The Alpine Flora of New Guinea

by

P. VAN ROYEN

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DEDICATED TO THE MEMORY
OF LEONARD JOHN BRASS

L.J. Brass (left) and the author in the new herbarium of the Department of Forests, Division of Botany, Lae, Papua New Guinea, on opening day, April 12, 1965.

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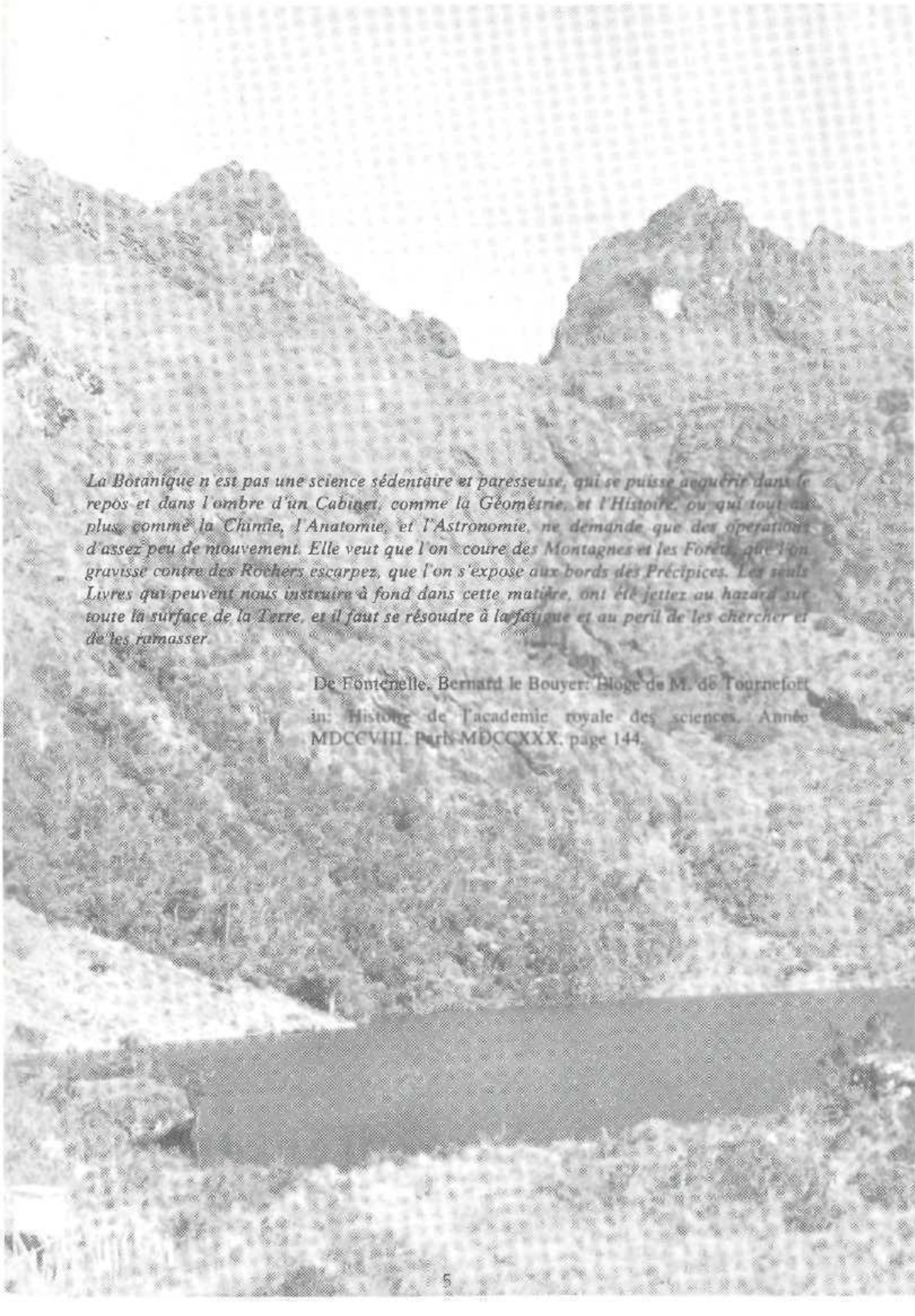

La Botanique n'est pas une science sédentaire et paresseuse, qui se puisse acquérir dans le repos et dans l'ombre d'un Cabinet, comme la Géométrie, et l'Histoire, ou qui tout au plus, comme la Chimie, l'Anatomie, et l'Astronomie, ne demande que des operations d'assez peu de mouvement. Elle veut que l'on coure des Montagnes et les Forêts, que l'on gravisse contre des Rochers escarpez, que l'on s'expose aux bords des Précipices. Les seuls Livres qui peuvent nous instruire à fond dans cette matière, ont été jettez au hazard sur toute la surface de la Terre, et il faut se résoudre à la fatigue et au peril de les chercher et de les ramasser.

De Fontenelle, Bernard le Bouyer: Eloge de M. de Tournefort

in: Histoire de l'academie royale des sciences. Année MDCCVIII. Paris MDCCXXX, page 144.

FOREWORD

Early November 1970 I asked Brass whether he could write a Foreword to the High Altitude Flora and Vegetation of New Guinea. At the end of March 1971 I received a letter from him saying that he could not do this due to his poor health. However, parts of his letter dealt with these volumes and can be constructed as his Foreword. I like to quote part of this letter, which is dated Cairns, 30 March 1971:

> *"I was most interested to learn some details of your New Guinea alpine project. It gives promise of being a very fine work and I feel greatly honoured that you should wish to dedicate it to Queen Wilhelmina and myself. In accepting the honour, I must say that it will be very difficult for me to write an introduction to the work. Since my stroke of two years ago, I find it hard to do anything at all. I have done no work at the herbarium, and am still not driving my motor car. I have given up writing for publication and write few ordinary letters."* ....

Some short time later the internal malignancy that led to a colostomy operation in 1962, took Len Brass away from us on August 29, 1971.

Contents

1. INTRODUCTION

When I entered the University of Utrecht, Netherlands, in October 1941, New Guinea was only a vague concept to me of an island at the eastern end of the then Dutch East Indies. In the short time that the German occupation allowed me to study biology until February 1942, I became acquainted with Professor A. Pulle. From him I learned somewhat more about New Guinea as he had been there in 1912 and 1913 in an exploration that touched the alpine vegetation. However, after the German Occupation Administration closed the universities in the Netherlands, it seemed that botany and New Guinea would fade completely for me, and it came as a surprise that after the war I could return to botany and Dr. Pulle. In the six years I spent in Utrecht, Pulle taught me a lot more about New Guinea and its flora and jokingly I mentioned one day that I would be director of the Flamingo Bay Herbarium in New Guinea. That institute never existed and probably never will. What remained however, was a desire to see New Guinea.

My first chance came after an appointment as assistant to Professor Dr. H.J. Lam, Director of the Rijksherbarium, Leiden, Netherlands, himself a student of Pulle. Lam had been in New Guinea in 1920 and 1921, had climbed Mount Doorman and brought back a large collection of alpine species. In 1952 we learned about the possibility of a grant to be given by one of Holland's outstanding foundations — the Hollandsche Maatschappij van Wetenschappen at Haarlem — which made the revenues available of the Pieter Langerhuis Lambertszoon Foundation for any botanical research anywhere in the tropics. Lam allowed me to apply for this grant and with the assistance of some funds made available by the Organization for Pure Scientific Research (Zuiver Wetenschappelijk Onderzoek) it was possible to prepare for a 12 month stay in New Guinea.

In 1954 and 1955 I explored many areas both in the eastern and western parts of the island but did not touch the alpine areas at all. In the mean time however, I had learned about Dr. L.J. Brass's exploration in the Mount Albert Edward area (1933/1934), and in the Mount Wilhelmina area (1938/1939). The material brought back by Len Brass is a treasure trove for any botanist and for one interested in alpine plants even more so. Mulling over Len's discoveries after my return to Leiden in 1955, I worked on an initial series of keys to all families and genera of plants in New Guinea, but the 7-year itch caught me and once again I applied for funding for a fieldtrip to New Guinea. In 1960 I left, accompanied by Dr. H. Sleumer, also of the Rijksherbarium, for West New Guinea. This time we explored areas somewhat closer to the alpine regions but nowhere did we touch them, though I saw my first alpine element, *Patersonia novoguineensis* Gibbs (now *P. lowii* Stapf), in the Tamrau Range.

In early 1962 I was appointed as botanist to the Division of Botany of the Department of Forests and was based in Lae. In that same year, September, Dr. F. Went, then from Arizona, U.S.A., visited New Guinea and expressed the wish to study some alpine regions. Mr. John S. Womersley, then Chief of the Division, proposed a visit to Mount Wilhelm, asking me to join him. So it was on the 20th September, 1962, that I first set foot in the alpine grasslands. The first plant collected happened to be *Triplostegia glandulifera* Wallich, but later, taller plants like *Dimorphanthera microphylla* Sleumer, and *Olearia platyphylla* Mattfeld were collected in the areas surrounding Lake Aunde.

Returning to Lae after the Mount Wilhelm trip I started developing the present flora, preparing the first drawings. The next alpine regions visited were those of Mount Enggom, part of the Sarawaket Range, in February and March 1963. A second, two-day trip was made by helicopter to Mount Bangeta on November 1 and 2, also in the Sarawakets. These trips set the process even more in motion that ultimately led to the present volumes. In between these two trips a short trip was made to the Wahgi - Jimmy Divide where I climbed Mount O'Dan. The high altitude vegetation is relatively confined to a small area but contains enough high altitude elements.

A final alpine trip with the Division of Botany, was made in January 1965 to the Mount Albert Edward region. Though it was intended to climb Mount Biota, the rain and fog prevented us from finding the right track. It did, however, lead us to some beautiful alpine grasslands in which numerous species could be collected. With memories of this last trip I left New Guinea in 1965, and once again it seemed uncertain that I could even continue a botanical career. It was not until my appointment in 1967 to the present position as Chairman of the Department of Botany at the B.P. Bishop Museum in Honolulu that I could start thinking again of continuing the alpine flora.

The first three years in Honolulu had to be devoted to a general reorganization of the Department of Botany, but later more time became available to go ahead with the proposed flora. A grant in 1970 from the National Science Foundation allowed me to visit several herbaria in Europe, and it appeared that the Flora could be finalized in another ten years.

After my return to Honolulu in 1971, plans were made for a last field trip to the beckoning and virtually unknown alpine regions of the

Carstensz Mountains. A grant was obtained from the National Science Foundation and in 1974 I set out first for Java to obtain the necessary permits, and from there for West New Guinea. Unfortunately in Jakarta, the Indonesian authorities, when all permits were obtained, asked me to postpone the exploration indefinitely. By permission of the National Science Foundation we were allowed to transfer the funds to the use of an exploration in several alpine regions in Papua New Guinea. In the short period of 4 months (May-August 1976), Mount Victoria, Mount Amungwiwa, Mount Giluwe, the Victor Emanuel Range, again Mount Giluwe, and ultimately the Finisterre Range, were visited. The last field trip to study the alpine regions of New Guinea was completed before originally scheduled due to the capable assistance of Mrs. B. Gagné-Harrison. This meant it was time to finalize the manuscript, find a publisher and present the readers with The Alpine Flora of New Guinea.

2. DEFINITIONS AND DESCRIPTIONS OF THE HIGH ALTITUDE VEGETATION TYPES

In these volumes on the high altitude flora and vegetation only the Angiosperms and Gymnosperms are included. The lower plants, probably in greater numbers than the two groups, are insufficiently known and do not form the most highly visible groups. However, J. Croft of the Lae Herbarium, is preparing a list of ferns found in the higher altitudes, and it is likely that this list will be included in the final pages of the last volume of this Flora. In delimiting the area of this flora quite arbitrarily, the 3000 meter contour has been chosen. Though seemingly arbitrarily, there are grounds — among them the experience of others, Grubb & Stevens, 1976, Smith 1967, and myself — to accept this altitude as a line of demarcation between the cloud forest or lower montane forest changing into the upper montane forest, subalpine forests, shrubberies, and alpine vegetations, although various factors much confuse this break in vegetation types (Walker, 1973). The mean break, apart from the species composition, is a structural one, from a 5-layered forest with up to 90 percent trees with microphyllous (< 1 cm) leaves to a 3-layered forest, from a closed canopy with straight trunks to an open canopy with crooked trunks, and a general height limit of c. 15 meters. In accepting the 3000 meter line, the floras and zones we are dealing with are the upper montane, subalpine, alpine, and nivale ones. In the present chapter only the main outline of these zones will be discussed with the exception of the nivale and aeolian zones. More detailed information is found in Hope's and Smith's chapters.

Above the alpine region, the upper limit of which is the highest position of growth of vascular plants, the aeolian zone is found as defined by Swan (1963). In this zone mosses and lichens are found but no vascular plants. It is a zone that depends on its food supplies from sources outside of it, carried in by wind and rain, and not upon local autotrophic flowering plants as in the alpine and lower regions. The aeolian zone is probably non-existent in New Guinea, though following its definition, it should be there. On Mount Wilhelm (4510 m), one finds *Styphelia suaveolens* up to the very summit, and it is likely that the aeolian zone may only be found in the Carstensz Mountains (4884 m). There too, at 4585 m, *Tetramolopium piloso-villosum*, *Scleranthus singuliflorus*, and *Epilobium detznerianum* have been reported from bare rocks between two tongues of the main glaciers (Hope, 1976). The aeolian zone is sometimes included in the nivale zone and sometimes kept separate. The alpine heath and tundra as distinguished by McVean and Wade (1969) do both have vascular plants, such as *Deyeuxia brassii, Carpha alpina, Oreobolus pumilio, Astelia alpina,* etc., so cannot be regarded as belonging to the aeolian zone in Swan's sense.

The difficulties of separating the alpine and subalpine floras from the upper montane flora, and more relevant, the possibility that a true alpine flora has not yet evolved in New Guinea (Hope, 1976, pp. 151-153), is such that it was only after some hesitation that the title "The Alpine Flora of New Guinea" was used for these volumes. Though not correct as it contains all the plants found growing over 3000 meter and not necessarily being alpine to boot, the shorter title than the original "The High Altitude Vegetation and Flora of New Guinea", was preferred. However, the terms alpine, subalpine and upper montane are used for the reason that as a vegetation these three types are fairly well distinguished (McVean & Wade, 1969, Hope, 1973, 1976).

The 3000 meter line mentioned earlier has to be regarded as an average altitude as from the studies for the present volumes it is clear that the change from upper montane flora to subalpine and alpine floras takes place in West New Guinea in the Carstensz Mountains at altitudes of 3200-3400 m and on Mount Dayman and Mount Simpson in the southeastern tip of Papua New Guinea at altitudes between 2790 and 2900 meter.

Upper Montane Zone

In general, the upper montane flora of Wade and McVean (1969) or the lower montane forests of Grubb & Stevens (1976) is composed of conifers and other trees, and has in its lowest parts a physiognomy similar to the lowland and lower montane rainforests. It is often invaded by clouds but contrary to the upper montane forests, these descend to ground level. This phenomenon is promoted by the generally open and lower forest than in the lower zones. Many trees and shrubs have some xerophytic adaptation in the form of thick, leathery leaves, and a dense pubescence. Inside the forest the relative humidity is still very high, mainly due to the high rainfall rather than to the density of the forest canopy. Due to lower temperatures many epiphytes found in the lower parts of the montane zone in the warmer crowns of the trees, descend to the warmer bases of the trunks or are becoming terrestrial by growing in the large moss cushions which particularly in the upper montane zone are very well developed (Lam, 1916). Epiphytes and terrestrial species are then found growing side by side in these cushions.

The montane forests, which in Brass' terminology (1941, 1956) are called beech forests and mossy forests, are really the upper montane forests of Grubb & Stevens (1976). They are the dominating life-forms and occupy, together with the lowland rainforests and the lower montane forests, most of New Guinea. As stated by Brass (1941), and easily confirmable by anyone crossing these regions, the beech forest (*Nothofagus* sp.) probably exceed all others in New Guinea as a source of durable hardwoods. In general the montane forests are rather open, and more often than the lower forests, is dominated by one or a few species. Usually these are *Nothofagus* species, *Casuarina* forests are reported from several areas. Conifers (*Papuacedrus, Dacrycarpus, Podocarpus* and *Phyllocladus* species) too are often found in large stands. In these types of forests hardly any mosses are growing, a picture that changes drastically in the upper montane belt. In the undergrowth of the montane forest mainly species of *Drimys, Elaeocarpus, Medinilla, Piper, Rhododendron,* and *Vaccinium* are found. In general, the number of *Ericaceae* increases at higher elevations until it reaches its maximum in the subalpine forests and shrublands. Another aspect of the upper montane forests in the mossy forest, or elfin forest. This forest is still of considerable stature and either with few mosses or with extensive development of the latter. In a way it is an intermediate stage towards the densely moss covered crooked trees of the upper montane forest. This mossy forest is dominated by *Dacrycarpus, Podocarpus, Rapanea, Syzygium,* and *Xanthomyrtus* species. The typical lowland families are either absent or represented by a few species only, such as *Annonaceae, Dipterocarpaceae, Leguminosae, Sapindaceae,* and *Sapotaceae.* They are replaced by *Ericaceae, Fagaceae, Cunoniaceae, Lauraceae, Myrtaceae, Myrsinaceae,* and conifers. The number of epiphytes increases and includes species of such genera as *Alyxia, Psychotria, Rapanea, Schefflera,* and *Amaracarpus, Piper,* and numerous orchids. Where the montane forests become more open species of *Elatostema, Piper,* and *Selaginella* take up large areas, and such ferns as *Gleichenia vulcanica* and several species of *Lycopodium* often make impenetrable thickets. This also is very true of several species of *Nastus,* a climbing bamboo, that makes crossing forests on Mount Wilhelmina, a very painful and tiring effort. The herbaceous vegetation compared with that of the lower regions shows distinctly different families such as *Boraginaceae, Campanulaceae, Gentianaceae, Ranunculaceae,* and *Araliaceae* (*Apiaceae* s.s.). Climbers are mainly species of *Rubus,* while the number of species of *Hydnophytum* and *Myrmecodia* increases.

In both the montane and upper montane zone seral shrub and herb vegetations soon develop when the primary forests are destroyed. In these types of vegetations many alpine and subalpine elements are found. The first to arrive are species of *Rhododendron, Gunnera, Gonocarpus, Olearia,* and *Pittosporum.*

Subalpine Zone

To define the subalpine zone of New Guinea is not easy as is the case in many other areas of the world. An example of the various names given for instance, to the montane forests is given by Boughey (1955), where not less than 39 names are quoted in English, French, and German. Though nobody has worked out the synonyms for subalpine and alpine the number of names is considerable though far less than for the montane forest.

In trying to define the subalpine zone and its vegetation one has to consider first whether it is a separate zone or merely a part of an alpine zone in the widest sense as has been done sometimes (Mani, 1962, 1968). In its simplest and most unsatisfactory sense the subalpine zone includes all vegetation types between the alpine grasslands, heaths and tundras on one side, and the upper montane forests and shrubberies on the other side. This means everything between the timberline and the aeolian zone, or everything between a closed forest in which the trees provide more than 50% coverage and the line formed by the highest vascular plants. Some authors (Mani, 1962) have named this entire biotic province "nivale" but this is too much lumping and underestimates the true difference between subalpine and alpine flora, but does account for similar types of faunas from the timberline to the highest peaks covered by permanent snow. The timberline in itself is usually not a sharply defined line but shows many transitional formations to the subalpine forests, shrubberies, and grasslands, varying from place to place in altitude, soil-conditions, climate, latitude of mountains, direction or aspect of slope, topography, and massiveness of the mountain range. Then there is the question in attempting to define subalpine whether it is in a biological, zoological, climatological, or geographical sense that we want to shape a definition, or try to define it by composition and ecology, an approach that probably makes more sense and is about the only one that can give a solution. Though on the other hand the influence of geological time with its consequence of drifting continents and plates from cooler to warmer climates could obscure the picture even more. As Löve points out "it is essential that the concept of biogeographical zones and belts is regarded from a very wide point of view", (*Arctic and Alpine Research* 2, 1970, 64).

The concept of a subalpine belt dated back to Wahlenberg (1812, 1813, 1814), who coined this term when describing the Scandinavian birch belt, at the same time making the latitudinal difference between the subalpine conifer forests of the European Alps and Carpathians, and the subalpine birch belt of Scandinavia. At first (Dansereau, 1957, Cordeeva & Strelkova, 1968) it was established that the arctic belt is treeless and the treeless alpine areas at high altitudes in the tropical mountains are gradually found at lower altitudes approaching the polar regions. This can be seen in South Island of New Zealand where the alpine flora merges into the antarctic flora at sealevel, while all intermediate vegetation types disappear. However, though the definitions of alpine and arctic zones more or less remained constant the definition of subalpine became more confused. For an excellent review of this it is referred here to Löve (1970).

The subalpine zone was first based on the composition alone, but gradually the influence of the temperature on the vegetation was taken into account. Thus in Alphonse de Candolle's works (1855, 1874), we find the earliest attempts to correlate temperature and vegetation, including the precipitation and genetic response of plants.

Brockman-Jerosch (1919) and Köppen (1919, 1936) already demonstrated a close parallelism between the timberline altitude and the midday atmospheric temperature of the vegetative season from May to September. Also the 10° C isotherm and the timberline coincide both at high altitudes and high latitudes. Löve comes to the conclusion that the subalpine zone is an "intervening belt of mixed meadow and heathlike vegetation and islands of trees or krummholz or dwarfshrubs." The lower limit for the subalpine belt can then be considered to be the timberline where the trees begin to have well developed stems and crowns, and cover more than 50% of the total ground surface with an undergrowth of herbs and bushes typical of forest communities. Therefore they introduce apart from all other considerations that determine the subalpine vegetation, (rainfaill, isotherm of 10° C mean daily temperature for the warmest month of the year), ecological considerations which are based on Raunkiaer's original work of 1934, and extended by Krajina and Domin (Krajina, 1933). These ecological considerations led Swan (1967) to try to summarize them in order to develop unifying concepts of the treeless zones of widely scattered mountains at high altitudes. Löve defines the subalpine belt as the natural belt below the treeless belt from the upper altitudinal treeline to the closed montane forest, and is thus an ecotone. This would plea for the use of the term nivale in a wide sense as is done by Mani (1962). The subalpine belt depends on climatic factors, such as temperature, moisture, wind and radiation, to which should be added soils and a different composition of gasses of the surrounding air. The exact altitudinal position of the subalpine belt, which ranges from very narrow to very wide, is related to the geographic position of the mountain.

How does the high altitude flora of New Guinea fit into these schemes? Wade and McVean in their monography of the alpine and subalpine vegetation of Mount Wilhelm (1969) distinguish a subalpine and alpine belt, in which the subalpine belt is composed of a lower and upper subalpine forest, a forest edge community and subalpine grasslands. In the alpine belt alpine grasslands, fern meadows, alpine heaths and tundras are distinguished. On page 221 of their paper they use the terms orosubantarctic for the tussock grasslands below 4100 meters and oroantarctic for arctic. Love points out in her review (1970) of the Wade and McVean paper that it is unfortunate that those terms were introduced by stating that the old nomenclature as proposed during the 3rd International Botanical Congress in Brussels (1910) and later by Meusel (1965) functions very well for the Mount Wilhelm vegetation. Also apart from being really tongue-twisters there is no need to use these long terms. If one only takes the outer physiognomy into account the terms subalpine and alpine can have a worldwide application even as they originally applied only to a limited area in the European Alps and Arctic, and in spite of the various interpretations that were given to these terms. Though there is quite a considerable species differentiation, and some characteristic pachycaulous species are missing like species of *Espeletia, Lobelia* and *Senecio,* the forests and grasslands in the alpine and subalpine vegetation in most parts of the world look somewhat similar. There are however, major visual differences, related to seasons (snow lie, avalanche tracks, phenology and in the vegetation species richness of highest forests, shape of trees, krummholz, response to the topographic features).

The various interpretations have been summarized by Mani (1962) from which it becomes clear that different mountains yield various conclusions. When one compares the alpine vegetations of the whole world, it turns out that "alpine" is moulded to fit diverse ecosystems. For instance in the Himalayas the upper limits of vascular plants is exceeded considerably by a life zone that is regarded by some (Swan, 1967) as independent from an alpine zone and is named "aeolian." But in New Guinea as a whole, the alpine zone is fairly uniform and Wade's distinction of various associations is applicable with minor variations over the entire island (Hope, 1973, 1976).

Swan (1967) distinguishes in the alpine region three basic types, the high latitude alpine region, the low latitude alpine region, and a depressed equatorial alpine region. The first permits vascular plants to grow to an altitude in excess of 6100 m, and has a long growing season. In his division the subalpine regions are simply a part of the alpine region. This is mainly based on the fact that both alpine and subalpine regions have in common an autotrophic nutrition, while the aeolian vegetation has a heterotrophic nutrition. However, from a descriptive vegetational standpoint and the different composition it is worthwhile to divide Swan's alpine region into a subalpine and alpine region, the upper limit of the first being groups of shrubs and small trees against grasslands, the upper limit of the former being the presence of vascular plants. Swan (1967) also insists that all subalpine (and alpine) biota have an underlying similarity — a basic climatic relationship — that permits comparison of the alpine regions of the world. Also broadly structural affinities between the communities in several parts of the world can be noticed.

In later studies carried out among others by Hope (1973, 1976) for the Carstensz Mountains, by J.M.B. Smith for Sigal Mugal, and by myself on Mount Giluwe and in the Finisterre Mountains (1976), the results, with minor variations, are the same as given by McVean and Wade. There is reason to believe that the scheme as drawn up for Mount Wilhelm is applicable to all high altitude regions over the entire island of New Guinea, be it with a few small alterations.

Contrasts between vegetation belts on mountains in the humid tropics and in the temperate zones and their controlling factors have been stressed by Troll (1959, 1973). The major ecological contrast lies in the limited variation in temperatures and daylength through the year on tropical mountains, by comparison with the harsh alternation of winter and summer conditions in the temperate zones. Thus periods of snow lie, avalanche tracks and a short frost-free growing season are factors of ecological importance only in the latter case. As a result, the vegetation of temperate mountains shows features not shared with its tropical counterpart, such as rigidly seasonal phenology, and forests at their upper limit consisting only of one or a few tree species. Factors controlling vegetation zonation are unlikely to be the same in the two situations.

Some workers have questioned whether terms used to describe vegetation belts in temperate zone mountains should be used as well for tropical mountains. Hedberg (e.g. 1864) has coined the term afroalpine for the vegetation above the forests of East African mountains. Troll (1959) proposes a series of terms for Andean vegetation belts which he suggests could be used for all mountain regions in the humid tropics.

In the New Guinea context J.M.B. Smith (1974, 1975) has rejected uncritical usage of the temperate zone terms alpine, subalpine and montane. Since Hedberg's term afroalpine has obvious regional connotations, and Troll's terminology is not appropriate (e.g. the lower paramo belt, characterized by pachycaulous megaphytes, has no clear New Guinea analog), Smith has proposed the term tropicalpine to describe environments above and outside the mountain forests. More specifically he suggests a series of terms (tropicalpine tundra, upper mountain grassland, natural and anthropogenic lower mountain grassland, mountain forest) which are primarily physiognomic in definition. and not intended for close comparison with terms applied to any other regions since the factors controlling vegetation distribution in New Guinea mountains are as yet poorly understood.

In the sequence from cloud forest or montane forest to alpine grasslands there is a distinct change in the coverage of the forest trees, a reduction in number of species and the disappearance of lianas, though climbing and scrambling shrubs like *Alyxia, Jasminum, Rubus,* and *Schefflera* are not uncommon in the subalpine ecotone. Gradually grasses and herbs of the subalpine grasslands appear in the picture with increasing altitude, but also from the interior of the forest to the grasslands at equal altitudes. Many of these herbs are of temperate origin like *Rhododendron, Vaccinium, Dimorphanthera, Potentilla, Gentiana,* and *Ranunculus* species, with the additional attraction that in New Guinea representatives of the northern *Ericaceae* meet representatives of the southern *Epacridaceae* in the same ecotone. In the upper subalpine zone the grasslands are the dominant feature with a mosaic of associations with bunch grasses, typical of the southern hemisphere and those with short grasses more typical for the northern hemisphere.

Alpine Zone

The concept of an alpine zone always has been a fairly constant one. It is a treeless zone bordering a transitional subalpine zone and along its higher altitudinal border limited by the last vascular plants (Du Rietz, 1928, 1964, Burnett, 1964, Meusel, 1965, Troll, 1959, Mani, 1962).

Definitions

Resuming all that has been stated the following definitions can be drawn up:

Upper Montane Zone

A 3-storied generally closed forest composed of one tree layer, one shrub layer, and one herb layer. Tree layer between 2-6 m high with the crowns apart, trunks often crooked; emergent trees up to 10 m sometimes present, mainly conifers.

Autotrophic system. Ground coverage by the trees 30-70 per cent. Average temperatur 10-12°C. Average humidity close to 100 per cent RH. Lower limit the gradual change over from a 5-layered closed forest to a 3-layered open forest. Upper limit determined by the 10°C isotherm for the warmest month of the year. No seasonal differences visible; diurnal differences extensive. Dominant genera: *Rhododendron, Vaccinium (Ericaceae), Papuacedrus (Cupressaceae), Dacrycarpus, Podocarpus (Podocarpaceae), Rapanea (Myrsinaceae), Xanthomyrtus, Decaspermum (Myrtaceae), Dendrobium, Bulbophyllum (Orchidaceae), Pittosporum (Pittosporaceae).* Bamboos (*Nastus* sp.) locally abundant.

Altitudinal range (2600-) 3000-3450 (-3800) m.

Subalpine Zone

A 3-storied open forest composed of one tree (usually crooked or shrublike) layer, one shrub layer, and one (sparse) herb layer. Tree layer 3-10 m high, with the crowns apart, trunks crooked; emergent trees still present. In higher altitudes grasslands with scattered shrubs. Autotrophic system. Ground coverage by trees 0-50 per cent. No seasonal differences, distinctly diurnal differences in all subalpine forests. Average humidity 25-50 per cent RH. Rainfall exceeding evaporation, mainly in the period from December to March.

Lower limit: gradual transition zone between upper montane forest and subalpine forest, though grasslands can extend well below this limit.

Upper limit: the changeover from shrubby forest to grassland with a transitional zone between 3400-3650 m from the lower subalpine grasslands, tall shrubs forming the limit to the grasslands.

Dominant genera in the lower (tree-shrub) part: *Dacrycarpus, Podocarpus (Podocarpaceae), Papuacedrus (Cupressaceae), Trochocarpa (Epa cridaceae), Rapanea (Myrsinaceae), Daphniphyllum (Daphniphyllaceae), Dimorphanthera, Rhododendron, Vaccinium (Ericaceae), Olearia, Senecio (Asteraceae), Pittosporum (Pittosporaceae), Schefflera (Araliaceae).* In the grasslands of the lower altitudes *Cyathea* sp. are dominant. Epiphytes less than in upper montane forests, mainly orchids. Dominant genera in higher (grassy) part: *Cyathea (Cyatheaceae), Gahnia, Carex (Cyperaceae), Danthonia, Deschampsia, Deyeuxia, Poa (Poaceae), Astelia (Liliaceae), Gaultheria (Ericaceae), Styphelia (Epacridaceae), Coprosma (Rubiaceae).*

Altitudinal range: (300-) 3360-3900 (-4200) m.

Alpine Zone

Grasslands alternating with tundras and heaths, composed of various communities of herbs. Autotrophic system. Ground coverage by grasses and herbs 5-100 per cent. No seasonal differences, marked diurnal differences in temperature and humidity. Average temperature (-3.2°-) 1.1°-4.4°(-8.3°)C, almost every night falling below zero. Average humidity (1-)5-39(-63) per cent RH. Rainfall less than evaporation, mainly in the period from December to March, sometimes as hail or snow.

Lower limit: gradual transition zone between subalpine grasslands and alpine grasslands. Upper limit: snowline (in N.G.), up to line of growth of highest vascular plants (outside N.G.).

Dominant genera: *Anthoxanthum, Danthonia, Deschampsia, Festuca, Poa (Poaceae), Carex, Carpha, Oreobolus, Uncinia (Cyperaceae), Scleranthus (Caryophyllaceae), Styphelia (Epacridaceae), Tetramolopium (Asteraceae), Epilobium (Onagraceae),* mosses, lichens, and some ferns.

Altitudinal range: (3000-) 3300-4100 (-4600) m.

Selected References

Ahti, T., L. Hamet-Ahti, J. Jalas, Vegetation zones and their sections in northwestern Europe - *Ann. Bot. Fenn.* 5 (1968) 169-211.

Boughey, A.A., The nomenclature of the vegetation zones on the mountains of tropical Africa - *Webbia* 11 (1955) 413-422.

Brass, L.J., The 1938-39 expedition to the Snow Mountains - *J. Arnold Arb.* 22 (1941) 271-342.

Brockmann-Jerosch, H., Baumgrenze und Klimacharacter — *Beitr. Geobot. Landesaufn.* 6 (1919) 255.

Candolle, Alph. de, Géographie botanique raisonnée ou exposition des faits principaux et des lois concernant la distribution géographique des plantes de l'epoque actuelle. 2 vls. (1855).

Candolle, Alph. de, Constitution dans le régne végétal de groupes physiologiques applicables a la géographie botanique ancienne et moderne - *Bibl Un Arch. Sc. Phys. Nat.*, N.S., 50 (1974) 5-42.

Candolle, Aug. de, Géographie agricole et botanique, in: Nouveau cours complet d'agriculture théorique et pratique, ou dictionnaire raisonnée et universelle d'agriculture. théorique et pratique, ou dictionnaire raisonnée et universelle d'agriculture. Vol. 6 (1809).

Clements, F.E., Nature and structure of the climax — *J. Ecol.* 24 (1936) 253-284.

Coe, M.J., The ecology of the alpine zone of Mount Kenya - *Monogr. Biol.* 17 (1967).

Cordeeva, T.H., and O.S. Strelkova. Prakticheskiy kurs geografii rastenyi (Practical course in plant geography) (1968) 335 pp.

Dansereau, P., Biogeography (1957) 394 pp.

Daubenmire, R.F., Alpine timberline in the Americas and their interpretation - *Butler Univ. Bot. Studies* 11 (1954) 119-136.

DuRietz, G.E., Nordsvenska vegetationsregioner, in - *Festskrift tilläagnad Carl Kempe 80 år*, 1884-1964 (1964) 309-324.

Gams, H., Die Waldklimate der Schweizer Alpen, ihre Darstellung und ihre Geschichte - *Verh. Naturf. Ges. Basel* 35 (1923) 262-276.

Gams, H., Pflanzenleben des Glocknergebietes, kurze Erläuterungen der Vegetationskarte - *Zeitschr. Deutsch-Oesterr. Alpenverein* 66 (1935) 157-176.

Grubb, P.J. & P.F. Stevens, The forests of the Fatima Basin and Mt Kerigomna and a review of Montane and Subalpine Forests elsewhere in Papua New Guinea - *ANU BG/5* (1976).

Hedberg, O., Vegetation belts in the East African mountains - *Sv. Bot. Tidskr.* 45 (1951) 140-202.

Hedberg, O., Afroalpine vascular plants. - *Symb. Bot. Upsal.* 15 (1957) 411.

Hedberg, O., Features of afroalpine plant ecology - *Acta Phytogeog. Suecica* 49 (1964) 144.

Hedberg, O., Evolution of the afroalpine flora - *Biotropica* 2, 1 (1970) 16-23.

Hnatiuk, R.J., J.M.B. Smith, D.N. McVean, The climate of Mount Wilhelm - Mount Wilhelm Studies 2. *A.N.U. BG/4.* Canberra (1976).

Hoogland, R.D., The alpine flora of Mount Wilhelm - *Blumea Suppl.* 4 (1958) 220-238.

Hope, G.S., The vegetation history of Mount Wilhelm, Thesis. Canberra (1973).

Hope, G.S., and others, The equatorial glaciers of New Guinea (1976).

Humboldt, A. von, De distributione geographica plantarum secundum coeli temperiem et altitudinem montium, prolegomena (1817).

Humboldt, A. von & A. Bonpland, Essai sur la géographie des plantes. (1805).

Kalela, A., A comparison of forest regions in North Ontario and Quebec with those in Finland, in: Baldwin, Report on the botanical excursion to the boreal forest region in Northern Quebec and Ontario (1962).

Kalkman, C., Description of vegetation types in the Star Mountains region, West New Guinea - *Blumea* 15 (1963) 247-261.

Köppen, W., Baumgrenze und Lufttemperatur - *Petermann's Mitt.* 65 (1919) 201-203.

Köppen, W., Das geographische System der Klimate in: *Handbuch der Klimatologie* 1 (1936) 1-44.

Krajina, V.J., Die Pflanzengesellschaften des Mlynice-Tales in den Vysoka Tary 1 - *Beih. Bot. Zentralbl.* 50 (1933) 774 - 957.

Lam, H.J., Fragmenta Papuana (1927-1929) (In Dutch). English translation in *Sargentia* 5 (1945). See for full citation in Selected References at end of Chapter on History of the Exploration of the high altitude regions of New Guinea.

Lane-Poole, C.E., The forest resources of the Territories of Papua and New Guinea (1925).

Löve, D., Book review in *Arctic and Alpine Research* 2 (1970) 231-232 (Wade & McVean, Mt. Wilhelm Studies 1, 1969).

Löve, D., Subarctic and subalpine: Where and what? - *Arctic and Alpine Research* 2 (1970) 63-73.

Mani, M.S., Introduction to high altitude insects (1968) 527 pp.

Meusel, H., E. Jaeger, E. Weinert, Vergleichende Chorologie der zentraleuropäischen Flora (1965).

Raunkiaer, C., The life forms of Plants and Statistical Plant Geography (1934).

Robbins, R.G., Montane formations in the Central Highlands of New Guinea in: Symposium Humid Tropics Vegetation (1958).

Schweinfurth, U., Die horizontale und vertikale Verbreitung der Vegetation in Himalaya - *Bonner Geogr. Abh.* 20 (1957) 373 pp.

Smith, J.M.B., Origins and ecology of the non-forest flora of Mount Wilhelm. Unpublished thesis. Canberra (1974).

Smith, J.M.B., Mountain grassland of New Guinea - *J. Biogeogr.* 2 (1975) 87-101.

Smith, J.M.B., Origins and ecology of the tropicalpine flora of Mt Wilhelm, New Guinea - *Biolog. J. Linnean Soc.* 9 (1977) 87-131.

Swan, L.W., Some environmental conditions influencing life at high altitudes - *Ecology* 33 (1952) 10-111.

Swan, L.W., The ecology of the high Himalayas - *Scientif. Amer.* 205 (1961) 68-78.

Swan, L.W., Alpine and Aeolian Regions. in W.E. Wight and W.H. Osburn, Arctic and Alpine Environments (1968) 29-54.

Troll, C., Der asymmetrische Aufbau der Vegetationszonen und Vegetationsstufen auf der Nord- und Südhalbkugel - *Ber. Geobot. Forsch. Inst. Rübel* (1947) 46-83.

Troll, C., Die tropischen Gebirge. Ihre dreidimensionale klimatische und pflanzengeographische Zonierung - *Bonner Geogr. Abh.* 25 (1959) 93.

Troll, C., Die "Baumfarnklima" und die Verbreitung der Baumfarne auf der Erde *Tübinger Geogr. Stud.* 34 (1970) 179-189.

Troll, C., The upper timberline in different climatic zones, in: J.D. Ives and K.A. Salzberg, Proc. Symp. I.G.U., Comiss. High Altitude Geoecology (1973) A 3-A 18 (*Arctic and Alpine Research* 5, 3, 2, 1973, Special Issue).

Troll, C., High Mountain belts between the polar caps and the equator: Their definition and lower limit, in: Ives & Salzberg, l.c., (1973) A 19-A 27.

Wade, L.K., The alpine and subalpine vegetation of Mount Wilhelm, New Guinea. Unpublished Thesis. Canberra. 1968.

Wade, L.K. & D.N. McVean, Mount Wilhelm Studies I: The Alpine and Subalpine Vegetation - *A.N.U., BG* 1 (1969) 225 pp.

Wahlenberg, G., Flora lapponica, exhibens plantas geographice et consideratis in Lapponis suecicis (1812).

Wahlenberg, G., De vegetatione et climate in Helvetia septentrionali inter flumina Rhenum et Arolam observatis et cum summi septentrionis comparatis tentamen (1813).

Wahlenberg, G., Flora Carpatorum principalium exhibens plantas in montibus Carpatis inter flumina Waagum et Dunanetz eroumque ramos Arvam et Popradum crescentes. Cui praemittitur Tractatus de altitudine, vegetatione, temperatura et meteoris horum montium in genera (1814).

Walker, D., A reconnaisance of the non-arboreal vegetation of the Piundaunde catchment, Mount Wilhelm - *J. Ecol.* 56 (1968) 445-466.

Walker, D., Highland vegetation - *Austr. Nat. Hist.* 17, 12 (1973) 410-419.

Weaver, J.E. & F.E. Clements, Plant Ecology (1938) 601 pp.

Webster, G., The altitudinal limits of vascular plants - *Ecology* 42 (1961) 587-590.

3. GEOLOGY AND GEOMORPHOLOGY OF THE NEW GUINEA HIGH MOUNTAINS

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1. Introduction

The dominant physiographic feature of the island is a rugged central mountain range stretching from west to east over the entire island. This central range or central cordillera as it is occasionally called, is not a simple mountain range but consists of a complex series of east-west trending ranges and occasional intervening upland plains (the so-called intramontane basins) and numerous volcanic cones and domes often towering above the surroundings. The central ranges are highest in West New Guinea where The Pyramid reaches the altidude of 4884 m and Mount Wilhelmina 4750. In Papua New Guinea the highest peaks are Mt Wilhelm (4510 m) and Mt Giluwe (4368 m).

North of and parallel to the central ranges run the much narrower northern ranges. These are separated from the central ranges by a major structural depression, the intermontane trough that also runs through the entire island from Geelvink Bay in the west to the Huon Gulf in the east where it continues as a submarine depression into the Solomon trough.

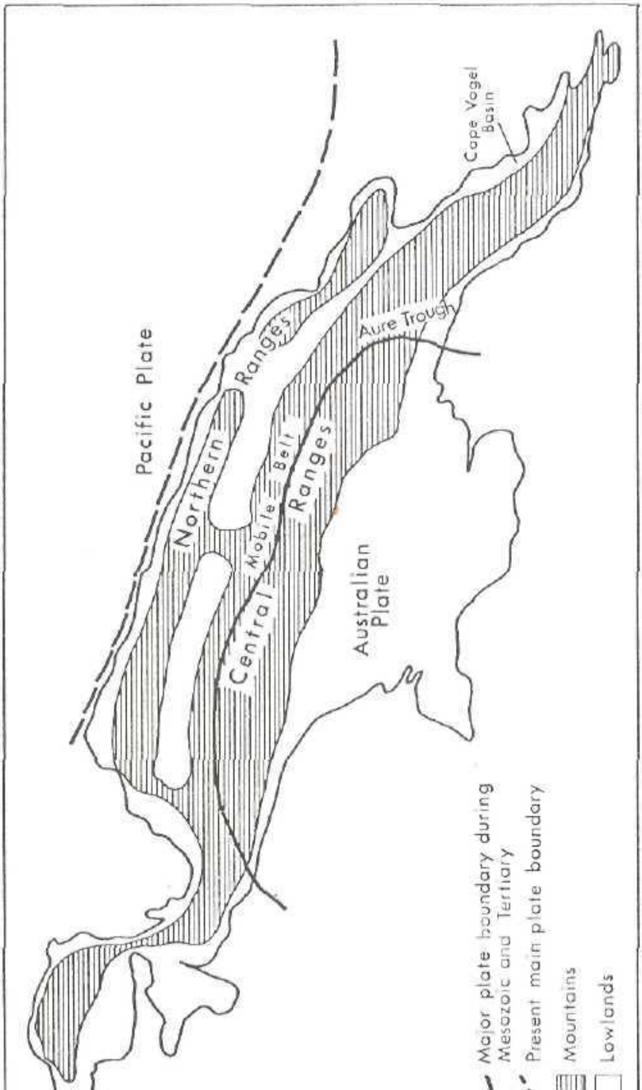

Fig. 1. Major geological features.

Although the central ranges contain most of the alpine environments that are of concern in this book there are some small alpine areas in the Sarawaket and Finisterre Ranges at the extreme eastern end of the northern ranges.

Since the geological and geomorphological development of the alpine mountain areas can not be explained in isolation from the surrounding areas it is necessary to start with a brief summary of the events leading to the formation of the present land mass of New Guinea and its mountains. This will be followed by a more detailed account of the geomorphology of the various alpine mountains.

2. Geological Evolution of New Guinea

New Guinea is situated between and is part of two major crustal elements, the continental land mass of Australia to the south and the deep ocean basin of the Pacific to the north. In terms of plate tectonics the two elements are the continental plate of Australia and the Pacific plate (Fig. 1). The development of the present land mass of New Guinea is the result of the interaction between and collision of these two plates with the Australian plate drifting northwards from its late Palaeozoic position in the vicinity of the south pole and southern New Guinea forming the northern rim of the advancing continent. It is obvious that the Australian continent must have moved through various climatic zones during this movement and the environment must have adapted to this continuous change to progressively warmer conditions. The final separation of the Australian plate from Antarctica took place about 53 million years ago at about the turn from Mesozoic to Tertiary and the Australian and southern New Guinea land mass has remained isolated from other land masses ever since (southern New Guinea was a submerged shallow shelf area for most of the Tertiary but it always formed part of the Australian land mass in the wider sense).

Since the Australian plate was moving north and the Pacific plate moving west the collision between the two plates resulted not only in compression but also in strike slip movements and rotations and differential movements of smaller plates particularly in the area northeast of mainland New Guinea.

The depositional environments on the two plate margins were strikingly different. Shallow water terrestrial and shelf type sediments were deposited on the continental plate while goesynclinal sediments were laid down on the southern margin of the Pacific plate in the so called mobile belt (Dow, 1977). The boundary between the two major plates roughly

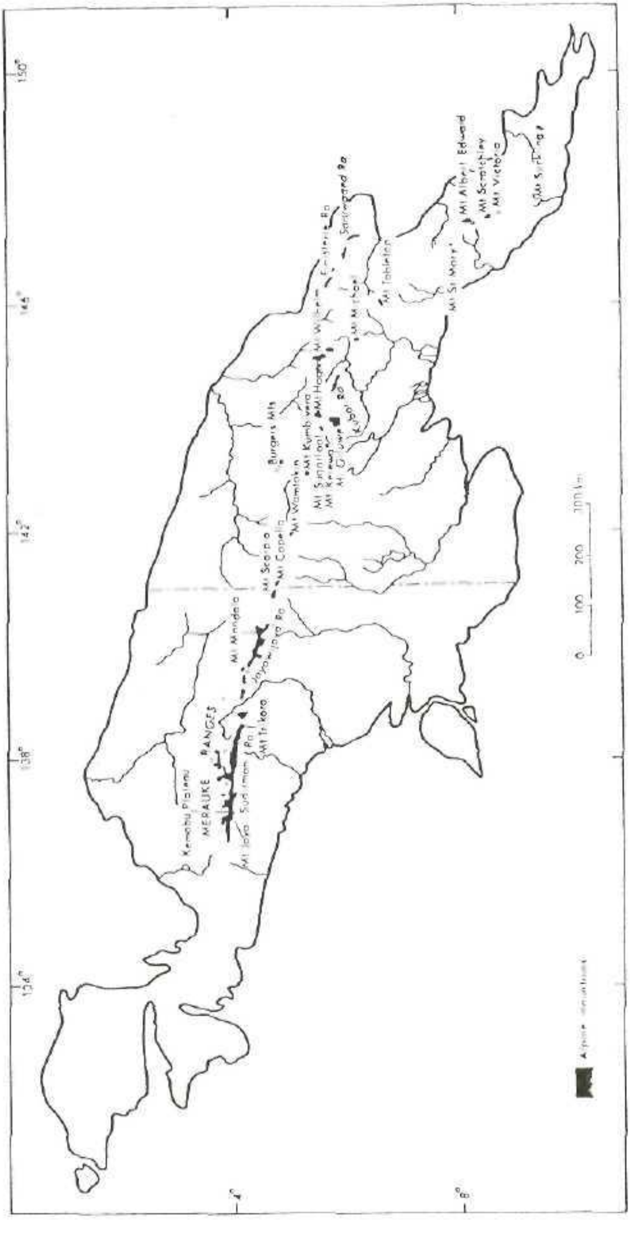

Fig. 2. Distribution of alpine areas (roughly coinciding with extent of Pleistocene glaciation). (After Löffler, 1972, Hope & Peterson, 1975).

coincides with the main watershed and is marked by prominent fault zones such as the Lagaip and Bismarck fault zones (Fig. 2). The sediments on the stable continental platform are largely horizontal or only gently warped except along the northern extremity where some broad folding and faulting has taken place leading to such prominent features as the Müller Anticline or the series of limestone hogbacks to the north of it. In contrast the sediments of the mobile belt have been considerably altered by metamorphism and plutonic and volcanic intrusions since the late Mesozoic. Intrusive activity is entirely absent from the platform and volcanic acitivity did not take place until the Pliocene-Pleistocene transition with the formation of the highland volcanoes.

The oldest rocks found in New Guinea are lower Paleozoic and occur in the northern mountain areas of the western peninsulas where they are overlain unconformably by Permo-Carboniferous rocks indicating a Paleozoic orogeny. In the central ranges, however, lower Paleozoic rocks are overlain conformably by Permo-Carboniferous rocks and no Paleozoic orogeny seems to have taken place there. A connection between the Paleozoic orogeny of the western peninsulas and the Tasman geosyncline in eastern Australia is therefore unlikely (Visser & Löffler, 1975).

During most of the Mesozoic, the Paleozoic basement block of the Australian plate to the south formed an area of terrestrial deposition with the accumulation of sandstone, greywackes and mudstones from probably a southern supply area since there is no indication of a land mass to the north. Deposition continued into the early Tertiary but the character of sediments changed from clastic to calcareous. The deposition of shallow limestone continued well into the Miocene resulting in massive beds of limestone that today form the spectacular karst country in the southern part of the central ranges.

In the mobile belt to the north of the basement block a great thickness of marine basic volcanics and volcanically derived sediments was deposited in the developing geosyncline from late Triassic times onwards (Dow, 1977). Periods of volcanism alternated with deposition of terrestrial material. In the Cretaceous and the Eocene the geosyncline reached its fullest development with the deposition of a great thickness of shales, turbidites, marine volcanics and limestone. A period of further volcanism in the middle Miocene was followed by intense tectonism accompanied by the emplacement of large plutons such as the Bismarck Granodiorite that now forms the highest mountain massif of Papua New Guinea. Faulting was intense resulting in series of complex faults with large vertical throws.

The present land mass of New Guinea started to develop in the lower Miocene with the emergence of the mobile belt which has remained dry land ever since. However, it was not until the Pliocene, some 5-6 million years ago, that the present land mass of New Guinea finally became established. Vertical movements in the order of several thousand metres occurred along major faultlines and created the present mountainous relief. Folding was not as important being largely restricted to the northern margin of the basement block where large amplitude folds such as the Müller Anticline were formed. Some tighter folding occurred in the transition zone between the basement block and the mobile belt where today we see series of steeply dipping limestone hogbacks.

In the eastern tail of the island the development was somewhat different as here Jurassic-Cretaceous crusts overrode the Mesozoic sediments in the lower Eocene which in turn was followed by extrusion of great volumes of basalt onto the deep ocean floor to the south-west of the metamorphosed zone. This is thought to have been the result of the opening of the Coral Sea by sea floor spreading (Davies & Smith, 1971). The emergence of the eastern land mass began in the upper Oligocene and continued throughout the Miocene and was accompanied by vigorous erosion leading to the filling up of the two adjoining basins, the Cape Vogel Basin to the east and the Aure through the west (Fig. 1).

Uplift has continued till today but the main centres of tectonic activity appear to have moved from the central ranges to the northern ranges where maximum rates of uplift are in the order of 3 m/1000 years (Chappell, 1974). It is important to realize that even though not noticeable on a human time scale, in geological terms this a spectacular rate of uplift and the rates of uplift of the New Guinea mountains even during times of intense tectonic activity are unlikely to have been much greater.

Uplift was not uniform and at least two major phases of uplift interrupted by a period of relative stability can be recognized. Evidence for this is found in plateau-like relict land surfaces of low relief along the main watershed of the Owen Stanley Range, possibly continuing into the Sarawaket Range (Löffler, 1977). Much of the highland area of Papua New Guinea also has the character of a relict surface.

Accompanying or closely following the uplift was extensive volcanism in the eastern half of the island. The exact date of the start of the volcanism is not known but it appears certain that by mid Pleistocene most of the volcanoes had been in existence for some time. The oldest dates reported in the literature have been 1.1 Million years B.P. from Kara Plug south-west of Mt Ialibu (Bain *et al.*, 1975) and 0.85 million years B.P. from Mt Iume north-west of Tari (Williams *et al.,* 1972). Dating of rocks from the Doma Peaks area give even older dates ranging from 1.6 million to 1.18 millian years B.P., while the oldest rocks so far found on Mt Hagen and Mt Giluwe are 1.27 and 0.86 million years (Löffler, in preparation).

The volcanoes formed at or close to their present altitudes since they erupted onto a deeply dissected mountain landscape with a drainage system very similar to the present one. A number of drainage basins were changed or disrupted by the volcanic events and this resulted in the formation of several intramontane basins. Some of these are simply valleys filled in with volcanic debris while others experienced more severe disruptions such as drainage reversals (Löffler, 1977). Not all the intramontane basins are the result of volcanic activity, some are tectonic or structural in origin while others may be relics of erosional basins formed close to sea level.

3. Quaternary Development

Apart from the vigorous fluvial erosion that affected the entire mountain area and created the typical ridge and V valley landforms the most important erosional process in the high mountains was glacial erosion and many of the alpine areas described in this book are in fact glacially modified mountains (Fig. 2). The total extent of these is in the order of 2000 km^2 which can be taken as a rough estimate also of the size of the alpine environments. The formerly glaciated mountains contrast sharply with the non-glaciated mountains because of the different appearance of the valleys with an open U-shaped or saucer-shaped cross section in the glaciated terrain and narrow V-shaped profiles in the non-glaciated areas. This contrast is often accentuated by the presence of grassland in the swampy valley floors of the glaciated valleys. The side-slopes of the glaciated valleys are usually very steep and often covered by rock screes originating from rocky cliffs higher up. However, most of the screes are not actively moving or forming at present. Only in altitudes above about 4350 m do we find active screes. Free rock faces are prominent at these altitudes and frost weathering seems to ensure a constant supply of rock debris to the screes.

There is now growing evidence that the New Guinea mountains experienced more than one glaciation. On Mt Giluwe volcanic eruptions alternated with periods of ice cover as long ago as 290 000 years and there is also pollen evidence for cold conditions well before 33 000 years B.P. (Williams *et al.,* 1972). There is also evidence from the Mt Carstensz area of glacial deposits outside the limits of the last glaciation but so far no dating has been possible (Dow, 1968; Hope *et al.*. (1976). This of course is a further proof that the New Guinea mountains must have reached altitudes similar to the present ones in the mid Pleistocene. The general lack of evidence for older glaciations is probably due to the removal by erosional processes of traces of this glacial activity or simply to the unexplored nature and difficulty of access of much of the area.

During the last glaciation which was synchronous with the Würm or Wisconsin glaciation of the northern hemisphere, the snowline was at about 3550-3600 m. The extent of the ice cover varied of course with the extent of the mountain mass above the snowline. The larger this area above the snowline, the greater was the extent of the ice cover. Glacial action was considerable and its traces are still clearly visible today with U-shaped valley, over-deepened rock basins often filled with lakes and long, well-preserved moraines making the alpine areas some of the scenically most attractive parts of the country.

The temperature depression was about 5-6° C in the mountain areas but seems to have decreased with decreasing altitude because of the likelihood of an increased lapse rate due to cooler, drier air masses (Nix & Kalma, 1972). This temperature depression resulted not only in the formation of glaciers but also in a general lowering of the vegetation zones and climatic geomorphological belts such as the zone of periglacial solifluction which is the zone of diurnal frost and thaw action. However, there is little geomorphic evidence that this shift of altitudinal zones had any significant geomorphic ramification other than glaciation. All evidence for Pleistocene periglacial activity has been found inside the formerly glaciated area and such activity must have taken place shortly after the ice had receded. This observation is not surprising if one looks at the present day distribution of the periglacial zone. Significant periglacial processes occur only from about 4350 m upwards. The zone is thus compressed to a mere 200-300 m altitude range which is surely the result of the great uniformity of the climate with its lack of diurnal temperature extremes. During the Pleistocene the ice on most mountains extended well below the snowline and thus covered most of the areas that were climatically suitable for periglacial activity.

Extensive grasslands covered much of the areas below the ice and there also seems to have been no significant increase or radical change of the erosion processes if one takes rate of the present day processes in the grassland areas as a measure. At present most grasslands extend down to about 3200 m but this is not the natural forest/grassland boundary which is at between 3800 and 3900 m. The dense cover of peaty soil and dense tussock grasses serve as good protectors against soil erosion and the lack of suspended material is typical for the alpine streams.

There is a problem in reconciling palynological evidence and geomorphic observations of the lower limit of the grassland. According to Hope (1976) and Walker (1970), Bowler *et al.* (1976) the grassland communities extended down to about 1900-2100 m between 38 000 and 30 000 years B.P. and to 2000-2500 m between 30 000 and 12 000 years B.P. This means that the depression of the grassland/forest boundary was nearly twice the amount of the lowering of the snowline which was depressed from its present position of about 4600 m to 3550 m. To explain this discrepancy would require considerable climatic changes in addition to the temperature depression. It would for instance demand a considerably lower precipitation and a more pronounced diurnal temperature range perhaps similar to the present day conditions on Mt Kenya where the altitude difference between forest/grassland boundary and snowline is 1500 m. The present day and Pleistocene snowlines are among the lowest tropical snowlines in the world and indicate relatively high levels of precipitation. Any substantial decrease in precipitation would have resulted in a relatively high, not low snowline. Also a more pronounced diurnal temperature variation would have resulted in frost action occurring at altitudes well below the snowline which again is not borne out by field evidence. Greater diurnal temperature variation could have resulted from a large increase in land mass but New Guinea almost certainly remained a highly oceanic climatic zone being surrounded by deep sea except for the Torres Strait area. In Torres Strait and the southern lowlands the climatic situation certainly changed to drier conditions but this would not have affected the high mountains (Nix & Kalma, 1972). A possible explanation for the discrepancy could be that the pollen evidence comes mainly from swampy basins that were forest free because of cold air drainage and swamp conditions and there are many present day examples of this kind of situation.

At about 14 000 years B.P. the ice receded rather rapidly and between 9000 and 7000 years B.P. all the New Guinea mountains were ice-free including those that have a present day ice cover (Hope & Peterson, 1975). Surprisingly neither the glacial activity nor the relatively rapid recession seem to have resulted in large-scale depositional processes such as the formation of fluvioglacial fans outside the glacially covered areas as was common in temperature zones. The reason for this is probably that the regime of melting of these tropical glaciers is diurnal not seasonal and results in relatively low discharge during the daytime spread evenly over the year and therefore a low ability of the glaciers to feed streams to transport sediments.

From about 9000 years B.P. man's impact on the land becomes evident in the widespread destruction of the forest which is indicated in the pollen record of some sites in the highlands and high mountains (Powell, 1970; Hope, 1976) and in the stratigraphy of the Kuk Swamp in the Waghi basin where sedimentation changes from predominantly organic to predominantly inorganic at about 9000 years B.P. (Golson & Hughes, personal communication).

In the high mountains evidence of burning is found at various times during the Holocene from 4000 years B.P. However, destructive as man's impact was in respect to the vegetation it had little effect on the landforming processes and a significant acceleration of processes can not be noted (Loffler, 1977).

4. The Merauke Range (Snow Mountains, Central Ranges)

This range is the highest and most rugged part of the central ranges and its divide is nearly continuously above 3000 m. The Merauke Range contains the highest mountains of the island with two peaks, Mt Carstensz and Mt Idenburg still supporting ice caps. The area used to be the remotest, most inaccessible and least well known alpine area of New Guinea but thanks to the efforts of the two Australian Universities Expeditions (Hope *et al.*, 1976) it has become one of the best researched alpine areas of New Guinea. The following account is based on this work. The centre of interest has been the recent glacial cover of Mt Carstensz and Mt Idenburg and the historic glacier fluctuations (Peterson *et al.*, 1973, Hope *et al.*, 1976) but other aspects of the alpine environment have also been studied.

Mt Carstensz is the highest mountain of New Guinea reaching in The Pyramid 4884 m about sea level. The mountain is part of a range that is capped by a massive limestone block which is bounded by cliffs up to 1000 m high on all sides except the west where the limestone dips down gently to the general level of the range. The limestone sheet is folded into two narrow anticlines and two wider synclines that have been opened up by glacial erosion.

To the south the Carstensz Mountains fall steeply to low foothills but to the north they abut the rolling Kemabu Plateau that extends north for 25 km with altitudes between 3400 and 3800 m. This plateau area has been the site of extensive glacial deposition and huge moraines up to 200 m high form prominent ridges. While on the plateau the moraines lie at about 3400 m altitude, on the southern fall the moraines descend as far down as 2300 m obviously because of the different topographic situation.

The total area covered by ice during the last glaciation amounted to nearly 1000 km^2 and the snowline has been estimated at 3600-3700 m (Hope & Peterson, 1975). The reason for the relative high snowline in comparison with the mountains further east could be somewhat drier conditions caused by the closure of Torres Strait and drying up of the Arafura Shelf. The south-east trades would then not have blown over warm ocean waters but over dry and probably semi arid land.

The recession of the Pleistocene glaciers coincided with the recession on the other New Guinea mountains at about 15 000 years B.P. or possibly earlier since these dates always give minimum ages.

As on Mt Giluwe and Mt Wilhelm the recession of ice was not a continuous melting away but was interrupted by minor readvances which are manifested in numerous recessional moraines. It appears that the glaciers retreated from their maximum extent from about 15 000 years B.P. onwards until they had entirely disappeared at about 7000 years B.P. Four new readvances were found by Hope and Peterson (1975) from 3500 years B.P. to the present.

The present ice cover on Mt Carstensz amounts to about 6.9 km^2, the ice being distributed over five small glaciers. The present glaciers have been retreating since they were first observed at the beginning of the century. The average retreat during the past 35 years has been measured at 33 m/yr for the largest glacier (Meren Glacier) and 16 m/yr for the Carstensz glacier (Hope *et al.*, 1976).

5. The Star Mountains

The Star Mountains are part of the central ranges and extend across the international border from about 141° 15'E to 140° E. Most of the alpine areas are thus situated in West New Guinea as are the highest elevations, but small areas of alpine environments are also to be found on the Papua New Guinea side of the range. The highest peaks are Mt Juliana (4700 m) in West New Guinea and Mt Capella (3850 m) and Mt Scorpion (3830 m) in Papua New Guinea.

There is some confusion about the naming of these ranges. Dutch maps and reports call the Central Range between 141° 15' and 140° the Star Mountains even though there is a distinct gap west of Mt Scorpion. Indonesian maps refer to the ranges on the west New Guinea side as Nassau ranges. In this paper I have used the terms eastern and western Star Mountains for the Papua New Guinea and West New Guinea sections respectively.

The Star Mountains are predominantly formed of massive limestone that is tilted to the north thus giving the mountains a markedly asymmetric cross profile with cliffed faces to the south and smoother gentler slopes to the north. This has of course also influenced the distribution of the glacial ice cover that is most extensive on the north facing slopes. The Pleistocene glaciation of the western Star Mountains has been investigated by Verstappen (1964) and that of the eastern Star Mountains by Shepherd (unpublished). Cirques, glacial valleys and moraines are well developed on both the eastern and western parts of the mountains but the extent of glaciation was considerably greater on the West New Guinea side. Verstappen (1964) estimates an area of 759 km^2 for the glacial cover but a more recent estimate of Hope (1976) is only about half that figure. The glaciers descended to an average altitude of 3200 m with some larger glaciers extending as low as 2940 m. The Pleistocene snowline of 3550-3600 m given by Verstappen agrees well with the estimates from the Papua New Guinea highlands (Löffler, 1972).

The main peak of the Star Mountains, Mt Juliana (4700 m) has a small ice cap covering about 0.29 km^2. The maximum thickness was about 50 m in 1959 (Verstappen, 1964) and the snowline at 4580 m. Since Verstappen's observations the ice cap has been further reduced in size and thickness (Peterson *et al.*, 1973).

6. The Highlands of Eastern New Guinea

The greatest expanse of alpine mountains in eastern New Guinea is to be found in the highland areas (Fig. 2). The term highlands has never been clearly defined but has been used for decades as a regional term describing the central upland areas of the central ranges which are characterized by relative low local relief, broad valleys and inland mountain basins and a dense population. Both Mt Wilhelm and Mt Giluwe have alpine environments measuring well over 100 km^2 in extent while Mt Hagen and the Kubor Range have alpine areas between 20 and 30 km^2 in size. Apart from these main areas of alpine environments there are several isolated mountain peaks that just extend into the alpine zone such as Mts Michael, Tabletop, Kumbivera, Sugarloaf, Kerewa and the Burgers Mountains. All the peaks have only a few square kilometres of alpine conditions.

Mt Giluwe is a huge volcanic dome built up of a succession of thin outwardly dipping lava flows (Plate 1). It rises from about 2000 m at the base to a summit height of 4368 m and measures over 100 km in circumference. The summit area above 3200 m was covered by a more

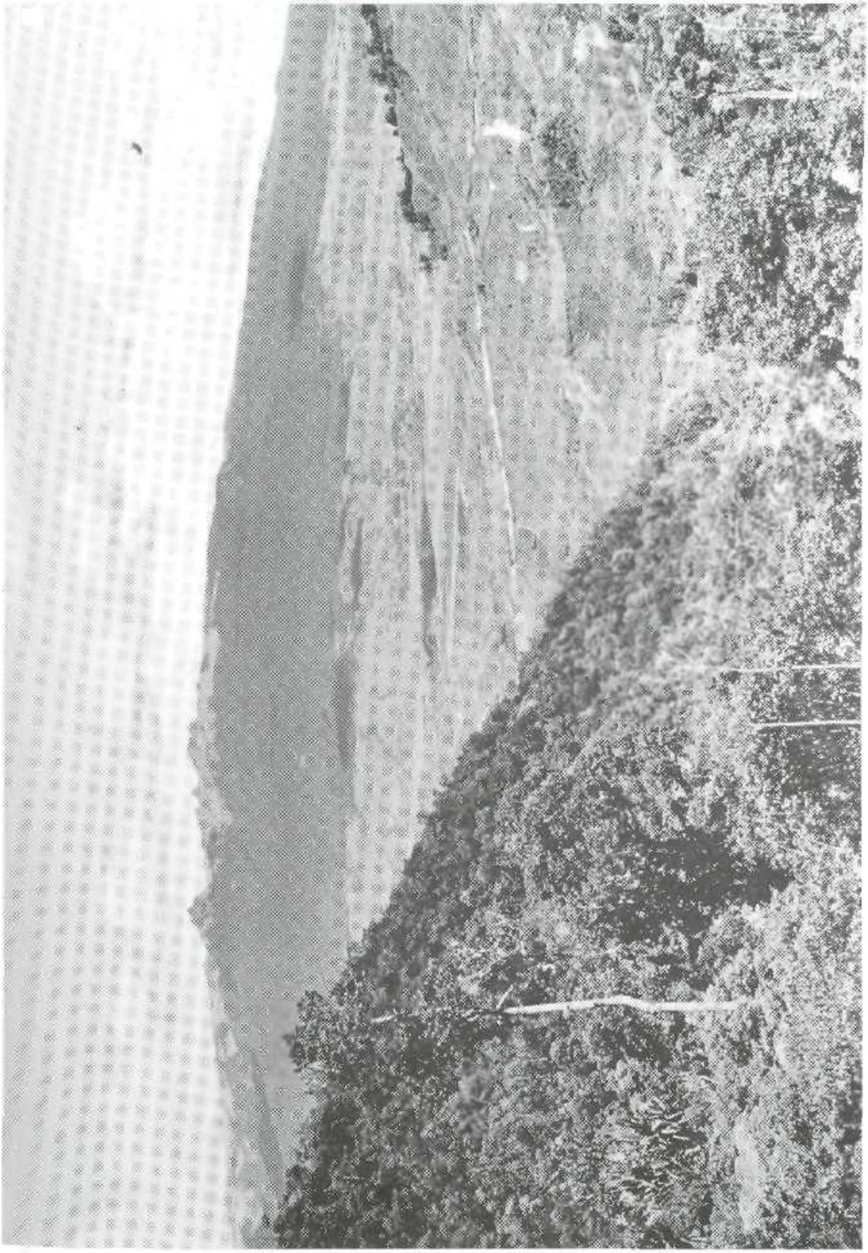

Plate 1. Mt Giluwe is a dome shaped volcano rising 2000 m above the surroundings to a summit height of 4368 m (peak at right). The glacially covered area measures about 188 km^2 and approximately coincides with the area presently under grass cover. (Photo E. Löffler).

Plate 2. Mt Giluwe seen from the east. In the foreground well preserved moraines mark the maximum extent of the last glaciation. Numerous recessional moraines and small glacial basins in the middle ground and castellated east and main peaks in the background. Because of the outward dip of the lavas there are no large glacial basins developed. (Photo E. Löffler).

or less continuous ice cap during the last glaciation and several valley glaciers descended further down to between 2750 and 3000 m.

The glacial landforms have been very well preserved but they are perhaps not as scenically exciting as those on Mt Wilhelm or Mt Albert Edward because of the virtual absence of deep glacial lakes (Plate 2). Nevertheless Mt Giluwe is one of the most interesting alpine mountains of New Guinea because it is the only one where glacial activity alternated with volcanic eruptions thus giving datable evidence for older glacial periods (Löffler, 1976). This evidence is moraine material sandwiched between two lava flows and pelagonitic breccia that must have formed under a considerable ice cover. Initial dating of these indicated that there were two older glacial periods, one at about 340 000 years B.P. the other at about 290 000 years B.P. but more recent results indicate that both the moraines and the pelagonitic breccia formed at the same time at about 285 000 years B.P.

During the last glaciation the summit area was covered by an ice cap covering 188 km^2. The maximum extent of this ice cap can easily be traced because of the excellent preservation of the terminal and lateral moraines that form a nearly continuous belt around the entire mountain (Plate 2). Another striking feature is the multitude of recessional moraines present. There are over 20 individual moraines forming low ridges 0.5-5 m high and they occur on the valley floors of U-shaped valleys, on the inner sides of lateral moraines and in bundles of 2 to 7 ridges on the eastern and south-western slopes (Plate 3). These recessional moraines represent minor readvances during the general ice retreat which started at about 15 000 years B.P. and was completed by about 10 000 years B.P.

Mt Wilhelm is an extensive granodiorite massif and is the highest mountain of Papua New Guinea. Although higher than Mt Giluwe the glaciated area is only little more than half that of Mt Giluwe. However, the glaciation is more truly alpine in character with deep cirques with precipitous cirque backwalls and over-deepened floors that contain large lakes, deep glacial troughs with shoulders and stepped valley profiles and extensive terminal and lateral moraines (Plate 4).

Most of the cirques are situated west and south-west of the summit ridge. This asymmetry in cirque distribution has been attributed to the preglacial asymmetry of the massif favouring extension of the ice in a westerly and south-wersterly direction (Reiner, 1960). This asymmetry is, however, not restricted to cirques and glaciers but is also apparent in general slope profiles with smoother and gentler east-facing slopes and more irregular and steep west-facing slopes.

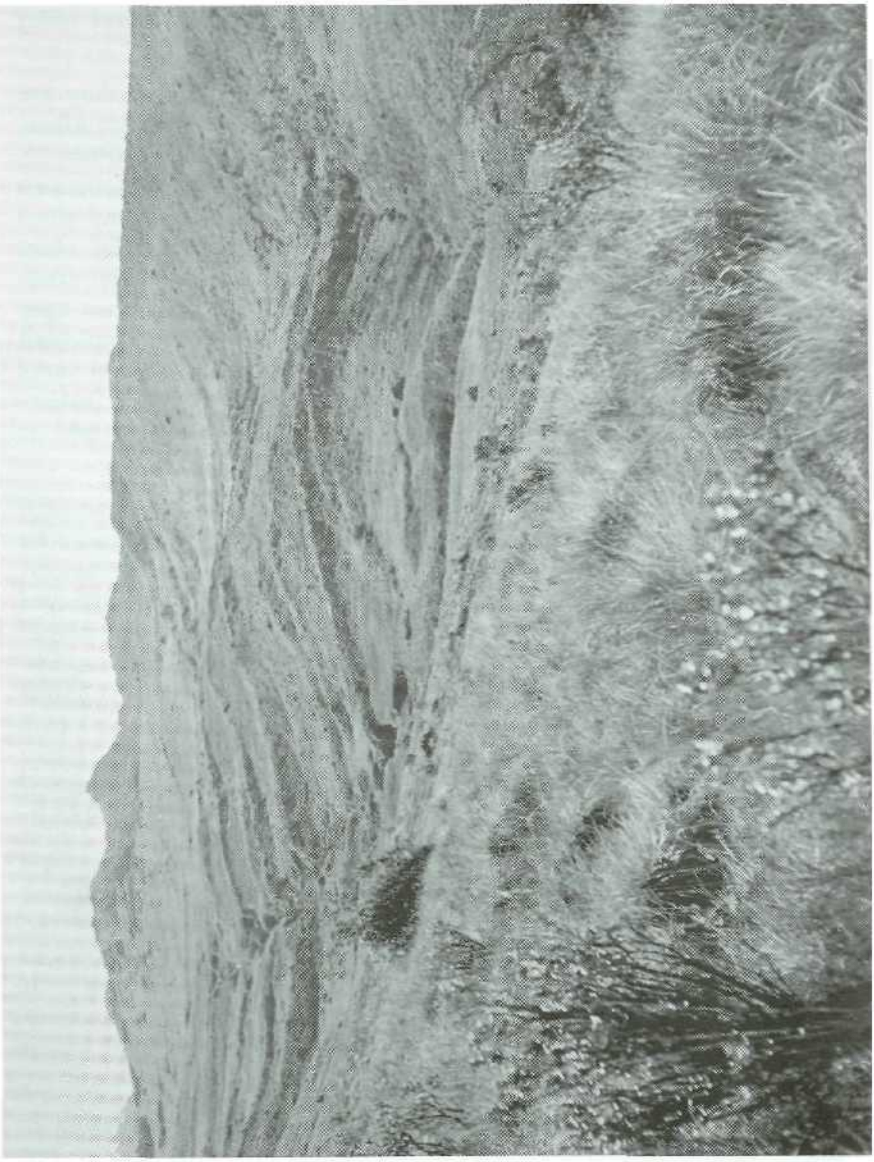

Plate 3. One of the most striking features on Mt Giluwe is the multitude of small recessional moraines on the eastern and western (shown here) slopes. Some of these even overtop the large moraines of the main glaciation (right) probably because they were formed by a thin ice cap very sensitive to small climatic fluctuations but with little erosive power. (Photo E. Löffler).

Plate 4. General view of Mt Wilhelm from the south-east showing the deep U-shaped valleys, rocky summit areas and the high, sharp-crested lateral and terminal moraines at the end of the glacial valleys (foreground). (Photo E. Löffler).

A similar asymmetry has been observed in mountains of subtropical latitudes but here it is a north-south asymmetry due to the difference in sun insolation between north and south aspect favouring glacial activity on the northern slopes but periglacial solifluction on the south sides. A similar explanation could be sought for Mt Wilhelm except that it is not the difference in insolation between north and south but between east and west caused by the fact that in the tropics east facing slopes receive more sun insolation than west facing slopes because of the rapidly increasing cloud cover during the day. A similar explanation has been used to explain the asymmetry in plant distribution on Mt Wilhelm which extends further up on eastern aspects than on western aspects (Smith, 1977).

One difficulty with this climatic explanation is that this kind of asymmetry is not present on other New Guinea mountains but it may be that there structural control overrides the climatic factors (Loffler, 1977).

Mt Wilhelm has also a small area of periglacial solifluction just below the main summit. Needle frost and pipkrake have been reported from as low as 3600 m (Smith, 1977) but these are occasional occurrences and have no geomorphic significance.

True periglacial solifluction does not take place regularly below about 4350 m as shown by solifluction screes, stone stripes and stone rings (Loffler, 1975) (Plate 5). The small vertical range of the solifluction zone is attributable to the uniformity of the oceanic tropical climate with its narrow range of diurnal temperatures.

Mt Hagen is situated some 40 km north of Mt Giluwe and is also an extinct volcano probably somewhat older than Mt Giluwe (Plate 6). Glacial features are restricted to the small summit area and include cirques and moraines none of which are particularly well developed. During the maximum extent of the glaciation about 21 km^2 were covered by an ice cap from which short lobes descended down to about 3400 m.

The Kubor Range is a west-north-westerly trending ridge formed of old Paleozoic rocks that are flanked on either side by Mesozoic and Tertiary rocks. Structurally the Kubor Range constitutes a broad anticline and this is well expressed topographically. Clear evidence of glaciation is visible along the main summit ridge where small cirques, rock thresholds and short glacial valleys with low moraines are present. The peak most extensively glaciated is Mt Digini at the eastern end of the range.

All the other peaks mentioned only had minor ice covers never exceeding a few square kilometres in size. Mt Kumbivera represents a limestone syncline with a broad central basin that was partially filled with

Plate 5. Summit Ridge of Mt Wilhelm with solifluction screes. (Photo E. Löffler).

glacial ice. Mts Kerewa and Sugarloaf are both volcanic and may have had small ice caps but this needs verification in the field. The Burgers Mountains and Mts Udan (Odan) and Tabletop show evidence of glacial cover on air photographs but only small areas were affected.

7. The Sarawaket and Finisterre Ranges

The Sarawaket and Finisterre Ranges are the easternmost and highest parts of the northern ranges of New Guinea and the only alpine areas outside the central ranges. They are also the most unstable and tectonically most active areas of New Guinea and rates of uplift have been measured from raised coral terraces along the adjacent coast to be in the order of 3 m/1000 years (Chappell, 1974). The highest peaks of the Ranges are Mt Bangeta (4121 m) on the Sarawaket Range (Plate 7) and Mt Finisterre (3917 m) on the Finisterre Range.

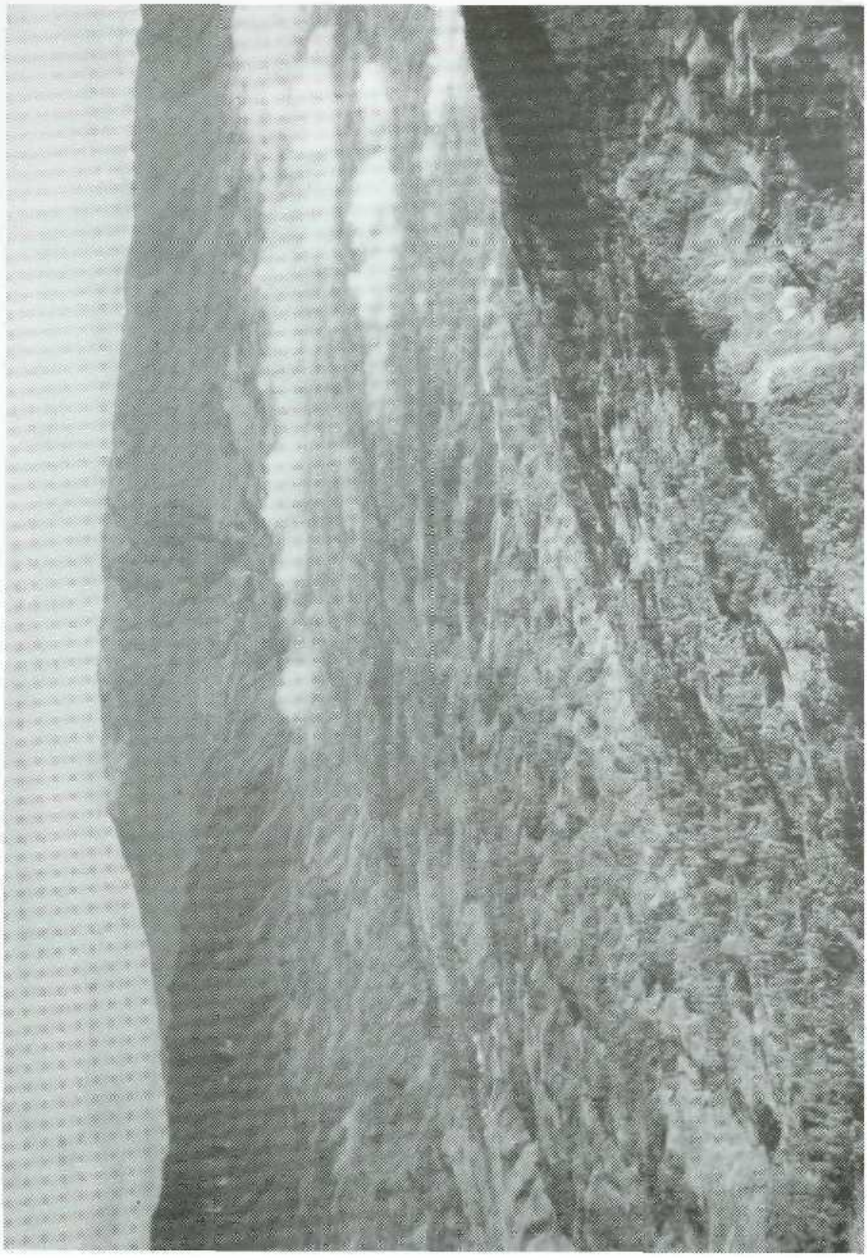

Plate 6. *General view of Mt Hagen volcano (background). Only the very summit of the* volcano had a small ice cap with short lobes of ice descending to about 3400 m. The broad open glacial valleys can be clearly seen on the photograph. (Photo E. Löffler).

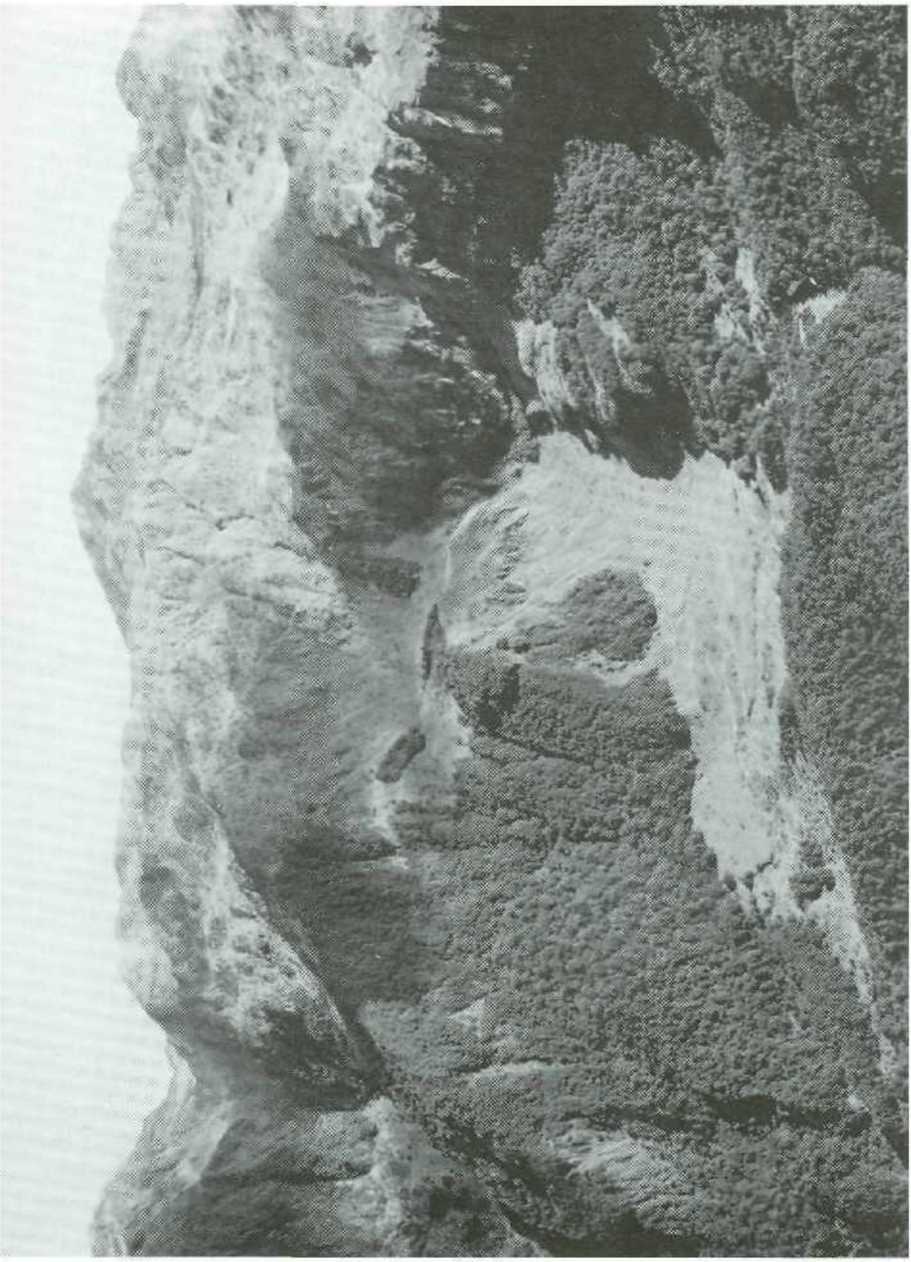

Plate 7. Northern part of the glaciated Sarawaket Mountains which consists of an irregular limestone plateau surface bounded by steep escarpments. Mt Bangeta (background) is 4121 m high. Short glacial valley with well developed moraine in the foreground. (Photo E. Löffler).

The summit areas of the Finisterre and western Sarawaket Ranges consist of a single narrow steep-sided ridge of limestone. The central and eastern Sarawakets, however, are formed of an irregular plateau surface which shows clear evidence of a former ice cover in its higher parts (Plate 7, 8). The plateau areas are formed of massive beds of Miocene limestone up to 1000 m thick. The limestone is faulted and dips north-east at angles form 10 to 25°. This dip is also reflected in the plateau surface that is tilted to the north and north-east. The plateau is bound by precipitous escarpments which along the southern margin fall nearly vertically for several hundreds of metres (Plate 7). To the north the falls are less high.

Glacial features on the Bangeta Plateau which is the highest part of the Sarawaket Range include cirques, overdeepened basins, short glacial valley and low moraines. The type of glaciation was similar to that on Mt Albert Edward with a continuous ice cap covering the plateau and short lobes of ice extending from it.

The smaller and lower Uruwa Plateau west of Bangeta supported mainly cirque glaciers and short valley glaciers as did the highest peaks of the Finisterre Range further west.

The Pleistocene snowline has been estimated at 3650-3700 m. This relatively high snowline in comparison to the values of the highland areas is probably due to postglacial uplift of the ranges. Much of the limestone plateau has also been affected by karst processes, i.e. solution processes in the limestone. The summit surface is locally pitted with dolines inside as well as outside the formerly glaciated areas. These dolines show up well in the grassland areas that cover most of the higher plateau. In the lower lying eastern parts of the plateau dolines are prominent in large enclosed basins which measure up to 20 km^2 in area.

8. The Owen Stanley Range

The Owen Stanley Range forms the rugged backbone of eastern New Guinea and consists of low metamorphic rocks in the north-west and basaltic rocks in the south-east. A distinctive feature of the Range is the presence of low relief, plateau-like surfaces along the main watershed and some off-branching divides. The most extensive of these is the Mt Albert Edward massif.

The Gorupu Mountains are the easternmost mountains with alpine environments. Geomorphologically they represent a structural dome with a well-developed north-easterly sloping structural surface. This structural surface is parallel to the foliation of the schist.

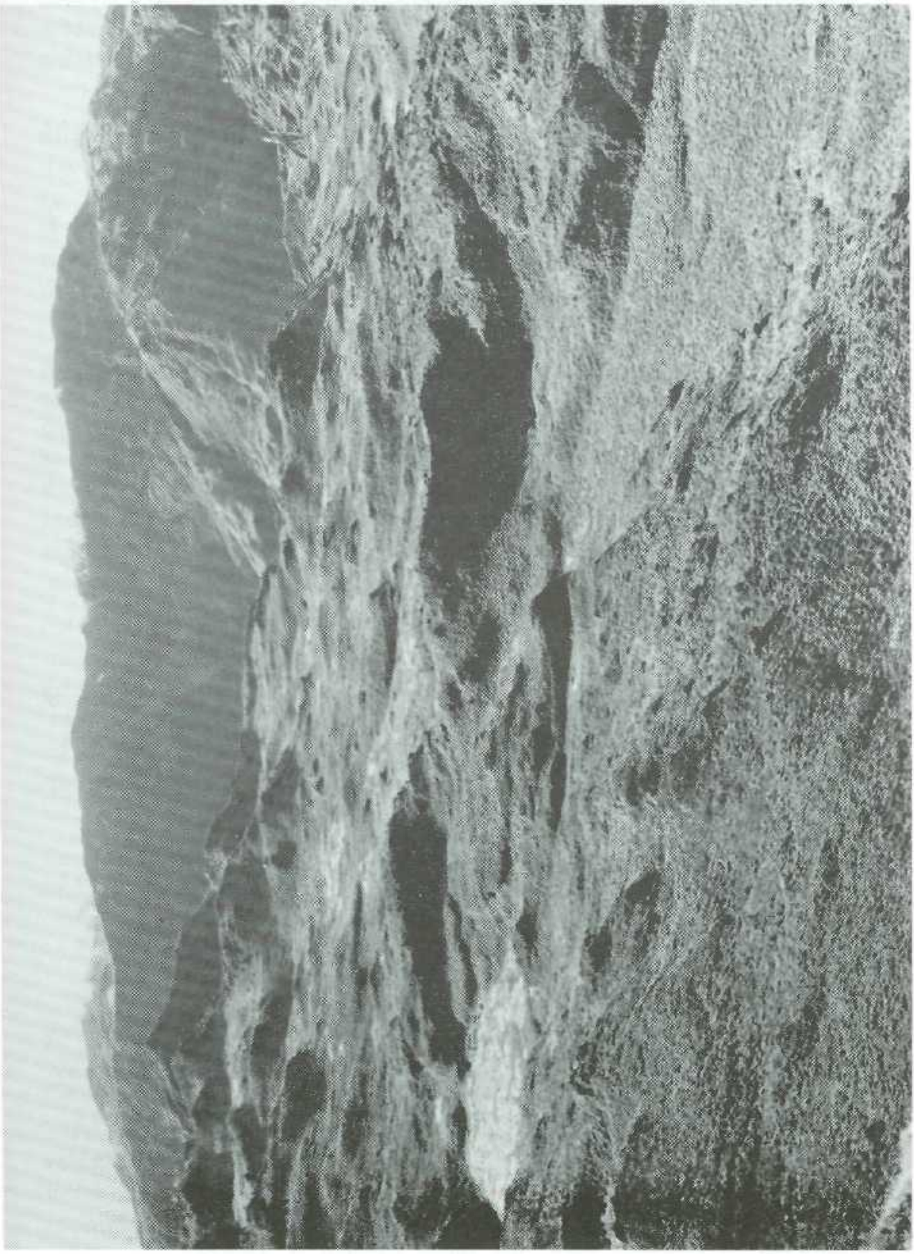

Plate 8. Summit surface of the Sarawaket Mountains with numerous basins, some of which may represent glacially modified dolines. (Photo E. Löffler).

The highest peaks are Mt Suckling (3675 m) (Plate 9) and Mt Dayman which form steep sided peaks. Although none show clear evidence of a glacial ice cover, Mt Suckling may have had a small snow cap covering its summit area since it just reaches the Pleistocene snowline.

Much more extensive are the alpine areas that begin further west with the narrow steep sided mountain ridge of Mt Victoria (4036 m). Although it is the highest peak of the Owen Stanley Range it shows only minor evidence of glacial activity obviously because the area available for snow accumulation was very small. There are two small cirques north-west of the main peak leading down to short glacial valleys with low moraines.

The Owen Stanley Range remains at altitudes above 3000 m between Mt Victoria and Mt Albert Edward and nearly the entire summit ridge can be regarded as alpine (Fig. 2). Glacial activity was most pronounced on Mt Albert Edward (Plate 10) and Mt Scratchley where areas of 90 km^2 and 28 km^2 respectively were covered by glacial ice. Both mountains are parts of the extensive relict surface and the great extent of the ice cover despite the relatively low altitudes is due to the fact that these plateau surfaces provide very suitable areas for snow accumulation.

The most outstanding features on Mt Albert Edward are two asymmetric summit ridges that rise some 200-300 m above the surrounding plateau and the numerous picturesque cirque lakes that fill the overdeepened rock basins (Plate 10). During the maximum extent of the glaciation the plateau area was covered by a nearly continuous ice cap down to about 3400 m. The snowline was at 3600-3650 m.

Mt Scratchley is a smaller plateau area right on the main watershed and was also covered by a continuous ice cap. Well-developed moraines and glacial valleys with stepped profiles and broad valley floors are prominent features and form a marked contrast to the surrounding non-glaciated area.

Traces of Pleistocene glacial activity are also present along the Wharton Range that extends between Mt Albert Edward and Mt Scratchley and on Mt St. Mary, a small isolated plateau rising to 3655 m 40 km north-west of Mt Albert Edward.

As already pointed out most of the alpine areas in the Owen Stanley Range occur on a relict surface that is characterized by a lower relief and less steep gradients of the rivers than the surrounding mountainous landscape. Associated with this relict surface is another interesting feature, the Neon Basin, a broad flat basin some 500 m below the general level of the Mt Albert Edward plateau (Plate 11). It is about

Plate 9. Mt Suckling, an isolated peak in the eastern Owen Stanley Range, reaches 3675 m but does not exhibit any traces of a Pleistocene ice cover. However, its vegetation is typically alpine. Note the large slump in the foreground which involves en bloc movement of a huge slope segment as well as numerous debris avalanches. (Photo CSIRO).

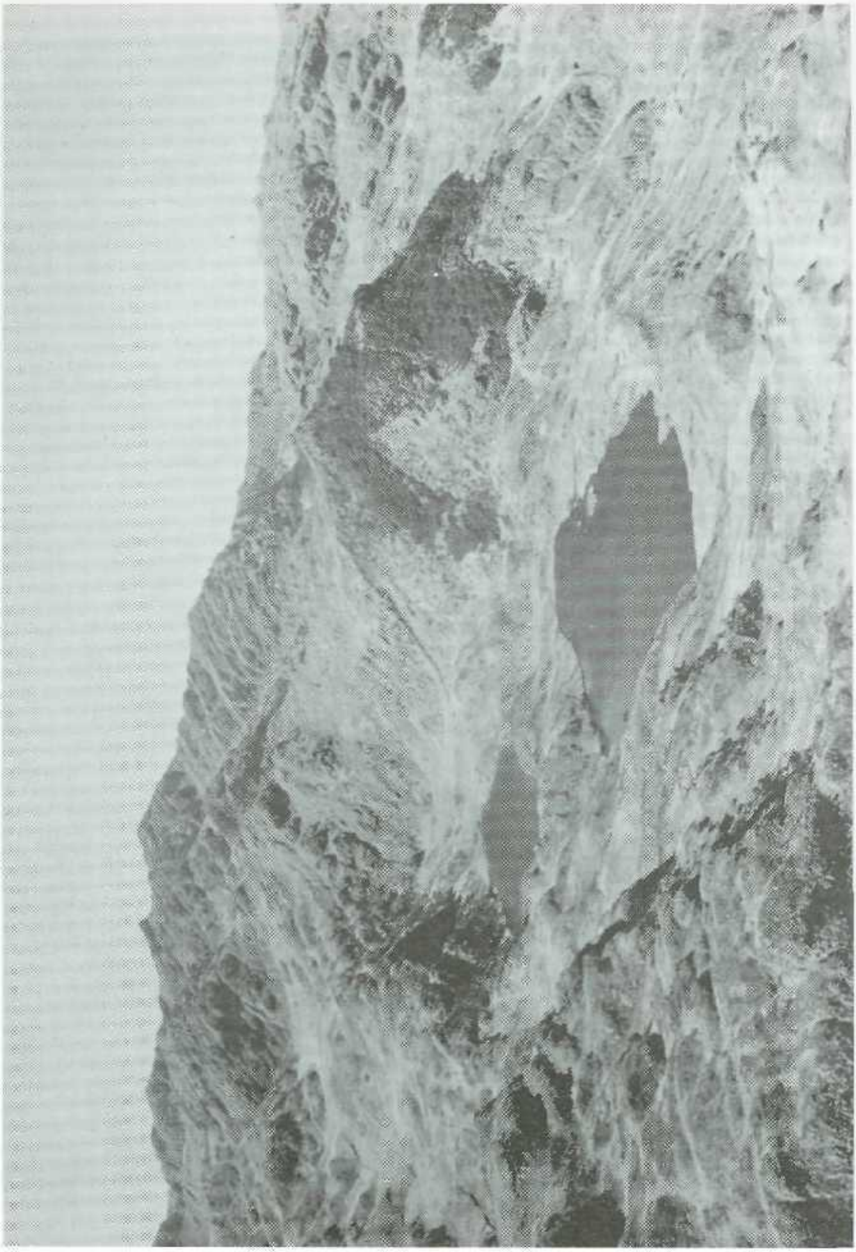

Plate 10. Mt Albert Edward is one of the scenically most attractive alpine mountains of New Guinea due to the numerous glacial lakes that fill the overdeepened cirque basins. There are two prominent summit ridges above the general level of the plateau area, one of which can be seen on the photograph. Also clearly discernible is the steep easterly dip of the schist which is responsible for much of the ruggedness of the mountain. (Photo E. Löffler).

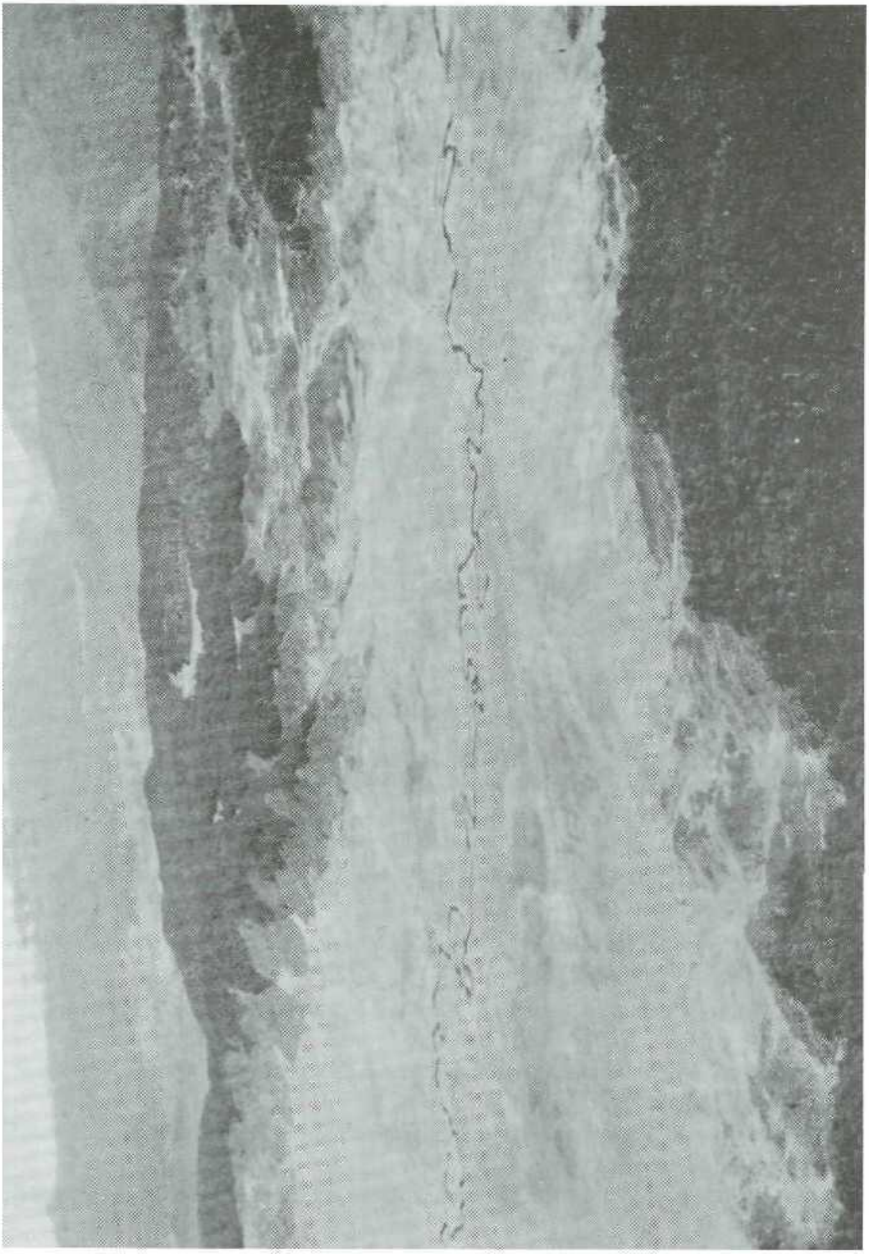

Plate 11. The Neon Basin to the west of Mt Albert Edward is situated at about 3000 m within a relict surface and may have formed as an erosional basin before the main uplift. (Photo E. Löffler).

3 km wide and 8 km long and consists of gently sloping more or less boggy fan surfaces merging into a swampy floodplain. The basin is filled with a peat to a depth of at least 2 m but it is not known what lies underneath this. Thin ash beds are also present in this upper peat layer. There is virtually no erosional or depositional activity at present and a C^{14} date of 4000 years B.P. from a depth of 1.5 m from the basin indicates that the only process has been the slow growth of raw peat.

The basin is traversed by the strongly meandering Gumini River, the narrow channel of which shows roundish pools at each bend so that from the air the river looks like a string of beads. These pools are caused by scouring and undercutting of the peat banks on the outside of the bend while there is nor deposition on the inside. This shows that the stream carries virtually no silt load, a reflection of the insignificance of soil erosion in these alpine environments.

Acknowledgement

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Selected References

Bain, J.H.C., D.E. Mackenzie & J. Ryburn, Geology of the Kubor Anticline-Central Highlands of Papua New Guinea - *Austr. Bur. Miner. Resour. Bull.* 155 (1975).

Bowler, J.M., G.S. Hope, J.N. Jennings, G. Singh & D. Walker, Late Quaternary climates of Australia and New Guinea - *Quat. Res.* 6 (1976) 359-394.

Chappell, J., Geology of coral terraces, Huon Peninsula, New Guinea - *Bull. Geol. Soc. Am.* 85 (1974) 553-570.

Coleman, P.J. & G.H. Packham, The Melanesian borderlands and India-Pacific plates boundary - *Earth Sc. Rev.* 12 (1976) 197-233.

Davies, H.L. & I.E. Smith, Geology of East Papua - *Bull. Geol. Soc. Am.* 82 (1971) 3299-3312.

Dow, D.B., A geological reconnaisance in the Nassau Range, West New Guinea - *Geol. en Mijnbouw* 47 (1968) 37-46.

Dow, D.B., A geological synthesis of Papua New Guinea - *Aust. Bur. Miner. Resour.* Bull. 201 (1977).

Hope, G.S., The vegetational history of Mt Wilhelm, Papua New Guinea - *Ecology* 64 (1976) 627-664.

Hope, G.S. & J.A. Peterson, Glaciation and vegetation in the high New Guinea mountains - *Bull. Roy. Soc. NZ* 13 (1975) 155-162.

Hope, G.S., J.A. Peterson, U. Radok & I. Allison, The equatorial glaciers of New Guinea. (1976).

Loffler, E., Pleistocene glaciation of Papua New Guinea - *Zeitschr. Geomorph., N.F. Suppl.* 13 (1972) 32-58.

Loffler, E., Beobachtungen zur periglazialen Hohenstufe in den Hochgebirgen von Papua Neu Guinea - *Erdkunde* 28 (1975) 13-18.

Loffler, E., Potassium-Argon dates and pre-Würm glaciations of Mount Giluwe volcano, Papua New Guinea - *Zeitschr. Gletscherk. Glazialgeol.* 12 (1976) 55-62.

Loffler, E., Geomorphology of Papua New Guinea. Canberra. (1977).

Nix, H.A. & J.D. Kalma, Climate as a dominant control in the biogeography of northern Australia and New Guinea, in *Bridge and Barrier· the Natural and Cultural History of Torres Strait,* ed. D. Walker - ANU BG/3 (1972) 61-91.

Peterson, J.A., G.S. Hope & R. Milton, Recession of snow and ice fields of Irian Jaya, Republic of Indonesia - *Zeitschr. Gletscherk. Glazialgeol.* 9 (1973) 73-87.

Powell, J.M., The history of agriculture in the New Guinea Highlands - *Search* 1 (1970) 199-200.

Smith, J.M.B., Vegetation and microclimate of east and west-facing slopes in the grasslands of Mt Wilhelm, Papua New Guinea - *J. Ecol.* 65 (1977) 39-53.

Reiner, E., The glaciation of Mt Wilhelm, Australian New Guinea - *Geogr. Rev.* 50 (1960) 491-503.

Verstappen, H. Th., Geomorphology of the Star Mountains - *Nova Guinea, Geology* 5 (1964) 101-155.

Visser, W.A. & E. Loffler, New Guinea, in *The Encyclopedia of World Regional Geology,* part 1, ed. R.W. Fairbridge. (1975) 377-382.

Visser, W.A. & J.J. Hermes, Geological results of the exploration for oil in Netherlands New Guinea - *Verh. Kon. Ned. Geol. Mijnbouw Gen. Geol.* Ser. 20 (1962).

Walker, D., The changing vegetation of the montane tropics - *Search* 1 (1970) 217-221.

Williams, P.N., I. McDougall & J.H. Powell, Aspects of the Quaternary geology of the Tari-Koroba area - *Geol. Soc. Austr.* 18 (1972) 333-347.

4. THE ALPINE SOILS OF THE NEW GUINEA HIGH MOUNTAINS

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1. Introduction

The alpine environment of New Guinea has been defined in simple terms in this chapter as the area at or above 3000 m (approximately 10 000 ft) and represents only 1% to 2% of the whole island. The combination of a wet, cool climate and steep slopes with shallow soils restricts the agricultural potential of this environment, an altitude of 2500 m being generally considered the upper limit of cultivation. This area is therefore only used for hunting and gathering by local inhabitants. Its scenic beauty, however, offers a considerable potential for tourism, although the inaccessibility of most appears a serious drawback. As a result of the limited potential very little research work has been carried out on the soils in this area. For the western part of the island some information is contained in Reynders (1964) and Hope, *et al.* (1976). For Papua New Guinea, more information is available. Most of this has been collected during CSIRO land resources surveys (Rutherford, 1964; Rutherford & Haantjens, 1965; Haantjens, 1970), but also some data on the soils are included in vegetation studies by Wade and McVean (1969) of Mt Wilhelm and Hope (unpublished data of Mt Albert Edward.

A synopsis of this rather limited and widely scattered information will be given in this chapter.

2. Physical Setting

The core of the island of New Guinea consists of a massive mountain chain extending some 2400 km from one end of the island to the other. Throughout this rugged mountain complex there are several areas reaching altitudes of more than 3000 m, and it even rises above 4500 m at one point in Papua New Guinea, and several points in West New Guinea. A few, small areas reaching altitudes of more than 3000 m also occur in the Finisterre and Saruwaged Ranges of the Huon Peninsula which is separated from the central mountains by the Markham-Ramu depression. The highest peak in West New Guinea is Mt Carstens at 4884 m, followed by Mt Wilhelmina 4750 m and Mt Juliana 4700 m. The highest mountain of Papua New Guinea is Mt Wilhelm rising to an altitude of 4510 m. One of the most interesting and best studied features of the mountains above 3600 m is the Pleistocene glaciation (Reiner, 1960; Verstappen, 1964; Löffler, 1972).

Apart from the features related to glaciation at the highest altitudes, the most typical land forms consist of irregular branching ridges narrow crests and long steep, but in detail rather irregular slopes. In limestones areas, which are very common in West New Guinea, the landscape becomes rugged and massive with steep to precipitous slopes and cliffs. In contrast the high altitude areas of Papua New Guinea show much more variety in rock types, andesite, granodiorite and metamorphic rocks being most common. Several mountains, such as Mt Giluwe and Mt Hagen, are volcanoes which erupted after the main orogenic movements. This variation in rocktype, however, appears to have had little effect on the soils, since topography, climate and vegetation are the dominant soil forming factors.

Climatic data for the New Guinea alpine areas are non-existent, except for Mt Wilhelm. Even Mt Wilhelm climate station was only attended intermittently and yearly rainfall figures are therefore incomplete. Estimates by McVean (1968) from a station located at 3480 m are a minimum rainfall of 3000 mm, while later estimates by Hnatiuk *et al.* (1976) vary between 3300 and 3500 mm per annum. Mt Wilhelm appears to have a seasonality between a wet and a less wet season. In

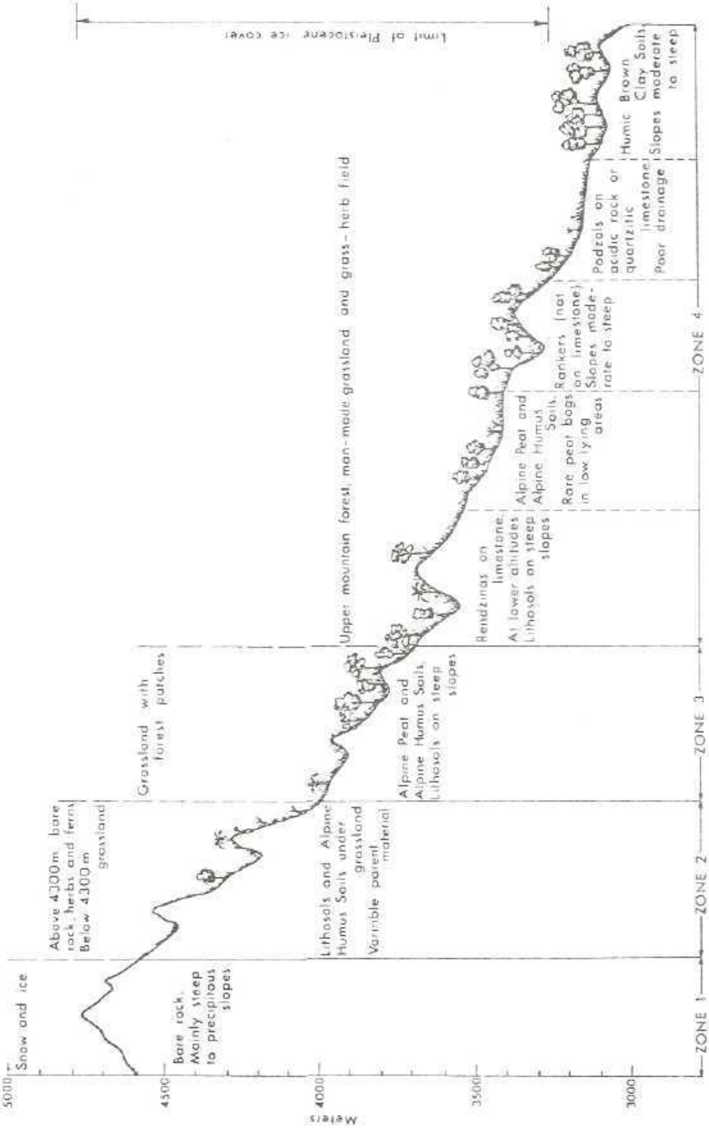

Fig. 3. Schematic cross section through high mountains showing soil zonality with altitude.

comparison sketchy data from Mt Carstensz in West New Guinea indicate little seasonal variation, although the total annual rainfall is probably higher than Mt Wilhelm (Hope *et al.,* 1976). Mt Albert Edward, located approximately 400 km south-east of Mt Wilhelm appears to have a much lower rainfall, and also shows a certain degree of seasonality like Mt Wilhelm (Hope, unpublished data). There is no clear relationship between rainfall and altitude in New Guinea, some mountains showing an increase, others a decrease with altitude. Rainfall is, however, more effective with increasing altitude because of the decrease in evapotranspiration, making the climate appear even wetter. Night frosts are common features in the high mountain areas.

The cool temperatures cause a considerable decrease in biological activity and hence a decrease in breakdown of organic matter. Physicochemical weathering is also slowed down in comparison with lower altitudes but at the same time mechanical weathering becomes more important due to the large diurnal temperature range and high percentages of bare rock exposure.

3. Soil Zonality in the High Mountains

The high mountain soils can be grouped in general according to several altitudinal zones each characterized by specific soils (Fig. 3). As shown in the figure the soil pattern tends to become more complex at lower altitudes mainly as a result of the more favourable climate interacting with other soil forming factors. Moving from higher to lower altitudes the following zones can be distinguished.

1. 4600-4800 m. Zone characterized by bare rock. No soils and vegetation. Bare peaks and mountain tops permanently covered by snow and ice. Limited to West New Guinea.

2. 4000-4600 m. Zone characterized by Lithosols together with bare rock. Shrubs, herbs, mosses, lichens and low ferns replace grasses as the dominant vegetation above 4300 m. Soil forming processes are rather restricted due to the low temperature, limited vegetation cover and generally steeply sloping terrain. The upper parts of this zone are on some rare occasions covered by snow, but diurnal night frosts are common.

3. 3700-4000 m. Zone characterized by Alpine Peat and Alpine Humus soils. Vegetation dominantly grasses and herbs with forest at lower altitudes and in protected valleys. The build up of organic matter by the vegetation, which is only slowly mineralized by soil organisms, causes humus and peat accumulation. On steeply sloping terrain Lithosols are also present.

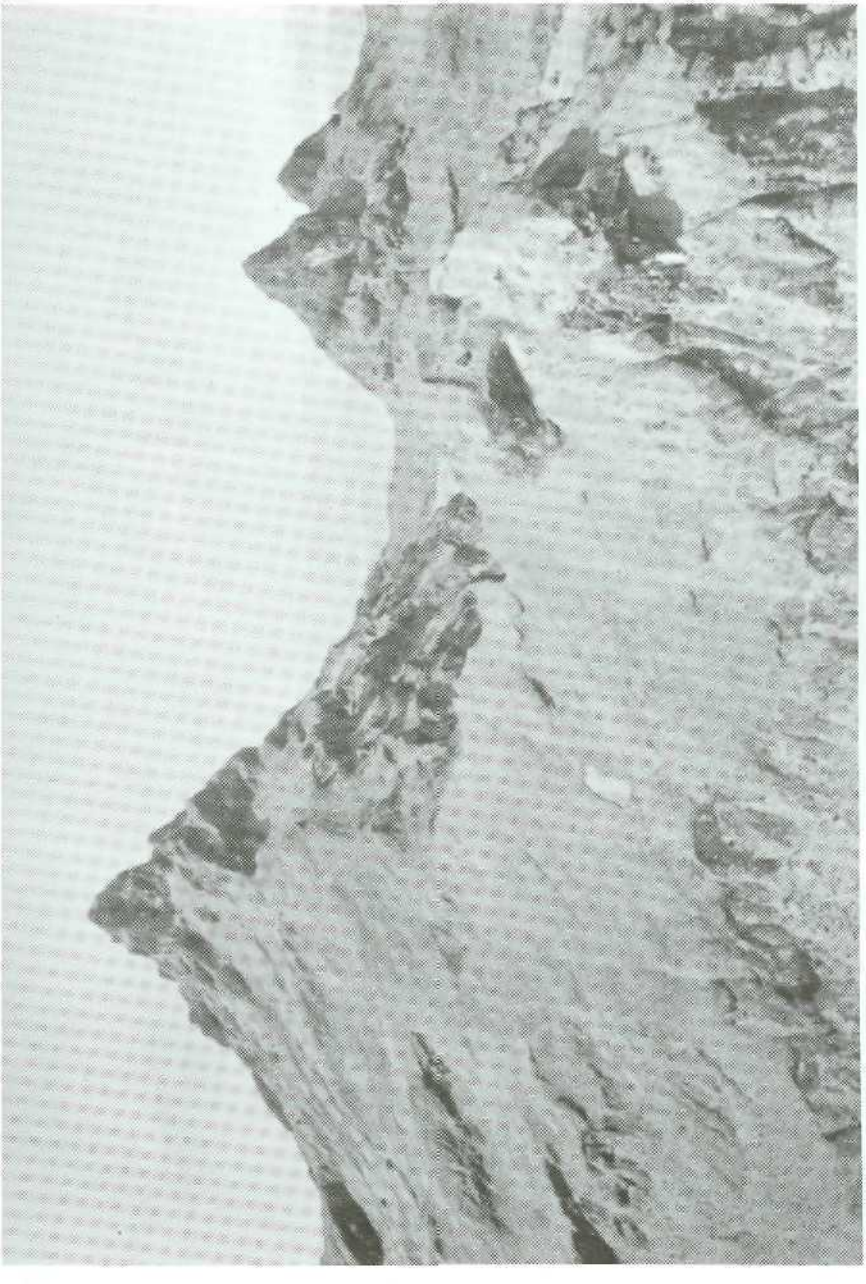

Plate 12. Eastern and higher peak of Mt Giluwe (4368 m) consisting mainly of bare rock, and vegetated scree slopes with Lithosols. A recent slip-scar is visible just left of the centre of the plate. (Photo CSIRO).

Plate 13. Exposure of a lateral moraine on Mt Giluwe (at 3400 m) showing bare rock and gravel alternating with pockets of Lithosols. (Photo CSIRO).

4. 3000-3700 m. Zone characterized by Alpine Peat and Alpine Humus soils in combination with Rankers and Humic Brown Clay soils at lower altitudes. Rendzinas are found in limestone country on steeply sloping terrain. Podzols are also occasionally present on level to gently sloping topography. The vegetation consists of upper mountain forest, characterized by a dense tree stand with mosses in a wet, cloudy and misty climate. Humus accumulation is the dominant soil forming process. On steep slopes subsurface erosion often takes place at the interface of the peat and mineral soil horizons.

4. The Soils

1. Bare Rock and Lithosols (Plate 12, 13)

Bare rocks, occasionally covered permanently by snow and ice dominates areas between 4600 and 4880 m in altitude. An interesting observation on soil formation on bare rock has been reported by Hope *et al.* (1976) from the Mt Carstensz area in West New Guinea. Here limestone till material abandoned by ice at about 1950 AD was still without any vegetation about twenty years later. Another site, located in the same valley, but vegetated since 1920-1930 AD, however, already showed a 2 cm thick mat of mosses with a pH of 7.0, overlying a mineral surface horizon with a pH of 9.0, while the pH of the underlying till material was approximately 10, similar to the first site. This shows that soil formation will take place, even at very high altitudes, but only when some type of vegetation has been established.

Lithosols predominate in areas between 4000 and 4600 m, but are also common at lower altitudes. They are very shallow soils which overlie at depths between 10 and 25 cm either hard bedrock or loose gravelly or stony material. The soil consists of mainly grey brown coloured loamy or clayey material often mixed with gravel and/or stones. The soil reaction varies from acid to alkaline depending on the type of parent material. At lower altitudes Lithosols are most common on steeply sloping terrain where soil erosion has kept pace with soil formation.

2. Alpine Peat and Alpine Humus Soils

Alpine Peat and Alpine Humus Soils are most common at altitudes between 3000 and 4000 m (Plate 14, 15) and have been described in detail by Haantjens (1970), Haantjens *et al.* (1967) and Rutherford & Haantjens (1965). Alpine Humus Soils are mainly restricted to grassland

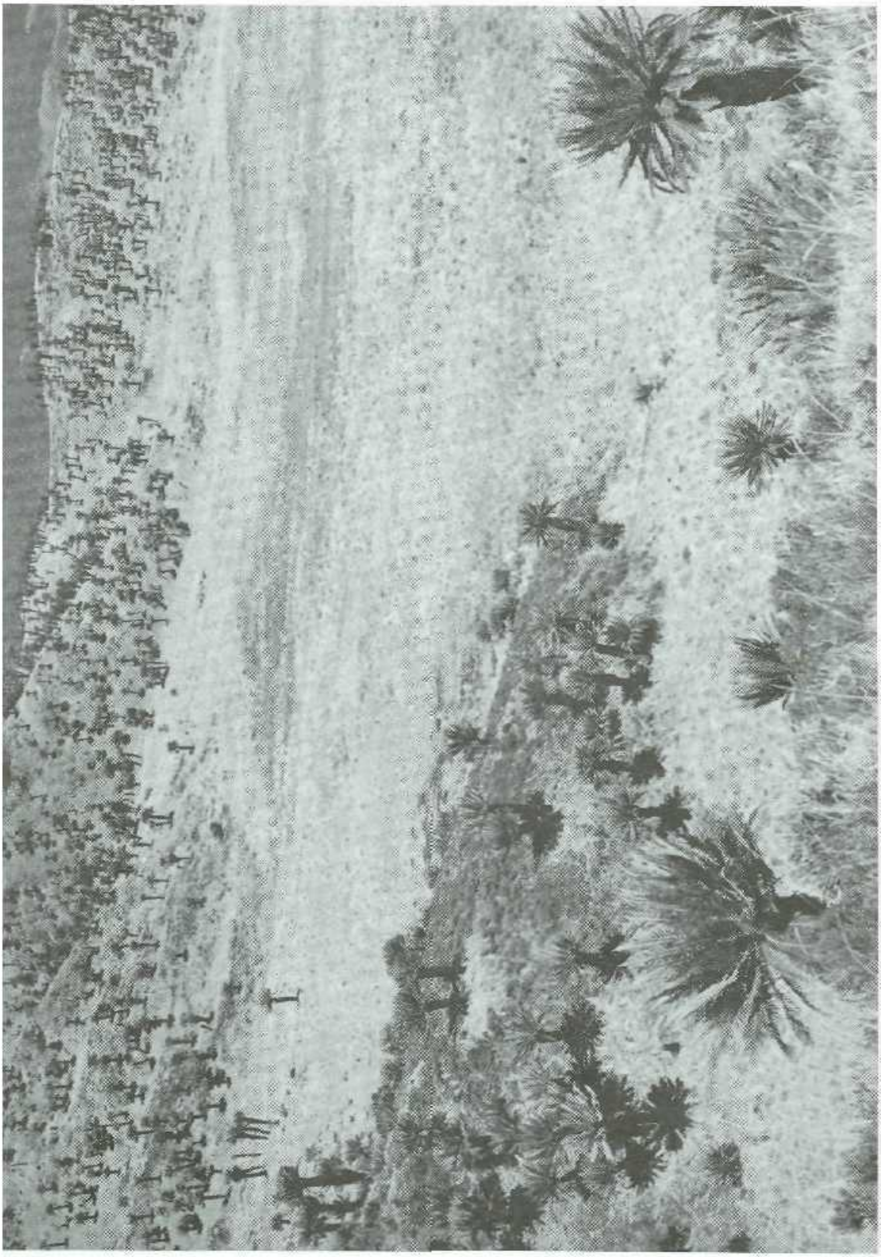

Plate 14. Mt Albert Edward, edge of Neon Basin (3000 m) showing moderately sloping hillsides covered by grassland and tree ferns and characterized by Alpine Peat and Humus soils. Lower down these hillslopes grade into very gently sloping fans, the Alpine Peat and Humus soils becoming poorer in drainage and merging at the wettest and lowest levels into Peaty Bog soils. (Photo CSIRO).

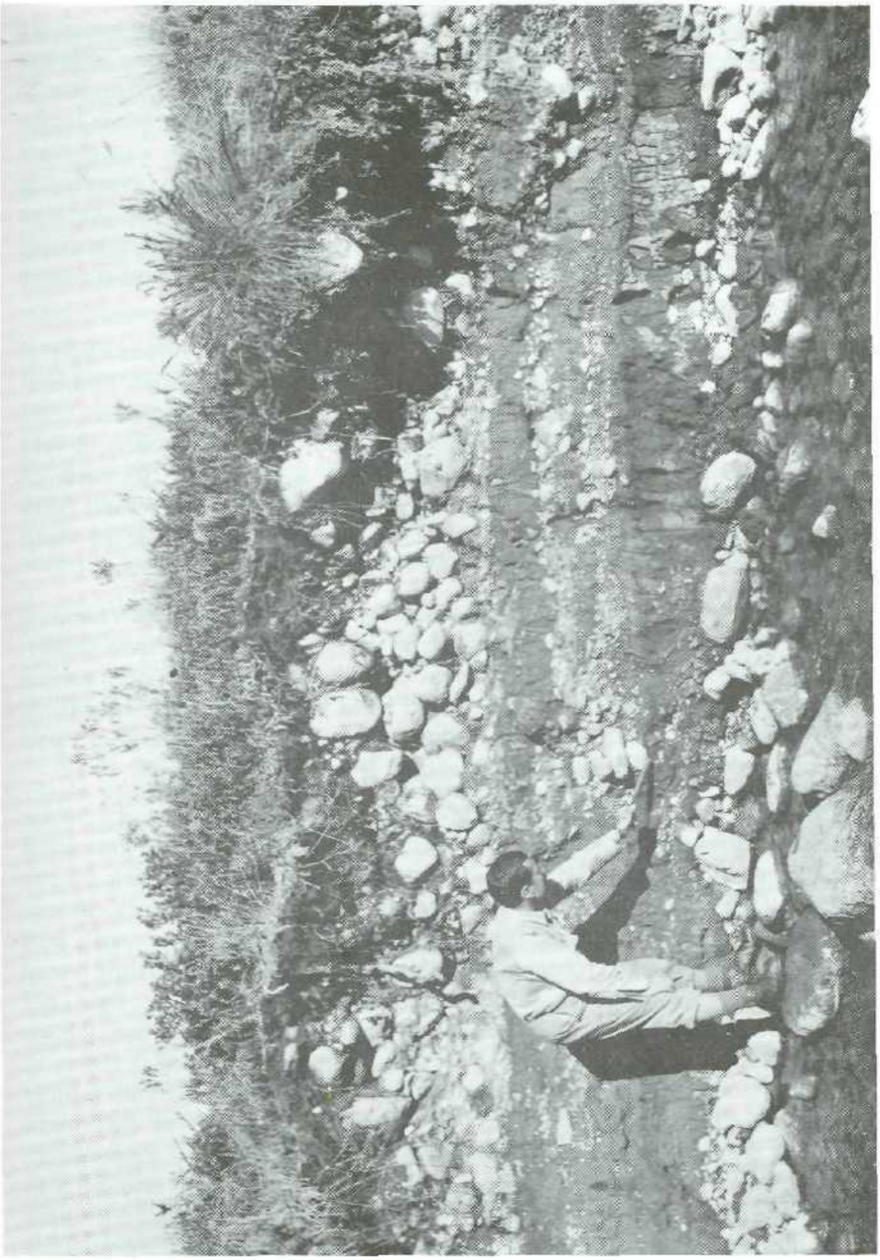

Plate 15. Soil exposure showing Alpine Peat and Humus soils intermixed with Lithosols on a river terrace at 3200 m on the western flank of Mt Giluwe. Two buried soil profiles dated 1800 and 4000 years B.P. are also present, the lower one being pointed at in the photograph. (Photo CSIRO).

areas, while the Alpine Peat soils have formed mainly under mountain forest and are therefore most common at lower altitudes. The soils are characterized by a strong accumulation of organic matter giving rise to very dark coloured surface horizons consisting of peaty or organic loams to clay loams. As mentioned previously, the permanently wet climate and low temperatures greatly enhance accumulation of plant waste which cannot be broken down sufficiently by soil organisms. At high altitudes the organisms responsible for mineralization are mainly fungi which, according to Mohr *et al.* (1972) are much less active and conserve the organic material for their own preservation.

Haantjens (1970) has subdivided the Alpine Peat and Humus Soils of the Goroka - Mt Hagen area in Papua New Guinea into three families; namely Pinde, Tomba and Pompameiri. The Pinde family occurs most wide-spread and has been described as shallow (40-80 cm) poorly to very poorly drained, clayey peat or peaty clay loam overlying hard of weathered rock or morainic sand or silt. The field pH decreases with depth from 6 to 5.5. This family is mainly found on gentle to steep slopes between altitudes of 3300-4000 m.

Hope *et al.* (1976) report that the profile characteristics and chemical properties of the Mt Carstensz soils are very similar to the Pinde family, although the organic matter content of the Mt Carstensz soils are an average higher. Near lakes in glaciated areas these soils grade into thick Peat Bog soils (Plate 14) which are permanently wet, have an acid reaction throughout, and directly overlie fresh parent material.

The two other families described by Haantjens (1970) cover a wider altitudinal range (2200-3700 m), but appear to have a more restricted distribution. Of these, the Tomba family is normally as thick as the Pinde family, but is well to imperfectly drained and consists of very dark grey brown to dark red-brown friable loam to clay loam with very high organic matter contents. This family is found on mainly steep slopes on igneous rocks and volcanic tuff and ash. The field pH increases from 5.0-5.5 in the dark topsoil, to 6.0-6.5 in the ash or weathered rock. The Pompameiri family occurs mainly under forest at altitudes below 3700 m and is much thicker, well drained and rapidly permeable. It has a 25-50 cm thick dark brown loam to clay loam topsoil rich in organic matter which overlies a 100 cm or more thick, very friable brown, sandy clay loam subsoil. The field pH is 6.0-6.5 in the topsoil decreasing commonly to 5.0-5.5 at 1 m depth. All three families are found intermixed throughout the high mountains, such as Mt Wilhelm, Mt Kubor and Mt Hagen. Their clay fraction consists either of codominant kaolinite and metahalloysite or kaolinite is dominant.

More information on the Mt Wilhelm soils is given in a vegetation study by Wade and McVean (1969) who collected thirty soil samples from the top 10 cm of soils representing plant associations in order to find correlations between vegetation and soil fertility. Sometimes more than one sample was collected from the same vegetation type at different localities to obtain also information on the variation in soil fertility within a vegetation type. No soil descriptions and other site data are given but one would expect the majority of these soils to belong to the Alpine Peat and Humus Soils. Results of the chemical analyses proved inconclusive in establishing soil fertility as the factor controlling differences in vegetation in the area. Wade and McVean (1969) also noted that the variation in fertility within similar vegetation types was often as great as or greater than between different vegetation types. This indicates topography and drainage have a controlling influence on soil fertility, parent material and rainfall being relatively uniform. On the other hand altitude and soil fertility appear to be correlated, cation exchange capacity, exchangeable Ca and Mg, and base saturation all showing lower figures with a decrease in altitude.

In the Wabag-Tari area, located west of the Goroka-Mt Hagen area, Rutherford (1964) and Rutherford and Haantjens (1965) have classified the Alpine Peat soils together with other organic soils into a major group of Peaty soils. Of these Peaty soils three families belong to the Alpine Peat soils, namely Wapu, Giluwe and Dibibi. The Wapu family is found on the Sugarloaf Mountain and its soils are so similar to the Pinde family of the Goroka-Mt Hagen area that they can be merged into one. The occurrence of both the Giluwe and Dibibi families is restricted to Mt Giluwe. Mt Giluwe is a Pleistocene shield volcano reaching an altitude of 4368 m. Volcanic ash covered at one stage the whole mountain and surrounding areas, but during the Pleistocene much of this ash was removed from the summit area by glacial erosion. Rutherford found a remarkable uniformity in soils throughout the summit area even on very variable land forms such as scree slopes, moraine ridges and fluvio-glacial deposits.

Soils belonging to the Giluwe family consist of an up to 20 cm thick, very dark brown mucky silty clay loam with a fine granular structure merging gradually into a 10 cm thick, black silty clay subsoil which has a markedly higher organic matter content. The pH is 5.0 throughout the soil and there is an abrupt boundary to the underlying parent material. Analytical data of the three summit area soils sampled by Rutherford (1964) show a pronounced increase in organic matter content in the subsoil, confirming the field observation. This in turn has also caused a higher cation exchange capacity, percentage nitrogen and total phosphorus content in the same horizon. Rutherford offers no explanation for the higher organic matter content in the subsoil, but suggests that some humus illuviation may have taken place. Although he considers it unlikely that postglacial ash showers have been added to the soil profile, recent field work indicates that young volcanic ash deposits occur much more widespread in the highlands than originally thought (Löffler, pers. communication). Granulometric analyses of the soils indicate very high coarse silt, and very low (<10%) clay contents. The mineral fraction of the whole soil is dominated by feldspars, while the clay mineralogy from one site at almost 4000 m altitude shows much amorphous material indicative of allophane, a weathering product of volcanic ash. In addition there are also appreciable amounts of montmorillonite and feldspar in the clay fraction.

The Dibibi family is limited to the gently sloping margins of the summit area of Mt Giluwe between 2900-3500 m. These soils have a peaty surface horizon, 15-45 cm thick, overlying a brown, and with depth yelowish brown to strong brown clay subsoil. This brown clayey subsoil is typical for the Humic Clay Soils, discussed later, to which this family forms a transition. The Dibibi family also shows similarities with both the Tomba and Pompameiri families of the Goroka-Mt Hagen area, but these are not strong enough to merge it with one of them. In general, the Mt Giluwe soils do not show higher organic matter contents with increasing altitude, as observed in other high altitude areas.

A limited amount of unpublished information on the soils of Mt Albert Edward has been collected by Hope*, This mountain consists of metamorphic rocks, is 3990 m high, and together with Mt Victoria forms part of the Owen Stanley Range which between these two mountains virtually remains above 3000 m. Both mountains form part of an extensive relict surface characterized by a lower relief and gentler slopes compared with other high altitude areas in New Guinea (Löffler, 1977), and Lithosols are for this reason rarely present on the summit plateau. Hope has described Alpine Humus soils and organic rich silty clays as the dominant soils in this area. Of these, the Alpine Humus soils closely resemble the Pinde family described by Haantjens (1970) from Mt Wilhelm. These soils are very poorly drained, usually deep peaty mucks with little profile differentiation. The organic rich silty clay loam soils are in comparison shallow with decomposed schist occurring at 25-40 cm depth. Hope noted at 10 cm below the porous, well structured surface horizon the presence of cutans, indicating clay illuviation into the dark brown subsoil. This subsoil in turn gradually becomes lighter coloured and shows an increase in mica minerals with depth. It is not clear if

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*G.S. Hope. Some notes on the non-forest vegetation and its environment northern flank of Mt Albert Edward, Central District, Papua New Guinea.

these soils can also be grouped together with the Alpine Peat and Humus Soils or if the clay movement has been pronounced enough to qualify for an argillic horizon. Their profile morphology does, however, show similarities to the Giluwe family described previously. Analytical data of the Mt Albert Edward soils show relatively low organic carbon and nitrogen contents, but the cation exchange capacities of the soils are generally very high due to the high mica contents of the underlying parent material. In addition recent volcanic ash, most likely derived from Mt Lamington 100 km to the south east, may have contributed to the soil fertility of the area and could also have caused the general lower levels of organic matter in the soils.

3. Podzols

Alpine Podzols have not yet been reported in Papua New Guinea. In West New Guinea, however, they have been described from the Star Mountains by Reynders (1960; 1964) where they are found on more acid rocks, including quartzitic limestone. The soils are characterised by a dark surface horizon overlying a strongly bleached subsurface horizon and a yellowish brown to brown subsoil which shows accumulation of organic matter and/or sesquioxides (= Al_2O_3 and Fe_2O_3). The subsoil generally also shows an increase in clay content with depth. Since Reynders did not observe any clay skins in the subsoils of the Podozols he attributed this increase to clay destruction and lateral removal from the upper soil horizons. This process is greatly enhanced by the very acid soil reaction (pH ± 4.5). The downward movement of sesquioxides released on weathering of silicate clays probably takes place at three different ways, namely; (1) as compounds with simple organic acids, (2) as complexes with organic matter or (3) as negatively charged humus protected sols. Humus may also be translocated independently of sesquioxides in coloidal form.

Intergrades between Podzols and Alpine Peat and Humus soils have been reported from the Antares Mountains in West New Guinea by Reynders (1964). He describes a peaty, ortstein Podzol occurring at an altitude of 3250 m in an Alpine Meadow region. While the surface horizon of this soil consists of peat, it abruptly overlies a thin humic sand horizon and a 1/2 cm thick rusty coloured ironpan. This ironpan in turn abruptly overlies weathered rock, consisting of grandiorite. Reynders has stressed the importance of topography and soil drainage information of Podzols, since a level topography will cause water stagnation and therefore more intensive leaching and podzolization. Conditions for the formation of peat are also more favourable on flat to gently sloping terrain. Rutherford and Haantjens (1965) have also locally recorded a 2-5 cm thick discontinuous ironband in volcanic ash soils occurring above 2100 m in the Papua New Guinea Highlands. This clearly shows that podzolization also takes place in the Highlands under very wet climate conditions, although, as mentioned previously, real podzols have not yet been found.

4. Humic Brown Clay Soils

Humic Brown Clay Soils* are among the less common soils of the high mountains of New Guinea. These soils are found mainly between 1200 and 2700 m in the highland provences of Papua New Guinea, but also occur occasionally at higher altitudes. They have been described in detail by Haantjens and Rutherford (1964). Occurring mainly on stable, but moderately to steeply sloping terrain these soils are characterised by their well developed black to very dark grey brown surface horizon. This horizon overlies a yellowish brown to strong subsoil with a weakly developed blocky structure. A slight increase in clay content with depth is most common. They are generally more than 1 m thick and occur on a great variety of parent materials, such as volcanic ash, sedimentary rocks, lava or alluvium. This large variation in parent materials appears to be reflected in the fertility, particularly at lower altitudes, which also shows a great range. Soil profiles on limestone, however, are characterised by higher pH, base saturation and P contents. While the total phosphate contents of Humic Brown Clay soils appear to be in general high, figures on available phosphate are mostly very low indicating strong phosphate fixation probably by organic matter and iron-aluminium compounds. Gibbsite is the dominant clay mineral in profiles developed on ash while soils on sediments are generally dominated by kaolinite (decreasing with depth) and illite (increasing with depth). As mentioned previously the Humic Brown Clay soils may grade at higher altitudes into Alpine Peat Soils, such as the Dibibi family of the Wabag-Tari area.

5. Rankers and Rendzinas

With increasing altitude and steeper sloping terrain Humic Brown Clay soils become gradually shallower and may grade into Rankers. These Rankers are shallow with an AC profile and weathered rock fragments commonly occur in the yellowish brown subsoil which is overlain by a well developed, black acid surface horizon.

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*Also called Humic Brown Latosols by Haantjens *et al.* (1967).

Other less common soils found at high altitudes in New Guinea are Rendzinas. These are lithomorphic soils, being associated typically with limestone and occurring mostly on steep slopes between altitudes of 3000-3700 m. Rendzinas are shallow dark soils with a well structured friable surface horizon which has a loam to clay texture and abruptly overlies limestone. The soil reaction varies between weakly acid and weakly alkaline, while the base saturation is usually very high. Rendzinas are closely associated with Alpine Peat and Humus Soils and bare rock in high altitude mountainous limestone areas.

5. Conclusion

It is difficult to establish a clear correlation between vegetation and soils since the occurrence of certain vegetation types is governed by climatic, topographic and drainage factors as well as soil and all these factors are interrelated. Topography seems to determine to a great degree the occurrence of grasslands which occupy all the broad valley floors of the formerly glaciated terrain and here Alpine Humus and Peat Bog soils are common. On slopes the situation is more complex and here various soil types can occur under the same type of vegetation. A complicating factor is the human interference to much of the alpine area and many slopes are not occupied by their natural climax vegetation of forest but by fire induced degraded shrubland and grassland. With increasing altitude climate becomes the main determinant of vegetation distribution and above 3850 m grassland with some shrubs is the natural vegetation type irrespective of soil but the vegetation cover on Lithosols is of course much poorer and sparser than on Alpine Peat and Humus Soils which still cover relatively large areas here. A major break occurs, however, at about 4300 m where diurnal night frosts lead to periglacial solifluction and frost heaving precluding the establishment of higher plants. But this boundary is by no means a sharp one and isolated occurrences of Alpine Peat with tussock grasses extend up to 100 m above this limit in protected locations.

The New Guinea alpine zone and its vegetation shows a remarkable similarity with that occurring on other tropical mountains in the world like the African high mountains and the Paramo areas in the Andes and it seems that climatic factors, primarly the diurnal regime of the climate with the lack of annual temperature variations and to a lesser degree also the lack of marked variations in precipitation combined with the low rates of evaporation, dominate this environment. In New Guinea the lack of temperature extremes even during the diurnal cycle is particularly pronounced and it is for this reason that the altitudinal zones of vegetation, soils and geomorphic processes like solifluction are more compressed, i.e. occupy a smaller altitudinal range than on other tropical mountains.

Acknowledgement

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Selected References

Haantjens, H.A., Soils of the Goroka - Mount Hagen area - *CSIRO Austr. Land. Res. Ser.* 27 (1970) 80-103.

Haantjens, H.A. & G.K. Rutherford, Soil zonality and parent rock in a very wet tropical mountain region - *Proc. 8th Int. Congr. Soil Sc.*, Bucharest, Rumania, 1964, vol. 5 (1967) 493-500.

Haantjens, H.A., J.J. Reynders, W.L.P.L. Mouthaan & F.A. van Baren, Major soil groups of New Guinea and their distribution - *Roy Trop. Inst., Amsterdam, Commun.* 55 (1967).

Hnatiuk, R.J., J.M.B. Smith & D.M. McVean, The climate of Mt Wilhelm - *ANU BG/*1 (1976).

Hope, G.S., J.A. Peterson, U. Radok & I. Allison, The equatorial glaciers of New Guinea. (1976).

Loffler, E., Pleistocene glaciation of Papua New Guinea - *Zeit Geomorph., N.F. Suppl.* 13 (1972) 32-58.

Loffler, E., Geomorphology of Papua New Guinea. (1977).

McVean, D.N., A year of weather records at 3480 m on Mt Wilhelm, New Guinea *Weather* 23 (1968) 377-381.

Mohr, E.C.J., F.A. van Balen & J. van Schuylenborgh, Tropical Soils. (1972).

Reiner, E., The glaciation of Mt Wilhelm, Australian New Guinea - *Geogr. Rev.* 50 (1960) 491-503.

Reynders, J.J., Voorlopige mededeling van het agrogeologisch onderzoek in het Sterrengebergte - *Tijdschr. Aardrijksk. Gen., Tweede Reeks* 77 (1960) 162-165.

Reynders, J.J., A pedo-ecological study of soil genesis in the tropics from sealevel to eternal snow (Star Mountains, Central New Guinea). (1964).

Rutherford, G.K., The tropical alpine soils of Mt Giluwe, Australian New Guinea - *Canadian Geogr.* 8 (1964) 27-33.

Rutherford, G.K. & H.A. Haantjens, Soils of the Wabag-Tari area, Papua and New Guinea - *CSIRO Austr. Land. Res. Ser.* 15 (1965) 85-99.

Verstappen, H.Th., Geomorphology of the Star Mountains - *Nova Guinea, Geology* 5 (1964) 101-155.

Wade, L.K. & D. N. McVean, Mt Wilhelm Studies 1; the alpine and subalpine vegetation - *ANU BG/*1 (1969).

5. MOUNTAIN CLIMATES OF NEW GUINEA

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1. Introduction

The climatic characteristics of equatorial high mountains are still relatively unknown, although the topic is of considerable interest from a meteorological and paleoclimatological standpoint, particularly in the case of New Guinea. Unlike the Andean ranges, the mountains of New Guinea are orientated more or less parallel to the predominant airflows.

Moreover, the region is a major equatorial heat source for the large-scale atmospheric circulation cells of low latitudes, which appear to interact with oceanographic conditions in the equatorial Pacific. The mountains extend well above tree line in many places and, in West New Guinea, small permanent ice bodies are present despite the low latitude. During the last major glacial maximum, about 18 000 years ago, a much lower snowline permitted the development of quite extensive ice caps and glaciers on mountain summits above about 3500 m.

This chapter emphasizes climatic conditions in the central ranges of Papua New Guinea, where some data at high elevations are available. Reference is also made to other areas where pertinent information exists. The meteorological characteristics of the region are described first, followed by a survey of the major climatic elements. Local conditions due to topography and microclimatic aspects are presented next, and finally climatic conditions in the area during the Last Glacial Maximum are discussed.

2. Meteorological Characteristics

The Large-Scale Circulation

New Guinea forms part of the so-called "maritime continent" (Ramage, 1968) of Malesia* which extends eastward from Malaysia and Indonesia. It is implied by this designation that in spite of its extensive water surface, the area has a continental regime of cloudiness. Indeed, Malesia is a primary tropical source of convective instability and thunderstorm area, like central Africa and South America, and it is one of the most persistently cloudy regions in equatorial latitudes (Atkinson & Sadler, 1970; Leigh, 1973).

The large-scale atmospheric circulation over the Pacific has been depicted by Troup (1965) as an exchange of air between the subtropical anticyclone of the eastern South Pacific and the equatorial low pressure over Indonesia. Troup suggests that air rises in the west over the heated land and warm sea surfaces, moves eastward in the upper troposphere (as an ageostrophic flow component) and subsides over the eastern Pacific. Recent streamline maps for the 200 mb level prepared by Sadler (1975) clearly show westerly flow over the central Pacific. This motion is at low levels compensated by the westward flow in the southeasterly trades. The model of Bjerknes (1969) showed the rising arm of this

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*Malesia denotes the archipelagic area from Malaya/Sumatra in the west to New Guinea in the east

east-west (zonal) circulation over the equatorial Pacific to be located about 170° E, but varying between 130° E and 170° W. However, Flohn and Fleer (1975) depict rising air over 150° E and subsidence at 90° W, with a separate Indonesian-Indian Ocean cell, while several other studies indicate that the convective outflow over Malesia is removed to the west (Krueger & Winston, 1974). Poleward outflow aloft in the meridional Hadley cells is also well-developed on this sector (Berson, 1961; Krishnamurti, 1971).

The large-scale equatorial circulation is still inadequately known, although the gradient airflow at sea level has been analyzed by Atkinson and Sadler (1970) and the upper tropospheric flow by Sadler (1975). The average circulation for 1968-1972 has also been presented by Gray *et al.* (1976) for four levels in the troposphere based on objective analyses.

Over New Guinea the 200 mb resultant-flow throughout the year is consistently from an easterly direction. From October through December winds are light, associated with an anticyclone center about 165°-170° E, 8°-10° S, becoming ESE 7 ms^{-1} on average in January-February as an anticyclone develops near 15° S over northwestern Australia. The flow becomes more easterly again in March and then weakens during April-June as the anticyclones move northward to about 7° S in May-June. In May, and to a lesser degree in November, there are some incursions of westerly influence from the southern westerlies. During July through September the mean resultant flow is ENE 7 ms^{-1}, associated primarily with a subequatorial ridge over the western North Pacific.

The lower tropospheric circulation shows strong seasonal regimes. Over Lae (6 7° S, 147° E), there is equatorial westerly flow at 700 mb from December through March, reflecting the influence of the Indonesian-Australian northwest monsoon (Berson, 1961), while tropical easterlies prevail from May through October (Wittwer, 1973). The area is thus transitional between the circulation regimes over the Indian Ocean-Indonesia and the western Pacific, especially with respect to the occurrence of equatorial westerlies.

The seasonal patterns of cloud cover evident in satellite photography depict the amalgamation of a cloud band from the southwest Pacific with that of the equatorial trough along the equator between 160°-130° E throughout the year (Atkinson & Sadler, 1970) (Plate 16). However, the convergence zone over Malesia may involve tropical easterlies in both hemispheres, equatorial westerlies and tropical easterlies, or equatorial and midlatitude westerlies, as Glen (1947) first pointed out.

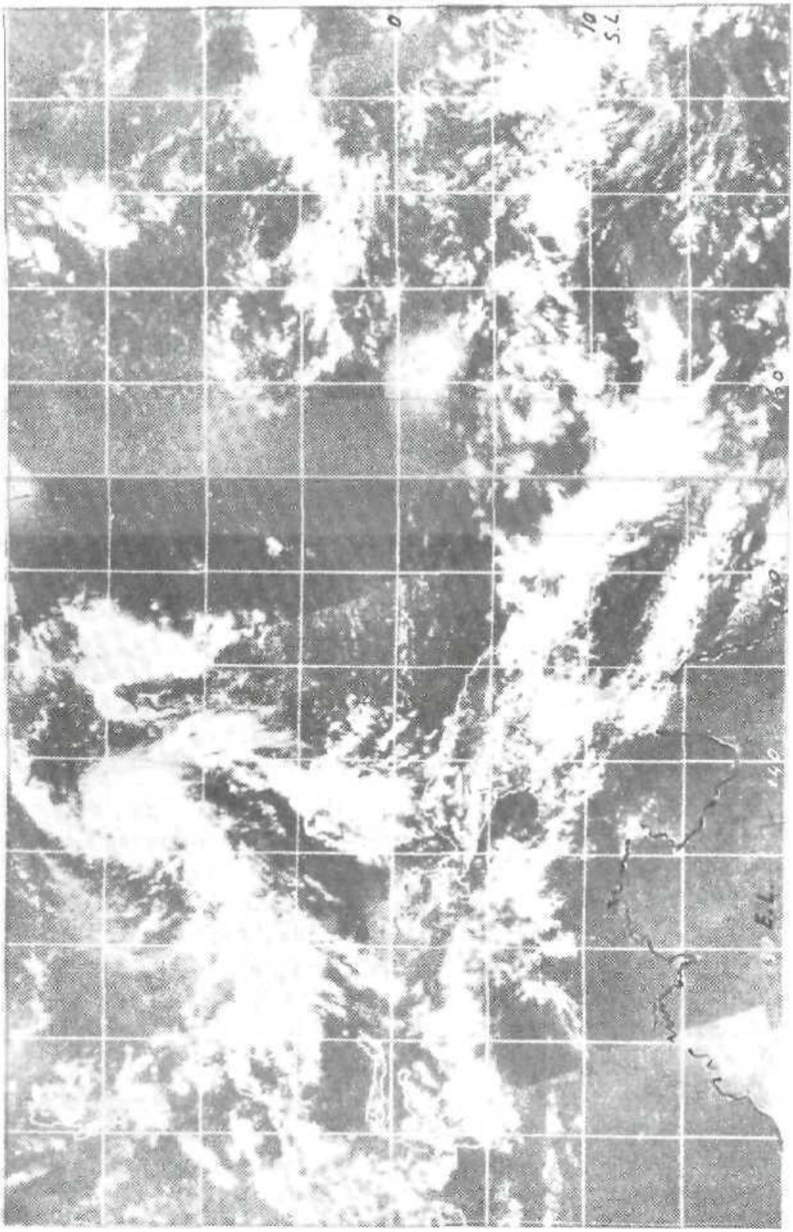

Plate 16. Cloud cover over the western Pacific Ocean on 15 August 1969 as viewed by ESSA-9. Orographic cloud is clearly visible over the highlands of New Guinea and there is also a cloud band, extending southeastward from about 145°E to 160°E, due to convergence in the southeasterly trades. Tropical storms, such as that located at 15°N, 137°E, occasionally affect the Coral Sea, but it has not been known for storm centers to affect the Higlands directly (Imagery provided by courtesy of Dr. C.S. Ramage, Honolulu).

Circulation Fluctuations

The tropical easterlies (trade winds) are the primary mechanism driving water across the Pacific in the South Equatorial Current (Wyrtki, 1974). This flows a few degrees south of the equator, reaching the northern coast of Papua New Guinea in the northern summer (Tabata, 1975). There is a separate westward-flowing arm located between 12°-20° S in the western Pacific from which waters enter the Coral Sea in November-December (M. Tsuchiya, 1968; Wyrtki, 1975a). By March-April this is replaced by a southeastward New Guinea Current (Tabata, 1975) driven by the monsoon westerlies. Wyrtki (1975b) proposed that strong southeasterlies build up a head of water in the western Pacific which returns eastward when the trades relax. Hence, the Peru Current and the intensity of upwelling off South America decrease, the South Equatorial Current weakens, and sea surface temperatures begin to rise over the western and central Pacific (Berlage, 1961; Quinn & Burt, 1970; Quinn, 1971). This pattern gives rise to heavier than average precipitation over the western and central equatorial Pacific. Rainfall anomalies associated with these changes in atmospheric and ocean circulations, do not display a consistent pattern over Malesia, however.

The existence of a standing fluctuation in the surface pressure fields across the Indo-Pacific region was first noted by Sir Gilbert Walker (1924) He referred to the opposed pressure anomalies in the two oceans as the Southern Oscillation. Subsequently, Bjerknes (1969) has termed the standing east-west (zonal) circulation cell over the equatorial Pacific (described above) the Walker circulation. Webster (1973) proposes that this cell represents an ultralong (Kelvin) wave response to seasonal changes in the pattern of latent-heat forcing while the Southern Oscillation represents longer term departures of the heating/cooling patterns which modulate these regular seasonal changes.

Studies on the fluctuations in intensity of the Walker circulation have been carried out by many investigators (Krishnamurti, 1971; Krueger & Gray, 1969; Krueger & Winston, 1974, 1975; Quinn & Burt, 1970; Ramage, 1975; Tsuchiya, 1971, 1975). In February 1971, for example, there was a strong Walker circulation with above normal convective activity over Malesia, whereas in February 1969, during a weak mode, there was more than usual convective activity over the central and eastern Pacific (Krueger & Winston, 1974). In this latter month there were well-developed equatorial westerlies at 700 mb across New Guinea. A similar contrast occurred between spring/summer 1971 and spring/summer 1972 (Krueger & Winston, 1975). During the weak mode of 1972, there were severe drought conditions in the Papua New Guinea highlands.

Spectral analyses of the Southern Oscillation as reflected by Darwin pressure data (Troup, 1965) or a Darwin-Tahiti index (Trenberth, 1976) reveal a major peak in the range 3-6 years. According to Berlage and de Boer (1960) there are also longer term variations in the relative intensity of this phenomenon.

An oscillation of 40 to 40 days has also been identified in surface pressure and upper troospheric wind data across the equatorial Indian and Pacific Oceans (Madden & Julian, 1972). This forms a zonal cell analogous to the much longer duration Walker cell. The peak to trough amplitude of surface pressure is close to 2 mb and that of 700 mb mixing ratio between about 0.5-1g kg^{-1}.

The Malesian region is also apparently influenced by fluctuations in the strength of the meridional links in circulation (Ramage, 1971, p. 231-6). From an analysis of annual precipitation amounts for 1879-1940, ten Hoopen and Schmidt (1951) have suggested that precipitation is augmented over western Java and diminished in Borneo when an intensified east Asian subtropical anticyclone causes equatorward displacement of the equatorial trough. The winter anticyclone over Australia may have an analogous effect on precipitation over New Guinea (Schmidt & Schimdt-ten Hoopen, 1951).

Fluctuations of Cloudiness and Precipitation

The zone of relative maximum cloudiness apparent on satellite imagery (Atkinson & Sadler, 1970) illustrates the tendency for rising air to predominate over Malesia (Plate 16). In most months there is confluence between a cloud band associated with the equatorial trough and one extending northwestward from Fiji to New Guinea (Barrett, 1971; Musk, 1976). Nephanalyses for 1965-1973 (J.C. Sadler, unpub. data, 1975) show a mean cloudiness of 5 to 6 oktas (62-75%) for June-October and December-March over 140°-145° E, 5°-7.5° S, and almost 5 oktas in the other months. Amounts over West New Guinea (135°-140° E, 2.5°-5° S) are about an okta less with a minimum of 4.1 oktas in October.

Anomalies from these monthly means show clear temporal and spatial coherence (Fig. 4), but they bear no similarity to the Southern Oscillation index of Troup (unpub. data). Murakami (1975) has examined this question in detail using Sadler's data. A spatial correlation analysis of the local anomaly of monthly cloudiness for June-August at 140° E, 0°, shows negative relationships with the equatorial eastern Pacific (-0.73 at 130° W, 0°) and the Indian Ocean (-0.55 at 80° E, 0°), suggestive of fluctuating Walker type circulations. The variability of the local anomaly

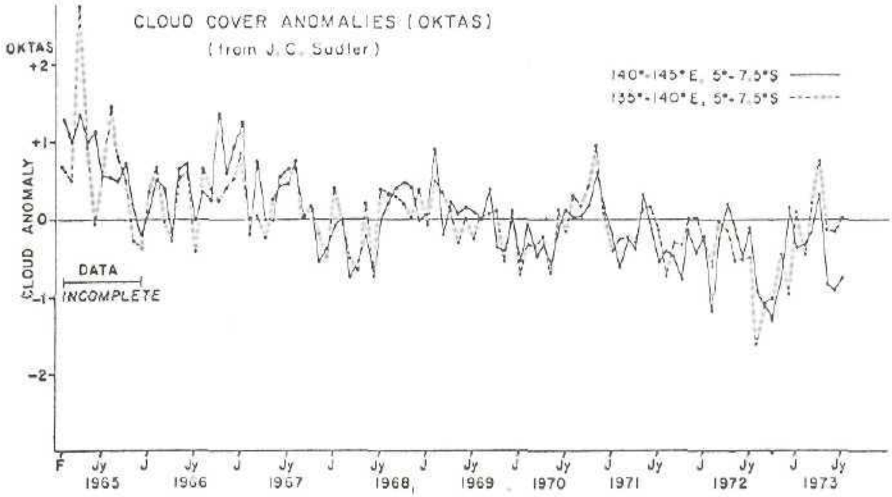

Fig. 4. Monthly cloud cover anomalies for two grid squares over New Guinea. The anomalies (in eighths) refer to the February 1965 — July 1973 mean cloudiness over each square determined from nephanalysis of satellite imagery. (Data provided by courtesy of Dr. J.C. Sadler, Honolulu).

of monthly cloudiness is largest over the equatorial western Pacific (140°-180°E) in all seasons, in accordance with Musk's (1976) finding for precipitation variability. This pattern of cloud variability is apparently dominated by the ultralong waves in the equatorial atmosphere, particularly wave number 2 between 5°N and 10°S. A time-lagged correlation analysis by Murakami further indicated that this pattern is a persistent feature in the Indonesian sector especially. For *lags of 2 to 5 months, an area of positive correlation over 140°E, 10°N* shifts southeastward to 175°E, 15°S, implying that a cloudiness anomaly over the western South Pacific develops about 5 months *after* one in the western North Pacific.

The possible relationship between fluctuations in the Southern Oscillation or the Walker circulation and precipitation in the Indonesian area, referred to above, was the first noted by Berlage (1961, 1966). This question has been further expored by Tsuchiya (1971, 1974) and Nicholls (1973). For 1953-1958, the June-August precipitation shows an inverse relationship between the Indonesian-New Guinea area and the central equatorial Pacific. Above average precipitation over Indonesia tends to be associated with strong Walker circulation and vice versa. However, the dividing line between these two sectors varies in location. In some years Papua New Guinea is like Indonesia; in other years it is like the central Pacific. The former case is represented by the dry years of 1953 and 1958 over Indonesia-New Guinea, but in 1954, 1955, 1956 and 1962 above normal rainfall over Indonesia affected only West New Guinea (Nicholls, 1973; Tsuchiya, 1971). Nevertheless, severe drought years (1941 and 1972) in Papua New Guinea seem to occur during periods of weak Walker circulation. Nicholls also draws attention to local anomalies. An inverse association exists at Lae (below average precipitation with strong Walker circulation), perhaps as a result of local wind effects.

3. Synoptic Climatology

Weather Systems

Braak (1921-1929) recognized that moving rain areas are not detectable over Indonesia, except in the Timor, Arafura and Coral Seas, and Mangunredjo (1964) attributes most weather in the area to airstream convergence zones. Examination of synoptic maps and satellite imagery confirms this general picture for New Guinea. The cloud systems tend to be either cumuliform bands associated with airstream convergence and topographic effects of the mountain ranges, or amorphous cloud masses within the equatorial trough zone, especially during December-March (Barrett, 1971). The synoptic features have been most fully described for Papua New Guinea by Falls (in press). From May through September, when southeasterlies prevail, particularly south of the main ranges, large-scale convective development is reduced although convective line disturbances still occur. According to Falls, some of these develop from former cold fronts in the Tasman Sea, whereas others form within the trade wind current. Mid-latitude troughs which extend equatorward and amplify in longitudes 140-150°E also contribute to cloud activity over the area in the Southern Hemisphere winter. During the monsoon season of equatorial westerlies, the moist, conditionally unstable flow develops cumulonimbus systems whenever there is low-level convergence and particularly when the westerlies strengthen in a "monsoon surge" (Falls, in press).

A special feature of the sector 150°-165°E during the April and November transition seasons is the tendency for disturbances ("monsoon depressions") in the equatorial trough zones to develop in pairs across the equator at about the same longitude (Leigh, 1969). This leads to an increase in the background vorticity and a cloud band forms in the convergent westerly flow between and to the west of the vortices.

From an analysis of Nimbus 3 MRIR (infrared) data covering the sector

25°S-15°N, 120°-170°E, for 23 April 1969 - 4 February 1970, Leigh (1973) shows that the New Guinea mainland is an area of maximum cloudiness in all months. Topographic effects on convective activity are pronounced and the data indicate no apparent nocturnal minimum, in spite of the expected effects of local circulation systems (Flohn, 1974).

Vertical Structure of Airstreams

During the southeasterly season, the trade wind inversion is apparent over Lae near the 2.5 km (725 mb) level about 15-20 percent of the time (Barry, 1978). However, the equally frequent presence of an upper stable layer at about 4 km (575 mb) is attributed by Falls (in press) to the effect of evaporative cooling and the sinking of potentially cold air in downdraughts associated with active precipitation cells rather than to an elevated trade wind inversion. Inspection of soundings for Lae shows that the humidity structure of the upper inversion does not display the deep dry layer characteristic of the trade wind type. The two types of stable layer rarely occur simultaneously and 50-60 percent of soundings show no inversions.

Falls notes that the average relative humidities in the upper troposphere over Lae are quite high compared with oceanic areas. Leigh's (1973) analysis of Nimbus 3 MRIR data suggests that this is the case over all of New Guinea, but probably with a greater seasonal range than the Lae soundings indicate. The high moisture content reflects the frequent occurrence of deep convective activity.

The occurrence of conditional instability and convective instability are important determinants of vertical motion (Gordon, 1973). From the mean sounding data presented by Falls (in press), conditional instability will generally exist over Lae when the relative humidity exceeds 80 percent near the surface during February, whereas in July instability is present above 85 percent relative humidity, but the air is stable for humidities below 79 percent near the surface. The humidity in the surface layer at Lae (1960-1969) averages 70 percent in February, but 80 percent in July. The greater frequency of conditionally unstable conditions in July helps to explain why that month receives double the rainfall of February at Lae. However, this precipitation regime is the reverse of that in the Chimbu region, so that the Lae soundings are unlikely to be indicative of the simultaneous atmospheric structure over the highlands. Moreover, as pointed out by Johnson (1969) there tends to be little difference between the mean soundings on wet and dry days in equatorial latitudes due to the fact that few of the soundings represent conditions in cumulonimbus updrafts.

It is worthwhile to note the interaction of different scales of vertical motion in low latitudes (Ramage, 1971, p. 244). On the synoptic scale, uplift spreads moisture into the middle and upper troposphere and reduces the lapse rate. Thus, thunderstorm activity is diminished although general rains are more likely. Conversely, large-scale subsidence dries the middle troposphere and diminishes general rainfall, but the increased lapse rate encourages local convective activity with showers. These two patterns probably represent general conditions over the central highlands during the westerly monsoon season and the southeasterly season, respectively, with a fair degree of accuracy.

Kinematic Characteristics

Theoretical and empirical studies show that at low latitudes there is a greater tendency for rising air and, therefore, precipitation in westerly flow than easterly flow (Flohn, 1960; Ramage, 1971). This arises from the effect of the latitudinal gradient of the Coriolis parameter in causing convergence (divergence) along the equator in westerly (easterly) flows, respectively. In addition to this large-scale factor, the role of horizontal cyclonic shear and curvature in the boundary layer must be considered, since these contribute strongly to frictional convergence and rising motion. Ascent is also favored by divergent flow and anticyclonic vorticity in the upper troposphere.

Analysis of the circulation characteristics over Papua New Guinea has been carried out using synoptic charts prepared at the Darwin Tropical Analysis Centre (Barry, 1978). Streamline charts for the 200 mb and 700 mb levels were used since the former is close to the level of maximum outflow from cumulonimbus clouds (Reed & Recker, 1971), and the elevated terrain of New Guinea renders the surface map largely meaningless in terms of mountain weather according to Falls (in press). Kinematic properties (streamline diffluence, speed divergence, curvature and shear) have been determined only as to sign (+, 0, -) for the eastern highlands of Papua New Guinea and scored accordingly for both levels. Daily streamline maps for 00GMT (1000 hours) were examined for 40 months during 1965-73, selected to provide months with strong contrasts in the montly mean cloudiness indicated by Sadler's data. Daily circulation types, according to the flow direction and curvature of the streamlines over Papua New Guinea, have also been identified for the 40 months. The type categories are as follows: 8 directions, subdivided according to anticyclonic, neutral or cyclonic curvature; cyclonic or anticyclonic center; and col. Following a preliminary frequency analysis, some groups were merged to provide larger samples.

	200 mb types											
700 mb types	A	NE_A	NE	E_A	E	SE_A	S_A	W_A	W	Col	700 mb totals	All cases
A				14							31	
NE				9							23	
E_A	10			81	26			7	9	12	185	
E	33	29	34	222	70	28	22	18	14	31	523	
SE_A				12	5						36	
SE	5			34	22		5			5	89	
S_A				11							21	
S			5	11							26	
Col				12	8	7					43	
E_C				8							19	
SE_C				9	8						21	
S_C				9	6						20	
W_C				18							39	
W		5	7	42	32	10				9	120	
NW				7	6						19	
200 mb totals	64	69	65	517	206	67	62	33	38	78		
all cases												1,261

Fig. 5. Contingency table for the major type-group (all months for $n \geq 5$).

Fig. 5 summarizes the frequencies of the major circulation type groups at the 700 mb and 200 mb levels. This contingency table illustrates the predominance of easterly circulations at both levels and the high frequency (40 percent of all days) of the anticyclonic easterly type at 200 mb. The westerly patterns at 700 mb, which occur mainly in the transition months and November-March, are also associated predominantly with easterly circulations at 200 mb.

The cloud data and kinematic parameters have been examined in relation to areal precipitation and to one another. Daily precipitation records at two groups of stations were used to determine areally averaged amounts. The stations in the Western Highlands group were Hagen, Muga, Sirunki and Wabag; those in the Eastern Highlands and Chimbu were Gembogl, Kerowagi, Kogl, Kundiawa and Nondugl. Not all stations in these groups had data throughout the period examined. Cloud data (from the nephanalyses of J.C. Sadler) for the grid squares 142.5°-145° E, 5°-7.5° S and 145°-147.5° E, 5°-7.5° S were used for comparison with the western and eastern areal averages of precipitation, respectively.

Season	Parameter	700 mb		200 mb	
		Precipitation	Cloud	Precipitation	Cloud
June-Sept.	Total score	n.s. (n.s.)	10%(n.s.)	n.s. (10%)	n.s.(n.s.)
	Wind	n.s. (n.s.)	n.s.(n.s.)	n.s. (1%)	n.s.(n.s.)
Apr.,May,Oct.	Total score	n.s. (n.s.)	n.s.(10%)	n.s. (n.s.)	1% (10%)
	Wind	n.s. (n.s.)	n.s.(n.s.)	n.s. (10%)	10% (n.s.)
Nov.-March	Total score	n.s. (n.s.)	n.s.(n.s.)	n.s. (10%)	n.s.(n.s.)
	Wind	n.s. (n.s.)	5% (n.s.)	n.s. (10%)	10% (1%)

The first colum of each entry refers to the Eastern Highlands/Chimbu stations (precipitation) or grid square 145°-147.5°E, 5°-7.5°S (cloud); the column in parentheses refers to the Western Highland stations (precipitation) or grid square 142.5°-145°E, 5°-7.5°S (cloud). n.s. denotes non-significant.

Fig. 6. Statistical significance by X^2 of contingency data for circulation parameters and climatic elements in two areas of the central highlands.

Contingency analyses of precipitation amounts versus cloud anomalies from the monthly averages for 1965-1973 show relationships significant at the 0.1 percent level by χ^2 for both areas. This result lends support to the analytical case studies of Barrett (1971) in this region. However, the results of similar tests for relationships between the kinematic indices and cloud anomalies or precipitation amounts show an unexpected degree of randomness (Fig. 6). The most that can be said is that the 200 mb indices are better indices of weather anomalies than those at the 700 mb level, and the wind velocity alone is rather better than the overall kinematic index. However, there is no evidence to support the suggestion by Falls (in press) that precipitation amounts in Papua New Guinea increase in response to surges in the lower tropospheric equatorial westerlies.

Analysis of the frequency of areally averaged precipitation amounts in both areas against the circulation types at 700 mb and 200 mb shows little useful discrimination of dry/wet days for June-September, or the transition months. However, comparison between the two areas in terms of precipitation frequencies shows that in June-September days with easterly circulations at 700 mb account for 80 percent of all days averaging $>$ 10 mm at the eastern stations, but 69 percent of days for the western area. There is a highly significant difference ($<$ 0.1 percent by χ^2) between the two areas for four categories of precipitation amounts. Also, there is a relatively lower proportion of dry days ($<$ 0.5 mm areal average) with easterly flow versus westerly and southerly flows in June-September in the eastern area ($<$ 0.1 percent by χ^2), but not in the western area. These results suggest that easterly flows cause more rainfall in the eastern part of the central highlands, where orographically induce vertical motion is presumably more important, than farther west.

In view of the limited usefulness of the regional indices in relation to local climatic anomalies in the central highlands, the largescale synoptic indices used by Krueger and Gray (1969) and Krueger and Winston (1974, 1975) have also been examined. Maps of monthly anomalies of wind components over the tropics, relative to the 6-year mean values (Gray *et al.*, 1976), were made available by J.S. Winston and T.I. Gray, Jr. A tabulation of the direction of the anomalous wind components over the area shows that, at 700 mb, June-August 1972 experienced southerly and westerly anomalies and even at 20 mb, the meridional anomaly was southerly for July-September 1972. This is in line with the evidence presented by Staff Members, Synoptic Research Branch (1972), that the general drought conditions were associated with a tendency for southerly flow from the Australian continent. The data for Mt Wilhelm indicate the following percentages of the 1965-1972 rainfall averages in 1972: May 96%, June 16%, July 191%, and August 50%. Above-average precipitation at Mt Wilhelm occurred in August 1968 and September 1969 when the anomalous 700 mb wind components over the region were northerly and westerly. The months of complete record at Mt Wilhelm are too few to examine this relationship extensively, but it is unlikely to be consistently reliable, as illustrated by the positive anomaly with southerly components in July 1972. Likewise, below average precipitation occurred in August 1970 when the 700 mb wind anomaly was northerly.

4. Climatic Elements

Radiation

The equatorial location of New Guinea ensures that there is little seasonal variation in daylength. At latitude 5° S it varies only between 11 h 50 min on June 21 and 12 h 25 min on December 21. Consequently, seasonal differences in solar radiation reaching the surface are primarily a result of shifts of the convergence zone and its associated cloudiness. The annual total global solar radiation is about 580 kJ cm^{-2} (140 k cal cm^{-2}) for the central ranges with slightly lower figures along the southern slopes according to estimates based on sunshine and cloudiness data by Kalma (1972). His maps of mid season months show minimum mean daily values (1.35 kJ cm^{-2}) over the central ranges in

July and maximum mean daily values (1.80 kJ cm^{-2}) in October. Measurements for 15-30 September 1975 with a pyranograph at Piundaunde (3480 m) Mt Wilhelm, averaged 1.97 kJ cm^{-2} day^{-1} (472 cal cm^{-2} day^{-1}) although calculations based on extraterrestrial values and assumed absorption indicate that this figure may be an overestimate of up to 12 per cent (Barry, 1977). Hnatiuk *et al.* (1976) report that pyranograph data for April - October 1970 at Piundaunde show little seasonal variation although no details are provided. However, measurements for 1974 and 1975 at Wau compiled by Allison (pers. comm. 1978) show a seasonal pattern like that identified by Kalma (1972). July had a clear minimum at both stations in each year. Allison's results also demonstrate that due to greater cloudiness the totals at Mt Kaindi (2362 m) near Wau are 17 per cent less than at 1200 m. Aproximate average for the two-year records are 1.50 kJ cm^{-2} day^{-1} at Wau (1200 m) and 1.25 kJ cm^{-2} day^{-1} at Mt Kaindi. The mean monthly ratios of the two stations (Mt Kaindi/Wau) ranged between 0.70 and 1.0, but with no systematic seasonal pattern.

At Carstensz, Allison and Bennett (1976) found an average global radiation in January - February 1972 of 1.625 kJ cm^{-2} (388 cal cm^{-2}) at 4434 m. This represents only 73 per cent of the 1960-61 means for these months at Wamena (1550 m) and reflects the greater cloud cover at the mountain station, averaging about 80 per cent cloudiness during the daylight hours. The diurnal regime of solar radiation in relation to cloudiness was examined during 15-30 September 1975 at Piundaunde by Barry (1978). Pyranograph traces suggest three basic patterns can be distinguished. Fig. 7 illustrates two of these putative types: type 1 is a

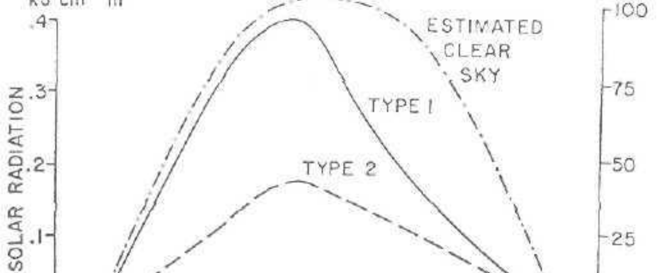

Fig. 7. Solar radiation estimates for clear sky conditions in September on type 1 and type 2 days at Piundaunde, and equinoctial "clear sky".

"dry weather" pattern, type 2 a "rainy weather" pattern. The third pattern is a composite of types 1 and 2 with irregular sunny intervals. Figure 7 also shows the estimated equinoctial "clear-sky" radiation at the site based on traces for hours with cloud-free conditions between sunrise and noon. The asymmetry of the type 1 days is shown by the fact that 65 percent of the radiation is received between sunrise and midday compared with 52 percent on type 2 days.

The transition season comprises weather spells representative of both the dry and rainy seasons and, although the observation period at Piundaunde was brief, the results are considered to be broadly representative of the range of radiation and temperature regimes that will occur in the eastern highlands. Based on daily rainfall frequency data given by McAlpine *et al.* (1975), type 1 days are estimated to have a frequency of 50-60 percent in the southeasterly season. During December-March, type 2 days will be the dominant pattern, probably representing 80 percent of all days. Radiation totals in June will be slightly less due to the lower solar elevation angle while in December-January the heavy cloud and precipitation on most days will offset the less pronounced solstice effects.

Spectral data are lacking from New Guinea. It is known that the altitudinal increase in radiative transmission is proportionately greater in the ultraviolet wavelengths, but the magnitude of this increase is still controversial (Barry & van Wie, 1974). Reduced scattering in the thinner atmosphere increases the direct beam component but reduces the diffuse (sky) radiation and the consequent net increase in global ultraviolet radiation may be only a few percent, particularly at high sun angles (Caldwell, 1968).

Net radiation data are virtually non-existent in New Guinea. Fifteen days of continuous record over a grass surface at Piundaunde (3480 m) (Barry, 1978) gave a daily average of 0.768 kJ cm^{-2} (188 cal cm^{-2}), or 40 percent of the incoming solar radiation. The diurnal trend is similar to that of solar radiation with a 1-hour lag. The net radiation reaches about 62 mW cm^{-2} at midday on type 1 days (Fig. 8) decreasing by half by

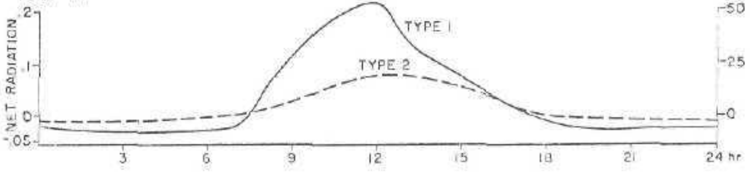

Fig. 8. Net radiation for type 1 and type 2 days at Piundaunde.

1400, with nocturnal values of -7 to -8 mW cm^{-2}. The daytime total of net radiation is 75 percent of the absorbed solar radiation on both type 1 and type 2 days. Net radiation totals on type 2 days are about 53 percent of type 1 days for the 24 hours and 45 percent for 0800-1700 hours.

Temperature

Air temperature in the highlands show the lack of seasonality characteristic of equatorial regimes (Troll, 1959). At Piundaunde there is an annual range of 3.7° C for mean monthly maxima and 1.6° C for minima (Hnatiuk *et al.*, 1976, p. 61). The mean diurnal range, by contrast, is 7.9° C in December and 8.1° C in June (Fig. 9), although this range diminishes with altitude, principally as a result of lower maximum temperatures due to greater mixing of slope air with that in the free atmosphere. Data from Mt Carstensz (Jaya) show a mean diurnal range of 3.4° C at 3600 m and only 2.7° C at 4250 m (Allison & Bennett, 1976).

Lapse rates of mean temperature in the New Guinea mountains are estimated to average between about -0.53° C per 100 m (Smith, 1975)

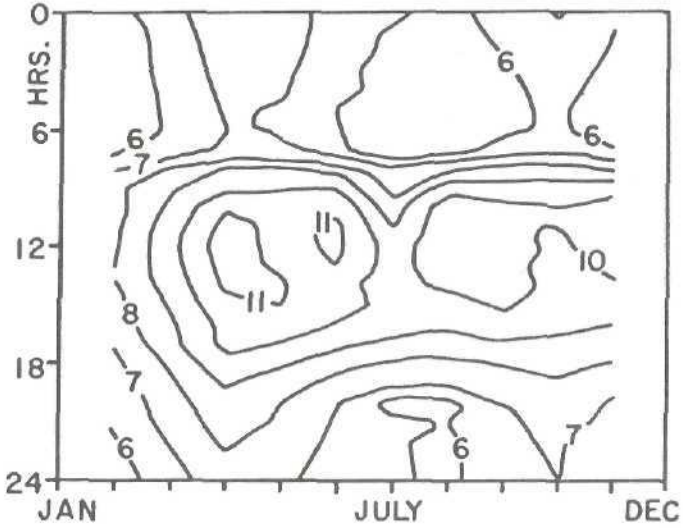

Fig. 9. Thermoisopleth diagram for air temperature (1.5 m) at Piundaunde (3480 m) in 1970. (After Hnatiuk *et al.*, 1976, by courtesy of the authors and Australian National University).

and -0.60° C per 100 m (Hnatiuk *et al.,* 1976, p. 33) based on Mt Wilhelm data. Allison and Bennett (1976) show a rate of -0.67° C per 100 m between 3600 m and the Carstensz base camp (4250 m), although this may be influenced by local cooling effects of the glacier. The mean freezing level is at about 4500 m over Lae, from sounding data, and on Mt Carstensz the modern firn line is at 4600 m (Peterson *et al.,* 1973).

Heavy dew or ground frost is an almost nightly occurrence in the mountains in the "dry" and transition seasons. During dry spells, frost is a serious hazard in upland valleys above 2000 m and on rare occasions, such as October 1972, it occurs down to 1600 m (Brown & Powell, 1974). Similar instances are on record in 1940 (or 1941) and in 1949, 1950, and 1962.

Humidity

Few record of humidity are available in the mountains. Limited hygrograph data from Piundaunde (Hnatiuk *et al.,* 1976, p. 22) indicate that the usual diurnal regime of high nocturnal values, decreasing with higher daytime air temperature, is not predominant during the south-easterly and transition seasons. Irregular variations occur, apparently related to the combined effects of large-scale subsidence (cf. the occurrence of upper inversion at Lae, p. 83) and local mountain-valley wind systems, as well as to temperature regime. For 175 days of observation at Piundaunde in April-November 1970, 63 percent of days experienced the daily minimum humidity between 0700-1300 hours and 20 percent during 1900-0700 hours, with no apparent seasonal trend. The median value for the daily minimum was 62% with 5 percent of minima below 40%.

By contrast, 2-hourly measurements at Carstensz (4251 m) from 22 December 1971 - 6 March 1972 show a daily mean of 88% with an overall standard deviation of only 12% (Allison & Bennett, 1976). The normal diurnal regime, with humidity varying inversely with temperature, was observed. It is probable that this regime is characteristic of the mountains during the westerly season.

Wind

The best general indication of wind speeds on mountain ridges and summits in New Guinea is provided by the upper air data. These show that winds are strongest in July - August with a vector mean speed at the 600 mb (4.1) km) level of 7 m sec^{-1} at Madang and 6 m sec^{-1} at Lae

(McAlpine *et al.*, 1975, Table 20). In the westerly season, winds are much lighter. For example, the mean speed at 4250 m on Carstensz between 22 December 1971 and 5 March 1973 was only 2.1 m sec^{-1} (Allison & Bennett, 1976).

Throughout the mountains, typical diurnal wind regimes occur in the valleys (Flohn, 1974). Winds tend to be upvalley during the day, due to slope heating effects, and downvalley in the early morning hours due to cold air drainage. Occasional strong gusts have been observed in the Pindaunde valley (Hnatiuk *et al* 1976, p. 26), mainly with down-valley winds. These occurred during the dry spells in 1972 and so would not appear to be related to convectional downdraughts.

Precipitation

No complete map of annual precipitation appears to exist for the whole of New Guinea. Paucity of data presents a serious problem. For Papua New Guinea, 18 percent (61) of all raingauges are in the altitude range 1500-1800 m which forms 3 percent of the land area, but there are only two gauges in the area above 2400 m which comprises almost 4 percent of the land area (Aitken *et al.*, 1972). For the western half a general map has been presented by Tsuchiya (1973), although for the mountains this can only be regarded as providing very generalized information. This map has been combined in Fig. 10 with a more detailed one for Papua New Guinea. The latter is a revised version (Snowy Mountains Engineering Corporation, 1974) of one prepared by Aitken *et al.* (1972) using data from 405 stations. Most of the discussion focuses on Papua New Guinea for this reason. The heaviest totals, exceeding 750 cm, fall on the southern slopes of the highlands in the upper Purari and Fly river basins. The middle Ramu basin, north of the Bismarck Range, and a small area in the upper Jimi basin also receive more than 400 cm. In contrast, totals around Goroka and in the upper Chimbu valley are only about 200 cm. Correspondingly, the highest totals in West New Guinea are on the southern slopes, with much lower values over the central ranges. Variability is generally low, with coefficients of variation of about 10-15 percent for annual totals in the highlands of Papua New Guinea (Brookfield & Hart, 1966; McAlpine *et al.*, 1975).

The two dominant seasonal circulation regimes strongly influence precipitation seasonality in the highlands. Seasonality is almost absent in western Papua New Guinea towards the border with West New Guinea (e.g., Telefomin, see Fig. 11), but in the Eastern Higlands and Chimbu area, June and July are relatively dry months. This pattern also occurs at Waimena in West New Guinea. The "classical" equatorial regime

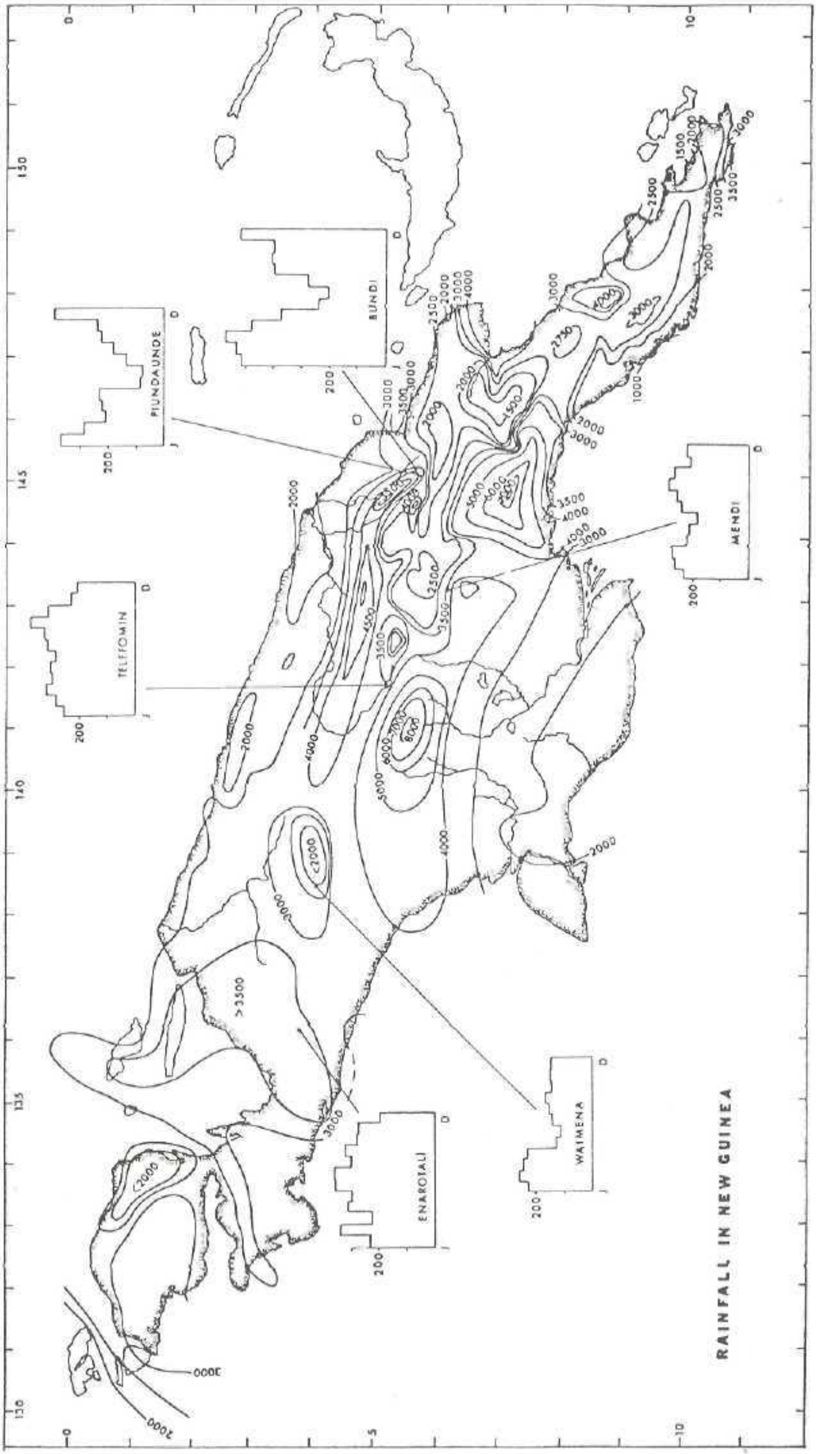

Fig. 10. Annual precipitation (mm) over New Guinea, based on Snowy Mountains Engineering Corporation (1974) and Tsuchiya (1973).

STATION	LAT(S), LONG(E)	ALTITUDE(m)	J	F	M	A	M	J	J	A	S	O	N	D	Yr.	Yrs. of record
North Slope:																
Bundi	5°44' 145°15'	1,400	516	535	567	479	377	239	204	274	396	402	398	511	4,875	13
Chimbu:																
Piundaunde	5°40' 145° 01'	3,480	365	(285E)	205	216	228	87	75	130	185	228	231	398	(2,633)	1-7
Keglsugl	5°46' 145° 08'	2,475	231	281	277	256	120	115	100	146	164	156	145	244	2,283	6
Gembogl	5°53' 145° 04'	2,210	198	241	245	152	117	75	75	93	146	156	175	213	1,914	9
Kundiawa	6°02' 144° 58'	1,495	249	238	288	241	152	97	84	117	182	200	185	224	2,249	13
Daulo Pass	6°02' 145° 14'	2,492	376	448	398	325	174	126	120	132	304	338	334	426	3,391	4
Western Highlands:																
Wabag	5°31' 143° 43'	1,980	300	301	343	293	199	136	127	193	265	266	262	310	3,015	8
South Slope:																
Mendi	6°09' 143° 39'	1,675	231	267	277	222	213	183	239	253	284	269	204	219	2,800	13
Victor Emanuel Range:																
Telefomin	5°08' 141° 38'	1,520	255	286	317	297	304	286	315	326	374	310	232	231	3,527	16
West New Guinea:																
Enarotali	3°56' 136° 21'	1,780	229	339	222	308	297	354	358	295	320	278	271	199	3,469	9
Wamena	4°04' 138° 57'	1,660	223	255	246	226	129	110	148	152	167	142	148	143	2,089	5

Note: — denotes maxima, ... denotes minima; E = estimate. Read Waimena for Wamena.

Fig. 11. Rainfall regimes (mm). From McAlpine *et al.* (1975) and Tsuchiya (1972).

with a double maximum occurs mainly in a narrow sector along the southern edge of the central cordilliera (e.g., Mendi). High elevations are strongly influenced by the "Northwest Season" from December through March. During the "Southeast Season," from May through September/October, the Eastern Highlands and the central mountains in West New Guinea experience drier conditions with, on average, minimum precipitation in June or July. Broad control is exerted by the trade wind inversion (at about 2000 m south of the mountains), but local circulations take on a dominant role during this season. Indeed, Brookfield & Hart (1966) argue that these circulations, together with orographic effects, are the primary determinants of local precipitation. Several studies have shown that even for annual rainfall, there is a low interstation correlation which lends support to this viewpoint (Aitken *et al.*, 1972; Shaw, 1972; McAlpine, pers. comm., 1975). However, there is also evidence of spatial coherence for extreme conditions. For example, the drought of June - September 1972 was widespread in the highlands, despite some isolated wet months at individual stations (Staff Members, Synoptic Research Branch, 1972). The question of spatial variability in tropical rainfall has been examined in detail for Tanzania by Jackson (1974). He shows that inter-station correlation varies complexly with distance as a function of season and suggests that storm type and location are more significant than topographic effects. Certainly there is no simple relationship between rainfall and physiographic factors.

Aitken *et al.* note that there appears to be a general increase of total precipitation with altitude, followed by a decrease at higher elevations. However, this decrease is less pronounced than in many equatorial mountain areas. In Java, de Boer (1950) reported a maximum about 1200 m for annual totals, although in west Java during the westerly monsoon season (December - February) the heaviest totals occur between 2000-3000 m. The distribution in the central highlands is indicated in Fig. 11. Altitudinal effects in the upper Chimbu tend to be obscured in the case of annual totals by the sharp northward increase towards the northern slopes (e.g., Bundi) (McVean, 1974). Short-term measurements on Mt Wilhelm at Saddle Camp (4380 m) show 10-20 percent more than at Piundaunde (3480 m) in 1966-1967) and April-November 1970, but 20 percent less at the higher station in August - October 1971 and April - September 1972 (Hnatiuk *et al.*, 1976). It is apparent, therefore, that altitudinal variations are not consistent for the same season in different years. Fig. 11 suggests that an altitudinal increase in the upper Chimbu is apparent during the period December - February (although the data for Piundaunde are only available for December 1968 and January 1969). During June - September, however, there is no indication of altitudinal effects.

There is evidence of a local minimum at Gembogl in the upper Chimbu, perhaps representing the "Troll effect" (Flohn, 1974). According to Brookfield (cited by Hope, 1973, p. 44), the upper Chimbu valley is orientated across the dominant airflow directions and is sheltered to the northwest by Mt Wilhelm and to the southeast by Mt Kerigoma. The "dry season" in particular appears to be more marked than in neighboring valleys. Observations by Brookfield and by Hope indicate that the cloud level is commonly about 3000 m in the Chimbu, but 2400 m in the Asaro valley and only 1300 m north of the Bismarck Range. Since the maximum rainfall is on average close to the mean cloud base, this may explain why precipitation increases at least between Gembogl and Piundaunde.

The only other mountain area of New Guinea with high altitude observations of precipitation is Mt Carstensz 4° 04'S, 137° 10'E, where the range is only 80 km north of the Arafura Sea. Some inland stations south of the divide show a weak or irregular maximum during the Southeast Season, whereas the majority near the south coast have a minimum at this season (Tsuchiya, 1973) due to divergence effects (Bryson & Kuhn, 1962). North of the divide there is generally no pronounced seasonality although January - April tends to have slightly higher totals. There are very few dry days during this season, with frequent drizzle and hill fog (low cloud) (Braak, 1929, pp. 241-2). In this mountain region, there is no indication of elevational changes in precipitation inland of the foothills (Allison & Bennett, 976). Altitude effects are obscured by local site factors, according to short-term measurements in the vicinity of Mt Carstensz in 1972.

Snow and graupel may fall quite frequently above about 3850 m altitude (Braak, 1929, p. 243) occurring on Mt Wilhelm at least several times a month in April - September and the westerly season months (Hope, 1973; McVean, 1974). On Mt Carstensz, above 4400 m, precipitation falls mostly as sleet or wet snow. Occasional heavy falls of dry snow occurred, even at 4250 m, associated with disturbances from the east and north (Allison & Bennett, 1976) (Plate 17). The snowline appears to have risen slightly during this century. A small ice cap observed on Mt Wilhelmina in 1910 and 1913 had entirely disappeared by 1962 and the Carstensz glaciers (Plate 18) have shown steady retreat since the 1930's (Peterson *et al.* (1973). Allison and Kruss (1977) have reported more fully on this recent minor climatic amelioration which may indicate a warming rate of 0.6°C per century according to their modelling analysis.

Plate 17 Snow on the summit ridge of Mt Wilhelm, 4300-4400 m. (Photo J M B Smith)

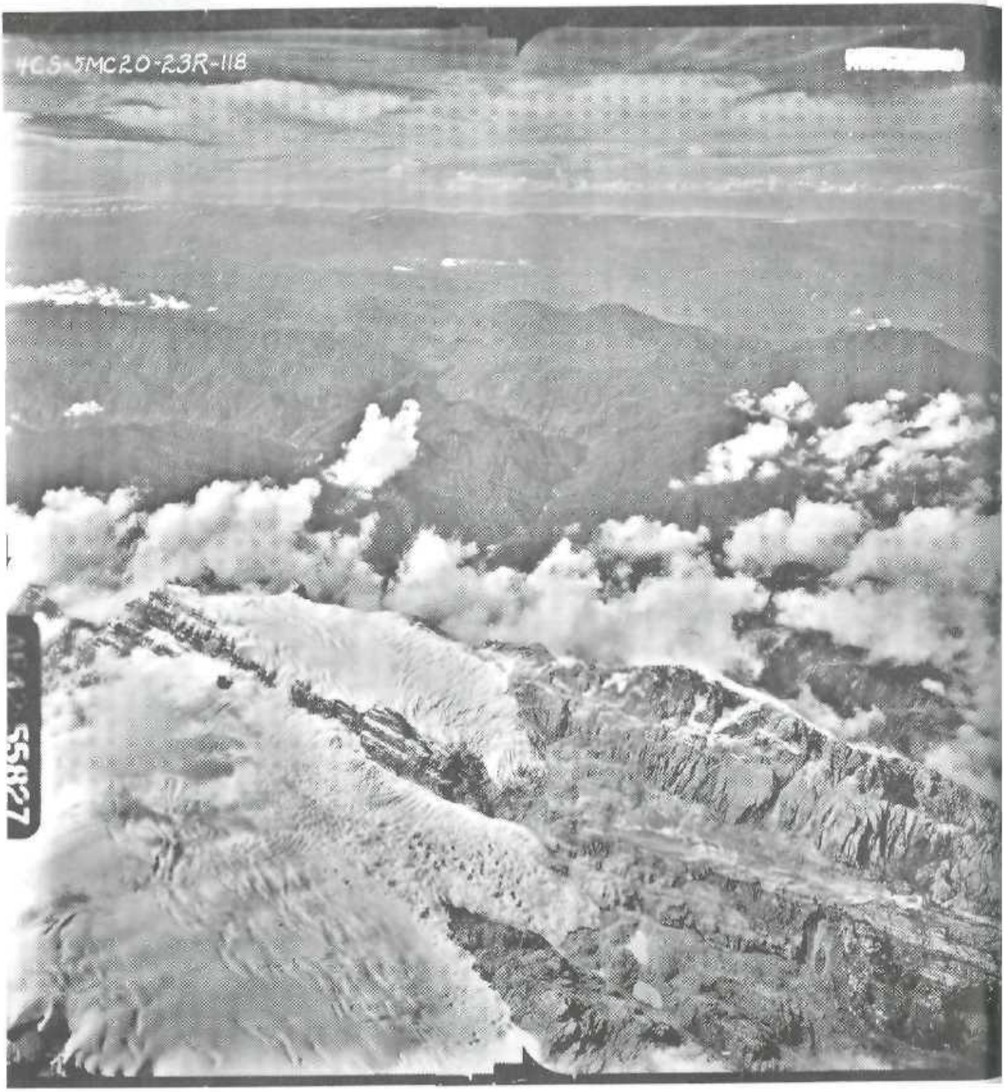

Plate 18. Aerial picture of the eastern end of the Carstensz Mts. In the left hand lower corner Northwall Firn with Meren Glacier branching off to the right; uppermost glacier is Carstensz Glacier. Slightly to the right of center the South Wall Hanging Glacier with the Pyramid. (United States Air Force picture, 1942).

Water Balance

Estimates of weekly water balance have been prepared for groups of stations in Papua New Guinea by McAlpine and Short (1976) using observed precipitation and estimated actual evaporation (based on 0.8 × *estimated* sunken tank evaporation). Mt Hagen, considered representative of a highland group of stations, has an estimated annual tank evaporation of 107 cm with between 7-8 cm per month in June-September and upto 10 cm per month during October-January.*

Figures in the mountains proper are probably much lower. Lysimeter measurements of potential evapotranspiration at Piundaunde (Hnatiuk *et al.*, 1976, p. 20) indicate about 2 cm per month in November 1966 and March-May 1967, about 3.5 cm in June 1967, July-September 1968, and October 1966 and 5.5 cm per month in July-September 1966 and July 1967. Short periods of water deficit were observed although all months had an overall substantial surplus. However, there are no data for really dry months. Limited comparative data at a site 265 m lower than Piundaunde indicate that potential evapotranspiration there tended to be higher than at Piundaunde by 1 cm per month on average.

Topo- and Microclimates

A major problem in describing mountain climates is the limited data representative of a range of sites. In New Guinea, this lack is especially evident, so that most of the following discussion is along general lines.

The primary factor in topo- and microclimatic variations is exposure to solar radiation. Barry (1978) notes that at 6° S, the sun rises at about 0600 local solar time at the equinoxes, but a west-facing slope of 30° is only just illuminated at 0800. The proportion of incident radiation falling on west-facing to east-facing slopes of 30° at the equinoxes is only 25 percent at 0900 and 50 percent at 1000 local solar time. Barry computed the potential global solar radiation under clear skies in the Mt Wilhelm area between 0600-1000 on 23 September. Four-hour totals show a 3 to 5:1 ratio for east- versus westfacing slopes. Measured soil temperatures on adjacent slopes with tussock grass at Piundaunde in September 1975 show upto 10° C difference at 1 cm depth before the morning build-up of cumuliform cloud (Fig. 12) and the effect is still apparent at 7 cm depth.

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*Additional tables of estimated values are given in McAlpine *et al.* (1975, Tables 14 and 15).

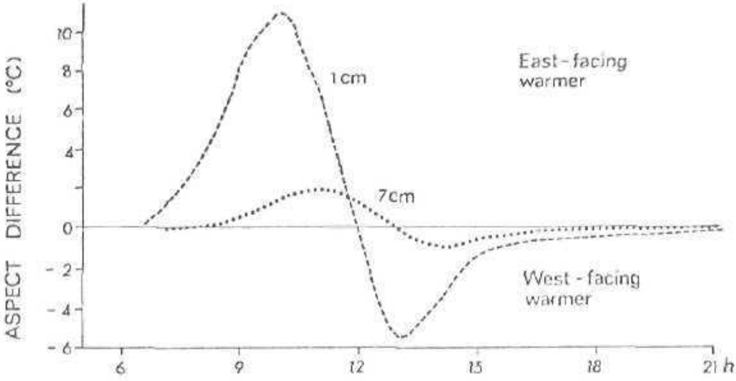

Fig. 12. Diurnal differences in soil temperature at 1 cm and 7 cm beneath tussock grass on east- and west-facing slopes of about 30° at Piundaunde (3480 m) in September 1975, on days with clear skies in the morning hours (type 1 days).

Additionally, Smith (1974, pp. 169-174; 1977; Hnatiuk *et al.*, 1976, p. 39-42) has reported lower "surface" (1 cm above ground) minimum temperatures on eastfacing slopes, perhaps as a result of drier soils due to greater evaporation on the preceding day. These lower minima were observed on east-facing slopes at 3480 m (almost all records for May-September), at 4020 m (a majority of records for 19 weeks) and at 4380 m (all records for 10 weeks). Also, maximum temperatures are consistently higher on east-facing slopes than west-facing ones at 4020 and 4380 m and at 3480 m for the average maximum.

In some localities these characteristics may modified during the day by cloud cover effects. The Imbuka Ridge on the northeast-side of the Piundaunde valley, for example, is especially subject to cloud banking-up against it from the north. In the Piundaunde valley the cloud may spread up-valley from the southeast or spill over the Imbuka Ridge according to the airflow. At night, cold air drainage and ponding of water bodies may introduce local variations. R. Corlett (pers. comm. (1976) found a 4° C difference in surface minimum temperature between the edge of lower Lake Piundaunde and a site 50 m away indicating the local ameliorative influence of the water body. Hnatiuk *et al.* (1976, p. 63) report that the lake temperature in the mornings at 5 cm depth during May-September 1972 ranged between 9° and 13° C. On 23 September 1975 when frost had formed overnight on grass surfaces, the surface temperature of the lake measured with a radiation thermometer (PRT-10) was 8° C and it increased to 18° C at 1430. At 1230 on 30 September it registered 22° C while a bare soil surface indicated 46° C.

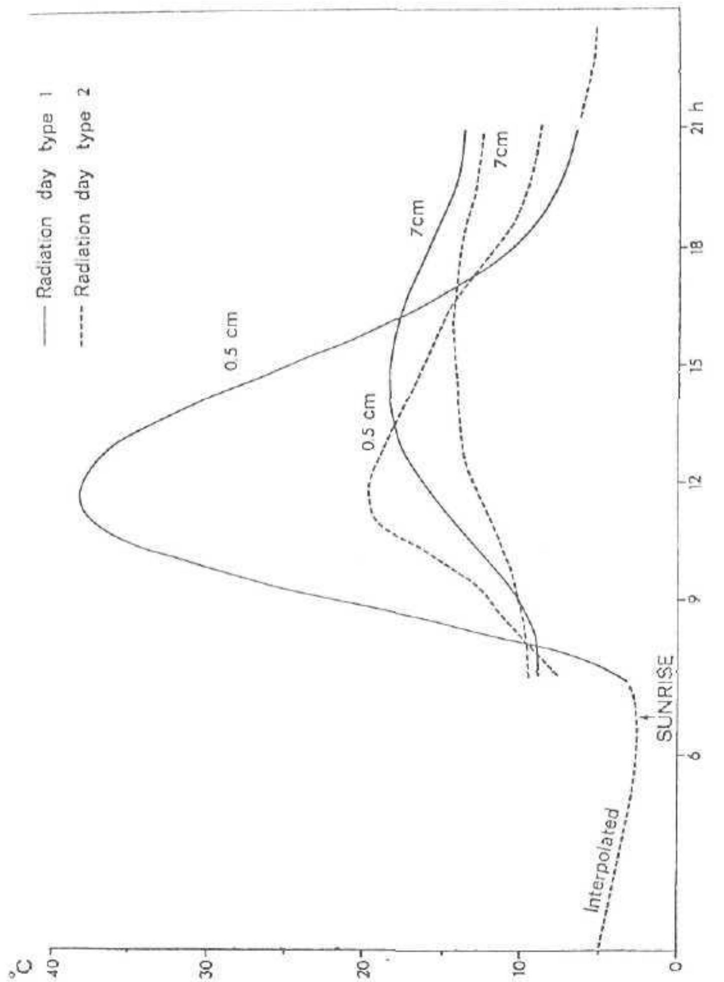

Fig. 13. Temperatures at 0.5 cm and 7 cm beneath a base soil surface on type 1 and type 2 days.

The soil microclimate is much more extreme than the air temperature at least for exposed soils. Barry (1978) reports a diurnal range of 35° C at 0.5 cm in a dark organic (unvegetated) soil on type 1 radiation days (see p. 88) and 12-13° C for type 2 days in September 1975 (Fig. 13). An extreme reading of 48° C was measured at 0.5 cm and the radiation thermometer on 27 September registered 69° C (corrected for emissivity) over the soil surface with a screen air temperature of 14° C. A similar range is to be expected for vegetation *surfaces*, although soil temperature variations under grass tussocks show a much smaller amplitude.

5. Quaternary Climatic Conditions

From recent studies of the geomorphological evidence of past glacial and periglacial activity (Bik, 1972; Galloway *et al.,* 1973; Löffler, 1972; Peterson & Hope, 1972; Reiner, 1960; Williams *et al.,* 1972) and from paleoclimatic reconstructions based on palynological evidence (Bowler *et al.,* 1976; Flenley, 1972; Hope 1976; Hope & Peterson, 1975), a clearer picture of Quaternary conditions in the New Guinea mountains is beginning to emerge. On the basis of these results, several preliminary syntheses of the paleoclimate in Malesia during and since the last glaciation have been attempted (Nix & Kalma, 1973; Quinn, 1971; Verstappen, 1975; Webster & Streten, 1972).

Three major controls on Quaternary glacial climates are identified by Verstappen (1975). They are as follows:

(1) the worldwide reduction in air and sea-surface temperatures;

(2) the lowering of sea level by about 100 m exposing approximately 3 million km^2 of continental shelf in the Java and South China Seas and Torres Strait (see also Walker, 1972);

(3) the location and intensity of the equatorial trough zone.

About 2000 km^2 of the New Guinea mountains were glacierized at the last glacial maximum, compared with an ice cover of only about 10 km^2 on three summits in West New Guinea at present (Bowler *et al.,* 1976). The glacial snowline was about 3400-3500 m in the central ranges, but 3650 m in western West New Guinea and also in the southeast on the Owen Stanley Range. A similar glacial snowline (ca. 3550 m) is indicated for Mt Kinabalu, Sabah (Koopmans & Stauffer, 1968). The modern firnline on Mt Carstensz is about 4600 m (Peterson *et al.,* 1973). Sounding data for Lae indicate that the mean freezing level is approximately 4500 m. These studies indicate a snowline lowering of 1000-1100 m, equivalent to a mean temperature reduction of 5°-6° C, assuming a similar temperature lapse rate to present. A ten percent correction of this lowering is required as a result of the 100 m lowering of sea level, however. Sea-surface temperatures in the central equatorial Pacific during the last glacial maximum (18 000 BP) were 7° C lower at 6° S, 150° W, but 2° C off eastern New Guinea and the Solomon Islands (CLIMAP Project Members, 1976), implying a steeper equatorial vertical temperature gradient than today, as inferred by Kraus (1973).

The emergence of the continental shelves must have had major consequences for oceanic and atmospheric conditions, although evapotranspiration from forested lowlands need not have been much less than from the present shallow seas (Nix & Kalma, 1972). The augmented land area would perhaps tend to increase local thunderstorm activity, but a case can be made for overall drier conditions. This is examined in more detail below. It is worth noting, in passing, that experiments with the NCAR general circulation model, using boundary conditions similar to those at 18 000 BP, indicated drier conditions than at present over the southern continents and over Malesia in July (Barry & Williams, 1975).

The primary control of precipitation during the Northwest Season is the development of monsoon disturbances in the equatorial trough zone. Webster and Streten (1972) argue that their frequency and intensity would be lessened due to the cooler sea surfaces and greater land area reducing the atmospheric moisture content. Similarly, precipitation during the Southeast Season, which is dependent primarily on convective bands within the trades, would also have been reduced by these same processes. Also, according to Webster and Streten (1972), since most of the total precipitation falls on a relatively small number of days, associated with organized disturbances, any increase in precipitation from local convective activity would have only a small offsetting effect on the overall reduction of precipitation. In the New Guinea highlands, rainfall intensities are less than in many tropical regions. Estimates of rainfall amounts per rain day, based on McAlpine *et al.* (1975, Table 7), indicate that about 30 percent of the total precipitation occurs on 10 percent of rain days and 90 percent of the total on 60 percent of rain days. Nevertheless, the general argument would essentially hold.

The probable reduction in intensity of the equatorial trough has been referred to already. The location of the trough zone is more problematic. Several sources (see Webster & Streten, 1972) consider that the middle latitude westerlies would have been displaced equatorward. In the Southern Hemisphere summer this would tend to maintain the trough zone closer to New Guinea while in winter meridional troughs would be a significant factor in the weather regime, bringing lower temperatures and precipitation in the form of snow at high elevations.

The character of the Walker circulation and Southern Oscillation may also have changed. Quinn (1971) postulates that the cool drift of the South Equatorial Current would be excluded from the immediate vicinity of New Guinea by the sea level lowering. He suggests that this would accentuate the rising arm of the Walker circulation over Malesia and thereby strengthen the South Pacific high and the southeasterly trades. This pattern would enhance cold upwelling in the central Pacific, which is certainly apparent in the CLIMAP compilation (CLIMAP Project Members, 1976). The establishment of such a quasi-permanent "high index" mode of the Southern Oscillation would lead to persistent dry conditions in the eastern Pacific and this has been identified on the Galapagos Islands (Colinvaux, 1972; Simpson, 1975). However, as discussed earlier, while Malesia generally should have received above average precipitation, the spatial extent of the anomaly is variable. Perhaps this factor accounts for the apparent precipitation reduction in New Guinea. Alternatively, the model is oversimplified and fails to account adequately for the complexities introduced by the regional changes in geographical conditions. As noted earlier, the air involved in convective ascent over Malesia at the present day apparently moves primarily westward in the upper troposphere.

An analysis of aspect effects on computed solar radiation and soil temperatures at Piundaunde, Mt Wilhelm (3480 m) shows that, under the present-day diurnal regime of convective cloud buildup, east-facing slopes are significantly warmer and drier than west-facing slopes during the Southeast Season (see p. 100) (Barry, 1978). This arises due to the high radiation intensities on east-facing slopes during the early morning, prior to cloud buildup. Löffler (1972) believed such aspect effects to be minimal in New Guinea and suggested that, as a result, the presence of glaciers should be related more closely to altitude than is the case in higher latitudes. However, Peterson *et al.* (1973) noted that the eastern snowline was 100 m higher than the western snowline on the Carstensz and Meren glaciers in January 1972. The field measurements referred to, and earlier data cited by Hnatiuk *et al.* (1976) indicate that Löffler's view is not wholly correct at least at the present day. The absence of clear-cut aspect differences in former snowline noted by Hope (1973, p. 223) must therefore imply more persistent cloudiness throughout the day than occurs at present.

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Selected References

Aitken, A.P., Ribeny, F.M.J. & J.A.H. Brown, The estimation of mean annual rainfall and runoff over the territory of Papua New Guinea - *Civil Eng. Trans. Inst. Eng. Austral.* CE 14 (1972) 49-56.

Allison, I. & J. Bennett, Climate and microclimate in: G.S. Hope, J.A. Peterson, I. Allison & U. Radok, The Equatorial Glaciers of New Guinea. (1976) 61-80.

Allison, I. & P. Kruss, Estimation of recent climate change in Irian Jaya by numerical modelling of tropical glacier systems - *Arct. Alp. Res.* 9 (1977) 49-60.

Allison, I. & J.A. Peterson, Ice areas on Mt Jaya; their extent and recent history, in G.S. Hope, etc., *The Equatorial Glaciers of New Guinea.* (1976) 27-38.

Atkinson, G.D. & J.C. Sadler, Mean-cloudiness and gradient-level wind charts over the tropics: Vol. 1, Data; Vol. 2, Charts. - *U.S. Air Weather Service, Techn. Rep.* 215 (1970) 48 pp.

Barrett, E.C., The tropical Far East: ESSA satellite evaluations of high season climatic patterns - *Geogr. J.* 137 (1971) 535-555.

Barry, R.G., Aspects of the precipitation characteristics of the New Guinea mountains - *J. Trop. Geogr.* 47 (1978) 13-30.

Barry, R.G., Diurnal effects on topoclimate on an equatorial mountain - 14. Internationale Tagung für Alpine Meteorologie (Rauris, 1976) - *Arbeiten, Zentralanstalt Met. Geodynam., Vienna* 32 (1978) 72/1-8.

Barry, R.G. & C.C. van Wie, Topo- and microclimatology in alpine areas, in: J.D. Ives & R.G. Barry, *Arctic and Alpine Environments* (1974) 73-83.

Barry, R.G. & J. Williams, Experiments with the NCAR global circulation model using glacial maximum boundary conditions: Southern Hemisphere results and interhemispheric comparison, in: R.P. Suggate & M.M. Cresswell, *Quaternary Studies - Roy. Soc. NZ, Bull* 13 (1975) 57-66.

Berlage, H.P., Variations in the athmospheric and hydrospheric circulation of periods of a few years duration affected by variations of solar activities - *Ann. NY Ac. Sc.* 95 (1961) 354-367.

Berlage, H.P., The Southern Oscillation and world weather - *Kon. Ned. Met. Inst., Meded. Verh.* 8 (1966) 152 pp.

Berlage, H.P. & H.J. de Boer, On the Southern Oscillation, its way of operation and how it affects pressure patterns in the higher latitudes - *Geof. pura e appl.* 46 (1960) 329-351.

Berson, F.A., Circulation and energy balance in a tropical monsoon - *Tellus* 13 (1961) 472-485.

Bik, M.J., Pleistocene glacial and periglacial landforms on Mt Giluwe and Mt Hagen, Western and Southern Highlands Districts, Territory of Papua and New Guinea - *Zeit. Geomorph.* 16 (1972) 1-15.

Bjerknes, J., Atmospheric teleconnections from the equatorial Pacific - *Mon. Weather Rev.* 97 (1969) 163-172.

de Boer, H.J., On the relation between rainfall and altitude in Java, Indonesia - *Chronica Naturae* 106 (1950) 424-427.

Bowler, J.M., G.S. Hope, J.N. Jennings, G. Singh & D. Walker, Late Quaternary climates of Australia and New Guinea - *Quat. Res.* 6 (1976) 359-394.

Braak, C., Het klimaat van Nederlandsch-Indie - *Kon. Magn. Meteorol. Obs. Batavia, Verhand.* 8, vol. 2, 3 (1929) pt 3. The archipelago without Sumatra and Java, pp. 403-545, and English summary, pp. 187-257.

Brookfield, H.C. & D. Hart, Rainfall in the tropical southwest Pacific - *ANU BG/3* (1966) 25 pp.

Brown, M. & J.M. Powell, Frost and drought in the highlands of Papua and New Guinea - *J. Trop. Geogr.* 38 (1974) 1-6.

Bryson, R.A. & P.M Kuhn, Stress differential induced divergence with application to littoral precipitation - *Erdkunde* 15 (1961) 287-294.

Caldwell, M.M., Solar ultraviolet radiation as an ecological factor for alpine plants - *Ecol. Monogr.* 38 (1968) 243-268.

CLIMAP Project Members, The surface of the Ice-Age earth - *Science* 191 (1976) 1131-1137.

Colinvaux, P.A., Climate and the Galapagos Islands - *Nature 240* (1972) 17-20.

Falls, R., Meteorological controls on climate and weather, in: McAlpine, J.R. & G. Keig, with R. Falls, *Climate and Water Resources of Papua and New Guinea. C.S.I.R.I., Div. Land Use Res.* (in press).

Flenley, J.R., Evidence of Quaternary vegetational change in New Guinea, in: P. & M. Ashton, *The Quaternary era in Malesia,* - *Un. Hull, Dep. Geogr., Misc. Ser.* 13 (1972) 99-108.

Flohn, H., Recent investigations on the mechanism of the "summer monsoon" of southern and eastern Asia, in: Basr, S. *et al., Monsoons of the World.* (1960) 75-88.

Flohn, H., Contributions to a comparative meteorology of mountain areas, in: J.D. Ives & R.G. Barry, *Arctic and Alpine Environments* (1974) 55-71.

Flohn, H. & H. Fleer, Climatic teleconnections with the Equatorial Pacific and the role of ocean-atmosphere coupling - *Atmosphere* 13 (1975) 96-109.

Galloway, R.W., G.S. Hope, E. Loffler & J.A. Peterson, Late Quaternary glaciation and periglacial phenomena in Australia and New Guinea, in: E.M. van Zinderen Bakker, *Palaeoecology of Africa,* vol. 8 (1973) 125-138.

Glen, A.H., Circulation and convergence in the equatorial zone between 95°E and 160°E: December to February - *Bull. Am. Met. Soc.* 28 (1947) 453-464.

Gordon, A.H., The great Philippine flood of 1972 - *Weather* 28 (1973) 404-415.

Gray, T.I., J.R. Irwin, A.F. Krueger & M.S. Varnadore, Average circulation in the tropics, NOAA, Dept. of Commerce, Washington, (1976) 12 pp.

Hnatiuk, R.J., J.M.B. Smith & D.N. McVean, Mt Wilhelm Studies II. The climate of Mt Wilhelm - *A.N.U.* BG/4 (1976) 76 pp.

Hope, G.S., The vegetation history of Mt Wilhelm. Thesis. Canberra. (1973) 460 pp.

Hope, G.S. The vegetational history of Mt Wilhelm, Papua New Guinea - *J. Ecol.* 64 (1976) 627-663.

Hope, G.S. & J.A. Peterson, Glaciation and vegetation in the high New Guinea mountains, in: R.P. Suggate & M.M. Cresswell, Quaternary Studies - *Roy. Soc. NZ Bull.* 13 (1975) 155-163.

Jackson, I.J., Inter-station rainfall correlation under tropical conditions - *Catena* 1 (1974) 235-256.

Johnson, D.H., The role of the tropics in global circulation, in G.A. Corby, The global circulation of the atmosphere - *Roy. Met. Soc.* (1969) 113-136.

Kalma, J.D., Solar radiation over New Guinea and adjacent islands - *Austr. Met. Mag.* 20 (1972) 116-127.

Koopmans, B.N. & P.H. Stauffer, Glacial phenomena on Mount Kinabalu, Sabah - *Borneo Reg. Malaysia Geol. Surv. Bull.* 8 (1968) 25-35.

Kraus, E.B., Comparison between ice age and present general circulations - *Nature* 245 (1973) 12-133.

Krishnamurti, T.N., Tropical east-west circulations during the northern summer - *J. Atmos. Sc.* 28 (1971) 1342-1347.

Krueger, A.F. & T.I. Gray, Long-term variations in equatorial circulation and rainfall - *Mon. Weather Rev.* 97 (1969) 700-711.

Krueger, A.F. & J.S. Winston, A comparison of the flow over the tropics during two contrasting circulation regimes - *J. Atmos Sc.* 31 (1974) 358-370.

Krueger, A.F. & J.S. Winston, Large-scale circulation anomalies over the tropics during 1971-1972 - *Mon. Weather Rev.* 103 (1975) 465-473.

Leigh, R.M., Some interpretations of meteorological satellite data over the New Guinea mainland and surrounding oceanic and island regions. Thesis. Port Moresby. (1969) 162 pp.

Leigh, R.M., Analyses of tropospheric water vapour and cloudiness for the western Pacific and Australian tropical regions from Nimbus 3 medium resolution infrared observations. Thesis. Townsville. (1973) 299 pp.

Löffler, E., Pleistocene glaciation in Papua and New Guinea - *Zeit. Geomorph., Suppl.* 13 (1972) 32-58.

Madden, R.A. & P.R. Julian. Description of global-scale circulation cells in the Tropics with a 40-50 day period - *J. Atmos. Sc.* 29 (1972) 1109-1123.

Mangunredjo, I., Synoptic weather analysis in Indonesia, in: J.W. Hutchings, *Proceedings of the Symposium on Tropical Meteorology*, New Zealand Meteorological Service. (1964) 347-351.

McAlpine, J.R. & K. Short, Water balance estimates for Papua New Guinea - *C.S.I.R.O., Div. Land Use Res., Techn. Mem.* 74/9 (1974) 72 pp.

McAlpine, J.R., G. Keig & K. Short, Climatic tables for Papua New Guinea - *C.S.I.R.O., Div. Land Use Res., Techn. Pap.* 37 (1975) 177 pp.

McVean, D.N., A year of weather records at 3480 m on Mt Wilhelm, New Guinea - *Weather* 23 (1968) 377-381.

McVean, D.N., Mountain climates of the southwest Pacific, in: J.R. Flenley, *Altitudinal zonation in Malesia, - Un. Hull. Dept. Geogr., Misc. Ser.* 16 (1974) 47-57.

Murakami, T., Interannual cloudiness changes - *Mon. Weather Rev.* 103 (1975) 996-1006.

Musk, L.F., Rainfall variability and the Walker cell in the equatorial Pacific ocean - *Weather* 31 (1976) 34-46.

Nicholls, N., The Walker circulation and Papua-New Guinea rainfall - *Bureau of Meteorology, Australia, Techn. Rep.* 6 (1973) 13 pp.

Nix, H.A. & J.D. Kalma, Climate as a dominant control in the biogeography of northern Australia and New Guinea, in: D. Walker, *Bridge and Barrier: the natural and cultural history of the Torres Strait - A.N.U.,* BG/3 (1972) 61-91.

Peterson, J.A. & G.S. Hope, A lower limit and maximum age for the last major advance of the Carstensz Glacier, West Irian - *Nature* 240 (1972) 36-37.

Peterson, J.A., G.S. Hope & R. Mitton, Recession of the snow and ice fields of Irian Jaya - *Zeitschr. Gletscherk. Glazialgeol.* 9 (1973) 73-87.

Quinn, W.H., Late Quaternary meteorological and oceanographic developments in the equatorial Pacific - *Nature* 229 (1971) 330-331.

Quinn, W.H. & W.V. Burt, Prediction of abnormally heavy precipitation over the equatorial Pacific dry zone - *J. Appl. Met.* 9 (1970) 20-28.

Ramage, C.S., Role of a tropical "maritime continent" in the atmospheric circulation - *Mon Weather Rev.* 96 (1968) 365-370.

Ramage, C.S., Monsoon meteorology. (1971) 296 pp.

Ramage, C.S., Preliminary discussion of the meteorology of the 1972-73 El Nino - *Bull. Am Met. Soc.* 56 (1975) 234-242.

Reed, R.J. & E.E. Recker, Structure and properties of synoptic-scale wave disturbances in the equatorial western Pacific - *J. Atmos. Sc.* 28 (1971) 1117-1113.

Reiner, R., The glaciation of Mt Wilhelm, Australian New Guinea - *Geog. Rev.* 50 (1960) 491-503.

Sadler, J.C., The upper tropospheric circulation over the global tropics - UHMET-75-5, Dept. of Meteorology, Un. Hawaii. (1975) 35 pp.

Schmidt, F.H. & K.J. Schidt-ten Hoopen, On climatic variations in Indonesia - *Djaw. Met. Geofis., Verhand.* 41 (1951) 43 pp.

Shaw, E.M., A hydrological assessment of precipitation in the Western Highlands of New Guinea, in: *Distribution of precipitation in mountainous area,* vol. 2, World Meteorological Organization, WMO No 326 (1972) 532-543.

Simpson, B.B., Glacial climates in the eastern tropical Pacific - *Nature* 253 (1975) 34-36.

Smith, J.M.B., Origins and ecology of the non-forest flora of Mt Wilhelm, New Guinea. Thesis Canberra. (1974) 270 pp.

Smith, J.M.B., Vegetation and microclimate of east- and west-facing slopes in the grasslands of Mt Wilhelm, Papua New Guinea - *J. Ecol.* 65 (1977) 39-53.

Snowy Mountains Engineering corporation. Map of mean annual rainfall - Papua New Guinea Water Resources Study. Fig. 5. Office of Minerals and Energy, Papua New Guinea. (1974).

Staff members, Synoptic Research Branch. Drought in Papua New Guinea Highlands during the period June to September 1972 - *Burea of Meteorology Working Paper* 16 (1972) 31 pp.

Tabata, S., The general circulation of the Pacific Ocean and a brief account of the oceanographic structure of the North Pacific Ocean. Part 1. Circulation and volume transports - *Atmosphere* 13 (1975) 133-168.

Tsuchiya, I. Fluctuations of rainfall in southeast Asia - Pacific and low and middle latitude circulations in the Southern Hemisphere, in: M.M. Yoshino, *Water balance of Monsoon Asia.* (1971) 217-239.

Tsuchiya, I., On the relation between the interannual rainfall fluctuations in and around New Guinea and the tropical circulations, in: M.M. Yoshino, *Water Resources of Monsoon Asia* (in Japanese) (1973) 175-190.

Tsuchiya, I., Interannual fluctuations in the rainfall of the India-equatorial Pacific region and in the tropical circulation - *Geophys. Mag.* 37 (1975) 163-173.

Tsuchiya, M., Upper Waters of the Intertropical Pacific Ocean. (1968) 50 pp.

Trenberth, K.E., Spatial and temporal variations of the Southern Oscillation - *Quart. J. Roy. Met. Soc.* 102 (1976) 639-653.

Troll, C., Die tropischen Gebirge. Ihre dreidimensionale klimatische und pflanzengeographische Zonierung - *Bonn. Geogr. Abhandl.* 25 (1959) 93 pp.

Troup, A.J., The "Southern Oscillation" - *Quart. J. Roy. Met. Soc.* 91 (1965) 490-506.

Verstappen, H.Th., On palaeoclimates and landform development in Malesia, in: G.J. Bartstra & W.A. Casparie, *Modern Quaternary Research in southeast Asia.* (1975) 3-35.

Walker, D., Bridge and barrier: the natural and cultural history of the Torres Strait - *A.N.U.* BG/3 (1972) 437 pp.

Walker, G.T., Correlation in seasonal variations of weather, IX: A further study of world weather - *Mem. Ind. Met. Dept.* 24 (1924) 275-332.

Webster, P.J., Temporal variation of low-latitude zonal circulations - *Mon. Weather Rev.* 101 (1973) 803-816.

Webster, P.J. & N.A. Streten, Aspects of Late Quaternary climate in tropical Australia, in: D. Walker, *Bridge and Barrier: the natural and cultural history of the Torres Strait - A.N.U.* BG/3 (1972) 144-181.

Williams, P.W., I. McDougall & J.M. Powell, Aspects of the Quaternary geology of the Tari-Koroba area, Papua - *J. Geol. Soc. Austral.* 18 (1972) 333-347.

Wittwer, E.L., Seasonal changes in wind regimes in northern Australia and adjoining intertropical area - *Austr. Geogr.* 12 (1973) 340-362.

Wyrtki, K., Equatorial currents in the Pacific 1950 to 1970 and their relations to the Trade Winds - *J. Phys. Oceanog.* 5 (1975) 450-459.

Wyrtki, K., El Nino - the dynamic response of the equatorial Pacific Ocean to atmospheric forcing - *J. Phys. Oceanog.* 5 (1975) 572-584.

Note Added In Proof

Since this paper was prepared an analysis and reconstruction of the late Quaternary paleoclimate conditions of the area has been published by Webster and Streten (1978). They concur with the views expressed on p. 103 that snowfall to maintain the New Guinea glaciers would necessitate frequent cold air outbreaks and that conditions were probably generally drier. They also note some apparent inconsistencies between the land records and the inferred CLIMAP sea surface temperatures.

Webster, P.J. & N.A. Streten, Late Quaternary ice age climates of tropical Australia: interpretations and reconstructions - *Quat. Res.* 10 (1978) 279-309.

6. ECOLOGY OF THE HIGH MOUNTAINS OF NEW GUINEA

by

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1. Introduction

High equatorial mountains are ecologically unique and of considerable interest. Their uniqueness stems largely from their combination of cool temperatures with a lack of marked seasons (except with regard to precipitation), distinguishing them from otherwise comparable environments at lower altitudes in the tropics as well as at higher latitudes. Their floras, at least outside the forests, have more in common with those of temperate zone mountains than of the adjacent lowlands, and this is especially true in New Guinea where the plants of high altitudes show close affinities with both mainland Asia and Australasia. These geographical features are explored further in the chapter following this one.

In the present chapter the environments of New Guinea's high moutains, and the ecological constraints operating upon their flora, are briefly explored. Because such environments are not closely comparable with those of higher latitude mountains (Troll, 1959) use of the temperate zone vegetation terms alpine, subalpine and montane (Wade and McVean, 1969) is incongruous. Instead Smith (1975) has suggested that the word tropicalpine be used to describe non-forest vegetation on mountains in New Guinea and elsewhere in the tropics. In the present general account, vegetation will be described using only structural and ecological terms (e.g. forest, tussock grassland, mire, short grass bog). Hope provides a more detailed account of the vegetation types found above 3000 m in New Guinea in his chapter on the mountain vegetation.

For reasons of remoteness, inaccessibility and uncomfortable climate, visits by biologists to high mountains in New Guinea have tended to be brief. Ecological research has reached only an early stage, the most detailed studies having all been done on Mt Wilhelm, the only mountain with a research station. However, general accounts have been published by plant collectors and others of several mountain environments. These include Mt Doormantop (Lam, 1945), Mt Carstensz (Ridley, 1916), Mt Wilhelmina (Archbold, Rand & Brass, 1942; Brass, 1941), the Star Mountains (Kalkman, 1963), Doma Peaks (Kalkman & Vink, 1970), the Bismarck Range including Mt Wilhelm (Brass, 1964; Hoogland, 1958; Pullen, 1957; Robbins, 1970), the Sarawaket Mountains (Lane-Poole, 1925), Mt Scratchley and Mt Strong (Coode & Stevens, 1972), Mt Albert Edward (Archbold & Rand, 1935; van Royen, 1967), and Mt Dayman (Brass, 1956). Other research publications are summarized and referred to below. The present author's experience is mainly from Mt Wilhelm. Unreferenced observations pertaining to this mountain are original and mainly previously unpublished, but for the bulk of the material summarised here I have relied heavily on the work of others.

2. Climatic Factors

The climate of New Guinea mountains has not been consistently recorded anywhere, due to the lack of permanently occupied research facilities. However, an account of the climate of Mt Wilhelm has been compiled from fragmentary records spanning eight years of intermittent occupation of the Australian National University research station there (Hnatiuk, Smith & McVean, 1976), and a preliminary description of the climate of Mt Carstensz has also been published (Allison & Bennett, 1976). There appears to be a gradient of increasing precipitation from east to west in the mountains, while perhaps as a result of increasing cloudiness, temperature extremes may become less along the same gradient.

Plants growing above 3000 m, except where sheltered by a higher canopy of vegetation, need to cope with "growth temperatures" and frosts throughout the year. Daytime temperatures, except on cloudy days at higher altitudes, are probably high enough to permit plant metabolism for many species on all days, resulting in tender new growth at all times of year. Night temperatures may fall below freezing-point on any night of the year, particularly on cloudless nights. Plants in these environments are therefore in a quite different situation from those in temperate alpine areas, where a brief but warm summer allows growth free from the risk of frost damage, though a "resting" season is mandatory during the long winter. In New Guinea mountains there is no resting season and no freedom from frost.

The climate is therefore a harsh one for plants, but is not uniformly so, there being wide variations both in local climate (microclimate) and in plant species' tolerance to climatic factors. Lack of moisture is seldom limiting. Although a less wet season occurs in most or all mountain areas in New Guinea from about May to September, precipitation is usually adequate throughout this season. Only rarely have wilting and mortality been noted, as for several small herbaceous species both native and alien during the very dry year 1972 on Mt Wilhelm.

Especially on cloudy days and at higher altitudes (and of course in the shade of other plants as on the forest floor), light may be inadequate or nearly so for the photosynthetic accumulation of carbohydrates in excess of those required in respiration, and so for growth. Hnatiuk (1975) stresses that the balance between photosynthesis and respiration is a delicate one. He suggests for the tussock grass *Deschampsia klossii* that the lower productivity he finds in anthropogenic grassland below 3800 m on Mt Wilhelm than at higher altitudes might be due to higher temperature resulting in a greater increase in the rate of respiration than of photosynthesis.

Probably the thermal regime is the most ecologically critical and important part of climate. In a general way the drop in temperatures with increasing altitude is obviously the cause of altitudinal zonation of vegetation in New Guinea mountains. However, local variations in thermal microclimate are large, important and ecologically revealing.

Beneath a forest or shrub canopy, temperatures are less extreme than in the open; maximum temperatures are lower and minima higher (McVean, 1968). Frosts are probably rare inside the forests, except perhaps at the highest altitudes. Outside the forests temperatures are more extreme at "grass" level than at the level of standard meteorological screen measurements, 1.5 m. At 3480 m in the Piundaunde Valley of Mt Wilhelm, near the research station, ground surface temperatures are generally about 8° C higher by day and 4° C lower by night under clear skies; more extreme differences have also been recorded. In cloudy weather the differences are small. Ground frosts are common on clear nights at this site, but freezing temperatures have seldom been recorded in the meteorological screen (Hnatiuk, Smith & McVean, 1976).

Little data have been collected on local variations in temperatures in New Guinea mountain regions. One such study, again on Mt Wilhelm, concerns climatic differences between slopes of different aspect (Hnatiuk, Smith & McVean, 1976; Smith, 1977). This study grew out of the observation, common to most or all of New Guinea's high mountains, that while clear, sunny mornings were frequent, cloud and often rain developed by late morning or early afternoon on most days. It was therefore likely that slopes facing east would receive more sunshine than those facing west.

Temperature data confirmed this. Over a range of altitudes east-facing slopes had fairly consistently both higher maximum temperatures and lower minima than their nearby west-facing counterparts on the opposite sides of the ridges, hillocks or valleys studied. The contrast was less on the generally cloudier Imbuka ridge, and greater at less moist sites. Soils were less wet on east-facing slopes (explaining the lower minimum temperatures), and there were also differences in vegetation. Grass tussocks were larger and shrubs fewer on east-facing slopes, and the forests were less widely destroyed by fire and regenerating faster on the damper west-facing slopes.

R.T. Corlett (personal comment, 1977) has made further observations upon aspect variations in the vegetation of Mt Wilhelm at about 3300-3800 m. Early morning observations in six valleys confirmed that relict forest patches, having survived burning, were shaded from morning sunshine more often than would be expected if their distribution were random. Often this shading was caused by a crag on the valley side or ridge where it would not be expected from simple valley orientation. Regeneration of forest was also better in grassland sites shaded from morning sunshine.

Quadrat studies also revealed other less conspicuous floristic differences. In particular it was shown that many species grow higher on slopes facing east than west, and lower on slopes facing west than east, while no species had the opposite distribution (Smith, 1977). Since temperatures are lower at higher altitudes, and both maximum and minimum temperatures are more extreme on east-facing slopes, this suggests the distributions are controlled by maximum temperatures or some factor related to them, rather than minimum temperatures. Maximum temperatures are typically critical for plants in arctic and alpine environments (Billings & Mooney, 1968) so this finding is not exceptional. Nevertheless in a situation of concurrent growth and frost, damage to young tissues by freezing may be expected to occur, and perhaps therefore to play a part in restricting species distributions at the tops of their ranges. Frost damage to a range of plants at various altitudes on Mt Wilhelm has been recorded. Although maximum temperatures are related to factors of major ecological importance, minimum temperatures cannot be neglected.

The harshness of the equatorial environment is largely a result of high levels of incoming radiation by day and outgoing radiation by night. Fragmentary radiation measurements on Mt Wilhelm confirm the expected high radiation values, although cloudiness ameliorates conditions by comparison with some African and Andean mountains. Morphological adaptations by plants to the climate of New Guinea's mountains are considered below.

3. Soil Factors

G.S. Hope (1976, pp. 118-121) presents soil analyses for Mt Carstensz (limestone), and compares them with soil analyses from Mt Wilhelm (granodiorite) reported by Wade & McVean (1969). Rutherford (1964) describes three soil profiles from the summit area of Mt Giluwe. Mountain soils in Papua New Guinea are also described by Haantjens (1970) and by Bleeker in Chapter 4 (p. 59-74).

Soils are generally peaty, as may be expected in such a cool, wet environment. Except for skeletal soils derived from limestone they are also acidic, pH values of 5-6 being recorded on Mt Wilhelm, around 5 on Mt Giluwe (Wade & McVean, 1969), and 5.5-7 on Mt Carstensz. Profile differentiation is poor, though soil mixing appears not to be great; rodent burrows are restricted to drained areas of locally positive relief, and earthworms may be scarce. Especially in the west, soils may be more or less waterlogged for most of the year.

The general level of soil fertility is low, especially with regard to nitrogen and exchangeable bases. Writing of Mt Wilhelm, though their remarks probably apply to all New Guinea high mountains, Wade and McVean state "the local plant species would appear to be well adapted to the low level of soil fertility and the scarcity of calcium and phosphorus. Top dressings of calcium hydrogen phosphate were applied to ... short grass bog around Piundaunde ... without producing any change in colour or increase in growth rate". However, some species assume a luxuriant appearance at sites of local pollution, and aliens may be restricted to such sites. For example *Poa annua* was common along an open drain carrying soapy water from the Mt Wilhelm research station in 1972, but absent from a nearby unpolluted drain.

The soil factors of ecological significance are probably not chemical, but related to depth and degree of waterlogging. Above 3800 m (the natural forest limit) and up to at least 4200 m on Mt Wilhelm, the critical factor determining whether tussock or short grassland occurs appears to be soil depth. Tussock grassland dominated by *Deschampsia klossii,* often with abundant finger fern, (*Papuapteris linearis*), only occurs on soils deeper than c. 40 cm. G.S. Hope (1976) has suggested that the tundra communities of Mt Wilhelm's summit ridge may be a successional stage towards tussock grassland, although a temperature-related factor is probably also involved as tussock grassland is more extensive and occurs higher on the northeast-facing slope, with higher maximum temperatures.

As might be expected in a region of such rugged topography, landslips are frequent, though usually small. On Mt Wilhelm these are probably most common in anthropogenic grasslands, though slips off forested slopes also occur. Elsewhere landslips may be large and more widespread, triggered by earthquakes (Pain, 1972), though there are no reports of this from areas above 3000 m. Succession is considered later, but it is pertinent to mention here that there appear to be no obligate pioneer native species of disturbed soils, at least on Mt Wilhelm. However, a series of landslip communities, usually dominated by *Rhododendron* species or by *Gonocarpus halconensis* can be recognised (Wade & McVean, 1969).

Especially at higher altitudes, and sometimes to at least as low as 3215 m (R.T. Corlett, pers. comm., 1977), needle ice develops on clear, frosty nights from the surface of wet unvegetated soil. This is extremely damaging to small plants, such as adventive seedlings, with the result that soil may remain bare for many years above about 3800 m. Such areas may eventually be revegetated only by vegetative spread from their margins, but in some cases on steep slopes continuing soil erosion may undercut the turf and enlarge the bared area.

Ill-drained depressions support a range of vegetation types in accordance with the duration and extent of water accumulation experienced. The ecological controls are not known in detail. Permanently wet ground supports a variety of mire communities. Ground which may dry at the surface periodically but is usually saturated supports short grass bog, though this vegetation type may be secondary, following forest burning (R.T. Corlett, pers. comm., 1977). Better drained sites including most of the slopes and ridges are forested or clothed by tussock grassland depending upon altitude and human impact, except where soils are shallow.

4. The Fauna

Faunas have been poorly studied in New Guinea's high mountains. J.H. Hope (1976) has written a summary account of what is known of the animals of Mt Carstensz and has reviewed earlier work on the mammals of other mountains. Birds of high altitudes are included in Rand & Gilliard's handbook (1967). Reptiles and amphibians are few above 3000 m, though two species of microhylid frog burrow in the tussock grasslands on Mt Wilhelm (Wade & McVean, 1969) as high as 4000 m, and other amphibians (*Litoria* sp. and *Xenobatrachus* sp.) and a lizard (*Lobulia* sp.) have been collected at well over 3000 m on Mt Carstensz (J.H. Hope, 1976). A few descriptive accounts of collections of mountain invertebrates have been made, but even less is known of the ecology of the invertebrates than in the case of the vertebrates. Aspects of lake biology on Mt Wilhelm are discussed by Löffler (1973) and Thomasson (1967), and of cryobiology on Mt Carstensz by Kol & Peterson (1976).

Mammal faunas of the mountains have in most cases been severely depleted in number of individuals if not of species by hunting man, and by the prehistorically introduced dog. On Mt Suckling, with no history of hunting, wallabies are common (P.F. Stevens, pers. comm., 1973), and Brass (1964) records heavy wallaby grazing in the grassland of Mt Otto. Wallabies also occur in basin grasslands at 2750-3000 m below Mt Victoria despite some hunting and evidence of former burning (R.T. Corlett, pers. comm., 1977), but they are scarce or absent from most other mountains with a history of human disturbance. The faunas of the mountain forests are richer than those of the grasslands, though many of the forest vertebrates may be found on occasion in grassland habitats.

The mammals of the high mountains include monotremes, marsupials and placentals. The monotreme *Zaglossus bruijni* is reported to be one of the commonest mammals at high altitudes on Mt Carstensz (J.H. Hope, 1976), but it is not as common on other mountains. Marsupials include wallabies (*Thylogale bruijni*), possums (*Pseudocheirus* spp.), tree-kangaroos (*Dendrolagus* spp.), bandicoots (*Peroryctes longicauda*), the pygmy possum (*Cercatetus caudatus*) and the dasyurid *Satanellus albopunctatus*. Though usually found in forests below 3000 m, *S. albopunctatus* has been collected at higher altitudes on some mountains but is apparently scarce, possibly as a result of competition with the "singing" dog introduced by man at least 3000 years ago. Native placental mammals above 3000 m are all murid rodents and include giant rats (*Mallomys rothschildii*), true rats (*Rattus* spp.), water rats (*Hydromys* spp.) and others.

The most varied bird family represented above 3000 m is the Meliphagidae (honeyeaters), common in forest and forest edge habitats. Some birds of paradise occur in similar environments, such as *Astrapia stephaniae* on Mt Wilhelm and *Macgregoria pulchra* on Mt Carstensz, but most species occur in lower altitude forests. Common on most of New Guinea's mountains outside the forests are the island thrush (*Turdus poliocephalus*) and mountain pipit (*Anthus gutturalis*) in grasslands, the glossy swiftlet (*Collocalia esculenta*) near cliffs, and Salvadori's teal (*Anas waigiuensis*) on water. Robins (*Petroica* spp.) and snow mountain quail (*Anurophasis monothonyx*) are also common in Mt Carstensz grasslands, and other birds are listed for Mt Carstensz by Schodde, van Tets, Champion & Hope (1975) and for Mt Wilhelm by Wade & McVean (1969) and Smith (1976).

The impact of animals (other than man) on vegetation is not well known. At least at present, grazing by both vertebrates and invertebrates appears to be slight. On Mt Wilhelm branches of some ericaceous shrubs may be defoliated by colonial web-building caterpillars, and leaves of *Olearia spectabilis* may be badly holed, presumably by insects. Wade & McVean (1969) drew attention to the possible but unknown impact of rodent seed predation, and R.T. Corlett (pers. comm., 1977) reports that most *Dacrycarpus* seeds dispersed to non-forest habitats suffer nibbling, tooth marks being discernible on some. Aphids, grasshoppers and butterflies are rare or absent.

Though many flowers are showy, insect pollination does not appear to be common and many species may habitually resort to self-pollination. Beetles have been observed motionless in *Ranunculus* flowers, and a fly to visit the flowers of *Gentiana ettingshausenii*, on Mt Wilhelm (Smith, 1977). Night-flying moths, particularly active on humid nights, appear common and varied and probably play a more important role in the pollination of some species. Birds are probably important pollinators of *Rhododendron* and some other woody, mainly ericaceous, plants.

Stevens (1976) has reported on pollination of *Rhododendron*. Most of the species regularly or solely occurring above 3000 m are red-flowered, while at lower altitudes orange and white-flowered species are also common. He suggests that the red-flowered species are habitually pollinated by birds (Meliphagidae), those with white flowers, often scented, by hawkmoths, and those with orange flowers by butterflies. The rather scanty direct observations of pollination support these conclusions. A possible reason for the preponderance of bird-pollination at higher altitudes is suggested by the work of Cruden (1972) on a similar situation in Mexico. There it was shown that humming-birds are more active and hence more effective pollinators than insects, the latter often being rendered inactive by the cold, wet climate.

Many plant species, mainly woody but also including *Astelia alpina, Nertera granadensis* and the aliens *Fragaria* cf. *vesca* and *Passiflora mollissima* have fleshy fruits (or false fruits) adapted to internal dispersal of seeds by animals, mainly birds. The thrush *Turdus poliocephalus* feeds of the fruits of *Coprosma* spp. and *Gaultheria mundula,* while two captive berry-peckers *Paramythia montium* lived healthily for many weeks on a diet of the same fruits and those of *Dimorphanthera* spp. and *Styphelia suaveolens.* Seedlings of *Passiflora mollissima* have been found growing from pig dung at 2790 m on Mt Wilhelm. Other plants have disseminules adapted to external carriage by animals through having hooks or a rough or glutinous outer surface. Many of these have been shown to be effectively if inadvertently dispersed by man on clothing or footwear (Smith, 1977) and it seems likely that other mammals and perhaps birds may also disperse such disseminules.

5. Human Impact

Man has been present in New Guinea for at least 25 000 years (White, Crook & Ruxton, 1970), but since he is now known to have lived in Australia over 40 000 years ago, comparable New Guinea antiquity may be assumed. As outlined in chapter 3 and 8 on palaeoenvironments, for more than half this probable period of residence man has experienced a glacial climate. Until roughly 12 000 years ago, mountain grasslands were far more extensive than today, and the forest limit was below 3000 m. Vegetation types were not only at lower altitudes but were in some cases different from those occurring today, and supported mammal faunas some of whose species are now extinct. The role of man, if any, in eliminating some mammal species of mountain grassland ecosystems is unknown, but is discussed by Hope and Hope (1976).

Present human impact upon New Guinea's high mountain environments is threefold: hunting, burning and introduction of alien species. All these aspects are discussed in the Mt Wilhelm context by Smith (1977).

Many species ar hunted for food and for decorative fur or plumes. This has certainly resulted in local diminution of the populations of many species, such as tree-kangaroos and birds-of-paradise, and in the local extinction of some such as the cassowary *Casuarius bennetti* on the southern flanks of Mt Wilhelm. Traditional hunting technique include snares, and bows and arrows, the latter often used in conjunction with small hunting dogs. In many areas, with the introduction of alternative protein foods and a cash economy, hunting activity is declining, but in some this is more than offset by the recent spread of a superior weapon, the shotgun. Most hunting is in the forests and at forest edges, including at high altitudes, wherever these are within walking distance (including on occasion expeditions of several days) of permanent settlements. The indirect effects of hunting upon vegetation and flora are not known.

Burning has a far more fundamental impact upon vegetation wherever it is practised, which appears to be on all accessible mountains (as well as at lower altitudes) except where, and when, conditions are too wet. Natural fires if they occur at all are probably very rare; thunderstorms at high altitudes are unusual and almost invariably accompanied by rain. However, man-set fires have been a part of many mountain environments for thousands of years (see chapter 3 and 8 on palaeoenvironments). Motives for lighting grass fires may be various: they may be used as an aid to hunting, during warfare, as a signal, or for warmth; today, however, most fires are lit simply for the pleasure of witnessing spectacular destruction. The impact of burning on New Guinea mountain vegetation has been discussed by many authors including R.T. Corlett (in prep.), Gillison (1969; 1970), Lane-Poole (1925), Paijmans & Löffler (1972), Smith (1975), and Wade & McVean (1969).

Although initial access and burning may have been along the drier ridges to summit grasslands (R.T. Corlett, pers. comm., 1977), fires below 3800 m may have been lit first in valley bottom sites where soil waterlogging prevented the growth of dense forest. Such sites commonly occur today at about 3200 m behind terminal moraines of Pleistocene valley glaciers, and at higher sites where drainage is blocked by glacial till. This more open vegetation not only provides obviously easier routes for visiting hunters but also, in dry weather and despite the wet soil, dries more quickly to an easily combustible condition, than the damp dense forests. When burnt the vegetation changes: woody plants are mostly killed or regenerate only from their bases, and grasses become more abundant, so making the vegetation more combustible than previously. Where fires reach the edge of dense forest, they are usually stopped, but kill the trees and shrubs of the outer metre or two of the forest. Mature trees of *Dacrycarpus compactus*, and sometimes other conifers, are an exception and commonly survive. Under dry conditions forests may also be burned, as recorded an Mt Dayman by Brass (1956).

The result is a progressive increase in grassland area at the expense of forest, isolated *Dacrycarpus* trees providing for many years a measure of the former forest extent. Within the grasslands, some species are favoured by repeated fires, such as *Swertia papuana* on Mt Giluwe and *Dichelachne rara* and *Poa saruwagetica** on Mt Wilhelm. In anthropogenic grasslands which remain unburned for several years, large shrubs

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*Now *Poa keysseri* ssp. *saruwagetica*.

(*Coprosma, Styphelia,* etc) develop, as do luxuriant specimens of the widely dominant tussock grass *Deschampsia klossii.* Anthropogenic grasslands a little below forest limit are floristically poorer than natural grasslands just above the forest limit. Number of species per unit area of grassland declines both above and below c. 3850 m on Mt Wilhelm (Smith, 1977), but increases again to another peak at about 3400 m (Wade & McVean, 1969). The latter peak perhaps represents an overlap between species native to grasslands at higher altitudes, and others of mire and riverbank habitats at lower altitudes.

The only mountain whose alien flora has been inventoried is Mt Wilhelm (Smith, 1977). 24 introduced species had been recorded above 3000 m by 1972, though several of these were based on single records and appeared to have become extinct. Some species are still in the process of spread, exemplified by *Plantago major* which did not grow above 2804 m in 1972 but which occurred as high as 3490 m in 1975. All alien plants in New Guinea's mountains are primarily found in disturbed sites, commonly pathsides and similar places, though wind-dispersed Compositae (*Crassocephalum crepidioides, Erigeron* spp. *Sonchus oleraceus*) often establish themselves also on natural landslips. *Plantago lanceolata* is established on streamsides in basin grasslands below Mt Victoria (R.T. Corlett, pers. comm., 1977).

6. Vegetation Succession

Sites of natural disturbance in New Guinea's high mountains, such as landslips and eroding streambanks, are usually small and transient. Many native species may take part in the earliest colonisation of such sites, but all of these are plants of nearby closed vegetation. There appear to be no species native to high altitudes which are obligate adventives.

On the other hand, on most mountains there are large areas of secondary grassland resulting from man-set fires. In some cases, as on Mt Wilhelm, burning may recently have been less frequent and widespread than in the past. Such areas may be undergoing secondary succession to forest, though the process is a slow one. Shrubs are today larger and more numerous in recently unburned grasslands as indicated by comparison of photographs taken of the same vistas ten or more years apart. Seedlings of forest species may establish themselves occasionally beneath shrubs though almost never in tussock grassland, and are of course killed by fire.

Up to the forest limit, about 3800 m on Mt Wilhelm though not necessarily the same on other mountains, forest vegetation is the climax.

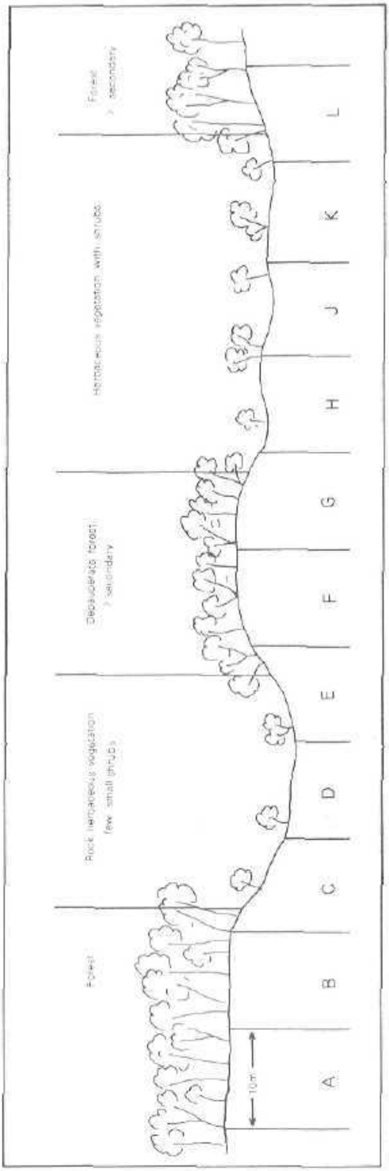

Fig. 14. Diagrammatic view of a transect across two landslips, north side of Piundaunde valley, Mt Wilhelm, 3430 m, viewed downslope.

The forest is variable, though distinct associations cannot readily be defined, and generally becomes lower in stature and poorer in number of species with increasing altitude. Above the forest *Deschampsia klossii* tussock grassland with scattered short shrubs, and often codominant with *Papuapteris linearis,* appears to be the end point in succession up to about 4300 m, though as seen today on some mountains it may be greatly influenced by fire. Sparse tundra communities occur still higher up to the limit of vascular plant occurrence, which may potentially be above the highest peaks in New Guinea. Tussock grasslands may also be dominated by species of *Poa,* especially where grasslands are burned, or by *Chionochloa archboldii* on damper slopes.

Some observations on succession have been made on newly exposed moraines at 4230-4600 m on Mt Carstensz by G.S. Hope (1976, p. 149). The earliest vascular plant to appear, within a few months, is the wind-dispersed *Epilobium detznerianum.* By a year, moss cushions, *Scleranthus singuliflorus* and the viviparous form of *Deschampsia klossii* are also present. By 30 years closed vegetation in the form of a low heath dominated by *Tetramolopium klossii* and the moss *Rhacomitrium crispulum* is developed.

Rock slabs at similar altitude (4175 m) on Mt Wilhelm support only *Rhacomitrium,* forming small terraces probably as a result of the physical effects of rain runoff (Smith, 1974). Lower down (3445 m) similar slabs are more clearly being covered by vegetation. Similar moss terraces consist of 3 species of *Campylopus* as well as of *Rhacomitrium crispulum,* and have accumulated more sand and humus. They have been invaded in places (especially where underlain by crevices) by vascular plants, notably several grasses, *Astelia alpina. Carpha alpina, Epilobium* spp., *Gleichenia bolanica, Ixeris laevigata, Ranunculus pseudolowii* and *Scirpus subcapitatus,* with occasional small woody plants of *Coprosma papuensis, Dacrycarpus compactus* and *Vaccinium amblyandrum.* In addition the decumbent shrubs *Trochocarpa dekockii* and *Vaccinium amblyandrum* were spreading by layering across the rock from its margin with shrub-rich tussock grassland, the rooting stems trapping a soil which supported several grass species.

On a southwest facing slope close to this rock slab, old landslip sites were studied to determine later stages in succession. The slips, at 3430 m, were of soil and the underlying till, exposing bare rock or unweathered till. Probably because of its rougher surface and more rapid weathering, succession on the till has proceeded further than on bare rock, and the slips may not have been simultaneous. A transect of 10 × 10 m squares aligned along the contour included vegetation types ranging from an open moss and herbaceous plant community, through

* entity *montis-wilhelmi*

Fig. 15. Distribution of vascular plant species encountered in three or more quadrats of a transect across two landslips, north side of Piundaunde valley, Mt Wilhelm, 3430 m. (Read *Astelia alpina, Danthonia oreoboloides, Glossorhyncha* sp., *Tasmannia* for *Astelia papuana, Monostachya oreoboloides, Giulianettia* sp. and *Drimys*).

a similar vegetation but including shrubs, two secondary forest communities of different statures and probably successional stages, to undisturbed forest; the transect is shown in diagrammatic section in Fig. 14.

Results are shown in Fig. 15 in which all species encountered in 3 or more of the 11 quadrats are included; 25 other species occurred in 1 or 2 quadrats only, 17 being herbaceous species growing outside the forest. Species in Fig. 15 are grouped into four categories. The first includes mainly herbaceous plants which occur only in open sites. The second is a similar but small group of species growing in the open but also able to persist in forest vegetation at later stages of the succession. The third category is of widespread species, including woody forest taxa able to establish in open sites, and appears to represent a forest edge element. The final category contains forest plants playing little or no part in earlier successional stages. It is notable that the large tussock grasses which dominate anthropogenic grasslands occur only rarely in this sequence, being dependent on deep but unshaded soil.

7. Evolution, Adaptations and Life-Forms

As has been stressed for other tropicalpine floras (e.g. in Africa, Hedberg, 1971; Morton, 1972), evolution is likely to be rapid at high altitudes in the tropics. Here small but fluctuating populations exist in environments which, over the last million years or so, have varied in area and in their connections with similar enviroments on other nearby mountains. This is especially true in non-forest habitats where most species also have fairly short life-cycles. Hence, it is particularly striking that many of the plants are so similar to their relatives on Asian and Australasian mountains, reflecting their relatively recent immigration in most cases (see next chapter). In addition the existence of species endemic to only one or a few peaks provides evidence for rapid evolution; migration between mountains within New Guinea (and so the elimination or spread of evolving endemic species) is likely to have been easier during glacial periods (with lowered vegetation zones) and as recently as about 12 000 years ago.

A distinction needs to be drawn here between forest and non-forest floras. Forest plants are likely to evolve less rapidly, due to longer life-cycles, and their lower altitudinal ranges result in larger and less discontinuous populations. They also, in general, probably have a much longer history in New Guinea, and have over this longer period evolved to fill the available ecological niches more completely. By contrast the youthful non-forest flora, with smaller and more fragmentary areas of distribution, appears to consist mostly of eurytopic species, with broad ecological tolerance and not well adapted to particular niches (see next chapter). This is reflected in the occurrence of most species in many different habitats and associations, the latter therefore being less distinct from each other floristically than might be anticipated by comparison with, for example, north temperate mountain vegetation (Wade & McVean, 1969).

Some life-forms are characteristic of New Guinea's mountains and can be compared with those of similar sites elsewhere. The trees are evergreen and have "shield-shaped" crowns, as occur in other tropical high mountain forests (Troll, 1959). Above the forests, and at lower altitudes after fire, the dominant life-form is the tussock. Hnatiuk (1975) has suggested that this involves the investment of less energy than the growth of woody stems to develop a life-form which can overtop potential competitors; this, he suggests, explains the dominance of the tussock in a variety of stressful environments. In the tropicalpine situation, the tussock form also provides effective thermal insulation for the basal growing points. In common with some other tropicalpine environments (e.g. East Africa; Hedberg, 1964) densely hairy leaves are found in many plants in New Guinea's high mountains (e.g. species of *Anaphalis, Gnaphalium, Senecio)* perhaps providing protection from high levels of solar radiation and wide fluctuations in temperatures.

Lacking in New Guinea are the bizarre megaphytes which are so characteristic of environments above the forests of mountains in East Africa, parts of the Andes, and elsewhere. Treeferns provide an apparent example of this life-form but their distribution, only below the climatic forest limit, shows that they are not ecologically comparable.

Most angiosperm species, in non-forest environments on Mt Wilhelm at least, do not have clear flowering periods (Smith, 1974; 1977). Over half of 105 native species and all 7 aliens examined at three sites there in 1972 flowered continuously. Some species, such as several rhododendrons, showed a flush of flowering but with odd individuals in bloom at other times. Only nine species had a clear flowering period. Four of these were woody species with probable forest ancestry, and it seems likely that many forest plants have evolved means of synchronising their flowering in the absence of clear seasons, presumably enhancing the chance of successful cross-pollination. The only herbaceous plants with synchronous periodic flowering behaviour were *Habenaria* sp., *Danthonia oreoboloides, D. vestita, Myriactis cabrerae* and *Parahebe ciliata.* One species of shrub, *Styphelia suaveolens,* had clear flowering, fruiting and growth periods in each individual, but different individuals were not in phase with each other.

This situation is of course in striking contrast to the rigid seasonality of climate and plant behaviour in temperate zone mountains. Yet another contrast related to seasonality is in the different proportions of biomass in different plant organs. Temperate zone alpine plants, in order to survive the long cold winter, typically store carbohydrates in their roots, and so have a small shoot:root biomass ratio. Though there are few detailed measurements from New Guinea mountains, it seems certain that this is not the case there, and that large shoot:root ratios are typical as shown for *Deschampsia klossii* by Hnatiuk (1975). R.T. Corlett (pers. comm., 1977) has found small shoot:root ratios in several Mt Wilhelm shrubs, probably related to fire damage.

Continuous growth throughout the year is typical of wet tropical conditions generally, including at high altitude. This is the probable reason for unusually high levels of standing crop biomass recorded in non-forest vegetation on Mt Wilhelm by comparison with that of temperate zone mountains (Walker, 1968). In particular, large amounts of dead leaf occur in tussock grassland (Hnatiuk, 1975), though this may be removed periodically by fire. Hnatiuk also shows that though tussocks of *Deschampsia klossii* become smaller, with shorter leaves, at higher altitudes, their photosynthetic efficiency is greater in the species' natural habitat above the forest limit than in the lower anthropogenic tussock grasslands.

8. Forest Limits

Forests reach their altitudinal limits at different altitudes on different mountains, though the reasons for this are unclear. The highest forests probably occur on the Mt Carstensz massif, at about 4030 m. On Mt Wilhelm, forests grow up to 3810 m in the undisturbed Imbukum valley, but remnants occur as high as 3870 m in the Piundaunde Valley. On smaller mountains forest limits are lower, for example, at 3539 m on Mt Sigal Mugal in the Kubor range, and below 3000 m on some peaks in the eastern Owen Stanley range. Grubb (1971) suggests that soil factors may be involved in maintenance of lower forest limits on smaller tropical mountains. Forest limits may be lowered through burning of forests on mountains subject to extensive human disturbance.

Two types of forest edge can often be recognised, the natural undisturbed type which is diffuse, and the artificial margin with anthropogenic grassland which is abrupt. The latter type often includes species which are particularly characteristic of this habitat: species of *Rhododendron* and *Olearia*, which are light-seeded and perhaps well adapted to the colonization of newly-burned forest edges, and scrambling shrubs and herbs like *Coprosma papuensis, Anaphalis mariae, Parahebe albiflora* and species of *Dimorphanthera*.

The limiting factors (apart from fire) upon forest's altitudinal distribution are unknown, although a thermal factor is presumably involved. The occurrence of the highest forests on Mt Carstensz, with what may be the wettest and most equable of New Guinea mountain climates, perhaps suggests that minimum rather than maximum temperatures are important. Minimum temperatures at the higher forest limit on Mt Carstensz and the lower one on Mt Wilhelm are likely to be much more similar than the corresponding maximum temperatures. If minimum temperatures are critical, the situation is not the same as for the grassland flora, many of whose species are controlled by maximum temperatures or factors related to them. However, it must be remembered that the seedling stage is likely to be the most critical, which for forest trees occurs in sites well insulated by the vegetative canopy.

An investigation into the climate of the Mt Wilhelm upper forest limit (Smith, 1975) suggested that forest fails to grow as high as might be expected by comparison with climatic conditions at forest limit in other regions. According to the Holdridge life-zone system (e.g. Holdrige, Grenke, Hatheway, Liang & Tosi, 1971, pp. 4-17) the forest limit should be at that altitude experiencing a mean annual biotemperature (nearly equivalent to actual temperature in this case) of 3.0° C. In fact the figure at forest limit is 6.0° C, the lower value not being reached until an altitude of 4380 m, over 500 metres above all stands of forest. The Holdridge system is one which involves much generalisation, and its failure to predict forest limit from climatic data on Mt Wilhelm may not be surprising. But it is also possible to speculate that were the mountains in New Guinea of sufficient age, woody plants better adapted to high altitude conditions (perhaps megaphytes) would have evolved, so raising forest limits.

Grasslands also occur in valley bottom and basin sites, surrounded by forests having "inverted" forest limits. Such basin grasslands may occur at almost any altitude in highland New Guinea, and their causation in most cases appears to be poor drainage, the waterlogged soil not permitting growth of large or numerous woody plants (Smith, 1975). A traverse across the Piundaunde valley of Mt Wilhelm at c. 3536 m showed a clear relationship between depth of watertable and occurrence of woody plants (Wade & McVean, 1969, p. 9). However, another possible causative factor is low minimum temperatures caused by radiative cooling possibly enhanced by cold air drainage, and such frost hollows have been demonstrated elsewhere, for example in montane south-east Australia (Moore & Williams, 1976). Such an explanation has been put forward in the New Guinea context by Wardle (1971). It receives some support from various observations. Some forest trees were killed by frost around basin grasslands below 2500 m due to nocturnal ponding of cold air, during the unusually dry and frosty year 1972 (Brown & Powell, 1974). In the much burned Neon Basin of Mt Albert Edward (Paijmans & Löffler, 1972), there is an apparently level lower limit to surviving *Dacrycarpus* trees, well above ill-drained ground lower down the slopes, and not easily explicable by fire (P. Wardle, pers. comm., 1976). A small basin grassland has been reported on the north side of Mt Capella (Star Mts) on subterraneously draining limestone (G.S. Hope, pers. comm., 1976) which cannot easily be attributed to waterlogged soil. In Java, van Steenis (van Steenis, Hamzah & Toha, 1972, pp. 29-32) considers comparable basin grasslands to be due to burning of vegetation, initially on wet ground. In New Guinea basin grasslands are commonly enlarged by burning.

There is probably no single explanation for basin grasslands and inverted forest limits. Waterlogging and low minimum temperatures may both be important in most cases, producing in combination a degree of stress precluding the growth of woody plants or at least their formation of a forest. Man-set fires often destroy what shrubs may survive in basins, and enlarge the area of grassland at the expense of the surviving forest.

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Selected References

Allison, I. & J. Bennett, Climate and microclimate, in: G.S. Hope, J.A. Peterson, I. Allison & U. Radok, The equatorial glaciers of New Guinea. (1976) 61-80.

Archbold, R. & A.L. Rand, Results of the Archbold Expeditions 7. Summary of the 1933-1934 Papuan Expeditions - *Bull. Am Mus. Nat. Hist.* 68 (1935) 527-579.

Archbold, R., A.L. Rand & L.J. Brass, Results of the Archbold Expeditions 41. Summary of the 1938-1939 New Guinea Expedition - *Bull. Am. Mus. Nat. Hist.* 79 (1942) 199-288.

Billings, W.D. & H.A. Mooney, The ecology of arctic and alpine plants - *Biol. Rev.* 43 (1968) 481-529.

Brass, L.J., The 1938-1939 expedition to the Snow Mountains, Netherlands New Guinea - *J. Arnold Arb.* 22 (1941) 271-342.

Brass, L.J., Results of the Archbold Expeditions 75. Summary of the 4th Archbold Expedition to New Guinea (1953) - ***Bull. Am. Mus. Nat. Hist.*** 111 (1956) 77-152.

Brass, L.J., Results of the Archbold Expeditions 86. Summary of the 6th Archbold Expedition to New Guinea (1959) - ***Bull. Am. Mus. Nat. Hist.*** 127 (1964) 145-216.

Brown, M. & J.M. Powell, Frost and drought in the highlands of Papua New Guinea - *J. Trop. Geogr.* 38 (1974) 1-6.

Coode, M.J.E. & P.F. Stevens, Notes on the flora of two Papuan mountains - ***Papua New Guinea Sc. Soc. Proc.*** 23 (1972) 18-25.

Cruden, R.W., Pollinators in high elevation ecosystems: relative effectiveness of birds and bees - *Science* 176 (1972) 1439-1440.

Gillison, A.N., Plant succession in an irregularly fired grassland area - Doma Peaks region, Papua - *J. Ecol.* 57 (1969) 415-428.

Gillison, A.N., Structure and floristics of a montane grassland/forest transition, Doma Peaks region, Papua - *Blumea* 18 (1970) 71-86.

Grubb, P.J., Interpretation of the "Massenerhebung" effect on tropical mountains - *Nature* 229 (1971) 44-45.

Haantjens, H.A., Soils of the Goroka - Mt Hagen area, in: H.A. Haantjens, Lands of the Goroka - Mount Hagen area - *CSIRO, Land. Res. Ser.* 27 (1970) 80-103.

Hedberg, O., Features of afroalpine plant ecology - ***Acta Phytogeogr. Suecica*** 19 (1964).

Hedberg, O. Evolution of the afroalpine flora, in: W.L. Stern, Adaptive aspects of insular evolution (1971) 16-23.

Hnatiuk, R.J., Aspects of the growth and climate of tussock grassland in montane New Guinea and Sub-Antarctic Islands. Thesis. A.N.U. Canberra. (1975).

Hnatiuk, R.J., J.M.B. Smith & D.N. McVean, Mt Wilhelm Studies 2. The climate of Mt Wilhelm - *A.N.U.* BG/4 (1976).

Holdridge, L.R., W.C. Grenke, W.H. Hatheway, T. Liang & J.A. Tosi Jr., Forest Environments in tropical life zones: a pilot study (1971).

Hoogland, R.D., The alpine flora of Mt Wilhelm - ***Blumea,*** Suppl. 4 (1958) 229-238.

Hope, G.S., The vegetational history of Mt Wilhelm, Papua New Guinea - *J. Ecol.* 64 (1976) 627-663.

Hope, G.S., Vegetation, in: G.S. Hope, J.A. Peterson, I. Allison & U. Radok, The equatorial glaciers of New Guinea (1976) 112-172.

Hope, J.H., Fauna, in: G.S. Hope, J.A. Peterson, I. Allison & U. Radok, The equatorial glaciers of New Guinea (1976) 207-224.

Hope, J.H. & G.S., Palaeoenvironments for man in New Guinea, in: R.L. Kirk & A.G. Thorne, The origin of the Australians - ***Austr. Inst. Aboriginal Stud.*** (1976) 29-54.

Kalkman, C., Description of vegetation types in the Star Mountains region, West New Guinea - *Nova Guinea, Bot.* 15 (1963) 247-261.

Kalkman, C. & W. Vink, Botanical exploration in the Doma Peaks region, New Guinea - ***Blumea*** 18 (1970) 87-135.

Kol, E. & J.A. Peterson, Cryobiology, in: G.S. Hope, J.A. Peterson, I. Allison & U. Radok, The equatorial glaciers of New Guinea. (1976) 81-91.

Lam, H.J., Fragmenta Papuana - *Sargentia* 5 (1945) 1-196.

Lane-Poole, C.E., The forest resources of the Territories of Papua and New Guinea. (1925).

Loffler, H., Tropical high mountain lakes of New Guinea and their zoogeographical relationship compared with other tropical high mountain lakes - *Arctic & Alp. Res.* 5, *Spec. Issue* (1973) A 193-A 198.

McVean, D.N., A year of weather records at 3,480 m on Mt Wilhelm, New Guinea - *Weather* 23 (1968) 377-381.

Moore, R.M. & J.D. Williams, A study of a subalpine woodland-grassland boundary - *Austr. J. Ecol.* 11 (1976) 145-153.

Morton, J.K., Phytogeography of the West African mountains, in: D.H. Valentine, Taxonomy, Phytogeography and Evolution (1972) 221-236.

Paijmans, K. & E. Löffler, High altitude forests and grasslands of Mt Albert Edward, New Guinea - *J. Trop. Geogr.* 34 (1972) 58-64.

Pain, C.F., Characteristics and geomorphic effects of earthquake initiated landslides in the Adelbert range, Papua New Guinea - Engin. Geol. 6 (1972) 261-274.

Pullen, R., Mount Wilhelm, highest mountain of Australian territory - *Walkabout* 24 (1957) 38-44.

Rand, A.L. & E.T. Gilliard, Handbook of New Guinea birds (1970).

Ridley, H.N., Botany of the Wollaston Expedition to Dutch New Guinea, 1912-1913 - *Trans. Linn. Soc., London, ser. 2, Bot.* 9 (1916) 247-351.

Robbins, R.G., Vegetation of the Goroka - Mt Hagen area, in: H.A. Haantjens, Lands of the Goroka - Mount Hagen area - *CSIRO, Land Res. Ser.* 27 (1970) 104-118.

van Royen, P., Some observations on the alpine vegetation of Mount Biota, Papua - *Acta Bot. Neerl.* 15 (1967) 530-534.

Rutherford, G.K., The tropical alpine soils of Mt Giluwe, Australian New Guinea - *Can. Geographer* 8 (1964) 27-33.

Schodde, R., G.F. van Tets, C.R. Champion & G.S. Hope, Observations on birds at glacial altitudes on the Carstensz Massif, western New Guinea - *Emu* 75 (1975) 65-72.

Smith, J.M.B., Origins and ecology of the non-forest flora of Mt Wilhelm, New Guinea. Thesis. Canberra. (1974).

Smith, J.M.B., Mountain grasslands of New Guinea - *J. Biogr.* 2 (1975) 27-44.

Smith, J.M.B., Notes on birds breeding above 3.215 metres on Mt Wilhelm, Papua New Guinea - *Emu* 76 (1976) 220-221.

Smith, J.M.B., Vegetation and microclimate of east- and west-facing slopes in the grasslands of Mt Wilhelm, Papua New Guinea - *J. Ecol.* 65 (1977) 39-53.

Smith, J.M.B., Man's impact upon some New Guinea mountain ecosystems, in T.P. Bayliss-Smith & R.G.A. Feachem, Subsistence and survival: Rural ecology in the Pacific (1977) 185-213.

Smith, J.M.B., Origins and ecology of the tropicalpine flora of Mt Wilhelm, New Guinea - *Biol. J. Linn. Soc.* 9 (1977) 87-131.

van Steenis, C.G.G.J., A. Hamzah & M. Toha, The mountain flora of Java. (1972).

Stevens, P.F., The altitudinal and geographical distributions of flower types in Rhododendron section Vireya, especially in the Papuasian species, and their significance - *Bot. J. Linn. Soc.* 72 (1976) 1-33.

Thomasson, K., Phytoplankton from some lakes on Mt Wilhelm, East New Guinea - *Blumea* 15 (1967) 285-296.

Troll, C., Die tropischen Gebirge. Ihre dreidimensionale klimatische und pflanzengeographische Zonierung - *Bonner Geogr. Abh.* 25 (1959).

Wade, L.K. & D.N. McVean, Mt Wilhelm Studies 1. The alpine and subalpine vegetation - *A.N.U.* BG/1 (1969).

Walker, D., A reconnaisance of the non-arboreal vegetation of the Pindaunde catchment, Mount Wilhelm, New Guinea - *J. Ecol.* 56 (1968) 455-466.

Wardle, P., An explanation for alpine timberline - *NZ J. Bot.* 9 (1971) 371-402.

White, J.P., K.A.W. Crook & B.P. Ruxton. Kosipe: a late Pleistocene site in the Papuan highlands - *Proc. Prehist. Soc.* 36 (1970) 152-169.

7. ORIGINS, AFFINITIES AND DISTRIBUTION OF THE HIGH ALTITUDE FLORA

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1. Introduction

Perhaps the main focus of botanical study in New Guinea's high mountains has been the geographical relationships of the plants. This interest has arisen from the startlingly close affinities between these plants and the members of floras of distant areas in, for example, southeast Australia, New Zealand and mainland Asia. The discovery of plant groups like the gentians, buttercups, epacrids and various festucoid grasses, familiar to botanists in one or both temperate zones but absent from the tropical lowlands, sparked off speculation and controversy concerning the timing and mechanisms of their migrations and the locations of their origins. While much remains to be discovered in the field, many diverse studies have begun to lay a basis of fact upon which further investigations may build.

In this chapter such studies are summarised. The history of New Guinea's high mountain environments, and the geographical affinities of their flora, are outlined. From this background the origins of the flora are discussed, and a picture of plant migration is suggested which receives some support from ecological research. Finally present plant distributions in the mountains of New Guinea are described and discussed.

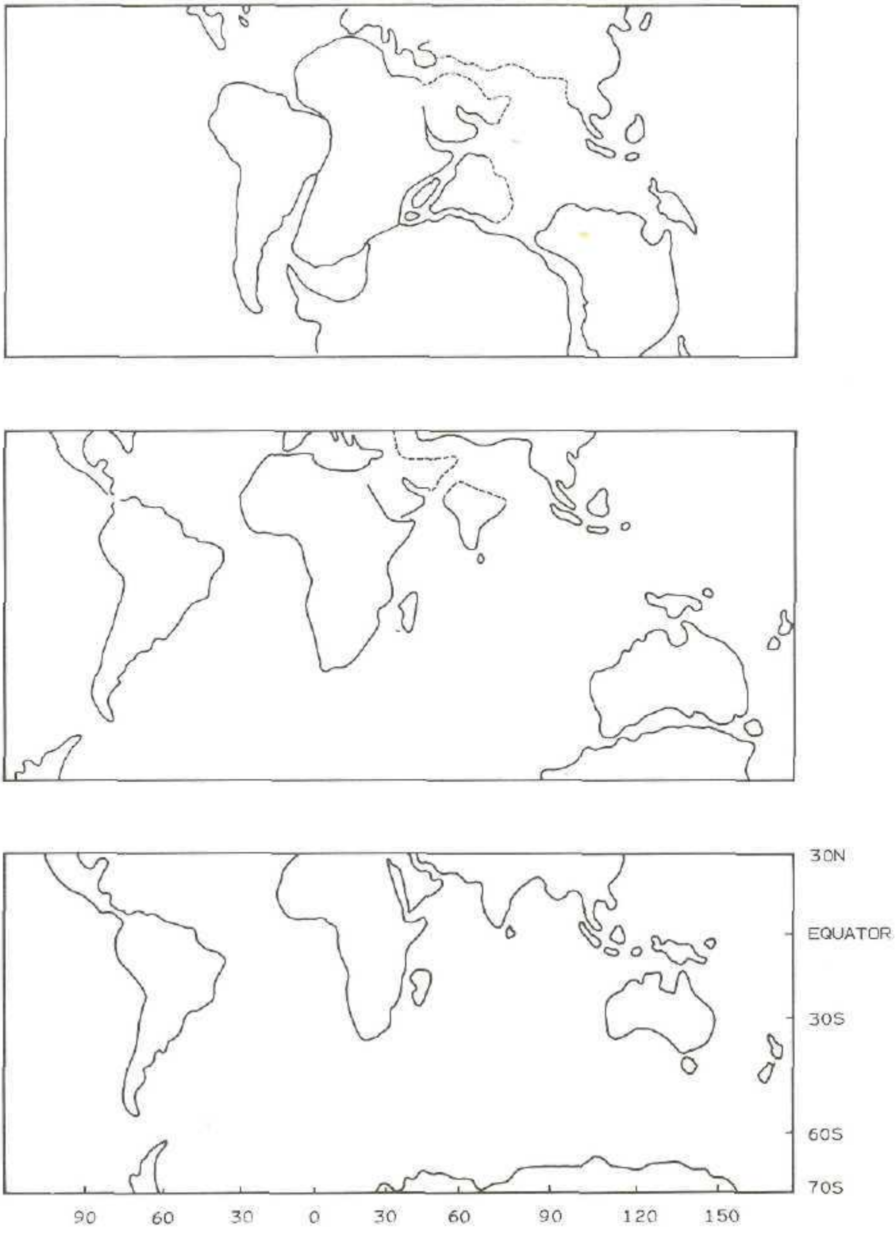


Fig. 16. Past and present geography of the world's southern regions: 100 million years ago (top), 50 million years ago (middle), present (bottom). (The two top figures are modified from A.G. Smith, J.C. Briden & G.E. Drewry, in N.F. Hughes, Spec. Pap. Palaeont. 12, pp. 1-42).

2. History of New Guinea's High Mountains

The southern part of New Guinea is geologically a part of the ancient and stable Australian continent, Torres Strait and the Arafura Sea being relatively shallow and transient marine environments. Australia was a part of the Southern supercontinent Gondwanaland until its fragmentation in the late Mesozoic era, some 100 million years ago. There were certainly land connections with Antarctica, then warmer and vegetated, until about 45 million years ago, and probable links via Antarctica with South America until about the same time. The oldest floristic affinities of New Guinea are therefore southwards, still clearly recognisable as discussed below. On the other hand geographical proximity and exchange of flora with southeast Asia is far more recent, dating back only a few million years (Schuster, 1972, 1976; Smith, 1974, 1975). Paleogeographic maps are provided in Fig. 16.

The mountains of New Guinea are mostly of relatively young rocks and all of relatively recent uplift. Their formation can be thought of loosely as being caused by the northward movement of the Australian plate ruckling the crustal rocks ahead of it. Geosynclinal sediments and coral limestones were thus raised far above sea-level, and igneous rocks both intrusive and volcanic added to the bulk of the newly created mountain ranges. Some islands formerly north of the New Guinea coast may have been incorporated as well. The overall result is a series of subparallel ranges trending east-west, the oldest being those furthest south, such as the Kubor range, and the youngest those to the north, like the Adelbert and Sarawaket ranges (Davies & Smith, 1971).

Tectonic activity was at its most violent during the Oligocene period (around 30 million years ago), and this may have provided New Guinea with its first highlands, as a large block of arched ocean floor was faulted and thrust upwards (Thompson, 1967). Further uplift continues to the present (Avias, 1973; Bain, 1973). Chappell (1974) has determined the present rate of uplift in the Sarawaket range area at 3.5 m per 1000 years.

From geological evidence it therefore appears that high ground has been present in New Guinea for no more than about 30 million years, and that mountains have been higher and most numerous more recently. During the same period Australia with New Guinea has been moving northwards, towards the equator. More than compensating for this in climatic terms, however, has been the general decline in world temperatures through the Tertiary era, except for a warmer period in the Miocene, and especially towards the start of the Quaternary, 2 million years ago (Dorman, 1966; Emiliani, 1954). Even apart from the local climatic effects of uplift, and in spite of New Guinea's increasingly equatorial position, it is probable that the climate of the region was cooling in late Tertiary times. Taken together with the appearance of the high mountains during the same period, this suggests that tropicalpine environments (such as occur today above 3200-3800 m) cannot have existed in New Guinea for long before Quaternary times, and the same may apply to a lesser degree to mountain forest environments (such as at altitudes over 1500 m today).

During the Quaternary, climates have usually been colder than today, interglacial periods exemplified by the present being of much shorter duration than the intervening glacial periods (Davis, 1976; Emiliani, 1972). Vegetation zones in the New Guinea mountains were lowered by at least 700 m during the last glacial period (Hope, 1976). Therefore for most of the last million years or more, the high altitude flora and vegetation has enjoyed a larger area with suitable climate than at present, though until late Tertiary times it may not have existed at all, at least in its tropicalpine aspect.

3. Geographical Affinities and History of the New Guinea Flora

Taxonomic relationships of New Guinea plants with other regions are mostly readily explained on the basis of the geological history outlined above. As in other parts of Australasia, floristic elements of differing histories show a tendency to remain ecologically and to some extent physiognomically discrete, rather than mingling haphazardly. The distributions of the four most important elements and vegetation types are indicated diagrammatically in Fig. 17.

The oldest element in the flora is that showing clear but not very close affinities with other regions derived from Gondwanaland which have retained a moist and relatively cool climate, especially upland New Caledonia, New Zealand, Tasmania and Fuegia. In many cases fossil pollen of their relatives is also known from Antarctica. This gondwanic element includes taxa such as the families Cunoniaceae, Podocarpacae and Winteraceae, and the genera *Helicia, Nothofagus* and *Pittosporum.*

They are found in New Guinea mainly in the mountain forests, which they usually dominate in numbers and structurally. Their species (as distinct from higher taxonomic units) are commonly endemic to New Guinea.

The gondwanic element may have been present in New Guinea throughout the region's history since Cretaceous times, as assumed by Smith (1974, 1975). Alternatively it may have migrated a relatively short

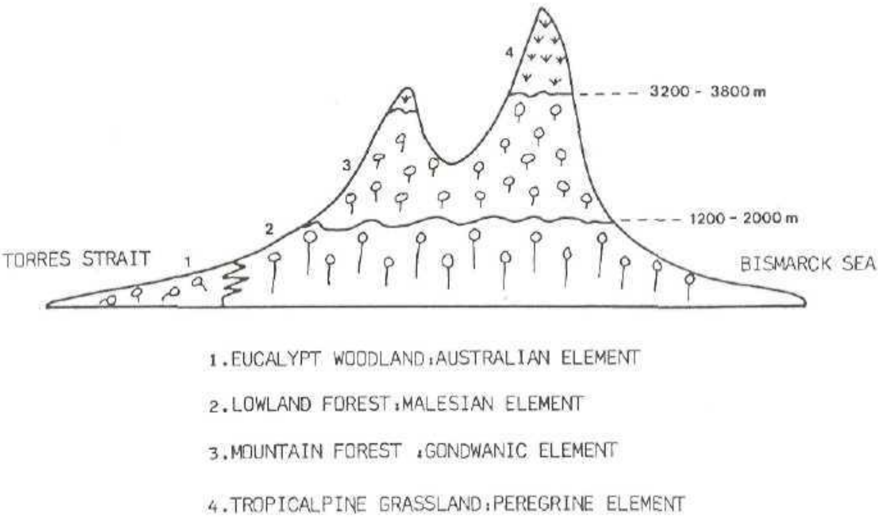


Fig. 17. Diagrammatic cross-section of New Guinea from south to north, showing distribution of major vegetation types.

distance in late Tertiary times from eroding mountains in Queensland to newly uplifted peaks in New Guinea as suggested by Schuster (1976) and Walker (1972). In either case any migration is likely to have been gradual, overland, and into similar environments.

In the woodlands of the Fly delta and Port Moresby areas another element is predominant, the Australian. Most of the largest trees here are species of *Eucalyptus,* most of which are shared with Cape York and other parts of northern Australia. Similarly a majority of the herbaceous plants appear also to be Australian, and it is clear that this represents a recently isolated fragment of a vegetation type adapted to seasonally dry (monsoonal) climate, and formerly continuous across Torres Strait, until its most recent submergence some 7000 years ago (Nix & Kalma, 1972). Several members of this floristic element, including *Eucalyptus,* evolved in the Tertiary from gondwanic ancestors as Australia became drier during its drift northwards into the region of subtropical high pressure cells.

Most of the area below the mountain forests is clothed by lowland forest, and though there is no clear demarcation between these two types of vegetation they are generally composed of different floristic elements. Affinities of the lowland forest are to the west and northwest, with Asia. Examples here are Dipterocarpaceae and *Albizzia,* and bordering the mountain forests, the oak relatives *Castanopsis* and *Lithocarpus.* A glance at the maps in Fig. 16 will show why this element cannot be of ancient migration from Asia to New Guinea: the two regions were mutually distant until late Tertiary times. Although no land connection has yet been made there are today only fairly narrow sea barriers, which have been repeatedly crossed, perhaps especially during glacial periods when sea-levels were lowered and straits further narrowed. The presence of some continued impediment to migration is shown by the zoological contrasts across what has become known as Wallace's Line (Schuster, 1972; 1976). It would appear that plants can migrate across marine straits more readily than vertebrate animals. The relative recency of the immigration of the Malesian element to New Guinea is confirmed by its rather slight differentiation there, many species and almost all genera being shared with parts of southeast Asia.

The element of most relevance to the theme of this book is called here the peregrine element, borrowing a term introduced by van Steenis (van Steenis, Hamzah & Toha, 1972, 63-67) and refined in the New Guinea tropicalpine context by Smith (1976). These are the plants mainly comprising the mountain grasslands and other non-forest environments.

Their affinities are various. Some genera and species are clearly of Asian origin, such as *Gentiana, Potentilla* and *Triplostegia glandulifera.* Others are equally obviously Australasian, like *Thelymitra, Uncinia* and *Styphelia suaveolens.* The largest category includes plants of nearly cosmopolitan temperate affinity and *Carex, Poa, Plantago, Ranunculus, Montia fontana* and *Hypericum japonicum* may be cited. Schodde (1973) found these affinities suggestive of "itinerant colonisation". The impression of recent immigration over long distances and from more than one source is confirmed by the low level of endemism, high level of polyploidy, and by the fact that many plants are closely related to species elsewhere which are efficient pioneers and weeds (Smith, 1977).

Although there is a clear relationship between broad vegetation categories on the one hand and geographical affinity and presumed origins on the other, as indicated in Fig. 17, it should not be supposed that there is complete coincidence. *Rhododendron,* for example, can best be included in the peregrine element and many species occur in tropicalpine environments, but other species have adapted themselves to lowland conditions and grow down to sea-level. There are also other vegetation types not included in Fig. 17, such as those of swamps and man-altered environments; they are mostly local and of "immature" environments, and many of their species are probably of fairly recent immigration, or at least not of gondwanic ancestry.

4. Origins of the High Mountain Flora

Above 3000 m in New Guinea there are both forest and non-forest environments, and the flora (excluding epiphytes) consists of about 46% woody plants and 54% herbaceous plants. One family of Eurasian affinity and origin, Ericaceae, includes nearly half the woody species. The peregrine element also includes some other woody plants and most of the herbaceous ones and is therefore the most important in the high altitude flora.

Although the gondwanic element is poorly represented in south-east Asia (*Nothofagus* being an example of a group of plants having been unable to migrate westwards across Wallace's Line), the peregrine element in New Guinea has much in common with other Malesian high montain floras, such as that of Mt Kinabalu, Borneo (Smith, 1977). Van Steenis speculated upon the origins of this element. Initially (e.g. 1964) he considered the isolated populations of mountain plants of temperate affinities to be relicts of a more continuous flora, occupying a Cretaceous mountain range which extended through Indonesia from mainland Asia to Australia some 60 million years ago. He explained the presence of this supposedly ancient flora on geologically young mountains by assuming inheritance of flora from older eroding mountains (van Steenis, 1967). Other workers such as Holloway (1970), Raven and Axelrod (1972) and Troll (1968) preferred to believe that late Tertiary mountain-building and Quaternary climatic cooling allowed migration of cold-adapted flora only during the last few million years. Seen in the light of continental movements demonstrated by earth scientists, van Steenis' earlier hypothesis becomes untenable, and he himself has more recently suggested late Tertiary migration of the peregrine element (van Steenis, Hamzah & Toha, 1972, 63-67).

On Mt Wilhelm a study has been made of the tropicalpine flora to more clearly define the migration history of its component plants (Smith, 1977). 197 species were included. These were categorised objectively on distributional and taxonomic criteria into three elements of apparently different migration histories, for subsequent ecological evaluation.

1. Ancient element. This category provisionally included those species whose distributions suggested an ancient Gondwanaland origin (southern generic distribution including South America, but New Guinea species distinct); and those in genera endemic to New Guinea indicating a long period of residence there. 35 species were included, in genera such as *Detzneria, Tasmannia, Keysseria, Oreomyrrhis* and *Pittosporum.*

2. Peregrine element. All native species other than those in the ancient element were included here, 147 species altogether. 49 of these grow also outside Malesia, 9 to the north, 23 to the south and 17 to both north and south. Two-thirds (58) of the 87 genera are very widespread, 11 being predominantly Eurasian and 18 Australasian.

3. Aliens. These are species introduced by man to highland New Guinea, and constitute the most recently immigrant group of plants. Although 54 alien species have been collected above 2515 m on Mt Wilhelm (Smith, 1977), only 39 of them were from higher altitudes and included in the study, and some of these appeared to have become locally extinct. Only *Erigeron canadensis, E. sumatrensis* and *Sonchus oleraceus* were found growing above 3500 m.

It was suggested that the elements so defined, having migrated during different periods in the past, would retain, to different degrees, an aggregate of characters conferring migration ability. It is well known that species best able to colonise distant or insular sites are those of pioneer strategy, initially invading open or species-poor sites.

Such sites were probably periodically widespread in New Guinea's mountains during Quaternary times through glacial and volcanic activity and, latterly, the impact of man. After initial establishment such invaders may undergo evolution to become better adapted to closed vegetation (Baker, 1972; Harper, 1961; MacArthur & Wilson, 1967; Margalef, 1959, 1968; Smith, 1978). Since the affinities and probable origins of most of the tropicalpine plants lie at higher latitudes, evolutionary changes towards adaptation to a diurnal rather than seasonal climate, with year-long liability to frost and lack of thermal or day-length seasons, may also be anticipated in the New Guinea context.

More specifically the study tested the following suggestions: that the three floristic elements would, in proportion to their supposed age of immigration, have lost to varying degrees dispersal ability; ability to colonise bared soil; rapid growth rate; and wide and generally low altitudinal ranges, all these characteristics being more appropriate to new immigrants: and in addition would have developed synchronised flowering behaviour controlled by factors other than gross seasonal changes of temperature or daylenth; and a shifting preference for slopes of different aspect in response to microclimate variations between such slopes (Smith, 1977), both these attributes being indicative of close adaptation to the peculiar environment and developed least in aliens and most in the ancient immigrants.

In all these ways except dispersal ability, differences between floristic elements were demonstrated in the expected direction. This provided confirmation for the view that the bulk of Mt Wilhelm's tropicalpine flora (the peregrine element) is of relatively recent migration, having not adapted as closely to its present environment as the minority of plants with more ancient ancestry in the region. Of course, as expected in a study as broad as this, anomalies arose some of which could only be resolved rather tentatively. One anomaly concerned dispersal ability. It was concluded that various mechanisms for seed dispersal (hooks, plumes, fleshy parts, etc.), while having significance for local dispersal, did not enhance a plant's chances of being dispersed over the several hundred kilometres to and between isolated mountains in the Malesian region including New Guinea. In other cases, some plant species seemed to fit rather uncomfortably within the elements to which they had been assigned, having the "wrong" ecology, or appearing for other reasons to have a migration history other than that suggested by the crude though objective application of generic and specific distribution data. Nevertheless the significance of the study as a whole provided striking confirmation for the relative youth of the tropicalpine flora.

In Quaternary times beginning about two million years ago, New Guinea mountains were higher and closer to Asia than ever before, climates were cooler than they had been for tens of millions of years, and large areas of bare ground were created by vulcanism and glaciation. These conditions allowed the immigration of a large cold-adapted adventive flora, composed of widespread plants many of which would be regarded as weeds in today's agricultural context. Simultaneously a smaller number of plants evolved at the upper edge of the pre-existing forest to take advantage of these new open, cold environments. The descendants of both these categories of plant comprise today's native tropicalpine flora, which is being supplemented by a new wave of immigrants whose initial transport to the region has been by man.

5. Present Plant Distributions

The remaining portions of this chapter present and discuss an analysis of the geographical and altitudinal distributions of New Guinea's high mountain flora. The data derive from early drafts of the taxonomic sections of this book. Only species growing above 3000 m are considered, and of these a few groups of plants are excluded from analysis because their details were not to hand at the time of writing. Epiphytic orchids were also not considered. The great majority of species in the high mountain flora were included, however, involving a total of over 700.

About a tenth of these species are known from very few, usually only single, collections. Most of the others have certainly not been collected from all extremes of their ranges. New species no doubt await discovery or recognition. Any discussion of the distribution patterns of the flora is therefore inevitably based upon largely incomplete and inadequate data, and can only be regarded as tentative. Nevertheless I believe that the general trends which are apparent will not be changed by further data collected in future.

In analysing plant distributions within New Guinea, 6 more or less discrete and comparable mountain regions were delineated:

a) west of the Baliem river, including Carstensz Mts and Mt Wilhelmina;

b) Oranje and Star Mts;

c) Central mountains, including Mts Hagen and Giluwe, and Doma peaks;

d) Bismarck and Kubor ranges and Kratke mountains, including Mt Wilhelm;

e) Sarawaket and adjacent ranges;

f) Owen Stanley range, including Mts Albert Edward, Victoria and Suckling.

In analysing world distributions of plant taxa found above 3000 m in New Guinea, another six regions were delineated:

a) New Guinea;

b) insular southeast Asia and tropical Pacific;

c) Australia and New Zealand;

d) mainland Eurasia with Japan and Taiwan;

e) Africa;

f) the Americas.

In each case plant distribution, either within or including New Guinea, was assessed as a score of one to six according to the number of regions from which the plant group has been recorded. Some results are represented in histogram form in Fig. 18, showing distributional extents of taxa in regions of the world including New Guinea, and in areas within montane New Guinea. The data are divided into those for woody and herbaceous plants respectively, expressed as percentages of the total for each of these categories.

The upper two diagrams in Fig. 18 show the distributions of genera and species respectively of the flora above 3000 m, in regions of the world.

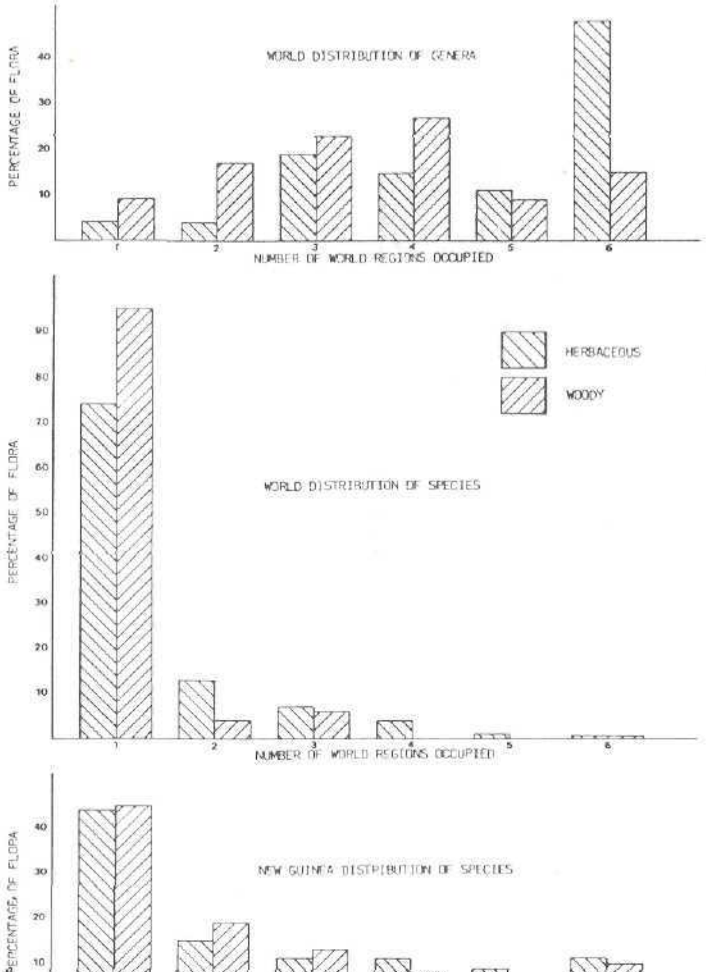


Fig. 18. Distributional extents of members of the high altitude flora of New Guinea.

Nearly half of the herbaceous genera occur in all six of the world's regions as defined here, and only 4% are restricted solely to New Guinea. This underlines the cosmopolitan character of the tropicalpine flora, and the probable relative recency of immigration of most of its members. Woody genera, including forest trees, show a different pattern. A majority grows in 3 or 4 world regions, 9% being endemic to

New Guinea and only 15% being found in all 6 regions. Clearly the woody plants, including many gondwanic taxa, are less capable of migration on a global scale.

The pattern shown by species, as distinct from genera, though different nevertheless shows the same contrast between woody and herbaceous species. While 74% of herbaceous species are endemic to New Guinea, 95% of woody ones are. Only one woody species, *Dodonea viscosa*, occurs in more than three world regions, but 22 herbaceous species do. Species of Cyperaceae are particularly notable for their wide distributions.

On the other hand if we look at species distributions in areas within New Guinea, woody and herbaceous plants do not seem to behave differently. There is a not very significant trend for herbaceous species to be more widely distributed, but this could easily be an artefact of collections, as botanists have generally put more effort into collecting plants in the grasslands than in the forests of New Guinea's mountains. The high proportion of species found in no more than one area includes a large number of plants which have been collected only once.

An attempt to correlate species distributions within New Guinea with those in world regions revealed no clear or interesting pattern, other than a trend for species of restricted distribution in New Guinea not to be globally widespread. Exceptions to the trend were all herbaceous species in the peregrine element.

If averages of distribution scores for all species within each genus are plotted, instead of considering every species separately, any bias in the results imposed by a few very large genera (such as *Rhododendron*, *Vaccinium*, *Carex* and *Gentiana*) can be avoided. However, when this is done the overall patterns shown are not changed.

In a previous analysis (of the tropicalpine flora only) degrees of floristic similarity between mountain areas in New Guinea were examined (Smith, 1975). The data used were derived from collections in the Lae herbarium of the Papua New Guinea Department of Forests which, though not representing well collections from West New Guinea, were otherwise extensive. Colgan's Index of Floral Diversity (Praeger, 1911; Wace & Dickson, 1965) was calculated for both species and genera, and an ordination analysis (Bray & Curtis, 1957) made of these indices. The results showed that the most dissimilar floras were those one or both of which had been poorly collected. However, for the better collected areas (Bismarck, Sarawaket and Owen Stanley ranges and Mt Hagen area) it was clear that floristic similarity was correlated with least distance, via "stepping-stone" areas in some cases, across land lower than 2400 m between the areas. This altitude is likely to have been at approximately the forest limit during the last glacial period (Hope, 1976), so that corridors of land at higher levels could have acted as bridges of tropicalpine vegetation. Such a correlation suggested that plant distributions can be explained on the basis of present geography within montane New Guinea, plants being able to spread between mountain areas in inverse proportion to the intervening distances. Since some mountains are only of late Pleistocene origin, the plant distribution patterns must be similarly recent.

Nevertheless the presence of local endemic species, and complexes of closely related species, shows that some isolation of plant populations in separate mountain areas has also occurred; without isolation, the evolution of different species is unlikely. Such isolation probably exists today, during the present period of high forest limits relative to their depressed position in glacial periods. Distributions of tropicalpine plants in New Guinea can perhaps be related, therefore, to alternating periods of lowered vegetations zones with migration during glacial periods, and raised vegetation zones with isolation and speciation during interglacials. Emphasising the importance of isolation for the evolution of new species was the observation that locally endemic species were most numerous at the eastern and western extremities of the New Guinea cordillera, and fewest in the central areas.

6. Altitudinal Distributions

The altitudinal distributions of high mountain plants in New Guinea tend to be wide. In the earlier study already quoted (Smith, 1975), it was found for the relatively well collected tropicalpine flora of Mt Wilhelm (but including data for the same species from all New Guinea) that 94% of herbaceous species spanned over 500 m altitude, and 77% over 1000 m. This situation is similar to that found on Mt Kenya and Mt Kilimanjaro by Wood (1971). A large majority of species therefore extends over wider altitudes than were involved in the upward movement of vegetative belts at the end of the last glacial period. Such width of range and the implied physiological variability and tolerance may have aided survival under conditions of changing climate: part of the population could have survived almost *in situ* during climatic change

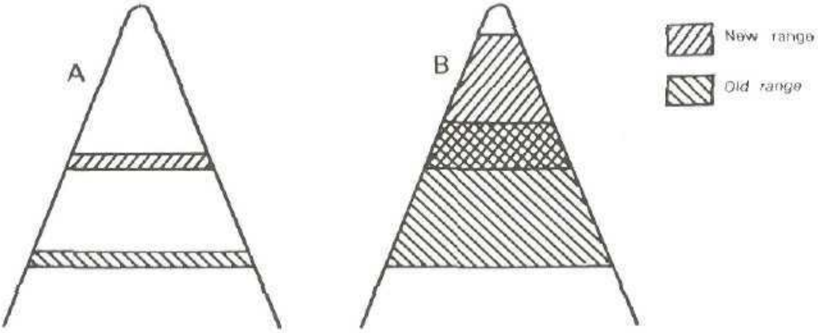


Fig. 19. The effect of warming upon the altitudinal ranges of a narrow-ranging mountain plant (A), and a wide-ranging plant (B).

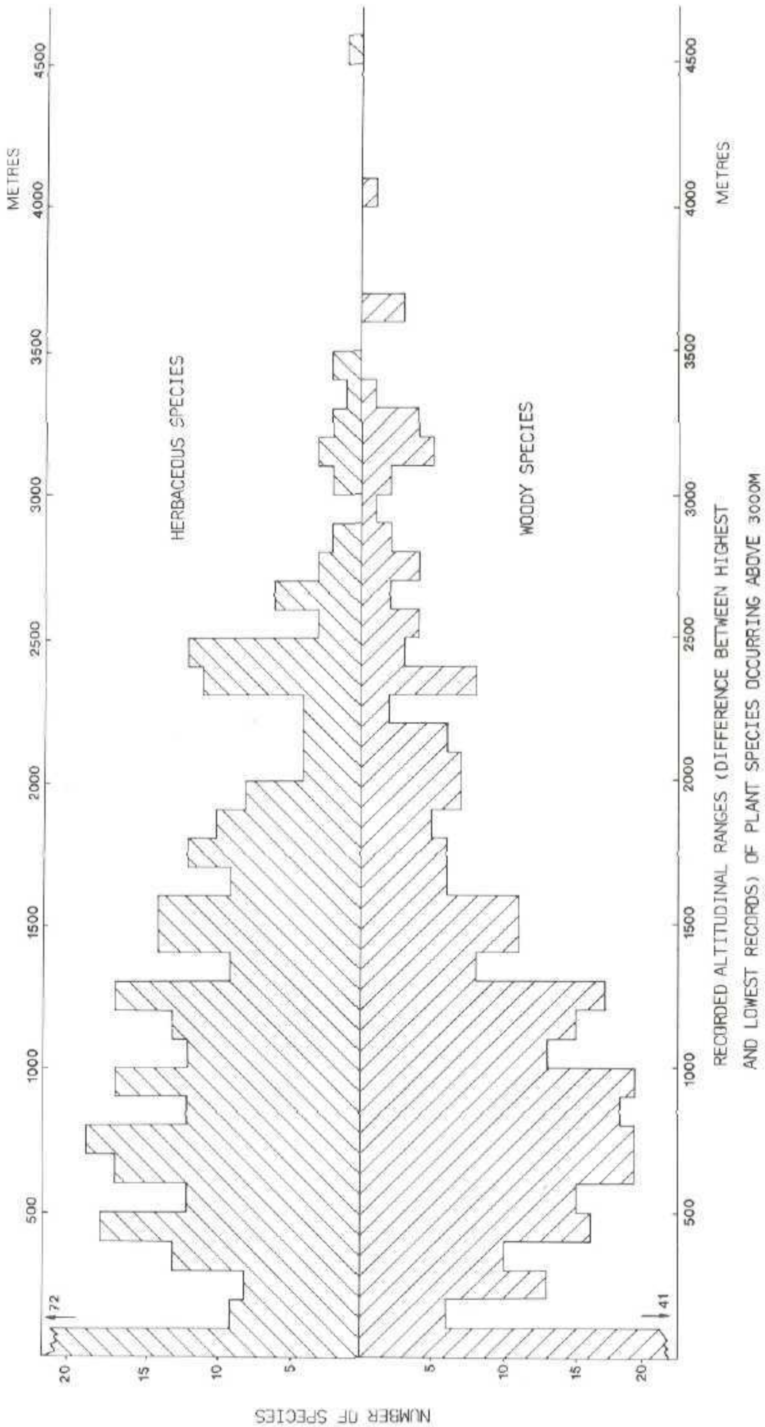
(Fig. 19) and intraspecific ecotypes could have migrated by gene flow through cross-pollination rather than by actual dispersal of seeds. The selective advantage of variability under conditions of long-term environmental fluctuation has been emphasised by Margalef (1959).

Altitudinal ranges of the larger number of species from present data show less spectactular width because many plants are included which have been poorly collected; they are displayed in Fig. 20. Nevertheless nearly half the species have ranges in excess of 1000 m, and 70% of 500 m. These proportions are the same for both herbaceous and woody plants.

Altitudinal ranges indicate only the vertical distance between highest and lowest records. To get an idea of the actual altitudes inhabiting by the same plants the mid-points of their ranges (the average of the highest and lowest records) are displayed in Fig. 21. Both herbaceous and woody species show maximum numbers with mid-points lying at about 3250 m. Below this level woody plants are in the majority, and above it, herbaceous plants. This is of course easily explained by the facts of vegetation zonation, forests not growing above 3900 m in New Guinea, and becoming richer in species and more continuous at lower altitudes (until the upper limits of agricultural activity are reached at about 2600 m).

Smith (1977) observed, for the Mt Wilhelm tropicalpine flora, that elements or more recent immigration to the region (most especially aliens) had both wider and lower altitudinal ranges. Wide altitudinal range, an indication of wide ecological tolerance, may be expected in a

Fig. 20. Altitudinal ranges of members of the high altitude flora of New Guinea.


METRES
500
1000
1500
2000
2500
3000
3500
4000
4500
HERBACEOUS SPECIES
WOODY SPECIES
72
41
20
15
10
5
5
10
15
20
NUMBER OF SPECIES
METRES
RECORDED ALTITUDINAL RANGES (DIFFERENCE BETWEEN HIGHEST
AND LOWEST RECORDS) OF PLANT SPECIES OCCURRING ABOVE 3000M

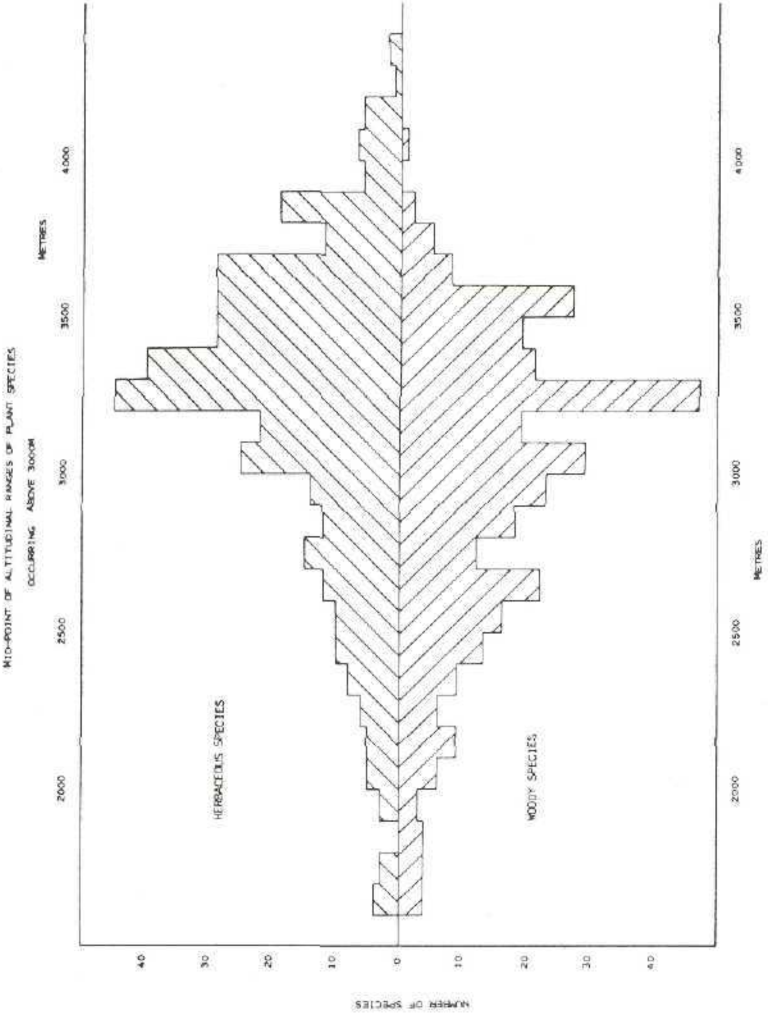


Fig. 21. Mid-points of altitudinal ranges of plant species occurring above 3000 m.

colonising species. Low altitudinal distributions in plants of similarly recent immigration can be explained in terms of the larger area of land at lower altitudes upon which chance long distance dispersed seeds may settle, so that more colonists were able to establish themselves lower down. It may also be true that a larger proportion of the pool of potential colonists were preadapted to the less rigorous conditions at lower altitudes. With time, the evolution of characters better fitting the colonists' descendants to New Guinea mountain environments included the development of tolerance to higher altitude conditions.

From this, Smith (1975) tentatively suggested how genera of the tropicalpine flora may have evolved their present diversity and distribution patterns.

Local lower altitude populations, not taxonomically distinct from their parent populations overseas, may have spread both laterally and, with the evolution of new species, upwards. The isolation of the higher altitude populations in particular may have resulted in local high altitude endemic species evolving in addition to more widely distributed lower altitude species. With further migration within New Guinea, altitudinally separated species may come to range widely in suitable habitats across the island.

As a generalisation it can be said that along a gradient of ecological stress, distributions of species are limited by physical factors of the environment at the harsher edge of their range, and by biotic factors such as competition and predation at the opposite edge. This is borne out by plants in the New Guinea mountains.

Van Steenis (1961) suggests that each species of mountain plant has an altitudinal zone of permanent establishment, in which it is most common and successful, flanked by upper and lower zones of temporary establishment in which populations are dependent in the long run on inflow of seeds from the zone of permanent establishment. Though impossible to define exactly, it appears that the upper zone of temporary sites of establishment includes individuals in sites of locally favourable microclimate. The highest recorded individuals of a variety of species on Mt Wilhelm, including *Acaena anserinifolia, Cardamine altigena, Gaultheria mundula, Oxalis magellanica* and *Poa keysseri,* were all growing near the bases of sheltered rock walls of easterly aspect; morning sunshine probably temporarily raised maximum temperatures in these places higher than was usual at their altitudes. Occasional vigorous individuals of the alien species *Crassocephalum crepidioides* could be found on landslip sites up to 3400 m, but were usually killed by frost before setting seed anywhere above about 3200 m.

The lower zone of temporary establishment appears to be wider, there existing for most tropicalpine species (at least) a wide zone of potential establishment from which the plants are excluded for reasons of competition in the form of forest shade. Its existence is demonstrated by the establishment in disturbed sites of colonies of tropicalpine plants far below their usual altitudes. Such sites may be naturally eroding riverbanks or landslips, for example, or the peaks of smaller mountains, or they may be larger areas of anthropogenic grassland. Under natural conditions most such lower altitude open sides would be clothed again by forest within a few years or decades, colonies of tropicalpine herbs being eliminated by its shade.

Selected References

Avias, J., Major features of the New Guinea-Louisiade-New Caledonia-Norfolk arc system, in P.J. Coleman, The Western Pacific, Island Arcs, Marginal Seas, Geochemistry. (1973) 113-126.

Bain, J.H.C., A summary of the main structural elements of Papua New Guinea. In P.J. Coleman, The Western Pacific. Island Arcs, Marginal Seas, Geochemistry. (1973) 147-161.

Baker, H.G., Migration of weeds, in D.H. Valentine, Taxonomy, Phytogeography and Evolution. (1972) 327-347.

Bray, J.R. & J.T. Curtis, An ordination of the upland forest communities of southern Wisconsin - *Ecol. Monogr.* 27 (1957) 325-349.

Chappell, J.M.A., Geology of coral terraces, Huon Peninsula, New Guinea: a study of Quaternary tectonic movements and sea level changes - *Bull. Am. Soc. Geol.* 85 (1974) 553-570.

Davies, H.O. & I.E. Smith, Geology of eastern Papua - *Bull. Geol. Soc. Amer.* 82 (1971) 3299-3312.

Davis, M.B., Pleistocene biogeography of temperate deciduous forests - *Geoscience and Man* 13 (1976) 13-26.

Dorman, F.H., Australian Tertiary paleotemperatures - J. Geol. 74 (1966) 49-61.

Emiliani, C. Quaternary hypsithermals - *Quat. Res.* 2 (1972) 270-273.

Harper, J.L., Approaches to the study of competition - *Symp. Soc. Exp. Biol.* 15 (1961) 1-39.

Holloway, J.D., The biogeographical analysis of a transect sample of the moth fauna of Mt Kinabalu, using numerical methods - *Biol. J. Linn. Soc.* 2 (1970) 259-286.

Hope, G.S., The vegetational history of Mt Wilhelm, Papua New Guinea - *J. Ecol.* 64 (1976) 627-663.

MacArthur, R.H. & E.O. Wilson, The Theory of Island Biogeography. (1967).

Margalef, R., Mode of evolution of species in relation to places in ecological succession - Proc. 15th Int. Congr. Zoology (1959) 787-789.

Margalef, R., Perspectives in Ecological Theory. (1968).

Nix, H.A. & J.D. Kalma, Climate as a dominant control in the biogeography of northern Australia and New Guinea, in D. Walker, Bridge and Barrier: the Natural and Cultural History of Torres Strait - *A.N.U.* BG/3 (1972) 61-91.

Praeger, R.L., Clare Island Survey, 10. Phanerogamia and Pteridophyta - *Proc. Roy. Irish Acad.* 31 (1911) 1-112.

Raven, P.H. & D.I. Axelrod, Plate Tectonics and Australasian paleobiogeography - *Science* 176 (1972) 1379-1386.

Schodde, R., General problems of fauna conservation in relation to the conservation of vegetation in New Guinea, in A.B. Costin & R.H. Groves, Nature Conservation in the Pacific. (1973) 123-144.

Schuster, R.M., Continental movements, "Wallace's Line" and Indomalayan Australasian dispersal of land plants: some eclectic concepts - *Bot. Rev.* 38 (1972) 3-86.

Schuster, R.M., Plate tectonics and its bearing on the geographical origin and dispersal of Angiosperms, in C.B. Beck, Origin and Early Evolution of Angiosperms. (1976) 48-138.

Smith, J.M.B., Southern biogeography on the basis of continental drift. A review - *Austr. Mammalogy* 1 (1974) 213-230.

Smith, J.M.B., Living fragments of the flora of Gondwanaland - *Austr. geogr. Stud.* 13 (1975) 3-12.

Smith, J.M.B., Notes on the distributions of herbaceous angiosperm species in the mountains of New Guinea - *J. Biogeogr.* 2 (1975) 87-101.

Smith, J.M.B., Vegetation and microclimate of east and west-facing slopes in the grasslands of Mt Wilhelm, Papua New Guinea - *J. Ecol.* 65 (1977) 39-53.

Smith, J.M.B., Origins and ecology of the tropicalpine flora of Mt Wilhelm, New Guinea - *Biol. J. Linn. Soc.* 9 (1977) 87-131.

Smith, J.M.B., An ecological comparison of two tropical high mountains - *J. trop. Geogr.* 44 (1977) 71-80.

Smith, J.M.B., Man's impact upon some New Guinea mountain ecosystems, in T.P. Bayliss-Smith and R.G.A. Feachem, Subsistence and Survival. Rural Ecology in the Pacific. (1977) 185-214.

Smith, J.M.B., Dispersal and establishment of plants in D. Walker & J.C. Guppy, Biology and Quaternary Environments. (1978) 207 223.

van Steenis, C.G.G.J., An attempt towards an explanation of the effect of mountain mass elevation - *Proc. Kon. Akad. Wet. Amsterdam* C 64 (1961) 435-442.

van Steenis, C.G.G.J., Plant geography of the mountain flora of Mt Kinabalu - *Proc. Roy. Soc. London* B 161 (1964) 7-38.

van Steenis, C.G.G.J., The age of the Kinabalu flora - *Malay. Nat. J.* 20 (1967) 39-43.

van Steenis, C.G.G.J., A Hamzah & M. Toha, The Mountain Flora of Java. (1972).

Thompson, J.E., A geological history of eastern New Guinea - *J. Austr. Petr. Expl. Ass.* 7 (1967) 83-93.

Troll, C., The cordilleras of the tropical Americas: aspects of climatic, phytogeographical and agrarian ecology, in Geoecology of the Mountainous Regions of the Tropical Americas - *Proc. Mexico Symp. UNESCO* 1966 (1968) 15-55.

Wace, N.M. & J.H. Dickson, The terrestrial botany of the Tristan da Cunha Islands - *Phil. Trans. Roy. Soc.* B 249 (1965) 273-360.

Walker, D., Bridge and Barrier, in D. Walker, Bridge and Barrier. The Natural and Cultural History of Torres Strait - *A.N.U.* BG/3 (1972) 399-405.

Wood, D., The adaptive significance of a wide altitudinal range for montane species - *Trans Bot. Soc. Edinburgh* 41 (1971) 119-124.

8. NEW GUINEA MOUNTAIN VEGETATION COMMUNITIES

by

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4. Short Grass Bog 208

1. Introduction

The early European visitors and officials who were stranded in the lowland swamps or on the hot coasts of New Guinea often looked inland to the blue ranges and imagined there the cool alpine meadows and heaths of their homelands. When the jungle defences of the high mountains were finally overcome, the summit vegetation thus revealed was in some ways a disappointment. Instead of green meadows dotted with flowers, there were large expanses of dun tussock grasslands and olive-brown mires. Wild flowers were there in plenty, but except for *Rhododendron* they were not showy. Groves of tree ferns with bunches of fronds on tip of robust trunks added to the bizarre appearance of the non-forest scene. The vegetation was, in fact, more like that of oceanic islands in the southern hemisphere than the seasonal alpine areas of Europe. This is a reflection of not only the phytogeographic affinities with the south but also the evercool, everwet climates of both areas. For the New Guinea mountains are, above all else, wet. They are also thermally equable by comparison with other mountain areas in either the tropics or temperate zones.

As the results of the various expeditions became available for comparison it became clear that many of the features of the vegetation, and the flora, were shared by mountains over 2000 km apart. In fact the floristic variety, with many local endemics peculiar to single mountains or ranges, seemed more striking than any differences in the vegetation. This situation arose because until recently most botanical work in the mountains has consisted of finding specimens. Incomplete collecting, the scattering of specimens to many herbaria around the world, and a concentration on novelties, has perhaps overemphasized the floristic differentiation between the New Guinea mountains, although many of the distinctions are real (see also Smith's chapters). The collectors tended to group the vegetation into a few structural types such as "alpine grassland" and "alpine shrubberies", although they acknowledged that these were very variable.

A much more complex picture emerged when Wade carried out the first detailed analysis of the vegetation of Mt Wilhelm in 1966-1968. (Wade & McVean, 1969). Wade rejected a completely objective approach, which would have required the study of a very large number of plots or releves located by some random method. He felt that given the great variety of topography and growth environments, such an approach would be logistically difficult and might fail to locate many dispersed but distinct communities. He initially chose to site his releves in subjectively chosen stands of apparently homogeneous vegetation occupying a complete range of the environments on Mt Wilhelm above

3140 m. He noted species on a combined frequency-abundance scale, allocated the releve data to floristic associations, and then studied further releves to check the consistency of possible ecotonal or minor vegetation units. The floristic assemblages are made from selected groupings of releve results, the groups being discriminated from one another on the basis of the constant species. These are species which appear in at least 80% of the releves allocated to a particular vegetation association. Where at least seven releves shared the same constants, Wade felt that an association was thus established. Where the data consisted of fewer releves, a community type was indicated that could be raised to association rank if further compatible releves could be found.

The floristically constant species of each community are not necessarily the dominant species for although they must be reasonably common, they need not be the tallest or have the greatest cover. There are several species which are constant (and sometimes dominant) in more than one community, so that much of the division of associations is based on "differential constants", that is those species that are restricted, at least as common species, to only one community. Structure, therefore, does not enter into the classification of the vegetation, except as it coincides with environmental constraints.

Wade grouped his associations by their environmental zones of altitude, drainage and topography. There was a broad structural correlation, i.e., forests, shrub-rich grasslands, mires (bogs and fens), and edaphically limited shrublands occur at intermediate ("subalpine") altitudes and dwarf heaths or herblands (including grasslands, fernlands and mosslands) are found at the highest levels ("alpine").

Wade's work remains the only complete analysis of mountain vegetation in New Guinea, and his choice of classificatory characters has shaped subsequent, more superficial, vegetation surveys on other mountains which have been reviewed by Johns (1977) and Paijmans (1976). Earlier work, principally that of the Archbold expeditions, e.g. Archbold & Rand (1935), Brass (1941, 1964), but including that of Lam (1945) and Kalkman (1963), combined a structural description with a floristic analysis of the dominant species and resulted in very broad, formation level, units. Robbins (1961) and Walker (1968) paid considerably more attention to structure in defining vegetation types on Mt Wilhelm. Their units are roughly equivalent to particular associations used by Wade.

The present state of knowledge is that one valley on one mountain is accurately known (although not mapped) and that some releve data is available from Mt Carstensz (Hope, 1976a), eastern Star Mountains (Hope, Veldkamp, unpublished), Burgers Mt (Veldkamp, 1978), Mt Giluwe (Johns, unpublished), Mt Kerigomna (Grubb & Stevens, 1979), Mt Strong (Coode & Stevens, 1971), Mt Albert Edward (van Royen, 1967; Hope, 1975), and Mt Suckling (Stevens & Veldkamp, 1977). In addition, observations by collectors now exist for almost all mountain areas in Papua New Guinea and scattered peaks in West New Guinea. The twenty nine communities defined on Mt Wilhelm have been valuable in focussing attention on structural and floristic similarities and differences in the vegetation of the other mountains.

2. Classification of Mountain Vegetation

In defining the mountain vegetation of the whole New Guinea cordillera, the question of method and level of classification arises. The results from Mt Wilhelm are too detailed to allow direct comparison with the less well defined communities of the other mountains, so that an enumeration of the vegetation at association level is impossible. On the other hand, the variety of formations represented in the per-humid, relatively stable environment is limited. Since the flora is well enough known on most mountains in terms of genera and families, the appropriate classificatory unit is the *alliance*, defined by Specht (1970, 1972) as "a series of climax ecosystems which have (a) the same structural characteristics, (b) related species as dominants in the uppermost stratum, and (c) possibly the same or related species in the understorey".

This approach has been followed by Hope (1976a), in comparing the vegetation of Mt Carstensz to that of Mt Wilhelm. Analogous communities were defined by comparing releve data from Mt Carstensz with releve tables of associations on Mt Wilhelm. A close match in floristics, at least at generic level, and in the cover of equivalent taxa was regarded as an analogous community. This represents a closer agreement than is required for membership of an alliance, but is roughly equivalent. The distribution of alliance vegetation units in the New Guinea mountains establishes the widespread extent of some. However, more information can be gained by examining alliances with restricted or disjunct distributions, for these may prove to be related to taxonomic, historical or environmental causes which can at least be postulated for future investigation. Since altitude shows the strongest correlation with major vegetation units (e.g. Wade & McVean, 1969; Hope, 1976a), the variations in altitudinal range of an alliance in different areas may be correlated with differences in range on varied aspects or microclimates in a single area. This provides tentative information about environments of relatively unknown mountains.

Life form and height of tallest stratum	Projective foliage cover of tallest stratum Dense (70-100%)	 Mid-dense (30-70%)	 Sparse ☆ (10-30%)
Trees > 30 m †	(Tall closed forest)	(Tall open forest)	
Trees 10-30 m	Closed-forest	(Open forest)	(Woodland)
Trees 5-10 m	Low closed-forest	(Low open forest)	
Shrubs 2-8 m †	Closed-scrub	Open scrub	Tall shrubland
Shrubs 0-2 m	(Closed-heath)	Open heath	Low shrubland
Herbs (including moss,	Closed herbland ‡	Herbland ‡	Open herbland ‡
ferns, chaemophytes	(1) Closed tussock grassland	(1) Tussock grassland	(1) Open tussock grassland
hemicryptophytes,	(2) Closed-grassland	(2) Grassland	(2) Open grassland
hydrophytes, helophytes	(3) (Closed-herbfield)	(3) Herbfield	(3) Open herbfield
	(4) Closed-sedgeland	(4) Sedgeland	(4) Open sedgeland
	(5) Closed-fernland	(5) Fernland	(5) Open fernland
	(6)	(6) Mossland	(6) Open mossland
Thallophytes (thallose and crustose lichens, filamentous or unicellular algae)		Lichen field Algal bloom	Algal bloom

() Formations in brackets are rare.

☆ Specht (1972) includes a 'very sparse' category of projective cover (< 10%) but only a few New Guinea herbland or thallophyte communities approach this cover value. Very scattered shrub or tree emergents are ignored in predominantly grassland, heath or shrubland formations.

† A tree is defined as a woody plant more than 5 m tall, usually with a single stem. A shrub is a woody plant less than 8 m tall, frequently with many stems arising at or near the base. Although tree ferns occasionally exceed 5 m in height, they are here regarded as shrubs.

‡ Appropriate names for the community will depend on the nature of dominant herb.

The alliances of the New Guinea mountains can be included in relatively few structural formations. Fig. 22 adapts for montane New Guinea the scheme developed by Specht (1972) for classifying Australian structural formations on the basis of cover and height of the dominant stratum. (It should be noted that Specht's scheme presents difficulties in lowland tropical areas). McVean & Womersley (1974) list eight formations as occurring above 3000 m in Papua New Guinea, and Fig. 22 includes three additional units, open forest, woodland and tall shrubland. The scheme employed makes a fundamental division between woody and herbaceous vegetation. However, it must be acknowledged that the dividing line between predominantly shrubby or herbaceous vegetation is an arbitrary one in the New Guinea mountains, because woody taxa occur in almost all vegetation associations except the wettest fens or very early seral communities. This chapter follows Wade and McVean (1969) in distinguishing as forests or shrublands only those communities with a dominant stratum of open to dense trees or shrubs of any height. Where the shrubs are scattered and only form a minor part of the canopy, or where the woody plants only contribute to an understorey, the communities are classified into herblands of various types. Wade and McVean differentiated subalpine grasslands, alpine grasslands, tundras and mires from the single 'alpine grasslands' of earlier authors. These environmental groupings represent a subdivision of various herbland formations, but they also generally coincide with distinct structural characteristics. The subalpine and alpine zones are distinguished by the presence or absence of scattered tall shrubs, while shrubs and grasses are unimportant in most tundra or mire alliances, which tend to be herbfields, sedgeland, fernland or mosslands.

Fig. 23 lists the alliances so far noted in New Guinea above 3000 m in groups that generally follow Wade and McVean's structural-environmental classification of the Mt Wilhelm vegetation. Additional groupings have been added, for example tall shrubland and heath, because of the existence of communities not found on Mt Wilhelm and to accommodate alliances included in a structurally and environmentally heterogeneous "landslip communities and related vegetation" category used by Wade and McVean.

The list is based on short term observations in most areas and there is no attempt to limit the alliances only to supposed climax ecosystems as required by the strict definition of an alliance given previously. Fig. 23 indicates the abundance of each alliance on eight selected mountain areas, and also provides an estimate of the diversity of the communities

Fig. 22. Structural formations above 3000 m, New Guinea (adapted from Specht, 1972).

Community	Distribution and diversity							
	Ca	W	St	D	G	Wi	Os	Sk
A. Forests								
1. Upper montane rainforest	C3	C3	C3	C2	C2	C1	C3	C4
2. Upper montane transition forest	C3	C3	C3	C3	C2	C1	C3	C4
3. Subalpine rainforest	C2	C2	S3	S2	C2	C1	C3	-
4. Treeline closed shrublands	C1	?R	C3	-	A	A	-	-
B. Scrub and tall shrublands								
1. *Coprosma* forest edge scrub	C3	C3	R3	C3	C2	C1	C3	?C
2. Ericaceae rocky slope shrublands	C4	C4	S4	C3	S3	S2	S4	S4
3. Montane treefern shrubland	S3	C3	R3	C2	C1	C1	C2	C3
4. Subalpine treefern shrubland	C1	C1	A	A	S3	C3	C3	S?
C. Heaths								
1. *Coprosma* - *Gaultheria* heath	A	A	A	A	A	A	C1	S1
2. Dwarf shrub heath	C2	R2	-	-	R1	C1	-	-
3. *Rhacomitrium* open heath	C3	?	-	-	?	C1	-	-
4. *Tetramolopium* open heath	S1	?	-	-	-	A	-	-
5. *Gleichenia bolanica* low shrubland	C2	C2	C2	C2	C2	C1	C2	C2
D. Shrub-rich Grasslands								
1. *Deschampsia* tussock grassland	C2	C2	R3	?	C1	C1	S3	A
2. *Poa* tussock grassland	C2	C2	A	?A	S1	C1	C3	A
3. *Danthonia vestita* tussock grassland	A	A	R2	-	C1	C1	A	-
4. *Chionochloa* tussock grassland	A	A	A	C3	R3	R3	C1	C2
5. *Gahnia javanica* tussock sedgeland	S2	?S	C2	C2	A3	A	C1	C2
6. *Poa erectifolia* short grassland	A	A	A	A	A	A	C1	C2
E. Alpine Herblands								
1. *Deschampsia* alpine grassland	C3	C3	A	-	C1	C1	R1	-
2. Short alpine grassland	R3	?	C2	-	S2	C1	?A	-
3. *Ranunculus* - *Tetramolopium* herbfield	A	?	R	-	A	A	-	-
4. *Astelia* alpine herbfield	R2	?	-	-	S1	C1	R1	-
5. Alpine mosslands	C4	C4	-	-	-	S1	-	-

Fig. 23. Vegetation alliances above 3000 m in New Guinea.

contained in each alliance, ranging from 1 for the "type" association that defines the alliance up to 4 for communities with only a broad floristic, structural and environmental relationship.

Each structural-environmental grouping is now discussed in the same order as Fig. 23, but detailed descriptions of alliances are only provided where no typical association has been defined previously.

Community	Distribution and diversity							
	Ca	W	St	D	G	Wi	Os	Sk
F. Mire Herblands								
1. *Vaccinium* - *Xanthomyrtus* bog	S1	?	R2	A	A	A	A	A
2. *Astelia* subalpine bog	S2	S2	C2	S2	C2	R1	S2	R2
3. *Gleichenia vulcanica* bog	A	A	C2	C1	C1	S2	R3	C3
4. Short grass bog	C2	C2	S2	S2	C1	C1	C1	S2
5. Hard cushion bog	C1	C1	C1	R1	C2	R2	C2	R2
6. Closed sedgeland	R3	?	R3	C3	C3	S1	C3	?
7. *Carpha alpina* fen	C1	C1	C1	-	C1	C1	C1	-
8. Wet open-sedgelands	S1	S1	S1	C1	C1	S1	C2	S2
9. *Isoetes* aquatic fernland	?A	S2	2	-	S2	A	S1	-
10. Aquatic communities	R	?	S	-	?	R	S	-
G. Thallophyte Communities								
1. *Stereocaulon* lichen field	S	?	-	-	R	R	R	-
2. Necrotic lichen field	R	?	R	-	A	A	S	S
3. Crustose lichen lithosere	C	C	C	R	S	C	S	S
4. Algal blooms	C	?	C	-	?	R	R	-
5. Cryoalgae	C1	-	-	-	-	-	-	-

Abundance	C	Common or dominant on suitable habitats
	S	Sparse or scattered
	R	Rare and never extensive
	A	Absent or not recorded, despite the presence of suitable environment
	-	No suitable environment
Diversity	1	Vegetation floristically and structurally belongs to the type association
	2	Same dominant species
	3	Same dominant genera and many shared species
	4	Some genera in common, and broad structural and habital similarities
Distribution	Ca	Mt Carstensz
	W	Mt Wilhelmina
	St	Star Mts, Mts Antares, Capella, Scorpion
	D	Doma Peaks, Mt Ne
	G	Mt Giluwe, Mt Hagen
	Wi	Mt Wilhelm, Mt Kerigomna
	Os	Northern Owen Stanley Range, Mt Strong, Mt Albert Edward, Mt Scratchley, Mt Victoria
	Sk	Mt Suckling

A. Forests

The definition and distributions of the mountain forests of New Guinea are provided by Grubb & Stevens (1979), and Fig. 23 follows their scheme. For Mt Wilhelm, Wade & McVean (1969) defined an upper and lower subalpine forest above cloud forest. An analysis of the altitudinal range and leaf-sizes of forest taxa led Grubb and Stevens to propose that upper montane rain forest (UMRF) gives way gradually via a transition forest to subalpine rain forest (SARF). The "lower subalpine forest" of Wade & McVean is thus mostly included in the transition forest of UMRF, as Grubb & Stevens point out that very few species are restricted to it. The upper montane rain forest formation consists of closed forest (less commonly tall closed forest >30 m) alliances. Several alliances have been described, but Grubb and Stevens stress that the forest is very variable and should perhaps not be prematurely divided into many individual communities. This accords with the view of Walker (1973) and Walker & Guppy (1976) who show that, at a generic level, forest plots in the central highlands of PNG can be broken into objective units, on floristic presence-absence grounds, but that no single or few genera characterize these units. Other authors have defined communities based on the dominance of single or groups of taxa, particularly *Nothofagus* spp., gymnosperms or small leafed Myrtaceae such as *Decaspermum* spp. As this problem in classification has been dealt with by Grubb and Stevens (1979) it is not reviewed here, beyond commenting that although Grubb and Stevens define only UMRF proper and transition forest in the UMRF formation, in discussing the forest in New Guinea they are forced to separate out some *Nothofagus* or gymnosperm dominated forests from those with no marked dominance by one taxonomic group.

1. Upper Montane Rainforest and Transition Forest

This formation is defined by the total generic spectrum present, and by considerations of life form and leaf size of this spectrum, not just the local dominant species. Nanophyll (<25 mm) leaves predominate, and many species which are also present in lower forests show reduced leaf size, height and sometimes a multi-trunked habit. This effect becomes even greater in the transition forest at its upper limit with subalpine rainforest (SARF).

The upper montane rainforest has been most carefully studied on Mt Wilhelm (the 'cloud' forest of Wade & McVean, 1969) and Mt Kerigomna (Grubb & Stevens, 1979). The typical genera throughout New Guinea listed by Grubb & Stevens are *Dacrycarpus, Papuacedrus, Elaeocarpus, Sericolea, Quintinia, Bubbia, Daphniphyllum, Tasmannia, Eurya, Macaranga, Pittosporum, Rapanea, Saurauia, Schuurmannsia,* and *Sphenostemon.* Small leafed species of Myrtaceae (*Decaspermum, Xanthomyrtus* and some *Syzygium* species) and Cunoniaceae (*Wein-*

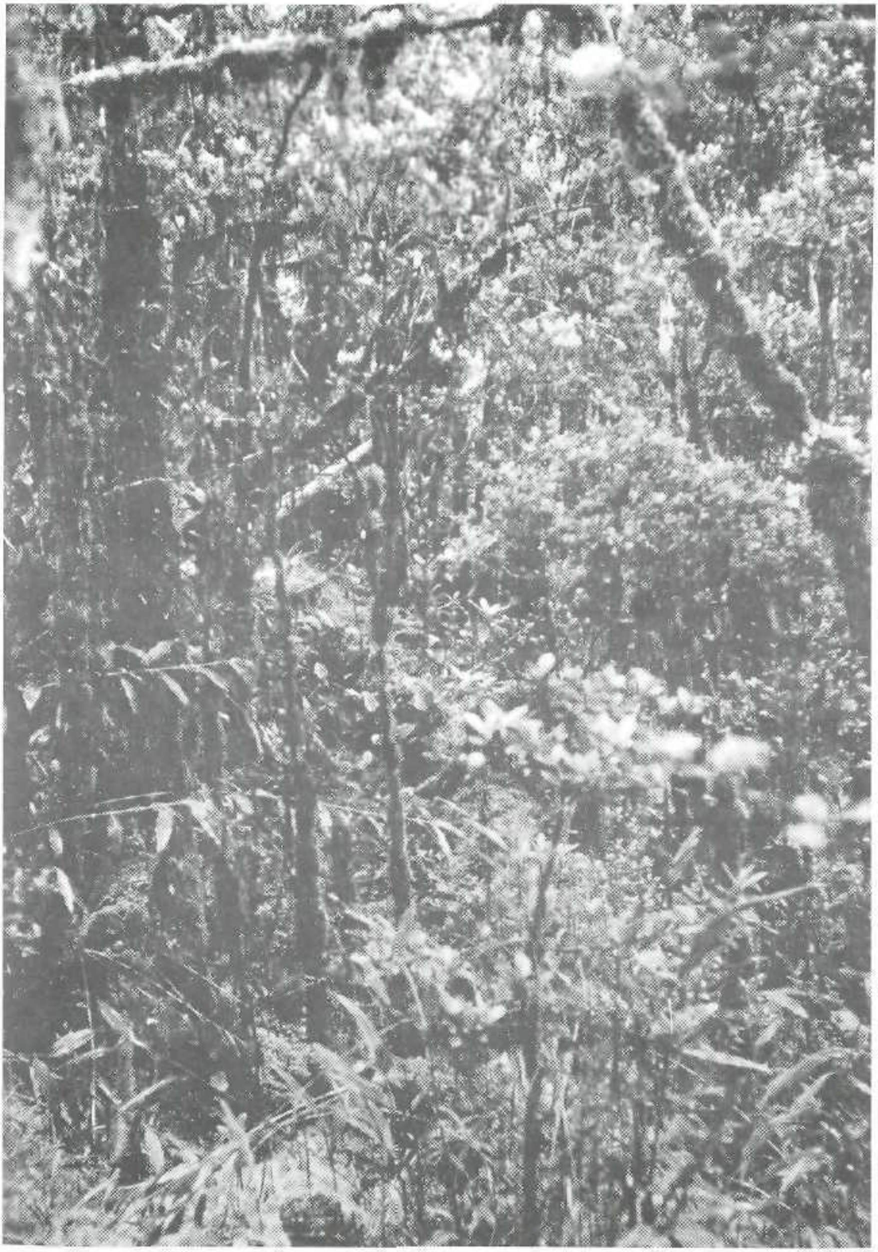
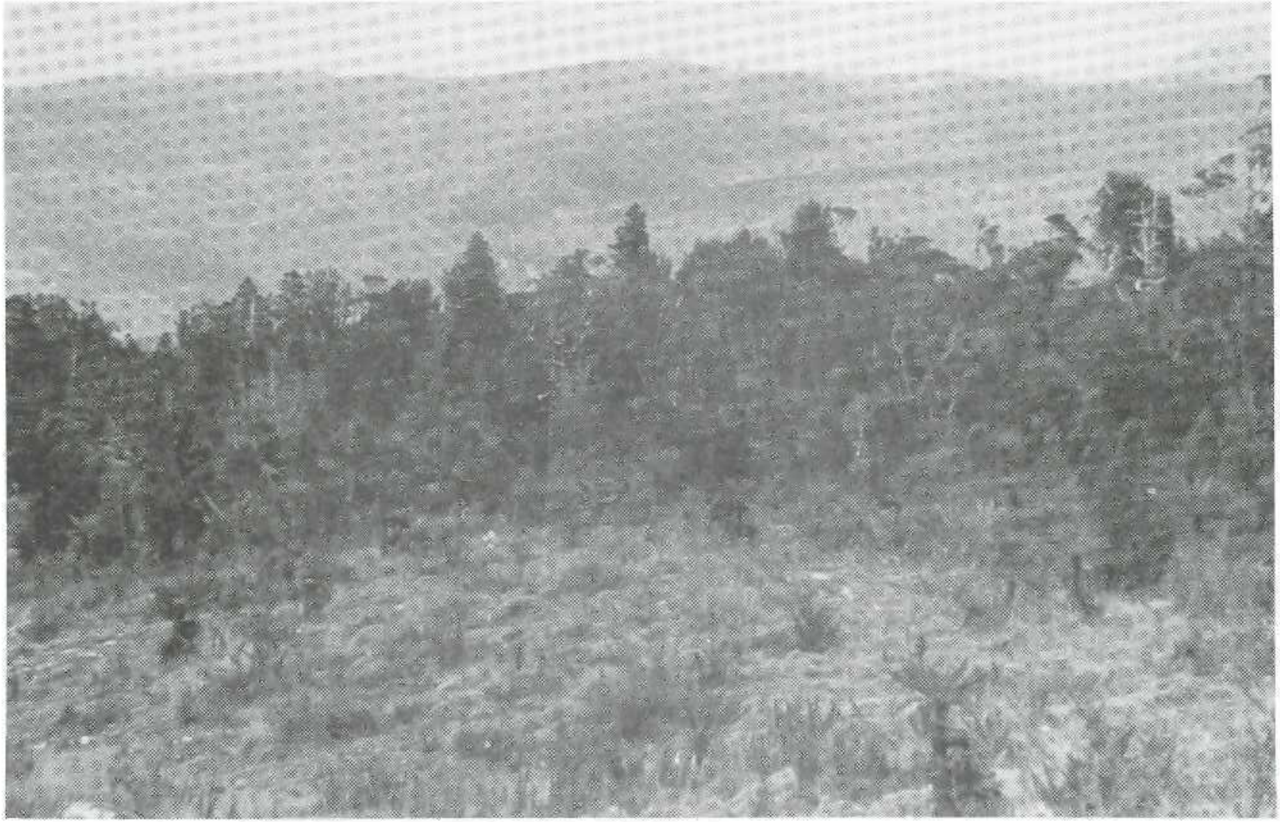


Plate 19. Transition forest (Upper montane forest formation), dominated by *Tasmannia, Eurya, Sericolea, Styphelia*, and *Vaccinium* species. Mt Albert Edward, S. edge of Neon Basin, 3300 m. 23 Jan. 1965.



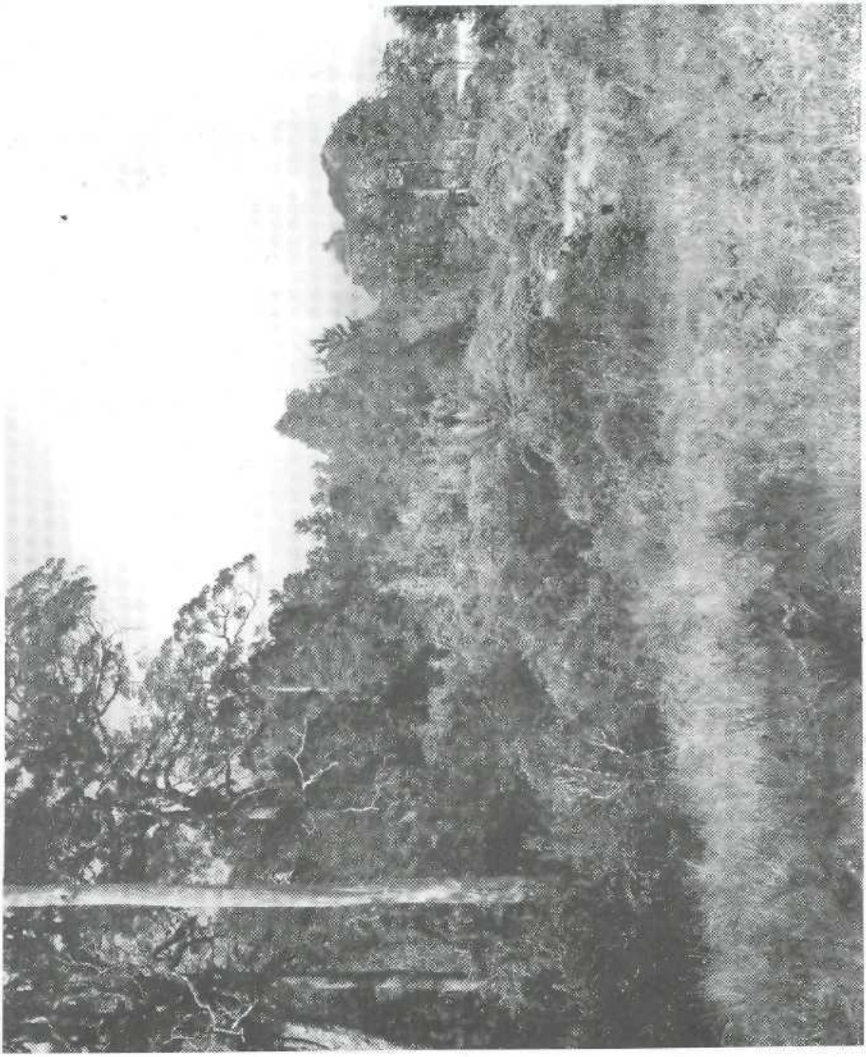


Plate 20. Mosaic of transition forest (A2) and tree fern shrublands (B4) with a Coprosma brassii forest edge scrub (B1). ***Papuacedrus papuana*** is a prominent canopy tree. Kemaboe Plateau, N. of Mt Carstensz, 3550 m. Feb. 1972 (Photo G. Hope).

Plate 21. Transition forest, Coprosma-Rhododendron forest edge shrublands (B1). Limestone ridge (left), Lake Habbema, 3225 m. Forest composed of an open stand of conifers *(Dacrycarpus compactus, Papuacedrus papuana* and some ***Phyllocladus hypophyllus),*** and a dense low canopy layer of ***Vaccinium dominans*** and ***Decaspermum lorentzii.*** Shrubberies largely of ***Styphelia*** sp., ***Rhododendron*** sp., ***Coprosma novoguineensis,*** and ***Tasmania piperita.*** August 1938 (Photo L.J. Brass).

mannia, Schizomeria) may be important, but are not common to all areas. Most of the taxa also occur at lower altitudes. and the forest owes much of its floristic character to the absence of many typical lower montane rainforest (LMRF) tree taxa, notably Lauraceae, Monimiaceae, Moraceae, Rhamnaceae and Sapindaceae. The characteristic life forms of stilt-rooted *Pandanus* and climbing bamboo are also usually lacking from UMRF.

The forest is generally about 20 m high and may support abundant bryophytic epiphytes to a greater or lesser extent (Plate 19). The terms "mossy forest" or "elfin forest" have been used for forests thickly carpeted by bryophytes, but Grubb and Stevens consider that communities from all three mountain formations (LMRF, UMRF, SARF) have been included under these titles. In general, tall closed forest marks the upper boundary of the LMRF, but on the northern slopes of the cordillera in West New Guinea forests 30-40 m in height dominated by *Nothofagus pullei* and *N. pseudoresinosa*, occur up to 3200 m and are regarded as UMRF because of their subsidiary genera. Some *Nothofagus* forests have an open canopy and are in fact open forest.

The transition forest has a lower stature and contains fewer genera than the main UMRF formation. It has been regarded as a subalpine forest by most writers, probably because it is characteristically dominated by gymnosperms, but Grubb and Stevens found that transition forest on Mt Kerigomna shares about 40% of its flora with subalpine forest and 55% with UMRF, with only 12% exclusive species. The transition is complete when all the UMRF taxa are absent. As with the main formation, the transition forest is very variable across New Guinea, partly because many UMRF species display different altitudinal limits on different mountains. *Papuacedrus papuana* and *Phyllocladus hypophyllus* are perhaps the most striking of these, being absent above 3000 m on Mt Wilhelm (and hence from transition forest) but being co-dominant on many other mountain areas up to 3500 m (Plates 20, 21). In comparing the neighbouring Mt Kerigomna and Mt Wilhelm transition forests, Grubb & Stevens (1979) found only two tree species, *Dacrycarpus compactus* and *Rapanea vaccinioides*, to have a high constancy in both, although the total floristic make up was so similar that they suggest that the mountains share common associations.

In reviewing the distribution of UMRF across New Guinea, Grubb and Stevens note very considerable variations in the altitudinal range of the formation, and defined a second UMRF alliance, with similar genera but completely separate species, at lower altitudes north of the main cordillera, exemplified by the vegetation of Mt Doorman described by Lam (1945). Of the higher altitude UMRF the upper and lower limits (including transition forests) are given by Grubb and Stevens. (Fig. 24).

Plate 22. Transition forest (A2). The canopy is very open, consisting of stunted *Papuacedrus papuana* and *Dacrycarpus compactus.* The very dense, tall shrubland understorey is restricted to limestone soils. Eastern Star Mts, Mt Capella. 3480 m. May 1975 (Photo G. Hope).

The formation occupies its narrowest range on the southeastern slopes of Mt Wilhelm, and reaches its lowest altitudes in the west and east of the cordillera. Grubb and Stevens suggest that areas experiencing persistent cloud and/or low soil fertility support UMRF at particularly low altitudes, there often including a few taxa typical of LMRF, such as *Pandanus*. The explanation of the variable range of the formation and individual taxa within it, is still not understood, although several possibilities are discussed by Grubb (1977).

Mountain	Lower Boundary m	Upper Boundary m
Mt Carstensz	2500-2800	3650
Mt Wilhelmina	2800	3500
Star Mountains	2300-2800	3500
Doma Peaks	2900	3400
Mt Wilhelm	3050	3550
Mt Albert Edward	2400	3450
Mt Suckling	2400	3450
Finisterre Range	2400	3200

Fig 24 Altitudinal limits of UMRF Formation (from Grubb & Stevens, 1979)

Although the structure of UMRF is typically a closed forest, apparently natural stands of open forest or woodland have been noted by the author on the eastern Star Mts. (Plate 22). Open to very scattered trees of *Papuacedrus papuana* and *Dacrycarpus cinctus* grow to 18 m above a dense, tall closed scrub of *Rapanea*, *Rhododendron* and *Xanthomyrtus* spp. The canopy of most of the trees appeared stunted, hinting at low growth rates for climatic or edaphic reasons. In other areas, including Mt Suckling and Mt Carstensz, the formation may be dwarfed, and structurally a tall closed scrub.

2. Subalpine Rain Forest (SARF)

The forest occurs above 3400-3600 m and is structurally a low closed forest or tall scrub. Wade has defined this formation (upper subalpine forest) on Mt Wilhelm. As for UMRF the forest is characterized by its total floristic make-up rather than individual dominant species. Tree or shrub genera typical of the forest are *Coprosma*, *Styphelia*, *Tasmannia*, *Olearia*, *Senecio* and *Trochocarpa*, but at the species level *Rhododendron*, *Vaccinium* and *Dimorphanthera* species, *Rapanea vaccinioides*

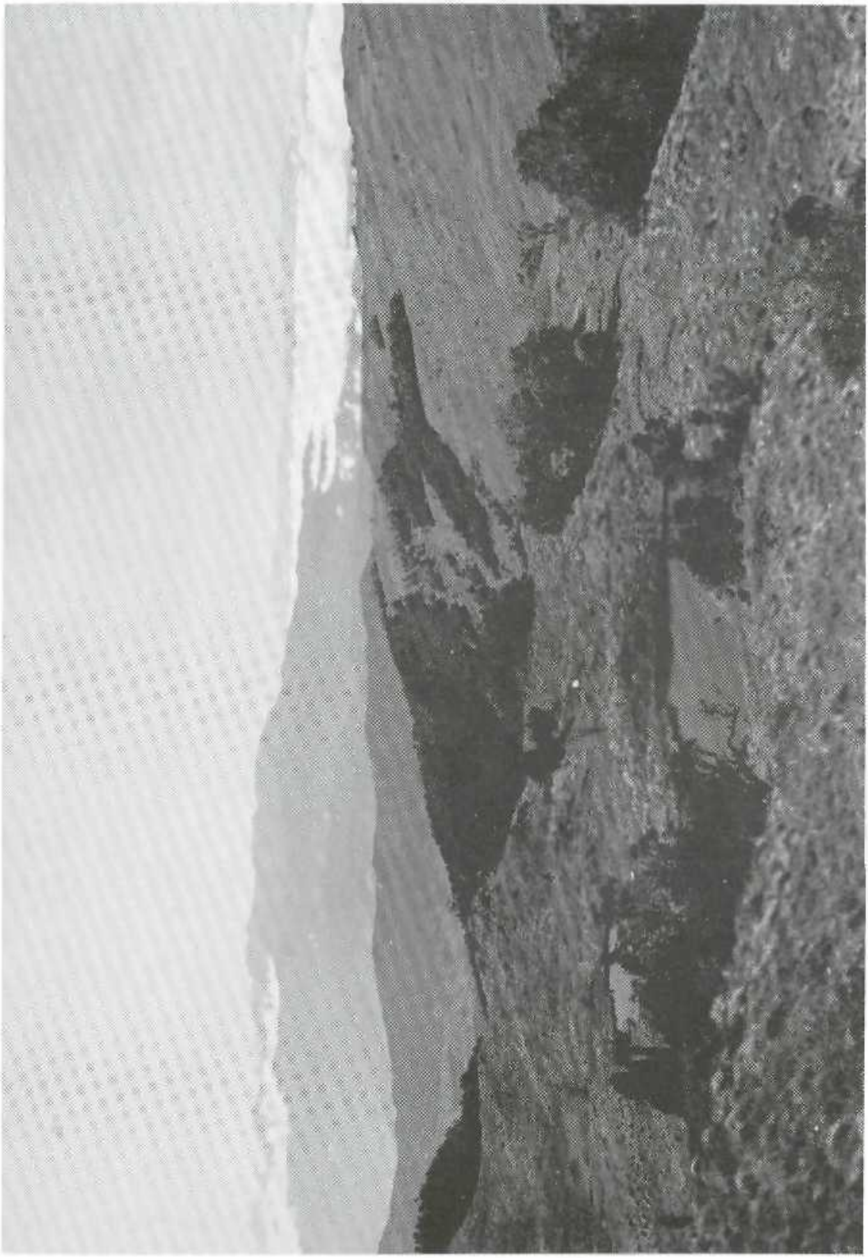


Plate 23. Alpine ponds alternating with subalpine forest (A2), Danthonia vestita - Deyeuxia brassii tussock grassland (D3), Deschampsia klossii alpine tussock grassland (E1), and short grass bogs on the flat areas (F4). Summit of NW peak of Mt Giluwe, 4000 m. June 1976.

Plate 24. Degraded subalpine forest (A3). Most trees have been killed, leaving *Dimorphanthera amplifolia* as a dominant. *Deschampsia klossii* tussock grassland surrounds the stand, but gives way to *Poa erectifolia* short grassland in the foreground. White areas in the forest are tarpaulins. Mt Albert Edward, 3680 m. June 1974 (Photo G. Hope).

(and related species) and *Dacrycarpus compactus* provide many of the notable dominants. Variation in the Ericaceae present and the role of *Dacrycarpus compactus* contributes greatly to the variation in the forest. *D. compactus* retains a robust, single-trunked tree habit up to the forest limit (about 3850 m) on Mt Wilhelm, Mt Albert Edward and Mt Giluwe. (Plate 23). However, on the Star Mts and Mt Wilhelmina *Dacrycarpus compactus* was not noted above 3500 m and various multi-trunked tall shrub genera, particularly *Rhododendron culminicolum* and other species, *Rapanea vaccinioides.Coprosma brassii, Tasmannia piperita* form a low closed-forest. On Mt Carstensz *Dacrycarpus compactus* occurs up to 3800 m but is not important above 3600 m. On the Owen Stanley Range *D. compactus* shares dominance of the forest with *Dimorphanthera amplifolia* and there *Rapanea vaccinioides* is not particularly important. (Plate 24). A similar forest probably existed on Mt Bangeta, Sarawaket Mts, before clearance (Costin, *et al.*, 1977) except that *Dacrycarpus* was absent. *Dacrycarpus* is similarly absent from Mt Suckling.

The SARF formation on Mt Wilhelm was named the *Dimorphanthera microphylla-Rhododendron gaultheriifolium-Trochocarpa dispersa* association by Wade & McVean (1969), but Grubb & Stevens (1979) found that SARF on Mt Kerigomna apparently lacked the latter two species, despite overall floristic similarity. Thus SARF probably occurs as many distinct associations, and probably at least three alliances. Shrub species that are widespread are rather few; they include *Rapanea vaccinioides* (*sens. lat.*), *Rhododendron culminicolum* and *Pittosporum pullifolium*. Common herbs appear to be *Anaphalis mariae, Schoenus curvulus* and probably some fern and bryophytic species. The presence or absence of *Dacrycarpus*, and characteristic arboreal Ericaceae, Asteraceae and *Schefflera* species have notable effects on the overall structure of the alliances.

3. Tall Closed Shrublands and the Treeline

Hope (1976a) described a closed shrubland formed by multi-branched *Rapanea vaccinioides* and *Coprosma brassii*, extending above the forest limit at 3900 m on Mt Carstensz up to 4100 m. This community is distinct from subalpine forest, and is known from the Snow Mts (Merauke Rge) and Star Mts and it is particularly well developed on limestone. (Plate 25). The altitudinal range, structure and detailed floristics distinguish this alliance from the subalpine forest but it is included in the SARF formation because the forest itself at lower altitudes is often reduced to tall open-scrub with only scattered emer-

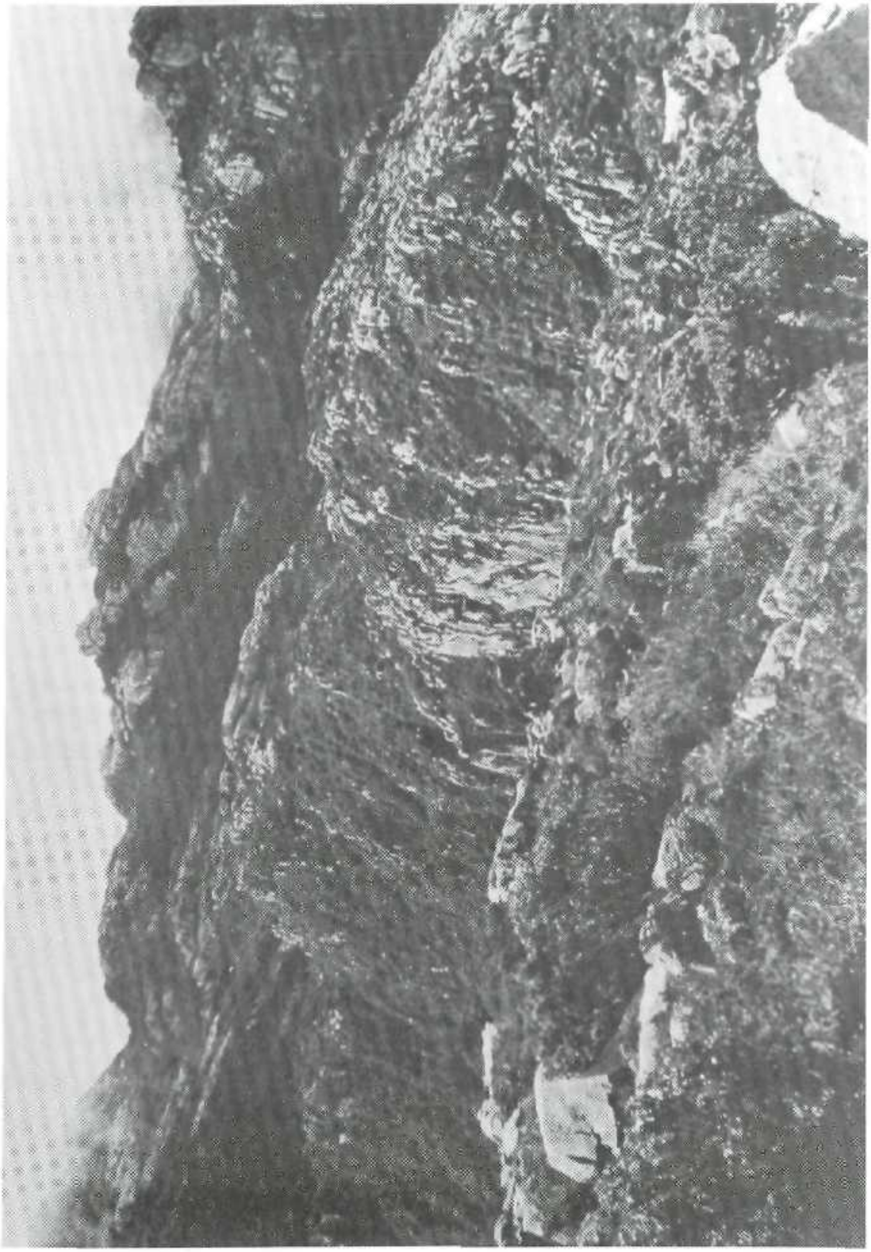


Plate 25. Treeline closed shrublands (A4). Principally *Coprosma brassii, Tasmannia* sp., *Styphelia suaveolens,* and *Rhododendron* sp. Eastern Star Mts, Mt Capella, 3850 m. May 1975 (Photo G. Hope).

gents of *Dacrycarpus compactus*, and is floristically related. On many mountains the nature of the forest limit is determined by burning (Smith, 1975; Hope, 1976a). The presence of isolated trees beyond forest limits on Mt Wilhelm, Mt Albert Edward and Mt Wilhelmina is evidence of former forest cover. The limit of closed forest or scrub cover occurs at very variable altitudes in New Guinea, but is generally at 3600-3800 m at the highest. Small stands of open shrublands or isolated low trees do not usually exceed 4250 m on limestone and are somewhat lower,4000-4150 m, on basaltic or granitic mountains. This observation is based on comparisons of neighbouring limestone and granidiorite peaks on Mt Carstensz and the eastern Star Mts. Despite these differences in absolute tree limits, the general community limits occur at approximately the same altitude on the different soils in both areas. The difference in absolute limits is unlikely to reflect nutrition but may be the result of better drainage on the limestone, providing a better thermal environment in the soil. Smith (1977, qv) has shown that the altitudinal limits of many species are lower on shaded compared to sunny slopes on Mt Wilhelm, and he suggests that maximum temperatures are closely correlated with this effect.

The treeline shrubland of the Snow and Star mountains is apparently absent from the more easterly mountains, where its altitudinal range is occupied by shrub-rich grasslands. Hope (1976a) concluded that this distribution is natural, and probably not the result of human interference at the timberline in the eastern New Guinean mountains.

Other closed shrublands are not included in SARF or UMF formations, and are described in the next section.

B. Tall Shrublands

The tall shrublands occupy the same altitudinal range as the two forest formations treated above, and, in general, are seral to forest or represent disclimaxes. Three groupings of alliances, which can be regarded as separate structural-floristic formations, have been defined by various workers, but these have not previously been grouped together. Forest-edge shrublands have been most carefully studied by Gillison (1970) on the Doma Peaks, but other examples come from Mt Carstensz (Hope, 1976a). Shrubland associations colonising landslips and rocky slopes have been described on Mt Wilhelm (Wade & McVean 1969), and Mt Carstensz (Hope, 1976a). Open to very open shrubland consisting of tree ferns (*Cyathea* spp.) above grasses and lower shrubs is widely known from most New Guinea mountains. Structurally these communities are all tall shrublands or scrub but they have been described under forest or grassland categories or lumped with non-shrubby seral communities.

1. Coprosma-Rhododendron Forest-Edge Shrublands

This formation probably includes several alliances as it varies with altitude as well as regionally. As defined on Mt Wilhelm ("Forest edge community" of Wade & McVean 1969) it consists of closed or open scrub 2-5 m in height, dominated by *Coprosma papuensis. Dimorphanthera* spp., *Vaccinium cruentum, Rhododendron womersleyii, Tasmannia piperita* and *Olearia* sp. (Plate 26). Ferns such as *Plagiogyria glauca* and *Gleichenia bolanica* are prominent while tree ferns may be locally dominant. (Plate 21). Herbs such as *Anaphalis mariae* and *Acaena anserinifolia* are also more common in this community than any other. Wade and McVean point out that the community appears variable at any point, but it is relatively homogeneous in floristic composition. Similar communities are found on nearly all New Guinea mountains. (Plates 21,27). Kalkman & Vink (1970) list several identical or closely related species as forming both a forest edge community and a more extensive community beyond the forest limit at about 3200 m on Doma Peaks. *Coprosma papuensis* has a restricted range, but *C. brassii* plays a similar role on Mt Carstensz together with other species of *Cyathea, Olearia, Rhododendron,* and *Schefflera.* (Plate 28). The formation does not occur above 3650 m, as it becomes increasingly depauperate with altitude and merges with the SARF or shrub-rich grasslands. Wherever it has been studied, however, authors have regarded the alliance as a distinctive community, whose major species may not be common within the forest. Forest-edge shrubland is regarded generally as a fire-seral community occupying formerly-forested areas. Observations of apparently natural forest boundaries on Mt Carstensz, Mt Wilhelm and Mt Scorpion support this view, for there the forest ends abruptly along edaphic boundaries, with few of the scrub species prominent.

2. Ericaceous Shrublands of Landslips and Rocky Slopes

A heterogeneous group of communities can be lumped under the above heading. Landslide scars and steep rocky slopes are gradually colonized by tall shrubs, often species of *Rhododendron* and *Coprosma,* to give medium to tall shrublands (1-3 m in height). (Plate 29). Examples are the *Rhododendron yelliotii* community on Mt Wilhelm, and releves on fissured limestone slabs at Mt Carstensz. The communities are basically edaphically controlled, but may sometimes compete with grassland or forest in colonising bared areas of deep peaty soils. Shrublands of soils

Plate 26. Poa tussock grassland (D2) with *Hierochloe* tussocks on W. bank of Lake Aunde, 3600 m. Sept. 1962.

Plate 27. Forest edge shrublands (B1). A narrow grassy glade in subalpine forest. Larger trees in background ***Dacrycarpus compactus.*** Fringing small trees or arborescent shrubs, mainly small-leaved, twiggy ***Coprosma papuensis; Tasmannia piperita*** also present. Tree ferns: *Cyathea macgregorii.* Grass on right: tussock-forming ***Danthonia archboldii.*** Mt Albert Edward, SE slopes, 3680 m. July 1933 (Photo L.J. Brass).

Plate 28. Coprosma-Rhododendron forest edge shrubland (B1). This is a transition forest in regrowth, dominated by ***Coprosma, Rhododendron,*** and ***Schefflera.*** Bare area in foreground is the result of erosion, probably the consequence of fire. Kemaboe Plateau, crest of Pleistocene moraine, 10 km N of Mt Carstensz ice areas, 3580 m. 23 Jan. 1972 (Photo G. Hope).

Plate 29. Shrublands (B2) on rock surfaces, Carstensz Meadow, 3710 m. At left Ertsberg. Jan. 1972 (Photo G. Hope).

of reduced fertility or waterlogging could thus be included in this general group, but these have not been described in New Guinea, although dwarfed UMRF and SARF are noted by Grubb & Stevens (1979). No tall shrublands seem to have developed as specialized mire communities in New Guinea, although it can be acknowledged that all New Guinea mountain communities are adapted to water logged soils to some degree.

These shrublands, and other seral communities, are very little studied and nothing can be said about their altitudinal or geographic ranges in New Guinea.

3. Montane and Subalpine Tree Fern Shrublands

By contrast, the tree fern shrublands have attracted much attention because of their peculiar appearance and considerable extent on many mountains. Wade & McVean (1969) included the tree fern dominated communities of Mt Wilhelm as shrub-rich grasslands but Paijmans and Löffler (1972) redefine this formation as "savanna" — a community dominated by grasses and with scattered trees. However, since tree ferns are usually 2-5 m in height, the formation is best treated as a tall shrubland. Also some areas support a quite dense growth of tree ferns with many understorey shrubs and rather sparse grass cover. so that the formation cannot be generally included in grassland.

Typically the shrublands consist of thick-trunked, stocky *Cyathea* species, with rigid, rather small crowns, set in tussock grassland with a variety of small shrubs and herbs. At least two alliances seem to exist which are dominated by species of *Cyathea* with different ecological tolerances. The montane tree fern alliance includes communities dominated by species of *Cyathea* which are also common within the UMRF, such as *C. atrox* and *C. aeneifolia.* These appear to be limited to areas below about 3400 m that do not experience severe frosts. Associations defined include the *C. atrox - Triplostegia glandulifera* tussock grassland association of Wade & McVean (1969). Examples occur as low as 2500 m in most areas of New Guinea, but are particularly noted for Mt Albert Edward, Sugarloaf Plateau, the Doma Peaks and grassland basins on Mt Capella. (Plate 30).The understorey includes many species of herbs, such as *Deschampsia klossii, Ranunculus* spp. and *Astelia alpina,* which otherwise are uncommon below 3300 m. However, several low shrub or herb taxa are present which are rare or absent in the subalpine grasslands, such as *Hypericum* spp., *Drosera peltata, Gonocarpus* spp. and many monocotyledonous species in the Poaceae, Cyperaceae and Eriocaulaceae and *Equisetum debile* and many fern

Plate 30. Montane tree fern shrubland (B3). *Cyathea atrox* is the main species, with a mixture of subalpine and montane grasses, forbs and shrubs below. This area was certainly formerly forested, but is now burnt regularly. Mt Albert Edward, Murray Pass, at about 2800 m. Aug. 1970 (Photo J. Hope).

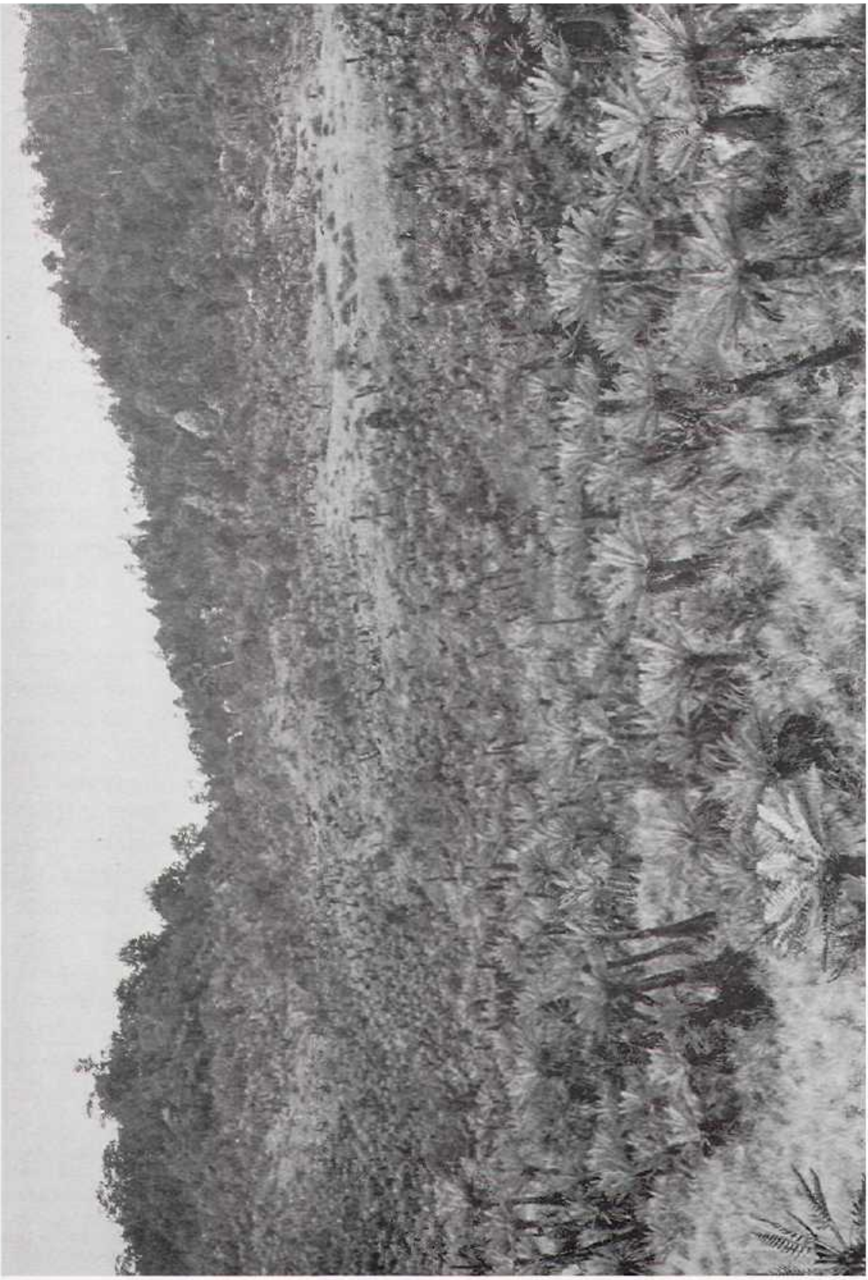


Plate 31. Tree fern shrublands (B4), and montane transition forest (A2). Kemaboe Plateau, N of Mt Carstensz, 3500 m. Feb. 1972 (Photo G. Hope).

species. Thus the alliance includes a mixture of montane and subalpine elements. This alliance is clearly related to a medium fire regime which follows forest retreat, and it is rapidly invaded by forest-edge shrublands in the absence of fire. Increased fire frequency causes reduced shrubbiness and ultimately loss of the tree ferns.

The subalpine tree fern alliance is dominated by species of *Cyathea* which are not usually found in the forest, such as *C. macgregorii*, *C. gleichenioides*, *C. muelleri* and *C. pseudomuelleri*. This alliance occupies cold valley bottoms up to 3700 m, and is usually associated with numerous low shrubs of *Styphelia suaveolens*, *Gaultheria* sp. and *Coprosma* sp. as well as tussock grasses. (Plate 31). As for the previous alliance, communities vary from an almost complete tree fern cover above lower shrubs to scattered tree ferns, among grasses, often occurring as a strip along well drained creek banks or the base of hill slopes. The communities cannot colonize waterlogged soils. Examples are described from Mt Carstensz (Hope, 1976a) and Mt Wilhelm (included in the *Coprosma-Poa* tussock grassland association). In the Neon Basin of Mt Albert Edward, both alliances are present, forming concentric zones around an extensive upland basin subject to frost and fire. (Plate 32).

A controversy exists concerning the status of the tree fern dominated alliances, which are regarded as wholly the result of disturbance by fire by Paijmans and Löffler (1972), and possibly natural, the results of exclusion of forest from frost hollows or the margins of mires by Wardle (1971). The separation of two alliances may help to clarify the problem, there being no doubt that the lower altitude alliance is derived largely from montane taxa following fires. However, the upper alliance has been noted by the author occurring as a restricted community in apparently undisturbed sites on Mt Capella (Plate 33) and Mt Carstensz. Hope (1976b) has shown that tree fern dominated communities once were widespread, apparently above the treeline, during the last glacial times. Thus, although the present extent of both alliances is the result of widespread forest destruction, recolonization by forest of areas dominated by the higher alliance may be very slow, even in the absence of fires, and these communities have probably expanded from "natural" stands (see also Chapter 9).

Insufficient taxonomic work has been done to define the distribution of the tree fern species and their communities, although it appears that *C. pseudomuelleri* shrubland is prominent in the Snow Mountains while *C. gleichenioides* shrubland is more common in eastern P.N.G.

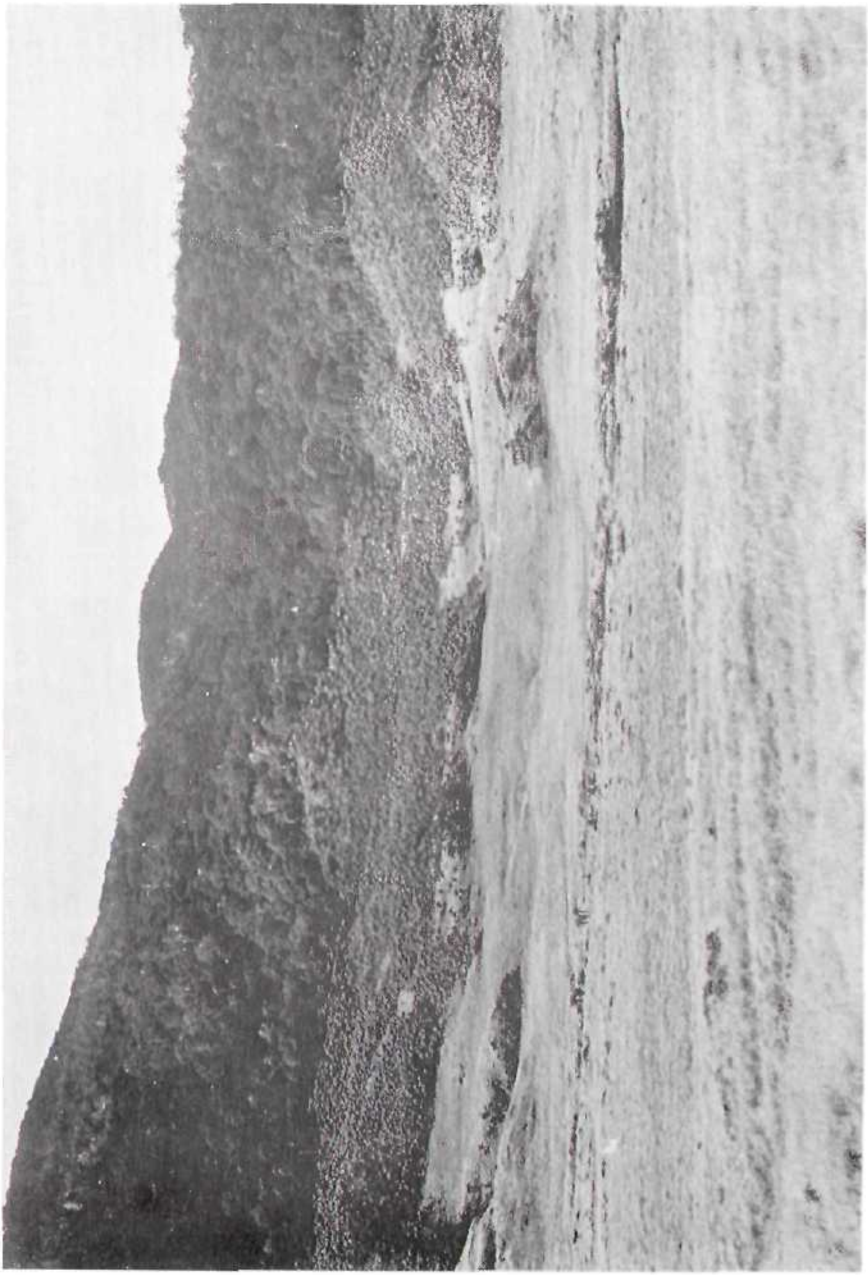


Plate 32. Subalpine grasslands, tree fern shrubland and montane forest (A1). Broader canopied montane tree ferns (B3) form a narrow zone between the forest margin and subalpine tree fern shrubland. Mt Albert Edward, Neon Basin, 2876 m. July 1974 (Photo G. Hope).

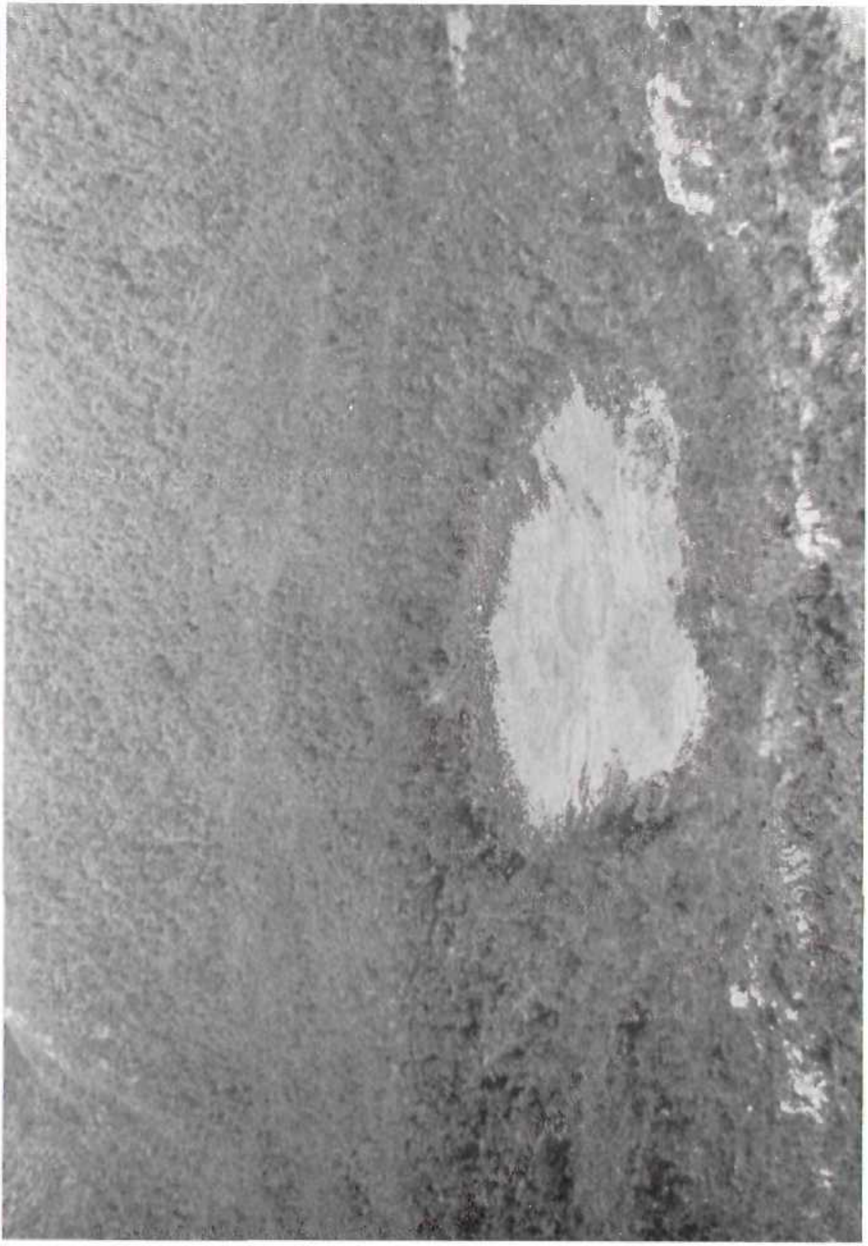


Plate 33. Apparently natural grassland bordered by tree fern shrublands (B4) in a closed basin behind a terminal moraine topped by transition forest. Eastern Star Mts, Mt Capella, S slope, 3450 m. May 1975 (Photo G. Hope).

C. Heaths

Low closed shrublands (heath and open heath) are rare in New Guinea, although communities of very scattered low shrubs set in grassland (which can be regarded as low open shrubland) are widespread in the subalpine regions. Following Wade & McVean (1969) the scattered shrublands are treated with the grasslands, for reasons given previously. Some of the tall shrublands defined above can occur as heaths during their development. A distinct subalpine heath community has only been described from Mt Albert Edward (Hope, 1975), but other heath communities are widespread in the alpine zone.

1. Coprosma - Gaultheria Heath

On Mt Albert Edward *Coprosma divergens, Gaultheria mundula, Styphelia suaveolens* and *Eurya brassii* combine to form a dense shrubland up to 1.5 m in height. (Plate 34). Grasses are common but dispersed in the heath, while other herbs are almost absent. The community is readily burnt after dry weather, and is restricted to sheltered gullies and well drained hilltops between 3450-3750 m. The component species are widespread on the New Guinea mountains, but normally only seem to form fragmentary stands of heath. Both *Styphelia suaveolens* and *Coprosma divergens* have distinctive habits on Mt Albert Edward, and may be genetically different from the central highland forms. The community is described by van Royen (1967) as *Eurya brassii* heath, and is apparently also present on Mt Suckling (Stevens & Veldkamp, 1977).

2. Dwarf Shrub Heath

Wade & McVean (1969) describe a heath consisting of a mat of dwarf shrubs 10-15 cm high, principally *Styphelia suaveolens* but including *Drapetes ericoides* and *Tetramolopium macrum*, with common sward-forming sedge and grass species and moss cushions. The community is only fragmentary on Mt Wilhelm in a very narrow altitudinal zone from 4230-4400 m on well drained, sunny sites with shallow stony soils. A very similar open heath including *Styphelia suaveolens*, but with other species of *Tetramolopium (T. klossii, T. piloso-villosum)* and *Parahebe (P. vanderwateri)*, occurs on Mt Carstensz, also on shallow, stony soil. However, the shrubs are somewhat taller, reaching 40-50 cm. The heath occurs on the margins of recent moraines, or steep, rocky slopes up to 4500 m on areas not affected by ice extensions of the last few centuries. The community is thus one of considerable maturity, and has a true alpine distribution, being known only from the highest peaks.

Plate 34. Coprosma divergens - Gaultheria mundula heath (C1). The heath is about 1 m high and includes occasional tree ferns. Mt Albert Edward, 3680 m. July 1974 (Photo G. Hope).

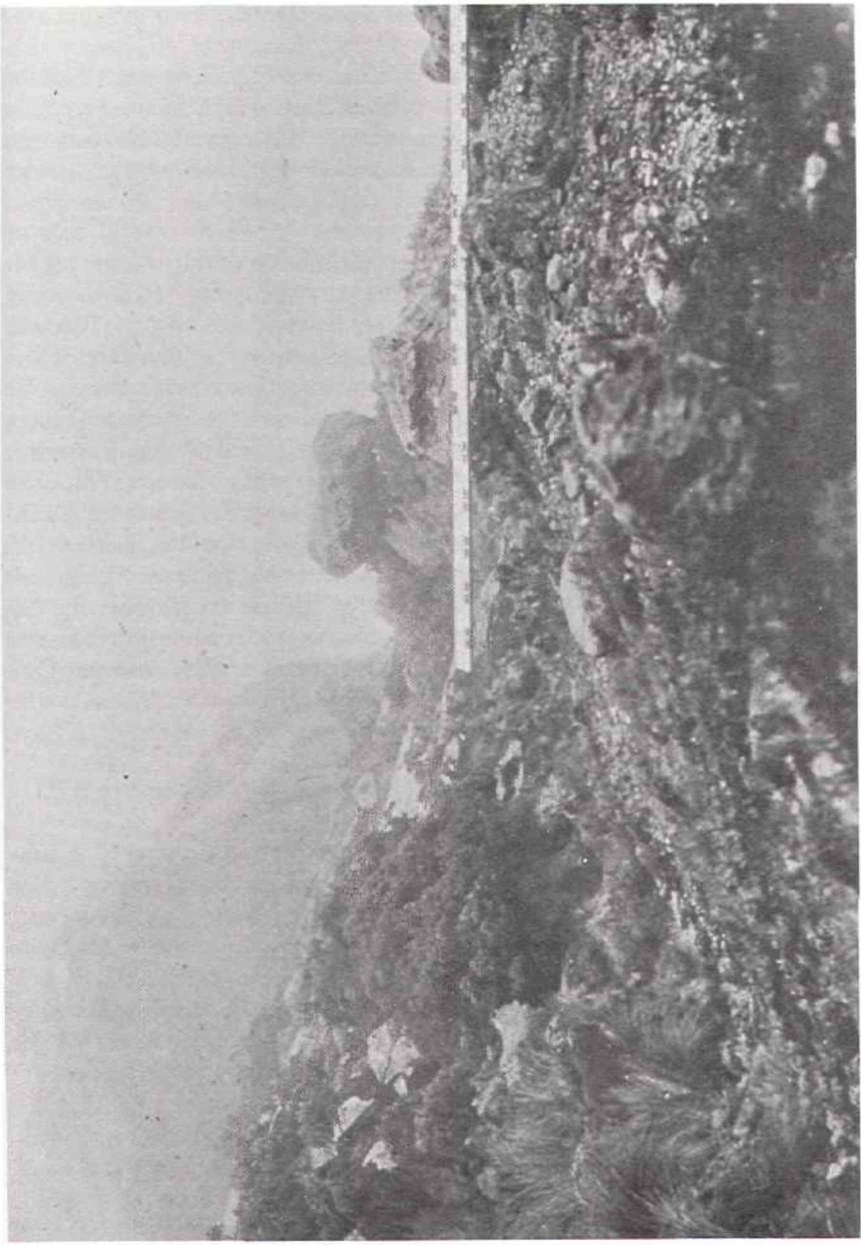


Plate 35. Dwarf alpine heath (C2) left, and Tetramolopium open heath (C4) right. The open heath is occupying an abandoned lateral moraine which marks the limit of a recent ice extension. Mt Carstensz, Upper Meren Valley, 4180 m. Dec. 1971 (Photo J. Peterson).

3. Rhacomitrium Open Heath

A closely related alliance to the dwarf shrub heath is described by Wade & McVean (1969). The dominant shrubs are again *Styphelia suaveolens* and *Tetramolopium macrum*, with several less common shrub species. However, the shrubs are widely dispersed, with an almost continuous mat of mosses, *Rhacomitrium lanuginosum*, *Rhacocarpus humboldtii* and *Campylopus atrofuscescens*, in which several tuft or cushion grass and sedge species can grow. The community occurs on Mt Wilhelm from 3800-4300 m, again generally occupying shallow, rocky soils, but spreading onto peaty waterlogged sites above 4000 m. Wade & McVean considered this community to closely resemble *Rhacomitrium* dominated alpine communities in the northern hemisphere. The alliance is recognizable in the summit vegetation of many New Guinea mountains. On Mt Carstensz, *Tetramolopium klossii - Rhacomitrium crispulum* heath can be regarded as a member of the alliance. (Plate 35). The Mt Carstensz community is extensive on areas exposed by glacial retreat, but more than 30 years old. The moss carpet is not complete on these areas, but older isolates stands on rocky slopes resemble the Mt Wilhelm community more closely. Under present conditions, the Mt Carstensz heath will become restricted to stony soils when grassland or dwarf shrub heath replaces it on favorable sites. The relationships of the alpine heaths to the other alpine communities are discussed later.

4. Tetramolopium distichum - Euphrasia lamii Open Heath

This heath has been described by Hope (1976a) as occupying a subalpine limestone fan on Mt Carstensz. The two dominant species occur as low shrubs to 25 cm, with abundant open ground occupied by tuft sedges and *Potentilla foersteriana* var. *brassii*. Most of the species involved are apparently restricted to the western Snow Mountains, and no equivalent communities have been described elsewhere in the subalpine zone. The heath is colonizing an area that is subject to periodic disturbance, but which has probably been stable for about 150 years.

5. Gleichenia bolanica - Gonocarpus halconensis Open Heath

This community is found on steep rocky slopes on Mt Wilhelm, and consists of a tangle of fern amongst scattered to frequent low shrubs. The habitat is created either by disturbance or lack of soil development. The small shrub species *Gonocarpus halconensis* has a limited distribution, but very similar fern-rich open heath or low shrublands occur on most mountains from less than 3000 m up to 3650 m.

This and the previous community are examples of what is probably a wide variety of edaphically-limited subalpine shrublands and heaths, which are grouped by Wade and McVean into "rocky slope communities". In fact the alpine heaths are also apparently edaphically limited, and thus can be linked with the subalpine communities, except for the restricted *Coprosma-Gaultheria* heath of Mt Albert Edward.

D. Shrub-rich Grasslands

The characteristic vegetation on most New Guinea mountains is a yellowish tussock grassland with scattered deep green or grey shrubs. The grasslands are most common along the valley floors, but extend up the slopes except on very rocky areas. Wade & McVean (1969) differentiated five shrub-rich tussock grassland communities on Mt Wilhelm (if the *Cyathea atrox* community is regarded as tall open shrubland). Insufficient work has been carried out to fully enumerate the grasslands of any other mountain area, but analogs to the Mt Wilhelm grasslands have been noted. Only two distinctive communities have been described which do not occur on Mt Wilhelm, but more work will undoubtedly extend this number. In areas where summit grasslands are joined to the mid-montane grasslands, the gradual exchange of high altitude species with the altitude limited shrubs and grasses presumably gives rise to many associations and ecotones which cannot be considered here.

1. Deschampsia klossii Tussock Grassland

Deschampsia klossii forms medium sized tussocks 25 cm across at the base and 30-90 cm in height. The species is an important component of several grassland associations and has a very wide altitudinal range, from 2000 m to 4500 m. Hnatiuk (1975) has shown that its growth rate is most favorable around 3500 m. On Mt Wilhelm the *Deschampsia klossii-Danthonia penicillata* association has a range from 3350-3750 m. It can consist of *Deschampsia klossii* almost alone, but where the tussocks are a little separate, several herb taxa and the tussocks *Anthoxanthum redolens* and *Poa keysserii* ssp. *saruwagetica* may be present. Shrubs are rare, usually *Styphelia suaveolens* and *Coprosma divergens*. The association forms a mosaic with tree fern shrublands.

This community is part of an alliance found on all New Guinea mountains, and particularly common in the Western Snow Mts (Plate 36) and P.N.G. highlands. (Plate 37). It is, however, only fragmentary on the eastern Star Mts and probably Mt Juliana. On Mt Albert Edward

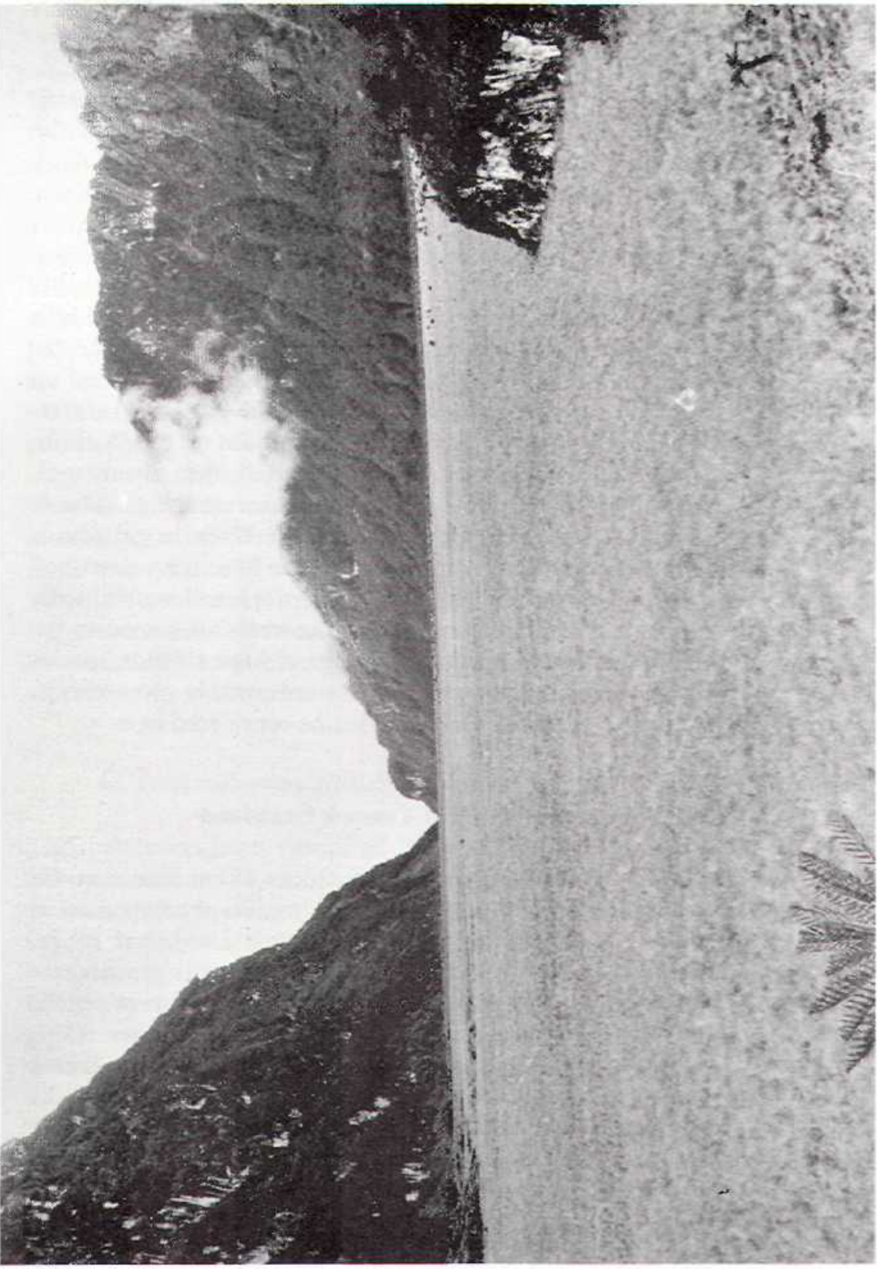


Plate 36. Deschampsia klossii subalpine tussock grassland (D1). Mt Carstensz, Carstensz Meadow, 3680 m. Jan 1972 (Photo G. Hope).

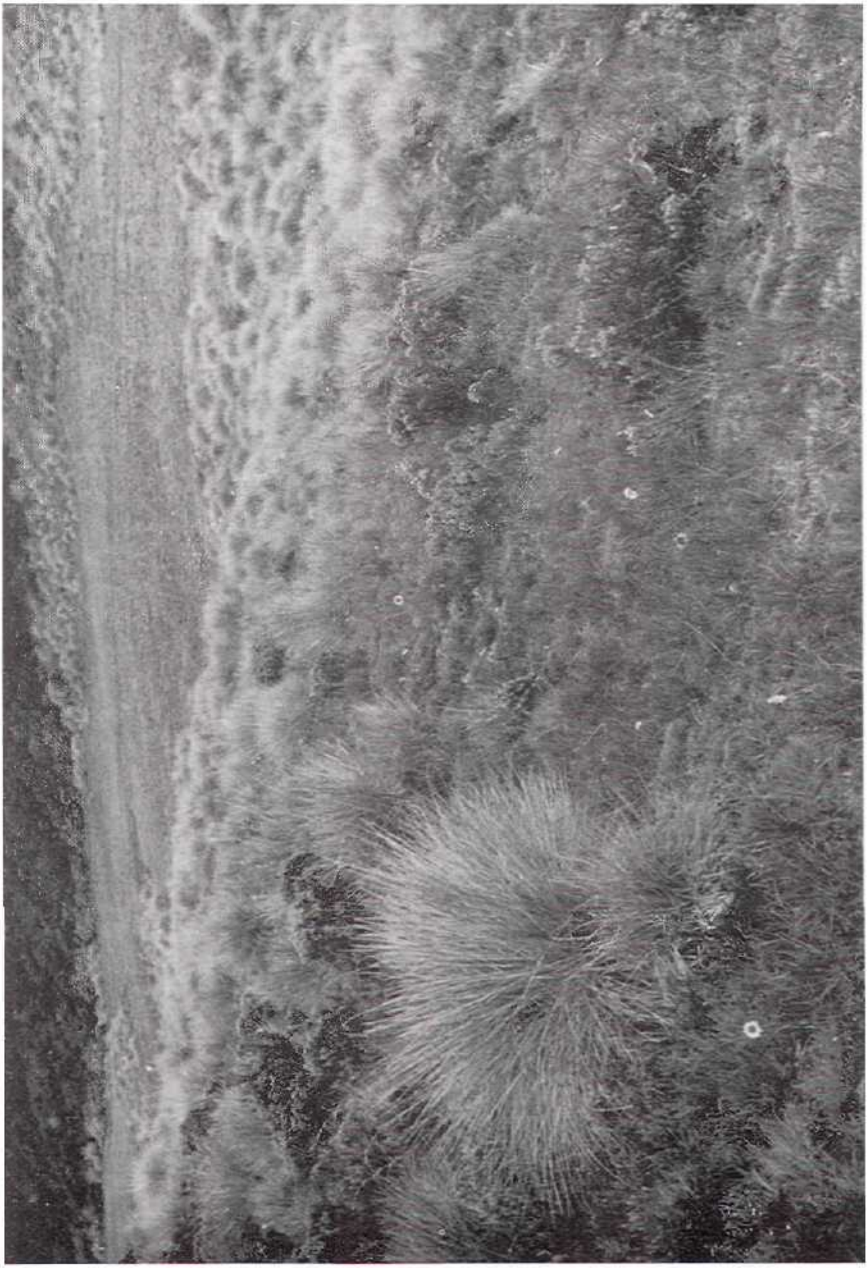


Plate 37. Deschampsia klossii tussock grassland (D1), large tussocks bordering the swampy parts, foreground Poa erectifolia-Styphelia short grassland (D6), with *Keysseria radicans*. Mt Enggom, 3600 m. Febr. 1963.

and elsewhere in the Owen Stanley ranges, it is common below 3300 m but is restricted above to the wettest parts of the valley bottoms.

2. Poa Tussock Grasslands

Tussock species of *Poa* such as *P. nivicola* and *P. keysserii* ssp. *saruwagetica* combine with shrubs such as *Gaultheria* sp. and *Coprosma* sp. to provide a more open tussock grassland in which abundant herbs are present. *Anthoxanthum redolens, Anaphalis, Gernaium, Ranunculus* and *Gentiana* spp. are characteristic (Plate 26) and *Deschampsia klossii* may be an important component. *Danthonia oreoboloides* forms a mat along paths through this community. At the alliance level two Mt Wilhelm associations, *Coprosma divergens - Poa keysserii* ssp. *saruwagetica* tussock grassland and *Poa keysserii* spp. *saruwagetica - Dichelachne novoguineensis* tussock grassland, can be combined. Wade & McVean (1969) state that the former occupies disturbed ground and probably develops into the latter with the growth of scattered shrubs and *Deschampsia*. The community is found on better drained slopes than *Deschampsia* tussock grassland, from 3400 to at least 3850 m on Mt Wilhelm and Mt Giluwe. A very similar grassland occurs on Mt Carstensz (Hope, 1976a), with *Poa nivicola* as the dominant and related minor grass and shrub species. On Mt Albert Edward the equivalent association contains all the major species of the *Coprosma-Poa* association on Mt Wilhelm, but in the area examined had less robust tussocks and wide gaps occupied by tuft grasses (Hope, 1975). It seems that this alliance has a wide distribution in New Guinea, although it is absent from the Star Mountains and has not been described from Mt Suckling or the Doma Peaks. It is regarded as secondary to forest in all areas, as it commonly contains old trunks or forest remnants. In the absence of fires on Mt Wilhelm, the shrubs have grown above the grass canopy and become more extensive (R.T. Corlett, personal communication). Wade & McVean (1969) noted the absence of forest taxa and concluded that reversion to forest was slow or non-existent.

3. Danthonia - Deyeuxia Tussock Grassland

The grassland has widely spaced small tussocks about 30 cm in height with a rich herb and small shrub flora growing in the gaps. On Mt Wilhelm it is the highest of the shrub-rich grasslands, occurring on well drained, sunny sites (Plates 38, 39) from 3850 to 4150 m, interdigitated with areas of alpine grasslands. The dominant grass species, *Danthonia vestita* and *Deyeuxia brassii* occur on all the mountain areas, but the alliance is only important on Mt Wilhelm and Mt Giluwe. A similar community is present as small stands on Mt Scorpion and Mt Bangeta but was not found in the Owen Stanley Range or Snow Mts. Wade & McVean (1969) regard it as a primary grassland, and Hope (1976a) suggests that it is absent from Mt Carstensz because its range is occupied there by the treeline shrubland.

R.T. Corlett (personal communication) has shown that the grassland has tolerated fire over the last 5000 years on Mt Wilhelm. On Mt Albert Edward the altitudinal zone is very restricted and rocky, but its habitat appears to be utilized by a *Poa erectifolia* short grassland or short alpine grassland.

4. Chionochloa archboldii Tussock Grasslands

Chionochloa (Danthonia) archboldii is the largest of the subalpine tussock grasses, and it forms a deep, dense grassland 80-120 cm in height. The community has been described on Mt Wilhelm by Wade & McVean (1969) as occupying very wet but well drained sites, such as steep rock walls and gravelly stream banks. It is rare on Mt Wilhelm, and is best developed on Mt Albert Edward, again occupying extremely steep but wet slopes. Ferns and low shrubs are common between the tussocks and *Cyathea gleichenioides* also occurs in some areas (Hope, 1975). The community is widespread in the Owen Stanley Range (Coode & Stevens, 1972; Stevens & Veldkamp, 1977) and on burnt slopes on Mt Michael, but is rare on Mt Wilhelm and Mt Giluwe and apparently absent from the Star and Snow mountains, despite the large extent of apparently suitable habitats on Mt Scorpion and near Mt Carstensz.

5. Gahnia javanica - Plagiogyria papuana Tussock Sedgeland

This sedgeland has not previously been formally defined, but is mentioned by Coode & Stevens (1972) for Mt Strong, and is known from most other mountains in New Guinea. *Gahnia javanica* forms a robust tussock about 80 cm in height, but the tussocks are usually not closely spaced. *Plagiogyria papuana* also has a tussock-like habit, with numerous fronds arising from a pedestal. Two 4 m^2 releves on Mt Scorpion at 3450 m had the following species frequencies (as defined by Wade & McVean, 1969 and Hope, 1976a). (Plate 40, fig. 25).

The community is usually found near forest edges, often with open patches of a necrotic lichen between the tussocks. It has been noted as low as 2850 m north of Mt Carstensz ranging up to about 3500 m. It is

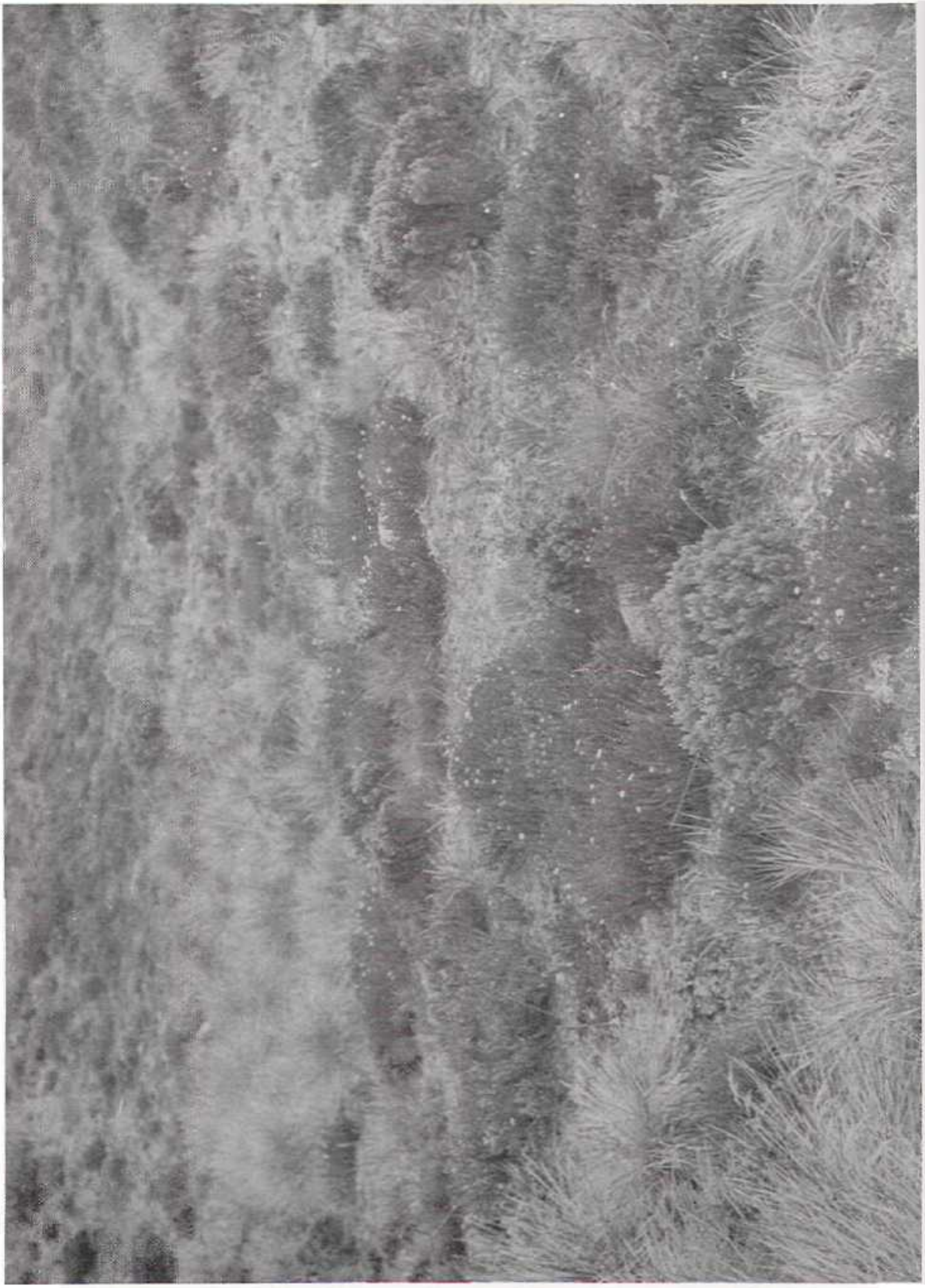


Plate 38. Danthonia vestita - Deyeuxia tussock grassland with *Tetramolopium macrum* (the dark, white-flowered bushes) and *Styphelia suaveolens* (light grey bushes). Mt Bangeta, 4100 m. Nov. 1963.

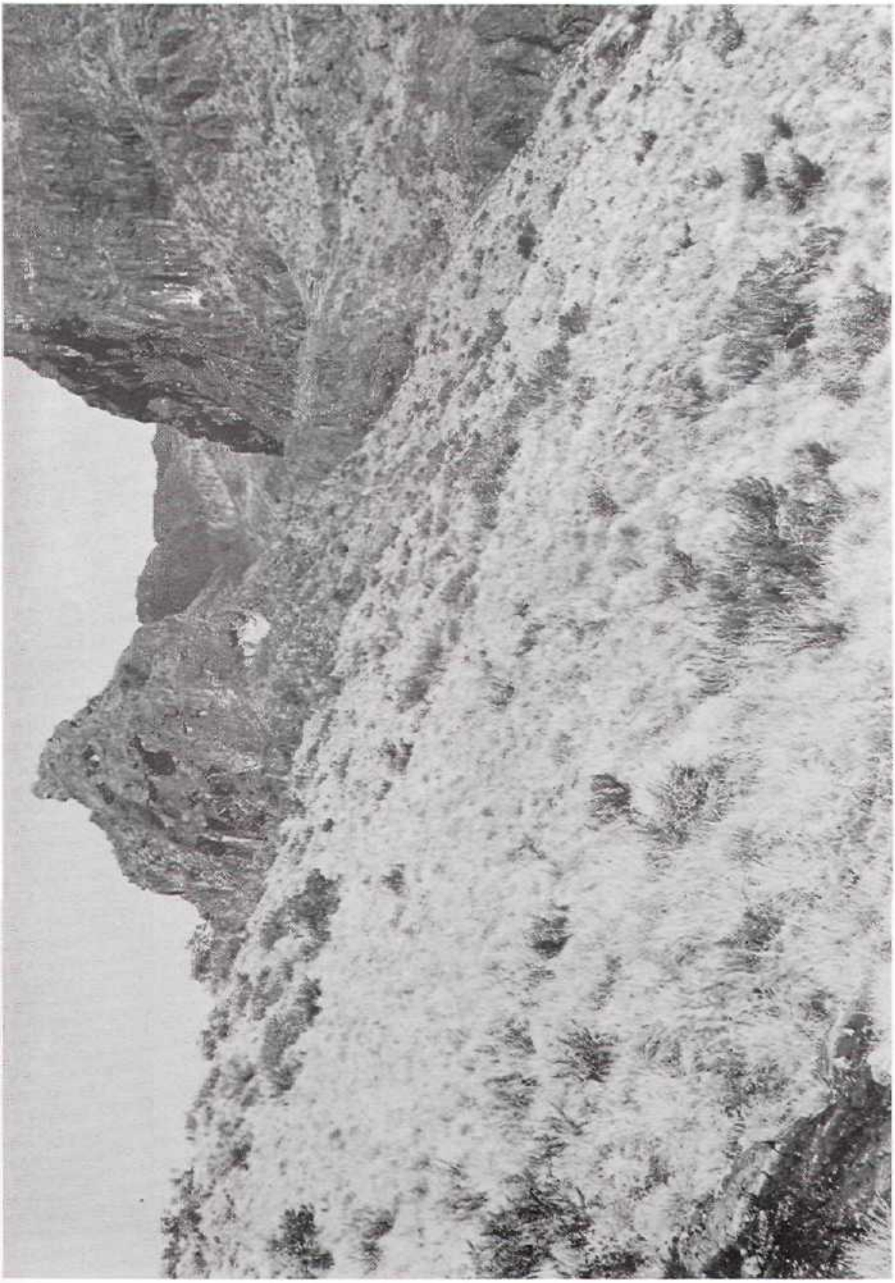


Plate 39. Danthonia vestita-Deyeuxia brassii tussock grassland (D3), with scattered *Coprosma* bushes. Mt Wilhelm, Bogunolto Ridge, 4000 m. March 1972 (Photo G. Hope).

Plate 40. Transition forest (A2) bordered by Gahnia-Plagiogyria tussock grassland (D5) and a zone of Gleichenia vulcanica bog (F3) on the lake edge. Eastern Star Mts, Mt Scorpion, 3320 m. May 1975 (Photo G. Hope).

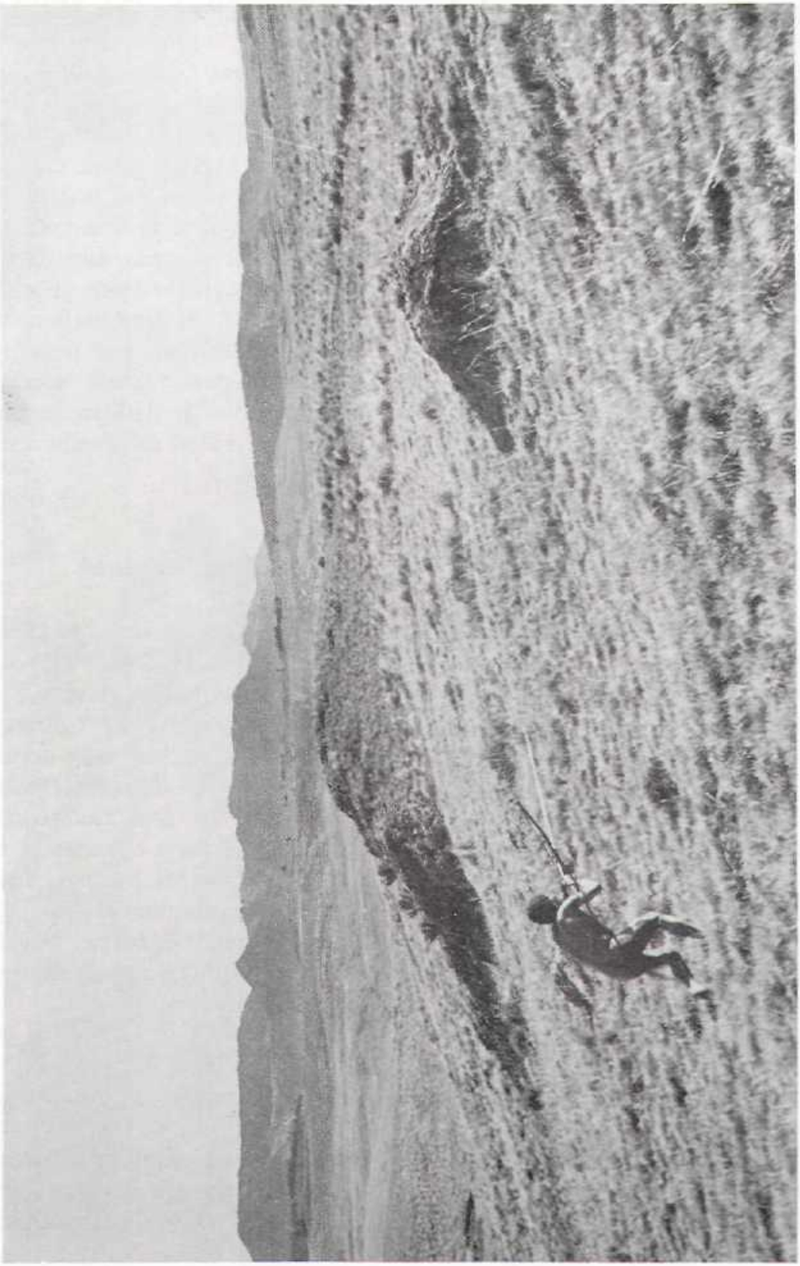


Plate 41. Poa erectifolia-Styphelia short grassland (D6). Wharton Range, lower end of Gerenda Plateau, peaks of Mt Albert Edward in background, 3600 m. June 1933 (Photo L.J. Brass).

present on Mt Carstensz, Mt Wilhelmina (Plate 21), the Star Mts, Mt Giluwe and the Owen Stanley Range and has been noted on Mt Amungwiwa (R.T. Corlett, personal communication). *Gahnia javanica* is absent from Mt Wilhelm although stands of *Plagiogyria* and *Blechnum revolutum* are common along forest edges. *Gahnia javanica* occurs from China to New Guinea and is a pioneer species on Javan volcanic craters at 1600-2700 m (van Steenis, 1972). Although the sedgeland occurs on well drained ground near forest, it is not known if it is a secondary community. It is commonest in relatively undisturbed areas, and shows little sign of shrub or tree development, even though the open ground suggests senescence in the sedge community itself. A combination of very infrequent but severe burning, soil nutrient depletion and possible plant inhibitors may be involved. The two dominant tussock species were observed to be sprouting after a severe fire at 3100 m in the Eastern Star Mts, which burnt into the soil and killed all shrubs and most other herb taxa.

6. Poa erectifolia - Styphelia suaveolens Short Grassland

This community consists of a dense sward of tuft species, including *Poa erectifolia* and *Deyeuxia* sp. Small rounded shrubs of *Styphelia suaveolens* are scattered amongst the grass. This community is very extensive on Mt Albert Edward (Hope, 1975), Mt Suckling and Mt Strong (the "general grassland" of Coode & Stevens, 1972), and may occur elsewhere on the Owen Stanley Range and possibly Mt Bangeta. (Plate 41). Lichens especially *Cladonia* sp., *Hypogymnia* sp. and *Thamnolia vermicularis* colonize the senescent grass tufts and form colonies of a few square metres extent (cf., the "lichen fields" of Mt Strong). The grassland soils are free draining and much less peaty then the alpine humus soils of the central highlands. The community is readily burnt after dry periods, but regenerates quickly; it is possibly a fire disclimax that has been established for several thousand years.

E. Alpine Grasslands and Herblands

This group includes all the "natural" alpine herb communities, but it is arguable if all the high-altitude herblands can be regarded as shrub-free for climatic reasons alone. The alpine heaths occur at similar altitudes, and may be excluded from many habitats by successional or edaphic considerations alone. Some of the mire herblands reach well into the alpine zone (for example *Carpha alpina* fen) and some of the alpine communities could be included with mire vegetation. Alpine vegetation

Plate 42. Alpine tussock grassland (E1). The dense but low tussocks occur on mature soils, but are excluded from active scree and highly erodable soft sandstone such as that exposed in the middle distance. Mt Carstensz, Northwall, 4400 m. Jan. 1972 (Photo G. Hope).

	Releve No:	4 A	4 B
Shrubs	Styphelia suaveolens	1	1
	Trochocarpa dekockii	3	2
	Rhododendron gaultheriifolium	4	2
	Vaccinium cf. amblyandrum	1	2
	Vaccinium sp.		1
	Xanthomyrtus sp.		3
	Coprosma brassii		2
Ferns	Blechnum revolutum		5
	Gleichenia bolanica	+	2
	G. vulcanica		+
	Plagiogyria papuana	6	4
Graminoids	Gahnia javanica	7	4
	Schoenus curvulus		2
	Chionochloa archboldii		1
	Deyeuxia brassii		1
Other herbs	Trachymene sp.		+
	Carex celebica		2
	Gentiana sp.	+	
	Sisyrinchium pulchellum	+	1
	Astelia alpina	1	+
	Glossorhyncha sp.		2
	Pterostylis sp.	+	+
	Thalictrum papuanum		+
	Potentilla foersteriana		1
	Pilea sp.		+
Bryophytes	Several taxa	4	3

Fig 25 Gahnia - Plagiogyria tussock sedgeland composition on Mt Scorpion, 3450 m.

has only been described in detail from Mt Wilhelm and Mt Carstensz, and the identification of fragmentary alpine communities on the lower mountain summits depends on these descriptions.

1. Deschampsia klossii Alpine Tussock Grassland

This association was shown by Wade & McVean to differ from subalpine tussock grassland in the smaller, denser tussocks, absence of any tall shrubs, and presence of alpine species of bryophytes. The grassland occupies well drained deep peaty soils on many peaks, and Hope (1976a) regards it as widespread on mature soils in the alpine zone of Mt Carstensz. (Plate 42). At the alliance level, the alpine fern meadow association of Mt Wilhelm must be included, as it differs principally in the presence of clumps of the fern *Polystichum (Papuapteris) linearis.* This fern is an obligate alpine species, rarely occurring below 3700 m.

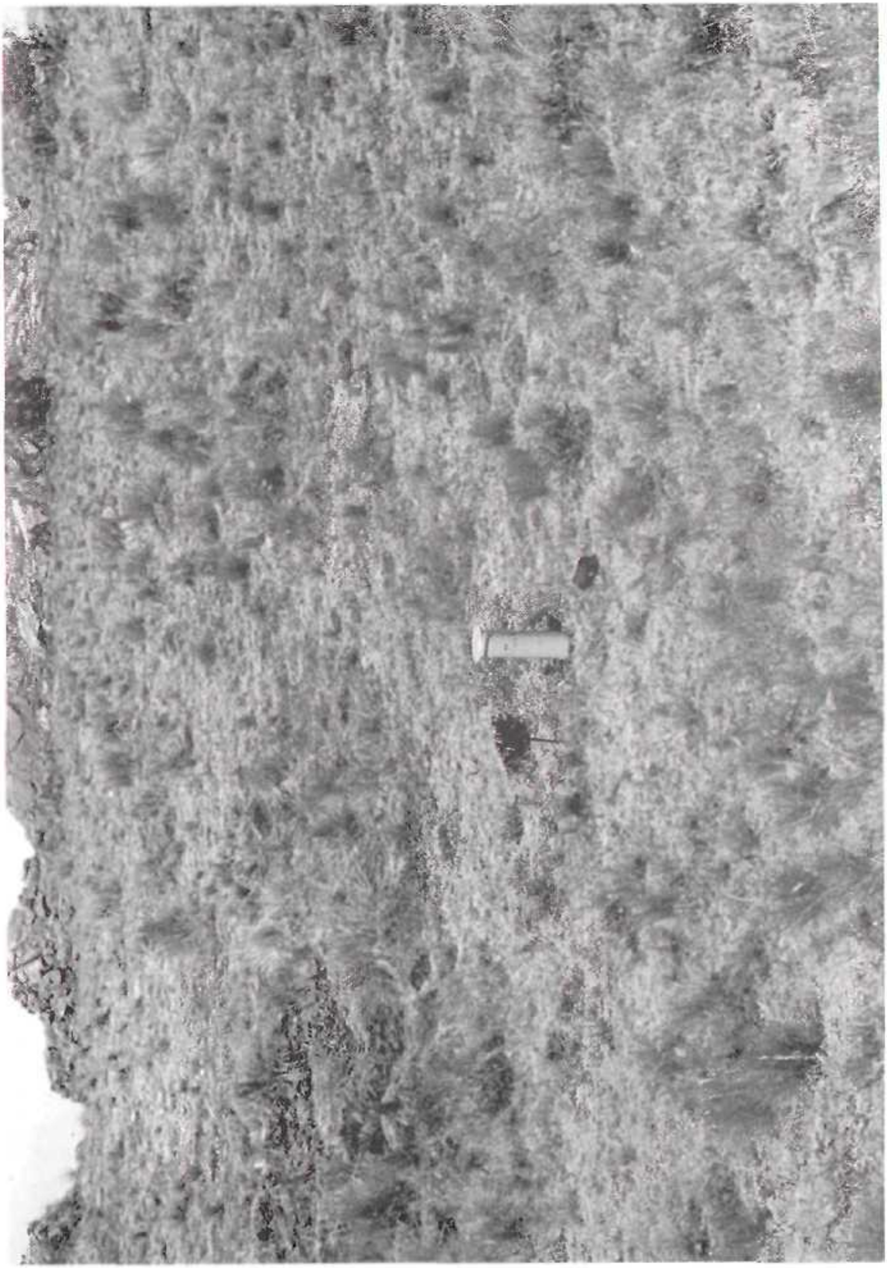


Plate 43. Short alpine grassland (E3). Tufts are mainly ***Danthonia vestita*** with scattered *Deschampsia klossii* tussocks. Cylinder is a pollen trap. Mt Wilhelm, Bogunolto, 4040 m. July 1970 (Photo G. Hope).

Its distribution includes the Owen Stanley Range, Mt Bangeta, Mt Wilhelm and Mt Giluwe, but it does not occur further west. However, *Polystichum cheilanthoides* is a minor species in alpine tussock grassland in the Star and Snow Mts. The fern-rich association merges with the alpine tussock grassland on Mt Wilhelm.

2. Short Alpine Grassland

The community is dominated by small cushion or tuft grasses and sedges forming an open sward. Common species are *Danthonia oreoboloides, Poa callosa, Carpha alpina, Carex* spp., *Astelia alpina,* together with several moss and lichen species. The community (Plate 43) has been defined on Mt Wilhelm, where Wade & McVean note that it extends down into the subalpine zone. Analogous communities have been noted on many other mountains in New Guinea except where free draining limestone soils are present. At many sites, for example Mt Scorpion, there are considerable areas of bare soil exposed, and necrotic lichens are colonizing some of the grass tufts. Some of the cushion plants are over-mature, forming broken rings with dead centers. Wade & McVean (1969) pointed out that the sites support many bog species, and may be badly drained, so that the community may be controlled by edaphic factors. The community occurs on exposed slopes and ridge crests on silty soils of moderate depth, often liable to needle ice formation. Stevens and Veldkamp (1977) consider the possible roles of wind, dessication, grazing and digging, waterlogging and freezing in the maintenance of *Danthonia oreoboloides* vegetation on Mt Suckling. The senescent, obviously slow-growing nature of the vegetation links it with *Gahnia javanica - Plagiogyria papuana* tussock sedgeland, *Poa erectifolia* short grassland and crustose lichen field (see below). All four alliances may well be influenced by former disturbance combined with possible nutrient depletion or growth inhibitors. However, the short alpine grassland seems to contain no higher plant species that do not grow more robustly in other associations, and it could perhaps be classified as a mossland or lichen field community.

3. Ranunculus - Tetramolopium Herbfield

This fragmentary community was observed on the summit ridge of Mt Scorpion, occupying shallow peaty soils. *Ranunculus* sp. and soft-leafed *Tetramolopium* sp. form low tufts to 20 cm, and cushions of *Astelia alpina, Carex* sp., *Danthonia oreoboloides* and *Trachymene* sp. are common. A few prostrate woody plants such as *Rhododendron saxi-*

fragoides. Vaccinium amblyandrum and *Trochocarpa dekockii* creep beneath the herb canopy. This community is not common on Mt Scorpion and has not been reported elsewhere, but may occur in the Oranje Mts.

4. Astelia alpina Alpine Herbfield

Wade & McVean (1969) include this community with the mire herblands but note that it occurs on moderate slopes at 4200 m on Mt Wilhelm. There seem to be few good reasons for classifying this community as a mire, since almost all the alpine communities occupy wet soils, and *Astelia* is not very tolerant of prolonged inundation. The subordinate species include a wide range of small shrubs, grasses and herbs but mire sedges are unimportant or absent. Mosses are important between the cushions. If the *Astelia* community is accepted as a herbfield, it clearly has a relationship with the *Ranunculus - Tetramolopium* herbfield described above, and with the *Rhacomitrium* heath. *Astelia* herbfields are widespread in the New Guinea mountains, but their distribution is largely alpine. The herbfield grades into the *Astelia* subalpine bog and cushion bog communities in the subalpine zone and the herbfield is probably excluded from moderately drained slopes there by grass or shrublands. It seems possible that the cushion habit is an advantage in colonising frost-disturbed ground in the alpine zone, but that this role is subordinate at lower altitudes to that of providing microrelief in boggy situations. In either role, the successful *Astelia* cushion becomes liable to invasion by dwarf shrubs or herbs, and *Astelia* communities probably undergo hummock and hollow reversions. *Astelia alpina* has an attractive (though insipid) red fruit that is readily dispersed by birds and rodents.

5. Alpine Mosslands

Wade & McVean (1969) described two moss dominated communities from the highest and most shaded summit area of Mt Wilhelm. They call the mosslands "dry alpine tundra" and "wet alpine tundra". Plant cover is incomplete and consists of small mats of moss with scattered small tuft or cushion species, including *Poa callosa. Potentilla foersteriana* and *Uncinia* sp. Wet alpine tundra contains abundant cushions of *Ranunculus saruwagedicus* while dry alpine tundra has more abundant grasses and *Parahebe ciliata.* (Plate 44). A closely analogous community to dry alpine tundra was decribed from Mt Carstensz, although there *Epilobium detznerianum* and *Scleranthus singuliflorus* are of consider-

Plate 44. Alpine mossland (wet alpine tundra E5). This site has several times supported tussock grassland. Mt Wilhelm, 4420 m. Aug. 1969 (Photo G. Hope).

able importance. Only a small area of equivalent wet alpine tundra was found on Mt Carstensz, and the association is probably an alpine mire.

The Mt Carstensz "tundra" communities were only found in areas that had been ice free for less than 50 years, and showed a clear successional trend to dwarf shrub heath. For Mt Wilhelm, the distribution of the tundra communities also coincides with the area believed to have been occupied by ice or semi-permanent firn about 50-100 years ago (Hope, 1976b). The alpine mossland alliance may thus be successional rather than a clear climax response to contemporary very cool wet conditions, and the term "tundra" should be used with caution. Hope (1976a) suggests that alpine tussock grassland and dwarf shrub heath alliances would in time develop on all ice-free alpine sites on Mt Carstensz, while Hope (1976b) has shown that alpine tussock grassland took over from tundra on Mt Wilhelm on several occasions in the Holocene. The mossland of wet habitats can also be regarded as an alpine mire community.

F. Mire Herblands

As noted above, the everwet conditions in the New Guinea mountains mean that almost all vegetation can tolerate periods of water logged soils and high humidity, and hence there is no clear distinction between dry land and wet land communities. In the subalpine zone, communities are usually classified as mires if water is so frequently at or near the surface that robust shrubs are excluded. This definition is unsatisfactory at lower altitudes, where swamp forests exist, and is of no use in discriminating specifically alpine mire communities. In practice only those subalpine mires which extend relatively unchanged into the alpine zone are differentiated from the other alpine herblands.

The high rainfall and abundant glacigenic basins and tarns result in extensive mire communities in the subalpine zone, and these are especially widespread where relict plateau surfaces (e.g. Owen Stanley Range, Mt Carstensz, or Sarawaket Mts) or large shield volcanoes (Mt Giluwe) form the high areas. The variety of mire communities is quite high and a relatively rich flora is involved. Structurally the mire vegetation can be divided into bogs, fens or aquatic communities. Bogs have a complex structure with considerable microrelief and little or no free surface water, fens are usually more open herblands with some free, often moving, water and aquatic communities have a completely free water surface. The direction and rates of hydroseres are still poorly understood in New Guinea but there is an obvious broad progression from aquatic through fen to bog vegetation with the accumulation of limnic and telmatic acid peats. The discontinuous nature of many mire habitats makes it very difficult to assess the potential altitudinal range of mire communities. The mire communities are listed below in order of increasing moisture requirements and decreasing complexity and canopy cover. The list is certainly incomplete as the mires are not well represented on Mt Wilhelm, where the most intensive studies have been made.

1. Vaccinium - Xanthomyrtus Bog Heath

On Mt Carstensz, Hope (1976a) describes a *Poa lamii - Vaccinium amblyandrum* bog in which a prostrate shrub mat of *Vaccinium - Xanthomyrtus klossii* is intergrown by cushion plants and tuft grasses. Scattered erect shrubs of *Rhododendron* sp., *Trochocarpa dekockii* and *Styphelia suaveolens* are present. A similar structured bog with *Vaccinium* and *Xanthomyrtus* (but not *Poa lamii*) occurs on Mt Scorpion. Mat-forming shrubs have not been described in bogs in eastern New Guinea, but one of the cushion forming bog shrubs, *Rhododendron saxifragoides*, extends as far east as Mt Giluwe. The altitudinal range of the *Vaccinium - Xanthomyrtus* bog alliance is quite wide as it occurs on paths as low as 3000 m and up to 4000 m on Mt Carstensz. The habitat does not seem to be sufficiently wet to exclude tussock grassland, and nutritional factors may play a role. The community is bordered by *Deschampsia klossii* tussock grassland on slopes, and grades to hard cushion bog on more inundated sites.

This is the only subalpine mire community in which shrubs have a significant structural role, and this is an interesting contrast to widespread heath or shrubland bog formations in other parts of the world. This is all the more surprising since some of the characteristic families of woody bog taxa, e.g., Epacridaceae, Ericaceae and Myrtaceae, are present.

2. Astelia alpina Subalpine Bog

Astelia alpina can occupy a wide range of habitats but it is dominant in a subalpine bog as robust cushions 30-60 cm in diameter and 10-30 cm thick. It has been described on Mt Wilhelm from restricted stands, but is much more extensive on Mt Giluwe, Mt Scorpion and Mt Albert Edward on poorly drained level areas from 2950-3850 m. A wide range of small grasses and herbs grow between the cushions, and stunted shrubs may be present. The habitat receives abundant surface water but seems to be fairly free draining, so that the community is common at

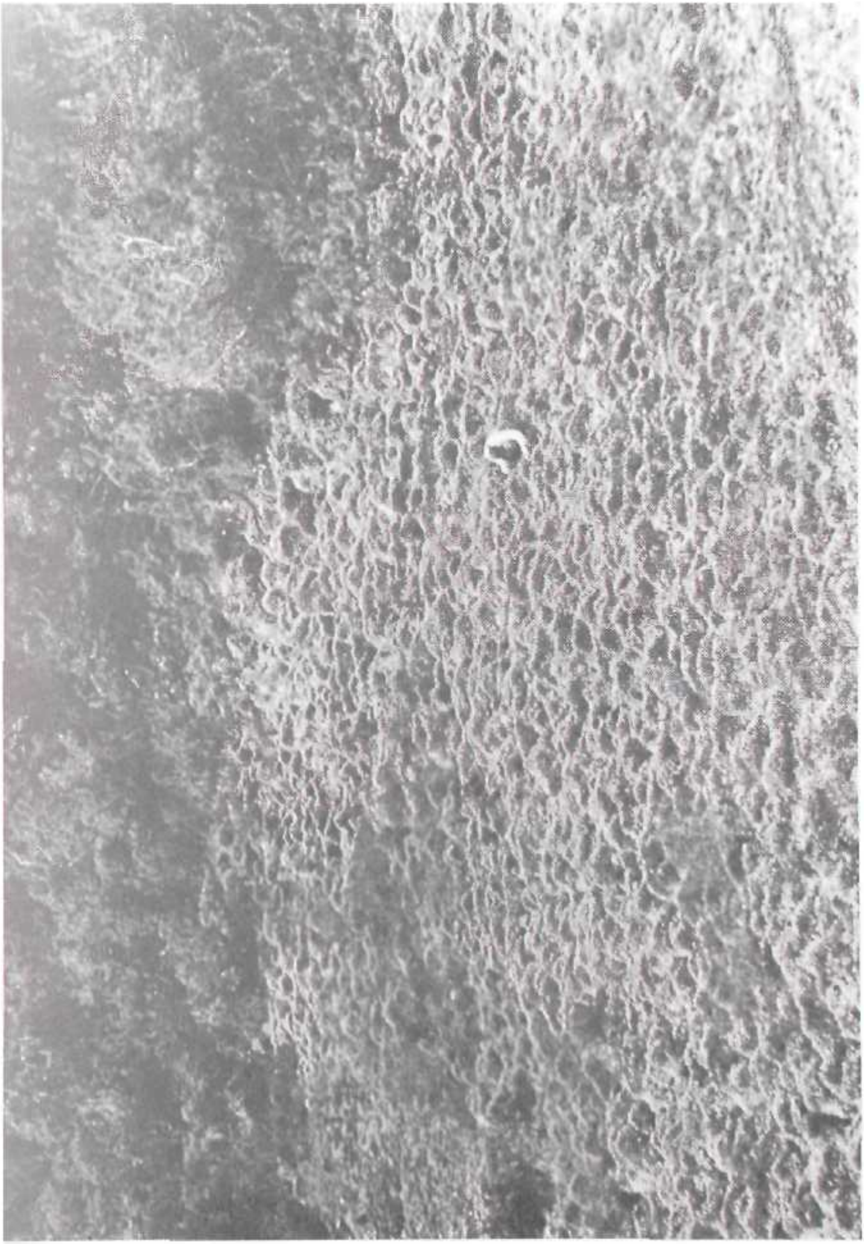


Plate 45. Astelia alpina subalpine bog (F2). This blanket bog is bordered by subalpine forest on steep, better drained slopes, and by hard cushion bog in flat areas. Eastern Star Mts, Mt Scorpion, 3480 m. May 1975 (Photo G. Hope).

the base of slopes and along channel margins. The subalpine bog merges with several mire communities including short grass bog and hard cushion bog. On very wet mountains such as Mt Scorpion the community forms a blanket bog. (Plate 45).

3. Gleichenia vulcanica Bog

Fronds of the rhizomatous fern, *Gleichenia vulcanica* can form a dense sward in which few other species are present. Although the community is described from Mt Wilhelm it is far more common on Mt Giluwe and Mt Scorpion where it is the most extensive subalpine community. Like the *Astelia* bog, it does not tolerate inundation, and forms a blanket bog on gentle slopes. The fern readily colonizes wet seepage areas on bare rock and consequently can be found on very steep slopes as well, in an association which Wade and McVean distinguish from the mire association. Many of the fronds in a mature stand are dead or dying, giving a somber grey-black appearance, and making the community liable to burning. The community regenerates quickly after a light fire by shooting from the rhizomes and this ability may explain its great extent on Mt Giluwe compared to grasslands. Severe fires following drought can burn the peat soil and kill the fern completely and since the fronds seem to be sterile, such sites are colonized by grassland which will only slowly be invaded by fern. (Plate 46). The importance of the *Gleichenia* bog on Mt Scorpion (which is almost devoid of grassland) reflects very wet conditions and widespread rock exposures which are due to a very low weathering rate of the diorite, rather than disturbance. The bog alliance is rare on Mt Albert Edward and the limestone mountains, but is apparently widespread on Mt Suckling (Stevens & Veldkamp, 1977).

4. Short Grass Bog

This widespread bog community has been reported from Mt Wilhelm, Mt Carstensz, and Mt Albert Edward, and the alliance occurs in some form throughout New Guinea, although several individual associations may exist. (Plate 47). The bog is characterized by a sparse growth of small tussocks and tufts of grasses and an abundant herb growth, particularly *Ranunculus, Plantago, Potentilla* and *Gentiana* species. Stunted shrubs of *Styphelia, Drapetes* and *Trochocarpa* are usually present, and cushion species are common, e.g. *Danthonia oreoboloides, Oreobolus pumilio, Centrolepis philippinensis, Eriocaulon* spp. and bryophytes. Tuft sedges are common in the wettest areas between the

Plate 46. Gleichenia vulcanica bog (F3), very badly burnt in August 1972. The fire burnt hollows into the peat and largely destroyed the rhizomes. Isolated tufts of grass are colonizing the hollows and some ferns are regenerating in the largest hummock. Mt Giluwe, 3620 m. Sept. 1973 (Photo G. Hope).

Plate 47. Stream vegetation (F10) with 2 communities. In the grasslands, Deschampsia klossii tussock grassland (D1), Poa grassland (D2), and short grass bog (F4). Stream edged by tall *Carex fascicularis* and beds of *Machaerina glomerata*, in streams *Scirpus crassiusculus*. Small shrubs on banks are *Tasmania piperita*, *Styphelia* cf. *vandewateri*, *Rhododendron* and *Rapanea* spp. Tree ferns are *Cyathea tomentosissima* Lake Habbema, 3225 m. Aug. 1938 (Photo L.J. Brass).

cushions. The habitat is wetter than that of the previous bog types and periodic inundation occurs. Hard cushion bog and tussock grassland merge with this community on the wetter and drier margins respectively.

Hard Cushion Bog

In very flat areas subject to inundation cushion forming plants become dominant and coalesce to form a firm, undulating surface with only scattered tufts of sedges and grass. Hope (1976a) lists the taxa involved on Mt Carstensz; in addition to those noted above in short grass bog are *Plantago polita, Oreobolus ambiguus, Carpha alpina* and *Astelia alpina* as widespread elements, while species such as *Potentilla foersteriana* var. *brassii, Ranunculus* sp., *Trachymene pulvilliforma* and *Isoetes*

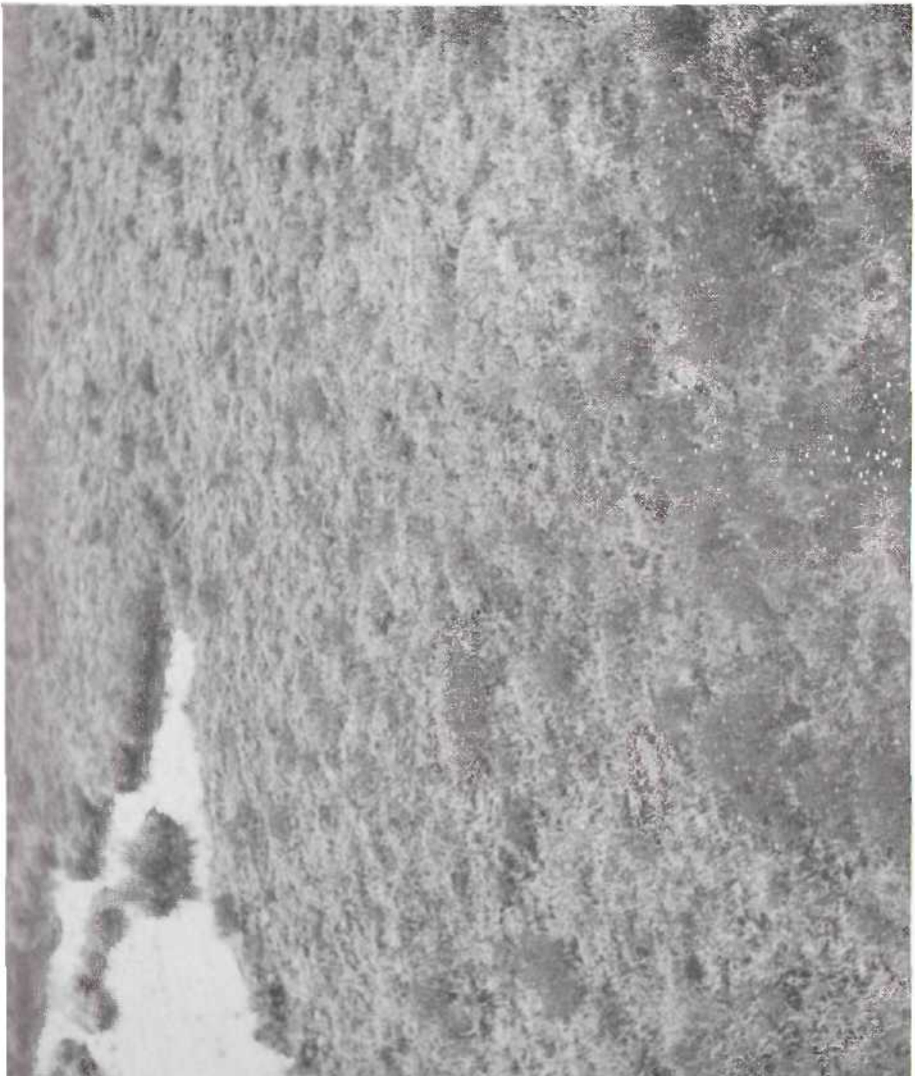


Plate 48. Hard cushion bog (F5) with Scirpus fen (F8). The bog is composed of a dense mat of *Oreobolus ambiguus, O. pumilio, Centrolepis phillippinensis, Eriocaulon* sp., *Plantago polita*, with small cushions of *Astelia alpina* and tufts of *Deschampsia klossii*. The small shrubs in foreground are *Tetramolopium alinae*. Saddle between Mt Bangeta and Lake Gwam, 3900 m. Nov. 1963.

Plate 49. Carpha alpina fen (F7). Mt Carstensz, 4250 m. Jan. 1972 (Photo G. Hope).

hopeii are characteristic of the Nassau Ra. Various species of *Gentiana, Plantago* and *Eriocaulon* may contribute to the bog in other areas. Hard cushion bog does not form large stands, but is a pronounced formation above 3500 m on Mt Albert Edward, Mt Bangeta, Finisterre Mts (Plate 48), Mt Giluwe, Mt Scorpion and Mt Carstensz although absent from Mt Wilhelm probably due to the steep topography there.

6. Brachypodium - Carex Closed Sedgeland

This fen association, found on Mt Wilhelm below 3450 m, is typical of a group of graminoid-dominated fens which has the structural form of a closed grassland or sedgeland 20-40 cm deep. These fens all occur at relatively low altitudes and may be related to montane rather than subalpine mire vegetation. *Carex capillacea* and several grasses are co-dominant on Mt Wilhelm and there is a sparse herbaceous understorey on the soft peat soils. A similarly structured fen (dominated by an unidentified sedge) occurs between 3300 and 3520 m on Mt Scorpion and analogous fens are known from Mt Albert Edward. Because of a superficial similarity to *Deschampsia klossii* grassland, which occupies adjacent, slightly better drained slopes, fens in this group have probably been ignored on many mountain areas, and the existence of one or more alliances is only tentatively proposed.

7. Carpha alpina Fen

Carpha alpina fen consists of open tufts and cushions of *Carpha* with tufts of stunted grasses and some other sedges, and abundant bryophytes or bare peats. (Plate 49). The community is common on areas subject to inundation over a wide altitudinal range on Mt Wilhelm and is also very common on other New Guinea mountains as high as 4300 m. Soils may be stony or organic, and the fen plays a pioneer role in colonizing lake and pond edges that are subject to flooding.

8. Open Wet Sedgelands

Wade & McVean (1969) distinguish three simple sedge fens, dominated respectively by *Carex echinata, C. gaudichaudiana* and *Scirpus crassiusculus* on Mt Wilhelm. All three associations consist of scattered to close packed tufts of sedge occupying peaty areas usually flooded by 5-20 cm of water, with relatively few subordinate species. As with the taller closed sedgeland fen, these associations can be regarded as representa-

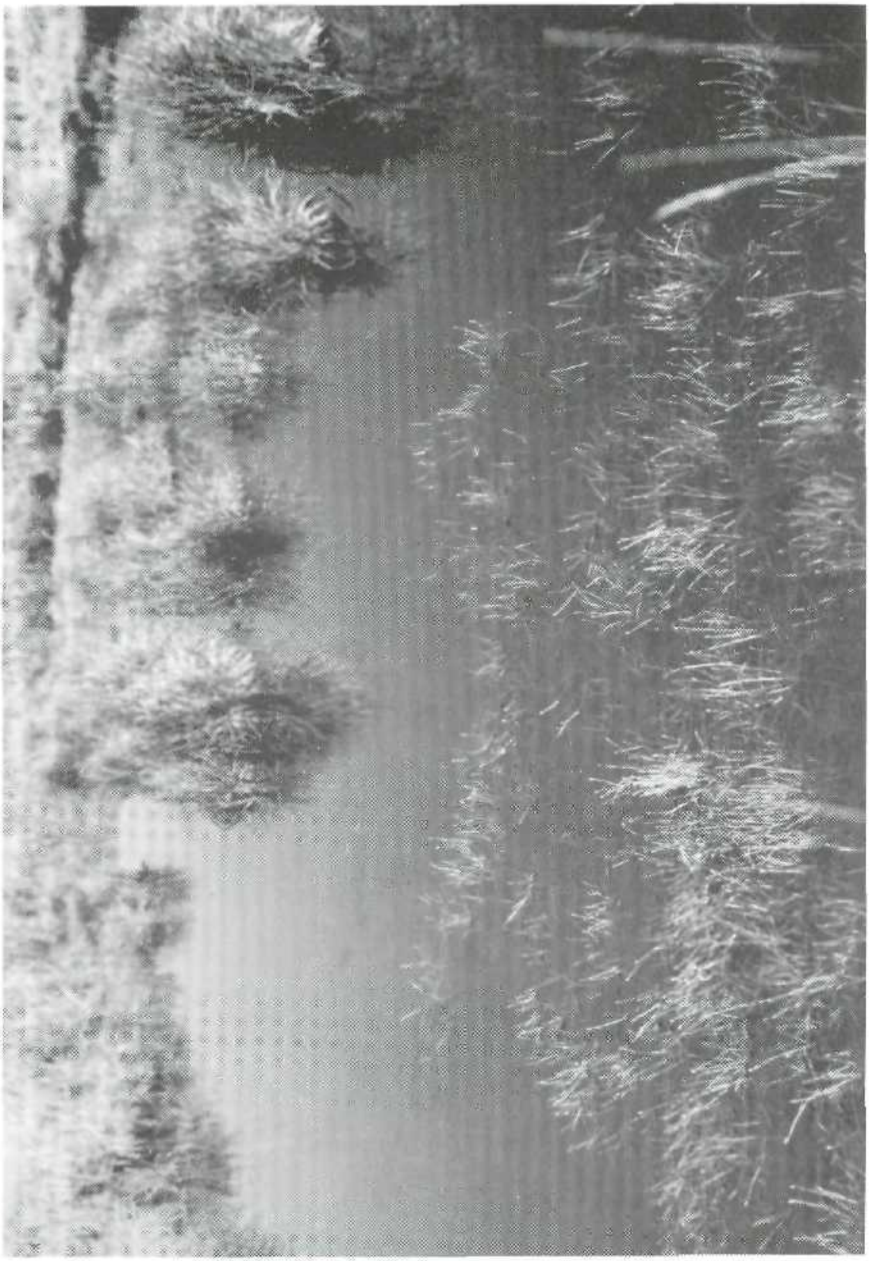


Plate 50. Open Scirpus fen (F8) with Isoetes stevensii tarn community (F9). NW slope of Mt Giluwe, 3600 m. June 1976.

tive of a group of fens which can invade shallow water bodies in the initial stages of hydroseres. (Plate 50). *Carex gaudichaudiana* fen at least appears to be common on Mt Carstensz and Mt Scorpion as well as Mt Edward, and a more detailed census would probably demonstrate several new associations, occupying particular niches and altitudes.

9. Isoetes Tarn Community

A distinctive aquatic community occupies tarn and lake floors in water depths averaging 50-100 cm. Large rosettes of *Isoetes habbemense* (Mt Wilhelmina, Mt Scorpion), *I. stevensii* (Mt Giluwe, Plate 50) and *I. neoguineensis* (Owen Stanley Range) up to 30 cm in diameter form an open, usually rather regular, cover in the soft organic oozes. The community has not been found on either Mt Carstensz or Mt Wilhelm (Croft, in press) although it clearly resembles mountain pond vegetation in Sumatra. The spores possibly arrive in new tarns with water birds.

10. Other Aquatic Vegetation

Several aquatic vegetation types are known, although few have been described. Wade and McVean (1969) mention *Callitriche palustris* and *Scirpus crassiusculus* aquatic communities in shallow water in tarns on Mt Wilhelm. Paijmans and Löffler (1972) remark on a *Carex curta* stream community on Mt Albert Edward and Hope (unpublished) has noted a *Gonocarpus micrantha* community in shallow water, and *Callitriche palustris* in deeper parts of a tarn at 3650 m on the same mountain. An unidentified sedge occupies some stream channels on Mt Scorpion. Brass (1941 and Plate 47) notes *Scirpus crassiusculus* in the water, and *Carex fascicularis* as riparian stands up to 80 cm tall, in the outlet stream and on the shores of Lake Habbema at 3250 m.

G. Thallophyte (Lichen and Algae) Dominated Communities

1. Stereocaulon thallose Lichen Field

Hope (1976a) describes areas of loose rocky gravel at 3650 m on Mt Carstensz occupied by a carpet of brittle white *Stereocaulon pseudomassartianum* with no other species except a few scattered bryophytes. The same species is important, though not extensive, as a colonist on old landslip scars on Mt Wilhelm and probably other mountains.

Plate 51. Short grass bog (F4) and treeline shrublands (A4). The stripes on the rock face are due to lichen growth (G3). Mt Carstensz, Zebra Flat, 3780 m. Jan. 1972 (Photo G. Hope).

2. Necrotic Lichen Fields

Coode & Stevens (1971) describe two communities at 3600 m on Mt Strong which are dominated by lichens, one of the forest-grassland boundary and the other amongst *Poa - Styphelia* short grassland. The lichens seem to be invading and spreading over bare ground or existing vegetation. Similar patches of lichens are found on Mt Suckling and Mt Albert Edward where they have been identified as *Cladonia* sp. and *Thamnolia vermicularis* (Hope, 1975). Necrotic lichens (cf. *Bacidia* sp.) are common on Mt Carstensz on well drained grassland areas. The nature of these colonies is not understood.

3. Other Lichen Communities

Although virtually no work has been carried out on them, lichen communities are of great importance as the initial colonizers of rock surfaces. (Plate 51). The moist climate results in a fairly complete lichen cover, even on cliffs, within a few years of exposure. This is mainly due to grey, white and black crustose lichens, but several small thallose lichens are also present. The taxonomy of the species presents a formidable problem.

4. Algal Communities

Similarly, the extent and nature of algal communities is simply not known. Algae are abundant in all tarns (e.g., Thomasson, 1967; Peterson, 1976), and are also important primary colonizers of moraines and scree. Cyanophyta quickly form a black layer on fresh soil or rock surfaces. On Mt Carstensz algae of uncertain affinities occur as brown grape-like bodies on fresh scree near the glaciers.

5. Cryovegetation

Kol and Peterson (1976) have described five floristic associations of snow or ice algae from the Meren Glacier of Mt Carstensz. The ice community colonized by *Nostoc fuscescens* can be quite dense and (Plate 52) significantly reduces the albedo. Most of the cryoalgae have Antarctic affinities.

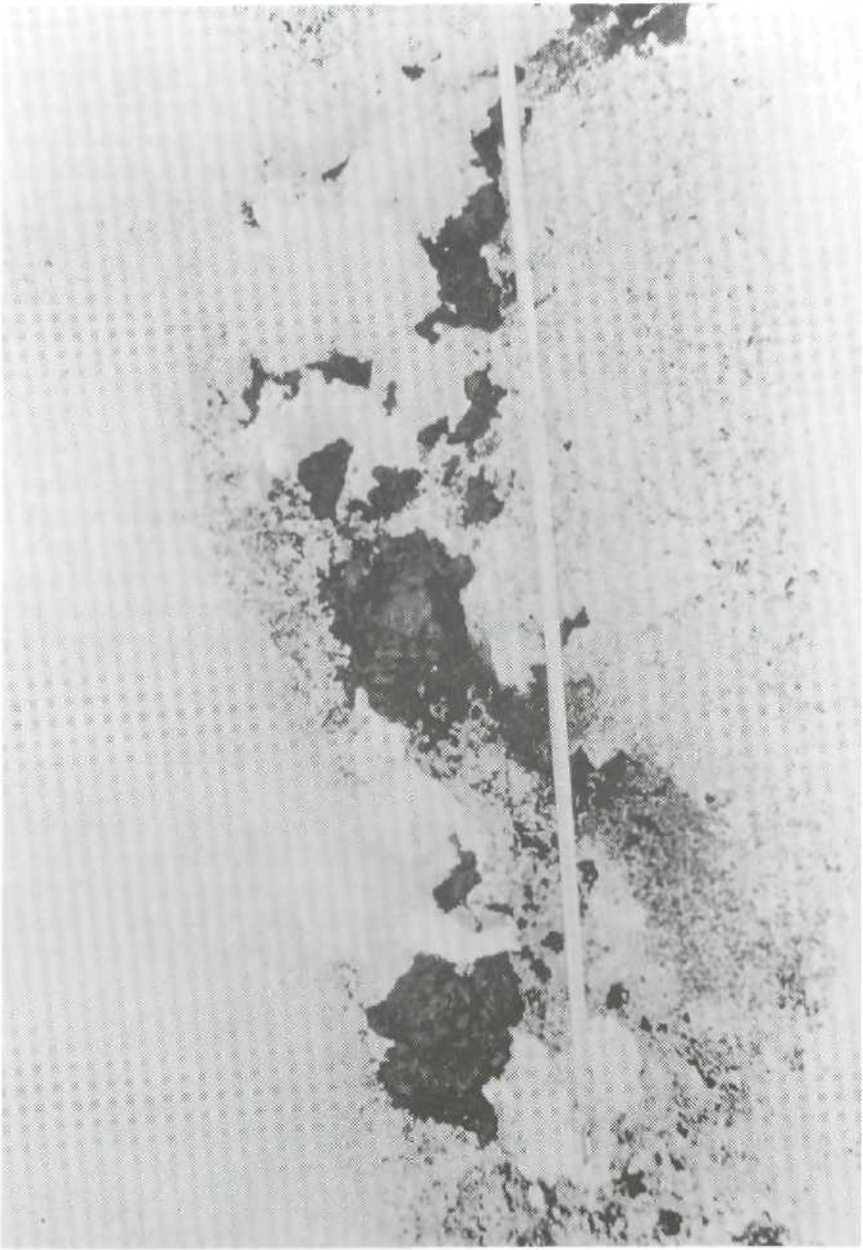


Plate 52. Dense cryoalgal colonies (G5) on Meren Glacier, Mt Carstensz, 4520 m. The major species is *Nostoc fuscescens*, the largest colonies are up to 10 cm in diameter. Jan. 1973 (Photo J. Peterson).

3. Discussion

This census of the vegetation units of the New Guinea mountains emphasizes the overall similarities at the alliance level between mountains. Mount Wilhelm supports a wide range of the alliances recorded, including almost all the major types. Wade & McVean (1969) discuss the representation of structural types compared to other tropical mountains. They make the following points which are supported by the additional data now available.

1. There is no equivalent in New Guinea to the alpine pachycaul vegetation of the Andes, Africa and Hawaii, although the subalpine *Cyathea* shrublands are matched in the subalpine areas on other tropical mountains. This may reflect the relatively slight diurnal temperature range of the New Guinea mountains rather than the absence of potential taxa or recent appearance of the habitat.

2. Tussock grassland associations are characteristic of oceanic climates in the southern hemisphere. (Hnatiuk 1975).

3. All the mire communities have world-wide affinities. Wade & McVean (1969) do not mention that hard cushion bog is widespread in the Andes and African tropical mountains, where its success is probably due to its ability to combat daily needle ice formation and waterlogging. Hard cushion bog is best represented in southern exposed subantarctic areas where resistance to wind may be a major control.

4. The alpine heath and mossland communities have floristic and structural affinities with mountain and boreal vegetation elsewhere, and are as rich floristically in many cases. There is, however, a wide diversity in alpine vegetation associations across New Guinea, apparently reflecting seral differences consequent upon recent contractions of ice cover. Many of the alpine communities must be relict when compared to a much wider extent during major glaciations.

5. Tall shrub heath, hard cushion bog, and herbfields are considered to be absent from Mt Wilhelm and Wade & McVean speculate that they might be excluded by low soil nutrition or moist climate. Examples of these are not widespread anywhere in New Guinea, but do occur on the Owen Stanley Ranges, which are slightly drier and more seasonal than Mt Wilhelm.

The survey made in this chapter shows that other alliances missing from Mt Wilhelm include treeline scrub, *Gahnia javanica* tussock sedgeland, *Poa erectifolia* short grassland and *Isoetes* aquatic fernland. On the other hand it is now clear that Mt Wilhelm has the best development of *Danthonia-Deyeuxia* tussock grassland and *Polystichum* fernland (included in the alpine tussock grassland alliance). All the mountain blocks surveyed have similar distinctive features in the presence and extent of the individual communities.

Despite these differences, the most important vegetation alliances occur on nearly all blocks and are dominated by widespread taxa. These are the subalpine rainforest, *Cyathea* shrublands, *Deschampsia* and *Poa* tussock grasslands, *Astelia* subalpine bog, short grass bog, various sedge fens, and alpine tussock grassland, short alpine grassland and dwarf shrub heath. Mt Albert Edward provides an exception with its major specialized grassland, and the role of *Gleichenia vulcanica* blanket bog also varies from dominant on Mt Giluwe and the Star Mts to fragmentary on the east and western ends of the cordillera.

The underlying causes of the distribution of the vegetation types are a combination of historical and environmental factors. The regionally restricted taxa influence the distribution of some communities, which mirror floristic regions. Examples are the treeline scrub, dominated by *Coprosma brassii*, or *Poa erectifolia* grassland. Although the vegetation on all mountains is strongly altitudinally zoned, the geology, acting principally through topography and drainage, and differences in climates contribute greatly to regional patterns. The Piundaunde Valley of Mt Wilhelm is relatively steep and dry, and Mt Wilhelm consequently lacks several mire associations, as do some of the limestone peaks. Widespread blanket bogs of *Gleichenia* or *Astelia* are conversely found on very wet mountains with impervious crystalline rocks. Finally the history and extent of human disturbance and climatic change varies considerably between mountain areas and many anthropogenic communities, such as some of the shrub-rich grasslands or tree fern shrublands, reflect this. The historical factors are considered further in Chapter 9.

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Selected Rererences

Archbold, R. & A.L. Rand, Summary of the 1933-34 Papua Expeditions - *Bull. Am. Mus. Nat. Hist.* 68 (1935) 527-579.

Brass, L.J., The 1938-39 expedition to the Snow Mountains, Netherlands New Guinea - *J. Arnold Arb.* 22 (1941) 271-342.

Brass, L.J., Summary of the Sixth Archbold Expediton to New Guinea (1959) - *Bull. Am. Mus. Nat. Hist.* 127 (1964) 145-216.

Coode, M.J.E. & P.F. Stevens, Notes on the flora of two Papuan mountains - *Papua New Guinea Sc. Soc. Proc.* 23 (1971) 18-25.

Costin, A.B., R.D. Hoogland & C. Lendon, Vegetation changes in the Lake Mamsin area, Saruwaged Plateau, New Guinea - *American Museum Novitates* 2628 (1977) 1-9.

Croft, J.R., A taxonomic revision of Isoetes L. (Isoetaceae) in Papuasia - *Blumea* (*in press*).

Gillison, A.N., Structure and floristics of a montane grassland/forest transition, Doma Peaks region - *Blumea* 18 (1970) 71-86.

Grubb, P.J., Control of forest growth and distribution on wet tropical mountains with special reference to mineral nutrition - *Ann. Rev. Ecol. System.* 8 (1977) 83-107.

Grubb, P.J. & P.J Stevens, The forests of the Fatima Basin and Mt Kerigomna and a review of montane and subalpine forests elsewhere in P.N.G. - *ANU BG/5* (1979).

Hnatiuk, R.J., Aspects of the growth and climate of tussock grassland in montane New Guinea and Sub-Antarctic islands - Ph.D. Thesis, ANU, Canberra (1975).

Hope, G.S., Some notes on the non-forest vegetation and its environment, northern flank of Mt Albert Edward, Central District, Papua New Guinea - Unpublished report, ANU, Canberra. (1975).

Hope, G.S., Vegetation, pp. 113-172 in the Equatorial Glaciers of New Guinea, eds. G.S. Hope, J.A. Peterson, I. Allison & U. Radok (1976).

Hope, G.S., The vegetational history of Mt Wilhelm, Papua New Guinea - *J. Ecol.* 64 (1976) 627-664.

Johns, R.J., The Vegetation of Papua New Guinea. Forestry College, Bulolo (1977).

Kalkman, C., Description of vegetation types in the Star Mountains region, West New Guinea - *Nova Guinea, Botany* No 15 (1963) 247-261.

Kalkman, C. & W. Vink, Botanical exploration in the Doma Peaks region, New Guinea - *Blumea* 18 (1970) 87-135.

Kol, E. & J.A. Peterson, Cryobiology, pp. 81-91 in The Equatorial Glaciers of New Guinea, eds. G. Hope, J.A. Peterson, I. Allison & U. Radok. (1976).

Lam, H.J., Fragmenta Papuana - *Sargentia* 5 (1945) 1-196.

McVean, D.N. & J.S. Womersley, Conservation in Papua New Guinea, pp. 591-605, in Conservation of major plant communities in Australia and Papua New Guinea, eds. R.L. Specht, E.M. Roe, & V.M. Boughton, in *Austr. J. Bot. Suppl.* 7 (1974).

Paijmans, K., Vegetation, pp. 23-105 in New Guinea Vegetation, ed. K. Paijmans. (1976).

Paijmans, K. & E. Loffler, High altitude forests and grasslands of Mt Albert Edward, New Guinea - *J. Trop. Geogr.* 34 (1972) 58-64.

Peterson, J.A., The lakes, pp. 93-112 in The Equatorial Glaciers of New Guinea, eds. G.S. Hope, J.A. Peterson, I. Allison, & U. Radok. (1976).

Robbins, R.G., The montane vegetation of New Guinea - *Tuatara* 8 (1961) 121-134.

Smith, J.M.B., Mountain grasslands of New Guinea - *J. Biogeogr.* 2 (1975) 27-44.

Smith, J.M.B., Vegetation and microclimate of east-and-west-facing slopes in the grasslands of Mt Wilhelm, Papua New Guinea - *J. Ecol.* 65 (1977) 39-53.

Specht, R.L., Vegetation, pp. 44-67 in The Australian Environment, ed. 4, ed. G.W. Leeper (1970).

Specht, R.L., The vegetation of South Australia, ed. 2 (1972).

Stevens, P.F. & J.F. Veldkamp, The Mount Suckling expedition, 1972, with notes on the flora and vegetation of the subalpine region. Unpublished report, National Herbarium, Lae (1977).

Thomasson, K., Phytoplankton from some lakes on Mt Wilhelm, East New Guinea - *Blumea* 15 (1967) 285-296.

van Royen, P., Some observations on the alpine vegetation of Mount Biota (Papua) - *Acta Bot. Neerl.* 15 (1967) 530-534.

van Steenis, C.G.G.J., Mountain Flora of Java (1972).

Veldkamp, J.F., A botanical trip to the Burgers Mt and Mt Kegum, Papua New Guinea. Unpublished Report, Rijksherbarium, Leiden (1978).

Wade, L.K. & D.N. McVean, Mt Wilhelm Studies I. The Alpine and Subalpine Vegetation - *ANU BG/1* (1969).

Walker, D., A reconnaisance of the non-arboreal vegetation of the Pindaunde catchment, Mt Wilhelm, New Guinea - *J. Ecol.* 56 (1968) 445-466.

Walker, D., Highlands vegetation - *Austr. Nat. Hist.* 17 (1973) 410-419.

Walker, D. & J.C. Guppy, Generic Plant Assemblages in the highland forests of Papua New Guinea - *Austr. J. Ecol.* 1 (1976) 203-212.

Wardle, P., An explanation for alpine timberline - *NZ J. Bot.* 9 (1971) 371-402.

9. HISTORICAL INFLUENCES ON THE NEW GUINEA FLORA

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1. Introduction

The tropical high mountains have been an important source of data for demonstrating that the equatorial regions have undergone past environmental changes equivalent in magnitude to those known at higher latitudes. The evidence for former widespread glaciation was noted at an early stage in Africa, South America and New Guinea, and this evidence provided a useful counter to the popular belief that the tropical regions have retained a stable, unchanging environment for a lengthy period. With better chronologies and the use of pollen and sediment analyses to add detail to the glacial change record, it is now realised that the tropics, and New Guinea in particular, have been anything but stable if examined on nearly any timescale.

This has great relevance to the study of the flora and its ecology on the New Guinea mountains; in addition to the usual evolutionary pressures calling for progressive adaptation to the niche in which a taxon finds itself, there are others which favour adaptability to change and the exploitation of new niches. Thus it is no accident that the New Guinea flora is still evolving rapidly and tends to fragmented distributions. A knowledge of the palaeoenvironments can help to explain present species distributions and may throw light on evolutionary trends and relationships.

The present knowledge of the New Guinea mountain palaeoenvironments is unfortunately scanty, particularly for the period prior to the last major ice retreat about 15,000 years ago. Geological speculation concerning plate tectonics and mountain building is still poorly dated but does provide a background for the establishment of the New Guinean mountain environment during the Tertiary. For the Quaternary there is only scattered evidence for earlier glacial phases than the last, but conditions of the last major refrigeration are now tentatively documented by pollen analyses from the highlands of Papua New Guinea extending back to perhaps 50,000 BP. It is within the high mountain areas themselves that the best pollen analytical framework is available, with pollen diagrams prepared from Mt Carstensz, Mt Scorpion, Mt Giluwe, Mt Wilhelm and Mt Albert Edward, but these only record the period since deglaciation.

Pollen analysis can usually only discriminate taxa at the generic or family level, and only those taxa which produce and disperse reasonable amounts of pollen are 'visible'. Work done by the author (Hope, 1973, 1976) has established the representation of the characteristic pollen types and their probable sources in the subalpine and alpine zones of New Guinea. Pollen trapping and surface sample analyses indicate that pollen is readily carried upslope and deposited in rain showers, but that pollen from alpine or subalpine elements are not found lower than the zones in which they are present. Vegetation communities have characteristic pollen spectra, so that some picture of vegetation around a bog or mire can be established. Hope (1976) lists the common pollen types found in the mountains; these represent only a small proportion of the taxa present, and in the absence of macrofossil data, no direct evidence is available about the bulk of the species.

This chapter considers the palaeoenvironments for plant growth, first for times of glacial maximum, then for times of general cool conditions, because it is now accepted that such conditions represent the 'average' for most of the Pleistocene epoch. Finally the processes involved in the establishment of the modern vegetation patterns are discussed. In the Holocene, the mountain flora has had to adjust not only to radically new climates but also to an increasing disturbance from man.

2. Environments of the Last Glaciation

Snowline and Temperatures

The maximum extent of ice in the last glaciation has been mapped on nearly all New Guinea mountains and is discussed by Loffler (chapter 3). The total area is estimated by J. and G. Hope (1976) to have been about 2000 km^2 (Fig. 26) based on accurate mapping in Papua New Guinea by Loffler (1972) and on map area above 3600 m in West New Guinea. Deglaciation dates from several areas show that the large, sharp edged moraines, the tarns and rock basin lakes all belong to the same glacial episode, in which ice reached its maximum extent about 18-15,000 years BP. The altitudes of the lowest snowline given in Fig. 26 (based on mean altitudes of the lowest rock basins or the altitude of emergence of the larger outer moraines below the excavated terrain) indicate that conditions may not have been uniform along the cordillera. Higher snowlines occur in the west (Mt Carstensz) and east (Owen Stanley Mountains) while the lowest snowline seems to occur on Mt Scorpion. If temperature was solely responsible, then a regional difference of 1.5°C would be implied. It is far more likely, however, that the snowline represents different precipitation/ablation regimes. The modern equilibrium line of the Meren Glacier on Mt Carstensz lies at 4580 with a mean temperature of about +1°C (Allison & Bennett 1976) reflecting an abundant snow supply to offset rapid melting. Using the Andean snowline as a guide (Nogami, 1976) we might expect that, relative to Mt Carstensz the modern theoretical equilibrium line would descend slightly to the east along the Snow Mountains in line with precipitation gradients and then rise gradually through the central highlands of Papua New Guinea, reaching its highest level in the most southerly areas of the Owen Stanley Mountains. There, lower precipitation and a distinct ablation season would cause the snowline to coincide with a mean air temperate of -0.8°C. The variation in the snowline at the last glacial maximum is of the same order of magnitude, and if it reflects similar precipitation controls it is likely that, then as now, the Star and eastern Snow Mountains were the wettest montane areas, and the Owen Stanley Mountains the driest. Mt Carstensz was substantially drier and an accentuation of the present rainfall gradient along the Snow Mountains

	Major Peaks				Mountain Areas				
	Altitude			Location	Present		ca 18,000 yrs BP		
					Ice Extent sq km	Mountain Grassland sq km	Ice Extent sq km	Mountain Grassland sq km	Lowest Snowline Altitudes
Mountain	Meters	°S	°E	Mountain Range					Meters
Kwoka	3000	1	132	Arfak Mountains				1400	
Kobowre	3890	4	136	Weyland Mountains		< 2	5	1050	
Carstensz	4884	4	137	Nassau Mountains	8	3900	980	16100	3680
Wilhelmina	4750	4	139	Oranje Mountains	< 2	250	390	7300	3450
Juliana	4700	5	140						
Antares	4120	5	141	Star Mountains		< 2	25	2550	3450
Burgers	3690	5	143	Western Highlands of PNG		320	225	14000	3550
Giluwe	4368	6	144						
Hagen	4000	6	144						
Kubor	3900	6	145	Kubor Range		20	27	1000	3500
Wilhelm	4510	6	145	Bismarck Range		90	108	3200	3500
Michael	3647	6	145	Kratke Range		40	4	3300	3550
Tabletop	3600	7	146						
Bangeta	4121	6	147	Sarawaket Mountains		120	92	1750	3675
Albert Edward	3990	8	147	Owen Stanley Range		240	133	6450	3650
Suckling	3675	10	149						
				Total	8	5000	2000	57,200	

Fig. 26. Major mountain areas.

is indicated. Mt Wilhelm and Mt Giluwe may have been relatively little affected. This does not imply that precipitation totals were anywhere higher than those of today; in fact it is likely that they were all somewhat reduced and the snowline pattern is an indication that this reduction was uneven, affecting Mt Carstensz more strongly than Mt Wilhelm, for example.

Taking Mt Scorpion during the Pleistocene as equivalent to Mt Carstensz now (and the area and altitudinal range of the modern Mt Carstensz ice areas are of the same scale as those present on Mt Scorpion during the ice maximum (Shepherd, 1965; Hope, unpublished data)) a depression of the +1°C isotherm by 1100 m is indicated. This indicates a temperature lowering of 7-7.5°C for mean air temperature, using contemporary lapse rates on Mt Carstensz as a guide. In considering thermal conditions at the time of glacial maximum, it must be remembered that a cooling by about 3°C occurs near the ice areas. The lapse rate estimates for the 500 m altitude zone below the ice on Mt Carstensz given by Allison and Bennett (1976) are 1.0°C/100 m for maximum temperatures and 0.1°C/100 m for minima. Cold air drainage during the night and radiation losses are responsible for the occurrence of freezing temperatures down to relatively low altitudes. In effect, the diurnal range increases in the vicinity of mountain peaks and this phenomenon would have been enhanced during times of general refrigeration, because sources of cold dense air well below freezing point would have existed. Allison and Bennett (1976) estimate the present day mean minimum at 4860 m as -3°C, but during the ice maximum all ice cap areas above 3800 m would presumably have experienced minima below this figure. Reductions in precipitation and humidity would enhance radiation losses and hence ground frosts. There are thus good grounds for supposing that alpine and subalpine environments were somewhat harsher during times of ice maximum. The lower limit of the zone of cold air drainage and relatively enhanced diurnal range is at present correlated with topography, but tends to occur at 2800-3300 m. Below these altitudes evening rain is common. Since this boundary appears to correlate with that of the change from upper montane rainforest to transition forest (Chapter 8), any changes in the nature and position of the frost-prone zone is relevant to understanding Pleistocene vegetation distributions.

Vegetation Zonation at the Time of Ice Maximum

The first results from pollen analysis in New Guinea established the remarkable fact that alpine or subalpine vegetation once extended

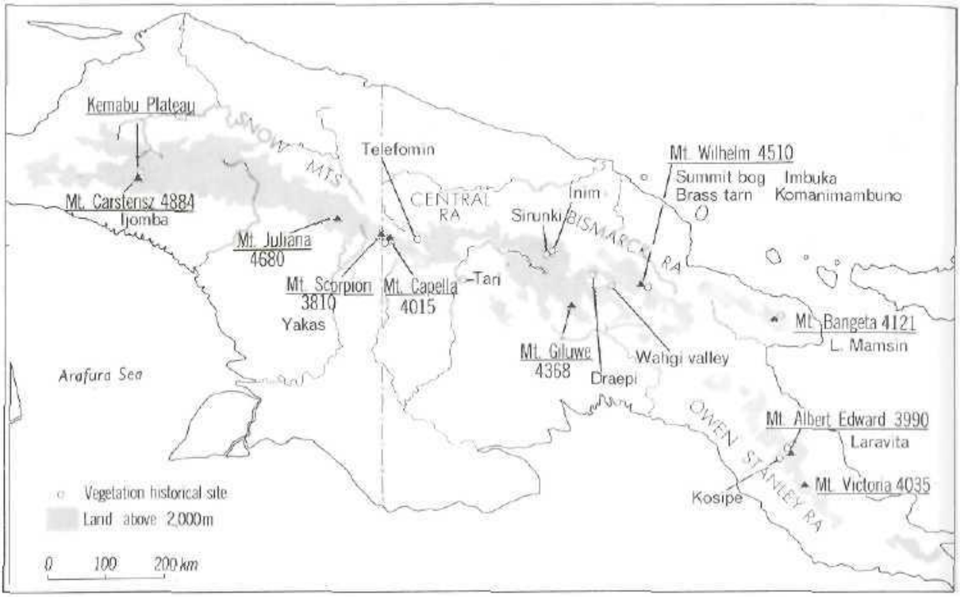

Fig. 27. Location of sites from which vegetation histories are available.

below 2550 m at Lake Inim in the central highlands near Wabag (Flenley, 1970, 1973; location of these and other sites is shown in Fig. 27). Work at nearby Sirunki, at 2500 m (Bowler, *et al.*, 1976; Walker & Flenley, 1979) confirms that around 17,000 years ago a treeless grassland with *Astelia, Drapetes* and a few shrubs was very extensive. The sites are in upland basins surrounded by ridges about 3000 m in height, well below the limit of glaciation, so that no ice masses were nearby to depress temperatures locally and prevent tree growth. These sites remain the lowest for which complete exclusion of forest during the time of the last maximum ice advance has been demonstrated. However, in the Mt Hagen area at 1880 m, Powell *et al.* (1975) show that *Nothofagus* forest was present during the time of last glaciation. It is thus possible to establish a treeline altitude of 2000-2250 m for the intermontane valleys of the central highlands. It is not known if this treeline altitude occurred in other parts of the island, or even on the outer flanks of the central highlands. Preliminary results (Hope, 1979) from Kosipe mission, at 1996 m on the southern flank of Mt Albert Edward, shows an incursion of subalpine elements including grass, *Styphelia, Ranunculus* and *Astelia* between about 25,000 and

12,000 years ago. However, the site retained its surrounding *Nothofagus* forest, so that the treeline lay somewhere upslope. On the other hand, lower montane forest at 1100 m at Telefomin (Hope, 1979) shows no significant change from well before 13,000 BP to the present. On theoretical grounds, the treeline may have been higher on the outer flanks and wetter areas of the mountains.

It is dangerous to extrapolate from the results so far available from a few localities, but a treeline at about 2000-2200 m throughout New Guinea does provide connections of subalpine vegetation sufficient to explain the many similarities in the now isolated mountain blocks. J. and G. Hope (1976) estimate that a general treeline at 2200 m would provide an area of 55,000 km^2 for subalpine and alpine communities beyond the ice margins. This area was broken up into blocks (Fig. 26) with a major disjunction to the east of the Star Mountains in the main cordillera, and between the central highlands of Papua New Guinea, the Owen Stanley Mountains and the Sarawaket-Finisterre Ranges. The Arfak Mountains and Mt Doorman would have remained quite isolated, as did the Mt Suckling complex in southeastern Papua.

The connections implicit in a low treeline at glacial times help explain the rather homogeneous nature of the subalpine flora in West New Guinea and the Star Mountains, although there are clearly many distinctions between the western and eastern ends. Similarly, close floristic relationships in the central highlands can be understood, despite the fragmented nature of subalpine environments there today. The explanations for the distribution of some elements are not assisted; for example the occurrence of *Detzneria tubata* on the Sarawaket Mountains and Bismarck Ranges but not on Mt Giluwe, or the distribution of *Rhododendron saxifragoides* in the Snow Mountains and as far as the western end of the central highlands but no further east. Bearing in mind the many widespread species, it would seem that the variation within and between mountain blocks of genera such as *Tasmannia* and *Rhododendron* and the ecotypic variation in species such as *Dacrycarpus compactus* and *Styphelia suaveolens* may have developed and been maintained while the taxa were sympatric. The alternative requires differentiation to take place within the last 10,000 years or be inherited from earlier periods of disjunction (Smith, Chapter 7).

Community Boundaries

Although the evidence is limited, the sites just below and above the treeline at the glacial maximum (Kosipe, Draepi, Sirunki and Lake Inim) tell us something of the nature of the communities. An additional site on Mt Wilhelm 2740 m (Komanimambuno, Hope, 1976) lay well above the contemporary treeline from 22,000 to 11,000 years BP. There are as yet no records from higher altitudes for full glacial times but the conditions immediately after ice retreat are indicative of the plant cover near the ice edge, and such records are available from Imbuka Mire, 3550 m, Mt Wilhelm (Hope, 1976); Laravita Tarn, 3620 m, Mt Albert Edward (Hope, unpublished); Yakas Tarn, 3480 m, Mt Scorpion (Hope, unpublished) and Ijomba Mire, 3630 m, Mt Carstensz (Hope & Peterson, 1976). There are several unusual features of the vegetation at the time of last glacial maximum, which show that it was not a simple depression of the vegetation zones. Had the then altitudinal treeline maintained its current relationship to the snowline, it would have been depressed by 1100 m or less, and would have occurred at 2600-3000 m, with the limit of the shrub-rich subalpine zone being about 2900-3000 m. The upper montane-transition forest boundary should have occurred at around 2000 m. The fact that the treeline was depressed by at least 1600 m - 400 m more than the snowline — requires explanation which is still not available. However, three points emerge from the palynological data. It appears that *Nothofagus* dominated UMRF was more widespread than today, and it certainly occurred much nearer, altitudinally, to the contemporary treeline than it does today. The subalpine forest taxa *Rapanea* and *Dacrycarpus* are less prominent in the pollen diagrams from Sirunki and Komanimambuno than they are in alpine areas above the treeline on Mt Carstensz and Mt Wilhelm today. Thirdly, at Sirunki, Lake Inim and notably Komanimambuno pollen from shrubs such as *Gaultheria, Rhododendron,* Epacridaceae, *Tasmania, Coprosma,* and the fern *Cyathea* are present in numbers indicating scattered local presence in the grassland. *Cyathea* spores also form an important element in the early deglaciation pollen diagrams, reflecting widespread tree ferns at lower altitudes.

It seems possible that the altitudinal position of the upper boundary of upper montane forest and of subalpine, shrub-rich grasslands did indeed lie at about the elevations that are predicted above. The striking difference is that subalpine forest seems to have been non-existent, or integrated into a narrow transition forest at about 2200 m altitude. Subalpine grassland communities evidently occupied a wider zone than at present, and *Cyathea* was an important component, in contrast to the role of modern species, which do not occur above the treeline, although they are very prominent in some subalpine grasslands below the treeline. The environment that caused these above-treeline shrub-rich communities is not yet defined; Loffler (Chapter 3) suggests that the tree line was exceptionally low near the pollen sites studied because they are frost-prone basins, or adjacent to ice caps. Following the observations on the very low lapse rates for minimum temperatures noted above, it seems likely that a greater diurnal range may have played a role. Since many of the shrub taxa, and *Cyathea* also, are nearly as sensitive to frost as are the subalpine forest trees, the exclusion of subalpine forest from a shrub-rich area may also be attributed to occasional but severe and widespread disturbance, for example periods of drought and very severe frost every thirty years or longer. This would prevent the spread of closed forest, but would allow shorter lived shrubs to succeed, and would not interfere with the glacial or periglacial zonation.

Because pollen records can never give a complete listing of component taxa it is impossible to know if exact analogues of extant communities were present at the time of the glacial maximum. However, it is likely that many of the shrub-rich subalpine grassland communities were represented, as well as alpine tussock grassland. Alpine communities, although widespread, may not have been as varied as at present because snow and ice would have covered most of the rocky areas of the mountains, below which mature soils would have persisted. Colonist taxa and cushion plants would have survived on outwash fans and near the ice margins.

3. Other Pleistocene Environments

The maximum lowering of sea levels and extension of ice sheets is only a relatively short interval in the 'glacial' periods of the Pleistocene. The last such episode took place from about 23,000 until 16,000 BP, compared to a time of sea levels lower than the present which extends from 123,000 BP to about 8500 BP. Several similar episodes of lower sea levels, demonstrating the existence of northern ice caps, are dated from the Huon Terraces of New Guinea (Chappell *et al.*, 1974). It is thus likely that the usual state of affairs consisted of climates about 3-5° C cooler than present, interspersed with periods of more extreme lowering, and occasional 'interglacials' with temperatures equivalent or greater than the present (Chappell, 1978).

Although only one other glacial period has been definitely shown to have affected the New Guinea mountains (Löffler, 1976) it seems likely that nival, alpine and subalpine environments have waxed and waned through most of the Pleistocene epoch.

Data on the vegetation prior to the last glacial maximum are limited to the Sirunki core (Walker & Flenley, 1979), Kosipe (Hope, unpublished) and discontinuous records from Draepi and Tari (Powell, unpublished and Williams *et al.*, 1972), all restricted to the last 50,000 years or so. The Sirunki pollen diagram shows three alternations from forest to grassland between 35,000 and 20,000 BP, so that the treeline evidently fluctuated. Kosipe and the Wahgi valley (1600-2000 m altitude) were occupied by *Nothofagus*-dominated forest, and show no effects of climatic change over the same period. At Tari (1400 m) a swamp forest was present at about 40,000 BP, together with significant amounts of *Astelia* pollen. This indicates a significantly lower record for this genus than any recovered during the last glacial maximum. A similar record occurs near the base of the Draepi core (1880 m) (Powell *et al.*, 1975). Difficulties with dating, and the absence of any period of extreme depression of vegetation between ca. 40,000 and 30,000 BP at Sirunki, points to one or more early periods of possibly even greater depression of vegetation boundaries than occurred during the last glacial maximum. However, there is no evidence so far to suggest that ice was ever significantly more extensive than during the last maximum.

Evidently the alpine and subalpine zones were not static during the glacial periods. The presence of icecaps on most mountains over 4000 m altitude would have meant widespread (though discontinuous) alpine habitats existed, especially favouring vegetation able to colonise areas abandoned by ice, such as the mosslands and dwarf shrub heath. In the subalpine areas, forests were able to advance on occasions. J. and G. Hope (1976) note that some species of large extinct marsupials were probably present in the subalpine and montane zone. Smaller kangaroos (e.g. *Thylogale bruijnii* and *Dorcopsulus vanheurni*) may also have been more prominent than they are at present. Thus the influences on the evolution of the New Guinea mountain flora may not have been confined to those of colder and fluctuating climates.

4. Establishment of Modern Distributions

The present day vegetation started to develop as the glaciers retreated after 15,000 BP, with the migration of subalpine and alpine communities to their present limits. This process is shown in Fig. 28 using data from all available sites. J. and G. Hope (1976) estimate that the 55,000 km^2 of non-forested subalpine, alpine and nival habitats at the time of maximum glaciation had shrunk to only 800 km^2 by 8500 BP. Much of this contraction is due to the spread of upper montane forest and the appearance of subalpine forest. It is indicative of the fact that subalpine forest was restricted that it did not migrate as a zone in front of montane forest. Hence it is upper montane forest which directly replaces subalpine grassland below 3000 m. This occurred at Sirunki (2500 m) about 14,000 BP and at Komanimambuno (2740 m) at 11,800

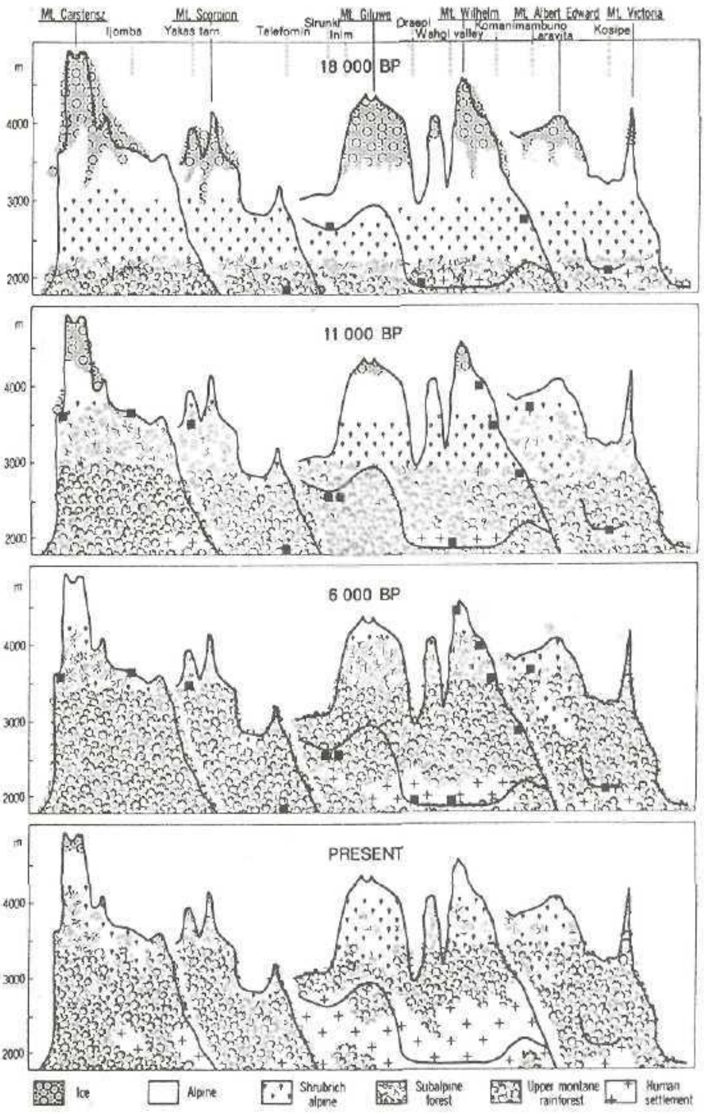

Fig. 28. Summary of vegetation changes over the last 18 000 years. Heavy squares indicate that vegetation reconstructions are available for the time and location shown. (The square for Telefomin lies above the actual altitude of 1100 m).

BP. The forests contained Elaeocarpaceae, Cunoniaceae, *Podocarpus, Phyllocladus* and some *Nothofagus* as well as *Dacrycarpus, Rapanea* and Ericaceae; they probably reached their present limits by about 9500 BP.

Changes in the formerly glaciated areas show interesting differences in detail in the nature and timing of the arrival of vegetation.

Mt Carstensz

Ijomba Mire (Hope & Peterson, 1976), at 3630 m, records the retreat of ice by 14,000 BP. Alpine tussock grassland developed around the tarn until *Rapanea* and *Coprosma* invaded the area about 13,500 BP. These taxa formed a simple shrubland-forest, which may have resembled the modern treeline shrublands above 3750 m, until around 10,750 BP when *Dacrycarpus*, Ericaceae and *Cyathea* reached the site, and *Phyllocladus* approached it. Subalpine forest substantially the same as at the present day was established by about 10,000 BP, and no further changes attributable to climatic change are seen. In contrast, at the same altitude in the glacial valley leading from the main ice area, shrubland was absent at 13,000 and 11,500 BP during times of ice retreat, when alpine plants and ferns colonised glacial moraines before a minor ice advance covered them up for the last time.

At higher altitudes in the alpine zone, a sequence of peats and lake sediments occur between till horizons. This demonstrates up to four minor ice advances reaching down to 4150 m. The vegetation histories (derived from organic sediments accumulated at times of retreat) indicate continued alpine environments from 3000 BP to present, with reversions from shrub heath (better developed than current vegetation on the site) to very sparse colonist vegetation, which presumably immediately followed ice retreat. (Plate 53).

Mt Scorpion, Eastern Star Mts

Preliminary pollen analysis on sediments from Yakas Tarn (3480 m) (Hope, unpublished, Plate 54), shows that it became ice-free about 13,500 BP and was colonised by a *Rapanea* shrubland by 12,800 BP. *Papuacedrus* and *Phyllocladus* entered the forest by 10,500 BP but *Dacrycarpus* was not significant until after 10,000 BP. By 8300 *Rapanea* was unimportant in the open forest around the tarn, but after 4500 BP *Papuacedrus*, *Rapanea* and *Dacrycarpus* increased at the expense of *Phyllocladus*. *Cyathea* and *Gleichenia* also became important at about this time. These changes show that the forest on this site has not remained stable throughout the Holocene, but seems to have first become richer in species and then more open. The vegetation at present consists of discontinuous forest of *Dacrycarpus*, *Papuacedrus* and *Ra-*

Plate 53. Trimline resulting from a recent glacial advance. Tetramolopium heath (C4) is colonizing the ice-affected area down to the terminal moraines at 3950 m with treeline shrublands (A4) above. A lower, diffuse treeline occurs on Mt Grasberg (4270 m), which is a granodiorite peak. The isolated ice cap and overnight snow is visible on Mt Idenburg (4717 m). Mt Carstensz, Meren Valley. Jan. 1972 (Photo G. Hope).

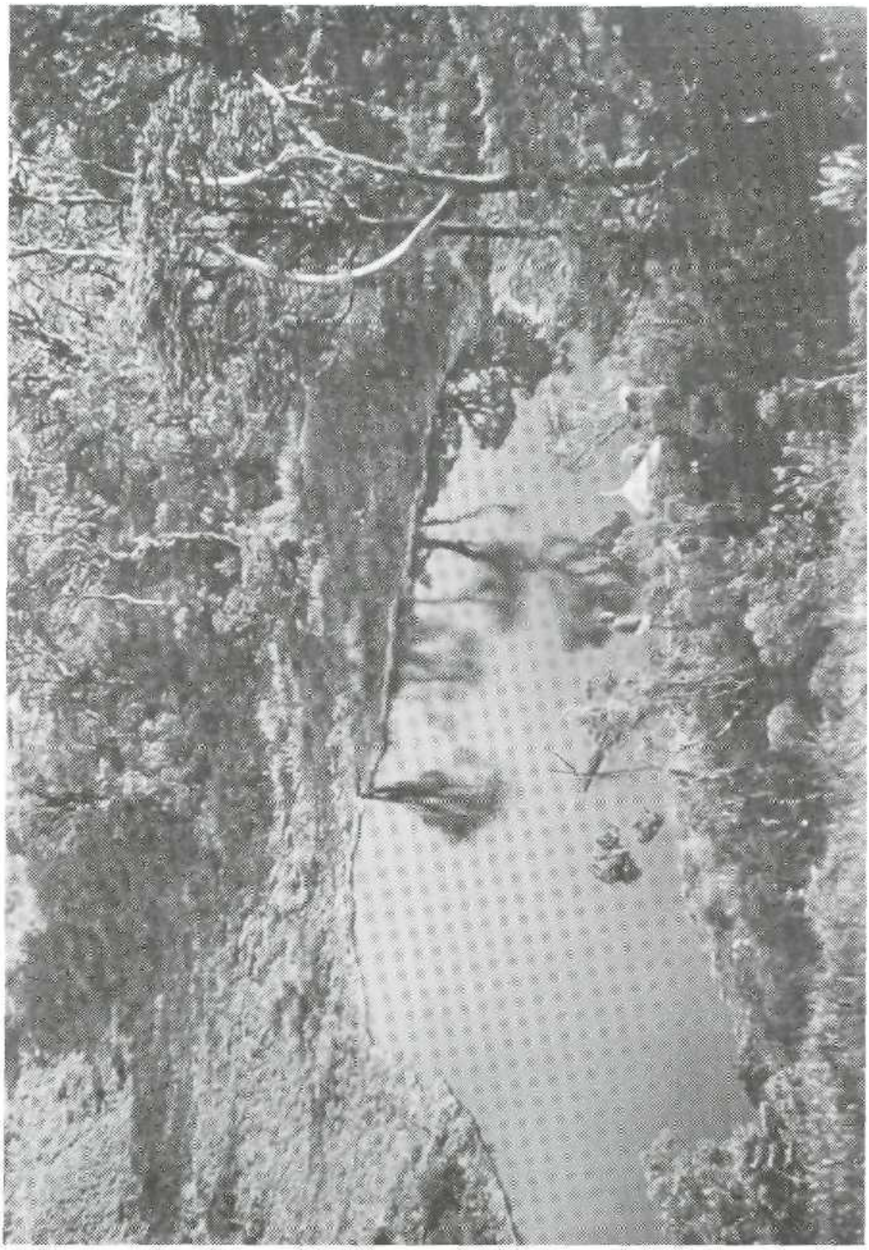

Plate 54. Subalpine rainforest (A3) and Gleichenia vulcanica bog (F3) separated by a narrow band of Gahnia - Plagiogyria tussock grassland (D5). Mt Scorpion, Yakas Tarn pollen analysis site, 3470 m. May 1975 (Photo G. Hope).

panea with an open, stunted canopy, covering about 35% of the valley floor. The remainder is occupied by *Gleichenia vulcanica* bog or *Astelia papuana* subalpine bog. From the pollen diagram it would appear that the present vegetation evolved from a previous denser forest about 4500 BP.

Mt Wilhelm

The process of recolonisation of the glaciated terrain of Mt Wilhelm has been studied at a series of sites at different altitudes, principally Imbuka (3550 m) (Plate 55), Brass Tarn (3910 m) and Summit Bog, (4420 m) (Hope, 1976; Hope & Peterson, 1975). As noted above it is montane forest which replaces shrub-rich grassland at Komanimambuno (2740 m) at about 11,500 BP. This post-dates the retreat of ice up the Piundaunde Valley past Imbuka site, which became ice free about 12,800 BP, following a still stand or minor advance that occurred about 13,000 BP and reached 3510 m in the floor of the Piundaunde Valley. A sparse herbland, including *Ranunculus*, Caryophyllaceae, *Astelia* and grasses, colonised the moraines around the small Imbuka pond. Dating is not precise for the Imbuka section, but there seems to have been a period of about 1500-2000 years when shrubs were absent although the grassland increased at the expense of the other herbs. About 10,500 BP *Styphelia*, *Coprosma*, *Pimelia* and Ericaceae were present, and a subalpine forest of *Rapanea* became established, almost excluding herbland, at 9500 BP. *Dacrycarpus* was at first a minor partner, together with Ericaceae and *Tasmannia*, in this forest, but at about 4500 BP the ratio was reversed and *Dacrycarpus* became dominant and *Polyosma* and *Quintinia* slightly increased. This forest colonised the swamp basin until 1000 BP, when clearance took place, and short grass bog occupied the site.

Brass Tarn (3910 m) records a similar progression from an initial colonisation by sparse herbland at 11,000 BP followed by development of grassland and arrival of *Rapanea* dominated subalpine forest at 8500 BP. An earlier, and more gradual change to dominance by *Dacrycarpus* takes place about 6500 BP, at which time the forest limit probably lay 100-200 m upslope. About 4900 BP the forest was replaced by shrub-rich grasslands which have remained until the present, although the proportions of shrubs and herbs have fluctuated.

At present large shrubs of *Rapanea* and an isolated tree of *Dacrycarpus compactus* occur near the tarn, but there is no evidence that closed forest persists at this altitude.

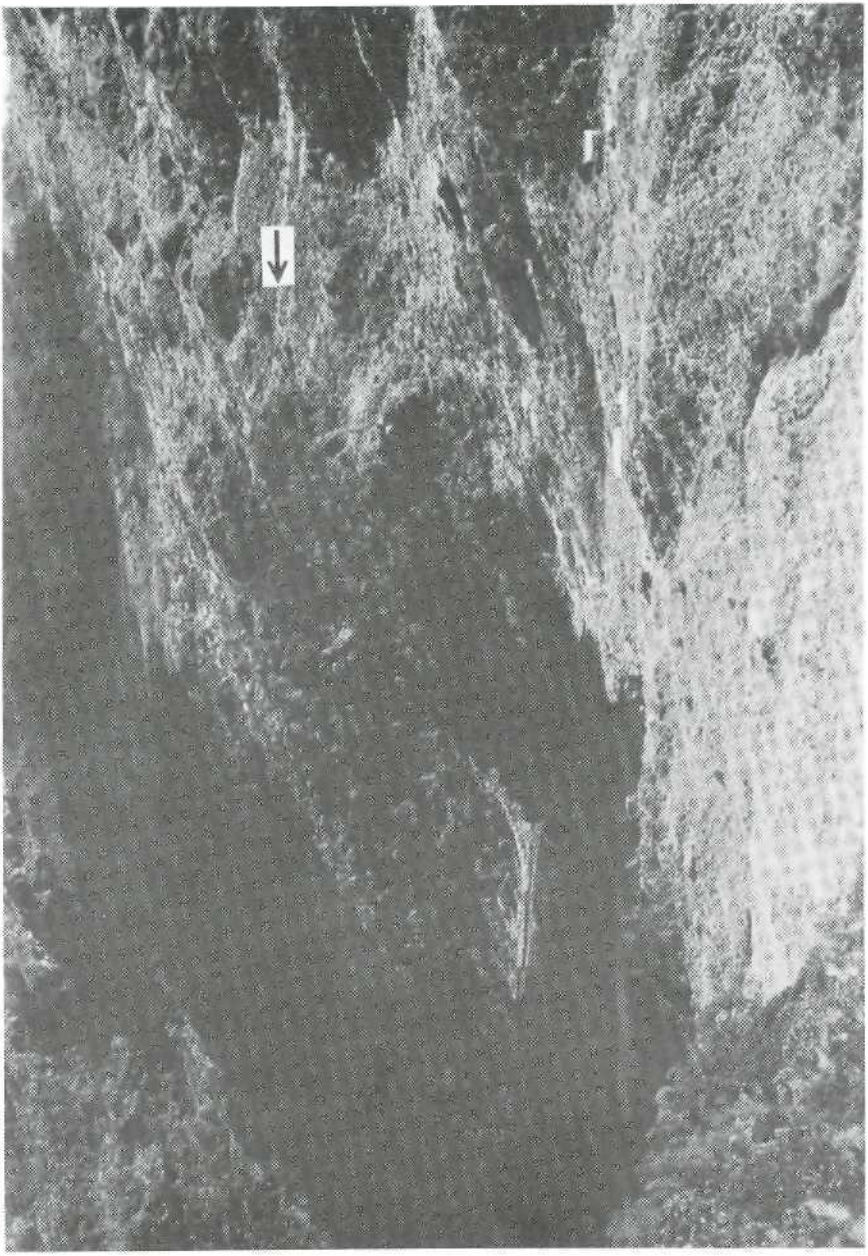

Plate 55. Lake Aunde (3480 m) and the Imbuka Ridge, with Imbuka pollen analysis site (arrow). Most of this area supported subalpine forest prior to 250 BP. July 1969 (Photo G. Hope).

The Summit Bog (4420 m) only became ice free about 9000 BP, but the area was rapidly occupied by alpine tussock grassland, after a short phase of colonisation by an open herbland containing *Ranunculus*, *Epilobium*, Caryophyllaceae, *Potentilla* and grasses. The grassland remained until some time after 6500 BP but for how long is not known because the site was eroded by probable minor glacial episodes. Undated peaty gravels formed after at least two of these episodes show a progression from *Ranunculus* herbfield to grassland. The present *Ranunculus saruwagedicus* mossland (wet alpine tundra) has been present for only 150 years or less, and is colonising previously bare terrain.

Taken together, the Mt Wilhelm sites record a steady retreat of ice from 14,500 until 9000 BP, the ice free areas being quickly colonised by a herbland or 'tundra' community, which soon developed into alpine grassland. Shrublands did not spread up the mountain until about 10,500 BP, and they were followed by subalpine forest, which formed a treeline higher than that at present by 8300 BP.

Mt Bangeta, Sarawaket Mts

Costin *et al.* (1977) report a date of 11,230 ± 100 (Y-1622) for peats near the Mt Bangeta summit, and this is evidence of a deglaciation broadly synchronous with the central Highlands. No details of the process of colonisation of this mountain after the ice had retreated are available. However, leaves and wood dated at about 6000 BP were recovered from lake sediments on the shores of Lake Mamsin (3500 m). These were predominantly *Podocarpus, Styphelia, Dimorphanthera amplifolia* and *Rapanea*, indicating that subalpine forest occupied the site at the time. The lake area is grassland now, probably due to burning. No *Podocarpus* species have been observed higher than about 3000 m in the area today and Costin *et al.* (1977) raise the possibility that cooler climates may have caused this reduced range for *P. brassii* within the last 5000 years. *Podocarpus* species are prominent elsewhere in New Guinea up to 3800 m.

Mt Albert Edward, Owen Stanley Mts

Laravita Tarn is a small mire and shallow pond at 3550 m on the northern plateau of Mt Albert Edward (Hope, 1975 and unpublished data). The site commenced as a shallow moraine dammed tarn, accumulating rock flour, and organic pond sediments started to build up a little before 12,850 ± 300 (GX-3659). About 12,000 BP the water was shallow enough to permit invasion by sedges and grasses and five metres of ropy terrestic peat has since built up to the present day. This apparently accumulated at a steady rate because two radiocarbon dated horizons (the 495 cm level is 11,400 ± 200 BP (SUA-596) and 195 cm is 4475 ± 110 BP (SUA-597)) demonstrate almost identical accumulation rates between each horizon and the surface.

The vegetation history from the site differs from those at equivalent altitudes on Mt Wilhelm and Mt Carstensz, in that although a subalpine forest including *Rapanea*, Ericaceae and *Dacrycarpus* appears at the site about 11,500 BP, it never surrounds the pond. In fact forest is not at any time more than marginally better established than the discontinuous small stands of the present day. Substantial areas of grassland seem to have remained in the area, even when *Dacrycarpus, Phyllocladus* and Ericaceae increased slightly at about 9500 BP. Tree ferns seem to have always been present in the grasslands, and these increase significantly about 4500 BP to present levels, with a concomitant reduction in subalpine shrubs (e.g. *Coprosma* and Epacridaceae).

Synthesis of Site Data

The subalpine and alpine records indicate that vegetation was close to its present distribution and zonation by 9500 BP. The most dramatic change was the invasion of most mountain areas by a scrub or low forest of *Rapanea*, apparently somewhat earlier in the west than on Mt Wilhelm or Mt Albert Edward. With the addition of slower-migrating or cold-sensitive taxa after 10,000 BP the modern subalpine forest evolved, utilising elements in the Pleistocene grasslands and treeline communities. If the subalpine forest has formed so relatively recently, this perhaps explains the wide range of responses of individual taxa such as *Dacrycarpus, Phyllocladus* and *Vaccinium* on different peaks. The forest is undoubtedly still adjusting to Holocene climates.

At this stage it is impossible to determine if the differences in the times of establishment of *Rapanea* scrub reflect ecotypic variation or differences in regional climates. Mt Wilhelm stands out as an area in which the initial establishment of forest came relatively late. Hope (1976) suggests that it was continuing cold conditions from 12,500 until about 10,000 BP that excluded large woody taxa. If so, the arrival of *Rapanea* scrub on Mt Carstensz and Mt Scorpion by 12,500 BP suggests that conditions may have been generally suitable in the west of the island earlier than in the east.

The expansion of subalpine and transition forests is synchronous with the near-extinction of some communities, the only trace of which is a scatter of component taxa occurring as minor species in other communities. For example *Scleranthus singuliflorus, Epilobium* spp. and *Parahebe* spp. are widespread in alpine tussock grassland and dwarf shrub heath. These species probably formed extensive seral communities on newly-exposed areas of till, but as a community this alpine open herbland is now restricted to the ice margins on Mt Carstensz. There are similar remnant communities on many mountains, but these can only be identified as having once been potentially widespread if relict stands still persist somewhere in the island. Examples include *Polystichum papuanum* alpine fern meadow, which was possibly once extensive on Mt Giluwe, Mt Albert Edward and Mt Bangeta, and *Gleichenia vulcanica* subalpine bog, which may have been more extensive on Mt Wilhelm and Mt Albert Edward.

In addition to communities favoured by Holocene climates, such as subalpine forest, or those severely constricted by them, such as alpine mosslands, there is a third group which was apparently extensive in the Pleistocene and is extensive now. These communities, the subalpine mires and shrub-rich grassland, each reflect opposing trends. In the case of the mires the process of succession reduces pond and mire areas and allows invasion by forest, as instanced at Imbuka, on Mt Wilhelm. However, the gentle glaciated topography exposed by ice retreat on some mountains has proved suitable for blanket bog and peat accumulation, and the consequent rise in the water table has extended mire habitats and created ponds and string bogs, for example on Mt Giluwe, Mt Scorpion and Mt Albert Edward. On Mt Albert Edward a section of a pond margin showed an alternation of terrestic and limnic sediments, demonstrating cyclic invasion of the pond by mire communities which impeded the drainage and raised the water table, thus extending the pond once more (Hope, 1975).

The shrub-rich grasslands and shrubland communities have also tended to be invaded by forest during the Holocene, but this process has been reversed in many areas by human disturbance of the forest, considered in more detail below.

5. Human Influences

Information about the effects of man on the vegetation comes directly from archaeological records, from vegetation histories and from charcoal and carbonised particles which indicate fire histories. Archaeological work in New Guinea (Golson, 1977) has established that man has

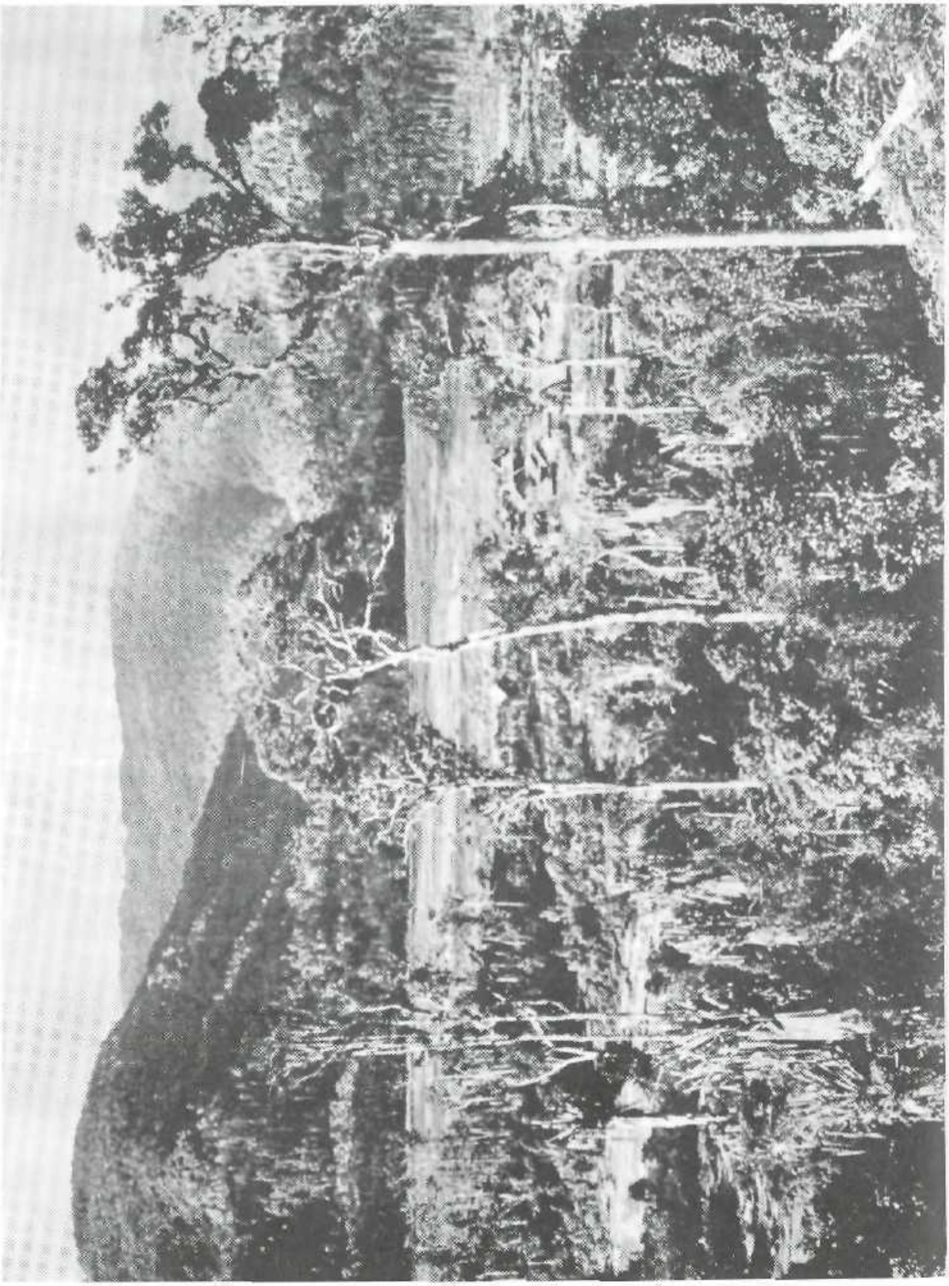

Plate 56. Nothofagus trees above regrowth forest, Kosipe, 1995 m. Owen Stanley Range. This area was occupied by man soon after 30 000 BP. June 1974 (Photo G. Hope).

been present in the highlands for more than 25,000 years, the oldest records coming from Kosipe (1995 m in the Owen Stanley Mountains) (Plate 56) and the Wahgi Valley (1650 m, central highlands). Most work has been carried out in the central highlands of Papua New Guinea, where many rockshelters were first inhabited 14,000-10,000 years ago. Early agriculture, associated with extensive clearance, has been demonstrated at Kuk, in the upper Wahgi Valley about 9000 years ago (Golson & Hughes, 1979). This agriculture appears to have taken place on the slopes and on the valley floor, where a complicated drainage network was established. The crops probably included taro as staple. The introduction of sweet potato, probably only about three hundred years ago, allowed gardens to extend onto higher, steeper slopes, and may be responsible for a considerable expansion in the population of the highlands, and in the area of cultivation. In the absence of archaeological results elsewhere in montane New Guinea it is not possible to know whether parallel changes occurred everywhere. Archaeological deposits known from high altitudes are restricted to small rockshelters on Mt Carstensz (G. & J. Hope, 1976). These indicate use by hunting parties at 5000 BP and more recently, and include the bones of a wide range of animals including two species of small wallaby (*Thylogale* spp.) which inhabited grassland-forest edges.

Dates on charcoal in formerly forested areas provide tentative minimum ages for human interference with the forest. On Mt Bangeta, Loffler (1971) reports a date of 4320 ± 100 BP (GaK-2164) which indicates disturbance about that time and which can be compared to the date of 5660 ± 80 (Y-1619) on wood from presumably closed subalpine forest in the Lake Mamsin deposit. Both dates come from sites now almost completely devoid of forest. Similarly Blake and Loffler (1971) report ages of 3800 and 1800 BP on large fragments of charcoal deposited in a gully at 3200 m on Mt Giluwe.

Fire histories are now available, utilising very small particles of carbonised plant material preserved, like pollen, in pond swamp sediments (Singh *et al.*, 1979). The most detailed results are from Mt Wilhelm, where a complex pattern of burning and associated clearance occurred after 300 BP on several parts of the mountain (R.T. Corlett, personal communication). The earliest clearance, for example the removal of subalpine forest at Imbuka (Hope, 1976) took place after 1000 BP. The role and causes of fire prior to widespread disturbance is not clear; R.T. Corlett (unpublished) reports the presence of carbonised particles at Brass Tarn after the removal of forest about 4900 BP, with several subsequent peaks and low frequencies of occurrence of carbonised particles. It is thus possible that this change in the treeline altitude was caused, or at least assisted to adjust, by fires in the adjacent grasslands.

Carbonised particle frequencies are available from the subalpine sites described above on Mt Carstensz, Mt Scorpion and Mt Albert Edward. The results from Ijomba, Mt Carstensz (Hope & Peterson, 1976) indicate that a significant increase in burning occurred at 10,800 BP, and was followed by opening out of the forest and an increase in grass and tree ferns. Still more burning is indicated between 6000 and about 1500 BP, coinciding with marked fluctuations in tree ferns and a continuing decline of subalpine forest taxa. After 1500 BP the carbonised particle curve declines to the very low levels of the present day. This result is supported by the observation that although the forest in the area has been widely destroyed there are few signs of recent disturbance, and shrublands and tree fern groves are widespread and dense. Including the archaeological evidence for human activity in the region for an unknown period after 5400 BP, it seems likely that the area has a very long history of disturbance which reached a peak a few thousand years ago, and has subsequently declined.

On Mt Scorpion, which is probably never visited by the distant and scattered population, carbonised particle frequencies in Yakas Tarn sediments are particularly low to absent. Low levels were recorded prior to the arrival of *Rapanea* scrub and again after about 2500 BP, the latter coinciding with an increase in *Cyathea* and *Gleichenia.* These changes may have resulted from very light local firing due to natural or anthropogenic causes, but they are so much less than those associated with known frequent firing that human disturbance cannot be demonstrated in the area.

By contrast, the sequence from Laravita Tarn, Mt Albert Edward shows high fire frequencies after 12,000 BP, although they fluctuate, with relatively lower periods around 9000 and 4500 BP. Continued fires appear to have been a feature of Mt Albert Edward following deglaciation. This is not surprising as carbonised particle frequencies from Kosipe Swamp (Plate 56), 16 km southeast of Laravita Tarn at 1996 m, indicate that burning there increased soon after 30,000 BP, and remained at high levels until after 8000 BP. As noted earlier, the treeline during times of glaciation lay not far above Kosipe and it seems possible that grasslands near the treeline would have been burnt during the period of occupation of Kosipe (J. & G. Hope, 1976). The widespread tree fern shrublands and the apparently fire adapted short grassland and *Coprosma* heath (Chapter 8) are presumably the results of a longer period of adaption to fire than seems to have occurred on other mountains so far studied in New Guinea. The subalpine forest has obviously had a greater extension at some time in the last 10,000 years since isolated trees and fallen logs can be found at places on the summit plateau. In addition to proximity to prehistoric populations, the drier and more seasonal nature of the climate of Mt Albert Edward presumably assists firing.

This scattered evidence from widely separated sites supports observations on traditional usage of the mountain areas. J. & G. Hope (1976) note that the mountains vary widely in the intensity of visits by people. Mt Albert Edward, Mt Giluwe and Mt Wilhelmina are traversed by many tracks, including important trade routes, and they are used for hunting. Other mountains, such as Mt Bangeta, Mt Wilhelm, the Kubor Range and Mt Carstensz have been widely cleared but are not so intensively used. Areas such as the Star Mountains and Mt Juliana seem to be rarely, if ever, visited. The degree of usage is apparently related to proximity to large populations. The prehistoric evidence available shows that there is a great deal of variation in the timing and degree of impact. It appears that Mt Wilhelm has suffered recent but intense disturbance which may well be indicative of recent expansion of large agricultural societies into the upper Chimbu Valley. Mt Carstensz experienced a very much longer history of disturbance with an intensive period that resulted in widespread clearance. Mt Albert Edward has been adjusted to fire for even longer, but is probably as badly affected by burning at present as at any time in the past. These results show that the modern vegetation pattern provides only a rough guide to the possible disturbance history of an area.

The vegetation response to frequent light firing, and occasional fires during dry periods which burn into the forest boundary, is the production of shrub-rich grasslands, and tree fern shrublands. (Plates 21, 31, 32). Many of the taxa present in these communities appear to be the same as those prominent in the Pleistocene grasslands that lay above the treeline. The role of fire in the Pleistocene communities is unknown, although it is notable that in all cores examined from subalpine sites, carbonised particles are present in higher frequencies during the colonist herbland phase following deglaciation then in subsequent scrub periods. Thus the Pleistocene grassland communities may have been adapted to fires (whether natural or anthropogenic) as well as cold conditions. It is to be expected that these taxa would spread to occupy former forest areas in the subalpine zone. Removal of the forest exposes the ground layer to frosts and drying which can prevent or impede the development of tree seedlings. This may explain why some shrub-rich communities are only reverting very slowly to forest in the absence of fires.

6. Conclusions

The fossil evidence shows that there have been very large changes in the distribution of the subalpine and alpine flora of New Guinea in response to climatic oscillations. It is clear that this flora is now experiencing relatively unusual climatic conditions, compared to the 'norm' of Pleistocene glacial periods when much greater areas of suitable habitats were available. Even at the height of the glaciations, the subalpine zone would have formed many discrete blocks, and alpine habitats would have been as fragmented as the subalpine is today.

The imposition of modern, interglacial climates coincided in some areas with new or renewed disturbance by man. Although the general effect was a widespread replacement of grass and shrublands by the newly developing subalpine forest, on some mountains the forest victory was not complete, or at best short lived. Although the climates resulting in subalpine grassland climax communities apparently no longer exist, the communities themselves (or close analogues) have expanded greatly after 5000 BP, and still further within last 300 years, because man has removed the forest. This process has perhaps been aided by deterioration of the climate over at least the last 3000 years.

Although the New Guinean mountain flora has been regarded as rather depauperate, and not well adapted to alpine habitats (Wade & McVean, 1969), the great fluctuations in conditions mean that many taxa may currently be out of balance while others may have become extinct within the last 15,000 years. Thus the situation of the mountain flora contrasts with the customary view of glacial periods as relatively harsh while interglacials are benign. This should make us cautious about inferring source areas or relationships from the modern distributions alone. The few secrets so far revealed show that the New Guinean mountains have had a rich and varied past.

Acknowledgements

This chapter is a first attempt to integrate both preliminary and completed work from a full range of mountain sites in New Guinea. As such it is liable to change when a better chronology, more historical data and especially a better understanding of the ecology of the mountain vegetation becomes available. In pursuing this project I am indebted to Donald Walker who initially proposed it (and me) to the Australian National University and Queen Elizabeth II Fellowship which have provided support since 1969. In addition to absorbing the wisdom of my fellow vegetation historians Richard Corlett, John

Flenley, Sam Garret-Jones, Joan Guppy and Jocelyn Powell, I have learnt much from discussions with geomorphologists and prehistorians working in New Guinea, notably Jim Peterson, Philip Hughes and Ernst Löffler, but including Ole Christensen, Jack Golson, Jeannette Hope, Dan Jorgensen, Bob Mitton, Colin Paine, Peter White and Doug Yen. the credit for my escaping hernia and bringing back the 'Pekpek bilong masta Djeff' from remote alpine bogs belongs to the many New Guinea people who have worked with me. Their cheerful help in trying conditions turned (logistic) mountains into molehills.

Selected References

Allison, I. & J. Bennett, Climate and microclimate, pp. 39-60, in G.S. Hope, J.A. Peterson, U. Radok & I. Allison, eds, Equatorial Glaciers of New Guinea (1976).

Bowler, J.M., G.S. Hope, J.N. Jennings, G. Singh & D. Walker, Late Quaternary climates of Australia and New Guinea - *Quat. Res.* 6 (1976) 359-94.

Chappell, J.M., A.L. Bloom, W.S. Broecker, R.R. Mathews & K.J. Mesolella, Quaternary sea level fluctuations on a tectonic coast: New Th^{230}/U^{234} dates from the Huon Peninsula, New Guinea - *Quat. Res.* 4 (1974) 185-205.

Chappell, J.M., Theories of Upper Quaternary ice ages: In Climatic Change and Variability, pp. 211-24 (1978).

Costin, A.B., R.D. Hoogland & C. Lendon, Vegetation changes in the Lake Mamsin area, Saruwaged Plateau, New Guinea - *Am. Mus. Novit.* 2628 (1977) 1-9.

Flenley, J.R., Evidence of Quaternary vegetational change in New Guinea, in P. & M. Ashton, eds, The Quaternary Era in Malesia, pp. 99-108. *Misc. Ser., Hull,* (1972).

Flenley, J.R., The use of modern pollen samples in the study of the vegetational history of tropical regions. Quaternary Plant Ecology; The 14th Symposium of the British Ecology Society (1973).

Golson, J., The Making of the New Guinea Highlands, in J.H. Winslow, ed. The Melanesian Environment, pp. 45-56 (1977).

Golson, J. & P.J. Hughes, The appearance of plant and animal domestication in New Guinea. Proc. Ninth Congress of the International Union of Pre- and Protohistoric Sciences (1979).

Hope, G.S., The vegetation history of Mt Wilhelm, Papua New Guinea. Ph.D. thesis, Canberra (1973).

Hope, G.S., Some notes on the non-forest vegetation and its environment, northern flank of Mt Albert Edward, Central District, Papua New Guinea. Unpublished report, Canberra (1975)

Hope, G.S., The vegetational history of Mt Wilhelm, Papua New Guinea - *J. Ecol.* 64 (1976) 627-64.

Hope, G.S., Tropical mountain forest in retrospect and prospect, in J.N. Jennings & G. Linge, eds, Essays in Honour of Oskar Spate. ANU Press: Canberra (1979).

Hope, G.S. & J.H. Hope, Man on Mt Jaya, pp 225-38, in G.S. Hope, J.A. Peterson, U. Radok & I. Allison, eds, The Equatorial Glaciers of New Guinea, (1976).

Hope, G.S. & J.A Peterson, Glaciation and vegetation in the high New Guinea mountains *Bull Roy Soc NZ* 139 (1975) pp. 155-62.

Hope, G.S. & J.A. Peterson, Palaeoenvironments, pp. 173-205, in G.S. Hope, J.A. Peterson, I. Allison & U. Radok, eds, The Equatorial Glaciers of New Guinea (1976).

Hope, J.H. & G.S. Hope, Palaeoenvironments for man in New Guinea, pp. 29-53, in R.L. Kirk & A.G. Thorne, eds, The Origins of the Australians (1976).

Loffler, E., The Pleistocene glaciation of the Saruwaged Range, Territory of New Guinea - *Austral. Geogr.* 11 (1971) 463-72.

Loffler, E., Pleistocene glaciation in Papua and New Guinea - *Zeitschr. Geomorph.,* Suppl. 13 (1972) 32-58.

Loffler, E., Potassium-Argon dates and pre-Wurm glaciations of Mt Giluwe volcano, Papua New Guinea - *Zeitschr. Gletscherk. Glazialgeol.* 12 (1976) 55-62.

Nogami, M., Altitude of the modern snowline and Pleistocene snowline in the Andes. *Geogr. Rep. Tokyo Met. Un.* 11 (1976) 71-86.

Powell, J.M., A. Kulunga, R. Moge, C. Pono, F. Zimike & J. Golson, Agricultural traditions of the Mt Hagen area - *UPNG Dept. Geog. Occ. Pap.* 12 (1975) 1-68.

Shepherd, M.J., Geomorphology of the eastern Star Mountains region. BA (Hons) thesis, University of Sydney (1965).

Singh, G., A.P. Kershaw & R.L. Clark, Quaternary vegetation and fire history in Australia, in A.M. Gill, R.H. Groves and I.M. Noble eds Fire and the Australian Biota (1979).

Walker, D. & J.R. Flenley, Late Quaternary vegetational history of the Enga District of upland Papua New Guinea. *Proc. Roy. Soc. London,* B. in press (1979).

Williams, P.W., I. McDougall & J.M. Powell, Aspects of the Quaternary geology of the Tari-Koroba area, Papua - *J. Geol. Soc. Austr.* 18 (1972) 333-47.

10. HISTORY OF THE EXPLORATION OF THE HIGH ALTITUDE REGIONS OF NEW GUINEA

That an alpine vegetation could be found in New Guinea can be surmised from the journal of the Dutch sea captain Jan Carstensz of his 1623 voyage in the ships Arnhem and Pera. On the 6th of February that year, he sailed along the south coast of New Guinea and described what he saw as follows:

"verthoonde hem overhooch geberchte dat op vele plaetsen met snee bedekt lach wesende certain vrij wat vreemts als op bergen, soo na de linie aquinoctialis gelegen, snee te hebben."

which translates into:

"showed him a very high range of mountains that in many places was white as it was covered with snow, which certainly is something strange to see on mountains so close to the equator."

What this view was, approximately, is shown in Plate 57, a view from the southeast coast. Plate 58 gives the view from the North. Few people have seen this view as most of the time the Snow Mountains, or Carstensz Moutains, are covered with clouds and only in the early mornings is it possible to see the snow covered peaks.

However, it was not until November 7, 1909, that this snow was reached, not at the Carstensz Mountains but on Mount Wilhelmina (Plate 59) some 175 km more to the east, when H.A. Lorentz on his third expedition in Dutch New Guinea (1909-1910) reached the glaciers at 4611 m (Lorentz, *Geographical Journal of London* 37, 1911, 491). The Carstensz Mountains glaciers were not reached until November 28, 1936 when H. Colijn and J. J. Dozy, by way of the Otomana Valley, Carstensz Meadow, and Meren Valley stepped on Meren Glacier. (Plate 69).

O. Beccari, in 1872 and 1875, was the first to penetrate into an area near where alpine elements were growing during his extensive trips in the Vogelkop Peninsula. He started out from Andai on the east coast of the peninsula south of Manokwari. However, he reached only an altitude of 1100 m and no alpine elements are represented in his collection.

In 1888 H. Zöller, a reporter for the Kölnische Zeitung, advancing from the Astrolabe Bay to the Finisterre Mountains at 2000 m altitude, looked southwest across the Ramu Valley and was the first to see and

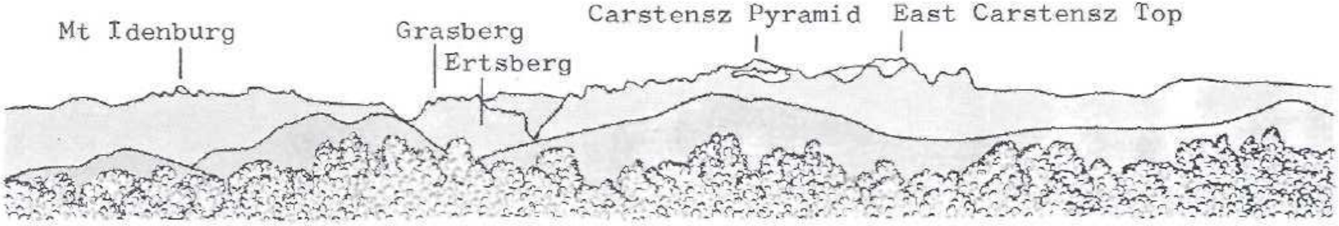

Plate 57. View from south coast of Mt Carstensz and Mt Idenburg at a range of 70 km. In 1623 when Jan Carstensz saw it the ice would have been twice as extensive. (From color slide by G.S. Hope, Dec. 1971).

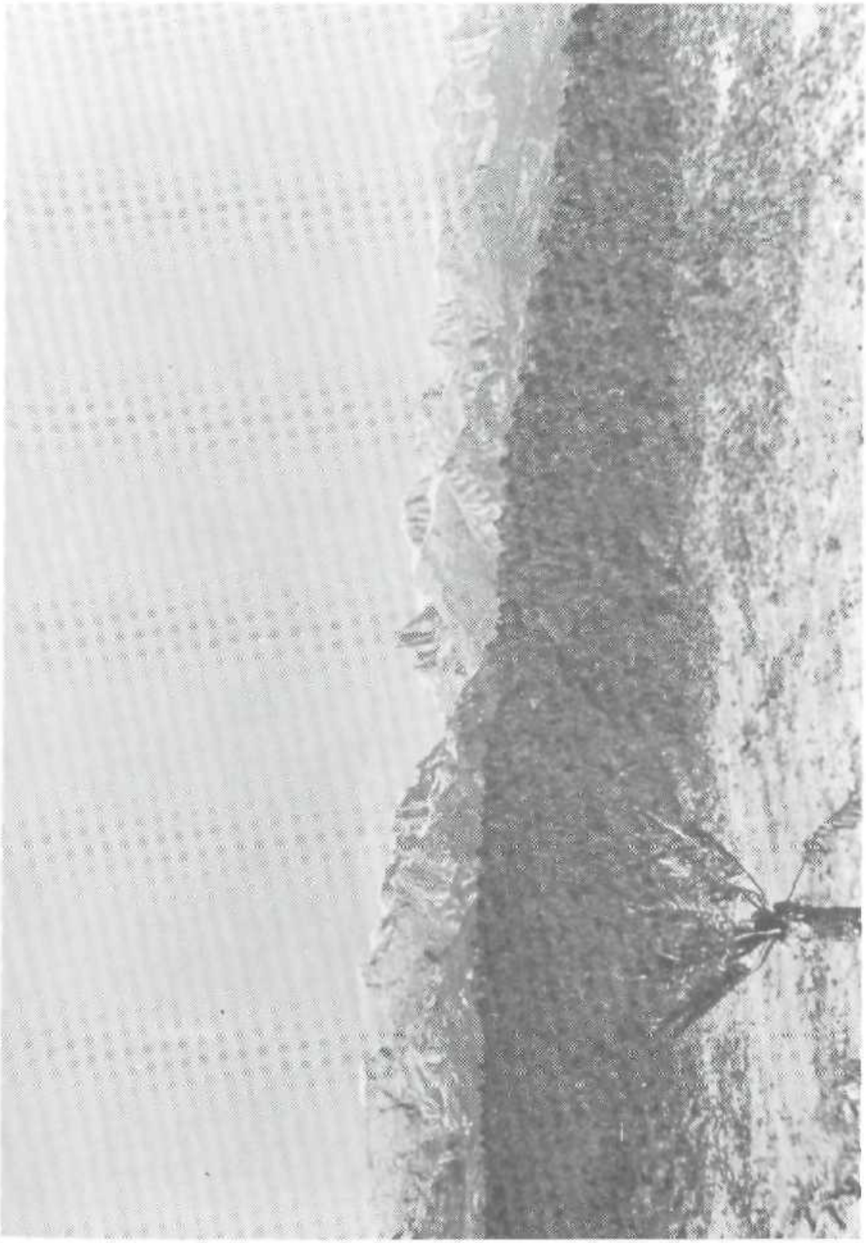

Plate 58. Subalpine forest on moraine ridges and treefern shrublands in valley bottoms. Mt Carstensz from the north and Kemaboe Plateau in foreground, 3550 m. Jan. 1972 (Photo G.S. Hope).

Plate 59. Oranje Mts, Mt Wilhelmina viewed over Lake Habbema (3225 m) and beyond lake, subalpine forest. In foreground ***Papuacedrus papuana*** and the treefern ***Cyathea tomentosissima*** grow in a shrubbery of ***Rhododendron*** and ***Styphelia nubicola*** on peat-covered sandstone. Large clumps of ***Gahnia javanica*** in lower left corner. August 1938 (Photo L.J. Brass).

name the Bismarck Range. The highest peaks he named Mount Otto (3569 m), Mount Herbert (4160 m) (Plate 60), Mount Wilhelm (4510 m) and Mount Marien (2440 m) but it was not until 1933 that civilians and missionaries crossed native tracks into the Upper Chimbu area between Mount Otto and Mount Wilhelm.

The first botanical specimens, however, were not brought down until 1889, 266 years after the sighting of snow, to prove that an alpine flora existed. Sir William MacGregor, at that time Administrator of the British Crown Colony of New Guinea, climbed Mount Victoria (11-12 May) (Plate 61) and Mount Knutsford (June 6, 16). In 1896 Sir William once again was in the alpine regions, this time at Mount Scratchley (September 12-14) and Mount Victoria (September 20). In the years 1890 and 1891, G. Belford with the Victorian Branch of the Royal Geographical Society of Australasia explored among others, Mount Yule, a massive square block of mountain somewhat isolated from the Owen Stanley Mountains. In 1896 A. Giulianetti explored the Wharton Range (20 July - 10 August, 24 August - 17 September, 20 September - 17 October). During part of the year 1897 Sir William, by now Lieutenant Governor General of Papua, and Giulianetti, together or separate, explored several summits in the Owen Stanley Mountains again. Both together with A.C. English, explored the Wharton Range and Mount Scratchley (9-27 October). Between September 18 and 29, Giulianetti attempted to climb Mount Albert Edward (Plate 62) but did not reach the summit. This feat was carried out in early 1906 by C.A.W. Monkton, an Australian Resident Magistrate of New Zealand origin. In the same year J.A.K. Mackay or G. Belford reached the summits of the Owen Stanley Mountains.

Sir William's plant specimens were given for identification to Ferdinand von Mueller, botanist and founder of the Melbourne Herbarium and Botanic Gardens. In 1889 (Trans. Roy. Soc. Victoria, N.S. 1, 2, 1-46) von Mueller described many species based on this material, and for the first time it was shown that such temperate genera as *Ranunculus*, *Euphrasia*, and *Viola* were growing in the high regions of New Guinea.

In 1904 A. van Oosterzee reached the Angi Lakes (Plates 72, 73) in the Vogelkop Peninsula but no alpine species, nor for that matter any other botanical material was collected with the exception of some living material that was sent to Bogor. In 1907 and later again in 1909, A.E. Pratt and his two sons stayed for about a year at the Angi Lakes, but only a few, mainly living plants were collected and sent to the Bogor Botanic Garden.

Though von Mueller's paper created a stir amongst botanists, the actual exploration of the alpine regions was not systematically undertaken

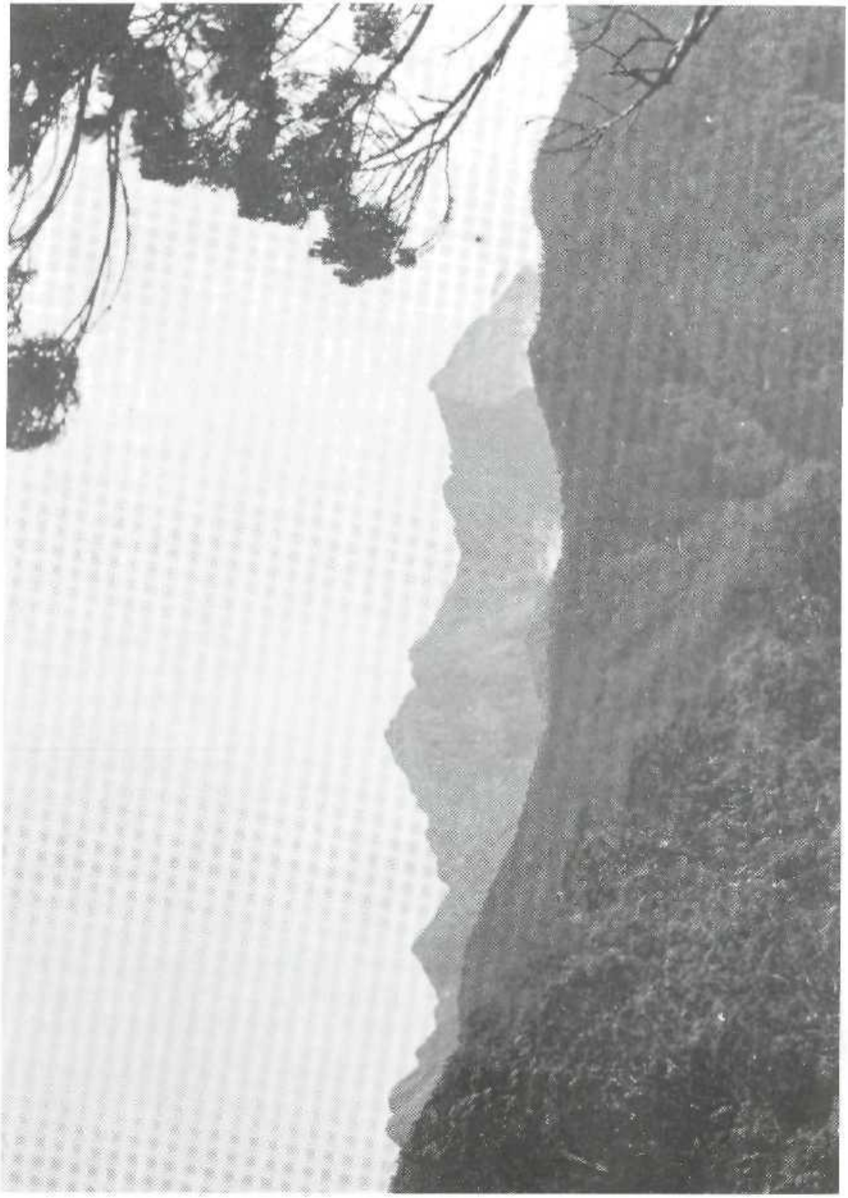

Plate 60. Mt Herbert (about 4200 m) viewed from Imbuka Ridge, Mt Wilhelm, 3650 m, looking northwest. *Dacrycarpus compactus* in foreground at right. Forests in central ridge mainly Nothofagus-conifer forests. (Photo J.M.B. Smith).

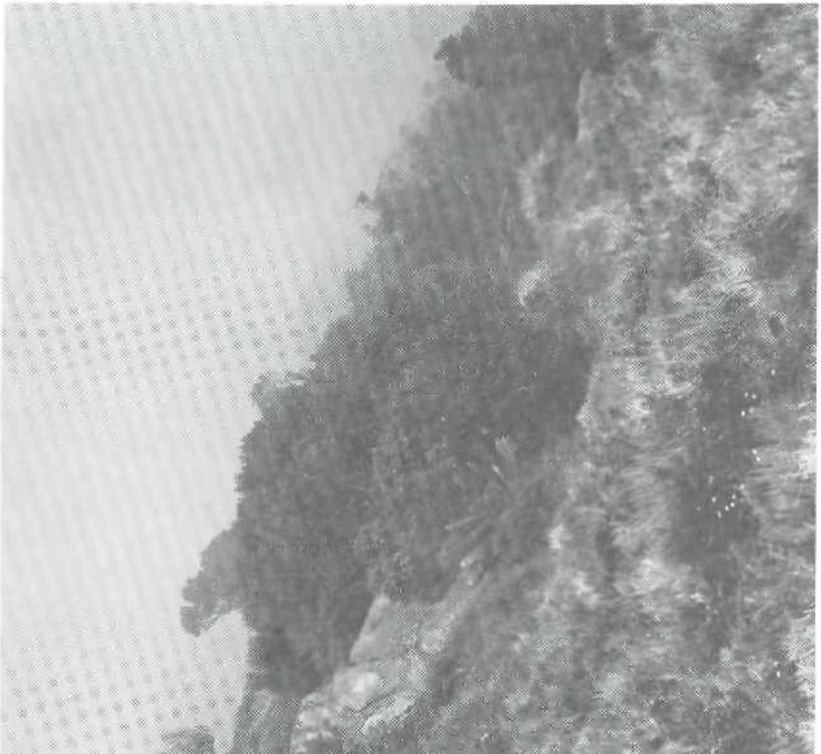

Plate 61. Mt Victoria area, in foreground the Rock Pile, 3660 m, leading to Mt Service, 3800 m. Alpine grasslands with a dominance of *Papuapteris linearis.* 21 May, 1976.

Plate 62. Central peak of Mt Albert Edward, 3980 m. Alpine grasslands with rocks, scattered grass tussocks, and short-grass community. June 1933 (Photo L.J. Brass, the right hand person in the picture).

until at least in the Dutch part, the Dutch Military Explorations between 1907 and 1915.

In 1903 H.A. Lorentz made his first trip to New Guinea in a team under the leadership of C.E.A. Wichmann. This exploration remained mainly in the lowlands. On his second trip to New Guinea Lorentz himself was in charge of the exploration team. In this 1907 exploration (the 1st Lorentz Expedition), Djibdja, student mantri of the Botanical Garden in Tjibodas, Java, was charged with collecting plants. Since he did not like the low temperatures in the mountains he pretended to be ill. No botanical specimens of the higher regions of the Hellwig Mountains were therefore collected. However, some plant material was collected by G.M.Versteeg, Medical Officer of the Army.

In the first few years of the Military Explorations, mainly the lower regions of the island were explored. On April 28, 1908, B. Branderhorst as Military Surgeon of the Army reached the summit of the Hellwig Mountains, assisted by Pringgo Atmodjo of the Bogor Herbarium. In February (4-25) 1911, A.C. de Kock reached the summit of Mount Goliath.

The 2nd Lorentz Expedition to Dutch South New Guinea in 1909 and 1910 was in particular charged with climbing Mount Wilhelmina and asked to report whether snow-covered mountains really existed in New Guinea. J.W. van Nouhuys, Captain of the Royal Dutch Navy accompanied Lorentz but was not allowed to go to the summit of Mount Wilhelmina. He collected well above the 3000 m contour on the lower slopes but the numbers were few. L.S.A.M. von Roemer, Medical Officer in the Navy, another member of the team, reached the snow, but once again, he too was not allowed to go to the summit. Lieutenant D. Habbema of the Army, was luckier in that he was allowed to accompany Lorentz to the summit on November 7, 1909. Botanically this last part of the trip was not a profitable one as only 7 specimens were collected. With other material collected by van Nouhuys and von Roemer these were the first alpine elements brought back from the Dutch part of the alpine regions. On November 9, 1909, when Lorentz and Habbema were on the summit of Mount Wilhelmina a lake north of the mountain was seen which later was given the name of Lake Habbema (Plate 59). During the descent from the summit, Lorentz slipped down one of the higher slopes and was seriously hurt. In much pain and after a long miserable trip, he reached the Mamberamo River at Alkmaar Bivouac, and was transported back from there to Java.

The 3rd Scientific Expedition to Dutch South New Guinea in February 1913 under the command of Captain A. Franssen Herderschee, reached the snow of Mount Wilhelmina also. The expedition was organized by the "Indisch Comité voor Wetenschappelijke Onderzoekingen", in co-operation with the "Maatschappij ter bevordering van het Natuurkundig Onderzoek der Nederlandsche Kolonien." Botanist during this exploration was my former teacher, A. Pulle. This team followed almost the same route as taken by the 2nd Lorentz Expedition of 1909-1910. As on previous trips, botanists were not allowed to go to the summit of Mount Wilhelmina. Pulle himself collected many alpine species anyhow, but it was G.M. Versteeg who went to the summit, reaching it on February 21, 1913. Though officially assigned to collect zoological specimens he also collected botanical specimens on the last stretch to the summit. Many of his specimens have been included in Pulle's series and are quoted in this publication as Pulle [Versteeg].

Independent from the southern military explorations K. Gjellerup in 1908 explored several parts along the north coast of the Dutch area. He collected in the Arfak Mountains and elsewhere. In 1913 Miss L.S. Gibbs also went to the Arfak Mountains and brought back a fairly large collection of alpine species. M. Moszkowski in December 1910, after exploring extensively along the north coast and along the Mamberamo River, made an attempt to reach the snowline, but failed to do so on account of food shortages. In the same year, in November and early December, M.S.C. Smith, Director of Mines and Agriculture in Papua, climbed Mount Murray and collected mostly ferns and mosses. Most of his collections were later lost in the Kikori River.

It was not only the Dutch who tried to reach the snow of New Guinea. In 1909-1910 a British expedition sponsored by the Ornithologists Union under the leadership of W. Goodfellow, the Mimika Expedition, tried to reach the Carstensz Mountains from the south following the Mimika River. Following the wrong valley, the expedition stopped well below the alpine limits. In 1912 a second expedition sponsored by the Ornithologists Union under the leadership of A.F.R. Wollaston once again tried to reach snow on Mount Carstensz. Following the Utakwa, Tsingarong, and Bandarong valleys, this expedition fared only slightly better than the first expedition. The 2nd expedition, though reaching the glaciers, was brought to a halt under the van de Water Glacier by a steep unclimbable slope. During the Mimika Expedition Wollaston was not only medical officer and entomologist, but was also the botanist. On the 2nd expedition C. Boden Kloss of the Federal Malay States Museum at Kuala Lumpur, Malaya, was charged with the botanical collecting. The expedition followed the valleys mentioned but at an altitude of 4534 m progress was barred "on the one side by precipitous rocks, and on the other by a steep wall of ice, the abrupt termination of the ice-field above" (Wollaston, *Geographical Journal of London* 43, 1914, 258).

Though the summit of the Carstensz Mountains was not reached, a large number (1903) of mostly alpine species were collected. The material was subsequently studied by H.N. Ridley (*Transactions of the Linnean Society of London*, ser. 2, Bot. 9, 1916, 1-264). This report and von Mueller's 1889 paper gave the botanical world an outline of the alpine flora of New Guinea. Though later expeditions added a large number of new species, the picture did not essentially change.

On the other side of the island in October 1912, C. Keysser, an evangelical missionary on the Neuendettelsauer Missionsgesellschaft climbed the Sarawaket Mountains. Erroneously he states that he climbed Mount Bolan (*Petermann's Mitteilungen* 59, 1913, 177-181). A mountain with that name does not exist and what he climbed was in fact Mount Bangeta (see also Löffler, *The Australian Geographer* 11, 1971, 463). Much of his material has been described in the various volumes of the *Botanische Jahrbucher*. In June and July Keysser made a second trip to the Sarawaket Mountains (Plate 63). The results were extensively published in the same periodical. Many orchids were collected and these were studied by R. Schlechter. He also provisionally named other specimens but his death in 1925 prevented further studies.

In December 1913 Miss L.S. Gibbs visited the Anggi Lakes which led to the publication in 1917 of her *Contribution to the Phytogeography and Flora of the Arfak Mountains*.

Lieutenant L.A.C.M. Doorman in 1914 by way of the Mamberamo and Rouffaer Rivers, ultimately reached the summit of a high mountain, Kemboe Top, on November 2-23. This 3550 m mountain was later renamed Mount Doorman. During this exploration by the 3rd Mamberamo Expedition under Captain J.V.L. Opperman, Doorman, at 2650 m altitude, had a magnificent view of the central ranges with the snow covered Idenburg and Carstensz Mountains (see LeRoux, *De Bergpapoea's van Nieuw Guinea*, etc. 1, 1948, 40). Few botanical collections were made.

In 1912 J.H.I. le Cocq d'Armandville reached the Johannes Keyts Mountains (December 7, 1911 - January 5, 1912). R.F. Janowsky in 1913 briefly reached the alpine regions. He climbed the summit of the Weyland Mountains, 3720 m, west of the Wissel Lakes, on or about June 15. However, no alpine species were collected.

When the war broke out in 1914 it signalled the end of all botanical explorations indefinitely, most certainly so in the alpine regions. These always have been difficult to reach, then even more so than now, and during a war funds are not available for this highly specialized type of research. After the war, in 1918, the situation was considerably changed.

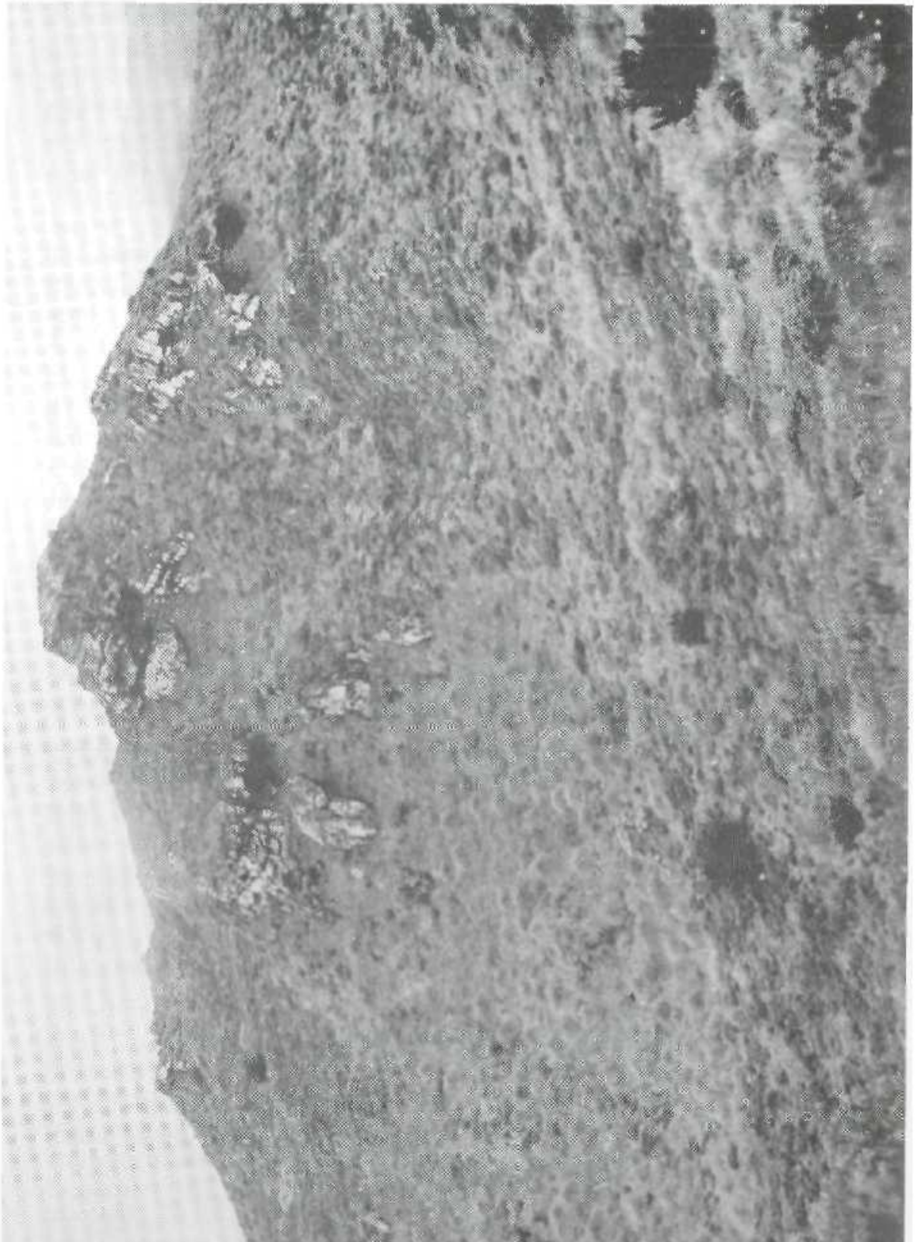

Plate 63. Sarawaket Mts, Mt Sarawaket seen from the SE slope of Mt Bangeta, 4100 m. Grasslands dominated by ***Chionochloa archboldii*** with scattered *Coprosma* shrubs. Nov. 1963.

Holland had remained neutral but there still was no money available to open up the New Guinea area. Hesitantly, much later, a few small outposts were established, e.g. at the Wissel Lakes in 1938-1939 at Enarotali, but by then the shadow of a larger World War was already looming up. Germany lost its New Guinea colony in 1918 and Australia was mandated by the League of Nations to administer the Territory of New Guinea. The Germans, in the short time of their administration (1889-1918), had energetically developed their colony, a development still benefiting the Australians long after Germany's surrender. Australia administrated both Papua and New Guinea but did not pay too much attention or money for the development of their parts.

After World War 1, the exploration of New Guinea and the alpine regions in particular, was taken up in the Dutch part by a large expedition sponsored by the "Indisch Comité voor Wetenschappelijke Onderzoekingen", aimed at climbing Mount Wilhelmina from the north.

In early February 1920, an expedition under Captain A.A.J. van Overeem, a great uncle of the present author, started from the Mamberamo River. The botanist accompanying this expedition was H.J. Lam, later to become Director of the Rijksherbarium, Leiden, and eventually the one who set me on the thorny path leading to the present volumes. During this trip Lam reached Mount Doorman on October 16 and November 6. Much new material was brought back and the identifications and publications of the results are mainly found in *Nova Guinea* and the *Botanische Jahrbücher.* Lam's report, — the *Fragmenta Papuana* I-VII (*Natuurkundig Tijdschrift voor Nederlandsch-Indie* 87, 88, and 89 of 1927, 1928, and 1929), is a classic for the study of the New Guinea vegetation and flora. It gives a clear picture not only of what Lam saw and experienced but at the same time drew up an outline of the vegetation of this big island. Together with his later *Materials towards a Study of the Flora of the Island of New Guinea* (*Blumea* 1, 1934, 115-159), a solid base was laid for further studies of the flora and vegetations of New Guinea, a base used to much profit by the author in his studies. Lam's *Fragmenta* were later translated into English by Miss Lilian Perry and published in *Sargentia* 5, 1945, 1-196, making the most important data more widely available.

The year 1925 brought a young ecologist to New Guinea, destined to increase not only our knowledge of the New Guinea flora tremendously, but also the amount of available material for botanical studies. Leonard John Brass carried out an Arnold Arboretum sponsored expedition in southeast New Guinea along the Gulf of Papua, ranging from sealevel at Port Moresby, Kikori River, etc., to the summits of the Owen Stanley

Mountains (May 4 - June 6), and the summit area between Mount Clarence and Mount Brown (May 19). Almost 1200 numbers were brought back and these were mainly studied by C.T. White, Government Botanist and Queensland. Most of the studies of this material appeared in the *Journal of the Arnold Arboretum.* Over the years White developed into one of the few experts on the New Guinea flora.

The Kremer expedition of 1921-1922 under Captain-Lieutenant J.H.G. Kremer, started also from the Mamberamo River and by way of the watershed between the Swart River and the Baliem Valley, crossed the Baliem Valley (17 November). On December 4, 1921, the summit of Mount Wilhelmina, 4750 m, was reached. P.E. Hubrecht, geologist of this exploration, also collected some botanical specimens.

C.E. Lane-Poole, an Australian forester, climbed Mount Sarawaket and Mount Bangeta in 1923 and collected several alpine plants near the summit. He was the first to point out that the alpine grasslands probably could be of secondary origin as he found evidence of forests having existed up to or much closer to the summit than is found presently. Much of his material is in the Brisbane Herbarium, though the material of the early parts of his journey was lost. In 1924, Lane-Poole climbed Mount Otto but no plants were collected.

In 1926 an airplane was used for the first time in natural history collections. The Stirling Expedition (Dutch-American Expedition to New Guinea) explored mainly in the Meervlakte, the large swampy plain north of the central ranges. W.M. Docters van Leeuwen accompanied this expedition as botanist but nowhere came near the alpine flora. The plane assisted this expedition in early April but it turned out not to be a great success. By July the plane had to be taken out of commission. Remnants of the plane were observed by J. van Eechoud, Resident of Dutch New Guinea in 1939, near the Batavia Falls in the Mamberamo River (Vergeten Aarde, 1952, 35). However, it was a start and anybody who has been in New Guinea, particularly in the lower level, swampy parts, can appreciate the assistance of a plane.

The successful attempt to reach the summits of the Carstensz Mountains in November 1936 by A. Colijn and his team was to a large extent made possible by aerial reconnaisance and supply well in advance of the actual trip. Taking into account when studying a map that it has its origin often only after tedious fieldwork (Plate 64) with instruments sometimes failing or not entirely accurate — after all, one second time difference in your chronometer makes a difference of about 400 meters in the field — it becomes obvious that an aerial picture gives a far more accurate chance of reaching one's aims. What would Goodfellow and Wollaston have given for an aerial picture of the Mimika River and

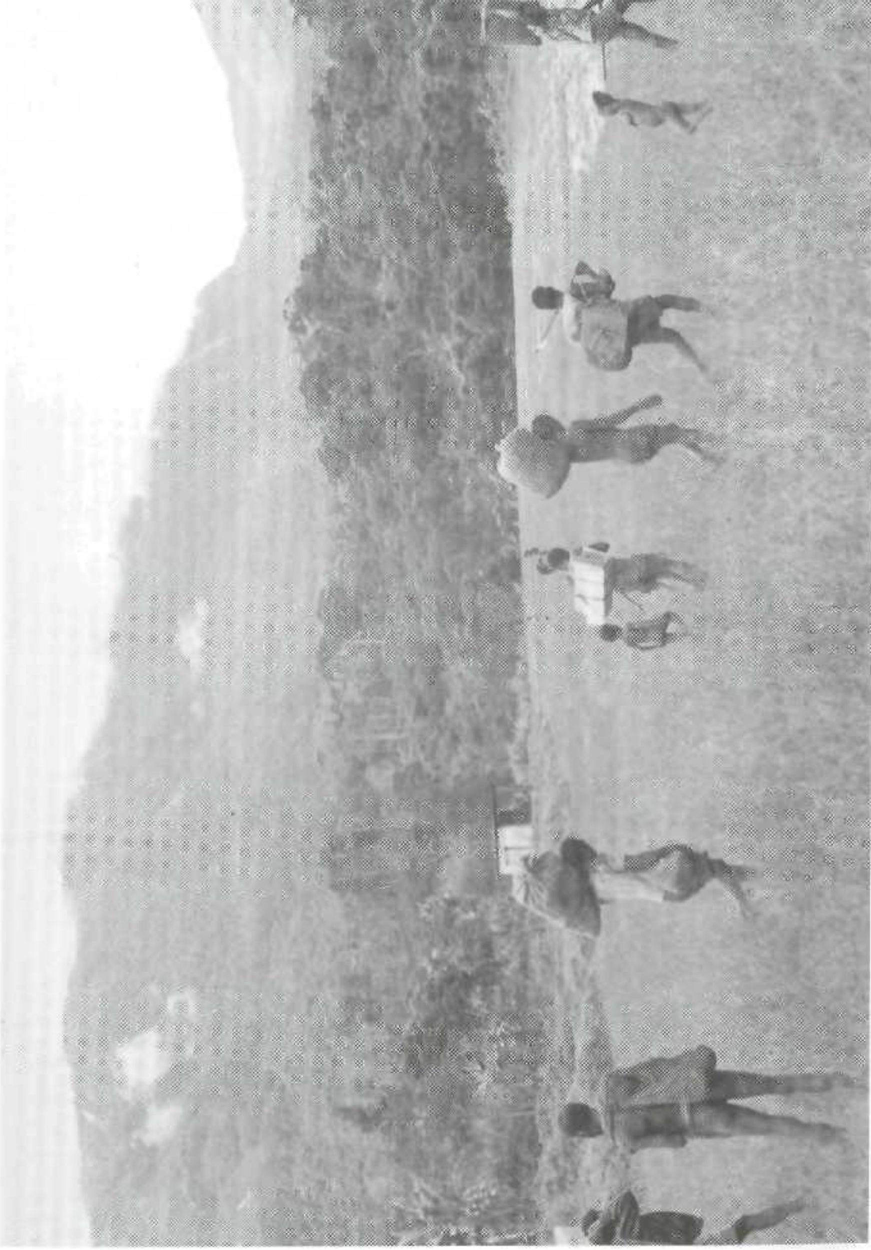

Plate 64. The old-fashioned way, a team of carriers putting one foot before the other. Departure of a carrier team from Feramin to the Victor Emanuel Range in the background. July 1976.

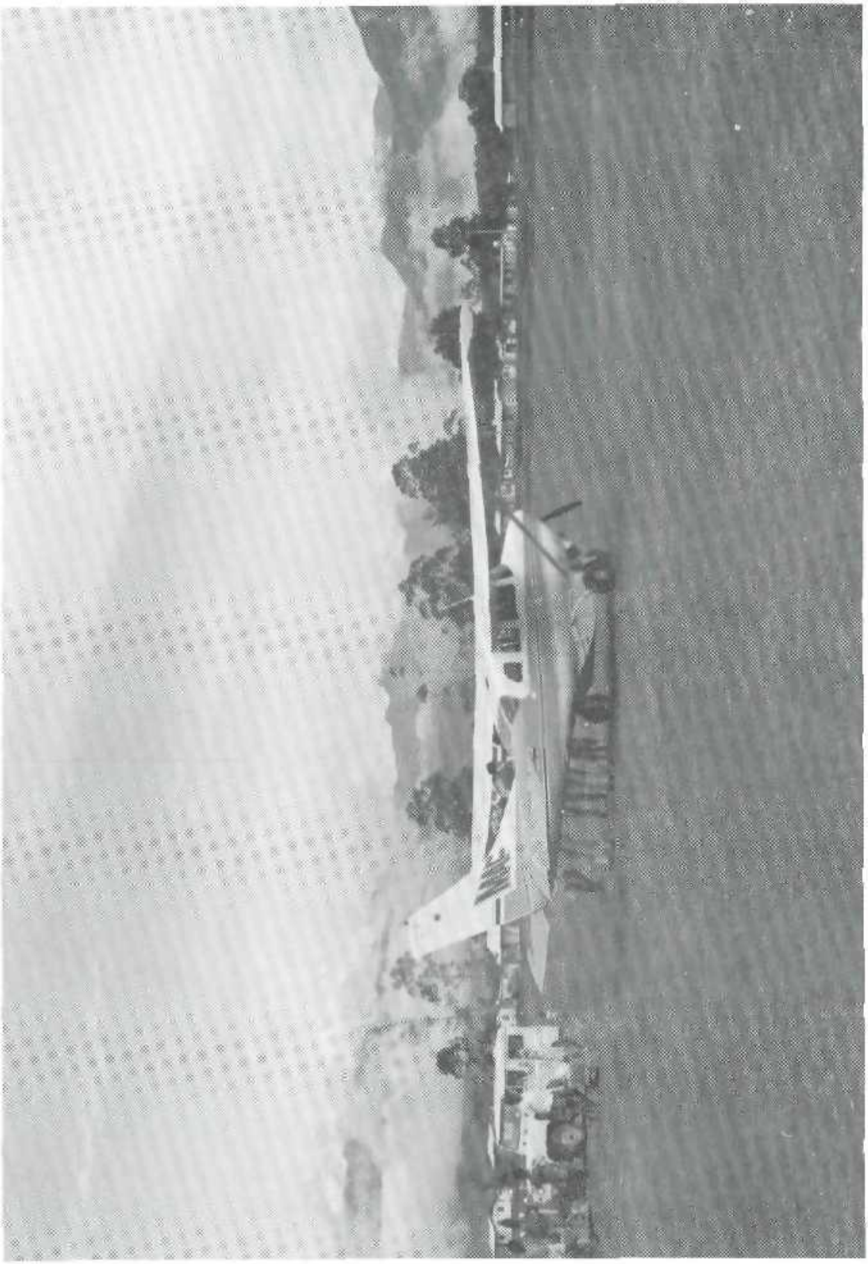

Plate 65. The modern way, a plane of the Missionary Alliance Fellowship at Telefomin Airstrip. This plane was used to shuttle the van Royen teams to Feramin saving a full days walk. July 1976.

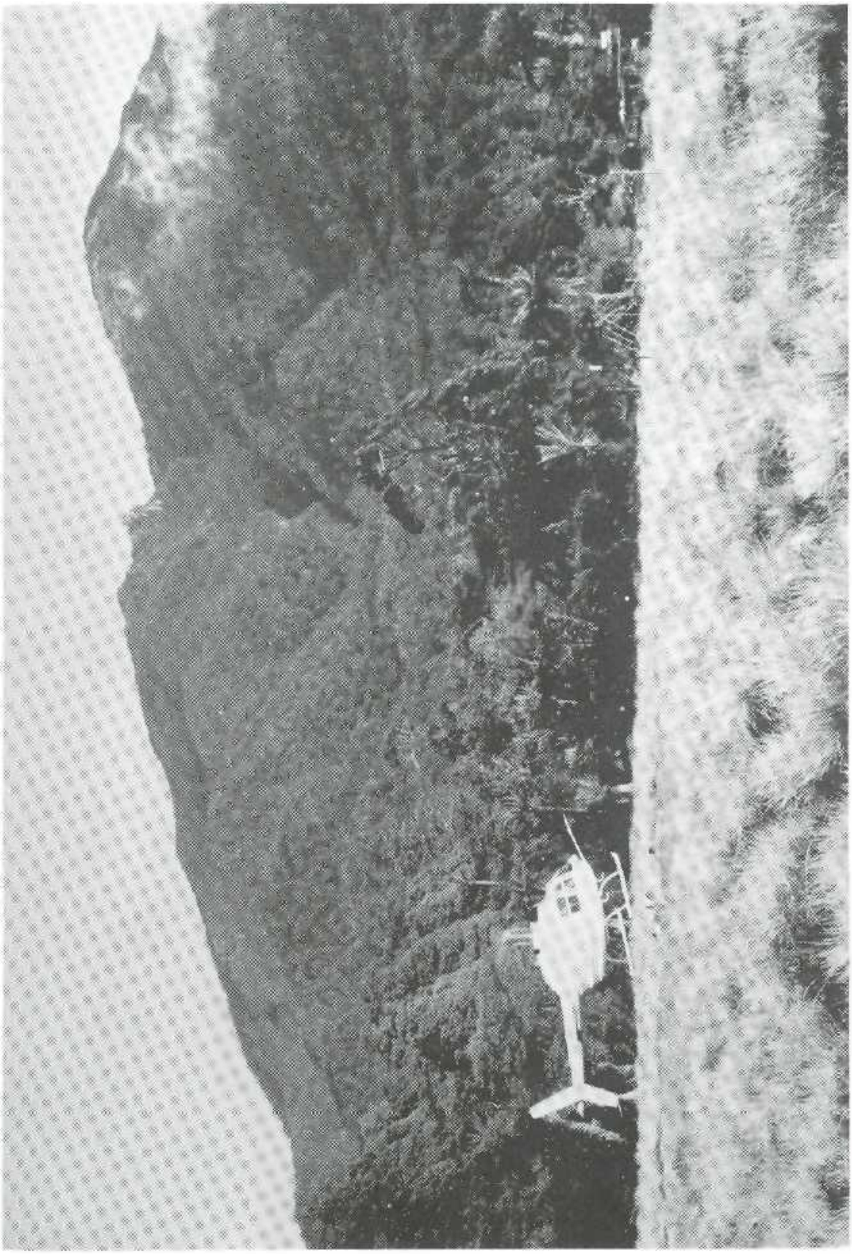

Plate 66. The best way, use a helicopter! This modern transport was used by the author to shuttle some personnel from Manumu to Iswan Swamp. Here the helicopter picks up the author to bring him back to Manumu. The Korean pilot Kim did not know the whereabouts of this team but still managed to find us. At right Mt Service, in centre the Rock Pile. June 1976.

Plate 67. Northwest summit of Mt Giluwe seen from the north. The central peak is Mt Belumba, to the right Mt Dekwak, 4400 m. At very right behind the branches the southern summit of Mt Giluwe. Secondary grasslands almost up to the summits, in center a strip of subalpine shrubbery with *Vaccinium, Pittosporum,* and *Coprosma* species. In foreground mainly *Deschampsia klossii.* June 1976.

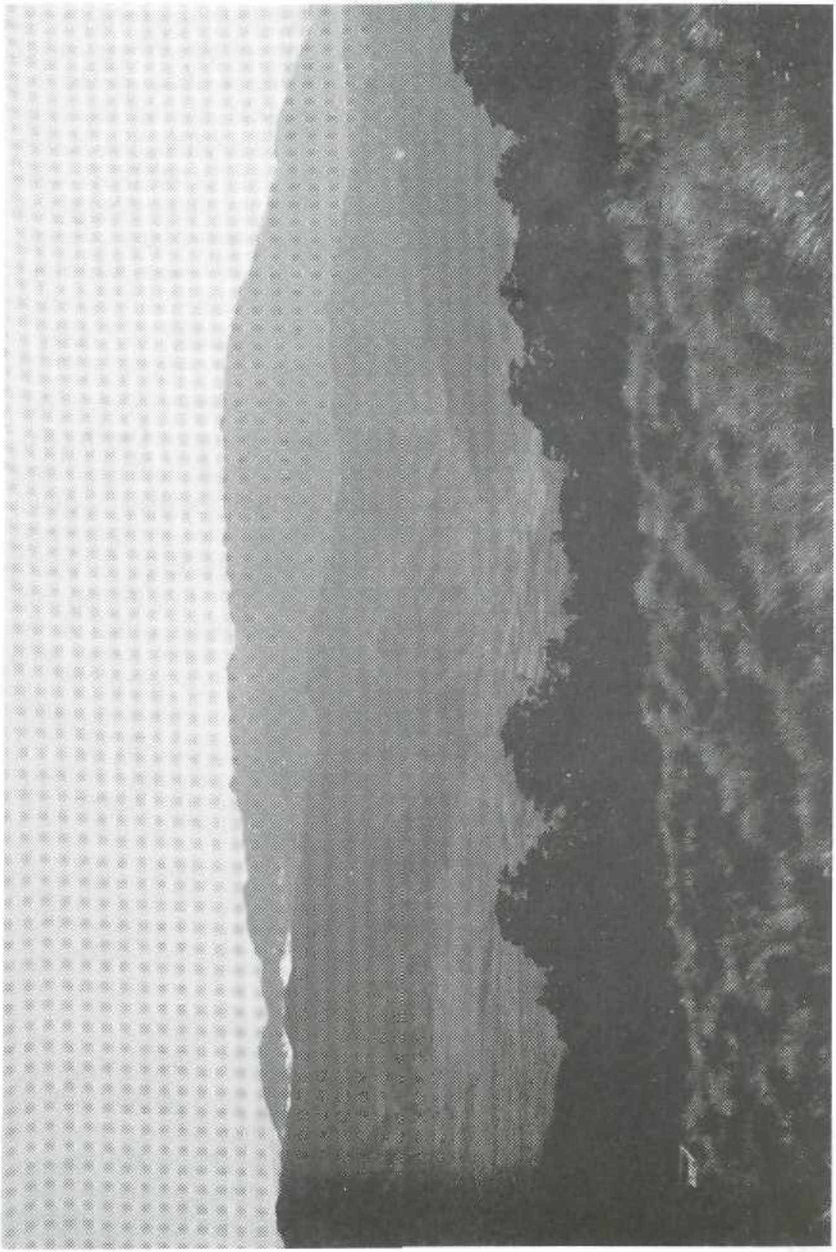

Plate 68. Mt Hagen Range seen from NE slope of Mt Giluwe at 3780 m. In foreground grasslands dominated by ***Deschampsia klossii.*** Subalpine shrubbery behind it composed of ***Podocarpus, Dacrycarpus, Phyllocladus, Rhododendron*** and ***Nothofagus*** species. In centre Tambul Valley with the gardens of Tambul Village. June 1976.

bordering valleys in order to successfully reach the Carstensz! It was also the plane that made possible the discovery of the Wissel Lakes, named after Commander F.J. Wissel who piloted the plane, in October 1936 (Plate 65). The plane also made a success of the mountain exploration of the 1938-1939 3rd Archbold Expedition to Mount Wilhelmina. More recently, the use of helicopters in 1959 enabled the Star Mountains Expedition to penetrate into the Mount Juliana and Mount Antares region. It also enabled me to study the Iswan - Mount Victoria area in 1976 when a helicopter dropped me in the swamp as fresh as a daisy without having to go through the long walk from Port Moresby to the Owen Stanley Mountains across the lowlands, a trip of at least 7 days (Plate 66).

After 1926 it seemed that the highland studies had come to a standstill. The initial flurry of establishing administrative centers in Dutch New Guinea came to an end when no additional funds were made available by the Dutch government. In the Australian part, no botanical exploration at all took place in the high mountains. This does not imply however, that nothing happened. In his constant search for gold, E.W. Rowlands in 1929 crossed over the Bismarck Range without collecting plants, gold being the more important commodity. Also it was the time of the wanderings of the three brothers Michael, Daniel, and Jim Leahy, who discovered the extensive Wahgi Valley in 1933, while in 1934 they climbed Mount Giluwe (Plate 67). The last of these extensive patrols, more important for administrative reasons than botanical, was the Mount Hagen-Sepik Patrol of 1938-1939 led by Assistant District Officer Jim L. Taylor. Provided with air communications and support they covered the areas north and south of the Papua-New Guinea border from Mount Hagen to Telefomin. Also in the thirties, missionaries were very active and in 1930/1931, the Lutheran Mission established a mission in Kainantu. In November 1933 Father William Ross crossed over the Bismarck Range from Bundi to the Chimbu Valley and from there proceeded to Mount Hagen.

In 1928/1929 E. Mayr, an ornithologist, visited New Guinea and collected mainly birds and a number of plants in the Cycloop Mountains and in the Vogelkop Peninsula. In the latter area he reached the Angi Lakes in June 1928. In 1929 he mainly explored in the Territory of New Guinea in the Sarawaket and Finisterre Mountains, among others. In 1933, with Brass as botanist, the 1st Archbold Expedition to New Guinea started botanical explorations in East New Guinea. In the period of June 16 - July 12, the summit area of Mount Albert Edward (Plate 62) was explored. The Archbold Expeditions were the brainchild of Richard Archbold, Research Associate of the American Museum of Natural History in New York. His attention was drawn to New Guinea in 1932 and in 1933 the first expedition was mounted. Over the years seven Archbold Expeditons went to various parts of New Guinea. At present the Archbold Expeditions Foundation is established in the American Museum of Natural History. It has its own staff working on the zoological material that is stored in the museum. The botanical collections are kept mainly in the herbarium of the Arnold Aboretum, Cambridge, Massachussets, except for the 1933-1934 material which is in the herbarium of the New York Botanical Garden. Duplicates have been distributed to many institutions and over the years Brass' collections have been studied by a variety of scientists. At first E.D. Merrill, L. Perry, A.C. Smith and others, but in later years often by the staff of the Rijksherbarium, Leiden, for the already extensive publications of the *Flora Malesiana*.

In 1935 H.J.T. Bijlmer climbed and crossed the Charles Louis Mountains southwest of the Wissel Lakes but no botanical material was collected. In 1935-1936 C.E. Carr spent 7 months in the Owen Stanley Mountains. He was mainly interested in orchids, but collected other plants as well though few alpine ones. He died of black fever in New Guinea. His material went to the British Museum and Singapore but is not yet fully worked over.

An interesting couple of botanists though not trained as such were Joseph and Mary Clemens, missionaries with the Lutheran Mission. They worked first in China and Indo-China, but went later to New Guinea, 1935-1942. Joseph died in 1936 but Mary went on collecting plants until forced by the Japanese invasion to leave Lae in 1942. Her last collections were left behind, were recovered by the Japanese, and after the war turned up in Japanese herbaria. In 1937 she explored the Sarawaket Mountains but it is doubtful whether she herself went to the summit. The numbering of her collections created various problems, particularly in the alpine material. Some of the numbers contain various species and it is likely that native helpers brought the material back to the lower camps where Mary wrote out the numbers.

During the Colijn Expedition of 1936 to the Carstensz, F.P. Wissel, the geologist, collected 184 numbers, mostly ferns and mosses. Unfortunately much of this material is scrappy, was not annotated nor studied due to the outbreak of World War II in 1939 and the subsequent occupation of Java by Japan. The collection was tentatively identified though by C.G.G.J. van Steenis shortly after its arrival in Bogor. The material was found back after the war and was further studied by van Steenis and others. The expedition, specifically aimed at reaching the snow at the highest summits ahead of British explorers to satisfy national honours, reached the Nggapoeloe at 5030 m and the East

Carstensz Top at 5010 m between November 30 (ascent of East Carstensz Peak) and December 5 (ascent of Nggapoeloe). An attempt on December 11 to reach the summit of the Pyramid failed by a few feet. Colijn at that time believed that the East Carstensz Peak was the highest summit. An exploration carried out by H. Harrer, Ph. Temple, and B. huizenga in 1962 established that the Pyramid is the higher of the two. Later measurements by the Australian Carstensz Glaciers Expedition 1971/1972 showed that the altitude is 4884 m, slightly different from Colijn's figure, and at the same time leading to the conclusion that all mountains in New Guinea are under 5000 m high (Plate 69).

In 1936 Brass arrived in New Guinea with the 2nd Archbold Expedition Here again a plane was used to fly equipment and personnel to the various localities, but after three months the aircraft was wrecked in early July, forcing the expedition to cancel their original plan to reach the central ranges by way of the Fly River. No material of the high mountains was collected.

More fortunate was the 3rd Archbold Expedition in 1938/1939. The exploration area was Mount Wilhelmina in Dutch New Guinea. Once again a modern way of transport was used, in this case a seaplane, to fly material and staff first from Hollandia to Bernhard Camp on the middle stretches of Idenburg River, and from there, or directly from Hollandia, to Lake Habbema at 3255 m. From the lake, the Baliem Valley was visited where an extensive settlement of a native population was discovered. Coming from the lake, Brass reached Mount Wilhelmina on August 1st and explored the lower slopes in the following few days (Plate 70). Between September 5 and 29, Brass reached the summit and collected extensively in that area. These collections were the largest made near the snowline in New Guinea. The expedition has been the most successful of all high altitude explorations before World War II.

Brass was sometimes assisted by C. Versteegh, later my companion on the 1954/1955 Rijksherbarium Expedition. E. Meyer-Drees, a forester of the Forest Research Institute at Bogor also accompanied Brass on this trip but after some disagreements left in September for Bogor to be replaced by Versteegh. Captain Teerink of the Dutch East Indian Army accompanied Brass to the summit and collected several specimens. In Brass' report (*J. Arnold Arb.* 22, 1941, 271-342) for the first time the major plant communities (p. 333) are given for New Guinea. Though incomplete the main outline of the vegetation remains still the same as it was then. For the alpine vegetation, the refinement came much later in 1969 when D. McVean and L. Wade reported on their studies on Mount Wilhelm. Much of the material collected by Brass has been

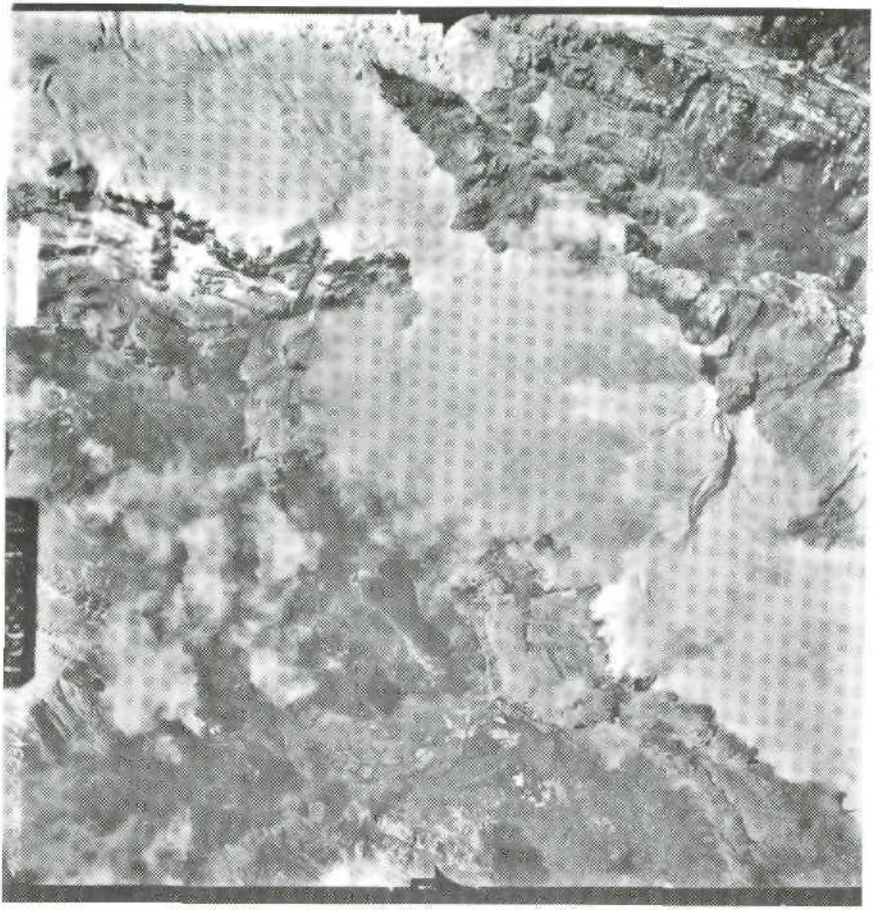

Plate 69. Aerial view of the central parts of the Carstensz Mts. Diagonally the following glaciers, from left to right: Northwall Firn, Meren Glacier running into Meren Valley with the smaller Blue Lake and the larger elongate Green Lake. The two lakes somewhat below the centre are foot-shaped Lake Dugundugu, and diamond-shaped Lake Larson. (United States Air Force, 1942).

reported in the various volumes of the *Journal of the Arnold Arboretum* under the heading *Plantae Archboldianae*, though research and publication about it is continuing to this day.

The Royal Netherlands Geographic Society at the close of the 30's (1939) organised a large expedition to the Wissel Lakes area under the leadership of C.C.F.M. LeRoux. Botanist during this exploration was P.J. Eyma of the Bogor Herbarium. However, though sometimes operating near the 3000 m contour line, Eyma did not collect many high altitude representatives. Much of the material was not yet properly annotated when World War II broke out. The team left New Guinea as soon as it received news of the outbreak of World War II.

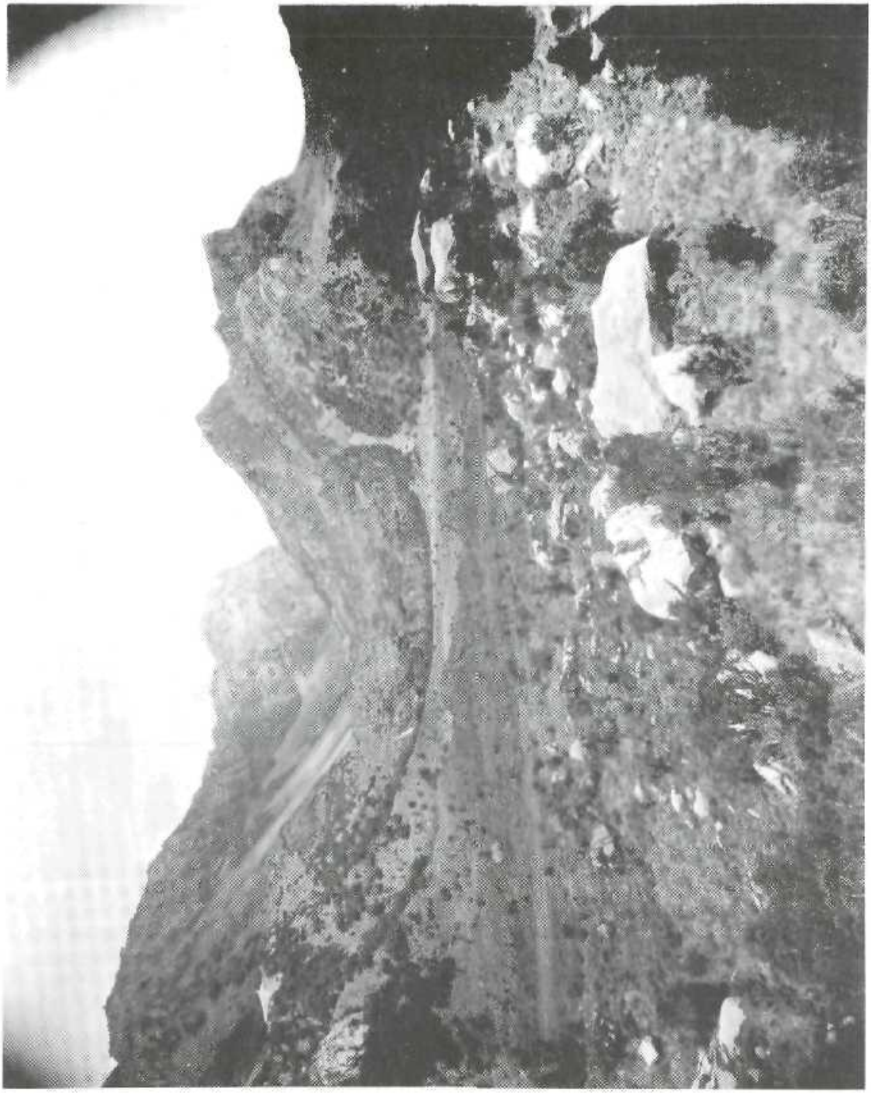

Plate 70. Oranje Mts. View about west up Scree Valley to Mt Wilhelmina from position on a limestone ridge about 400 m east of Scree Valley or 3800 m camp, (position marked by waterfall towards left of center). Stunted subalpine forest of *Vaccinium dominans,* etc. broken by rocks and grassy glades, straggles up the slopes to altitudes of 3900-4100 m. Dotted over the grassland and draped with a dark brown liverwort *(Brass 10150)* is the shrub *Coprosma.* Whitish rocks in foreground and mid-distance are a hard, resonant limestone; grey rocks are sandstone. Geological structure of summit line: 1. left of notch near extreme left - sandstone; 2. main ridge and Mt Wilhelmina - limestone; 3. double false peak right of center - sandstone; 4. saddle and rise on extreme right - fossiliferous marly limestone. Sept. 1938 (Photo L.J. Brass).

Plate 71. Summit of Mt Wilhelm (4510 m) with melting snow. On the summit a beacon for air traffic. (Photo J.M.B. Smith).

Just before Japan entered the war, R. Kanehira and S. Hatusima made an exploration trip mainly in the Vogelkop Peninsula and reached among others, the Anggi Lakes in April 1940. The results of their collecting trips have been reported in the *Botanical Magazine of Tokyo* 55-57, 1941-1943.

In the Australian part just before the start of WW II on August 15, 1938, a Patrol Officer, L.G. Vial, ascended Mount Wilhelm, 4510 m, the highest mountain in Papua New Guinea (Plate 71). On June 27, 1939, he made a second ascent, accompanied by L.O. Noakes. A sounding of the Piundaunde Lakes was carried out by A.M Rapson in September 1959 and recorded as 27 fathoms (49.38 m) for Lake Piunde and 18 fathoms (32.92 m) for Lake Aunde.

The outbreak of World War II signalled tremendous changes in the world, the Pacific, and New Guinea. The northwestern part of New Guinea was occupied by Japan, stopping all botanical explorations in that area. V. de Bruyn, the Jungle Pimpernel, Patrol Officer in the Dutch Administration, was ordered in June 1940 to evacuate the Wissel Lakes administrative post at Enarotali. However, he returned 5 months later and continued his eastward exploration in an attempt to reach the Baliem Valley over the roof of New Guinea. From June until August 1940 he walked eastwards but did not reach farther than 56 km east of Hitalipa, still well away from the valley. Botanical collections were not made. Enarotali was occupied by Japanese forces on May 26, 1943, but the remaining highlands east of the Wissel Lakes remained in Dutch hands.

The situation in the Australian part of the island was just as bad. Japanese forces occupied most of the coastline of the north and northeast coast, penetrating from Lae and Salamaua into the mountains and from Buna to Port Moresby, but were stopped by Australian forces near Kokoda. When the tide turned again in East New Guinea with the arrival of American forces the Japanese Army fell back. Only very minor botanical collecting in the high mountains seemed to have been carried out by C.R. Stonor on Mount Hagen and Mount Wilhelm, to which he returned in 1949.

Dutch New Guinea after the capitulation of Japan in August 1945 was at the start of a time promising extensive development, but also drama and disappointments. The Dutch East Indies became, with the exception of Dutch New Guinea, the Republic of Indonesia. Dutch military intervention in Java and the Celebes did not alter the course of history for long and by the Round Table Agreement of the Hague on December 27, 1949, the sovereignity over the Dutch East Indies was transferred to Indonesia. West New Guinea was excluded from the transfer and on

December 29, 1949, the Netherlands changed the Residency of New Guinea into a separate territory with its own Governor, making it a bone of contention with Indonesia until on May 1, 1963, West New Guinea was officially incorporated into Indonesia.

In 1948 A.J.G.H. Kostermans made a short trip to the Anggi Lakes and some surrounding mountains. In 1949 S. Bergman, an ornithologist, also reached the lakes but his botanical collections were small.

Between 1949 and 1963 Holland decided on an accelerated development and later Papuanization of West New Guinea. It meant opening many areas, construction of airstrips, new radio and air communications, light beacons, etc. However, as late as 1957, only half the estimated population was under Administration control, but this included, among others, the large Baliem Valley opened in 1954. The crash program of developing West New Guinea was mainly concerned with education and political development. Scientific explorations were few and most of it was carried out by locally based scientists of the various departments. The Department of Forests founded its own herbarium, based first in Hollandia, later (1958) moving to Manokwari. The first botanist appointed was C. Kalkman, followed by W. Vink. The collections by collectors of the herbarium were mainly made in the lowlands up to about 2000 m.

1949 brought a colourful character to New Guinea. Not a trained botanist but with a burning interest for plants, particularly orchids, Andrée Norma Miller arrived in New Guinea. After some teaching in Bulolo she was appointed to the Lae Botanic Garden in 1956. From that base she made trips to many parts of Papua New Guinea. Also in that position she came in contact with virtually every botanist who visited the eastern part of the island. Though not the easiest person to get along with, her energy and knowledge of the country has been a tremendous help to many of these botanists. I made several trips with her, two of them to the alpine areas of Mount Wilhelm (1962) and to the Sarawaket Mountains (1963). On her own she visited Mount Albert Edward, Mount Giluwe and others. Shortly before the arrival of Andrée, J.S. Womersley in June 1946 was appointed Forest Botanist in the Division of Botany at Lae, to become later the Chief of Division. In this position, where he stayed until 1973, he built up the Lae Herbarium from a poorly housed one in an old Army Quonsett hut to a large, 2-storied brick building in an illustrious garden. In this period of 27 years the Lae Herbarium developed rapidly and several botanists were attached to the division. This group of botanists collected all over the eastern parts of New Guinea. Womersley himself sometimes went to the high altitude regions, sometimes accompanying overseas expeditions. His collection of

New Guinea plants is the largest made in that area and is a valuable contribution to science.

The author in 1954 started a hopefully very long series of explorations sponsored by the Rijksherbarium, Leiden. On my first trip I never reached the alpine grasslands. The closest I came to them was when flying with the Royal Dutch Airlines (K.L.M.) from Hollandia to Merauke and back, the pilot detoured over Mount Juliana. The second exploration from May - December 1961, was accompanied by H. Sleumer. We explored mainly the lowland regions up to 2500 m altitude in the Tamrau Mountains of West New Guinea. Sleumer and I had to beat a somewhat hasty retreat from the Kebar Valley to Manokwari when Indonesian paratroopers were dropped not too far away from our valley. We had to leave our collections behind but fortunately a final flight by a K.L.M. charter managed to get our material out. It was quickly shipped to Holland before West New Guinea was handed over to Indonesia. On both occasions I made large collections but very few species of the alpine regions were represented. After my return to Holland in 1962, Sleumer went on with W. Vink to visit the Angi Lakes area climbing, among others, Mount Sensenemes. (Plates 72, 73).

The last large scale exploration in the highlands of Dutch New Guinea was carried out by the multidisciplinary Star Mountains Expedition in 1959. Assisted by a military party and two helicopters the exploration started from the Sibil Valley in the direction of the Orion Mountains and Mount Juliana. As seemed to be the fate of many botanists in West New Guinea, C. Kalkman and B.O. van Zanten, botanists of the team, were not allowed to climb Mount Juliana. The summit of Mount Juliana at 4700 m, the third of the four permanent snow-covered mountains* in Dutch New Guinea, was reached on September 9. Kalkman and van Zanten, however, climbed Mount Antares (3650 m), though not the summit itself but a peak of 3380 m somewhat more to the west. Most of the collections are in the Rijksherbarium with the exception of the mosses collected by van Zanten which are in Groningen.

In 1950 E.T. Gilliard, an American ornithologist from the American Museum of Natural History, New York, collected several alpine specimens on Mount Hagen and Mount Wilhelm. This was the first, preliminary sampling of the alpine flora of these mountains. His material is kept in the Arnold Arboretum. He also collected in the

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*It was established in 1962 that the snow on Mount Wilhelmina was entirely gone. (Peterson, J.A., G.S. Hope & Mitton, Recession of snow and icefields of Irian Jaya, Rep. of Indonesia - *Zeitschr. Gletscherkunde Glazialgeol.* 9, 1973, 73-87).

Plate 72. The Angi Lakes in the Arfak Mts. View from Mt Kobreimot over Anggi Gigi (1920 m). At extreme left Mt Sensenemes, grasslands with remnants of Nothofagus-Lithocarpus forest. 1962 (Photo H.O. Sleumer).

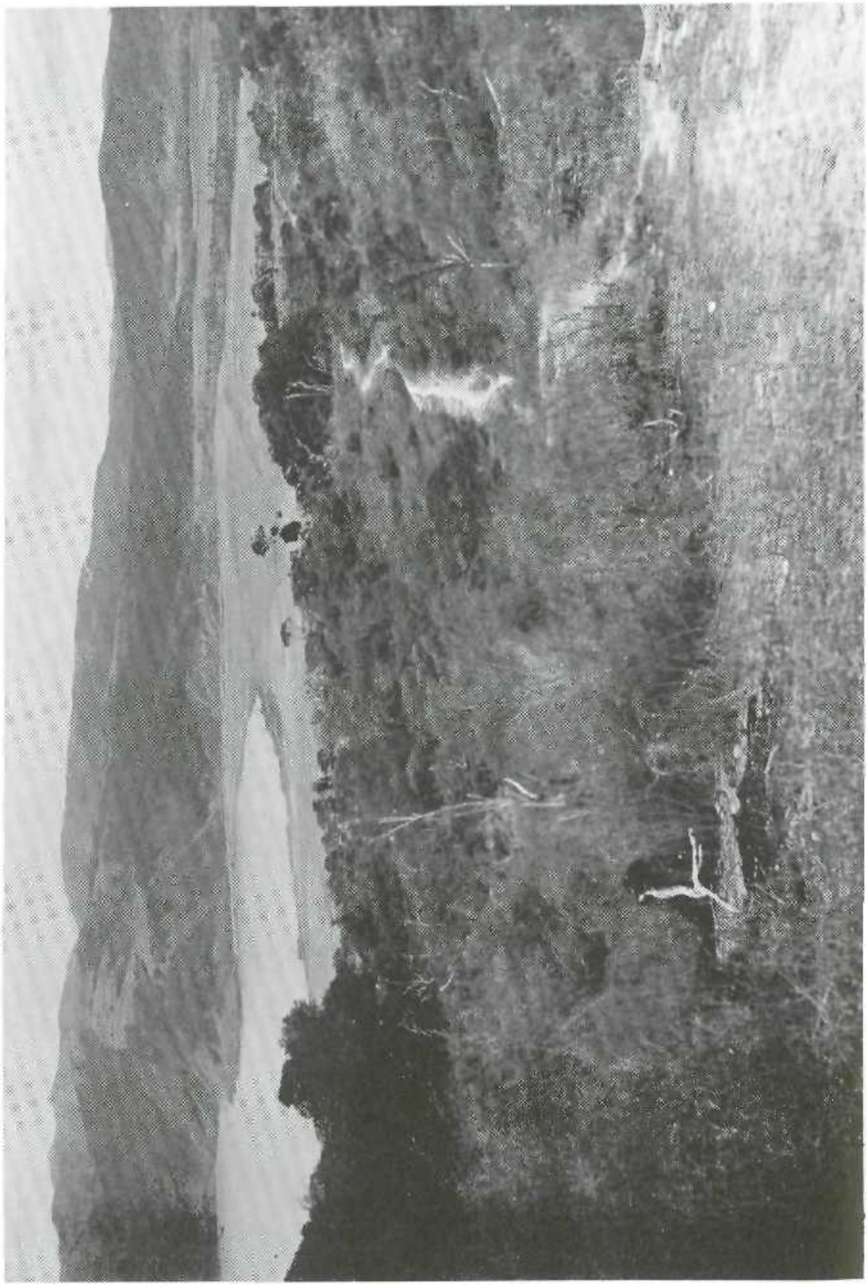


Plate 73. The Angi Lakes in the Arfak Mts. View from junction of Mt Tidjei and Mt Kobreimot (2400 m) to the NW over Angi Gigi and the marsh between Iray River and Swons River (1920 m), habitat of ***Rhododendron laetum***. Forests are mainly of the Nothofagus-Lithocarpus type. Foreground dominated by the fire-resistant ***Baeckia frutescens.*** 1962 (Photo H.O. Sleumer).

Kubor Range but did not reach the alpine regions. One year later, in 1951, F.W. Shaw-Mayer, a friendly, mild mannered ornithologist, who later was put in charge of the Fauna Section of the Halstrom Livestock and Fauna Station of Nondugl, collected on Mount Giluwe up to 2220 m altitude and Mount Hagen up to the summit. His small collection of about 80 specimens is held in the British Museum (Natural History) of London. Gilliard was back in New Guinea in 1952 and collected birds but no plants in the Kubor Range, Mount Hagen, and in the Bayer Valley. In April - July 1954, he collected in the Victor Emanuel (Plate 74) and Hindenburg Mountains but once again no botanical specimens were collected.

N.M. Stemple and L.T. Rayner, accompanied on their Mount Wilhelm trip by Patrol Officer A.M Keogh, collected 40 botanical specimens on that mountain (Plate 75). Both went later to Mount Giluwe. Neither of them was a botanist and were mainly on a holiday trip to New Guinea. A collection of 8 specimens was made.

From 1952 onwards exploration in the Australian part of the island developed quickly due to several factors. One of which was the extension of the activities of the Department of Forest's Division of Botany in Lae where a local herbarium was started with collections made in 1944 by L.S. Smith and C.T. White, both from the Queensland Herbarium, Brisbane. A second factor was the formation of the New Guinea team of the Commonwealth Scientific and Industrial Research Organization (C.S.I.R.O), Divison of Land Research and Regional Survey. This team was based in Canberra and from its inception in 1952 to its demise in 1974, botanists frequently were sent out. One of the first was R.D. Hoogland, assisted by, among others, P. Darbyshire, R. Pullen, R. Schodde, and L. Craven. Botanists in later years were A. Kanis, P. Heyligers, and T.G. Hartley. When the New Guinea team was dissolved some of the members were appointed to the Herbarium Australiense of C.S.I.R.O., also in Canberra.

A third factor that may have stimulated the botanical exploration, in fact the scientific studies in general, was the fear by the Australians that Dutch New Guinea might develop faster — which it did, and that this might influence a move among the natives in Papua New Guinea for earlier independence than Australia was prepared to grant. This dissatisfaction with Australian reluctance might lead to an ouster of Australian personnel. All this came to pass though for other reasons than mentioned here. In the first place, Dutch New Guinea became a part of Indonesia and virtually all botanical studies stopped. Secondly, Australia granted independence to Papua New Guinea in 1975 and many Australians left the country. Botanical research did not stop, but became more difficult.

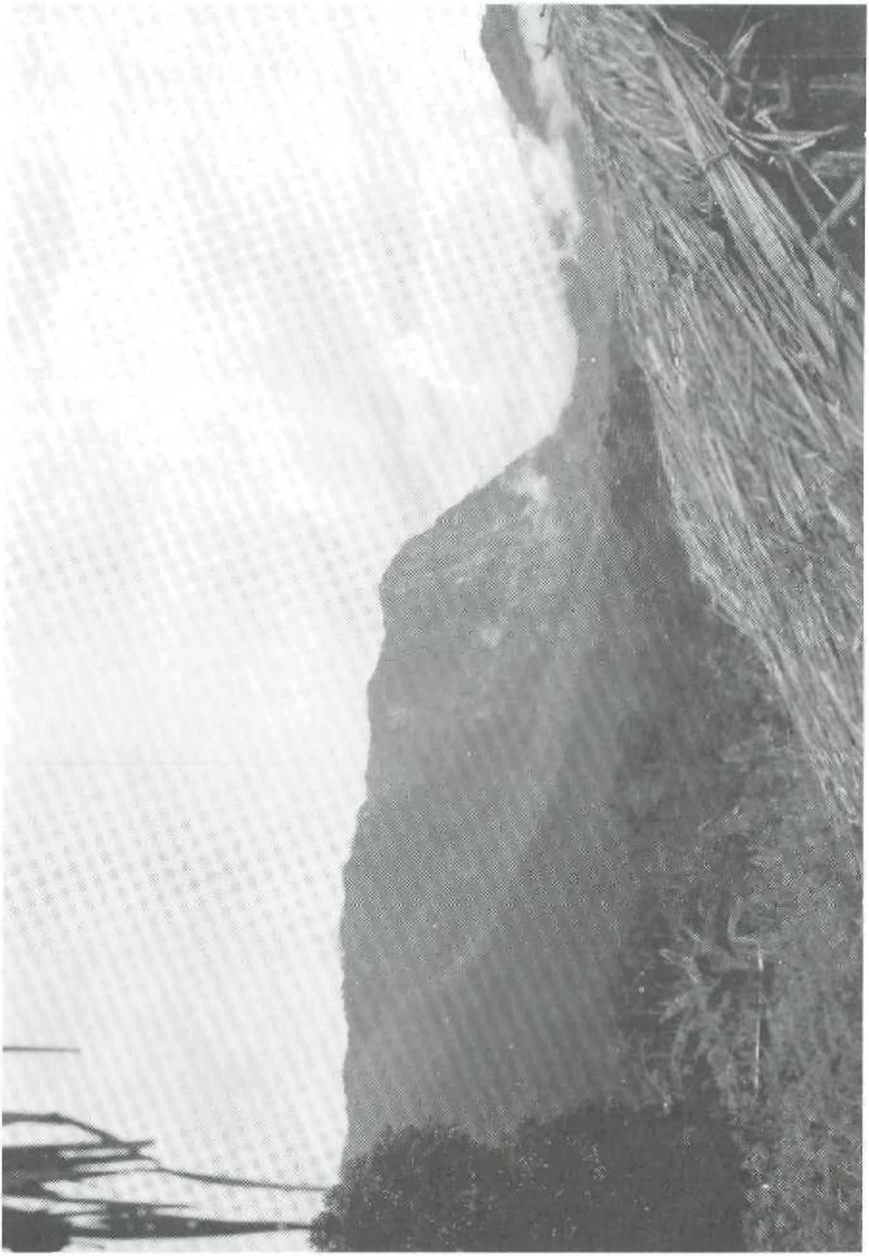


Plate 74. Victor Emanuel Mts, Mt Kefalabim (2880 m) seen from Feramin looking east. July 1976.

Plate 75. Mt Wilhelm, view from west bank of Lake Aunde towards the lake, the waterfall between Lake Piunde and Lake Aunde, the ledge carrying Brass' Tarn, and Monolithic Rock. The summit itself in the clouds to the right of Monolithic Rock. At left in foreground the old grass hut later replaced by the field station. To the right of the hut subalpine shrubbery with ***Podocarpus*, *Dacrycarpus*, *Rhododendron*,** and ***Senecio*** species. Sept. 1962.

The list of botanists, professionals and amateurs, and horticulturists, becomes very long and most of them and their explorations can only be treated summarily.

In 1953 Brass once again came to New Guinea with the 4th Archbold Expedition. The geographical coverage was mainly the Cape Vogel Peninsula in Southeast Papua and Goodenough Island. During this trip the high altitude flora was explored in the Mount Dayman area.

In 1954 J.F.U. Zieck, senior forest officier of the Subdivision of Forest Resources and Survey at Manokwari made a short trip to the Angi Lakes but the botanical material was collected by Ch. Versteeg, assistant forest botanist at the Manokwari Herbarium. In 1955 C.J. Stefels, a forester, made also a trip to the lakes. He tried to sound the depth of the lakes and found a deepest point of 100 m. Between 1957 and 1962 the lakes were visited by several members of the Forestry Service in Manokwari (C.J. Stefels, R.P. Mangold, W. Vink, C. Koster.)

Also in 1954 H. McKee explored the Wahgi Valley and the Eastern Highlands. In 1956 the first team was sent out by C.S.I.R.O. - L.R.R.S. in which R.D. Hoogland and R. Pullen visited Mount Wilhelm. Womersley and M. Galore, the present Assistant Director of the Division of Botany and Director of the Lae Herbarium, accompanied both botanists for a short time. This team was followed by R.G. Robbins in August 1957 who also went to Mount Wilhelm, but visited Mount Hagen and Mount Giluwe as well. In the same year, J.C. Saunders explored the Kubor Mountains.

In 1956 the 5th Archbold Expedition once again with Brass as botanist visited the island groups off the coast of Milne Bay District in Papua. In 1957 C.O. Grassl visited mainly the lowland area of New Guinea in search of *Andropogoneae*. In the higher regions he visited the Angi and Wissel Lakes. In 1959 Brass once again went to New Guinea, this time with the 6th Archbold Expedition. From June until September of that year Brass visited among others, Mount Wilhelm, Mount Otto, and Mount Michael, sometimes accompanied by Womersley and J.D. Collins. It turned out later that this was Brass' last field trip. He would return only to New Guinea in 1965 during the celebrations of the opening of the new Lae Herbarium.

In 1960, Father E. Borgmann studied the flora of Mount Wilhelm and was the first to study chromosome numbers in the New Guinea plants.

R.D. Hoogland, R. Schodde, and R. Robbins explored the Mount Sugarloaf area west of Mount Hagen in 1960 (Plate 76) and J.A.R. Anderson made a short trip to Mount Wilhelm. In 1961 Hoogland and P. Darbyshire worked in the Aitape area, while Darbyshire later went

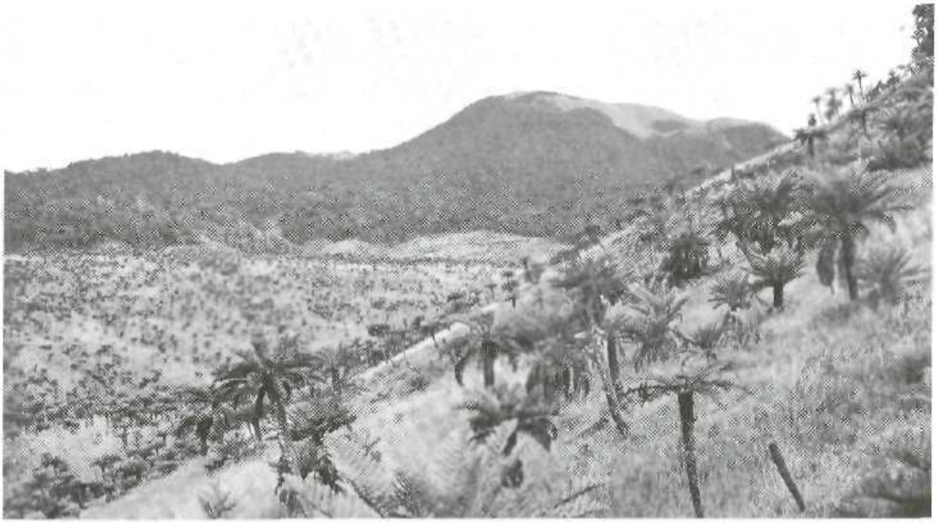


Plate 76. Mt Sugarloaf from the north. Nothofagus-Lithocarpus forest except for grasslands near summit. In foreground secondary grasslands with treeferns. (Photo R.D. Hoogland).

alone to the Torricelli Mountains. Also in 1961, van Royen and Sleumer carried out the 2nd Rijksherbarium Expedition to New Guinea. Though coming close to the 3000 m contour line, neither of us saw the alpine vegetation. During a break in the West New Guinea exploration, Sleumer went to Mount Wilhelm. Joining van Royen, the exploration continued in the Tamrau Mountains, but on learning of my appointment as botanist to the Lae Herbarium I left late December for Holland. Sleumer went on to visit the Angi Lakes area together with W. Vink. In 1961 also, D.E. Cooper joined the New Zealand New Guinea Expedition to the Carstensz Mountains. One of the other members was

Ph. Temple who one year later reached the summit of the Pyramid together with H. Harrer. This expedition collected some botanical materials.

I reached Lae in early June 1962 and remained there until June 1965. In the company of F.W. Went I reached on September 21, 1962 for the first time the alpine grasslands on Mount Wilhelm. Shortly after the return of this trip I started work on the present flora. In 1963 W. Vink and R. Pullen studied several mountain peaks of the Kubor Range (Plate 77). In February 1963 S. Carlquist on a world tour studying mainly Asteraceae arrived in New Guinea. Accompanied by van Royen he made a trip to the Rawlinson Range and the Sarawaket Mountains. With E. Henty he made shortly afterwards a trip to Mount Piora (March 9-13) where the endemic genus *Piora* (*Asteraceae*) was found for the first time. In August 1963 F. Kleckham of the Department of Agriculture collected a few alpine species on Mount Strong. In the same year H.U. Stauffer on his world trip in search of *Santalaceae,* visited among others, Mount Wilhelm. C. Rosenberg, a member of the Commonwealth Division of Mapping, Canberra, visited several mountains but only from Mount Amungwiwa were some alpine species collected. From 1962-1964 T. Hartley stayed in Papua New Guinea. As a member of C.S.I.R.O.'s Phytochemical Survey he was particularly charged with collecting pharmaceutically important material. This gave him ample opportunity to visit several areas of Papua New Guinea such as Mount Sarawaket in January 1963 and Mount Dickson in February 1964. From both these high summits large collections were made. In 1964 the 7th Archbold Expedition came to New Guinea but instead of Brass, R.D. Hoogland was the botanist. This exploration concentrated on the Cromwell, Rawlinson and Sarawaket Mountains. In the same year a combined Japanese - University of Cenderawasih team made a trip to the Carstensz Mountains but no high alpine plants were collected.

Lower plants in general were hardly collected by most botanists and only in 1964 did the first expedition arrive to concentrate on ferns and other cryptogams. The British Museum (Natural History) — Newcastle upon Tyne expedition led by A.C. Jermy led a team to the Finisterre Mountains in late 1964 and early 1965. In February and March of 1965 they collected on Mount Wilhelm. Also paying attention to lower plants was B.O. van Zanten who in 1959 participated in the Dutch Star Mountains Expedition. In 1968, sometimes accompanied by D. McVean, W.A. Weber, and R. Johns, he collected on Mount Wilhelm, Mount Giluwe, and other mountains.

R. Schodde graduated in botany in 1961 from the University of Adelaide but was an ornithologist at heart. As a member of the C.S.I.R.O. -

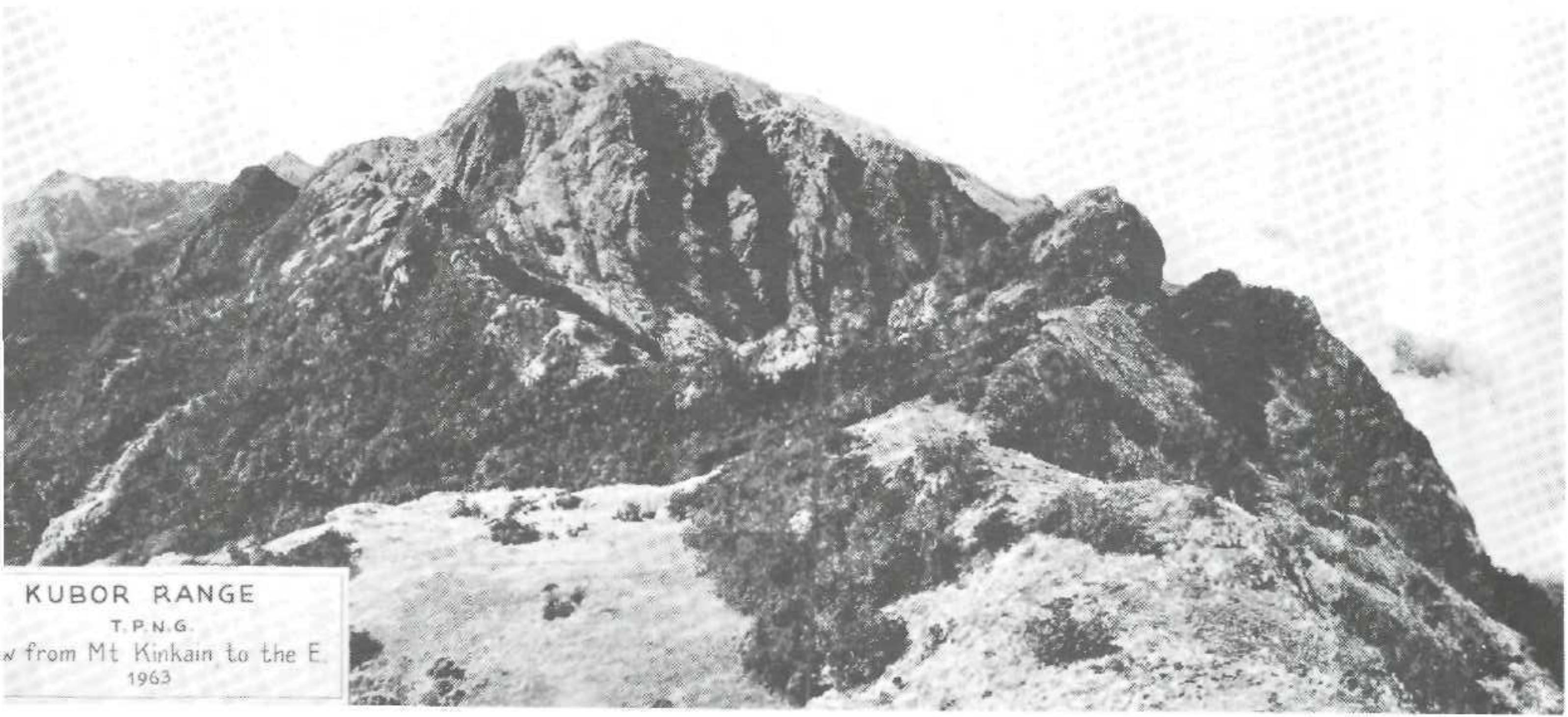


Plate 77. Kubor Range, view from Mt Kinkain to the east. 1963 (Photo W. Vink).

L.R.R.S. team he collected in several parts of Papua New Guinea. With R.D. Hoogland in 1960 he collected in the Mount Sugarloaf area, and is one of the few botanists who has traveled in all three parts of the island. In 1961 he explored the Baliem Valley in Dutch New Guinea, reaching the foot of Mount Wilhelmina. In the same year he visited Mount Giluwe in Papua. In 1969 he explored the Owen Stanley Mountains and Mount Wadinama, the east summit of the Mount Simpson massif.

A. Gillison started working for the Lae Herbarium in 1964 and in the following years made several mountain trips. In 1965 he accompanied the author together with J. Buderus for a trip to Mount Biota, the west dome of Mount Albert Edward. In 1966 he accompanied C. Kalkman and W. Vink to the Doma Peaks.

L. Craven, a botanical collector for C.S.I.R.O.'s Herbarium Australiense arrived in 1964 in New Guinea but did not see the alpine flora until 1974 when visiting Mount Victoria in a joint exploration with J. Croft of the Lae Herbarium. In 1965 M. Black came to New Guinea mainly to collect horticulturally important plants. He collected mainly Rhododendrons as live material, though some dried specimens of alpine species were preserved. B. Craig in 1965 visited the Sirius Plateau, west of Telefomin and made some collections which are kept in the Lae Herbarium. In early April 1965 Craig was in the alpine grasslands east of the peaks of Mount Scorpion and Mount Capella at which time most of his alpine species were collected. In the same year, Hj. Eichler visited Mount Wilhelm after participating in the official opening of the new Lae Herbarium. He mainly collected *Ranunculus* species, a group in which he is deeply interested. In 1966 A.J.G.H. Kostermans visited among others, the Baliem Valley but did not reach the higher altitudes.

A remarkable collector in the New Guinea field explorations is Reverend Norman E.G. Cruttwell. Appointed to the New Guinea area in 1946 with the Anglican Mission, he was also a good part-time botanist. The New Guinea flora raised his interest and over the years he roamed over many of Papua's southeastern mountains such as Mount Simpson (1947), Mount Dayman, (1951), and Mount Aniata (1959). In 1968 he made a trip with P. Woods to Mount Simpson and in 1972 to Mount Suckling as part of the Rijksherbarium Expedition team of J.F. Veldkamp accompanied by P.F. Stevens of the Lae Herbarium and R. Pullen of C.S.I.R.O. In 1976 Cruttwell was transferred to Goroka. He arrived there in a charter plane "with 2 suitcases and 400 Rhododendrons and orchids", that filled up the plane from nose to tail.

Another botanist of the Rijksherbarium came to New Guinea in 1965. M.M.J. van Balgooy on a world trip stopped long enough in New Guinea to visit Mount Wilhelm for several months, by now the happy hunting ground of so many botanists, amateur and professional. New Guinea had a fatal attraction for the Rijksherbarium because in 1966 C. Kalkman and W. Vink arrived to explore the Doma Peaks and the Hindenburg Range. They were accompanied by A. Gillison and D. Frodin, who from 1965-1967 was my successor as botanist with the Division of Botany in Lae. C. Ridsdale who succeeded D. Frodin in the Lae Herbarium in 1967, climbed in February of that year Mount Wilhelm, and in 1968 joined P. Woods for a climb of Mount Albert Edward. J.R. Flenley in 1968 made a short visit to Mount Wilhelm.

In the exploration of any given flora there are four steps, viz. 1. the pioneer or exploratory stage, 2. the consolidation stage, 3. the stage of biosystematy and ecology, and 4. the encyclopedic stage. In the exploration of the New Guinea flora by 1965 the first stage was beginning to give way to the second, third, and fourth stages, the study of the why's, when and where of vegetation types. Brass in 1933 had already drawn up some plant formations. References to the mosaic-like pattern of alpine vegetation types was mentioned in van Royen's paper on Mount Biota (1967). A full-fledged ecological study of an alpine flora was finally carried out in 1966-1967 by D. McVean and L. Wade. A small survey by D. Walker preceded in 1968 the publication of the larger study by McVean and Wade.

In 1965 the Department of Geography of the Australian National University Research School of Pacific Studies, with the financial assistance of the Bernice P. Bishop Museum, Honolulu, established a field station at Lake Aunde. This made it possible for later scientists like McVean and Wade to stay for extensive periods in the alpine surroundings. In 1969 W.A. Philipson visited Mount Wilhelm on August 21 mainly to collect *Rhododendrons* and *Araliaceae*. In 1970 H.F. Winters and J.J. Higgins from the United States Department of Agriculture were sent to New Guinea to collect species of horticultural importance. They explored mainly the montane regions and their collection does not contain any alpine elements.

The New Guinea team of C.S.I.R.O. sent A. Kanis in 1969 to the Owen Stanley Mountains but no alpine material was collected. In the same year M. Coode, another botanist with the Lae Herbarium, climbed Mount Giluwe. In 1971 he joined P.J. Stevens for a trip to Mount Strong and Mount Scratchley (April). In 1970 K. Paijmans explored Mount Albert Edward as part of his vegetation studies. In the same year P.J. Grubb and J.P. Edwards explored Mount Kerigomna. Ecological studies were carried out between 1963 and 1968 by P.J. Heyligers but these were mainly directed at lowland vegetations.

The encyclopedic stage of the vegetation study was reached in New Guinea when in 1971 R.J. Johns and P.F. Stevens published their checklist of species found on Mount Wilhelm. Two years earlier, G.S. Hope also explored this mountain. His studies though, are mainly directed at the palaeohistory. His Ph.D. thesis published in 1973 dealt extensively with the history of the vegetation of Mount Wilhelm. In 1969 and 1970 Hope also visited the alpine regions of Mount Giluwe and Mount Albert Edward, thus becoming one of the few botanists who has explored in all three parts of New Guinea. Hope was a participant of the Carstensz Glacier Exploration of the University of Melbourne, Meteorology Department in 1972. He made extensive collections of plants in the Carstensz Mountains and the Kemabu Plateau north of the range. Surprisingly enough the collection did not contain many new additions and it seems that the extensive Dutch and American collections in the higher ranges of West New Guinea have filled in the botanical picture to a considerable degree. Hope collected also species that were known only from the southeastern end of New Guinea such as *Scleranthus singuliflorus* which F. von Mueller had found up to then only on Mount Victoria, and *Papuzilla laeteviridis* van Royen, up to then only found on Mount Bangeta. Hope not only collected plants but was able to prepare several drillings to enable him to study the development of the alpine flora over the last 14,000 years. Hope returned several times to New Guinea, and in March 1972 visited Mount Wilhelm, in August-September 1973 explored Mount Giluwe and in June 1974 climbed Mount Albert Edward. In April-June 1975 he accompanied the Rijksherbarium Exploration of the Papua New Guinea Star Mountains, viz. Mount Capella, Mount Scorpion, and Mount Auriga. On this trip J.F. Veldkamp and A. Touw of the Rijksherbarium were accompanied, apart from Hope, by J. Croft and W.R. Barker of the Lae Herbarium.

In 1963 van Royen explored the Sarawaket Mountains on two occasions, February 20 - March 2 and November 1, respectively to Mount Enggom and Mount Bangeta. From September 2-9 he visited Mount O'Dan on the Wahgi-Jimmy Divide. In 1965 (January 7-26) a trip was made to Mount Biota, the western summit of the Mount Albert Edward series. The eastern dome was already explored by Brass in 1933 and once again by K. Paijmans in 1970. A Japanese expedition in 1975 also visited Mount Albert Edward, apart from going up the Sarawaket Mountains. S. Kurokawa mainly collected lower plants in both ranges. Though essentially an entomologist, J.L. Gressit of the Bishop Museum and later Director of the Wau Ecology Institute, collected plants as long as they were host plants to his bugs. In 1971 he visited Mount Piora but other mountains have been studied by him also. In 1955 he visited several highland areas in West New Guinea such as the Wissel Lakes and Baliem Valley. All his botanical collections are in the Bishop Museum.

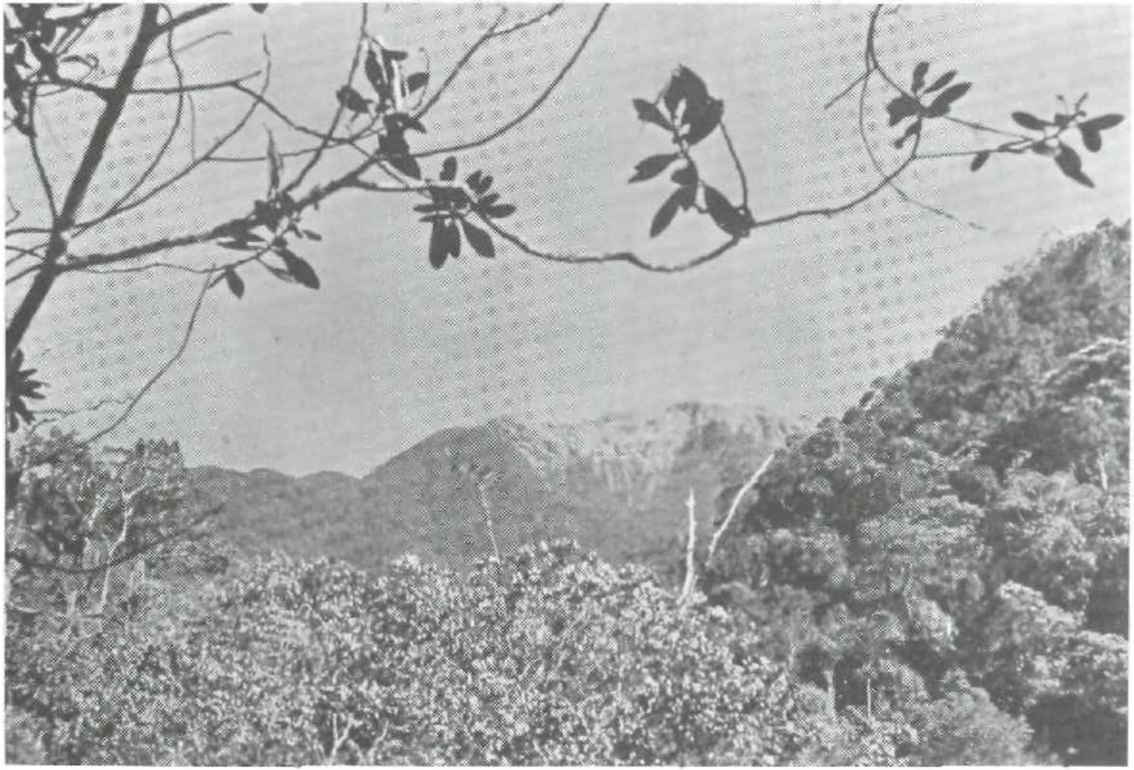


Plate 78. Kubor Range, Mt Sigal Mugal, looking northeast from 2300 m. The mountain rises to about 3700 m. (Photo J.M.B. Smith).

In West New Guinea, some explorations were carried out from 1964-1970 by Japanese teams. In 1969-1970, Y. Kobayashi was in charge of a team of specialists of lower plants. The same team went to Waimena in West New Guinea, and Mount Wilhelm, Mount Hagen, and Oksapmin in Papua New Guinea in 1970-1971, (*Bull. Nat. Sc. Mus. Tokyo* 14, 1971, 371).

In 1972 J.M.B. Smith made some collections on Mount Sigal Mugal (Plate 78).

J. Raynal from April 27 - May 19, 1973, visited the Carstensz Mountains. A large collection of plants was brought back to Paris.

In 1974 P. Kores received a grant from the Stanley Smith Horticultural Foundation for studying Rhododendrons, their growth and cultivation. Kores was based at the Wau Ecology Institute and made extensive field trips. Cuttings of many Papua New Guinea Rhododendron species were transferred to Wau and after a period of growth sent overseas to Kew, Edinburgh, Adelaide, and other gardens. Kores was able to explore many alpine regions but his collections were usually restricted to Rhododendrons.

In 1976 the author made his last trip to New Guinea. Originally scheduled as a trip to West New Guinea to explore the Carstensz Mountains the plan had to change into the exploration of several mountains in Papua New Guinea. Accompanied by P. Kores, D. Frodin, and R. Corlett, a soil specialist, Mount Victoria was explored from the base camp at the Iswan Swamp from May to June 1976. Mount Amungwiwa was explored June 9-18, accompanied by Mrs. B. Gagné-Harrison, followed by Mount Giluwe June 25 to 28 in the company of P. Kores and Mrs. Gagné. The Victor Emanuel Mountains were explored in July 4-13 with Kores Mrs Gagné, W. Gagné and J.L. Gressitt. On the return to Goroka a short trip was made to the south slope of Mount Giluwe, July 18-23. The trip finished with the exploration of the Finisterre Mountains August 3-10 where these ranges pass into the Sarawaket Mountains, the Naitmambi Range.

In 1978 P. Kores and J.F. Veldkamp explored the Burgers Mountain (3690 m) at the eastern end of the Schattenburg Mountains and Mount Kegum (3700 m) at the northern end of the Mount Hagen Range. They explored the high altitude grasslands of Burgers Mountain between March 22 and April 3. Kores left Veldkamp on March 29 while the latter proceeded to Mount Hagen township on the 31st. Mount Kegum was explored by Veldkamp between April 5 and 12.

Selected References

d'Albertis, L.M., New Guinea: What I did and What I saw. (1880).

An Annotated Bibliography of the Southwest Pacific and Adjacent Areas. Allied Geographical Section. (1944).

Annual Report of the Lieutenant-Governor, 1906/1907, 1908/1909, 1910/1911, 1940/1941.

Archbold, R., Unknown New Guinea - *Nat. Geogr. Mag.* (March 1941) 315-344.

Archbold, R. & A.L. Rand, Summary of the 1933-1934 Papua Expedition - *Bull. Am. Mus. Nat. Hist.* 68 (1935) 527-579, pl. 18-26.

Archbold, R. & A.L. Rand, With plane and radio in Stone Age New Guinea - *Nat. Hist. Mag. Am. Mus. Nat. Hist.* 11 (1937) 567-576.

Archbold, R. & A.L. Rand, New Guinea Expedition. (1940).

Baines, J., L.U. Murray & R.J. Isherwood, The Hong Kong Mountaineering Club Expedition to the Snow Mountains of New Guinea. Report of the Hong Kong Mountaineering Club.

Behrmann, W., Detzner's Untersuchungen in Neuguinea - *Zeitschr. Ges. Erdk. Berlin* (1919) 371-376.

Bijlmer, H.J.T., Met de Centraal Nieuw Guinea Expeditie A^{0} 1920 naar een onbekenden volksstam in het hooggebergte - *Tijdschr. Kon Ned. Aardr. Gen.* 39 (1922) 156-395.

Bijlmer, H.J.T., Naar de Achterhoek der Aarde: de Mimika Expeditie naar Nederlandsch Nieuw Guinea. (1936).

Borgmann, E., Anteil der Polyploiden in der Flora des Bismarckgebirges von Ost Neuguinea - *Zeitschr Bot* 52 (1964) 118-172, 1 map, 21 fgs.

Brass, L.J., Notes on the vegetation of the Fly and Wassi Kussa Rivers - *J. Arnold Arb.* 19 (1938) 175-190, 3 pl.

Brass, L.J., The 1938-1939 expedition to the Snow Mountains, Netherlands New Guinea - *J. Arnold Arb.* 22 (1941) 271-295, 297-342, 7 pl.

Brass, L.J., Summary of the fourth Archbold Expedition to New Guinea (1953) - *Bull. Am. Mus. Nat. Hist.* 111 (1956) 83-152, 21 pl.

Brass, L.J., Summary of the fifth Archbold Expedition to New Guinea (1956-1957) - *Bull. Am. Mus. Nat. Hist.* 118 (1959) 7-69, 8 pl.

Brass, L.J., Summary of the 6th Archbold Expedition to New Guinea (1959) - *Bull. Am. Mus. Nat. Hist.* 127 (1964) 145-216, 13 pl.

Brongersma, L.D. & G.D. Venema, Naar het witte hart van Nieuw Guinea (1960)

Brongersma, L.D. & G.F. Venema, To the mountains of the Stars. (1962).

Champion, C.R. & U. Radok, Carstensz Glaciers Expedition, 1971/1972. Preliminary Report, Univ. Melbourne, Meteorology Dept., June 1972.

Champion, C.R., J. Bennett, G.S. Hope, J.A. Peterson & R. Muggleton, The Carstensz Glaciers Expedition - *Irian* 2, 3 (1973) 38-48.

Cocq d'Armandville, J.H.I. le, in J.J. Smith, De exploratie van Nieuw-Guinea - *Tijdschr. Kon. Ned. Aardr. Gen.* ser. 2, 29 (1912) 76-80.

Colijn, A.H., The Carstensz Massif - *Alp. Journ.* 49 (1937) 177-189.

Colijn, A.H., Naar de eeuwige sneeuw van tropisch Nederland - *Tijdschr. Kon. Aardr. Gen.* (1937) 576-587.

Colijn, A.H., Naar de eeuwige sneeuw van tropisch Nederland. (1937).

Coode, M.J.E. & P.F. Stevens, Notes on the flora of two Papuan mountains - *Pap. N.G. Sc. Soc. Proc.* 1971 (1972) 18-25.

Cooper, D., Some botanical and phytochemical observations in Netherlands New Guinea - *Econ. Bot.* 25 (1971) 345-355.

Costin, A., Alpine ecosystems of the Australasian Region, in H.E. Wright & W.H. Osburn, Arctic and Alpine Environments (1967) 55-62.

Cruttwell, N.E.G., The ascent of South Suckling - *The Rhododendron* 11 (Dec. 1972) 7-13.

Diels, L., Die pflanzengeographische Stellung der Gebirgsflora von Neu-Guinea - *Ber. freien Verein Pfl. geogr. and syst. Bot. fur die Jahre 1919* (1921) 15-59.

Diels, L., Beitr. zur Flora des Saruwaged Gebirges - *Bot. Jahrb.* 62 (1929).

Diels, L., Ein Beitrag zur Analyse der Hochgebirgsflora von Neu-Guinea - *Bot. Jahrb.* 63 (1929) 324-329.

Docters van Leeuwen, W.M., Schets van de flora en fauna van het van Reesgeberte rondom Albatros-bivak, Nieuw Guinea - *Trop. Nat.* 15 (1926) 177-186, 10 fgs; and *Tijdschr. Kon. Ned. Aardr. Gen.* 43 (1926) 271-272, 747-750.

Dow, D.B., A geological reconnaisance in the Nassau Range, West New Guinea - *Geol. en Mijnbouw* 47 (1968) 37-46.

Flenley, J.R., The present and former vegetation of the Wabag region of New Guinea. Thesis. Canberra. (1957).

Flenley, J.R., The vegetation of the Wabag Region, New Guinea Highlands: a numerical study - *J. Ecol.* 57 (1969) 465-490, 8 fgs, 4 tab.

Galis, K.W., Bibliography of West New Guinea. (1956).

Gibbs, L.S., Dutch N.W. New Guinea. A contribution to the Phyto geography and Flora of the Arfak Mountains. (1917).

Gillison, A.N., Plant succession' in an irregularly fired grassland area - Doma Peaks region, Papua - *J. Ecol.* 57 (1969) 415-429.

Gillison, A.N., Structure and floristics of a montane grassland/forest transition, Doma Peaks region, Papua - *Blumea* 18 (1970) 71-86.

Gjellerup, K., Report on Arfak Mountains trip in *Tijdschr. Kon. Ned. Aardr. Gen.*, ser. 2, 30 (1913) 77-78.

Grubb, P.J. & P.F. Stevens, The forests of the Fatima Basin and Mount Kerigomna and a review of Montane and Subalpine forests elsewhere in Papua New Guinea. Dept. Biogeogr. and Geomorph. - *A.N.U., BG/5*, Canberra. (1976).

Harrer, H., I come from the stone age. (1971)

Harrer, H., Ich komme aus der Steinzeit. (1964)

Hitchcock, W.B., An introduction to the Natural History of a New Guinea Higland Community - *The Emu* 63 (1964) 351-372, ill., map.

Hope, G.S., The vegetation history of Mount Wilhelm. - Thesis. Canberra. (1973).

Hope, G.S., The vegetational history of Mount Wilhelm, Papua New Guinea - *J. Ecol.* 64 (1976) 627-661, 8 fgs, 2 pl.

Hope, G.S., J.A. Peterson, I. Allison & U. Radok, The Equatorial Glaciers of New Guinea. (1976).

Huber, H., Deutsche Neu-Guinea-Expedition 1974. Roneo Report.

Huber, H., Carstensz-Pyramide - *Alpinismus* 8/74 (1974) 32-39.

Jermy, A.C. & C.D. Sayers, An expedition to the Finisterre Mountains of Eastern New Guinea - *J. Roy. Hort. Soc.* 92 (1967) 117-128, f. 54-55, 57-63, map.

Johns, R.J., Vegetation, in Encycl. Papua and New Guinea 2 (1972) 1163-1170.

Johns, R.J. & P.F. Stevens, Mount Wilhelm Flora, a checklist of the species - *Botany Bull.* 6 (1971) 1-60.

Kalkman, C., Description of vegetation types in the Star Mountains region, West New Guinea - *Nova Guinea, Bot.* 15 (1963) 247-261.

Kalkman, C. & W. Vink, Botanical exploration of the Doma Peaks and adjacent mountains in the Southern Highlands District, Territory of Papua, Australian New Guinea - WOTRO Report 1966 (1967) 50-52.

Kalkman, C. & W. Vink, Botanical exploration in the Doma Peaks region, New Guinea - *Blumea* 18 (1970) 87-135, 5 fgs, 1 map.

Kanehira, R. & S. Hatusima, Plants collected during the Kanehira - Hatusima 1940 collection in New Guinea - *Bot. Mag. Tokyo* 55-57 (1941-1943).

Keysser, C., Die erste Ersteigung des östlichen Gipfel des Finisterregebirges (Kaiser Wilhelmsland) - *Peterm. Mitt.* 59, 2 (1913) 177-181, 2 pl., map; 60, 2 (1914) 138.

Klein, W.C., Nieuw Guinea, 3 vls. (1935-1938); ed. 2 (1953-1954).

Kremer, J.H.G., De expeditie naar het centraal geberte van Nieuw Guinea (den Wilhelminatop) 1920-1922 - *Onze Vloot* 14 & 15 (1922, 1923).

Lam, H.J., Fragmenta Papuana 1-7 - *Natuurkundig Tijdschr. Ned-Indie* 87 (1927) 110-130; 130-138; 139-180; 88 (1928) 187-227; 252-324; 89 (1929) 67-130; 291-380; Appendix in vol. 89 (1929) 381-385; translated edition by L.M. Perry in *Sargentia* 5 (1945) 1-196.

Lam, H.J., Materials towards a study of the flora of the island of New Guinea - *Blumea* 1 (1934) 115-159, map.

Lane-Poole, C.E., The Forest Resources of the Territories of Papua and New Guinea. (1925).

Leahy, M., The Central Highlands of New Guinea - *Geogr. J.* 87 (1936) 229-262.

Leahy, M. & M. Crain, The Land that Time forgot. (1937).

Le Roux, C.C.F.M., De Bergpapoeas van Nieuw Guinea en hun woongebied, 3 vls. (1948-1950).

Le Roux, C.C.F.M., Expeditie naar det Nassau-gebergte in Centraal Noord Nieuw Guinea - *Tijdschr. Ind. Taal-, Land-, en Volkskunde* 66 (1926) 447-513.

Lorentz, H.A., Enige maanden onder de Papoeas. (1905).

Lorentz, H.A., Zwarte Mensen - Witte Bergen. (1913).

Lugt, H.J., Die Carstensz-Expedition 1936 (Niederlandisch Neu-Guinea) - *Die Alpen* (1943) 348-352.

Mayr, E., My Dutch New Guinea Expedition - *Nov. Zool.* 36 (1928) 20-26.

Mayr, E., A tenderfoot explorer in New Guinea - *Am. Mus. J. Nat. Hist.* 32 (1932) 83-97.

Moskowski, M., Vorlaufiger Bericht über die Deutsche Mamberamo-Expedition in Niederländisch-Neu-Guinea - ***Zeitschr. Ges. Erdk. Berlin*** 43 (1911) 185-192.

Moszkowski, M., Ins unerforschte Neuguinea. Erlebnisse mit Kopfjagern und Kannibalen. (1928).

Paijmans, K., Vegetation of eastern Papua. Land-Form Types and Vegetation of Eastern Papua. ***C.S.I.R.O. Land Research Series*** 32 (1973) 89-125.

Paijmans, K., Explanatory Notes to the Vegetation Map of Papua New Guinea - ***C.S.I.R.O. Land Research Series*** 35 (1975).

Paijmans, K. & E. Löffler, High altitude forests and grasslands of Mount Albert Edward, New Guinea - *J. Trop. Geogr.* 34 (1972) 58-64.

Peterson, J.A., Preliminary Report of the second Carstensz Glaciers Expedition, 1973. Univ. Melbourne, Meteorology Dept. (1973).

Pratt, A.E., Two years among New Guinea cannibals. (1906).

Pulle, A., Naar het Sneeuwgebergte van Nieuw Guinea met de derde Nederlandsche Expeditie. (1915).

Rand, A.L. & L.J. Brass, Summary of the 1936-1937 New Guinea Expedition - ***Bull. Am. Mus. Nat. Hist.*** 77 (1940) 341-380, pl. 21-42, 2 maps.

Rawling, C.G., The land of the New Guinea Pygmies. (1913).

Rhys, L., Jungle Pimpernel: The story of a District Officer in Central Netherlands New Guinea. (1947).

Ridley, H.N., Report on the Botany of the Wollaston Expedition to Dutch New Guinea - ***Trans. Linn. Soc.***, ser. 2, Bot. 9 (1916) 1-269, 7 pl.

Robbins, R.G., Montane Formations in the central highlands of New Guinea - Proc. ***Symp. Humid Tropics Veget. Tjiawi*** (Indonesia). (Dec. 1958) 176-185.

Robbins, R.G., The Montane Vegetation of New Guinea - ***Tuatara*** 8 (1961) 121-134.

Robbins, R.G., The Vegetation of New Guinea - ***Austr. Terr.*** 1 (1961) 1-12.

Schodde, R., Important plant structural formations and alliances recorded in Papua New Guinea, etc., in Conservation of Major Plant Communities in Australia and Papua New Guinea. (1974) 596-604 - ***Austr. J. Bot., Suppl. Series*** 7.

Simpson, C., Adam in Plumes. (1954).

Simpson, C., Adam with Arrows. (1955).

Sleumer, H., Itinerary of the second Rijksherbarium New Guinea Expedition - ***Fl. Mal. Bull.*** 17 (1962) 887-890.

Smith, J.M.B., Flora of Sigal Mugal, Kubor Range, Papua New Guinea. Report for Dept. of Biogeogr. and Geomorph., A.N.U., Canberra. (1972).

Smith, J.M.B., Mountain grasslands of New Guinea - *J. Biogr.* 2 (1975) 27 - 44, 9 fgs.

Smith, J.M.B., Vegetation and Microclimate of East- and West-facing slopes in the grasslands of Mount Wilhelm, Papua New Guinea - *J. Ecol.* 65 (1977) 39-53.

Souter, G., New Guinea, the Last Unknown. (1964).

Temple, P., The elusive mountains - *N.Z. Alp. J.* 19 (1961) 50-61.

Temple, P., Nawok. (1962).

Temple, P., Seventeen years after - *N.Z. Alp. J.* 20 (1963).

Temple, P., Mountains of the White Arrow - *Alp. J.* 68 (1963) 78-89.

Touw, A. & J.F. Veldkamp, Een botanische expeditie naar de Star Mountains, Papua New Guinea. Rijksherbarium Report. (1975).

van Eechoud, J., Vergeten Aarde. (1952).

van Royen, P., Kebar Valley, land of Araucarias - *Netherlands New Guinea* 3, 4 (1955) 12-13.

van Royen, P., The scientific expedition to the Star Mountains, Netherlands New Guinea - *Tijdschr. Kon. Ned. Aard. Gen.* 76 (1959) 211-213, 4 fgs.

van Royen, P., Notes on the vegetation of the Wissel Lakes area (in cooperation with F.W. Rappard) - *Nova Guinea*, N.S. 10 (1959) 159-176, 8 fgs.

van Royen, P., Sketch of the alpine vegetation of Mount Bangeta - *Trans. P. NG Scient. Soc.* (1964) 14-20, 2 pl.

van Royen, P., The vegetation of the Cycloop Mountains - *Nova Guinea, Bot.* 21 (1965) 451-469, 4 fgs.

van Royen, P., Notes on the vegetation of Mount Biota (Papua) - *Acta Bot. Neerl.* 15 (1967) 530-534.

van Steenis-Kruseman, M.J., Cyclopedia of Collectors, Fl. Mal., ser. 1, 1 (1950) 3-639; ser. 1, 5 (1958) 17-108; ser. 1, 8 (1974) 9-115.

Veldkamp, J.F., A botanical expedition to Mount Suckling (Goropu Mountains), Papua New Guinea. Rijksherbarium Report. (1972).

Veldkamp, J.F., A botanical trip to the Burgers Mt and Mt Kegum, Papua New Guinea, 1977. Rijksherbarium Report. (1978).

Verslag van de Militaire Exploratie van Nederlandsch Nieuw Guinea 1907-1915. (1920).

Vink, W., Botanical Exploration of the Arfak Mountains - *Nova Guinea, Bot.* 22 (1965) 471-494, 6 fgs, 5 pl.

Walker, D., A reconnaisance of the non-arboreal vegetation of the Piundaunde catchment, Mount Wilhelm, New Guinea - *J. Ecol.* 56 (1968) 445-466, 5 fgs, 2 tab.

Walker, D., The changing vegetation of the montane tropics - *Search* 1 (1970) 217-221.

Walker, D., Highlands vegetation - *Austr. Nat. Hist.* 17 (1973) 410-419.

Walker, D. & J.C. Guppy, Generic plant assemblages in the highland forests of Papua New Guinea - *Austr. J. Ecol.* 1 (1976) 203-212, 1 f.

Wichmann, A., Entdeckungsgeschichte von Neu Guinea - *Nova Guinea* 1 (1909); 2, 1 (1910); 2, 2 (1912).

Wollaston, A.F.R., Pygmies and Papuans. (1912).

Wollaston, A.F.R., Account of the 2nd Expedition - *Geogr. J. London* 43 (1914) 248-273, map.

Womersley, J.S., A brief history of botanical exploration of Papua and New Guinea - *P.N.G. Gazette* 8, 2 (Oct. 1953) 32-39.

Zoeller, H., Deutsch-Neuguinea und meine Ersteigung des Finisterre-Gebirges. (1891).

11. LANGUAGES AND NATIVE NAMES

The New Guinea languages can broadly be arranged into two groups, the Austronesian and the non-Austronesian or Papuan group. The first group is formed by immigrant languages, the second by the original Papuan languages. A final classification of the latter is not possible as many are not studied yet. Wurm (1975), however, gives an excellent review of what is available.

We gratefully acknowledge permission received by the editor of Pacific Linguistics to use the maps and their legends prepared by Dr S.A. Wurm. They give a far better idea of the complexity of the distribution of the languages in New Guinea than could be prepared by a botanist.

The Austronesian (Malayo-Polynesian) group is mainly represented by the Indonesian languages, found along the Northwestern and Southwestern coasts, though after the occupation of West New Guinea by Indonesia that language is enforced on the population as the main language.

The Melanesian languages are found mainly around the Port Moresby area as Motu, and in general are coastal along the North and Northwest coasts up to the Vogelkop, and scattered along the West coast as far south as Fakfak. Of this family Motu is the largest, followed by Dobu on Normanby Island, Louisiades, and Trobriand Islands. In West New Guinea the Numfor or Biak language belongs to this group and is found on Biak, Numfor, Japen, with sporadic cases around Manokwari and the north coast of the Vogelkop Peninsula.

The original Papuan languages are many and variable. A clear figure for their number is not yet reached. Some are not yet recognized, some are extinct. The largest groups are the West New Guinea Highlands and Central Highlands of Papua New Guinea language groups, smaller being the Ekari around the Wissel Lakes and the Ok languages between these two large groups. The Dani language-group between the Baliem Valley and the Kemabu Plateau is also of considerable size. Wurm (1975) distinguishes 5 main phyla and a number of minor phyla. Of the main phyla the Trans-New Guinea phylum is the largest covering virtually the entire island. (Fig. 29). At the same time the language one will encounter in the high altitude regions all belong to this phylum. This does, however, not mean that the Ekaris around the Wissel Lakes will understand the Dagan language in the extreme southeast tail of New Guinea. For the approximate extent of the various languages I refer to Fig. 30 and 31, both derived from Wurms paper, combined with the legend derived from his paper.

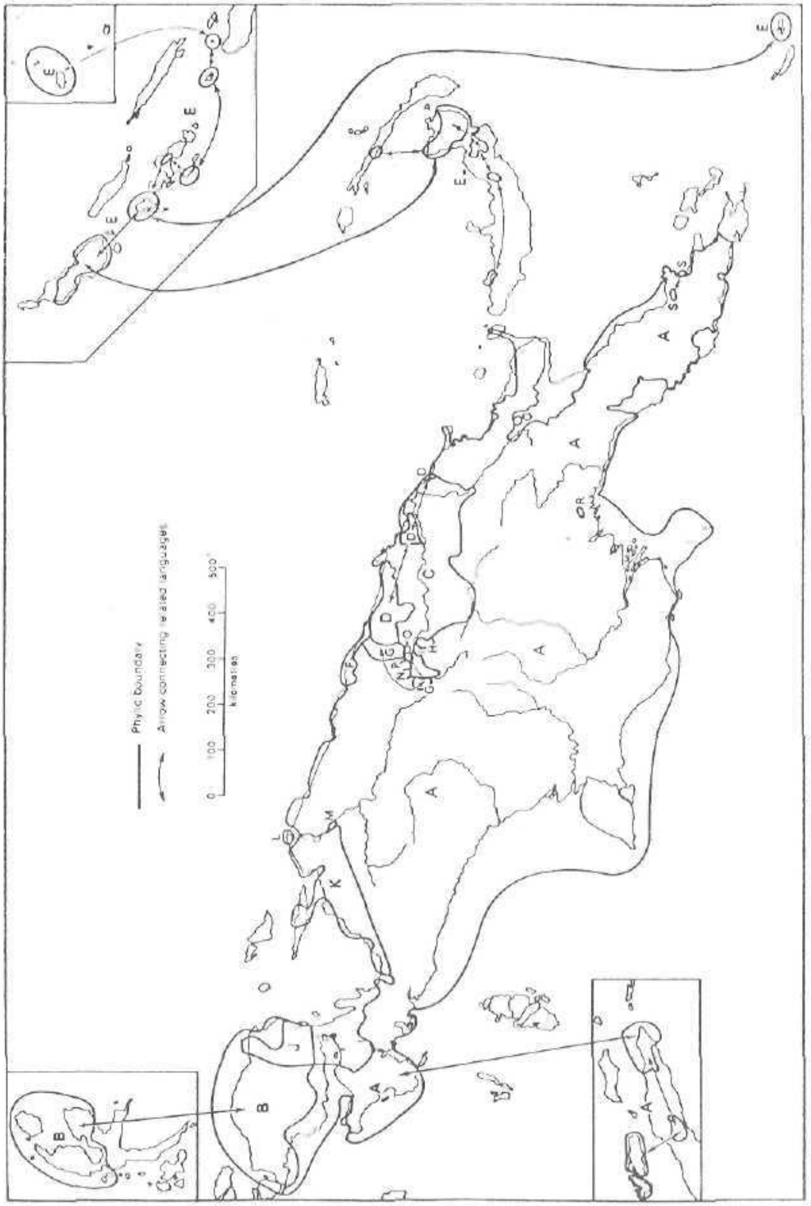


Fig. 29. Papuan Phylic Language Groups. - A. Trans-New Guinea - B. West Papuan phylum - C. Sepik - Ramu phylum - D. Torricelli phylum - E. East Papuan phylum - F. Sko phylum-level stock - G. Kwomtari phylum-level stock - H. Arai (Left May) phyllum-level family - I. Amto-Musian phylum level stock - J. East Bird's Head phylum-level stock K. Geelvink Bay phylum - L. Warenbori phylum-level isolate - M. Taurap (Boromeso)

Wherever available native names of the plants are included. The use of these names need careful consideration. Often it was found that when asked a name there was some long hesitation to give one. This could be due to a hesitancy to reveal tribal secrets, but in most cases it was merely a lack of knowledge. In order not to loose face a name was given of a plant that looked somewhat similar but was in fact a totally different species, sometimes belonging to a different family as well. Also it was noticeable that in particular the younger people did not know their plants. As in general the older people with a better knowledge of names did not accompany the many explorations few names could be obtained. An additional difficulty in New Guinea is that several languages are not yet studied. Therefore often a tribal language is given that can not be traced back with the assistance of Wurms maps as given here. This means in general that the use of native names in New Guinea is difficult and not too much reliance should be placed on them.

Selected References

Capell, A., Distribution of languages in the Central Highlands, New Guinea - *Oceania* 19 (1948) 104-129, 234-253; 19 (1949) 349-377.

Capell, A., in Encyclopaedia of Papua New Guinea 2 (1972) 610-615.

Ellenberger, J.D., On leadership among the Damals (Uhundunis) north of the Carstensz Mountain Range, in Working Paper in Dani Ethnography 31 (1962) 10-15.

Galis, K.W., Talen en dialecten van Nederlandsch Nieuw-Guinea - *Nieuw Guinea* 16 (1955-1956) 109-117, 134-145, 161-177.

Heider, K., The Dugum Fani. (1964).

Hope, G.S. & J.H., Man on Mt Jaya, in G.S. Hope, J.A. Peterson, I. Allison, and U. Radok, The equatorial Glaciers of New Guinea. (1976) 225-227.

Keysser, C., Wörterbuch der Kâte-Sprache gesprochen in Neuguinea. (1925).

Larson, G.F. & M.O., The Ekagi-Wodano-Moni language family of West Irian - *Irian* 1 (1972) 80-95.

Laycock, D.C., The Ndu Language Family. (1965).

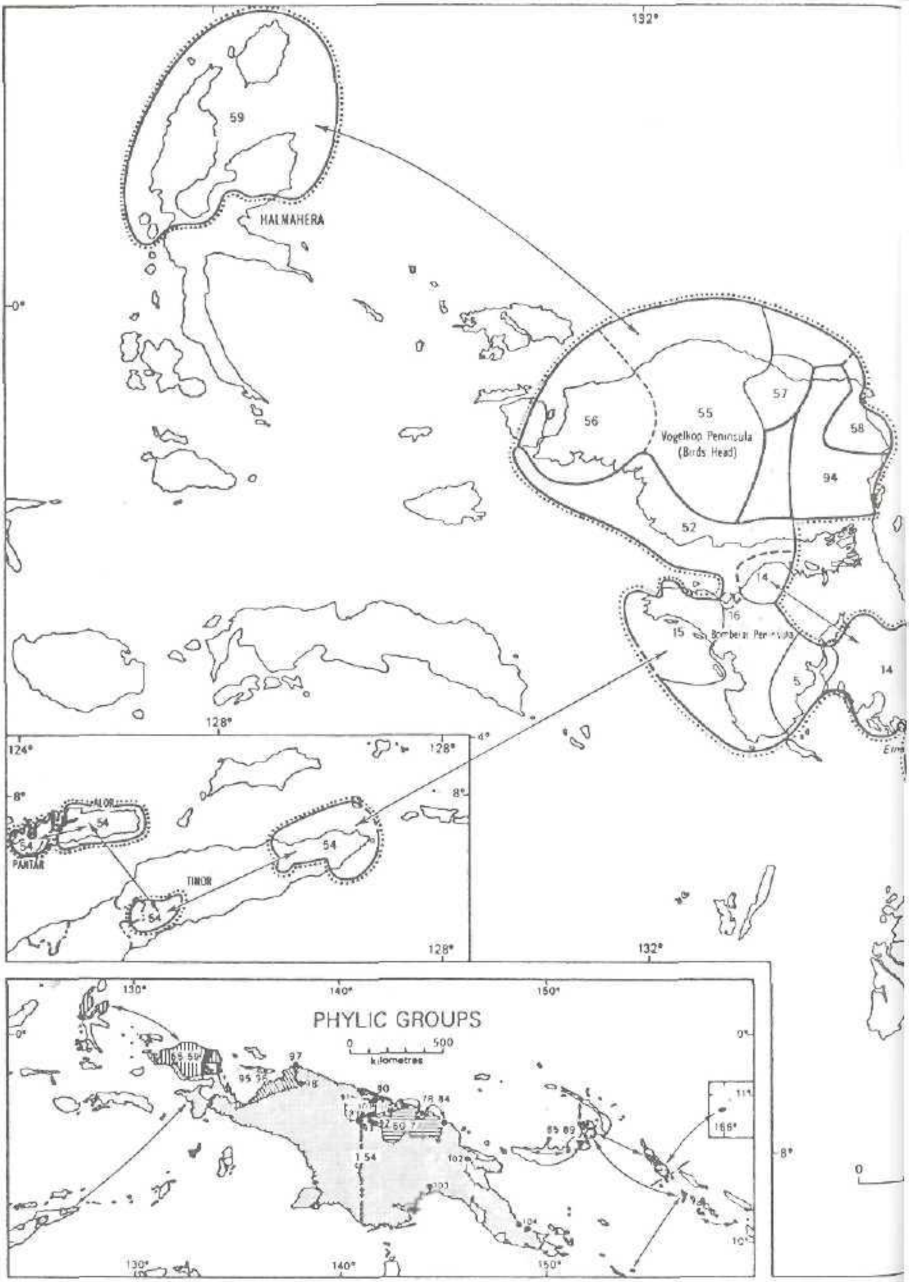
LeRoux, C.C.F.M., De Bergpapoea's van Nieuw-Guinea en hun woongebied. (1948-1950) 776-913.

Pilhofer, G., Grammatic der Kâte-Sprache in Neuguinea. (1933).

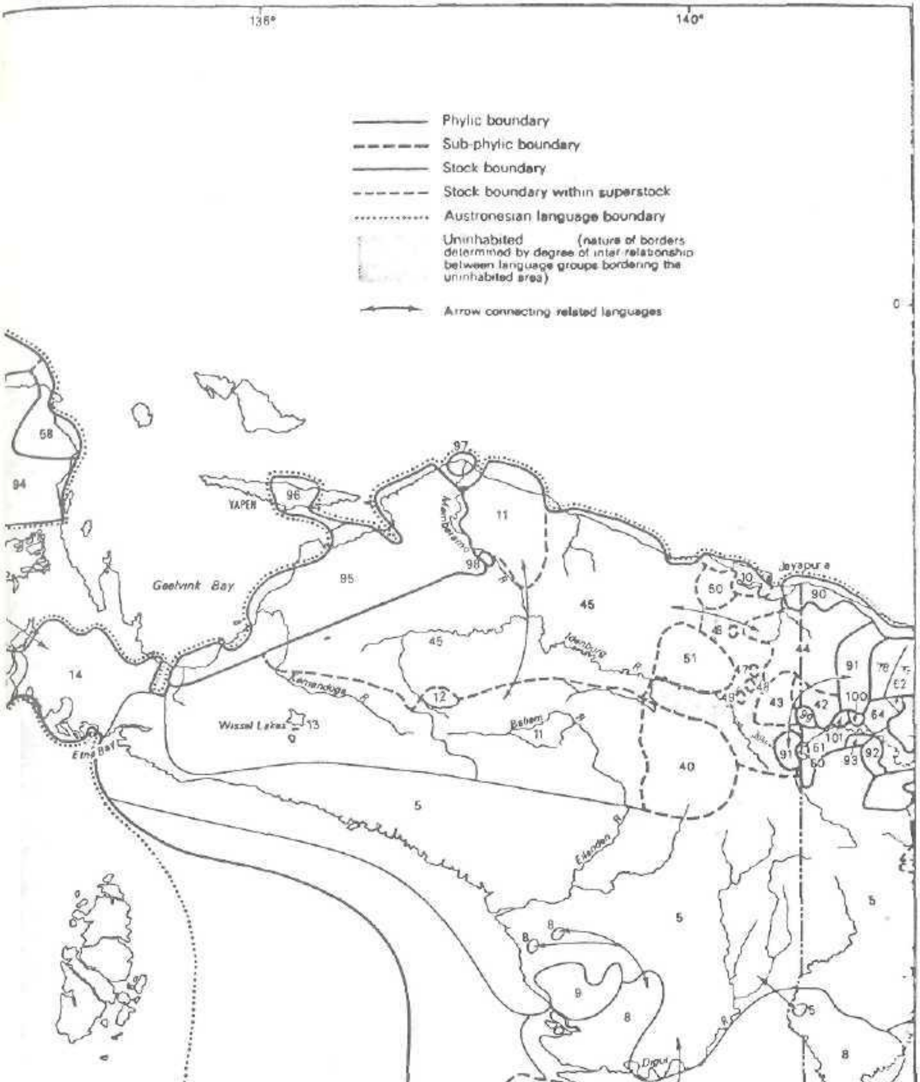
Pospisil, L., The Kapauku Papuans of West New Guinea. (1963).

Temple, P., Nawok. (1962).

phylum-level isolate - N. Yuri phylum-level isolate - O. Busa phylum-level isolate - P. Nagatman phylum-level isolate - Q. Wasembo (Gusap) phylum-level isolate - R. Porome (Kibiri) phylum-level isolate - S. Maisin (Austronesian-Papuan "mixed" languages. (After S.W. Wurm, 1975).



Figs. 30, 31. Papuan language stock.

136°
140°
Phylic boundary
Sub-phylic boundary
Stock boundary
Stock boundary within superstock
Austronesian language boundary
Uninhabited (nature of borders determined by degree of inter-relationship between language groups bordering the uninhabited area)
Arrow connecting related languages
0
YAPEN
Geelvink Bay
Mamberamo
Jayapura
Idenburg R.
Kamenduga R.
Wissel Lakes
Etna Bay
Baliem R.
Eilanden R.
Digul
FREDERIK 53 HENDRIK (KOLOPOM)
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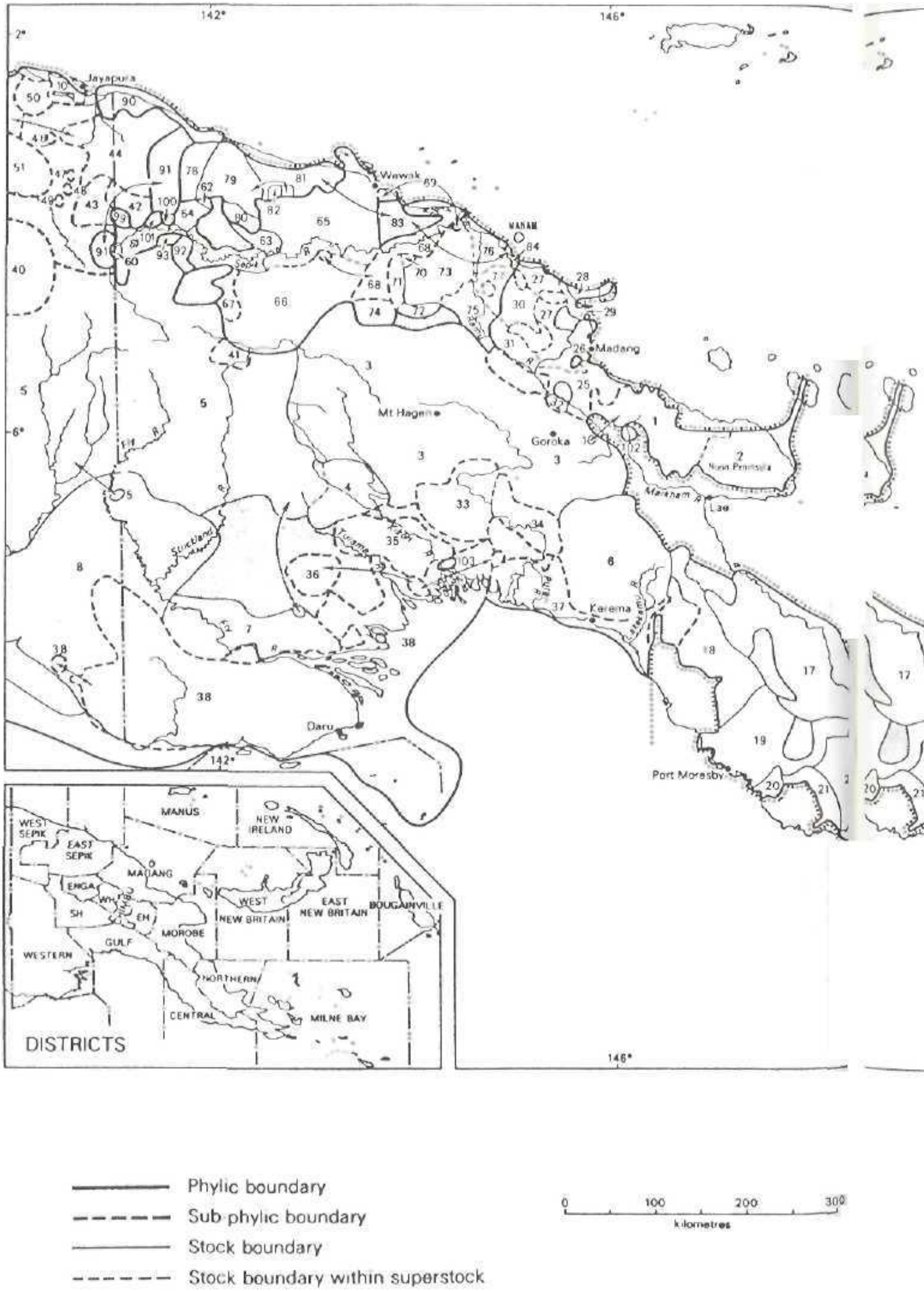
142°
146°
2°
6°
Jayapura
Wewak
MANAM
Madang
Mt Hagen
Goroka
Huon Peninsula
Markham R
Lae
Kerema
Purari R
Lakekamu R
Port Moresby
Daru
Sepik
Strickland R
Fly R
Turama
Kikori R
Ramu
10
50
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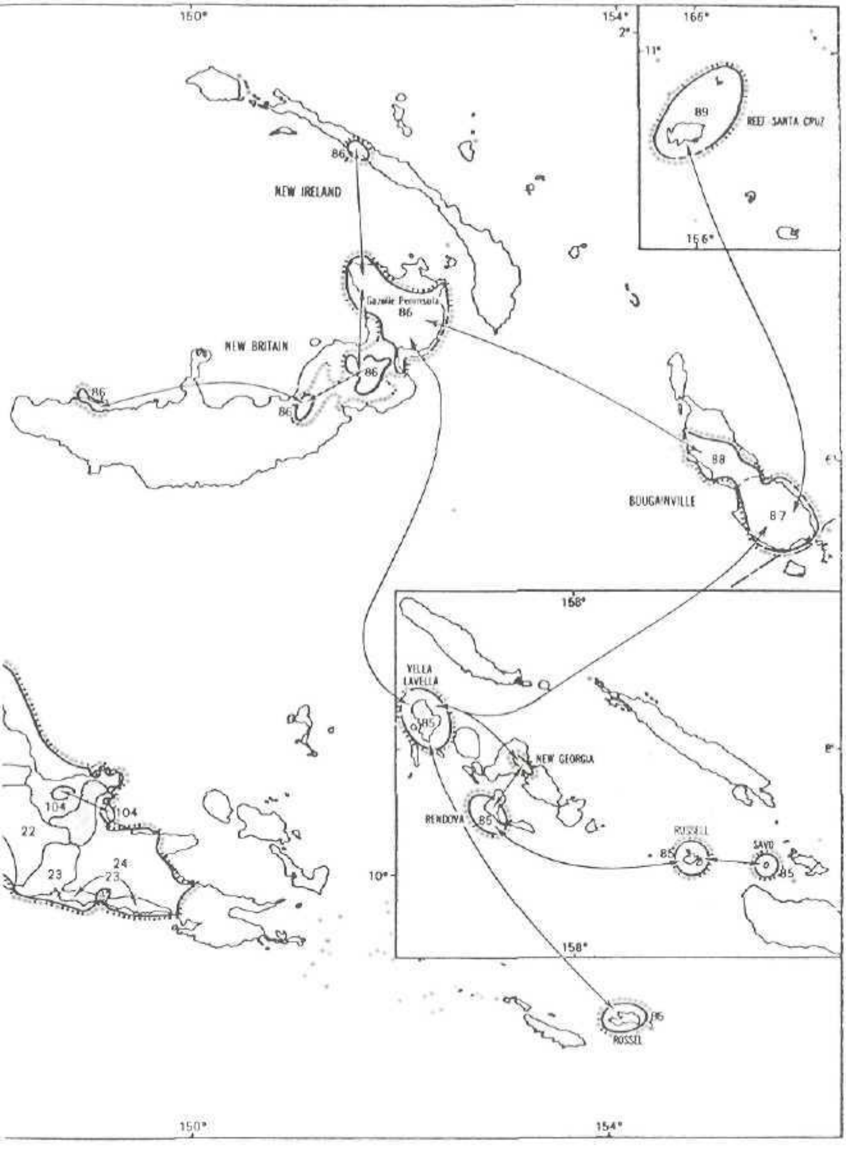
DISTRICTS
WEST SEPIK
EAST SEPIK
MANUS
NEW IRELAND
MADANG
ENGA
WH
SH
EH
CHIMBU
WEST NEW BRITAIN
EAST NEW BRITAIN
BOUGAINVILLE
MOROBE
GULF
WESTERN
NORTHERN
CENTRAL
MILNE BAY
Phylic boundary
Sub-phylic boundary
Stock boundary
Stock boundary within superstock
0
100
200
300
kilometres



·············· Austronesian language boundary

▨ Uninhabited (nature of borders determined by degree of inter-relationship between language groups bordering the uninhabited area)

⟷ Arrow connecting related languages

van Hasselt, F.J.F., Spraakkunst der Nufoorsche Taal (= Numfor). (1905).

Waterhouse, J.H.L., A New Guinea Language Book. (1939).

Wurm, S.A., The changing linguistic picture of New Guinea - *Oceania* 31, 2 (1960) 121-136.

Wurm, S.A., The linguistic situation in the Highlands Districts of Papua and New Guinea - *Australian Territories* 1 (1961) 14-23, 1 map.

Wurm, S.A., Languages of the Eastern, Western and Southern Higlands. (1961).

Wurn, S.A., Australian New Guinea Higlands Languages and the distribution of their typological features - *American Anthropologist* 66 (1964). Special Publication.

Wurm, S.A., New Guinea linguistic scene - *Pacific Linguistics,* Ser. C, 38 (1975) 1-1038.

Trans-New Guinea Phylum

Main section

Central and Western part

1. Finisterre Stock, 2. Huon stock, 3. East New Guinea Highlands stock

Central and South New Guinea-Kutubuan superstock

4. Kutubuan stock, 5. Central and South New Guinea stock, 6. Angan stock-level family, 7. Gogodala-Suki stock, 8. Marind stock, 9. Kayagar stock-level family, 10. Sentani stock, 11. Dani-Kwerba stock, 12. Dem stock-level family, 13. Wissel Lakes-Kemandoga stock, 14. Mairasi-Tanah Merah stock, 15. West Bomerai stock, 16. Mor stock-level family

Eastern part

17. Binandere stock, 18. Goilalan stock-level family, 19. Koiarian stock-level family. 20. Kwalean stock-level family, 21. Manubaran stock-level family, 22. Yareban stock-level family, 23. Mailuan stock-level family, 23. Dagan stock-level family

Sub-phyla

Madang and Adelbert RAnge subphylum

Rai Coast-Mabuso (Madang) superstock

25. Rai coast stock, 26. Mabuso stock

Adelbert Range superstock

Pihom-Isumrud-Mugil section

27. Pihom stock, 28. Isumrud stock, 29. Mugil stock-level isolate

Josephstaal-Wanang section

30. Josephstaal stock, 31. Wanang stock

Brahman section

32. Brahman section

Teberan-Paiawan subphyllum-level superstock

33. Teberan stock-level family, 34. Pawaian stock-level family, 35. Turama-Kikorian subphyllum, 36. Inland Gulf subphylum, 37. Eleman subphylum

Trans-Fly-Bulaka River subphylum-level superstock

38. Trans-Fly stock, 39. Bulaka River (or Yelmek-Maklew) stock-level family, 40. Goliath subphylum-level family, 41. Oksapmin subphylum-level isolate, 42. Senagi subphylumlevel family, 43. Pauwası subphylum

Border-Tor-lake Plain subphylum-level superstock

44. Border stock, 45. Tor-lake Plain stock, 46. Morwap subphylum-level isolate, 47. Molof subphyllum-level isolate, 48. Usku subphylum-level isolate, 49. Tofamna subphylum-level isolate, 50. Nimboran subphylum-level family, 51. Kaure subphylum, 52. South Bird's Head (or Vogelkop) subphylum, 53. Kolopom (or Frederik Hendrik Island) subphylum-level family, 54. Timor-Alor-Pantar subphylum.

West Papuan Phylum

Bird's Head superstock

55. Central Bird's Head stock, 56. West Bird's Head stock-level family, 57. Amberbaken stock-level family, 58. Borai-Hattam subphylum-level family, 59. Northern Halmahera stock-level family.

Sepik-Ramu Phylum

Sepik subphylum

60. Biksi stock-level isolate

Upper Sepik superstock

61. Upper Sepik stock, 62. Ramu stock-level family, 63. Tama stock-level family

Middle Sepik superstock

64. Yellow River stock-level family, 65. Middle Sepik stock, 66. Sepik Hill stock-level family, 67. Leonhard Schultze subphylum-level family, 68. Lower Sepik (nor-Pondo) subphylum, 69. Gapun subphylum-level family

Ramu subphylum

Yuat superstock

70. Mongol-Langam stock-level family, 71. Yuat stock-level family, 72. Piawi stock-level family

Ramu superstock

73. Grass stock, 74. Arafundi stock-level family, 75. Annaberg stock, 77. Goam stock.

Torricelli Phylum

78. West Wapei stock-level family, 79. Wapei-Palei stock, 80. Maimai stock, 81. Kombio stock, 82. Urim stock-level isolate, 83. Marienberg stock-level family, 84. Monumbo stock-level family.

East Papuan Phylum

Yele-Solomons-New Britain subphylum-level superstock

85. Yele-Solomons stock, 86. New Britain stock

Bougainville subphylum-level superstock

87. East Bougainville stock, 88. West Bougainville stock, 89. Reef Islands-Santa Cruz subphylum-level family.

Minor Phyla

90. Sko phylum-level, 91. Kwomtari phylum-level stock, 92. Arai (or Left May) phylum-level family, 93. Amto-Musian phylum-level stock, 94. East Bird's Head phylum-level stock.

Geelvink Bay Phylum

95. East Geelvink Bay stock-level family, 96. Yava stock-level isolate.

Phylum Level Isolates

97. Warenbori phylum-level isolate, 98. Taurap (Boromeso) phylum-level isolate, 99. Yuri phylum-level isolate, 100. Busa phylum-level isolate, 101. Nagatman phylum-level isolate, 102. Wasembo (Gusap) phylum-level isolate, 103. Porome (Kibiri) phylum-level isolate, 104. Maisin (Austronesian-Papuan "mixed" languages).

12. GEOGRAPHY OF HIGH ALTITUDE REGIONS

Using the 3000 meter contour line as the lowest altitude delimitating the high altitude regions it becomes clear that they are found mainly in the central ranges of the island. There are, however, some coastal mountains that reach over 3000 meter altitude, while such mountains as Mount Dayman and Mount Simpson would have to be excluded. This would lead to the anomaly that the extensive grasslands there with numerous alpine elements should not be included in these volumes. In itself this shows the arbitrariness of the 3000 meter line if one does not take into account the physiognomy and composition of these high altitude floras. As has been set out elsewhere the 3000 meter line is taken as an average line. The change from montane flora to subalpine and alpine flora takes place around that altitude. It changes at higher altitudes in the Carstensz Mountains, at lower altitudes in the Mount Dayman region.

Taking these variations into account the high altitude floras, whether primary or secondary in origin, are found in the following regions. In several cases mountain ranges are included of which nothing is known but where it is likely that highland floras will be encountered. The approximate positions of the high altitude regions are given in Fig. 32, while a list of coordinates and their highest point is given at the end of this chapter.

1. Tamrau Mountains. The coastal range in the Vogelkop Peninsula has not been explored to the summit, at least not by botanists. Several native tracks lead from the Warsamson and Isjon Valley to the north coast. Van Royen in 1960 coming from the Isjon River reached an altitude of 2200 m but was prevented from going further by a deep valley. However, as far as could be observed and confirmed by aerial pictures no grasslands are found but only shrubberies. Only very small spots of grassy areas are found and these presumably carry some high altitude elements.

2. Nettoti Range. This range does not reach higher than 2200 m and by our definitions falls well outside the high altitude flora. It is only included here because of the extensive heath vegetations of crooked shrubs with large, open grassy areas in between. This vegetation is a secondary vegetation but in places is a distinct primary ecotype due to the underlying impenetrable clay that precludes the formation of a forest. The number of alpine elements is negligable. (van Royen & Sleumer exploration, 1960).

3. Arfak Mountains. This rather extensive north-south running coastal range south of Manokwari has several areas that have a highland flora. This applies in particular to the heathswamps around the Angi Lakes, both well below the 3000 m contour line, and to the surrounding higher peaks. The number of high altitude elements as reported for these volumes is low. On the higher mountains surrounding the lakes such as Mount Sensenemes, a grassland vegetation is found of secondary origin up to 3300 m altitude. Several high altitude elements are found but genera like *Tetramolopium, Cardamine,* and *Euphrasia* are missing.

The previous three regions are all situated in the Vogelkop Peninsula, but all following are part of the main ranges ranging as far as Mount Simpson in the southeast. North of these main ranges some lower are found such as the Van Rees, Gauttier, Cycloop, Bougainville, Torricelli, and Adelbert Mountains. Some of these reach the 3000 m line and all of them have some elements that are sometimes found in the high altitude regions. Sizable grasslands are not found here and in general the vegetation is a montane forest vegetation reaching well up to the summits of these ranges.

4. The main high altitude vegetations are found in the central backbone of New Guinea from the Charles Louis and Weyland Mountains in the west to Mount Simpson in the Southeast. However, this does not mean that it is one long, uninterrupted belt. On the contrary the area is split up in many parts, of which probably less than half is known to have a high altitude vegetation, others are unexplored and we have to assume that this type of vegetation is there.

Starting from the Charles Louis and Weyland Mountains we find two ranges reaching up to 3700 m (?). The Charles Louis Mountains were crossed in 1935 by the Bijlmer expedition but no botanical reports are known. The same applies to the Weyland Mountains briefly visited in 1913 by F.R. Janowsky. Here too no reports of botanical interest are known. Both ranges were seen during the Military Explorations between 1907 and 1915, but were not visited.

The vegetation around the Wissel Lakes is essentially a lower montane to montane flora with few high altitude elements.

5. North of the Wissel Lakes the extensive Minimitari Mountains reach up to 3535 m but nothing is known of any high altitude vegetations. The same applies to the somewhat more eastward Biandora and Hegenarai Mountains reaching up to 3750 m in Mount Hegenarai.

6. Little is known of the Ngoeloemboeloe Mountains including the 4040 m high Mount Ngoeloemboeloe. This gloomy dark massif is clearly visible to the north from the track from Ilaga to the Carstensz Moun-

tains (Hope exploration 1971/1972). Extensive grasslands are reported but no botanical reports are known.

7. Somewhat further east is Mount Doorman of which quite a fair bit is known due to the Lam exploration in 1923. This mountain reaches 3550 m and has alternating grasslands, shrubberies, and low forests. An excellent botanical report is found in Lam's Fragmenta Papuana (1927-1929).

8. In the southern mountains of the Nassau Range (also occasionally named Snow Mountains or Ranges, Merauke Range, or Central Ranges) we find the highest peaks of New Guinea culminating in Mount Idenburg (4810 m), and the Pyramid (4884 m) in the Carstensz Mountains, both with small glaciers. Extensive grasslands with alpine elements are reported here along the entire crest and on the extensive Kemaboe Plateau north of the Carstensz Mountains (Wollaston, Colijn, and Hope explorations). These high altitude vegetations are reported from Tafelberg (3043 m) somewhat east of the Wissel Lakes, to the Oranje Mountains. Among these are Mount Leonhard Darwin (4255 m) which like a crenellate castle drops down steeply to the southern foothills according to Rawlins being "far and away the greatest precipice in the world".

9. Little is known about the western parts of the Oranje Mountains. The Emma Mountains reach up to 4200 m but nothing is known of their high altitude vegetation. Much better is the position in the central parts with Mount Wilhelmina at 4750 m the highest peak. This mountain was crowned up to 1962 by a small glacier. There are several mountains well above the 3000 m contour but only Mount Wilhelmina has been extensively explored.

10. Between Mount Wilhelmina and Mount Juliana in the eastern part of the Oranje Mountains several high peaks are found in the Van der Willigen, Valentijn, J.P. Coen, and Goliath Mountains. Only from the latter something is known (A.C. de Kock exploration).

11. Mount Juliana (4700 m) is the fourth summit with a glacier. This mountain is the culminating point in this area and though it is known that there are extensive high altitude vegetation types, no botanical exploration of these ranges have been carried out. This applies also to several high parts north and east of Mount Juliana.

12. Of the Orion Mountains between Mount Juliana and the Star Mountains nothing is known. This range was seen and partly explored during the 1961 Star Mountains Expedition, but no botanical data are known. The mountains reach well over 3000 m and therefore open grasslands could be expected.

13. In the Star Mountains, at least the western part, something is known only from Mount Antares, explored botanically by C. Kalkman and B.O. van Zanten. The vegetation is more an open shrubbery rather than grasslands. In the extension of the Star Mountains into the eastern part of New Guinea extensive high altitude grasslands and shrubberies are reported from Mount Auriga, Mount Capella, and Mount Scorpion. (J.F. Veldkamp and A. Touw exploration, 1975).

14. In the Hindenburg Range south and east of the Star Mountains a high altitude vegetation is found but no open grasslands. An extensive search in 1976 by van Royen's team revealed also that the Victor Emanuel Mountains have no open grasslands but only extensive shrubberies on exposed crests.

15. From the Victor Emanuel Range to Mount Simpson quite an extensive knowledge is available of the high altitude vegetation alternating with grasslands, mainly due to the activities of Australian botanists. Nothing is known of the Muller Mountains (4117 m). The Burgers Mountain (3690 m) were visited in 1977 by J.F. Veldkamp and P. Kores and some grasslands are present. The Doma Peaks however, have been extensively studied by Kalkman, including the Mount Ne and Mount Kerewa peaks. In the same general area reports from the Sugarloaf Mountains also indicate that high altitude shrubberies and open grasslands with tree ferns are well represented.

16. The high altitude floras of Mount Giluwe and Mount Hagen are well explored. Those of the former are quite extensive but very much damaged, those of the latter considerably smaller but richer. However, in particular Mount Giluwe is worthwhile studying on a larger and more systematical scale because of the very large size of the grasslands and the rather high altitudes reached on this mountain. Mount Jalibu, south of Mount Giluwe is covered almost to its summit with forests, leaving some very small alpine grasslands.

17. The Kubor Range is fairly well studied as it has been explored several times. Mount Sigal Mugal was explored by J.M.B. Smith, Mount Kubor, Mount Kinkain and others by R. Pullen and W. Vink.

The extensions of the Kubor Range to Mount Michael, Kratke Mountains, and Mount Piora in the south, and the Sepik-Wahgi Divide, Mount Wilhelm, Mount Kerigomna, and Mount Otto along a northern arc, terminating in the Ramu-Markham Valley in the east, and along the Watut River in the south are all studied. The best studied area is the Mount Wilhelm area (Brass, Hoogland, Hope, Smith, Wade & McVean, van Balgooy, van Royen, etc.). All have extensive grasslands mostly of secondary origin, with a few patches of primary alpine vegetations.

18. Somewhat isolated from the previously mentioned areas are the Finisterre and Sarawaket Mountains in the Huon Peninsula. The former have been explored several times from Keysser's time till van Royen in 1976. The Sarawaket, Rawlinson and Cromwell Mountains all are more or less well studied and in particular the Sarawaket Mountains have extensive open high altitude areas, growing one of the very few endemic genera of the high altitude regions, viz. *Detzneria*.

19. Crossing the Watut River valley towards the southeastern tail of New Guinea the first mountain with extensive high altitude floras is Mount Amungwiwa. A study by van Royen's team in 1976 revealed, however, that in comparison with, for instance Mount Wilhelm, Mount Albert Edward, and Mount Victoria, these vegetations are very poor. A total of 52 genera and species regularly found on the three other mountains was missing, among them such genera as *Euphrasia*, *Trigonotis*, and *Tetramolopium*.

20. Following Mount Amungwiwa is Mount Lawson and the high peaks of the Chapman Mountains, with Mount Strong the highest summit. On Mount Strong extensive grasslands are reported but collections are few. These mountains are followed by a series of high peaks with extensive high altitude vegetations. A characteristic mountain in this area is Mount Yule with only shrubberies and some poorly developed grasslands on its flat top. Mount St Mary, poorly explored, has only small grasslands, but Mount Dickson, explored by T.G. Hartley has extensive grasslands. Other mountains in this series are Mount Chamberlain, Mount Murray, and the two domes of Mount Albert Edward. The latter has the most extensive grasslands which are very well studied (Brass, Gillison, Hope, van Royen, etc.). Somewhat more to the southeast of Mount Albert Edward are the relatively small high altitude grasslands of Mount Scratchley, Winter Height, McIlwraith, and Mount Thumb. Of the latter two nothing is known, but more is known of Mount Victoria. The latter has rich alpine grasslands alternating with extensive shrubberies and low forests.

21. From Mount Thumb southwards on the Owen Stanley Mountains most of the ranges are rarely higher than 3000 m. The highest are Mount Obree (3130 m) and Mount Suckling (3675 m), but even on such lower mountains as Mount Monkton (2853 m), Mount Dayman (2990 m) and Mount Simpson (2843 m) extensive grasslands with many high altitude elements are found.

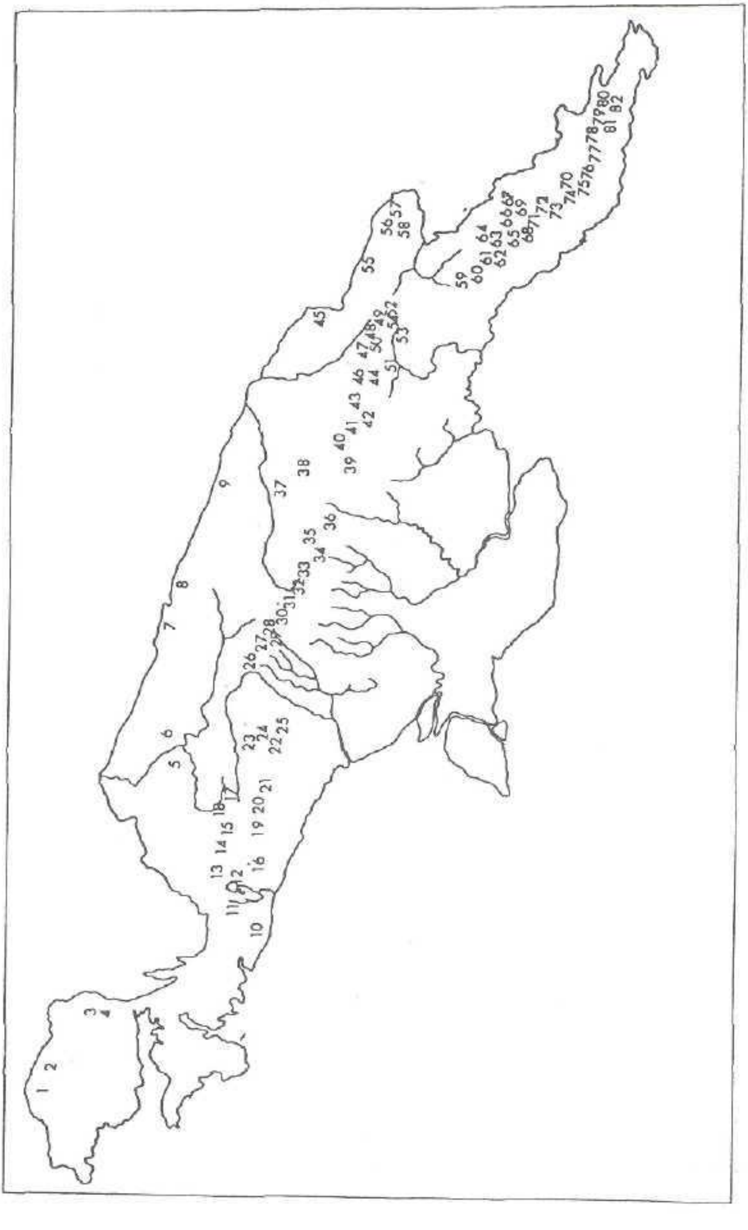


Fig. 32. Outline of New Guinea with the approximate positions of some geographical features. The numbers of the map correspond with those of the list on page 313.

List of High Altitude Regions and their Coordinates

In presenting this list the coordinates in most cases only are approximative. In the first place there are no reliable maps of New Guinea giving the exact coordinates of rivers, villages, mountains, etc. Often mountains are on the map that could not be found back in the field, villages moved over the years, and different tribes gave different names to characteristic features.

In the second place trying to give an exact coordinate is misunderstanding the difficulties that explorers encounter in the field when trying to pinpoint a certain landmark. As an example can be given the name and landmark The Rock Pile. This name is nowhere on any map since the name was coined on my last exploration of the Mount Victoria area in May 1976. The Rock Pile is a group of huge boulders, in fact is a cracked-up rocky outcrop that is situated at the middle slopes of Mount Service, one of the three peaks, with Huxley's Pinnacles and Mount Victoria proper, that constitute the Mount Victoria massif. Mount Victoria itself is only a few feet higher than the other two peaks. The Rock Pile at 3660 m altitude is much lower than the three peaks, but nevertheless is a very distinct landmark that can be observed from Port Moresby, a distance of 50 kilometers away. As a lot of plants were collected around the Rock Pile we were forced to give it a name to enable others to find the place back.

	Longitude East Degree Minutes	Latitude South Degree Minutes	Altitude of Summit meters
1. Tamrau Mountains	133 00	1 00	3000
2. Nettoti Mountains	133 00	1 30	2200
3. Arfak Mountains	134 00	1 40	2760
4. Angi Lakes	134 00	1 40	1840-1920
5. van Rees Mountains	138 00	2 30	975
6. Gauttier Mountains	138 40	2 30	2195
7. Cycloop Mountains	140 30	2 30	1880
8. Bougainville Mountains	141 00	2 40	1220
9. Torricelli Mountains	142 15	3 25	1306
10. Charles Louis Mountains	135 30	4 10	3323
11. Weyland Mountains	135 40	3 50	3720
12. Wissel Lakes	136 20	4 50	1700
13. Minimitari Mountains	136 15	3 30	3535
14. Biandora Mountains	136 40	3 32	3456
15. Kegenarai Mountains	136 55	3 38	3750
16. Tafelberg	136 36	4 02	3043
17. Ngoeloemboeloe Mountains	137 20	3 45	4040
18. Mount Doorman	137 13	3 32	3550

19. Leonard Darwin Peaks	136 56	3 58	4255
20. Idenburg Mountains	137 04	4 05	4378
21. Carstensz Mountains	137 09	4 05	4884
22. Emma Mountains	138 30	4 10	4169
23. Lake Habbema	138 53	4 10	3225
24. Mount Wilhelmina (Oranje Mountains)	138 53	4 15	4750
25. Hellwig Mountains	138 42	4 32	2549
26. Valentijn Mountains	139 45	4 28	2745
27. van der Willigen Mountains	139 48	4 28	4413
28. J.P. Coen Mountains	139 52	4 31	3702
29. Mount Goliath	139 50	4 42	3340
30. Mount Juliana	140 24	4 31	4700
31. Orion Mountains	140 35	4 50	4077
32. Star Mountains	140 30	4 05	4120
33. Mount Capella	141 05	5 00	3850
34. Hindenburg Mountains	141 15	5 15	3303
35. Victor Emanuel Mountains	141 40	5 15	3000
36. Muller Mountains	142 15	5 35	4117
37. Hunstein Mountains	142 40	4 30	1524
38. Burgers Mountains	143 05	5 10	3690
39. Doma Peaks	143 10	5 55	
Mount Ambua			3567
Mount Ne			3355
40. Sugarloaf Mountains	143 45	5 50	3964
41. Mount Giluwe	143 50	6 05	4368
42. Mount Jalibu	144 00	6 15	3355
43. Mount Hagen	144 05	5 45	4000
44. Kubor Range	144 40	6 05	3900
45. Adelbert Mountains	145 30	4 50	2000
46. Sepik-Wahgi Divide	144 40	5 40	
Mount O'Dan			3812
47. Bismarck Mountains	145 10	5 45	
Mount Wilhelm			4510
48. Mount Herbert	145 00	5 40	4160
49. Mount Marien	145 35 (?)	6 04 (?)	2440
50. Mount Kerigomna	145 03	5 28	3660
51. Mount Michael	145 15	6 25	3647
52. Mount Otto	145 30	6 00	3569
53. Kratke Mountains	145 45	6 30	3647
54. Mount Piora	145 55	6 40	3600
55. Finisterre Mountains	146 10	5 50	3917
56. Sarawaket Mountains	147 00	6 15	
Mount Bangeta			4121
57. Cromwell Mountains	147 20	6 15	2940
58. Rawlinson Mountains	147 20	6 30	2260
59. Mount Amungwiwa	146 35	7 27	3156
60. Mount Lawson	146 40	7 45	3217
61. Mount Strong	146 55	7 55	3378
62. Mount Yule	146 45	8 15	3294
63. Mount St Mary	146 52	8 08	3660
64. Mount Dickson	147 10	8 05	3533
65. Mount Tafa	147 10	8 35	2725
66. Mount Chamberlain	147 15	8 15	3423
67. Mount Murray	147 20	8 20	3660

68. Wharton Range	147 28	8 35	3000
69. Mount Albert Edward	147 20	8 25	3990
70. Owen Stanley Mountains	147 35	9 05	4075
71. Mount Knutsford	147 28	8 42	3385
72. Mount Scratchley	147 30	8 40	3812
73. Winter Height	147 30	8 50	3471
74. Mount Victoria	147 30	8 55	4036
75. Mount McIlwraith	147 29	8 45	3355
76. Mount Thumb	147 35	9 00	3355
77. Mount Kenevi	147 45	9 10	2585
78. Mount Monkton	147 58	9 05	2853
79. Mount Suckling	149 00	9 40	3675
80. Mount Wadimana	149 39	10 03	2320
81. Mount Dayman	149 15	9 50	2989
82. Mount Simpson	149 30	10 00	2853

Note: The altitude of 20. Mt Idenburg is 4717 m, and 81. Mt Dayman 2990 m.

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