THE VEGETATION HISTORY OF MT WILHELM

by

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FRONTISPIECE

Pinde kinde kua yama,
Pinde waiye kamen yama,
Na dienga windoro.

Dark clouds gather over the lake,
Rain falls on the still water,
I beg you, come.

Chimbu song recorded at Bomkan,
Upper Chimbu, 1970.

DECLARATION

Except where otherwise acknowledged in the text, this thesis represents the original research of the author.

G. S. Hope

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ABSTRACT

It has long been recognised that most mountains higher than 3,800 m in New Guinea were formerly glaciated. This thesis reports an investigation of the vegetation beyond the margins of the glaciers at the time of the last maximum advance, and of the subsequent history of this vegetation as it migrated higher onto areas left bare as the ice retreated. Mt Wilhelm, 4,510 m, $5^{\circ}47'$S, $145^{\circ}01'$E, was chosen because the modern vegetation there is better known than elsewhere in New Guinea.

The technique of pollen analysis of sediment raised from mires and tarns was employed. To support the interpretation of the results, a study was made of the relationship between the modern vegetation and modern pollen deposition in a wide range of plant communities at different altitudes. This study, reported in Chapters 3-6, shows how percentages of pollen types can be related to particular plant communities, pollen transfer mechanisms and climatic processes.

Four sediment sections from sites at 4,420 m, 3,910 m, 3,550 m and 2,740 m altitude were obtained for pollen analysis and ^{14}C dating. (Chapters 7-10). The lowest site was situated below the limits of former glaciation and provided a record over the last 22,000 years. The higher sites were exposed by ice retreat that took place between 14,000 and 9,000 years ago. The vegetation history provided by the sites is described and compared with palaeoenvironmental data from elsewhere in New Guinea (Chapters 11-12).

A tentative reconstruction of the palaeoenvironments suggests that before 10,000 BP cooler and drier conditions prevailed in the mountains. The glaciers retreated after 14,000 BP but the vegetation indicates that cold conditions persisted during this retreat. It is possible that a weakened circulation and dry southeasterly winds were responsible for the climate, and these were partly related to the presence of a dry land area joining Australia and New Guinea.

By 8,300 BP, subalpine forests colonised Mt Wilhelm up to 4,000 m, but at 5,000 BP the treeline retreated to its present position at about 3,800 - 3,900 m. Forest at lower altitudes also changed after 6,500 - 5,000 BP. These forests were extensively cleared after 800 BP when planting of gardens took place below 2,500 m. At about the same time grasslands began to replace the subalpine forest. The changes that took place after 6,500 BP can be attributed either wholly to man, or else partly to a deterioration in climate which caused glacier advances in West Irian and a possible increase in erosion on the summit of Mt Wilhelm. The evidence is insufficient to distinguish between the effects of climate change and the activities of man.

CONTENTS

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

LIST OF PLATES

LIST OF PLATES

ACKNOWLEDGMENTS

After a few months in the field in New Guinea one tends to think back to dry, rolling plains with scattered trees and clear blue afternoon skies, with the luxuries of straight smooth roads, hot water on tap, shops and libraries. One may vow never to walk again along muddy tracks, dreaming of a day without wet feet. But within a short time of returning to the laboratory bench, a reversal of attitude takes place. One thinks instead of the unbelievable tangle of ridges rising up to mountain peaks of dun grasslands and the gleam of ice, with clouds swirling down over sombre still lakes or clinging to sheer rock walls and deep green forests. The pleasure of being so fit that a 1,500 m climb is of no more concern than a walk over level ground is remembered when all the discomforts of any walking in New Guinea are forgotten. Although the contrasting pulls of New Guinea and Canberra will always remain for me, I am very grateful to the people who have introduced me to both worlds.

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PREFACE

Certain conventions of nomenclature or useage have been adopted in this thesis.

The name New Guinea here refers to the whole island, which is divided into a western half, called West Irian (a province of the Republic of Indonesia), and an eastern half presently known as Papua New Guinea. As far as possible, place names used are those approved by nomenclature boards. Some mountains in West Irian are so well known by former names that these have been retained. These are:

Carstensz Mts	Puntjak Jaya Kusumu (Pk Sukarno)
Carstensz Pyramid	Pk Carstenz
Mt Wilhelmina	Pk Trikora
Mt Juliana	Pk Mandala

Confusion surrounds the correct naming of the two lakes in the Pindaunde Valley on Mt Wilhelm. The names Pinde and Aunde have both been applied to each lake by different authors, so the lakes are referred to here as the Upper Pindaunde Lake and the Lower Pindaunde Lake.

Where altitudes differ from those previously published, I have followed the most recent survey data or height estimates available. This does not always imply greater reliability.

All ^{14}C dates are given in years before present (BP) which is 1950 AD by convention. The ages are based on the Libby ^{14}C half life and are not adjusted for Suess effects.

Plant names follow Johns and Stevens (1971) and Division of Botany (1969). Nomenclature of vegetation communities generally follows Wade and McVean (1969).

Pollen identification status follows Benninghoff and Kapp (1962). Most pollen terms are defined in Chapter 3.

CHAPTER 1

INTRODUCTION

The high mountains of the tropics resemble islands in the fascination they exert on many people, not least biogeographers and ecologists. The recent knowledge that these areas, in common with other parts of the world, have experienced changes in the extent of glaciers and vegetation types provides a reason for the palaeoecologist to turn his attention to them. He may already have considered tropical palaeoecology and will have discovered the bewildering complexity of the low altitude tropical vegetation. An attraction of the mountains is the possibility of relating past changes in the vegetation to the history of the glaciers, because both respond (albeit in a complex manner) to climatic factors. He may hope that at least some climatic effects can be separated from the wide range of factors possibly responsible for vegetation change, including for example autogenic succession or human interference. A consideration of the records of glaciation and vegetation change together can provide insights into both, and indirectly help to interpret vegetation history at lower altitudes.

The palaeoecologist working on high equatorial mountains may be in a position to throw light on the stability and nature of the mountain vegetation and flora. This is of interest because such floras are often completely isolated by lowland vegetation and may present special biogeographic and evolutionary problems. In addition, a history of climatic change may emerge which will be valuable in itself and can also provide criteria against which the theoretical approach to understanding weather on a regional or even global scale can be tested. The network of data on possible past changes in atmospheric circulation is, perhaps, least well known for the equatorial areas, even though these export a large part of the heat that drives the circulation. Although contributions to this network are an exciting possibility, the primary aim of the palaeoecologist is a fuller understanding of ecosystems, with an examination of time as one aspect of their operation. This generalisation includes the biogeographers' interest in the extent in time and space of species and species associations.

Three equatorial ($10^{o}S$-$10^{o}N$) mountain areas carry glaciers today and supported more extensive ice in the past: the Andes of South America, the rift volcanoes and Ruwenzori Mountains of East Africa and the central highlands of the island of New Guinea. This thesis is concerned with studies in pollen analysis and glacial history on the New Guinea mountains. To put this into perspective, the three equatorial mountain regions are first described in terms of their rather different climates and environments and what is known of their late Quaternary histories.

South America

The tropical Andes straddle the equator, extending from $8^{o}N$ as far south as the Tropic of Capricorn. They consist of a discontinuous belt of ranges about 2,200 km long and 100 km wide. The highest of all equatorial peaks, Huascaran, Peru ($8^{o}S$, 6,768 m) occurs in the Andes. The long north-south range interferes with zonal wind patterns and this results in a marked difference between the eastern and western slopes. The western coast of South America is close to the mountains and the continental shelf is very narrow. Part of the western coastal plain is relatively dry and even semi-arid, while the eastern equatorial slopes receive abundant rainfall from trade winds and the intertropical convergence zone. Consequently there is a difference in snowline altitudes, which may be as low as 4,600 m on the east, but are about 5,000 m on the west. To the south the snowline rises to 6,000 m at $20^{o}S$, where the mountains are semi-arid.

Rainfall increases after oceanic air crosses the coastal plains and rises into the slopes of the windward mountains. Lauer *et al* (1952) and Troll (1958) record annual rainfalls exceeding 7,000 mm in the Cordillera Occidental of Colombia between 1,000-1,300 m, but the intermontane valleys and inner western slopes receive less (700-3,000 mm) until the crest of the range is crossed to the east, when precipitation rises to about 4,000 mm. There is apparently a reduction in rainfall on the west-facing slopes with increasing altitude above the rainfall maximum. Bogota, at about 2,600 m, receives only 938 mm. The eastern slopes of the Andes are relatively little known. Rain is derived from the northeast 'monsoon' and the southeast 'trades' (Flint 1971) which provide a seasonality which differs from region to region but usually results in a May-October maximum, particularly north of the equator. However the extrapolation of these trends to areas above 4,000 m may be unfounded.

Elegant diagrammatic representations of the vegetation show higher vegetation boundaries and lower snowline on the east of the Colombian Ranges (Troll 1959, 1961, Gonzalez *et al* 1966). Below the snowline is an area of varying altitudinal width in which forest is discontinuous or absent, and which has been divided by Cuatrecasas (1958, cited by Gonzalez *et al* 1966) into three zones, the subparamo, paramo and superparamo. The subparamo consists of scattered shrubs and trees in grasslands, and runs from 3,300 m to over 4,000 m. The paramo consists of meadows and grasslands but may contain 'tree' species, especially *Espeletia*. It encloses areas of subparamo in very sheltered places, and extends from about 4,000 m to 4,500 m. The superparamo is an area of bare rock and moraines supporting a discontinuous growth of tuft grasses and herbs, and extends down to 4,100 m on young (recently deglaciated) moraines.

Earlier ice cover in the Andes (excepting Chile and Argentina) was about 70,000 km^2 (Flint 1971). Clapperton (1972) found evidence of four retreat stages in Central Peru that he believes have occurred since the last Würm maximum, but no evidence for earlier glaciations. However, he cites a suggestion by Tricart (1965) that three of the moraine series relate to three major ice periods equivalent to Würm I and II and Riss. Neither author offers ^{14}C dates to support his claims. Gonzalez *et al* (1966) provide a minimal deglaciation date for an ice retreat moraine of 12,320 ± 100 BP (GrN-3247) in the eastern Colombian mountains (6^oN) at 3,880 m.

Evidence for earlier glaciations comes from pollen analysis of a 203 m section of lake sediment from a site near Bogota in Colombia (van der Hammen and Gonzalez 1960a, 1964). Forest and grassland have replaced each other many times in the past and the changes have been attributed to climatic change of a magnitude that must reflect glaciation in the mountains. ^{14}C dating in the upper part of the core suggested that the grassland phases approximately coincided with times of cold climate in Europe, and forest peaks with times of warmer climate there. Van der Hammen and Gonzalez inferred a connection between the 'cold' periods and relatively increased precipitation, while the 'warm' periods were held to reflect relatively dry conditions. In subsequent pollen analysis work in Colombia, a detailed climatic correlation with the European sequence has been suggested for the last 13,000 years (van der Hammen and Gonzalez 1960b, 1965a,b, van der Hammen 1961, Gonzalez *et al* 1966, van der Hammen and Vogel 1966).

Consistent vegetation changes were not found at all sites, however. For example, increased grassland (taken to imply cool conditions) was found at Cienaga del Vistador at 3,300 m after 10,000 BP (van der Hammen and Gonzalez 1965b), whereas a warmer period has been postulated for this time from other sites. The authors explain this anomaly by postulating very dry conditions locally at Cienaga del Vistador, which permitted grassland to remain there after 10,000 BP, when a generally warm climate had allowed forest to be established everywhere else. This made Cienaga del Vistador appear relatively well forested during the inferred cold period. Mercer (1969) has pointed out that new ^{14}C dates alter the parallel nature of some of the climatic reconstructions. For example, an inferred warmer period was correlated with the Allerod interstadial of Europe, but it has now been dated at about 8,000 BP instead of 10,900 - 11,900 BP. Mercer (1969, 1972) believes that detailed correlations with the post-glacial European sequence are at present unproven for this area.

An additional problem with the correlation is that some of the changes attributed to climatic influences may be due to fire, possibly man-induced. Powell (1970a) has commented that some dates, up to 9,000 BP, used in the Colombian sequence are based on charcoal, demonstrating the presence of fire. Human influence, suggested by increasing weed pollen, has only been acknowledged by van der Hammen and Gonzalez (1960a) after 300 BP, but earlier human occupation in tropical South America is well established. For example, Lanning and Patterson (1967) have obtained ^{14}C ages of 10,300 BP from a coastal archaeological site in Peru, and they believe that hunter-gatherercommunities have been present in South America for 14,000 years.

In summary, the rather large amount of research that has so far been carried out on equatorial South America has not dated glacier changes widely, nor have the vegetational changes found there been unequivocably related to simple climatic parameters. The mountain areas are so complex that many fossil sites will have to be investigated to set out the vegetation history. Detailed correlations cannot be expected between different areas in the Andes as local factors may possibly have been more important than regional effects.

East Africa

The equatorial mountains of Africa differ markedly from the Andes in that they are isolated from each other and from the ocean. They rise from semi-arid high plateaux on both sides of the Great Rift Valley, the highest mountain being Kilimanjaro at 5,895 m. Mt Kilimanjaro, Mt Kenya, and the Ruwenzori Mts have the only permanent snow-bearing peaks, but other mountains also exceed 4,000 m. These mountains are the best known from an environmental standpoint, and many of the interpretations of other tropical mountains are based on Mt Kenya and Mt Kilimanjaro as 'type localities', although both must be regarded as the driest of equatorial mountains.

The area has very seasonal precipitation, with equinoctial rainfall which is variously distributed (Coetzee 1967). The Ruwenzori, in the west, receive two peaks of rainfall centred about April and September, while Kilimanjaro has a major rainfall season only in September. The most spectacular characteristic of the rainfall pattern is that it increases up to an altitude of 1,600-3,000 m where cloud formation is rather constant. Above this level, which varies with aspect, the rainfall decreases. There are also important total precipitation differences with aspect. On the Ruwenzori Mts, precipitation is heavier on the eastern slopes, whereas the southern and southeastern slopes of Mt Kenya receive the highest annual falls. The wetter eastern slopes of Ruwenzori, at or above 3,200 m, receive 2,200-2,800 mm (Livingstone 1967). A similar amount is received at about 1,700 m on the southern side of Kilimanjaro, but the total declines rapidly above 3,000 m and is under 500 mm at 4,100 m and possibly only 250 mm near the summit.

These rather complex rainfall patterns lead to a great difference in the snowline and glacier altitudes. The Ruwenzori snowline lies at about 4,600 m and glaciers descend to 4,270 m on the west, but to 4,150 m on the east, partly because of the easterly precipitation (Hedberg 1964). On Mt Kenya the snowline is higher, at 4,730 m, with glaciers descending to 4,400 m on the west, but only to 4,700 m on the east. Mt Kilimanjaro has a snowline at about 5,400 m and again the glaciers show a marked aspect difference, extending out to 4,700 m on the south and southeast but only to 5,700 m to the northeast. The aspect difference in ice and snow extent has been attributed to insolation (Coetzee 1967), which is strong most mornings on these dry mountains but less effective during the afternoons because clouds tend to wreathe the summits. Thus snow accumulation to the west is favoured, except on very cloudy mountains such as the Ruwenzori.

The vegetation of the African mountains has been described by many authors (eg Hedberg 1951, 1954, 1964, Troll 1959, Coetzee 1967, Coe 1967, Livingstone 1967), and again differs with location and aspect. Most authors agree with a zonation analogous to that of the South American montane vegetation. Montane forests give way at about 3,000-3,300 m to an ericaceous shrubland zone with an upper limit of 3,550-4,100 m, and an alpine zone which contains scattered arborescent 'afroalpine' species in grasslands, giving way to open grasslands and finally rock and bare moraines. The 'afroalpine' species include tomentose-leafed, pachycaulous *Dendrosenecio* and *Lobelia* species, which grow up to 4 m high, and parallel the *Espeletia* spp. of the Andes. These plants are extremely frost resistant and extend well beyond the 'timberline' of normal shrubs, a phenomenon discussed by Wardle (1971).

The Pleistocene extension of the glaciers of the Ruwenzori has been discussed by Livingstone (1967) from unpublished work by Osmaston (1965). Three well-preserved moraine series were distinguished: Lac Gris, represented by small frontal moraines near the present glaciers at 4,200 m, probable age 100-700 BP; Omurubaho moraines at 3,600-3,900 m, with an estimated age of 10,000 - 15,000 years BP; Lake Mahoma, represented by large latero-terminal moraines extending as low as 1,740 m, with a minimum deglaciation date from 2,960 m of 14,750 ± 290 (I-556) (Livingstone 1962). On the other mountains, terminal moraines occur between 3,400 and 3,600 m, but have not been directly dated (Flint 1971). Older glaciation may be indicated on Mt Kenya, where an old drift sequence underlies fresher moraine (Flint 1971). To the east of the Ruwenzori Mts, Osmaston has identified two possible very old moraine sequences, of very great extent (Livingstone 1967). Flint (1971 p. 699) apparently does not accept these occurrences.

Again, pollen analyses in the mountains have disclosed considerable vegetation change over the past 30,000 years, early grasslands being replaced by forest at several localities (Hedberg 1954, van Zinderen Bakker 1962, 1964, Coetzee 1964, 1967, Livingstone 1967). These changes have been interpreted as reflecting migration of the altitudinal vegetational zones. In some cases (eg Coetzee 1967) very exact correlations of levels of vegetation belts within these zones have been made, and past temperatures inferred from the present distribution of the belts. Morrison (1966) and Livingstone (1967) have criticised this procedure both on the accuracy of identification of individual communities in narrow altitudinal limits within the vegetation zones, and on the correlation of the communities with particular temperatures. They point out that successional changes or climatic influences other than temperature might have been important. Certainly large changes in lake levels, and probably net precipitation, are known to have occurred in nearby lowland lakes in the past 14,000 years (eg Kendall 1969, Richardson 1966).

The effect of man on the high altitude vegetation seems to be poorly known, although the widespread use of fire by man in East Africa seems certain from before 40,000 BP (Davies 1967). Cultivation and herding probably commenced before 6,000 BP. Morrison (1966) has pointed out that some plant communities may be artificial and maintained by fire. Thus palaeoclimatic inferences should not be made from the appearance of these communities at other altitudes in the past. A related factor is that of grazing (Hedberg 1964). Elephants have been reported occasionally from the alpine grassland (Coe 1967) and the possibility of grazing having affected the more extensive grasslands of the past has not been considered.

At present the detailed correlation of vegetation changes with climate as claimed by Coetzee (1967) must be regarded with some caution. However, the combined chronology of glacial, vegetation and lake level changes supports a general agreement with the major climatic events of the last 20-30,000 years elsewhere (Kendall 1969). Flint (1971 p. 692), in assessing the earlier palaeoenvironmental work, stated that no consistent, understandable picture of glacial-age climates exists for Africa, and blamed this partly on

> "an assumption that all changes must have been synchronous and areally regular. This has led to widespread correlation of local sequences with generalised 'standard' sequences."

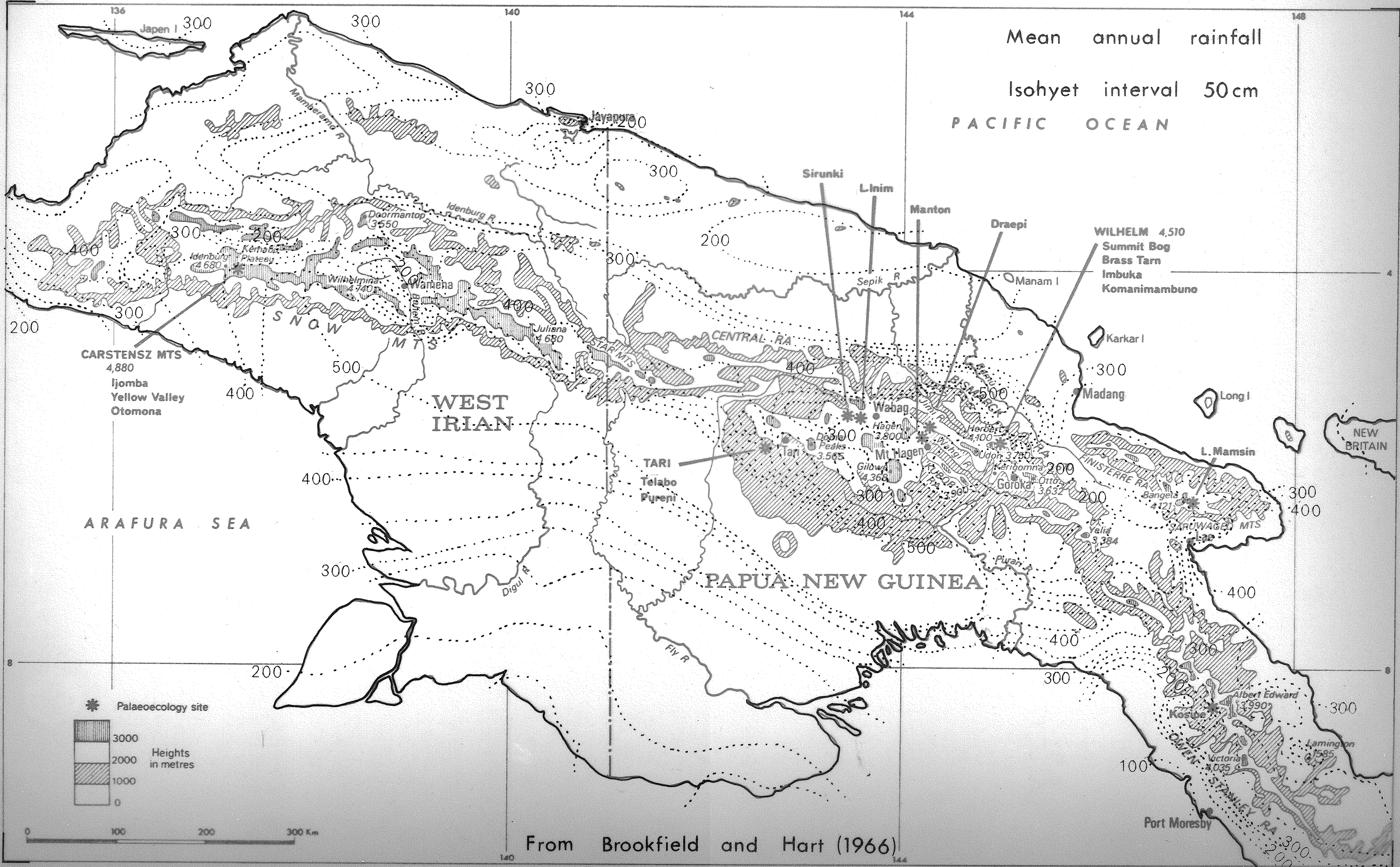
Southeast Asia

The existence of permanent snow in the Asian tropics was first recorded by Jan Carstensz in 1623 (Wollaston 1912), only a century after news of the Andes snowfields had been conveyed to Europe and more than two centuries before the African mountains became known there. As far as modern research into ecology and palaeoenvironments is concerned, the higher mountains of Southeast Asia are only now receiving attention, other than floristic exploration. The review of the African and South American areas has summarised some of the literature postdating Troll's (1959) account of the tropical mountains. In his book Troll had to rely on very scattered information about the mountains of Borneo, Java and New Guinea. With the exception of the Javan volcanoes (van Steenis 1934-6), most of the information was obtained from expedition reports and collections. As in South America and Africa, it is difficult to generalise about the high mountains as a single entity from any point of view, as variations in climate, geology, vegetation and history make each mountain a special case.

Only one mountain in equatorial Southeast Asia outside New Guinea has been glaciated in the past. Mt Kinabalu (Sabah, Malaysia, 4,101 m) on the island of Borneo (Kalimantan) supported a small ice cap about 4 km^2 in size (Koopmans and Stauffer 1967, Jacobson 1970). The summit vegetation today is not regarded as alpine because shrubs grow in favoured localities (Corner 1964, Smith 1970). Closed shrubland could probably occupy the area but for unfavourable edaphic factors.

In New Guinea about 4,500 km^2 of land in West Irian and 600 km^2 in Papua New Guinea is above 3,500 m. Fig 1.1 shows the distribution of these high mountain areas and the location of places to be mentioned in the text. The mountain ranges form a spine running for about 2,500 km along the island, with only one significant gap, from the Vogelkop Peninsula in the northwest to the southeastern tip of Papua. To the west the mountains form a

FIGURE 1.1 Location of palaeoecology sites in New Guinea



central chain about 50-100 km wide but in Papua New Guinea this cordillera splits, with a northern arm extending out onto the island of New Britain and a southern arm veering to the southeast. Permanent ice caps are present on Mt Idenberg, the Carstensz Mts and Mt Juliana, while a fourth peak, Mt Wilhelmina, lost its ice cap after 1958. The present snowline is 4,400-4,700 m (Löffler 1972, Verstappen 1964, Champion and Radok 1972). All these mountains are in West Irian, and are part of the Snow Mts, a range formed of folded, uplifted late Miocene sediments. The ranges in Papua New Guinea are discontinuous, with isolated, though large, areas exceeding 3,000 m. These mountains include stratovolcanoes, uplifted granite batholiths and metamorphic rocks in addition to folded and faulted geosynclinal sediments.

Nix and Kalma (1972) have reviewed the basic climatic processes of New Guinea. The intertropical convergence zone (ITCZ) and the perturbations which occur on either or both sides of it form a belt which leads, in New Guinea, to westerly vortices with varying winds and discontinuous inflows of moist, unstable, equatorial, maritime air masses. These reach farthest to the south in January - February, and are fairly shallow, extending up to 3,000 m. South of the perturbation belt, and extending farthest to the north during May-August, are the southeasterly 'trade' winds, which are stable and dry at 20°S. The lower layers become warm and moist as they cross the topical seas, and thus become increasingly unstable as they move towards the equator. These warmed layers become deeper northwards also, reaching 4,000-4,800 m (Brookfield and Hart 1966). Both the ITCZ perturbations and the southeasterly air streams are responsible for precipitation in New Guinea, but the former is more important and results in a single maximum for rain over much of New Guinea between December and March. However, where the southeasterly winds impinge on the rising coastal or orographic barriers, such as the slopes of the southern cordillera, heavy rainfall occurs between May and August, and the December - March maximum may be absent. Because both air masses are shallow, they are affected by the mountain barriers to a great degree (overlay, Fig 1.1).

Brookfield and Hart (1966) have attributed rainfall south of the cordillera during the perturbation season to locally induced circulation alone, and such local patterns are important rain sources, so much so that the two areas of the island receiving more than 5,100 mm per year (southern slopes of the cordillera and northern slopes of the Bismarck Range) are those with the most active local (diurnal) circulations. A second result of the shallow air masses is that local circulation becomes dominant above 3,000-4,000 m, although it is usually strengthened during the dominant rain season. For example, the Carstensz Mts form the southern face of the cordillera and the slopes between 500 and 3,000 m receive very heavy rain (more than 4,000 mm) all year round, despite a pronounced 'dry' season between December and February below 500 m. Above 3,000 m a December - February rainfall minimum becomes apparent although uplift winds bring consistent and sometimes heavy rain during that time. There appears to be a May - October maximum coinciding with the southeasterlies. By contrast, the Bismarck Range, which is one of the northern ranges of the main cordillera, has a distinct minimum at this time, and this may include some weeks without rain on the southern side. The local circulation from the north may bring some showers during such periods to all levels on the northern slopes,(Plate 1), while the southern slopes are exposed to diurnal thunderstorms which often do not produce rain above 3,000 m.

Major factors controlling all these weather systems are the sea temperature and the equatorial current that flows in the shallow Arafura Sea south of New Guinea. The shallow water south of New Guinea and to the east in the Indonesian archipelago is a major source of latent heat regarded as the dominant driving mechanism of low latitude circulation (Webster and Streten 1972).

The vegetation of New Guinea is still poorly known although vegetational groups have been defined into which most communities can be pigeon-holed. These groups are regarded as either altitudinally or anthropogenically controlled. Tropical rainforest occurs in the lowlands together with vast expanses of swamps around the four great river systems that drain the central cordillera to the north and south. Above this montane rainforests of many distinctive types extend up to a treeline at about 3,800 m. These include mixed oak (*Castanopsis* sp., *Lithocarpus* spp.)forest, beech (*Nothofagus* spp.)forest, mixed mountain, moss or cloud forest and subalpine forest. They have been described, together with specialised swamp forests, by Lane-Poole (1925), Womersley and McAdam (1957), Brass (1941, 1956, 1959), Robbins (1958), Robbins and Pullen (1965), Flenley (1969) and Johns (1972). Native gardens, fallow lands and regrowth grasslands, shrublands and secondary forest are very extensive both in some lowland valleys and in the intermontane basins such as the Wahgi and Baliem Valleys (Powell 1970a).

The communities above the tree line differ from those found in the alpine zones of the African and Andean mountains. The closed treeline gives way to a zone of shrub-rich open grasslands which may range from 3,000 m to 4,100 m (Plate 2), and the lower levels of this are thought to have developed following the firing of original forest (Paijmans and Löffler 1972). Above this zone are areas of dense tussock grassland growing on deep peat soils, often with dwarf shrubs. These reach right to the summits of most peaks except on very rocky areas, where moss- and lichen-rich tundras may be present. The snowline in West Irian has obviously risen in the last 50 years, and a zone of bare rock does exist there between grasslands and ice, but on suitable morainic tills grasses will grow to 4,600 m, next to the edges of the glaciers, and a true climatic limit to plant growth does not appear to be reached.

There are no 'afroalpine' megaphytes or giant rosettes as in Africa and the Andes, but there are very large areas of shrub-rich grassland, sometimes dominated by tree ferns (*Cyathea* spp.) which have a pachycaulous habit (eg Plates 15, 34) and are apparently frost resistant. Woody *Senecio* species with tomentose leaves are also present in the subalpine forests above 3,300 m, and on moraines to 4,400 m in the Carstensz Mts. Wade (1968) has pointed out that the diurnal temperature range on Mt Wilhelm is far less than in Africa or the Andes at a given altitude, and attributes this to the moister conditions. The very cold air and ground temperatures characteristic of the 'afroalpine' belt apparently do not exist on any mountain in New Guinea.

A feature of the vegetation is the marked floristic diversity on different peaks, with an intriguing distribution of species, some of which occur on widely separated peaks but not on intermediate ones. For example, *Papuzilla laeteviridis* occurs at 3,800 m on the Saruwaged Mts and 1,200 km west in the Carstensz Mts. It has not been recorded at intermediate sites. The treeline vegetation in particular is varied and many 'species' have markedly different altitudinal ranges in different areas, in apparently analogous vegetation types. *Papuacedrus (Libocedrus) papuana* is often mentioned as a subalpine forest tree (Troll 1959) occurring near the treeline at 3,800 m on the Saruwaged and Carstensz Mts; on Mt Wilhelm it is present only below 3,300 m. Ecotypic variation is probably very common.

The maximum extent of ice in New Guinea occurred during the late Pleistocene (Galloway *et al* 1973). The Snow Mts of West Irian supported a more or less continuous ice cap of about 4,500 km^2 (Verstappen 1964, Dow 1965, Champion *et al* 1972). The mountain areas of Papua New Guinea supported several ice caps, the largest of which was 180 km^2 in area on Mt Giluwe. The total area was about 600 km^2 (Löffler 1972). At the maximum extent of glaciation, the snowline was at 3,500-3,600 m, about 1,100 m lower than at present, with glacier tongues reaching lower altitudes, generally to 3,000-3,300 m, and even lower in a few cases. Pollen analysis in the highlands of Papua New Guinea has established that grasslands containing alpine and subalpine species were widespread above 2,500 m from before 30,000 years to about 12,000 to 8,000 years ago (Flenley 1967, Powell 1970a, Walker 1970). Analogous communities are now only found 500-700 m higher. This suggests a shift of the higher vegetation belts consistent with the snowline shift of 1,100 m. Recent work suggests that even more extreme vegetation shifts occurred earlier than 34,000 BP (Williams, McDougall and Powell 1972), but the glacial evidence does not yet provide clear support for earlier or more extensive glaciations.

During times of low sea level New Guinea was joined to Australia by the exposure of the Arafura shelf (Jennings 1972). This must have had great climatic effects (Gentilli 1961), as much of the moisture carried by the southeast 'trade' comes from the warm shallow waters of the sea to the south of New Guinea. Rather dry conditions have been postulated for this exposed land area (Galloway and Löffler 1972), from evidence of saline lake deposits (Van Andel *et al* 1967, Phipps 1970). The sea to the north of New Guinea is deep and only a small coastal area would have been exposed by a drop in sea level of 180 m.

The known history of man in New Guinea extends back to 26,000 BP (White *et al* 1971), with continuous evidence for his presence from about 11,000 years ago.

> "At that time small groups, presumably hunters and gatherers, became semi-permanent occupants of the Highlands. It seems likely that they lived mostly in the main valleys where it was warmer, though they would hunt in the high altitude forests. The first economic change seen in the archaeological record is the presence of pig around 6,500 BP. On available evidence its arrival had no technical correlates and until the economic status (feral or domesticated) is known, the economic and social changes its arrival may have caused cannot be assessed. It is at ca 5,000 BP that some major changes in the use of rock shelters occurred and one might begin to look for the beginnings of horticulture in the Highlands. Recent pollen evidence however shows that extensive forest clearance occurred at two sites in the Wahgi Valley more than 5,000 years ago (Powell 1970a) and this, together with the presence of pigs, provides strong support for the suggestion that horticulture was being practised. Horticulture, using complex methods, was definitely established in at least one main valley by 2,500 BP or earlier (Golson *et al* 1967). The change probably occurred at different times throughout the Highlands. The adoption of horticulture presumably allowed a general increase in population density, with increasing pressure on the forest leading to the formation of grasslands in environmentally less favourable areas. The most recent prehistoric changes probably occurred less than 400 years ago with the arrival of the sweet potato (introduced by Europeans to the Philippines in the 16th century). This new addition to the crops would have been easily adopted into a horticultural system already based on root crops, especially as it allowed occupation to extend higher up the valley slopes."
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> (White 1972: 147-148)

The antiquity of man in the West Irian highlands is not known, but there is no reason to suppose that it is substantially different (Allen 1972).

About two million people inhabit Papua New Guinea, with about one million in West Irian. Over 40% live in the intermontane valleys at 1,400-2,200 m in the central highlands, where some very dense populations are found. Much of the remainder of the island has very low population densities, particularly West Irian. Most people still live by subsistence gardening, with a relatively efficient, permanent system of crop rotation in the highlands (Clarke 1971). Gardens of sweet potato (*Ipomoea batatas*) and taro (*Colocasia esculenta*) are found as high as 2,700 m. Brookfield (1964) has suggested that the highest altitude of settlement is limited in a few places by frost, but that the level of persistent daily cloud formation is possibly the most compelling factor inhibiting agriculture. The forests and grasslands of most mountain areas are constantly visited by hunters and traversed by trade routes so that man's influence is felt even above 4,000 m.

Conclusions

All three equatorial mountain areas have sharp contrasts in geomorphology and climate. The Andes form a barrier blocking zonal climatic effects; the New Guinea cordillera acts as a barrier to meridional climate influences and the African mountains are isolated in the centre of their continent. New Guinea is the wettest of the three areas. Past sea level changes can be expected to have had drastic effects in Southeast Asia, but less in the other two areas. The indicated reduction in the firn line at the last period of maximum glaciation is similar in all three areas, and the most recent glacial maximum stage seems to have been broadly synchronous in all. Despite optimistic claims, the climatic histories of equatorial South America and East Africa cannot be definitely related to the standardised (if not universally accepted) European sequence, and that of New Guinea has never been so related. The great variability within each region means that far more work will have to be done over a wide range of sites, taking local influences into account, before regional palaeoclimates can be reconstructed. It is likely that a world-wide change may have very different results in different areas (eg Mercer 1969).

In New Guinea, past changes in the extent of ice and of alpine grasslands demonstrate that some climatic change has taken place, while the effects of man on the vegetation have also been detected. This study has been designed to complement the work on glacial geomorphology at very high altitudes and that on vegetation histories at lower altitudes, by examining the vegetation history of an area within and slightly below the limits of previous glaciation. It could be expected that vegetation belt boundaries were most sensitive to temperature-related climate change in the high mountains, and could thus be related to glacial features and history to provide a control for vegetation changes at lower altitudes where the effects of ice caps and large temperature gradients would have been less marked. The lower altitude vegetation histories in turn provide a control for anthropogenic change in high altitude communities, since man's effect