roads.

Example 2 - Land system description in the Morehead-Kiunga Survey area (after Paijmans *et al.* 1971)

MIWA LAND SYSTEM (8590 km^2)

Intricate pattern of low ridges and narrow valleys, with latosols and closed rainforest.

Geology - Clay, silt, and sand; Pleistocene. Minor alluvial clay and peat; Recent.



Unit	Area (%)	Land Forms	Soils	Vegetation	Limitations
1	55	Hill slopes: 3-15°, average 8°; up to 180 m long, convex, straight, locally stepped; gullies and pits up to 4 m deep occasionally present	Clay loams to clays: acid to strongly acid, well drained, locally imperfectly drained (IODX*-9 obs, locally IODP-2 obs, UOTOI-7 obs, UOP2-6 obs, UOP1, UUP2-each 2 obs, UUT, UAPI-each 1 obs.)	Closed rain-forest, locally very dense and thin-stemmed; minor monsoon forest in south and south-west	e1-3, locally w1, p4, d1, m1, a2 and a5, locally g3-4
2	15	Ridge crests: 15-60 m wide, average 30 m; gently undulating slopes 0-3°; knolls up to 1 m high locally present	Loams to clay loams merging into clays, and uniform textured clay loams to clays; acid to strongly acid, well to imperfectly drained (UOP2-8 obs, UOTO1, UUP2, and UAPO1-each 2 obs, UAPU2, UOP1, and UUT-each 1 obs, IODX-5 obs, IODP-1 obs.)		Located e1, locally w1, p4, d1, m1, a2 and a5, g3
3	15	Hill slopes: 15-40° average 25°; up to 45 m long, generally straight	As unit 1, but well drained (IODX-3 obs, UOTO1-2 obs, UOP1-1 obs.)		e4-6, p4, d1, m1, a2 and a5
4	10	Flat valley floors; generally <400 m wide; slopes <1°	Alluvial clay loams to clays: acid to strongly acid, very poorly drained to swampy (EAA3-5 obs, EAHO3-3 obs); locally imperfectly drained (EUHA2, EUHA3-each 1 obs). Organic soils (H2)	Sago - *Campnosperma* swamp woodland, swamp forest	Locally f3, locally i5 and i2-3, commonly w3-4, locally w1, p1 and p4-5, locally d2, locally m1, a2 and a5, g1
5	5	Plateaux: up to 10 km wide (west of Lake Murray); undulating; slopes 0-3°	Clay loams merging into clays: thick dark topsoils commonly present, acid to strongly acid, well to imperfectly drained (UUP2-2 obs, locally UOP2)	Closed rain-forest	As unit 1

Agricultural potential - High for tree crops, moderate for improved pastures, low for arable crops. Soil nutrient status (15 soils): nitrogen moderate to low, available phosphate very low, potash low to very low.
Observations - 71.

* See footnote in example 1.

Geomorphology - Random reticulate pattern of narrow ridges and minor undulating plateaux with a closely spaced dendritic drainage network consisting of flat-bottomed major valleys and narrow V-shaped tributary valleys.

Terrain Parameters - Altitude: 3-60 m. Relief: 10-30 m. Characteristic slope: 8°. Grain: 120 m.

Example 3 - Landform type description of the south-east Papua Survey area (after Blake and Paijmans 1973a)

FSn LANDFORM TYPE

Undissected alluvial fans associated with swiftly flowing braided rivers, formed on unconsolidated sediments.

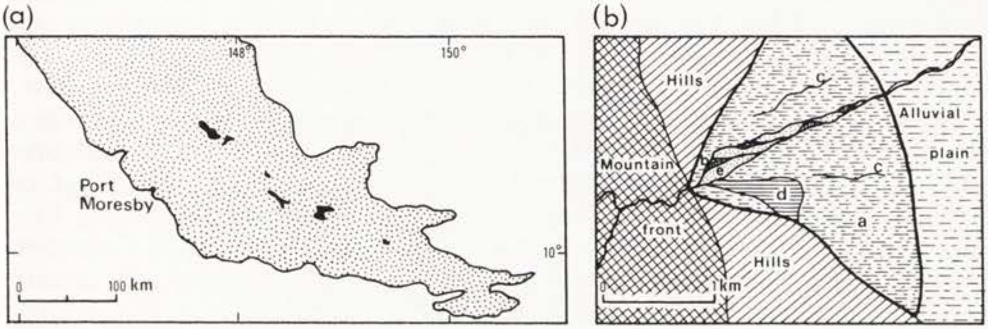


Figure 2. A. Distribution of FSn landform type. B. Plan of FSn landform type.

Area - 320 km²; 0.5% of total area mapped.

Terrain Parameters - Altitude: 100-1000 m. Relief: less than 10 m. Characteristic slopes: 1-5°.

Climate - Zones II-IV.

Geology - Unconsolidated alluvial gravel, sand, silt, and clay; minor colluvial material. Recent. Veneer of andesitic volcanic ash present locally near Mt Lamington.

Landforms - Alluvial fans crossed by shallowly incised braided rivers. Unit 1 (95%): (a) fan surfaces; smooth to slightly undulating, slopes 1-5°, (b) discontinuous low terraces, (c) prior channels, (d) bouldery surfaces; channelled microrelief present locally. Unit 2 (5%): (e) floodplains of braided rivers: incised 2-10 m into unit 1; microrelief of channels separated by bouldery and gravelly rises.

Stream Pattern - Generally subparallel to subradial, with braided major rivers.

Soils - Unit 1: mainly black to very dark greyish brown friable loam to clay, pH 6.5-7.0, over olive-brown to dark brown friable silty loam, and clay, pH 6.0-7.5; moderately permeable.
Unit 2: grey to brown loose sand over gravel, stones and boulders; pH 6.0-7.0; rapidly permeable.

Drainage - Unit 1: well drained because soils moderately permeable, water table generally over 2 m deep, and flooding rare.
Unit 2: imperfectly to poorly drained because of shallow water table and frequent short-lived flooding.

Vegetation - Originally mainly large-crowned tall forest, slightly deciduous in climatic zones II and III, but now widely replaced by gardens, garden regrowth, secondary forest, and, in climatic zone II, by tall grassland and savanna.
Unit 1: large-crowned tall forest (*Pometia*, *Octomeles*, *Alstonia scholaris*; where slightly deciduous *Terminalia* spp., *Anisoptera*, *Intsia*); tall grassland (*Saccharum spontaneum-Imperata cylindrica*); minor savanna (*Eucalyptus tereticornis* with *Nauclea-Antidesma* in slight depressions, ground layer of *Imperata cylindrica*, *Themeda australis*, *Alloteropsis semialata*).
Unit 2: bare ground; stands of *Saccharum spontaneum*, lines of *Casuarina cunninghamiana* and *C. papuana*.

Forest Resources - Moderate to high stocking rate forest (50 m^3 timber per ha from 27 trees over 1.5 m girth per ha) covers 40% of the land mainly on unit 1.

Land Use Potential - Unit 1: mostly suitable for cultivation with only minor limiting factors.
Unit 2: unsuitable for commercial land use because of frequent flooding hazard.

Correlations - Includes Ilimo land system of the Buna-Kokoda area (Haantjens *et al.* 1964) and Liamu and parts of Ubo and Safia land systems of the Safia-Pongani area (Ruxton *et al.* 1967).

Relationships - Locally grades into dissected fans and alluvial plains but is generally sharply bounded by other landform types.

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