Climatic Change, Human Impact and Catastrophic Events during the last 20,000 years in Papua New Guinea

Trip Organisers:
Simon Haberle and Geoffrey Hope
TIMETABLE

<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>Location and activity</th>
<th>Accommodation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Saturday 4 August PX184 POM- HGU dep 15:10 arr. 17:05</td>
<td>Port Moresby: Meet at AirNuigini domestic at 1.30pm for flight to Mt Hagen via Lae</td>
<td>Highlander Hotel, Mt Hagen (675) 542 1355</td>
</tr>
<tr>
<td>2</td>
<td>Sunday 5 August</td>
<td>Mt Hagen area. Volcanic lahars, highlands agriculture, Kuk archaeological site</td>
<td>Highlander Hotel</td>
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<tr>
<td>3</td>
<td>Monday 6 August</td>
<td>Travel by road to Keglsugl through Wahgi Valley the upper Simbu. Intensive agriculture, karst landscapes</td>
<td>Hostel at Keglsugl (8000ft, 2400m)</td>
</tr>
<tr>
<td>4</td>
<td>Tuesday 7 August</td>
<td>Climb to Mt Wilhelm glacial lakes Mt Wilhelm glacial features and vegetation history</td>
<td>Camping in huts at 3550m</td>
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<tr>
<td>5</td>
<td>Wednesday 8 August</td>
<td>Mt Wilhelm Descend in the afternoon</td>
<td>Hostel at Keglsugl</td>
</tr>
<tr>
<td>6</td>
<td>Thursday 9 August PX961, PX856 Dep GKA10.45 Arr PNP 13:30</td>
<td>Drive via Daulo Pass to Goroka. Highlands caves</td>
<td>Bird of Paradise hotel, Goroka 675 731 3100</td>
</tr>
<tr>
<td>7</td>
<td>Friday 10 August PX856 Dep GKA10.45 Arr PNP 13:30</td>
<td>Fly to Popondetta. 1956 volcanic eruption and pyroclastic flow, Mt Lamington.</td>
<td>Lamington Hotel, Popondetta 675 329 7222</td>
</tr>
<tr>
<td>8</td>
<td>Saturday 11 August PX 857 Dep 13:50 Arr 14:25</td>
<td>Visit Oro Bay. Popondetta to Port Moresby. Holocene lakes and savannah.</td>
<td>Lamana Hotel, Port Moresby 675 323 2333</td>
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<tr>
<td>9</td>
<td>Sunday 12 August</td>
<td>Port Moresby- Cairns or other destination</td>
<td>Morning tour for those departing in afternoon</td>
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We will mostly be in the highlands (1600-2000m) with pleasant days and possible afternoon rain and cool nights. In the lowlands Popondetta and Port Moresby can be hot (30°C) and sunny.

**Travelling to Mt Wilhelm.** The drive to Mt Wilhelm is spectacular but also arduous and unpredictable, lasting at least 5hr from Mt Hagen. The road is rough and narrow so we will need to be prepared for some delays (sometimes the road is washed away). Once we have reached Kegusugl, the village at the base of Mt Wilhelm, we will arrange local accommodation for our stay. You will need your own sleeping bag and mat for this. Camping in tents here is not recommended.

**Climbing Mt Wilhelm.** Climbing Mt Wilhelm is the highlight for many travellers coming to PNG. If we are lucky and the day is clear we will be able to see the northern coastline of New Guinea from the summit. If we do not reach the summit there is still some fantastic glacial landscapes in the alpine region. We will organise guides to help us up the mountain and there are 2 huts (one a former ANU fieldstation) at 3500m asl that we can use to stay overnight. There are 2 options for our stay in the area. (1) is to spend the day walking between Kegusugl and Lake Pindaunde viewing forest to alpine transition and glacial features on the way, returning the next day. This is not very difficult and is recommended. (2) On Wednesday some of us will attempt to reach the summit (4509m asl), which is a hard 7hr walk (up and then back to Keglsugl) requiring an early morning start (from Lake Pindaunde hut at ~4am) to reach the summit ridge by early morning to have a chance of getting a view. The climb to the summit is not technically difficult but should only be attempted by those who are fit and able to cope with the effects of high altitude and quite cold temperatures. Those who stay at the huts can climb a shorter route to Imbuka Ridge for a view to the north.
Mt Wilhelm – Pindaunde Valley.

Other stops: We have booked good quality hotels (twin share) and will be traveling in a minibus with short walks involved. Some will be to soft or muddy ground.

To bring (in preparation for wet and cold weather): warm sleeping bag, sleeping mat and a small pillow. You will also need good quality walking boots, a warm jacket, a gortex (or equivalent) rain jacket and a woolen hat for high altitudes. We recommend long-sleeved shirts and trousers even in the lowlands (prevention from sun burn and insect bites) and you will need a broad brimmed hat as well. Bring a torch/headlamp, water bottle, plastic cup, sleeping bag inner sheet, and lighter clothes for the hotels. New Guinea is very informal so you won’t need ties, jackets or equivalent. Sun screen and mosquito repellent can be purchased in Cairns or Mt Hagen. We must try to keep luggage compact and recommend soft bags (eg kit bags) as these pack well and are preferred by carriers over frame packs. You can exchange Pounds, Yen, US$ and AU$ in the international terminal (not domestic) on arrival. Money can also be obtained from bank teller machines in the main towns using credit cards.

<table>
<thead>
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<th>Intrepid Expedition members:</th>
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<tr>
<td>Dr</td>
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<td>Prof</td>
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<tr>
<td>Ms</td>
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<td>Dr</td>
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<td>Dr</td>
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<td>Dr</td>
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New Guinea in August is generally drier and cooler than any other month, but showers can be expected in the afternoon in the highlands. On Mt Wilhelm light frosts (-2°C) can be expected and advice on a suitable sleeping bag and clothing will be provided. Geoff Hope and Simon Haberle are palynologists who have a lot of familiarity with the areas to be visited. We also hope that a vulcanologist can also join
us for the trip to Popondetta. New Guinea is a fascinating country of great contrasts and this short trip will show you a range of remarkable environments, Quaternary problems and opportunities.

**Geography of Papua New Guinea**

Papua New Guinea, a country in Oceania, occupying the eastern half of the island of New Guinea and numerous offshore islands (the western portion of the island is occupied by the Indonesian provinces of Papua and West Irian Jaya). It is located in the southwestern Pacific Ocean, in a region defined since the early 19th century as Melanesia. Its capital, and one of its few major cities, is Port Moresby. It is one of the most diverse countries on Earth, with over 850 indigenous languages and at least as many traditional societies, out of a population of just under 6 million. It is also one of the most rural, with only 18 per cent of its people living in urban centres. The country is also one of the world's least explored, culturally and geographically, and many undiscovered species of plants and animals are thought to exist in the interior of Papua New Guinea.

At 178,691 sq.mi (462,840 km²), Papua New Guinea is the world's fifty fourth-largest country (after Cameroon). It is comparable in size to Sweden, and somewhat larger than the US state of California. Papua New Guinea is mostly mountainous (highest peak: Mount Wilhelm at 4,509 m; 14,793 ft) and mostly covered with rain forest, as well as very large wetland areas surrounding the Sepik and Fly rivers. The country is situated on the Pacific Ring of Fire, at the point of collision of several tectonic plates. There are a number of active volcanoes and eruptions are frequent. Earthquakes are relatively common, sometimes accompanied by tsunamis.

The mainland of the country is the eastern half of New Guinea island, where the largest towns are also located, including the capital Port Moresby and Lae; other major islands within Papua New Guinea include New Ireland, New Britain, Manus and Bougainville. Papua New Guinea is one of the few regions close to the equator that experience snowfall, which occurs in the most elevated parts of the mainland.

The majority of the population live in traditional societies and practise subsistence-based agriculture. These societies and clans have some explicit acknowledgement within the nation's constitutional framework. The PNG Constitution (Preamble 5(4)) expresses the wish for traditional villages and communities to remain as viable units of Papua New Guinean society, and for active steps to be taken in their preservation. The PNG legislature has enacted various laws in which a type of tenure called "customary land title" is recognised, meaning that the traditional lands of the indigenous peoples have some legal basis to inalienable tenure. This customary land notionally covers most of the usable land in the country (some 97% of total land area); alienated land is either held privately under State Lease or is government land. Freehold Title (also known as fee simple) can only be held by Papua New Guinea citizens.

The country's geography is similarly diverse and, in places, extremely rugged. A spine of mountains runs the length of the island of New Guinea, forming a populous highlands region. Dense rainforests can be found in the lowland and coastal areas. This terrain has made it difficult for the country to develop transportation infrastructure. In some areas, planes are the only mode of transport. After being colonised by three external powers since 1884, Papua New Guinea gained its independence from Australia in 1975.

**Ecology**

Papua New Guinea is part of the Australasia ecozone, which also includes Australia, New Zealand, eastern Indonesia, and several Pacific island groups, including the Solomon Islands and Vanuatu. Geologically, the island of New Guinea is a northern extension of the Indo-Australian tectonic plate, forming part of a single landmass Australia-New Guinea (also called Sahul or Meganesia). It is connected to the Australian segment by a shallow continental shelf across the Torres Strait, which in former ages had lain exposed as a land bridge — particularly during ice ages when sea levels were lower than at present.

The green jungle of Papua New Guinea bears a stark contrast to the nearby desert of Australia. Consequently, many species of birds and mammals found on New Guinea have close genetic links with corresponding species found in Australia. One notable feature in common for the two landmasses is the existence of several species of marsupial mammals, including some kangaroos and possums, which are not found elsewhere.
Many of the other islands within PNG territory, including New Britain, New Ireland, Bougainville, the Admiralty Islands, the Trobriand Islands, and the Louisiade Archipelago, were never linked to New Guinea by land bridges, and they lack many of the land mammals and flightless birds that are common to New Guinea and Australia.

Australia and New Guinea are portions of the ancient supercontinent of Gondwana, which started to break into smaller continents in the Cretaceous era, 130–65 million years ago. Australia finally broke free from Antarctica about 45 million years ago. All the Australasian lands are home to the Antarctic flora, descended from the flora of southern Gondwana, including the coniferous podocarps and Araucaria pines, and the broadleafed southern beech (Nothofagus). These plant families are still present in Papua New Guinea.

As the Indo-Australian Plate (which includes landmasses of India, Australia, and the Indian Ocean floor in-between) drifts north, it collides with the Eurasian Plate, and the collision of the two plates pushed up the Himalayas, the Indonesian islands, and New Guinea's Central Range. The Central Range is much younger and higher than the mountains of Australia, so high that it is home to rare equatorial glaciers. New Guinea is part of the humid tropics, and many Indomalayan rainforest plants spread across the narrow straits from Asia, mixing together with the old Australian and Antarctic floras.

**History of Papua New Guinea**

Human remains have been found on New Guinea which have been dated to about 50,000 years ago. These ancient inhabitants probably had their origins in Southeast Asia. Agriculture was independently developed in the New Guinea highlands around 9,000 years ago, making it one of the few areas of original plant domestication in the world. A major migration of Austronesian speaking peoples came to coastal regions roughly 2,500 years ago, and this is correlated with the introduction of pottery, pigs, and certain fishing techniques. More recently, some 300 years ago, the sweet potato entered New Guinea having been introduced to the Moluccas from South America by the then-locally dominant colonial power, Portugal. The far higher crop yields from sweet potato gardens radically transformed traditional agriculture; sweet potato largely supplanted the previous staple, taro, and gave rise to a significant increase in population in the highlands.

Little was known in the West about the island until the nineteenth century, although traders from Southeast Asia had been visiting New Guinea as long as 5,000 years ago collecting bird of paradise plumes, and European explorers had encountered it as early as the sixteenth century. The country was named in the nineteenth century: the word papua is derived from a Malay word describing the frizzy Melanesian hair, and "New Guinea" (Nueva Guinea) was the name coined by the Spanish explorer Yñigo Ortiz de Retez, who in 1545 noted the resemblance of the people to those he had earlier seen along the Guinea coast of Africa.

The northern half of the country came into German hands in 1884 as German New Guinea. During World War I, it was occupied by Australia, which had begun administering the southern part as Papua (from 1884, British New Guinea) in 1915. After World War I, Australia was given a mandate to administer the former German New Guinea by the League of Nations. Papua, by contrast, was deemed to be an External Territory of the Australian Commonwealth, though as a matter of law it remained a British possession, an issue which had significance for the country's post-Independence legal system after 1975. This difference in legal status meant that Papua and New Guinea had entirely separate administrations, both controlled by Australia.

The two territories were combined into the Territory of Papua and New Guinea after World War II, which later was simply referred to as "Papua New Guinea". The Administration of Papua was now also open to United Nations oversight. However, certain statutes continued (and continue) to have application only in one of the two territories, a matter considerably complicated today by the adjustment of the former boundary among contiguous provinces with respect to road access and language groups, so that such statutes apply on one side only of a boundary which no longer exists.

Peaceful independence from Australia occurred on September 16, 1975, and close ties remain (Australia remains the largest bilateral aid donor to Papua New Guinea). A secessionist revolt which claimed 20,000 lives raged on the island of Bougainville from 1988 until it was resolved in 1997. Autonomous Bougainville recently elected Joseph Kabui as president.
The National Capital District

The National Capital District of Papua New Guinea is the incorporated area around Port Moresby, which is the capital of Papua New Guinea. It covers an area of 240 km² and has a population of 254,158 (2000 census). Although it is surrounded by Central Province, where Port Moresby is also the capital, it is technically not a part of that province.

Western Highlands Province

The provincial capital of the Western Highlands Province is Mount Hagen. The province covers an area of 8,500 km², and there are 440,025 inhabitants (2000 census), making the Western Highlands one of the most densely populated provinces. Tea and coffee are grown in the Western Highlands. Mount Wilhelm, the tallest mountain in Papua New Guinea, is on the border of the Western Highlands.

Simbu Province

Simbu, also known as and official Chimbu, is a highland province in Papua New Guinea. The province has an area of 6,100 km² and a population of 259,703 (2000 census). The capital of the province is Kundiawa. Mount Wilhelm, the tallest mountain in Papua New Guinea, is on the border of Simbu.

Eastern Highlands Province

Eastern Highlands is a highlands province of Papua New Guinea. The provincial capital is Goroka. The province covers an area of 11,200 km², and has a population of 432,972 (2000 census). The province is the home of the Asaro mud mask that is displayed at shows and festivals within the province and in the country. It is reachable by air and road transport.

Oro Province

Oro Province, formerly (and officially still) Northern Province, is a coastal province of Papua New Guinea. The provincial capital is Popondetta. The province covers 22,800 km², and has 133,065 inhabitants (2000 census). The northern end of the Kokoda Trail terminates at the village of Kokoda in the province and the active volcano Mount Lamington. Once the Kokoda Trail was taken and provided access from Port Moresby to the hinterland during the Second World War, the coast of the then Northern District was also the scene of heavy fighting; the Buna, Gona and Sanananda campaigns are particularly well remembered.
Origins of Agriculture at Kuk Swamp in the Highlands of New Guinea


Multidisciplinary investigations at Kuk Swamp in the Highlands of New Guinea show that agriculture arose independently in New Guinea by at least 6950 to 6440 calibrated years before the present (cal yr B.P.). Plant exploitation and some cultivation occurred on the wetland margin at 10,220 to 9910 cal yr B.P. (phase 1), mounding cultivation began by 6950 to 6440 cal yr B.P. (phase 2), and ditched cultivation began by 4350 to 3980 cal yr B.P. (phase 3). Clearance of lower montane rainforests began in the early Holocene, with modification to grassland at 6950 to 6440 cal yr B.P. Taro (Colocasia esculenta) was utilized in the early Holocene, and bananas (Musa spp.) were intensively cultivated by at least 6950 to 6440 cal yr B.P.

Investigations into the antiquity of agriculture began in the Highlands of Papua New Guinea in 1966, with subsequent excavations in the 1970s at Kuk Swamp in the Wahgi Valley. The finds from Kuk were the oldest and most comprehensive of any wetland archaeological site in the interior (1, 2) and were claimed to represent the independent origins of agriculture in New Guinea during the early Holocene (3). These claims were, however, largely unsubstantiated. Archaeological remains of former cultivation dating back to the early Holocene at Kuk were reported but never fully published (1, 2). Previous researchers noted an association between Musa spp. phytoliths and archaeological phases (4) and documented the presence of numerous edible plants throughout the Holocene (5). The mechanisms of dispersal and anthropogenic associations of these plant remains were uncertain. Erosion rates in the catchment (6) and palynology at several sites in the Highlands (7, 8) were suggestive of accelerated forest clearance beginning in the early Holocene, but the timing and nature of initial clearance were unknown. Given these problems, the notion of early independent agricultural development in New Guinea has been questioned (9, 10).

Here we present multidisciplinary data from renewed investigations at Kuk that show that agriculture arose independently in New Guinea by at least 6950 to 6440 calibrated years before the present (cal yr B.P.). We conducted new archaeological investigations and used radiocarbon dating, stratigraphic analyses, and a suite of archeobotanical and paleoecological analyses (including diatom, insect, phytolith, pollen, and starch grain analyses). These findings contribute to our knowledge of agricultural origins across the globe and have broader implications for understanding the development of human societies.

Site and stratigraphy. Kuk Swamp is located in a large intermontane valley in the interior of New Guinea at 1560 m above mean sea level (AMSL) (Fig. 1). The Wahgi Valley has a slightly seasonal lower montane humid climate with a mean annual temperature of ~19°C and mean annual rainfall of ~2700 mm. The Kuk site is situated on a wetland margin comprising a low-gradient alluvial fan deposited after the Last Glacial Maximum (LGM) at 21,500 cal yr B.P. (6). These alluvial deposits overlay lacustrine and paludal peats that accumulated during the last glacial period.

The early to mid-Holocene stratigraphy represents immature paleosol profiles, which are characteristic of periodically waterlogged environments (Fig. 2A). Despite this pedogenesis, biostratigraphic signatures, as indicated by distinctive phytolith and pollen assemblages, are retained between and within individual units. These biostratigraphic signatures are corroborated by synchronous samples collected from deeper, well-preserved, and largely unaltered fills of ditch- es and paleochannels.

Paleoecological evidence. Paleoecological records from several sites in New Guinea show that from 17,500 cal yr B.P. to the end of the last glacial period, open grasslands between 1200 and 2000 m AMSL were completely replaced by forests dominated by Nothofagus (11). The altitudinal expansion of forests was caused by warming climates, increased precipitation, and less frequent fires (12). In the absence of anthropogenic disturbance, the upland valleys during the Holocene would be expected to support montane rainforest on dry slopes and vegetation ranging from seral swamp forest to open grass and/or sedge in wetlands (11). The first signs of human impact are recognized as a reduction or change in the forest composition, followed by the expansion of open herbaceous vegetation and, in many cases, increased concentrations of charcoal in sediments (13, 14).

Today, upland valleys are dominated by anthropogenic grasslands frequently burned by people. The timing of the earliest anthropogenic impacts on upland landscapes is variable and occurs as early as 7800 cal yr B.P. in the Baliem Valley of the Indonesian province of Papua (8) and as late as 1700 cal yr B.P. in the Tari Basin of Papua New Guinea (11).

To investigate the nature and timing of the transition from forest to grassland in the Wahgi Valley, we took 24 sediment samples from overlapping monoliths containing 1.3 m of continuous Holocene strata and Pleistocene peat (Fig. 2A). Samples from this section were augmented with 14 samples selected from the fills of prehistoric agricultural features excavated at proximal locations at the site. A minimum of 300 pollen grains and 200 phytoliths were counted for each sample. We obtained radiocarbon dates on paired and other organic material collected during excavation.

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Fig. 1. Site location map.
The paleoecological data from Kuk Swamp indicate that, like other areas of the Highlands, a mosaic of cold-adapted grasslands and montane forest persisted across the valley floor before the Holocene (Fig. 3). Unlike other valleys in the uplands, the grasslands within the Kuk Swamp catchment did not succumb to forest advance at the onset of the Holocene. Instead, the grasslands and fern flora increased at the expense of forest between 10,200 and 7400 cal yr B.P. under the influence of periodic fire episodes and probably anthropogenic clearance. At the same time, forest composition in the catchment changed from a dominance of montane canopy taxa such as *Nothofagus*, *Castanopsis*, and gymnosperms to a predominance of subcanopy taxa, particularly *Pandanus*, Zingiberaceae, and Musaceae sect. *Eumusa*. At 6950 to 6440 cal yr B.P., the data imply that forest declined abruptly as burning increased within the catchment and an open grass-sedge swamp-land became established. Musaceae phytoliths reach a maximum of 15% of total phytolith counts in this period (Fig. 3), which we interpret to be derived from bananas (including Musaceae sect. *Eumusa*) growing locally within an open grassland environment.

**Archaeological evidence.** The archaeological remains at Kuk have been divided into six phases of wetland use (1–3). The earliest three phases are relevant to the origins of agriculture in New Guinea, because they pre-date known Southeast Asian influence on the island at ~3500 cal yr B.P. at the earliest (15) (Table 1).

The oldest archaeological features at Kuk (phase 1) are pits, stakeholes, postholes, and runnels that are restricted to slightly elevated and better-drained levees of a paleochannel (Fig. 2B). These features are consistent with planting, digging, and tethering of plants and localized drainage in a cultivated plot and are interpreted to represent a single period of shifting cultivation on the wetland edge. The paleochannel is dated to 10,220 to 9910 cal yr B.P. (tables S1 and S2), and two dates from a feature on an adjacent surface are slightly earlier and later than this date, respectively. Based on functional associations among these features and their ages, we interpret them to be contemporaneous. The use of the wetland margin at this time was not specialized and represents the spatial extension of shifting cultivation practices (that is, dryland practices) onto the wetland margin during a drier period.

The phase 2 palaeosurface consists of the preserved circular and subcircular bases of regularly distributed mounds, as well as less organized features (Fig. 2C). The palaeosurface is dated to 6950 to 6440 cal yr B.P., which accords with the date of an overlying and infilling deposit, R+W ash, at 6440 to 5990 cal yr B.P. (tables S1 and S2). Regular morphologies of features, numerous stake- and postholes, and heterogeneous feature fills with elevated charcoal frequencies are all consistent with a cultivated palaeosurface. The mounds created better-aerated soils along the moist, poorly drained wetland margin. The innovation of mounded cultivation indicates greater reliance on the wetland for subsistence in a resource-poor grassland landscape.

**Fig. 2.** Archaeostratigraphic representation of phases 1, 2, and 3.
Phase 3 is composed of sequential ditch networks that articulate with major drainage channels, and an earlier curvilinear feature has also been included in this phase (Fig. 2D). The earliest ditch networks are rectilinear, similarly aligned, and contain similar fill types. These early ditch networks date to ~4350 to 3980 cal yr B.P. and pre-date R ash [dated to 3980 to 3630 cal yr B.P. (tables S1 and S2)]. Late ditch networks are older than 3260 to 2800 cal yr B.P. and the deposition of an overlying tephra, Y ash.

Younger ditches form more complex networks that exhibit dendritic, rectilinear, and triangular arrangements. Major drainage channels articulate with both early and late networks; for example, channel 107 pre-dates the deposition of a diagnostic tephra (R ash) and articulates with two ditches of the early subphase and one ditch of the late subphase (Fig. 2D). The innovation of ditching indicates a further refinement of, and reliance on, wetland cultivation within resource-poor anthropogenic grassland.

Archaeobotanical evidence. There is a variety of evidence for numerous edible plants being present in the Kuk vicinity from the last Pleistocene (table S3). The lack of an intimate association of most plant remains with archaeological features indicates that the plants grew in the forested landscape. Modifications to the catchment and wetland margin at the end of Pleistocene and early Holocene may have been intended to increase the availability of edible and other useful plants. Many of these plants are still gathered, transplanted, and cultivated from wild forms in the Highlands today (16). Microfossils from two plants with abundant starch—taro (Colocasia esculenta) and banana (Musa spp.)—both record their earliest presence in early Holocene contexts. These two crops were potentially the most important food staples in the Highlands before the introduction of the sweet potato (Ipomoea batatas) after European exploration of the Pacific.

Starch grains from Colocasia taro are present on the worked edges of three stone tools from phase 1, phase 2, and the intervening gray clay. The size, shape, surface morphology, clustering, and co-occurrence of raphides (calcium oxalate crystals) removed from the used edge of a phase 1 flake (K76/S29B) all signify C. esculenta. C. esculenta has also been documented from a Pleistocene site in Island Melanesia (17) and an early Holocene site in lowland New Guinea (18). C. esculenta is considered to be a lowland crop, and its current range in New Guinea, exceeding 2000 m AMSL, is considered to be a product of anthropogenic selection (19). Its presence and use at Kuk in the early Holocene are suggestive of deliberate movement of the plant into the Highlands.

Musaceae, including Musa spp. (banana), phytoliths are present throughout the Holocene stratigraphy at Kuk (Fig. 3). High percentages are evident in disturbed habitats before 6950 to 6440 cal yr B.P., but these are only suggestive of deliberate planting, because bananas are known to exist in wooded and edge habitats from which they colonize disturbed areas. The high percentages of banana phytoliths in grassland contexts during phase 2 and in the earliest phase 3 feature (dated to 4840 to 4440 cal yr B.P.) are, however, anomalous. First, grasses produce abundant phytoliths, whereas bananas produce relatively few phytoliths in their leaves, bracts, seeds, and pseudostems. Thus,

Table 1. Chronology for archaeological phases 1, 2, and 3 at Kuk Swamp (see tables S1 and S2 for dates and calibrations).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Golson 1977 (a)</th>
<th>Subphase</th>
<th>Wetland remains</th>
<th>New dates (cal yr B.P.)</th>
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<tr>
<td>1</td>
<td>~9000</td>
<td>None</td>
<td>Amorphous palaearaceous</td>
<td>10,220 to 9910</td>
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<tr>
<td>2</td>
<td>6000 to 5500</td>
<td>None</td>
<td>Subcircular paleosurfaces</td>
<td>6950 to 6440</td>
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<tr>
<td>3</td>
<td>4000 to 2500</td>
<td>Earliest</td>
<td>Sinuous runnel</td>
<td>4840 to 4440</td>
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<td></td>
<td></td>
<td>Early</td>
<td>Rectilinear ditch networks</td>
<td>4350 to 3980</td>
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<tr>
<td></td>
<td></td>
<td>Mid-late</td>
<td>Rectilinear ditch networks</td>
<td>3630 to 3260</td>
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<tr>
<td></td>
<td></td>
<td>Late</td>
<td>Rectilinear ditch networks</td>
<td>Pre-3260 to 2800</td>
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</table>

Fig. 3. Selected pollen and phytolith data from the Kuk Swamp samples (n = 38). Ages are based on radiocarbon dating of stratigraphic features associated with phases 1, 2, and 3 and intervening stratigraphy (that is, gray clay). Samples are arranged in order of oldest (sample 1, right-hand side of the diagram) to youngest (sample 38, left-hand side). The lower half of the diagram depicts pollen and spore summary curves (for ferns, herbs, and trees and shrubs) and charcoal density (as area of pollen slide). The upper half of the diagram shows Poaceae (as percentage of total sum of pollen and spores) and Musaceae phytoliths (as percentage of total phytolith sum), with the presence of diagnostic seed phytoliths assigned to Eumusa, Ensete sp., and Musa ingens depicted as symbols.
high banana phytolith percentages reflect large plant populations rather than high phytolith production relative to other species. Second, large quantities of Musa bananas would not be expected in a grassland subject to periodic burning. Other banana species, such as Ensete glaucum, are more fire-tolerant and might be expected to thrive in repeatedly burned landscapes; however, they account for only a minor component of Musaceae phytoliths during the Holocene at Kuk. The large percentages of bananas within a managed grassed landscape beginning at 6950 to 6440 cal yr B.P. are interpreted to be diagnostic of deliberate planting.

Eumusa bananas were identified from diagnostic seed phytolith morphotypes throughout the Holocene sequence. Although no diagnostic seed phytoliths of Australimusa bananas were found, other species, including Musa ingens and Ensete glaucum, were present (Fig. 4). The presence of Eumusa bananas has implications for understanding mainstream banana domestication involving hundreds of diploid and polyploid varieties. Eumusa cultivars were formerly considered to be Southeast Asian domesticates (20). More recent genetic research suggests that the wild Eumusa seeded banana, Musa acuminata ssp. banksii, was domesticated in New Guinea and subsequently dispersed to Southeast Asia, where hybridization with local varieties occurred (21). The Eumusa morphotypes in early Holocene contexts at Kuk, including both seed and leaf morphotypes identical to those found in Musa acuminata ssp. banksii, corroborate these interpretations.

**Conclusion.** The gradual emergence of agriculture in the Highlands of New Guinea during the early Holocene is suggested by cumulative anthropogenic forest disturbance, the archaeological remains of cultivation on the wetland margin at Kuk, the use of Colocasia taro, and the presence of Eumusa bananas. Although this evidence is consistent with shifting cultivation practices, more substantial evidence for deliberate planting and incipient domestication is not unequivocally demonstrable until the mid-Holocene. By 6950 to 6440 cal yr B.P., land use patterns changed dramatically with intensive wetland cultivation (mounding); the creation and maintenance of an anthropogenic grassland landscape; and the deliberate planting of bananas, including Eumusa bananas from which the most important and largest group of banana domesticates arose. These multidisciplinary lines of evidence signify that agriculture was being practiced within an anthropogenic landscape.

The idea of early and independent agricultural origins in New Guinea challenges entrenched and pervasive assumptions about the genesis and diffusion of agriculture and about the development of human societies. First, New Guinea has generally been considered to be a secondary center, where agricultural development was derived from or triggered by the arrival of domesticates from Southeast Asia (22, 23). The evidence from Kuk confirms that New Guinea was a primary center of agricultural development and plant domestication before any known Southeast Asian influence. The archaeobotanical finds corroborate genetic interpretations that Eumusa bananas and C. esculenta were independently domesticated in Melanesia (21). Only after 3500 cal yr B.P. was New Guinea a recipient of domesticated plants from Southeast Asia, after Austronesian expansion into the region (15).

Second, early and independent agriculture is often linked to large-scale demographic expansions, social stratification, and the rise of “civilization” (23, 24), none of which are typical of New Guinean societies today or in

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**Fig. 4.** Photographs illustrating discrimination of contemporary and prehistoric Musa spp. phytoliths. (A) Articulated phytoliths from seed of Musa acuminata ssp. banksii showing distinct dorsal ridging of Eumusa seed phytoliths (modern reference: sample QH067962). (B) Seed phytolith from seed of Musa ingens (modern reference sample). (C) Dorsal and lateral views of Ensete glaucum seed phytoliths (modern reference: sample QH356652). (D) Fossil Eumusa seed phytolith with distinct dorsal ridging found in the phytolith assemblage from the base of a phase 2 feature fill (sample 5). (E) Faceted phytolith morphotype found in the phytolith assemblage from the upper fill of the phase 1 paleochannel (sample 19). It is similar to the seed morphotype of Musa ingens, although its surface is more heavily textured. (F) Lateral view of Ensete seed morphotype found in a phase 2 feature fill and the clayey black sediment above (samples 3 and 4). (G) Articulated chain of Musa leaf phytoliths from within the gray clay sequence between phase 1 and phase 2 (sample 10). (H) Fossil leaf phytolith of Musa acuminata from the upper fill of the phase 1 paleochannel (sample 19).
the past. Although agriculture may have arisen there over 6500 years ago, highland New Guinea societies are still relatively egalitarian, often teleological, interpretations of human prehistory.

### References and Notes


25. T. P.D. directed the multidisciplinary research and conducted the archaeological, pedological, and sedimentological investigations. S.G.H. undertook pollen and charcoal particle identifications and counts, with an emphasis on *Musa spp.* R.F. and M.T. undertook starch grain analysis of stone tool residues. N.P. undertook insect identifications. B.W. undertook diatom identifications and counts.

A Young White Dwarf Companion to Pulsar B1620-26: Evidence for Early Planet Formation

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The pulsar B1620-26 has two companions, one of stellar mass and one of planetary mass. We detected the stellar companion with the use of Hubble Space Telescope observations. The color and magnitude of the stellar companion indicate that it is an undersized white dwarf (0.34 ± 0.04 solar mass) of age 480 × 10^6 ± 140 × 10^6 years. This places a constraint on the recent history of this triple system and supports a scenario in which the current configuration arose through a dynamical exchange interaction in the cluster core. This implies that planets may be relatively common in low-metallicity globular clusters and that planet formation is more widespread and has happened earlier than previously believed.

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R E S E A R C H A R T I C L E

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Introduction

Humans have been in the upland valleys of New Guinea for at least 30,000 years and presumably occupied the savannah plains that then connected the island to Australia for as much as 50,000 years or more. Through this immense time they have adapted and changed their environments until very few places on the island can be considered unaltered. In place of primary rainforests and seasonal forests they have created human landscapes such as the grasslands, secondary forests, and coastal woodlands. Prograded estuaries, infill in valleys and eroded slopes may be partially caused by human actions, together with the deliberate creation of terraced slopes and ditched plains. Fauna has become extinct and rare, offset by introductions through time. Dramatic climate change has also changed landscape and affected the potential of human societies over the same period. Did these events leave an imprint on populations or language? The record must be read from archaeology and studies of palaeoenvironments. This chapter reviews the history of human–environment interactions in New Guinea in three periods. These periods, roughly equating to pre-agriculture (ca 55,000–20,000 years ago), the spread of agriculture (20,000–5000 years ago) and post-Austronesian changes (5000 years ago to present) are not yet precisely defined; we do not have enough information to know how general and synchronous these were everywhere across the island. These periods span the whole prehistory of New Guinea during which modern people arrived from southeast Asia and became adapted to a new environment of strange animals and plants. The continuity of 2000 generations is expressed through language, stories and culture. The very broad periods discussed here represent the widespread adoption of new ways of life (perhaps cultural revolutions) that may have erased the previous cultures. But understanding the past may help understand the present.

Humans litter the landscape with the tools they use and stand out from other mammals by their use of fire. Evidence for their more indirect effects comes from dating geomorphological features such as alluvial fans, buried surfaces, activated sandsheets, and peaty infills in basins. Attribution of these features to human-caused erosion usually depends on correlations with archaeological deposits and specific human-caused features.
such as ditches, earthworks and quarries. The other main line of evidence comes from palaeoecology, in which the vegetation and faunas are reconstructed from dated fossil sequences. In New Guinea the main effort has been to use pollen, although some specialised swamp ditch systems have also been investigated, for example by Haberle et al. (1991), Golson (1991) and Sullivan et al. (1987). Past fire is inferred from swamp and lake sediments by counting microscopic charcoal fragments, and by dating larger fragments in a range of other deposits (Haberle et al. 2001).

At the time of European contact the population was concentrated along the coastal fringe with quite sparse and isolated groups in the rainforests and mountain slopes (Figure 1). Some areas, such as the Fojes Mountains, seemed to be totally without habitation. The large intermontane valleys with complex agriculture based on root cropping centered on the altitudes of 1400–1850 m were a major discovery of the twentieth century. Brookfield (1964) showed that this pattern reflects the chances for success with agriculture. The outer flanks of the mountains are perhumid, with precipitation more than double evaporation in almost all months. Under such misty conditions crops do not thrive (Hanson et al. 2001). In the intermontane valleys the mountains cut off the orographic rain and local circulations dominate in most seasons. Here air rises each day up the warmed slopes and descends over the valley, giving sunny conditions with adequate rainfall from afternoon thunderstorms. Away from the large highland basins, even small valleys may have this effect, and may thus support small hamlets. In these marginal settlements techniques of ditching and mounding are used to shed water from the fields. There is a north west-south east gradient from asessional precipitation to the appearance of a weakly defined dry season, and from relatively infertile limestones and mudstones in west Papua to richer soils fertilised by volcanic ash falls in Papua New Guinea east of the Strickland River.

The advent of humans, their spread into the range of environments, and their impact

**Period 1: 55,000–20,000 years**

The timing of the arrival of people in New Guinea is part of the wider controversy of when people arrived in the Australian region, since the two landmasses had continuous connections across the then dry Torresian Plain until only 8000 years ago. Dates of 55–60,000 BP have been suggested from southeastern and northern Australia (for example Thorne et al. 1999) while a faunal extinction event that takes place 48–43,000 has also been proposed (Roberts et al. 2001) as marking early occupation. Others (O’Connell & Allen 2000) have pointed out that this evidence is tenuous and have disputed any ages greater than ca 38,000 BP. Coastal occupation in the oceanic islands east and west of New Guinea is proven from at least 33,000 BP (Spriggs 1997; Irwin et al. 1999). The oldest claimed site in New Guinea is still the Huon Peninsular where finds of stone adzes were made on a raised marine terrace (Groube et al. 1986). The terrace formed about 55,000 years ago when sea level was 65 m lower than present, and was occupied after initial uplift, at an estimated 48,000 BP. However only a few scattered archaeological sites are currently known for this period, including 30,000 BP sites in the Birds Head (Pasveer 2003) and Lachitu near Vanimo (Gorecki et al. 1991). A similar age site is also known from Lemdubu Cave on the Aru islands, southwest of New Guinea but then connected to it and Australia by the Torresian landbridge (O’Connor et al. 2002).
Perhaps because of the higher populations and a greater concentration of research, evidence for early settlement in the highlands is slightly more abundant. People are present by 32,000 or earlier at Kosipe (White et al. 1970), near Chuave (Mountain 1993), Mount Hagen and the Baliem Valley (Hope 1998; Haberle et al. 2001). Although our knowledge of earliest settlement is extremely sketchy, there is a better understanding of the Pleistocene climates, thanks in part to long environmental records from marine cores (for example Wang et al. 1999), which allow extrapolation of less continuous terrestrial records. From these it is known that the ice age climates of New Guinea were drier than present, grasslands and savannah probably extending right across the Torresian Plain. The climate at high altitudes was also colder, with ice caps on many mountains along the central ranges. Alpine vegetation covered over 50,000 km$^2$ above 2700 m altitude at the height of the glaciation about 20–15,000 years ago (Hope 1996) compared to ca 800 km$^2$ today above 3900 m. Despite changes in composition through time, the mountain flanks and northern coasts may not have changed very much. Pollen evidence from peat sections near Mount Trikora (Hope et al. 1993), Tari (Haberle 1998) and Lake Sentani (Hope & Tulip 1994) provide records back 50,000 years or more. These suggest that closed tropical and montane forests have continuously occupied many areas from before the likely arrival times for people. The wet conditions that supported the rainforests seem to have been maintained all along, indicating that the warm tropical waters north of New Guinea named the Western Pacific Warm Pool have persisted through the late Pleistocene (Thunnell et al. 1994). However it is likely that rainshadow effects north of the main range were strengthened. The Popondetta, Markham, upper Ramu, Sepik and Sentani areas may have been drier than present, dominated by Nauclea woodlands and possibly experiencing...
natural fires. *Eucalyptus* savannah, like that around Port Moresby today, was probably more extensive all along the southern coast.

**Faunal change**

New Guinea has a curious fauna which included several large mammal species at the time that people first arrived (Flannery et al. 2002). The island lacks some families of marsupials found in Australia but has a rich rodent fauna. Mammalian predators are almost lacking, their niche being filled by pythons and large birds of prey. Several cave and swamp sites are known (Flannery 1995; Menzies & Ballard 1994) from the central highlands of the island which contain bones of extinct taxa, principally species of large kangaroos (*Protemnodon* spp.) and diprotodontids (for example *Hulitherium*, *Zygomaturus* and *Maokopia*). These are poorly dated but occur around 35,000 years or older, suggesting that they may have been contemporary with humans. For example a calf-sized diprotodontid, *Maokopia ronaldii* has been recovered from Kwiyawagi in central Irian Jaya where it seems to have been adapted to extensive subalpine grasslands. It lived until perhaps 30,000 years ago, but no association of its remains with human artefacts has been found. However fire is apparent from around 33,000 years ago in the Baliem Valley, the same catchment as the fossils (Hope 1998). The subalpine fauna seems to have disappeared well before the climate warmed after 14,000 years BP at which time forest limits rose and the mountain grasslands diminished. Hence some other cause (which may include human hunting or disturbance) must be involved.

A more direct case for human interaction is known from Nombe Cave in the Simbu of Papua New Guinea (Flannery et al. 1983). Here extinct fauna occurs in the horizons just preceding human artefacts. The altitude of Nombe makes it likely that it was forested, hence hunting may have been a more gradual process than in open country. Humans have also been responsible for introducing biota to islands in the Pleistocene and subsequently. An example is the Northern Common Cuscus (*Phalanger orientalis*) which arrived in New Ireland about 20,000 years ago (Heinsohn 2001).

**Fire**

Human hearths up to 30,000 years old are known from the Bamiem, the Wahgi peatlands and Kosipe Mission (Hope 1998). Some sedimentary sequences, for example peat beds at Tari and Lake Hordorli in the Cyclops Mountains, record no fires at all over tens of millennia in the Pleistocene. In such places the appearance of charcoal is probably an indicator of human activity (Haberle et al. 2001). The pollen record from the Tari Basin is the only record that shows a continuous sequence from before 28,000 BP through to the present (Haberle 1998). The study shows that, prior to 21,000 BP, forests dominated by *Nothofagus*, *Castanopsis*, and Myrtaceae covered the basin floor. Just before the onset of the last glacial maximum at around 21,000 BP we find the first evidence for burning that created a mosaic of grassland and forest. Although there is no direct archaeological evidence for humans in the basin at this time, the rapid increase in burning and opening up of the vegetation is unprecedented in earlier glacial records from the basin and is therefore considered to be a consequence of the arrival of humans in the region. This is at least 10,000 years later than the charcoal records from the Bamiem and Kosipe and archaeological sites at Chuave. It may represent a later occupation of the wetter sites.
Kosipe is a large swamp 100 km north of Port Moresby which provides a record of more than 40,000 years from 2,000 m altitude. Although subalpine plants were more common during the glacial times the area was always forested. Records of human occupation are preserved in the cool climate organic soils of the slope above the swamp, from ca 28,000 years BP (White et al. 1970). Fire is evident from about 30,000 BP in the swamp sediments while hearths have been identified in the slope mantle. It seems likely that people occupied or visited this high altitude site to collect the large heads of *Pandanus* nuts. They left behind massive stone blades, possibly adzes. The usage to which these were put is still not known.

**The manipulation of plants and landscapes leading to agriculture**

*Period II 20,000–5000 years ago*

Evidence for the extension of human landscapes is apparent on sensitive ecological boundaries such as the savannah-rainforest in the lowlands and the alpine treeline during the period of climate transition about 12–10,000 years ago. In these locations the encroachment on areas by forest has been resisted by fire and perhaps active clearance. The highlands have always supported forest and here the timing of clearance is quite variable, although the large basins so far looked at seem to have substantial clearances by 7000 years ago (Hope & Golson 1995). Similarly the long history of occupation along trade routes far from modern settlements demonstrates that the linkages have an extensive past. The highlanders are separated today by wet lower montane forests from the coastal resources. Although this ecological zone has not been well investigated, available data suggest that clearance is relatively recent (Gorecki & Gillieson 1989). It may be that this zone has contributed to the isolation of the highland peoples, despite the obvious passage of people and trade goods through it.

**The highland valleys**

In the montane zone there are relatively few pollen records that are continuous through this time period (Figure 2). Reasons for this may be the cooler and possibly drier climate that prevailed during the late glacial transition which altered conditions for deposition and preservation of organic material in sedimentary basins. Alternatively, increased burning and manipulation of forested environments by people may have caused erosion or deflation of sediments resulting in breaks in sedimentary records. However, it remains true that the separation of human activity from climate change as driving forces behind the sediment records we study is problematic in the absence of independent archaeological or palaeoclimatological data. This problem is exacerbated in the last glacial period when human activity in the landscape may have been strongly influenced by climate change rather than outpacing or overriding the climate signal (Haberle & Chepstow-Lusty 2000).

During the last glacial maximum at around 18,000 BP the highland valleys between 1500 and 1700 m asl were subject to a much cooler climate, perhaps as much as 7°C cooler than present mean annual temperatures, and frequent frosts and droughts (Haberle 1998). At Haeapugua in the Tari Basin (1630 m asl), where *Nothofagus* forests and open grasslands formed a mosaic vegetation pattern, the appearance of cold-adapted herbs such as *Astelia* (only found above 2700 m asl today) reflect the influence of cold mean annual temperatures on the basin floor. At Kuk Swamp in the Wahgi Valley (1580 m asl; Powell...
1982, 1984) and at Telefomin (1500 m asl; Gillieson & Hope 1989) forest cover dominated the valley floors with some minor fire disturbance being recorded.

Figure 2: Charcoal histories through time from selected sites in New Guinea (Figure from Haberle et al. 2001)

As global temperatures warmed and glaciers retreated, the late glacial transition in the highlands was achieved in a two-phase warming sequence with an initial period of climatic instability between 14,500 and 12,000 BP, followed by a more persistent warming between 12,000 and 8500 BP. At high altitude this led to an elevation in forest growth limits and a replacement of treeferns and grasslands with a closed upper montane forest (Hope 1989). In the highland valleys the combination of increasing mean annual temperatures, high atmospheric CO$_2$, and strengthening monsoon influence (Haberle et al. 2001) would be expected to result in expansion of forests into grassland habitat. This process is retarded in the Haeapugua and Kuk Swamp (reported in Powell 1984 and Denham et al. 2004) sites where burning is persistent and frequent from around 21,000 to 8500 BP, resulting in the maintenance of grasslands at a time when forests are expanding in other areas. In response to increasing temperatures a shift in composition of existing forests occurs from a *Nothofagus* dominated community to a more mixed *Nothofagus* forest incorporating forest taxa from lower altitudes such as *Castanopsis/Lithocarpus* and Myrtaceae. Climate stability during this time may have been disrupted by a strengthening and possibly unstable monsoon system coupled with enhanced El Niño-related climate variability, resulting in an increased incidence of frost and drought (Haberle et al. 2001). This may have increased the probability of fire in the highlands, however, the increase in archaeological evidence for human occupation sites during this period points to an alternative interpretation. This is
one of *in situ* development of food-plant promotion and management in the highlands under a cold, highly variable environment subject to severe drought stress particularly during the late glacial transition period (14,500–8500 BP, Haberle 1998).

Despite the high fire activity at the end of the last glacial period the driving force behind forest expansion into grassland overrides the persistence of fire activity such that, in all sites that cover the early Holocene, we find swamp forest dominated by *Syzygium*, *Pandanus* and some gymnosperm taxa developed around wetlands in the valley floors. The relatively high biodiversity and resource value associated with swamp forests, including the high density of utilisable *Pandanus* species (*P. antaresensis, P. brosimos/julianettii* complex; Haberle 1995) may have led to these environments being a focus of human activity throughout the Holocene.

The appearance and spread of ‘agriculture’ in the highland valleys is covered elsewhere in this volume. However the earliest indications of ditching within a mosaic of forest and grassland around 9000 BP (Denham et al. 2003; Haberle 2003), accord remarkably well with the transition to ‘modern’ Holocene climates, points to the possibility that expansion of clearing and plant manipulation was partly environmentally controlled. By 7–6000 years ago the lower parts of the major highland valleys were cleared and would have looked similar to their appearance in 1933 (minus sweet potato cultivation). It is possible that the early Holocene was a time of more reliable climates, the El Niño-related drought and frost being much rarer (Grove & Chappell 2000). This would have rewarded experimental taro and banana planting and water manipulation (Denham et al. 2003, Denham et al. 2004).

*Above and below the intermontane*

In the areas around the great highland valleys the records are very varied. Subalpine areas near Mount Albert Edward, and north of Mount Trikora record fire almost as soon as the ice retreats, and pollen diagrams show continuing disturbance to the present day. At Mount Jaya firing starts about 11,000 years ago and the Mapala rockshelter records hunting from 5500 years ago that resulted in the extinction of a small wallaby (*Thylogale christensenii*). Hope et al. (1993) speculate that pressure of hunting allowed the copper ringtail possum (*Pseudocheiropsis cupreus*) to expand into the subalpine niche. This hunting post-dates the development of large human populations at lower altitudes. Other mountains, such as Mount Wilhelm, experience clearance only within the last millennium, apparently associated with rising limits to agriculture (Corlett 1984).

Isolated valleys and lower montane sites generally are cleared in the middle or late Holocene. For example Sirunki, on the Wabag divide at 2500 m altitude is cleared about 4500 BP (Walker & Flenley 1979). Telefomin on the other hand has at least three clearance events, reverting to dense forest between each one (Gillieson & Hope 1989). The Jimi Valley, at around 800 m, was cleared about 3000 years ago but clearance in isolated valleys near it is less than 300 years old (Gillieson et al. 1989).

*The lowlands*

Considering the long period of occupation of the coast and lowlands (O’Connor & Chappell 2004), it is curious that the disturbance history resembles that of the highlands. Expansion of grasslands occurs in the Lake Sentani region at 11,200 BP (Hope 1996) and it is likely that this also applies to the seasonal woodlands of the Markham Valley as Lake Wanum records burning from the base of a core dated to ca 9000 BP (Garrett-Jones 1979).
There are no data on the history of the southern eucalypt savannah woodlands which remain cryptic, since occupation there is only known from the mid-Holocene. Early occupation and the transfer of fauna to the islands of New Britain and New Ireland and the Admiralties by 30–20,000 years ago (O’Connor & Chappell 2004) is not mirrored by evidence of substantial environmental change. Local clearance (in a parallel to Kosipe) has been found at 24,000 BP at Yombon, in inland New Britain (Pavlides & Gosden 1994).

The difference between the southern and northern coasts of New Guinea is that the former has an extensive shelf while the latter is steep. Thus sea level change saw much more dramatic changes to the southern coast (Chappell this volume). An exception to this is the large river systems of the Ramu and Sepik (and to a lesser extent the Mamberamo) which had cut down more than 100 m below their present mouths during the time of lower sea levels. Widespread mangrove remains and shell tools, hundreds of kilometres up river (Swadling & Hope 1992), indicate that a large estuary existed for a few thousand years before it silted up to the present backswamp complex. Although valleys were not incised, similar change has occurred along the south coast as the shores established about 6000 years ago. Rapid siltation and coastal progradation has been demonstrated along the southern coast of Papua (Ellison 2005).

The arrival and effects of Austronesian-speaking agriculturalists

Period III ca 4000–Present

The Austronesian arrival around 4000 years ago shows very little correlation with environmental change. Some indications (but almost no local evidence) are that the minor climatic fluctuations known as the little ice ages probably commenced after 3500 BP with small variations in ice extent on the highest mountains. These alternations of slight cooling and warming probably did not change the forest at lower altitudes. However the frequency and severity of El Niño events may have increased, ushering in the drought and frost events that have an effect on cropping and societies at all altitudes (Brookfield 1989; Brookfield & Allen 1989). These droughts may also have allowed fire to extend grasslands into humid forests. Grasslands of *Imperata cylindrica* (kunai) occur in many areas on poor soils such as the iron- and magnesium-rich ultramafics of Sentani, Telefomin and Popondetta. These clearings are probably of considerable antiquity as regeneration may take thousands of years. In New Ireland and the Jimi Valley, forest clearance within the last 3000 years leads to a short-term phase of gardens for perhaps a few centuries. The sites are abandoned and the mineral soil buried by the buildup of peat swamp due to increased runoff from open vegetation into the valley bottoms (for example Gorecki & Gillieson 1989).

The adjustments of the coast to the establishment of high sea level at 6000 BP continues throughout the late Holocene. For example, beach ridges in New Ireland contain sequences of pottery that are stranded up to 800 m inland by coastal progradation (White et al. 1991). At this time villages probably moved frequently. This earlier dynamic coastline of beach building was replaced by a static lagoonal strand as the growth of coral reefs caught up with the sea level rise and blocked wave action. The modern reef flat is largely dead as it has reached mean sea level, and its growth is concentrated on the seaward edge. This process has been widespread except where abundant river sediment or sand movement has hindered coral growth. Thus for many coastal villages the marine resources available have changed radically in the last 5000 years, with open coasts being replaced by active reefs and finally lower reef productivity.
The pollen of *Casuarina* becomes much more common across the highlands after ca 1800 years ago suggesting that this was a time of widespread silvicultural planting. This rapid spread supports an hypothesis that there was effective diffusion of ideas despite linguistic and social barriers. Similarly the spread of crop plants such as sweet potato also seems to have been almost universal in the highlands resulting in the new clearance of slopes and higher altitudes that becomes apparent in the last few centuries, and in the abandonment of some swampland field systems.

**Discussion**

This thumbnail sketch of 50,000 years of history conceals the major feature of New Guinea that operates through time as well as across the island—its habitat diversity and unusual position as one of the world’s wettest regions. The topographic range and position next to the Western Pacific Warm Pool has preserved this diversity through the climatic fluctuations of the late Pleistocene, but boundaries have shifted dramatically and few places have been unaffected. The general picture of change can not yet be predicted at the local level and this has hindered the reconstruction of human environments. We can be quite sure that the modern barrier that separates the highlands from the coast—the everwet lower mountain forest zone—has remained intact throughout the period of human occupancy. Yet this is principally a barrier to agriculture and might have had some attractions for hunting and foraging, although humans do not thrive there today due to malaria, skin diseases and other problems (Riley 1983). At higher altitudes the highland valleys also supported dense wet forests with few resources during glacial times yet some settlement did take place.

New Guinea possibly had its ‘big game hunters’ in the Pleistocene, but the evidence is so diffuse that we can only note another unexplained extinction event and wonder if there might be anything in the origin myths of strange animals and birds. However the loss of species of rodents in the islands (Spriggs 1997) around 30,000 years ago is clearly coincident with human settlement. Flannery (1992) has suggested that a second phase of effective hunting of arboreal mammals could only start when the dog arrived about 3500 years ago. With the establishment of large areas of secondary vegetation a reduction in the significance of hunting has continued to the present day. In the upper Chimbu Valley in Simbu the animal called *Inkomugl* in the vernacular was widely remembered in 1970, even though no-one had ever seen one (Sterly 1997). This was the monotreme *Zaglossus bruijnii*, now probably wiped out near large population centres but preserved in stories.

The diversity of culture and language must reflect the need for local adaptation to specific environments that change over distances of a few kilometres. Yet on a long time scale of many centuries similar patterns of settlement and technology appear at the same time across the island. Diffusion of cultivars, land management practices and other techniques such as pottery or silviculture was probably relatively rapid despite the isolation of groups. The most rapid time of climate change and coastal stress, from ca 15–8000 years ago, rewarded adaptive cultures. The burning of some of the high altitude grasslands by 13,000 BP, 4000 years before the substantial clearance in the montane basins, suggests that trading links were in place across the mountains before the agricultural populations had increased. Similarly the scattered evidence for clearance and burning by 30,000 BP suggests that some ecological manipulation and selection was already taking place. Hence the emergence of an agricultural landscape in the highlands of
New Guinea can be seen as a result of gradual indigenous development punctuated by external influences such as introduced domestic plants and climate change and variability. Any ‘foreign’ influences would be small and possibly isolated to single locations in the cordillera. Our records come from swamps and these may have been the birthplace of an agriculture that depended on aroids and banana.

There is much we still do not know about the environmental history of the island. One example is that we are unsure of the causes of a ‘gap’ in sedimentation that occurs in many sites. At Kuk no sediments are known from the period 16–9000 BP, and the peatland is not present until 5500 years ago, by which time the catchment is virtually as deforested as the present day. From the handful of sites that cover this gap, such as Hordorli or Tari, there are few clues. Perhaps a phase of dry weather and widespread fires occurred and catchment clearance may be implicated. This lack of detail is frustrating because of our inability to relate the modern diversity to its past history. This will remain a major aim as the framework of sites and records is strengthened.

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Mount Wilhelm, at 14,760 (4,510m) the highest point in the Bismarck Ranges and in Niugini, lies about 55 miles west of Goroka on the northern side of the Wahgi valley. It is a massif of about 100 sq. miles formed by a steeply sloping east-west ridge which drops away steeply to the north but which is deeply dissected by valleys to the south. The summit ridge, made up of several peaks above 14,400ft, extends for about 1½ miles SE-NW. The most northerly peak is the true summit. Five major valleys run from this ridge: to the west the Bendenumbun valley, which is the source of the Jimi River, and contains two lakes; to the south the Koromonk valley (three lakes), whose stream flows through Kerowagi to the Wahgi; to the south-east the valleys of Giwi mawi (two lakes) and Gorugakul (one lake), giving rise to Gwaki O'k which flows past Denglagu mission to join waters from the eastern valley; and to the east Pindaunde valley which contains two lakes at 11,600ft and 12,100ft. Three other lakes occur in minor valleys (Kwory, Tegepaungwa, Badmenangdongwa) and there are several more small tarns or ponds.

In pre-contact times it is doubtful if the alpine areas were visited by the Chimbu or Jimi peoples but important tracks led into the grasslands to 11,500ft connecting Keglsugl with Kerowagi, Keglsugl with Yandera (to the north), and the Jimi valley with the western villages of the Bundi peoples. Denglagu Roman Catholic Mission was established in 1934, the Pindaunde lakes were seen by Europeans in 1936 and the mountain climbed in 1938. A U.S.A.F. aircraft, reported to be a Liberator bomber, crashed on Mount Wilhelm in 1943 and fragments of it are still strewn near the summit track at 13,100ft. Since the war an increasing number of visitors has climbed Mount Wilhelm usually by the Pindaunde route (although ascents have been made by way of the Jimi-Wahgi divide) and now between one and two hundred people come to Pindaunde annually. A few people are not prepared for the bitter cold and rain nor for the altitude effects of fatigue, headache, vomiting and risk of heart attack which assail those who attempt too much for their level of fitness. Some walkers, used to the coast of New Guinea, arrive in shorts and shorts with no food or tents, confident that a trade store and rest house is somewhere ahead. There is a shelter hut near the lower lake at Pindaunde, erected by the Mount Wilhelm Local Government Council for which a fee is charged. The only alternative is camping. The track from Keglsugl to the Pindaunde valley is clearly defined and it can take over four hours to reach the lower lake while a further four hours is needed to reach the summit.
Climate

At the summit, more than one-third of the thickness of the earth's atmosphere lies below and the ice point (where permanent ice could persist) is only 400ft higher up. There is a very great daily temperature range but virtually no seasonal variation. The thin air has a low heat capacity so that the hot sun can quickly heat up exposed surfaces to 100°F and the unshielded ultraviolet causes intense sunburn. Then, at night, heat is quickly radiated away and up to two inches of needle ice may form on the ground, where temperatures often fall as low as 20°F. Such surface temperatures are common down to about 11,000ft although the average air temperatures vary from 46°F (av. max. 53°, av. min. 39°) at Pindaunde to about 37°F at the summit. Because of afternoon cloudiness, maxima are usually reached by 10 a.m. and minima just before sunrise, which varies from 5.45 to 6.10 a.m. Pindaunde receives about 120 inches of rain a year, all months except June, July and August receiving more than 12 inches, and rain days usually exceeding 20 each month. However, dry spells of up to 28 days have been recorded. Snow is common above 13,500ft, but it does not persist for more than a day or two. Most rain approaches from the north and the northern summits are usually misted by 9.30 a.m., although the Pindaunde valley may remain clear for much longer because of warm dry air rising from the Chimbu valley.

Geomorphology

Probably as recently as 15,000 years ago, Mount Wilhelm was covered by ice and snow down to 11,500ft and glacier tongues pushed down the valleys. This ice, thousands of feet thick, hollowed out the lake basins, carved the 'U' shaped valleys and plucked the jagged summit ridge. When the glaciers melted, they left ridges of debris (moraines) such as those that are crossed by the Pindaunde track where it first enters the grasslands. The lower Pindaunde lake is 66ft deep and the large rocks in it and around its shores are glacial erratics dropped by the retreating ice. The upper lake, 300ft higher, is 196ft deep.

Perhaps 12,000 years ago the ice had retreated, the tarns and lakes started to fill with sediment and plants began to creep back onto the shattered rocks. By 10,000 years ago alpine vegetation was established in the summit area and shrublands covered much of the mountain. The upper Chimbu valley was probably not cleared by man until the last 1,000 years. Since then the higher forests have been cut and burnt and the sub-alpine grasslands extended. Deep peaty soils have formed under the vegetation and these protect the rocks against erosion so that the streams are always clear and sediment free.

Biology

The Mount Wilhelm flora includes many species or genera that occur in temperate latitudes as well as a distinctive element of its own. The buttercups, eyebrights, heaths, grasses and sedges are all reminders of temperate areas to the north or south. There is even a common, dark green pine-like tree (Dacrycarpus compactus) which is a podocarp, a family of the southern hemisphere related to the better known conifers. Many distinctive New Guinea plants are present such
as the alpine finger fern (*Papuapteris linearis*), the many red
flowered shrubs in the heather family (*Ericaceae*) and the tree ferns
in the grassland. The thick moss carpet of the higher forest is also
typical of New Guinea high mountains although the alpine communities
are usually different on each; the alpine tundras, heaths and mires
are particularly interesting on Mt Wilhelm.

The tree line reaches 13,000ft in sheltered well drained areas
but has been artificially lowered by fire and cutting in many valleys.
Besides *Dacrycarpus* the chief tree line plant is *Rapanea vaccinioidea*.
Shrubs such as *Coprosmia divergens*, *Detzneria tubata*, *Bunya brassii* and
*Drimys piperita* struggle on to about 13,500ft amongst the tussock
grasses.

About 30 species of mammals live above 8,000ft and at least
four (a bandicoot and 3 species of native rodents) occur in the alpine
zone above 13,500ft. The native rodents are remarkably diverse; for
example there is a giant rat (*Mellomys*) up to 4lb in weight and
vegetarian, a water rat (*Hydromys*) found in the lower Pindaunde lake
and a very common rat (*Rattus riobi*) which burrows under the grass
tussocks. Wallabies, tree kangaroos, ringtail possums, pygmy possums
and sugar gliders are among the marsupials of the forests while
bandicoots are common in the grasslands.

The main predator, other than man, is the wild 'singing' dog
which roams the mountain at night with melodious howls. Their lairs
are at the tree line and they are very wary and shy.

Princess Stephanie's bird of paradise is found in the forests
around the lakes and honey eaters and parrots are also very common.
On the lakes pairs of Salvadori's teal are found. Snakes and lizards
do not live above 9,000ft but there are two high altitude frog species
occurring in damp tussock to 13,000ft.

The magnificent scenery and unusual ecology of the alpine and
sub-alpine zones has led to Mount Wilhelm being considered as a
future National Park. Australian National University studies on the
climate, vegetation, geomorphology and mammals will provide a basis
for effective management. At present most visitors want to see as
little change as possible in this wilderness area. Camping and any
building should only be allowed downstream from the lower Pindaunde
lake, thus preventing lake pollution and disturbance of the sensitive
high altitude plant communities by trampling, litter and fire. Huge
amounts of tourist litter have already been removed from the summit
by the Australian National University scientists. The motto of the
future park visitors should perhaps be 'What goes up must come down.'

Current Research

The Sixth Archbold Expedition visited the Pindaunde valley in
1959 to collect animals and plants and in 1966 the Australian National
University with assistance from the B.P. Bishop Museum, Hawaii,
established its high altitude research station there. The building,
prefabricated in Melbourne, was flown to Keglaugl from Madang and
carried up the mountain. It comprises a laboratory and workshop with
a small living area suitable for four persons for extended stays.
Several projects are in progress or completed and some of their results are incorporated in this description of the environment of Mount Wilhelm.

The results of this work by the Australian National University are being published by the Department of Biogeography and Geomorphology in its own publications and in scientific journals. One work describing the plant communities (No.9 below) is available from the A.N.U. Press Canberra for $2.50 (plus postage). Forthcoming contributions in the Mt Wilhelm Studies series will cover: meteorology and climate, geomorphology, plant systematics and mammals. Further studies are planned on vegetation history, tussock grasslands, and the ecology of selected species.

Selected bibliography


Map drawn by Research School Pacific Studies, A.N.U. 1-8-71, from planimetric base and air photographs.
Glaciation and Vegetation in the High New Guinea Mountains

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Abstract

The extensive high mountains of New Guinea have abundant depositional and erosional evidence of former glaciations. Wood, peat and gyttja have been collected from the bases of deposits forming in glacial rock basins and moraine-dammed hollows, or else trapped between layers of moraine. Radiocarbon ages for these materials have established maximum and minimum dates for deglaciation and reglaciation. Pollen analysis of the dated sediments helps to reconstruct the contemporary palaeoenvironment; the degree of vegetation development is then used to indicate the time elapsed since deglaciation.

The results from four mountain areas show that a general retreat of ice caps covering about 2,000 km² took place about 13,000 yr BP, with subsequent advances after 13,000 and 11,000 yr BP in some sites. The first evidence for neoglacialization, with at least three small advances in the last 2,400 years, is presented.

Introduction

The presence of traces of presumed Pleistocene glaciation has been recognised for a considerable time on several high peaks in New Guinea, and the nature and extent of the former ice cover has been summarised by Bik (1972), Löffler (1972), and Verstappen (1964). Figure 1 shows the distribution of high areas in the island with the western half (Irian Jaya) dominated by the single wall of the Maoke (Snow) Mountains, while the eastern half is broken into several distinct ranges and isolated mountains. The peaks considered here are all equatorial (4° S to 8° S) and experience a wet, relatively non-seasonal climate, with precipitation from 2,500 to 4,500 mm at 4,000 m altitude. Snow falls occasionally down to 3,800 m but does not lie for more than a few hours below 4,400 m. Small ice caps are found on Mt Mandala (Juliana) and Mt Idenburg about 4,650 m in height and an ice cap with small glaciers totalling about 8 km² occurs on the highest mountain, Mt Jaya (Carstensz), 4,884 m in height. The present snowline is difficult to estimate; the firm line on the shaded western face of the Meren Glacier lies at about 4,500 m but is at 4,600 m on the east side, which is exposed to morning ablation. However, the ice cap of Mt Trikora (Wilhelmina) at 4,740 m has disappeared (see Peterson et al. 1973).

The glacial landforms include both valley and ice-cap forms with deep, stepped U-shaped valleys above 3,500 m and large latero-terminal moraines extending

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Fig. 1.—The central cordillera of New Guinea. Location of mountain areas named in the text.

down to 3,200 m or lower. These moraines tend to be well preserved, though overlain by peat soils, and suggest a single final phase of glacial advance. Upriver from the massive moraines, smaller moraines are found that cannot be correlated regionally. Löffler (1972) has defined five well-preserved series of small moraines on Mt Giluwe, left by the retreat of a thin ice cap there, but other mountains have fewer or no minor moraines. The total area of ice at the time of formation of the large moraines has been calculated at 600 km² for the eastern half of the island (Papua New Guinea, PNG) by Löffler (1972). Verstappen (1964) estimates that an area of 5,000-6,000 km² was once glaciated in Irian Jaya, but field observations near Mt. Jaya suggest that, at the time of formation of the large moraines, ice would have covered only about 1,400 km² in Irian Jaya. This estimate is based on map areas supported by the first reliable altitude measurements made in the Maoke Range. The snowline associated with the large moraine phase was at about 3,650-3,700 m in the Saruwaged Mountains, the Owen Stanley Ranges and the western Maoke Range, but was 100-200 m lower in the centre of the island from Mt. Wilhelm to Mt. Mandalau (Löffler 1972, Verstappen 1964).

The authors spent 12 months on Mt. Wilhelm, 5 months on Mt. Jaya, and made short visits to Mt. Giluwe and Mt. Albert Edward, investigating the glacial landforms, vegetation history, and modern pollen deposition. The current results of the continuing program of radiocarbon dating and vegetation history investigations relative to the history of glaciation in New Guinea are reported here. The data are presented in four chronological groups.

**EARLY GLACIATION**

There is only sparse evidence for glaciation earlier than the advances which created the widespread, large moraine series noted earlier. Discontinuous areas of weathered drift can be found well beyond the large moraine margins on the Kamabu Plateau, which extends at 3,400-3,600 m for about 20 km north of the Jaya Mountains. Dow (1968) mapped this drift, and the authors found apparent erratics on pediments of limestone till (Fig. 2).

Blake and Löffler (1971) also found evidence of an early though not necessarily very extensive glaciation on Mt. Giluwe. A palagonitic lava outcrop there is partially covered by subaerial lava that is, in turn, glacially eroded, suggesting the presence of an earlier ice cap during an eruption.

Two factors besides insufficient field work may contribute to the general lack of evidence for early glaciation. Galloway et al. (1973) pointed out that for many mountains in the New Guinea area, evidence for earlier glaciations could have been obliterated by later ones, which were more extensive because of the topographic legacy of earlier ice action. In a few areas such as the Saruwaged Range, continuing uplift is documented (e.g. Veeh and Chappell 1970), and this tectonic effect would have the same result as cirque preparation (Galloway 1967). Although Verstappen (1963) postulated that final uplift may have caused the New Guinea mountains to be raised above the snowline only shortly before the last glacial period, it is likely that scattered evidence for earlier glaciation will eventually be found on many mountains.

**THE LAST MAJOR GLACIATION**

The age of the onset of the last glaciation is still unknown, but vegetation histories (Williams et al. 1972; Powell 1970; Walker 1970; Fenley 1970; Hope 1973) from the central PNG highlands indicate very great depression of vegetation boundaries prior to 37,000 yr BP followed by a gradual rise until about 30,000 yr BP. Then followed stable cold conditions, persisting until 11,000-10,000 years ago, with a treeline at about 2,200-2,400 m. Such a treeline, if it applied to the whole island, resulted in areas of mountain grasslands totalling 55,000 km², extending almost continuously along the spine of New Guinea.

Mt Wilhelm

At Kominamambu pollen analysis site, 2,740 m, on the eastern flank of Mt. Wilhelm, peats started forming in a cut-off stream channel a little before 21,760 ± 350 years BP (ANU-800). The stream channel is formed in a weathered tilloid gravel apron that may be of glacial or glacioluvial origin. Either origin indicates earlier, more extensive, glacial erosion than do the fresh large moraines at 3,200 m, 1.2 km up the valley. It would be premature to suggest that the greater depression of vegetation boundaries prior to about 30,000 yr BP correlated with this greater extension of the ice. The vegetation histories do imply, however, that a large area of ice persisted on the mountains for more than 30,000 years.

The vegetation history of Kominamambu shows that mountain grasslands occupied the site from
earlier than 22,000 yr BP until about 10,000 yr BP. Inferred ages are based on average peat accumulation rates between the basal ANU-808 sample and levels dated at 14,710 ± 200 (ANU-825) and 11,570 ± 80 (ANU-828) yr BP. Shrubs growing around the site decrease between 17,800 yr BP and 15,300 yr BP. This may indicate a slight cooling, and is followed by an increase in subalpine bog vegetation elements until montane forest, similar to the present vegetation, occupied the site after 11,000 yr BP.

Sites on Mt Wilhelm within the glaciated area (Fig. 4) provide an altitudinal series of deglaciation ages by which the probable retreat of the glacier in the eastern Pindaunde Valley may be estimated. Figure 3 shows the 14C dates at four sites. Lines connect minimum and maximum estimates of actual deglaciation. The estimates are for the commencement of sedimentation in rock basins and are based on sediment accumulation rates below the basal 14C date horizon with a check by pollen analysis. The latter indicates that the basal samples of sediment were all formed at a time of very sparse local alpine vegetation which could have grown around the tarns immediately after deglaciation. Modern pollen samples from neoglacial moraines of various ages on Mt Jaya helped in the interpretation; an open vegetation cover is apparently established within 50 years of moraine abandonment, but pioneer grasses and herbs grow right to the ice fronts. The reported age of one sample, 10,700 ± 800 yr BP (GaK-2890) from the Summit Bog appears to be anomalous. On the basis of other dates from an adjacent core, the same horizon (identified by correlation of pollen spectra and the volcanic ash stratigraphy) has an inferred age of 8,750 ± 350 yr BP which differs from the reported age by 2,280. The deglaciation estimate for the Summit Bog is based on ANU-1006 and ANU-821 (see Fig. 3). At the same site the basal 17 cm of sediments could not be collected, but at Brass Tarn, Pengagl and Imbuka the basal samples represent organic accumulation that probably began within 100 years of deglaciation.

The deglaciation estimates show that a major retreat of the Pindaunde Valley Glacier began before 13,000 yr BP. A rather steady altitudinal retreat rate of 100 m altitude per 400 ± 25 years (24-31 cm/yr) is indicated by the straight lines joining the inferred deglaciation estimates at each site. Extrapolating these rates downwards and upwards suggests that a steady retreat from the terminal moraines might have started 14,200-15,000 yr BP and that the last ice would have disappeared from the summit of Mt Wilhelm 8,600-9,300 yr BP. For the Pindaunde Glacier this corresponds to an average linear retreat of the ice front of 1.2 m per year. However, small moraines at 3,420, 3,500, and 3,600 m in the Pindaunde Valley suggest that the retreat was interrupted at various times.

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**Fig. 3.** Deglaciation of the Pindaunde Valley, Mt Wilhelm, PNG. All 14C dates obtained within the glaciated area are shown at the altitude at which the sediment was collected. 14C dates most closely associated with deglaciation are 12,570 ± 290 (ANU-815), 10,660 ± 270 (ANU-810) and 8,390 ± 150 (ANU-821) yr BP, indicating a steady retreat of ice from the mountain.
The estimated beginning of deglaciation coincides with the end of the phase of reduction of shrubs in the nearby Komanimbambou grassland between 17,800 and 15,300 yr BP. It is thus possible that the large moraines were formed during this period, although the volume of till is such that reworking of earlier moraines seems likely. The retreat of the ice was not matched by any large regional change in the vegetation, however, and shrub-free alpine grasslands occupied all higher sites until after 10,000 yr BP, when the treeline began to rise. The delay in treeline response relative to the progressive retreat of the ice, suggests that the climate remained colder than at present during most of the retreat period. Warmer conditions after 10,000 yr BP allowed the tree line to reach its present position at 3,850 m about 8,600 yr BP.

Mt Jaya

Much of the area above 4,200 m on this mountain forms a broad southwest-facing basin of 26 km² which fed ice southwards into the upper Otomona Valley (Fig. 5). Peat and peaty sands were found overlying glacially smoothed bedrock at 3,680 m at the head of this valley. These were dated at 13,275 ± 160 yr BP (SU-174A), which is supported by a date of 11,820 ± 150 yr BP (SU-28B) on peat within overlying till beds. Pollen analyses indicate that only scattered bog plants and ferns were present at the time of the older deposit, but that a slightly better developed alpine bog and fern meadow occurred around the younger deposit. This demonstrates substantially more alpine conditions than those of the area today, but lack of time for colonisation, as well as cold conditions, may have contributed to this situation.

To the north of the present ice cap the Ijomba pollen analysis site at 3,580 m provided sediments from a moraine-dammed lake which was sampled to 960 cm but not penetrated to the lake floor. The 962 cm level gave an age of 14,160 ± 260 yr BP (SU-107), and the pollen analysis indicates shrubless open vegetation in contrast with the forested valley slopes of the present. Thus the date is probably fairly close to the age of deglaciation at which time the ice had retreated about 2 km from its terminal moraine.

Saruwaged Mountains

Near Mt Bangeta in the Saruwaged Mountains at 3,800 m, Costin et al. (in press) report an age of 11,230 ± 100 yr BP (Y-1622) (Stuiver 1969) from peats taken from the base of a pit excavated in soils formed within the glaciated area. This is a minimal deglaciation date only, because the relationship of the sediments with the glaciated surface is not known, and no pollen analysis results are available.

However, this age and those from Mt Jaya and Mt Wilhelm, reported above, suggest that the large moraine series could have been abandoned about 15,000 years ago on most mountains.

Readvances

Preliminary evidence from Mt Jaya and Mt Giluwe supports the possibility that glaciers advanced again on some mountains after the initial retreat. The
dates from the organic sediments at the Ertzberg deposit at 3,680 m mentioned above (15,275 ± 160 and 11,580 ± 110 yr BP) are separated from one another and overlain by two till deposits up to 5 m in thickness. These reflect at least two advances to the south. Peterson and Hope (1972) have described logs crushed by tilloid deposit at 1,705 m (location shown in Fig. 5) and dated at 10,300 yr BP. They suggested that the deposit may be correlated with the younger group (less than 11,600 yr BP) of the Ertzberg tills, and named the advance the Ootoma Advance. Pollen analysis of underlying stream sediments shows that the logs were part of a mixed mountain forest dominated by Nothofagus, similar to modern vegetation observed between 2,900 and 2,200 m north of the range but not noted to the south. Although the authors and Dozy (1939) consider that this low-altitude deposit may be a till, this view is now made less certain by evidence that a cold lahar of reworked till reached 1,820 m after 3,760 ± 90 yr BP (SUA-173). This lahar deposit contained shattered wood and some churned sections which are not observed in the older tilloid, but more work will be necessary to establish the identity of the latter and the magnitude of the Ootoma Advance is uncertain.

On the southwestern flank of Mt Giluwe, Löfler (1972) reports ages of 7,070 ± 150 yr BP (Gak-2699), 6,480 ± 30 yr BP (Gak-2697) and 3,350 ± 100 yr BP (Gak-2698) from peat in pits behind moraines between 3,550 and 3,650 m altitude. These ages are minimal deglaciation dates and have no palaeoenvironmental control, although re-collection for this purpose has been undertaken. Considered with the Ertzberg and Ootoma dates, they leave the possibility open of a somewhat later final ice retreat on the southern flanks of mountains forming the southern slopes of the cordillera, than on such northern slope ranges as Mt. Wilhelm and the Saruwaged Mountains. This presumably implies relative increases in southerly precipitation during the time of continuing cold climate indicated on Mt. Wilhelm. It is important to investigate this possibility, as it would provide valuable evidence for the nature of the glacial climate.

Neoglacial

There is no evidence for ice on any of the New Guinea mountains between about 7,000 and 5,000 yr

1 G. S. Hope and Dr. E. Löfler recently obtained the following preliminary ages for basal sediments from three sites on Mt Giluwe: 13,050 ± 700 yr BP ANU-1339 Southwestern flank, 3510 m; 11,250 ± 550 yr BP ANU-1342A Northern flank, 3710 m; 9,950 ± 200 yr BP ANU-1337 Western summit, 4,160 m. These dates provide ages of minimal deglaciation which fit extremely well with the deglaciation record obtained from Mt. Wilhelm (Figure 3) and indicate that the dates given by Löfler (1972) for Mt Giluwe probably postdate deglaciation by considerable periods.
BP, and in fact the tree line of Mt Wilhelm was as much as 200 m above its present position from 8,500 to 5,000 yr BP. The highest site examined (Wilhelm Summit Bog, 4,400 m) is a rock basin completely filled by 317 cm of sediment. Pollen analyses and dating of the pond sediments forming the lowest 230 cm show that the surrounding area supported well-developed tussock grasslands from 8,700 until at least 6,990 ± 20 yr BP (ANU-1006). At some time, possibly much after the latter date, any pond sediments lying above 70 cm depth were removed, possibly by the action of a small ice cap on the sheltered southwestern side of the summit ridge. More recently peaty sands and gravels were deposited to form the top 70 cm of the deposit, and pollen analyses indicate at least two periods of less intensive erosion, which nevertheless twice stripped the southwestern summit area of grassland and peaty soil, leaving pioneer tundra communities on bare rock. A correlation of pollen spectra with those in a dated pollen horizon at lower sites (Hope 1973) suggests that the last erosive period ceased only 100-200 years ago. The disturbances that are recorded may have removed evidence of other erosive periods.

The Yellow Valley, Mt Jaya, part of which is occupied by the present Carstensz Glacier (Fig. 5), is floored by recent till and ice-smoothed limestone above 4,200 m, whereas the lower parts of the valley show intensive weathering of the Pleistocene glacial surfaces. A gully section through the till at 4,270 m reveals a series of tills intercalated with lake deposits (Fig. 6). Peaty soil above the oldest till found was dated at 2,930 ± 100 yr BP (SUA-20/2), and peat above the lake sediments trapped behind this till gave an age of 2,470 ± 80 yr BP (SUA-19). The lake sediments are deformed and overridden by a younger till which impounded a lake which in turn is overridden by a thick till sheet with low retreat moraines on the surface. This sheet evidently represents two advances as in places small lenses of in situ pond sediment were found, one of which was dated 1,555 ± 90 yr BP (SUA-177). Two dates were also obtained on a nearby peat deposit supporting thick woody plant stems in growth positions exposed by gulling near the margin of the youngest till at 4,400 m. The stems gave an age of 1,350 ± 80 yr BP (SUA-217) and the peat 2,455 ± 80 yr BP (SUA-216); presumably reflecting later shrub growth on a fossil peat. There is thus good evidence for four ice advances to about 4,200 m during the last 3,500 years with retreats above 4,200 m at 3,000 to 2,400 yr BP, a period after 2,400 yr BP, 1,550-1,550 yr BP, and the current retreat. The Carstensz Glacier has retreated about 2 km from the terminal moraines of the last advance and the retreat rate over the last 36 years suggests that they may have been abandoned about 100-140 yr BP (Peterson et al. 1973).

The last of these minor ice fluctuations at least does not appear to have affected vegetation outside the glaciated area. This may reflect the fact that minor increases in precipitation or reduction in abla-

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Fig. 6.—Gully section in valley floor at 4,270 m, Yellow Valley, Mt Jaya.
A. Deformed lake sediments overlain by a black peat horizon dated at 2,470 ± 80 yr BP (SUA-19).
B. Till overlying old lake.
C. Undisturbed laminated lake sediments formed behind moraine B.
D. Till with minor surface moraines, probably representing two ice advances, one before and one after 1,555 ± 90 years BP (SUA-177).
tion due to increased cloudiness would change the equilibrium of the glacier without limiting plant growth.

**Discussion**

The greater height and size of the Mt Jaya area (Carstenz Mountains) with its high plateau country next to the crestal ridges, together with the karst character, has probably been a major reason why its record of glacier fluctuations in New Guinea seems to be the best and most extensively preserved. The still extant glaciers have afforded the opportunity for direct observation of the interaction of climate, glacier mass-balance, ice extent, and ecological distribution patterns (Champion et al. 1975). These characteristics have helped in correlation and interpretation of glacial and palaeoclimatic data from the other New Guinea mountains.

An older glaciation was probably widespread above 3,600 m for areas where major uplifting of the crestal ridges had already taken place. Evidence is best preserved on the highest limestone plateau country where the till-like deposits extend well beyond the margins of the younger major moraine ridges. This older glaciation certainly pre-dates the major moraine phase by a considerable interval and may be compared with the weathered and eroded Rwimi Basin and Katabarua drifts beyond the sharp crested Mahoma moraines of the East African Ruwenzori area, discussed by Osmaston (Livingstone 1967).

The large latero-terminal moraines across New Guinea appear to have been abandoned 14,500-15,500 years ago. These moraines at Mt Wilhelm are lower than comparable ones at Mt Jaya. This difference in ice extent may have reflected a comparative dryness in the western Maoke Mountains caused by the widespread expanse of land on the Aru-Faure Shelf during the low sea level times, in contrast with little change on the northern New Guinea coast near Mt Wilhelm. The suggested synchroneity of the retreats is of interest and presumably reflects increasing temperature throughout the island.

Large moraines beyond the neoglacial deposits have also been reported from tropical Africa and South America (Livingstone 1967; Downie 1964; Gonzalez et al. 1966). Livingstone (1967) gives a date of 14,750 ± 290 yr BP (1-556) for deglaciation of the Lake Mahoma stand in the Ruwenzori, and in the tropical Andes it seems that some of the larger outer moraine ridges show contrasts with later ones in soil and vegetation cover and some preservation and weathering features. These seem to be analogous with those in New Guinea. Although neoglacial advances in the tropics have been shown (e.g. Downie 1964; Clapperton 1972), the stratigraphy and chronology from the Yellow Valley of Mt Jaya is so far the most detailed. The additional evidence from Mt Wilhelm for ice-cap formation on the highest lee (south-facing) slope in neoglacial times suggests that the Jaya record reflects events that were common to the highest parts of New Guinea. Pollen analysis at Mt Wilhelm shows that the treeline was depressed about 5,000 years ago (Hope 1973) and has remained so. Evidently any climate changes associated with neoglacial advances have not been sufficient to cause marked fluctuations in treeline there. Broad synchrony with the greater detail available from extra-tropical areas is apparent (e.g. Denton and Porter 1970; Den-  

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Prehistoric human impact on rainforest biodiversity in highland New Guinea

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In the highlands of New Guinea, the development of agriculture as an indigenous innovation during the Early Holocene is considered to have resulted in rapid loss of forest cover, a decrease in forest biodiversity and increased land degradation over thousands of years. But how important is human activity in shaping the diversity of vegetation communities over millennial time-scales? An evaluation of the change in biodiversity of forest habitats through the Late Glacial transition to the present in five palaeoecological sites from highland valleys, where intensive agriculture is practised today, is presented. A detailed analysis of the longest and most continuous record from Papua New Guinea is also presented using available biodiversity indices (palynological richness and biodiversity indicator taxa) as a means of identifying changes in diversity. The analysis shows that the collapse of key forest habitats in the highland valleys is evident during the Mid–Late Holocene. These changes are best explained by the adoption of new land management practices and altered disturbance regimes associated with agricultural activity, though climate change may also play a role. The implications of these findings for ecosystem conservation and sustainability of agriculture in New Guinea are discussed.

Keywords: pollen; palynological richness; biodiversity indicator taxa; swamp forest; Papua New Guinea

1. INTRODUCTION

New Guinea is one of the most biodiverse regions on the globe as it is believed to harbour over 5% of the world's biodiversity in less than 1% of the land area (Johns 1993; Miller et al. 1994; Heads 2001). In the current century, the greatest threat to regional New Guinea–Australian tropical biodiversity is an ever-increasing human population and pressures from global economic activity that have led to accelerated forest clearing, ecological degradation and climate change (Sekhran & Miller 1994; Haberle 2003a; Hilbert et al. 2004). In contrast to conditions in Southeast Asia to the west, at least 70% of the natural environment of the island remains intact and represents the third most significant expanse of tropical rainforest wilderness on Earth after the Amazonian and Congoli forest blocks (Mittermeier et al. 2005). While large-scale short-term assessments of the region’s vulnerability to biodiversity loss have generally excluded New Guinea from the category of 'biodiversity hotspot' (Mittermeier et al. 2005), this approach ignores the potential that small-scale processes and long-term influence of human activity may also have a significant impact on biodiversity change.

The broad changes in vegetation since the arrival of humans in the highlands1 of New Guinea around 30 000 calendar years before the present (yr BP; Kosipe record, White et al. 1970) have been established from 19 swamp and lake sites (Haberle 2003b). These records show that at the time of early deglaciation, beginning around 14 500 yr BP, the forest limit rises and montane forests invade valley floor grasslands in response to warmer temperatures and rising atmospheric CO₂, though conditions were not uniformly suitable for forest development until after 9000 yr BP. The palaeoecological records from highland valleys point to a sustained and gradual intensification of forest clearance and burning from at least 7000 yr BP (Haberle 2003b), though evidence from the archaeological site of Kuk Swamp in the Wahgi Valley (figure 1) suggests that at least here the valley floor was never completely forested during the Early Holocene. During this time, people were using fire to increasingly disturb and modify the montane forest and soils on the valley floor for the purpose of managing and harvesting significant food plants (Denham et al. 2004).

The development of agriculture as an indigenous innovation during the Early Holocene is considered to have resulted in increased population pressures, rapid loss of forest cover and increased land degradation over thousands of years (Haberle & David 2004). A review of the evidence for early agriculture in New Guinea supported by new data from Kuk Swamp demonstrates that cultivation had begun there by at least 7000 yr BP and probably much earlier (Denham et al. 2004). The focus of early agricultural activity was in the intermontane valleys between 1000 and 1900 m above sea level, where the Early Holocene organic-rich soils and swamp forest cover provided a suitable environment for

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1 In this case, the term 'highlands' refers to the inland regions of the island of New Guinea above an altitude of about 1000 m and not exclusively to the present day Highlands provinces of Papua New Guinea.
agricultural development. Today, these intermontane valleys have been substantially transformed through human activities associated with agriculture, leading to the original organic-rich soils and swamp forest cover being replaced by organic-depleted soils supporting grasslands (figure 4).

While swamp forests persist in the intermontane valleys, today the community is restricted to small patches that fringe the grass or sedge peat swamps of the valley floors (Paijmans 1976). Most swamp forest trees grow on hummocks separated by pools of water, creating a sparse or open canopy with dense layer of small trees and shrubs (figure 5). The common trees include *Syzygium* and other Myrtaceae, conifers (especially *Dacrydium* and *Podocarpus*), *Pandanus* and *Nothofagus*. *Pandanus* are often dominant as their stilt roots are ideally suited to an ever-wet soil environment. The conifers (e.g. *Dacrydium nidulum*) are also an important component in disturbed swamp forests where they form dominant stands in early stages of swamp forest recovery towards a diverse mixed swamp forest assemblage (Johns 1980). These swamp forests are assumed to represent the remnants of a once much more extensive forest community that covered the wet peaty soils of the intermontane valley floors. Here, I review the palaeoecological evidence from five major intermontane valleys in New Guinea (figure 1) and use two measures of past biodiversity to address the following questions:

(i) Are the present day swamp forests remnants of a once much more extensive forest community?
(ii) How rapidly did the transformation from swamp forest to grassland occur and was the change ubiquitous in time and space?
(iii) What influence did anthropogenic fires and forest clearance activities have upon shaping the present day landscape?
(iv) What has been the overall impact on biodiversity and are there key taxa now missing as a result of past human activities?
(v) What were the consequences of biodiversity loss for human populations in the highlands during the Mid–Late Holocene?

2. METHODOLOGY AND STUDY SITES

(a) Measures of biodiversity through time using palaeoecological techniques

Estimating the diversity of past vegetation communities from pollen data is potentially a powerful tool to measure plant biodiversity through time. One approach is to use simple counts of pollen types in a sample as an estimate of diversity, though this requires a standardized or constant count size as the number of pollen types increases as the pollen count increases (Bennett & Willis 2001). The calculation of palynological richness was developed by Birks & Line (1992) as a way of standardizing the pollen count between samples and thus allowing comparisons within a pollen sequence. However, the taxonomic uncertainties associated with pollen morphological types means that species diversity may change but not be registered in pollen morphological type change (e.g. changes in Poaceae species are generally not visible in the pollen record), resulting in a potential underestimate of biodiversity change.

A second approach is to target key biodiversity indicator taxa in the pollen record, where these taxa (or taxon) are representative of a distinct diverse vegetation

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community of interest through time. The montane swamp forests of New Guinea are readily identified in the pollen records by high percentage representation in the pollen assemblage of Myrtaceae (mainly Syzygium), Dacrydium and Pandanus (Haberle 1998b). The assumption here is that a loss or reduction of all or part of these key indicators from the pollen record is indicative of a loss or reduction in the extent of the associated vegetation community and therefore a loss in local biodiversity. A major uncertainty in this approach is the temporal constancy of the association between the key indicator types and their vegetation community which could lead to a potential over-estimate of biodiversity change.

(b) Study sites
The island of New Guinea lies within the humid tropics and is strongly influenced by seasonal fluctuations of the major equatorial circulation patterns. During the austral winter, New Guinea is under the influence of deep tropical easterly air flow (southeast trade winds), while during the austral summer monsoon, equatorial north-westerlies dominate. Throughout the year, the region is a locus of airstream convergence known as the intertropical convergence zone (ITCZ) and, as a result, is one of the most persistently cloudy regions around the equator (McAlpine et al. 1983). Circulation patterns over the region are strongly affected by the Southern Oscillation, though the influence is strongest during the pre-monsoon from September to November (McBride 1999). The severity of the 1997–1998 El Niño event was brought about by an anomalous eastwards displacement of the ITCZ from over the maritime continent towards the central Pacific and a subsequent failure of the austral summer monsoon (Webster et al. 1998).

The large highland valleys with complex agriculture based on root cropping centred on the altitudes of 1400–1850 m were a major discovery of the twentieth century (Brookfield 1964). The outer flanks of the mountains are perhumid, with precipitation more than double evaporation in almost all months. In the highland or intermontane valleys, the mountains cut off the orographic rain and local circulations dominate in most seasons. Here, air rises each day up the warmed slopes and descends over the valley, giving sunny conditions with adequate rainfall from afternoon thunderstorms. Away from the large highland basins, even small valleys may have this effect and may thus support small hamlets. In these marginal settlements, techniques of ditching and mounding are used to shed water from the fields. There is a northwest–southeast gradient from asseasonal precipitation to the appearance of a weakly defined dry season, and from relatively infertile limestones and mudstones in West Papua to richer soils fertilized by volcanic ash falls in Papua New Guinea east of the Strickland River (Hope & Haberle 2005).

Despite the present day restriction of forested areas to the surrounding mountainous slopes and degraded patches on highland valley floors, the structure and composition of lower montane forest found between 800 and 2200 m altitude is highly variable with the common canopy trees including Castanopsis, Nothofagus, Elaeocarpus, Beilschmiedia, Melastomataceae, Phyllocladus and the emergent gymnosperms Araucaria hunsteinii and Araucaria cunninghamii. Nothofagus is found as a scattered element of mixed lower montane forest, though it commonly forms a continuous forest between 2200 and 2700 m, possibly in response to persistent cloud cover and infrequent but large-scale disturbance (Read & Hope 1996). Grasslands resulting from anthropogenic activity have replaced much of the lower montane forests throughout the major highland valleys, with Leersia and Phragmites common in wetter areas and the tall Miscanthus floridulus common in areas experiencing more seasonal precipitation. Where precipitation has a more pronounced seasonality and fires are more frequent, particularly in the east, the short Imperata grassland communities are dominant. Using the two biodiversity indices discussed above (palynological richness and key biodiversity indicator taxa) as a means of tracking changes in biodiversity through time, selected pollen records from five highland valley floors where intensive agriculture is practised today are examined (figure 1).

3. SWAMP FOREST LOSS DURING THE HOLOCENE IN NEW GUINEA
Pollen records from New Guinea spanning the Late Glacial to Holocene period show that vegetation, at least within montane and alpine regions, has a remarkable ability to track climate change (Hope 1976; Haberle 2003b). In highland valleys where human settlement and deforestation are prominent features of the contemporary landscape, palaeoecological records are generally not continuous, perhaps due to anthropogenic-related disturbance and lack of detailed chronological control. One exception to this is the Tari Basin record which is the longest and most continuous record from the island of New Guinea (Haberle 1998b). Despite these problems, five sites have been selected from highland valleys extending from the central ranges of Irian Jaya to the eastern highlands of Papua New Guinea, representing the general nature of vegetation change through the Holocene. A summary diagram (figure 2) is presented for each site that includes the relative proportions of forest trees, swamp forest (Myrtaceae), a disturbance and arboriculture indicator (Casuarina), and charcoal particle concentration as an indicator of fire. The Casuarina pollen type is most probably associated with Casuarina oligodon which is a nitrogen fixing tree that is commonly planted by people throughout the highlands and used for multiple purposes (house/fencing material, crop shade, fallow tree, etc.). Loss of local forest cover is believed to have led to the adoption of agroforestry techniques to compensate for loss of forest resources (Haberle 1998a).

(a) Baliem Valley
The western-most site in the transect is Kelela Swamp at 1400 m altitude in the Baliem Valley (Haberle et al. 1991), which has a long, possibly discontinuous, pollen record dating back to some time before 7000 yr BP. In the earliest phase, regional forest cover was dominated...
that the montane tree Nothofagus out the record, though other trees, including other indicator taxa are used to develop an understanding of biodiversity change through time in the Tari Basin, and is the only published continuous pollen record from the highlands of New Guinea that spans at least 30 000 yr BP to the present (Haberle 1998). The record shows that the montane tree Nothofagus is important throughout the record, though other trees, including Castanopsis/Lithocarpus, Myrtaceae, Dacrydium and Pandanus, attain dominance at different times. The Early Holocene is marked by the development of swamp forest vegetation and a peak in the pollen diversity. This is maintained until around 3000 yr BP when there are indications of swamp forest disturbance, a decline in the pollen diversity and the key indicator taxa, followed by swamp forest clearance commencing around 1700 yr BP.

(b) Iftaman Valley
The township of Telefomin lies in the Iftaman Valley at an altitude of around 1500 m. In contrast to the Balam Valley, Nothofagus-rich forest remains a relatively important forest element throughout the 20 000-year pollen record, despite the relatively low elevation (Hope 1983). Around 12 000 yr BP, regional warming produced a shift in forest composition to a more mixed Nothofagus forest, with only a slight rise in Castanopsis/Lithocarpus. The Telefomin pollen record shows a major disturbance event between 11 500 and 8500 yr BP, which is possibly discontinuous (inferred from Hope 1983; figure 3), and is interpreted as anthropogenic burning and local forest clearance followed by abandonment and reestablishment of primary forest. Another period of disturbance occurs only after 4500 yr BP, when grassland expands rapidly to its present extent, and forest and Myrtaceae swamp forest are cleared from the site. Casuarina appears to be grown in the valley only after 1000 yr BP, in line with the evidence from the Tari Basin and the Balam Valley. However, unlike these two regions, the extensive grasslands around Telefomin today are rarely used for agricultural purposes and are infrequently burnt.

(c) The Tari Basin
Haeapugua lies at an altitude of 1650 m in the Tari Basin and is the only published continuous pollen record from the highlands of New Guinea that spans at least 30 000 yr BP to the present (Haberle 1998b). The record shows that the montane tree Nothofagus is important throughout the record, though other trees, including Castanopsis/Lithocarpus, Myrtaceae, Dacrydium and Pandanus, attain dominance at different times. The Early Holocene is marked by the development of swamp forest vegetation and a peak in the pollen diversity. This is maintained until around 3000 yr BP when there are indications of swamp forest disturbance, a decline in the pollen diversity and the key indicator taxa, followed by swamp forest clearance commencing around 1700 yr BP.

(d) Jimi Valley
Nurenk Swamp (Gillieson et al. 1989) lies at an altitude of 1900 m in the Jimi Valley and shows that a Myrtaceae swamp forest existed around the site prior to 3500 yr BP. Possible watertable changes, tephra-fall events and human activity may have disturbed the site and resulted in the loss of swamp forest cover. Forest disturbance continues until 300–400 yr BP when increased burning and a rise in Casuarina pollen indicated a strong human influence on the site.

(e) Kainantu Valley
Norikori Swamp (Haberle 1996) lies at an altitude of 1750 m in the Kainantu Valley and shows that a Myrtaceae–Pandanus swamp forest existed on the site for an undetermined time before 5000 yr BP. Disturbance of forest and clearance is already evident by the time Holocene sedimentation begins around 5000 yr BP. Features purported to be fossil agricultural structures in the nearby Arona Valley are dated to around 4500 yr BP and are associated with pollen assemblages representing deforested conditions (Golson & Gardner 1990; Haberle 1996). Forest clearance and burning continue gradually until 1500 yr BP when rapid vegetation change towards an extensive grassland landscape, similar to the present, occurs. Casuarina begins to increase around 600 yr BP.

4. PALYNOCOLOGICAL RICHNESS AS AN INDICATOR OF BIODIVERSITY LOSS IN SWAMP FORESTS DURING THE HOLOCENE
Palynological richness and the presence of key indicator taxa are used to develop an understanding of biodiversity change through time in the Tari Basin, the one site in the highland valleys that has a continuous record over at least 30 000 years (Haberle 1998b). The pollen diagram (figure 3) and a summary
of the pollen zone interpretations are given in table 1. Palynological richness analysis shows that there has been considerable change in pollen-type diversity over at least the past 30,000 years coinciding with major changes in vegetation in this region. Prior to the Last Glacial Maximum, the basin floor is forested with a diverse mosaic of Nothofagus-rich montane forest and mixed swamp forest in the wetter areas and palynological richness is high. At around the time of the Last Glacial Maximum, grassland is established under the influence of increased burning which is considered to be the consequence of climate change as well as the arrival of humans in the region. Between 18,000 and 9000 yr BP, burning is sufficient to maintain grasslands in the valley floors and while forest is present in the valley the overall diversity is low as are the key indicators of biodiversity. The Early Holocene is marked by the development of swamp forest vegetation and a peak in both the key indicator types and the pollen diversity. This is maintained until around 3000 yr BP when there are indications of swamp forest disturbance, a decline in the pollen diversity and the key indicator taxa, followed by swamp forest clearance commencing around 1700 yr BP (figures 4 and 5).

In the Haeapugua record, lower palynological richness generally coincides with the establishment of open vegetation on the site, which may be explained by a true loss of overall plant diversity from the site or it may reflect the lower pollen taxonomic resolution available from grasslands relative to forests. While there is no evidence to support or deny the latter assertion, this may serve as a cautionary note for interpretation of palynological richness as an indicator of biodiversity. What is certain is that forest biodiversity is reduced through the retreat or total loss of forests from the site. Currently, Haeapugua Swamp does not support any swamp forest, though remnant swamp forest patches survive in other parts of the Tari Basin. The extirpation of swamp forest from the Haeapugua catchment is indicative of a much wider phenomenon evident through an examination of the key pollen indicators of swamp forest from the five major valleys where local swamp forest loss outstrips the overall forest loss under pressure from increased burning and forest clearance activity for agriculture (figure 2). In the Haeapugua record, the combination of both indicators of biodiversity provides a useful insight into the relationship between vegetation community change and biodiversity change. The coincidence in loss of swamp Myrtaceae with lower palynological richness between approximately 18,000 and 14,500 yr BP and after 3000 yr BP to the present provides a strong argument for true biodiversity loss at the site as the former tends to overestimate biodiversity change and the latter underestimates biodiversity change. In contrast, the phases of vegetation change prior to 18,000 yr BP show a lack of consistency between the two indicators in table 1. The low palynological richness values associated with forest cover that included swamp forest indicators during the earliest phase (prior to around 27,500 yr BP; figure 3) in the record may point to a shift in relative dominance of tree species cover (particularly Nothofagus). In this case, swamp forest dynamics driven by disturbance factors or climate change may have led to greater dominance of a single taxonomic group and a perceived loss of diversity at the site.

5. DISCUSSION

(a) Are the present day swamp forests remnants of a once much more extensive forest community?

Palaeoecological records from the five major highland valleys examined in New Guinea point to a sustained and gradual intensification of forest clearance and burning from at least 7000 yr BP that led to the loss of swamp forest cover at different times. This process is widespread across the highlands and within the valleys as well. The loss of swamp forest cover reflected in the Haeapugua record is not simply restricted to the local swamp environment. Buried wood in peat sections recorded throughout the basin attest to a much more widespread phenomenon in the Tari Basin (Haberle 1998b), though the variability in the timing of these changes in one single valley has yet to be determined.
Figure 3. Pollen diagram for Haeapugua, Tari Basin (Haberle 1998b). Pollen counts are expressed as percentages of the total pollen and spore sum, excluding pollen and spores of aquatic vascular plants. Palynological richness provides a comparative estimate of the expected number of taxa in each sample and is determined by rarefaction analysis (Birks & Line 1992). Detailed counting of carbonized particles follows the point counting method outlined by Clark (1982). Numerical zonation was performed with only major taxa whose pollen or spore values exceeded 5% at least once and employed optimal splitting by sum of squares analysis to partition the data into six zones for Haeapugua of which the latest four are represented here. All numerical analyses have been implemented within Psimpoll, a C program for plotting pollen data, developed by Bennett (1994).
The composition of swamp forests that covered these valley floors is similar across the highlands, with all pollen records that contain pollen assemblages from the Early Holocene depicting a mixed montane swamp forest with Myrtaceae (mostly *Syzygium*), *Pandanus* and to a lesser extent *Dacrydium*, dominating the forest taxa assemblage. The dominance of the latter two taxa appears to be determined by increased frequencies of disturbance that may have impacted upon the ecosystem through natural processes (climate, competition) or human impact (selective exploitation of useful plant species, fire). What is clear from this analysis is that the present day swamp forests are remnants of a once much more extensive forest community.

**(b) How rapidly did the transformation from swamp forest to grassland occur and was the change ubiquitous in time and space?**

The pace at which this change took place appears to vary from as much as around 1500 years in the Baliem Valley to less than 500 years in the Kainantu Valley (figure 2). A comparison of the timing of swamp forest loss between the five valley records in figure 2 shows that at this scale the loss is neither strictly time transgressive nor is it synchronous along the transect. This is not consistent with what might be expected under a ‘Neolithic Transition’ model where diffusion of agricultural techniques and crops may have been rapid and the impacts widespread. Nor is it consistent with a climate change model in which a shift to more frequent and intense El Niño-related drought events around 4500 yr BP (Gagan et al. 2004) may have contributed to increased disturbance, burning and water loss which could have led to widespread loss of swamp forest cover after this time. A more complex model of landscape history is suggested by the palaeoecological results for swamp forest loss in which an increased focus on wetland agriculture during the Mid–Late Holocene (Denham et al. 2004), perhaps in combination with ongoing climate changes, led to rapid clearance of the swamp forest type at different times across the highlands.

**(c) What influence did anthropogenic fires and forest clearance activities have upon shaping the present day landscape?**

While the timing and nature of these changes can be identified, the reason for these changes at different times is not clear. Part of the reason may lie in the relative intensity of exploitation of each site and its vulnerability to the external forces of change. These
forces may have included direct forest clearance or alteration of the forest disturbance regime, perhaps through selective forest clearance practices, burning activity or climate change. For example, a shift in fire regimes may be human or climate driven. Climate changes are generally considered to be relatively minor during the past 10 000 years, though it has been suggested that the impact of short-term climate variability, such as increased drought stress and fire associated with El Niño-Southern Oscillation (ENSO) events, has had a significant influence on vegetation dynamics in the New Guinea region over the past five millennia (Haberle & Chepstow-Lusty 2000; Haberle et al. 2001). This has been supported further by records showing landscape destabilization from the South American coast (Sandweiss et al. 1996) and increased disturbance of vegetation in Australia (Shulmeister & Lees 1995) between 5000 and 4000 years ago. Neoglacial advances of highland glaciers during the past 3500 years have been reported by Hope & Peterson (1976), suggesting that minor temperature fluctuations were probably experienced in the occupied valleys.

Recent studies have shown that, under increasing pressures from external forces of change, ecosystems are vulnerable to loss of resilience which may lead to switches to alternative states with consequential species losses (Molinari et al. 2005). In the Tari Basin example (figure 3), the swamp forest appears to have responded to an increase in fire-related disturbance after 3000 yr BP with a shift from Myrtaceae to Dacrydium–Pandanus dominated swamp forest. The reason for the final loss of forest cover and its replacement by grass-sedge swampland by 1700 yr BP may have been direct clearance or a switch to an alternate state under continued high fire-related disturbance frequencies. Either way, human activity appears to be the primary driver of ecosystem change, though it remains difficult to exclude the possibility that El Niño-related climate change may have played a partial role in enhancing the rate of swamp forest loss during the Mid–Late Holocene.

What were the consequences of biodiversity loss for human populations in the highlands during the Mid–Late Holocene?

The story of agricultural development in the highlands of New Guinea is one of the continued indigenous innovation in agricultural techniques in the face of increased land degradation and climate change (Haberle & David 2004). The adoption of Casuarina agroforestry techniques around 1200 years ago as a strategy to alleviate the local loss of forest resources previously available in swamp forests is an example (figure 2). Furthermore, Bayliss-Smith & Golson (1992) believe that the widespread planting of Casuarina facilitated the rehabilitation of soils after gardening through nitrogen fixation, its use for firewood and building material and the elimination of taro beetle infestation in gardens where it was planted, and that this practice was successful enough in the dryland for labour-intensive wetland cultivation and swamp forest clearance to be reduced or given up. Bourke (1997) cautions placing too much emphasis on the importance of Casuarina tree-fallowing alone throughout the highlands and suggests that the initial rise in Casuarina pollen may have been related to people planting Casuarina trees in and near villages to provide timber as supplies became scarce with the continued clearance of forests. Either way, the innovation of planting of utilitarian forest products close to settlements would have reduced the need for further primary forest clearance and perhaps reduced further biodiversity loss.

The remaining highland swamp forests should be considered as a conservation priority as their current relict distribution within densely populated valley floors makes them an extremely vulnerable plant community. Part of this conservation effort has been underway in the indigenous community as some swamp forest patches are conserved as significant sacred sites by land owners. Although agrarian populations in the highlands of Papua New Guinea have almost doubled over the past 25 years, the area of agricultural land has expanded by only 11% (MacAlpine & Freyne 2001). This implies ongoing intensification of existing agricultural areas through the incorporation of new crop species and agricultural techniques. While this is a positive indication of potential buffers for forest resource management, ongoing population increases will lead to further pressures to clear forested land and particularly valley floor swamp forests. The impacts of continued intensification on land degradation and the long-term sustainability of relict forest communities have yet to be realized.

What has been the overall impact on biodiversity and are there key taxa now missing as a result of past human activities?

None of the pollen records from New Guinea indicates an extinction event in the swamp forest plant community as a result of past human activities. What is evident is that widespread extirpation of diverse swamp forest communities has occurred at different times over the past 7000 yr BP. The implications for vulnerability to extinction of the plant and animal species within swamp forest communities are the same as for any species whose spatial distribution is reduced through human activity: the vulnerability to extinction may increase with fragmentation and aerial reduction of the community. The current lack of knowledge about the nature of species diversity within swamp forests of the highlands also hinders any definitive measure of potential extinction. However, given the extremely high diversity and local endemism in families such as the Orchidaceae, it may be reasonable to assume that loss of swamp forest habitat in a single valley may have led to extinctions in a number of plant species that are not registered in the pollen records.

Extinctions in the animal kingdom have been recorded in the highlands of New Guinea during the past 50 000 years. Fossil fauna have been recovered from swamp forest sites in the Tari Basin and elsewhere in New Guinea. The now extinct large forest-browsing mammal group known as *Hulitherium tomasettii* is believed to have browsed within swamp forest environments and may have been a target for early human hunting, which is considered the primary cause of their extinction during the Last Glacial Period (Menzies & Ballard 1994).

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6. CONCLUSIONS
An evaluation of the change in biodiversity of forest habitats through the Late Glacial transition to the present in five palaeoecological sites from highland valleys in New Guinea, where intensive agriculture is practised today, has shown that people have had a significant impact on forest community composition, function and diversity over many thousands of years. The palaeoecological record of vegetation change can provide a deeper time perspective on the relative vulnerability of any given vegetation community to external forces that may result in biodiversity change. Consideration of long-term (1000–100 000 years) as well as short-term (10–100 years) time-scales should be incorporated into biodiversity planning. The conservation of relict forest communities most at risk from recent agricultural intensification will require an integrated approach between current land owners, government, conservation biologists and ecologists with an understanding of long-term biodiversity change.

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Plant Succession on Recent Volcanoes in Papua

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PLANT SUCCESSION ON RECENT VOLCANOES IN PAPUA

By B. W. TAYLOR*

(With Plate 14 and two Figures in the Text)

INTRODUCTION

Within the territory of Papua, part of the island of New Guinea, only three volcanoes are known to be active. These volcanoes, Mt. Lamington, Waiowa Volcano and Mt. Victory, are all situated within 30 km. of the north coast, in the Northern Division of Papua.

Climatically, the Northern Division is part of the wet tropics with a mean temperature at sea-level of 27° C. and a rainfall ranging from 2800 mm. to over 3600 mm. There is a yearly 'dry' season but nowhere does the driest month average less than 100 mm. of rain. Typically the area consists of a wide alluvial plain extending from the high central ranges to the sea. This plain is broken in many places by volcanic ranges and cones, the great majority being of Pleistocene age.

The author was able to visit the blast areas of the three volcanoes while taking part in a land resources survey undertaken by a team from the Commonwealth Scientific and Industrial Research Organization on behalf of the Administration of Papua and New Guinea. The time available for the investigation of these blast areas was limited, 5 days being spent on Mt. Lamington, in July, 1953, 1½ days on Waiowa Volcano and 6 days on Mt. Victory. As a result it is possible to give only an outline of the plant communities present.

Grateful thanks are due to other members of the survey team, particularly Mr. H. A. Haantjens who is responsible for most of the information on soils, and to Dr. R. D. Hoogland and Mr. J. Saunders who are responsible for the collection numbers quoted in the text. The full collections of Dr. Hoogland and Mr. Saunders are lodged in the Herbarium Australiense, Canberra, and Department of Forests Herbarium, Lae, New Guinea. Duplicates of almost all numbers have been lodged in the following herbaria — Leiden, Arnold Arboretum, Grey, Kew, British Museum, Brisbane, U.S. National and Melbourne. Native names were used as an aid to field identification and where quoted in the text these have been followed by (Or) indicating Orokaiva language and (On) Onjob language. Further thanks are due to E. Taylor and J. Thompson, Bureau of Mineral Resources, Canberra, for helpful discussions on vulcanism in the region. The ecological concepts used in this paper follow Beadle and Costin (1952) with some additions from Beard (1955).

Mt. Lamington

Mt. Lamington, 1600 m. high, was believed to be extinct until it erupted in January 1951. The eruption was of the Pelean type and spread a glowing cloud of hot ash with great force over an area of approximately 200 km.* This explosion laid flat

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every tree and spread a deep deposit of hot ash over the blast area. After this first eruption a dome built up and a second eruption took place in March 1951, after which a second dome was formed, and then activity gradually lessened. During these eruptions a lahar, or mud stream, ran from the base of the dome northwards for 9 km., and this left a deep deposit of rubble which has received the name Avalanche Valley. No true lava flow was formed although flows from previous eruptions are in evidence.

The only information available on the previous vegetation is an oblique aerial photograph of the lower slopes taken 10 years earlier. This shows a pattern of garden regrowth stages with few stands higher than 35 m.

No detailed account is available of happenings within the blast area after the eruption but all eye-witness accounts indicate that erosion was widespread and regeneration of the vegetation was extremely rapid. After a very few months the blast area was a mass of green. One of the most conspicuous features of this early vegetation was the vigorous growth of taro, *Colocasia antiquorum* Schott and bananas, *Musa* spp., on the sites of former native gardens.

By July 1953 an almost continuous range of vegetation types from woodland, exceeding 12 m. in height, to an edaphic desert of scattered moss plants was found. The ash cover had remained on extensive flats but on slopes most of it had been eroded. In many areas the topsoil was exposed and on the steeper slopes only subsoils remained. The depth of ash varied considerably; 2 km. from the dome large flats were covered by 60 cm. of ash and 8 km. from the dome the ash cover was 15 cm. deep. This ash consisted of fragmented andesite and had the size and physical properties of medium to fine sand.

On the deep lahar deposits of Avalanche Valley the distribution of the vegetation depends directly on the availability of water. At the base of the dome, 1000 m. elevation, the surface deposits are coarse gravel and rock, with little finer material. Although the annual rainfall here is probably in excess of 3600 mm., with over 200 rainy days, the vegetation is an edaphic desert with only scattered moss plants and ferns present. Nowhere in this section does ground cover exceed 5 per cent and the great majority of the area has less than one 1 cent cover. In this desert are scattered patches of more luxuriant growth where plants are growing on a layer of finer material deposited by surface wash after occasional heavy rains. This layer never exceeds 5 cm. in depth and the vegetation present varies with its depth and texture. The thickest layer, consisting predominantly of fine silt, carries a 50 per cent cover of *Saccharum spontaneum* L., 1 m. high, the intervening ground being covered by a mat of moss. Further down Avalanche Valley the percentage of finer material gradually increases. At the same time the ground cover becomes denser, the grasses *Imperata cylindrica* Beauv. and *Saccharum spontaneum* L. predominating. The ground cover is 50 per cent 3 km. from the dome, while at 8 km. a 3 m. high dense stand of *Saccharum spontaneum* is found.

Elsewhere in the blast area the vegetation is more luxuriant and has been grouped into several associes. It is recognized, however, that these associes are merely convenient subdivisions for a continuous range of communities. The distribution of each of these associes shows a direct correlation with the extent of erosion.

The *Saccharum spontaneum* associes is dominated by the tall grass *Saccharum spontaneum* which frequently forms tussocks. It ranges in height from 2 to over 4 m., has from 80 to 100 per cent soil cover and is very similar to the community of
Saccharum spontaneum at the bottom of Avalanche Valley. Other species are infrequent but include Imperata cylindrica, Pennisetum macrostachyum Trin., cf. Scleria sp., Scaevola novoguineensis K. Sch. 3338, Vitacea 3337 and several ferns. The community occurs on sites covered by ash from 30 cm. to over $1\frac{1}{2}$ m. in depth.

The Euroschninus papuanus associes grows in the more favourable sites within the blast area where only part of the topsoil has been removed, or where the topsoil is intact and the ash cover is less than 15 cm. deep. The community is a woodland 6-12 m. in height with Euroschninus papuanus Merr. and Perry predominating. A few other tree species were recorded from this community. These are Ficus pungens Bl., Ficus sp., 'mumbura' (Or), Ficus sp., 'topu' (Or), Octomeles sumatrana Miq., Homalanthus sp., 'ugaho' (Or) and Albizia falcata (L.) Backer. The ground layer is fairly dense and consists of Saccharum spontaneum, Imperata cylindrica, ferns, Compositae and Orchidaceae. The transition between these two associes is of common occurrence occurring at sites covered by ash from 10-35 cm. in depth. The community consists of a dense stand of Saccharum spontaneum with scattered trees common in the Euroschninus papuanus associes.

The Euroschninus papuanus — Musa spp. associes is somewhat lower in height than the Euroschninus papuanus associes and occupies sites where most of the topsoil has been removed by erosion. The community is dominated by species of Musaceae, 'hura' and 'hubibi' (Or), together with tree species of the Euroschninus papuanus associes.
The *Trema* sp. associes occurs on the steeper slopes where all the topsoil has been removed by erosion. It is a woodland community dominated by *Trema* sp., 'siha' (Or). Other tree species are rare. Those recorded are *Ficus* spp., 'topu', 'ahorni' and 'sombahu' (Or), and *Pipturus* sp. 3348. The ground layer may be sparse to dense and consists predominantly of *Imperata cylindrica*.

The *Saccharum spontaneum*—*Lycopodium cernuum* associes occurs on the steeper slopes of the old crater where erosion has been most severe and the lower layers of the subsoil are exposed. The associes ranges from an almost continuous stand of tussocks of *Saccharum spontaneum* separated by a dense mat of moss or *Lycopodium cernuum* L. to almost bare ground with a scattered cover of moss and *Lycopodium cernuum*. In small gullies on the old crater walls occur small societies dominated by the trailing herb *Gunnera macrophylla* Bl. 3327. These societies frequently have 100 per cent ground cover and receive additional water by drainage from the surrounding slopes.

There are many active steam vents arising from the dome of Mt. Lamington, but no trace of sulphur was found. With one exception these vents are devoid of vegetation. The exception is the lowest vent at 1000 m. elevation. Immediately around this vent is a relatively lush growth consisting of many mosses, grasses, ten species of ferns and one dicotyledon seedling, probably *Octomeles sumatrana*. This community drew the greater part of its water supply from steam which could be seen condensing on leaves and rocks. Surrounding the steam vent community was the usual desert of scattered moss plants typical of the upper part of Avalanche Valley.

As a result of the deposition of volcanic material from streams draining from Mt. Lamington, large areas of forest have been destroyed and a fresh sequence of seral communities formed outside the blast area. These are very similar to communities on riverine deposits elsewhere in the region and consist of scattered tussocks of *Saccharum spontaneum* or stands of small trees in the upper reaches where the deposits are coarse. In the lower reaches, where the deposits are finer and flooding more frequent, the community is dominated by a dense tall stand of *Saccharum spontaneum* or *Phragmites* sp. or by a dense mass of numerous water-loving herbaceous species.

**WAIOWA VOLCANO**

Waiowa Volcano is situated near the junction of a piedmont plain with the foothills of the Goropu mountains, 20 km. south-west of the coastal village of Uiaku. The plain at this point is at 270 m. elevation and the small cone of the volcano is another 100 m. higher.

The history of the eruption has been reported by Baker (1949). Volcanic activity had not been reported from this area before December 1943, but during the next six months there were three major eruptions and long-continued ejection of gas, steam and ash and a flow of blocky lava. The eruptions were of the Perret type and a glowing cloud of hot ash devastated an area of 40 km.², mostly on the piedmont plain. The plain surrounding Waiowa Volcano is virtually uninhabited and outside the blast area it is covered by a mature tropical rainforest of very mixed floristic composition. Some of the more frequent species in this forest are *Pometia pinnata* Forst., *Tetrameles nudiflora* R. Br., *Syzygium* spp., *Dysoxylum* spp., *Tristriopsis subangula* K. Sch., *Alstonia scholaris* R. Br., *Pterocarpus indicus* Willd. and *Palaquim* sp.
Within the blast area there is a small central crater composed of blocky lava covered by a thin layer of ash. Surrounding this crater is an area of the piedmont plain covered by ash generally over 30 cm. in depth. In addition, a section of the plain is covered by lahar deposits of considerable depth. A few steam vents are active but devoid of vegetation. No sign of sulphur was noted although sulphurous fumes had been reported during the eruption by Baker. In addition, there is a small section of the steep Gorupu mountains within the blast area, but this area was not visited. The vegetation ranges from a forest community to an open community of scattered herbs, and these vegetation types are closely correlated with the edaphic conditions.

Several distinct communities are found on the crater walls. Growing on the greatest part of the area is an open community dominated by the grasses Saccharum spontaneum and Imperata cylindrica, which is very similar to the grass communities found on Avalanche Valley 2 km. from the dome of Mt. Lamington. The deposits on which these two communities are growing are very similar in texture. On the lower slopes of the crater wall the open community is invaded by a few species of small trees; Euroschinus papuanus, Terminalia sp., 'gorli' (On), Pipturus sp., 'kuraika' (Or) and Casuarina papuana S. Moore. In small depressions these species form a low woodland with a dense ground layer of ferns and grasses. Other tree species are uncommon. A second woodland up to 8 m. in height is found on the many small dry gullies which drain radially down the crater walls. The soils in these gullies consist mainly of sand and gravel but finer fractions are more abundant than under the surrounding open grassland and remain moist for a much longer period. This woodland is dominated by Casuarina papuana with 80 per cent cover. Other species present are Euroschinus papuanus, Terminalia sp., 'gorli' (On), Octomeles sumatrana, Ficus pungens and Pipturus sp. The ground layer is very sparse but climbers are frequent.

The vegetation on the almost flat lahar deposits consists of tall grassland surrounding scattered bare areas. These bare areas cover 20 per cent of the deposit and have a surface crust 5 cm. thick. The grassland, 4 m. in height, is growing on coarse sand and consists of an almost pure stand of Saccharum spontaneum, other grasses, small trees and twining plants being rarely found.

The piedmont plain is covered by a deposit of coarse ash from 30 cm. to over 1 m. in depth, and carries a relatively open forest community, 20 m. in height. The tallest

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**Fig. 2. Environmental distribution of communities. Mt. Lamington blast area.**
stands of this forest have a well-developed dominant layer, a very sparse second tree layer at 7 m. and a dense ground layer 2-3 m. in height. Up to 80 per cent of the trees of the dominant layer are *Octomeles sumatrana* but many other species occur. Species recorded are: *Casuarina papuana; Neonauclea* sp., 'kafora' (On); *Albizia falcata, Dysoxylum* sp., 'jomo' (Or); *Alstonia* sp., 'ibuga' (Or); *Vitex cofassus* Reinw. and *Ficus* sp., 'mumbura' (Or). The dense ground layer consists of *Saccharum spontaneum, Saccharum* sp., 'ohogo' (Or), *Imperata cylindrica* and many species of ferns. The transition between this forest community and the woodland communities is gradual and consists of a gradual-reduction in height and an increase in importance of *Casuarina papuana*. The boundary with the surrounding climax rainforest is exceedingly sharp, due to the nature of the eruption, and this transition area is marked by an abundance of climbing palms, *Calamus* spp., in the *Octomeles sumatrana* forest.

**Mt. Victory**

Mt. Victory is an 1800 m. high volcano situated 40 km. due north of Waiowa Volcano. The date of the last eruption of this volcano is not known, but the tentative date of 1870 is suggested. European settlement did not come to this area until the present century, but in the closing years of the nineteenth century the smoke from Mt. Victory was used as a landmark by mariners and the explosion is still fresh in the legends of the native peoples.

The eruption is presumed to be very similar to the explosion of Mt. Lamington in 1951, with the main devastation being due to a glowing cloud of hot ash covering an area of 400 km². Lava flows from this last eruption are absent, but there are extensive lahar deposits consisting predominantly of sand and gravel, often of considerable depth. Nothing is known of the pre-eruption vegetation, but presumably at lower levels this was similar to the tall tropical rainforest now growing just outside the blast area. This forest is 35-45 m. in height and is of very mixed floristic composition and rich in species; the most frequent are *Syzygium* sp., 'dara' (Or), *Tristriropsis subangula, Pometia pinnata, Terminalia* sp., 'kowuja' (Or), *Anisoptera polyandra* Bl. and *Cedrela toona* Roxb.

At present the major changes in the vegetation are associated with differences in elevation. Three zones are recognized; a lowland zone generally below 700 m. elevation, a lower montane zone 700-900 m. in elevation and a montane zone above 900 m. Due to the limited time available only the lowland zone was investigated in any detail.

**Lowland zone.** Variations in composition and structure within this zone are associated with edaphic conditions. The greater part of the area is covered by a mature soil of considerable age. The topsoil consists of a dark brown loam or clay loam, 20-40 cm. deep, and this overlies a yellow to yellow-brown subsoil ranging in texture from clay loam to loamy sand. This mature soil is generally free of recent ash but is occasionally covered to a depth of 30 cm. The remainder of the lowland zone is covered by lahar deposits.

On the mature soils the vegetation is a high rainforest with three tree layers, the uppermost layer frequently exceeding 50 m. in height. Two species predominate in this layer, *Octomeles sumatrana* and *Albizia falcata*. Other common species are *Endospermum* sp., 'poporga' (Or), *Artocarpus incisa* L., *Elaeocarpus* sp., 'roroku' (On), *Tetrameles nudiflora, Canarium* spp. and *Ficus* spp. Another fifty species have been


Phot. 3. Lowland zone of the Mt. Victory blast area. Large tree, *Tetrameles nudiflora.*
recorded as present in this layer and probably many more species occur but were not recorded. The two most abundant species have very large open crowns and as a result the second tree layer is well developed.

Species found in the second tree layer can be classed into three groups. The largest group consists of species already present in the dominant layer, but *Octomeles sumatrana* and *Albizia falcata* are very rare. Seedlings of these two species have been observed elsewhere in the Northern Division to be light-demanding and do not normally regenerate in their own shade. The second group consists of species which have reached their maximum height and this group includes many species of *Myristicaceae*, two species of *Pandanus*, several *Palmae*, *Macaranga* spp., *Ficus* spp. and *Litsea* sp., 'wovrae' (On). The third group is smallest in number of individuals but rich in species and includes young individuals of species absent or very rare in the dominant layer but characteristically found in the dominant layer of climax rain-forest outside the blast area. The more important of these species are *Pometia pinnata*, *Tristiropsis subangula*, *Chisocheton* sp., *Dysoxylum* spp., *Alstonia scholaris* and *Palaquium* sp. The lowest tree layer is made up of species present in the second layer and of species commonly found in forest openings or in young regrowth on abandoned native gardens.

Because of the large number of species involved, no two stands have the same composition, even if only the dominant layer is considered. Over the greater part of this area the variations seem mainly dependent on chance, but in the south-east portion near the edge of the blast area *Octomeles sumatrana* and *Albizia falcata* are rare and the predominant species in the dominant layer are *Pometia pinnata* and *Tristiropsis subangula*; otherwise the communities are very similar. As is usual for the blast area of Mt. Victory there is a sharp change between this section and the surrounding climax forest, but the change to a community dominated by *O. sumatrana* and *A. falcata* is gradual. The eruption was probably less severe in this small section and permitted the rapid regeneration of some species of the climax forest. Elsewhere in the Northern Division *Pometia pinnata* and *Tristiropsis subangula* have been noted to regenerate rapidly when forest is cleared but not burnt.

On the lahar deposits the vegetation ranges from 10-40 m. in height, varying with the texture and depth of the deposits. These communities are closely related floristically to communities on mature soils but have only one or two tree layers.

*Lower montane and montane zone.* Only one day was available to investigate the higher sections of the blast area and during this day a track was cut to an elevation of 1400 m. The great majority of species encountered were new to the author as well as to the local natives who accompanied him. As a result, notes are confined mainly to the structure of the communities encountered and these notes may be applicable only to the ridge on the northern slope where the ascent was made.

At approximately 700 m. elevation the vegetation changes sharply from the typical lowland community to a two tree layered sub-montane rainforest 30-35 m. in height. The two most common species have been provisionally identified as a *Dipterocarpacea* and *Syzygium* sp. This forest is the equivalent of the sub-montane rainforest of Beard (1944) but would be included in tropical rainforest by Richards (1952).

At the top of a particularly steep section of the ridge at 900 m. elevation the vegetation changes to montane thicket as described by Beard (1955). This type is intermediate between the mid-mountain forest and mossy forest as described by Lane-Poole (1925) and Richards (1952). The community ranges from 6-13 m. in
height with generally two layers of trees but occasionally only one. The shrub layer is dense and includes dwarf palms and *Pandanus* spp. The trees branch low and their trunks and branches are completely covered by moss. The leaves are predominately simple and most of the older leaves are encrusted with epiphylls. Lianes are abundant. This formation continues, with only slight reduction in height, up to the maximum elevation reached. The soil on this section of the ridge is a deep, dark brown, fine sandy loam or loam, with patches of fine grey sand. At 1400 m. elevation the soil is covered by a layer 10-15 cm. deep of root mass and organic matter.

**Survival of species**

There is no doubt that there are a number of species present in the Mt. Lamington blast area that have survived the eruption. This is illustrated by the presence of food plants which are restricted in occurrence to sites of native gardens. These species include most of the important food plants of the natives, notably, taro, *Colocasia antiquorum*; bananas, *Musa* spp.; sweet potato, *Ipomoea batatas* Lam. and mandioc, *Manihot utilissima* Pohl. Many ornamental species have also survived and are restricted in occurrence to the sites of native villages or European settlements. These species include crotons, *Codiaeum variegatum* Blume; poinsettias, *Euphorbia pulcherrima* Willd.; *Canna indica* L. and *Angelonia goyayensis* Benth.; and a shade tree, *Leucaena glauca* Benth. A further indication of survival can be found on the site of an old parade ground which is now covered by a dense stand of *Saccharum spontaneum* and *Imperata cylindrica* 1½ m. in height but differs from all other such stands in that there is a scattered ground layer 2-20 cm. high consisting of *Chrysopogon aciculatus* Trin., *Paspalum conjugatum* Berg. and *Desmodium triflorum* D.C. These species typically dominate on cut lawns elsewhere in the Northern Division. The restricted occurrence of all these species to sites where they could reasonably be expected to have been growing before the eruption indicates that they have survived the eruption. It is significant that a high proportion of these species can reproduce vegetatively by means of underground organs.

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Area of blast</th>
<th>Secondary species</th>
<th>Climax species</th>
<th>Total</th>
<th>Tree species in richest sample (2 ha.)</th>
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</thead>
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<td>Mt. Lamington</td>
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<td>26</td>
<td>0</td>
<td>26</td>
<td>10</td>
</tr>
<tr>
<td>Waiowa</td>
<td>40 km.²</td>
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<td>8</td>
<td>25</td>
<td>15</td>
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<tr>
<td>Mt. Victory</td>
<td>300 km.²</td>
<td>54</td>
<td>56</td>
<td>110</td>
<td>60</td>
</tr>
</tbody>
</table>

A very large number of herbaceous species are present in all three blast areas but the records available on these species are incomplete.

The figures available for tree species (see Table 1) are more complete. However, it is expected that a more detailed examination would have considerably increased the numbers recorded from Waiowa Volcano where time was short and from the relatively rich Mt. Victory. Nevertheless the total figures would fall far short of the number of tree species present before the eruptions. For the small and relatively uniform blast area of Waiowa Volcano a conservative estimate of tree species originally present would be in excess of 500, with the other two volcanoes much higher. The figures for the number of tree species present in the richest
sample (2 ha.) for each volcano show an increase with age of the blast area and are all far below the numbers found in a comparable stage of garden regrowth. It is apparent then that the great majority of tree species originally present have been destroyed and that fresh species are gradually entering the flora of the blast areas. These species increase in number and proportion on the older blast areas where they are mainly found as rare individuals in sub-dominant layers of the communities. The entry of these species must be very gradual as even after 80 years the tree flora of Mt. Victory is still far poorer than a similar extent of climax forest. This increase in number of species is similar to the steady increase on Krakatau where investigations have been far more extensive (Treub, 1888; Docters van Leeuwen, 1936).

DISCUSSION

The various communities described for each individual volcano show marked correlations with the environment. On the Waiowa Volcano, where the climatic range is small, there is a direct correlation with edaphic conditions. The recent communities on Mt. Lamington also show a major response to edaphic factors with only slight modifications due to climatic factors. Climatic factors, however, exert the greatest influence on vegetation types now present on Mt. Victory. This would indicate that as the succession progressed, the amelioration of edaphic conditions would make climatic variation of greater significance.

The actual course of the various successions cannot be traced but may be inferred by a comparison of communities present in the three volcanoes. On Mt. Victory lahar deposits carry a forest community which is similar in structure to stages in garden regrowth, but similar deposits on Mt. Lamington and Waiowa Volcano now carry an open herbaceous community. These open communities can therefore be expected to be dominated by trees and a closed canopy to be formed within the next 50 years. Similarly the dome of Mt. Lamington, the most unfavourable site for plant growth within the blast area, is now devoid of vegetation, yet the dome of Mt. Victory, apparently of very similar structure, can be seen from air photographs to be covered by a closed woodland community. This is in accord with successions traced on Krakatau where coarse deposits bearing an open fern community in 1886 carried a woodland community in 1932 and the succession is apparently heading towards climax rainforest (Richards, 1952).

Unlike Krakatau, there are many sites within the blast areas which have been pioneered by tree species rapidly forming a closed woodland community. Such communities occur whenever edaphic conditions are not too severe, and the future course of such successions will depend on the height and age to which the pioneer species can grow and the rate of entry of other species into the community. The Octomeles sumatrana community on Mt. Victory is dominated by a large number of light-demanding species which could only have become established in the early stages of the succession. A percentage of these trees is dying, leaving a break in the canopy which is being filled up by species present in the second and third layer, a proportion of which are species characteristic of climax forest. It is expected, however, that the change over to a climax forest will take several centuries to complete.

The woodland communities on Waiowa Volcano will probably parallel the succession on Mt. Victory, as in every community there is a sufficiently high proportion of
individuals of fast-growing species of tall trees to ensure that the community is dominated by pioneer species for the next century. The most important of these species are *Octomeles sumatrana* and *Casuarina papuana* both of which reach a height of over 50 m.

The succession of woodland communities on Mt. Lamington may revert to climax forest much more quickly, as there are only rare individuals present belonging to species which reach a height in excess of 20 m. The succession here may parallel the regrowth on abandoned gardens just outside the blast area, where the succession is continued by taller growing secondary species and species of the climax forest. These species are, however, now absent but the distance to undamaged trees is only a few kilometres and this barrier can hardly operate to exclude their presence for many more years.

The montane thicket found at 900 m. on Mt. Victory is considerably lower in elevation than is usual for such communities in Papua. Lane-Poole (1925) quotes the average lower elevation in Papua for his mid-mountain forest as 1650 m. and of mossy forest as 2250 m. A community, then, of similar structure to montane thicket, could normally be expected to have a lower limit of 2000 m. A parallel case may be noted on the Soufrière, a volcano on St. Vincent, West Indies, where a community resembling elfin woodland occurs far below its normal altitudinal limit. Beard (1945) attributes this fact to the deterioration of moisture relations following the deposition of a layer of volcanic ash. However, patches of ash are now rare at higher elevations on Mt. Victory and the presence of montane communities at low altitudes is probably due to the ‘Massenerhebung’ effect, Mt. Victory being a relatively small coastal mountain isolated by a broad alluvial plain from the main cordillera of Papua, the Owen Stanley range. This is borne out by observations during the stay in the area when cloud cover was observed much more frequently at low altitudes on Mt. Victory than on the foothills of the Owen Stanley range.

No vegetation corresponding to Beard’s montane rainforest was observed on Mt. Victory but the absence of this formation is quite probably confined to the one ridge ascended. Here the zone immediately below montane thicket is extremely steep and carries a low sub-climax vegetation.

**Summary**

The type of eruption and edaphic conditions present are described for three volcanoes in Papua. The vegetation types ranging from tall tropical rainforest to an open herbaceous community are described and correlations drawn with environmental conditions. It is pointed out that some species have survived the eruption of at least one volcano but that in all cases the majority of species originally present have been destroyed. These species are gradually returning to the blast areas, but even after 80 years the number of species present is well below the figure expected from a similar area of climax forest. Comparisons are drawn between the vegetation types on the three volcanoes and some conclusions reached on the probable future course of succession.

**References**


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