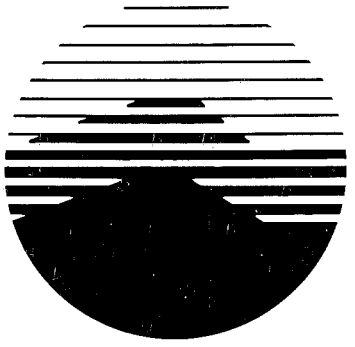

CENTRE FOR AUSTRALIAN REGOLITH STUDIES

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by

Bryan P. Ruxton

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Occasional Publication No. 4
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PREFACE

Bryan Ruxton has had a long interest in the regolith. His geological and teaching career has spanned more than forty years. In 1952 he joined the Geological Survey of Sudan where he worked on regional mapping and damsite investigations. From 1954-56 he was Lecturer in Geology at the University of Hong Kong. He returned to the Sudan until 1958, and then taught for two years at the University of Ghana. From 1963-71 he worked in Papua New Guinea with the CSIRO Division of Land Research. From these early days Bryan continued his work and research on regolith in Hong Kong and Papua New Guinea, including numerous consultancies on slope stability and regolith cementation problems in the territory of Hong Kong.

Bryan is currently retired but is still actively involved in research into the regolith and other earth phenomena.

This publication presents a distillation of observations made by the author on regolith in areas of humid rainforest in Papua New Guinea and Hong Kong. In particular it describes some of the organic materials which are an important component of regolith in these settings. It also examines the role of fire in modifying these materials, an aspect rarely considered by most regolith researchers.

K.G. McQueen
Co-Director, CARS
December, 1996.

The author (right and in the lead) immersed in very moist regolith. Kerema Vailala area, Papua New Guinea, 1966. Reproduced by permission of CSIRO Australia (CSIRO, 1970).

The Influence of Organic Matter and Fire on Accreting Regolith in Tropical Rainforest

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Abstract

Plant and insect debris are incorporated into the soil and then they age, decompose and alter to humus. Under tropical rainforest, cuticle wax and resin enter too. The contribution of such organic-derived material to regolith is not widely recognised or well understood. This article presents some observations and interpretations of materials and processes in well dated accreting regolith profiles from Papua New Guinea and Hong Kong.

At the three sites studied in detail past fires occurred, and charcoal, tar, ozocerite and sometimes corundum in paleosol marked their passing. Fire fronts can reach over 1000°C but only for a few hours then log groups and stumps may burn and smoulder for several days. Soil is a good insulator and only reaches subordinate temperatures unless under burning logs. Thus fires are spotty in their affects.

Plants and organic materials are originally very diverse but with time only lignin, humin, fat, wax, resin and seeds survive. Heat waves produce ground ozone which decomposes humus to organic acids. With heating, fat and wax will melt sticking to and coating mineral grains, but resin only scorches and hardens to amber. Wax is an ester variably present in phytoliths in the leaves of palm trees and it may maturate to n-alkanes (ozocerite). Resin, a polymerised space network of CHO(N), is very durable. Lignin decomposes to sugars and amino acids which polymerise to humus. Humified lignin is very resistant and, like charred wood, may persist for tens of thousands of years.

In landslide deposits, plant debris may be present in the colluvium but evidence of fire marks the gaps between major units. In tephra, fire is most likely at times of slower deposition and optimal biomass build up.

Organic matter and fire are relevant to landscape evolution and the development of regolith. They also have important implications for geochemical processes such as organo-complexing and sudden decomplexing of metals.

Introduction

The nature and formation of organic matter in the regolith is not well understood particularly with fire in rainforest. In tropical swamps in Papua New Guinea and the Everglades in Florida fire is an essential part of the ecology. With severe enough droughts rainforest will burn (Crutzen and Goldammer, 1993) as in the great fire of Borneo. Fire in other environments is discussed in Gill *et al.* (1981) and Kozlowski and Ahlgren (1994). Slash and burn and garden fires are very small compared with full scale forest fires. The former have been extensively studied with variable results due to high water contents of the biomass and soil. Moreover most take place on land marginal to the main body of rainforest. This paper considers fires mostly in undisturbed primary rainforest.

Three accreting regolith profiles (Figs 1 and 2; Table 1) under rainforest with organic matter (Plate Ia) are described at a macroscopic and microscopic level, though detailed organic chemistry is not attempted. The sites have well dated profiles and show clear evidence of fire events, making them ideal case studies for investigating the effects in regolith of organic addition and fire in humid rainforest settings. The results are of interest to the studies of regolith, petroleum geology, and humus. Field and laboratory work has spanned the period from 1963 to 1995 as information has accumulated on oil geology and wildfires.

Table 1. Major aspects of the three sites examined in this study.

Region	NORTHEAST	PAPUA	HONG KONG
Site No.	1	2	3
Location	Guava	Bua	Mid-Levels
Rainfall mm	2500	1600	2100
Altitude m	1350	750	150
T°C	16.5	19	23
Rainforest Type	Mossy Lower Montane	Lowland Deciduous	Seasonal Sea Level
Organic Carbon %	5	0.7	0.13
Phytoliths	Opal	Grey wax	Whewellite
Special Features	Amber	Oleo-resin	Corundum

Methods

Geological maps and descriptions are available for all three areas partly based on early work by the author (Ruxton, 1966a and b; 1994; Anon., 1982). Twenty C^{14} dates are available in north-east Papua (Ruxton, 1988). Over fifty samples were fully chemically analysed and eighteen soil thin sections made.

Samples were bench dried, dry sieved and the fine sand fraction (0.212-0.076 mm) retained. Heavy liquid separation in bromoform using an ultrasonic probe was then carried out. Acetone and bromoform mixtures separated quartz from iron oxide cemented grains. In Hong Kong some samples were oven dried at 100°C and ground in a mortar and pestle then wet sieved using sodium polyphosphate as a dispersant. Shear strength tests went in parallel with saturation, void ratio and bulk density measurements.

Material was examined using an optical microscope, and some was also studied under the scanning electron microscope. For the organic fraction only general categories could be recognised. The guidelines of Staplin (1982) were used.

Guava, Site 1

Sites 1 and 2 (Fig. 1) lie to the south of Popondetta and south and southeast of Mount Lamington. Mount Lamington volcano has been a big andesite ash producer for 90,000 years with a tendency for ash flow in the last 14,000 years. Many chemical analyses of the ash are available (see Ruxton, 1988) and representative analyses of two fresh andesitic ashes are shown in Appendix 2 (Table 9).

Palynological evidence suggests a constant climate for the last 10,000 years (Flenley, 1979) with the last glacial maximum at 18,000 BP when temperatures in the mountains were 10° C

cooler. At sea level the drop was only 5 to 6° C cooler allowing tropical rainforest to continue. Rainforest fires occurred periodically throughout this period from natural causes, volcanic eruptions, and probably from human activity. Evidence from the Papua Highlands, including fire charcoal, axe-adzes and waisted blades, indicates human occupation for at least the last 27,000 years (White *et al.*, 1970).

Site 1 on the Guava Range (Fig. 2) is located on a small crest at 1350 m altitude in a col cut in basic-ultrabasic rock veneered with 15 m of Mount Lamington andesitic ash. The upper ash was laid down at an average rate of 9 cm ka^{-1} with halts at three intervals accompanied by topsoil formation (Ruxton, 1988). Probably for the last 10,000 years a primary mossy lower montane forest has prevailed. Today, trees are up to 25 m tall with a dense shrub layer; climbers and surface roots are common. Leaf litter and duff form a layer 8 cm thick. Decay of organic matter is in two stages; fast then slow (Ruxton, 1990).

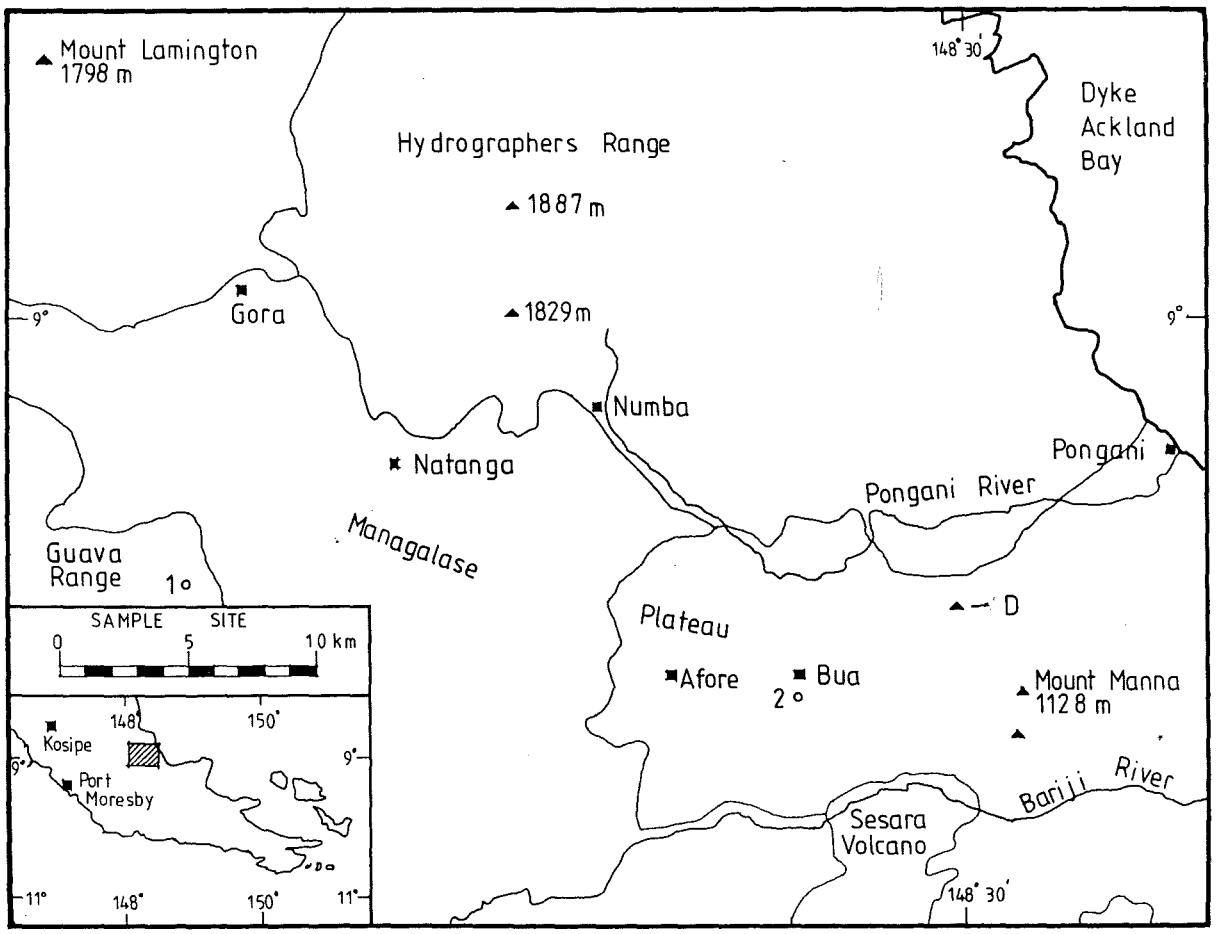

Fig. 1. Map of the Mount Lamington area showing the locations of Site 1 (Guava) and Site 2 (Bua). Small triangles indicate some important volcanic peaks.

The ash (Plate Ib) is composed of glass, plagioclase and hornblende of medium sand size. The two upper eruptive sequences are separated by paleosols of very dark brown ash the top one with 7% organic matter. The main features of profiles observed in pits in this vicinity are given in Table 2. Near the surface, mites mix soil and leaf debris to 8 cm depth. Below this, brown humus jackets on pumice and phenocrysts dominate to 30 cm, corresponding to 5,000 years BP. Beyond 30 cm the humus forms a hard skin and sometimes minerals fall out leaving a humus sheath. Throughout, plant debris includes cellular material, broken leaves, twigs, wood,

spores, seeds and a tiny Hoop Pine bud. Cuticle wax is common ranging in form from spongy grey to shiny brown. It melts, coats, and surrounds minerals and again may be left as sheaths. It can be difficult to distinguish between waxy humin and cuticle wax.

Palm tree wax, grey banded and with a "crystal" shape, is an ester and also occurs at Bua (Site 2). Levels of tar and charcoal indicate heating, probably by forest fires which caused distillation and charring. Some wax pieces are shot through with soot indicating impregnation on the ash bed (Humphreys and Lambert, 1965). Tree exudates are resin and amber (with insects) and opal phytoliths also occur. Some charred wood, not heated above 350°C, comes from the forested crater of Mount Lamington and was used to date the ash. Organic matter comprises 31% of the topsoil, 7% of the top paleosol, 3% elsewhere and 1% at the base. Charcoal and tar are found at several levels, particularly those corresponding to 5,000, 7,000 and 12,500 years ago (Fig. 2). These times coincide with suggested world warming periods (Boulton, 1992).

In the Guava area colour of the ash is an indication of both degree of weathering and content of organic carbon and varies on the Munsell Soil Colour chart from light olive brown, 2.5y 5/6, through dark yellowish brown, 10yr 3/4, to very dark brown, 10yr 2/2. Both parameters are dependent on the rate of deposition of the ash.

Table 2. The principal features down profile in the top metre of volcanic ash at Site 1 (Guava).

ORGANIC MATTER	MINERALS	CHEMISTRY HALF LIFE (element loss)
Leaf litter, root mat	Pumice (1951 eruption)	2% nitrogen
	SOIL SURFACE	
Mite fecal pellets, opal	Pumice jackets	15 years sulphur
Leaves, twigs, buds	Pumice jackets	0.7% nitrogen
Humus jackets	Thin walled pumice	500 years, phosphorus
Humus kerogen	Remnant jackets	1,500 years potassium
Hardening, maturation	Etched augite (etching < 1μm)	6,000 years calcium, magnesium
Humified lignin, resin, wax	Etched plagioclase	Irregular sodium
Tar, charcoal	Etched hornblende	Silica precipitates
	PALEOSOL	

Bua, Site 2

At Bua a kaolinitic, muddy, stony soil (derived from explosion pits) and basalt ash (from basalt cones) cover a pumice layer not visible at the surface. The recent tephra extends over 50 km^2 and is up to 20 m thick. Bedrock geology was described by Ruxton (1966a). Pits and auger holes were put down through the tephra and the one described here has a complete section (Fig. 2). The present lowland rainforest is well developed, containing trees with long straight clear boles (178-230 cm in girth) and emergents to 45-50 m. There is a moderate shrub layer, climbers are common, and there are abundant low buttresses.

The top 120 cm of the profile is nearly the same as an adjacent soil described by Bleeker and Healy (1980, p. 575) as an argudall with pH 6.5 to 7.0 and 2.4% organic carbon. The soil has humus, wax, resin and charcoal and in this case the charcoal may be anthropogenic (it is near the village) and is dated as 600 years B.P.

The underlying dacite pumice contains lapilli up to 5 cm in diameter and extends from 1.2 to 4.2 m depth. The whole unit has a median diameter of 2 mm and poor sorting ($\sigma\phi$ = 1.70; Fig. 5; Table 7). Whole rock analyses of this material are shown in Appendix 2 (Table 9). The fine sand fraction of this material comprises 1% and is composed of plagioclase (containing some microscopic inclusions of silver), amphiboles and minor quartz. In the field seven indistinct layers were sampled which in the laboratory showed alternations of highly pumiceous and less pumiceous glass and brown, green, and tremolitic amphiboles. The top of the pumice is dated at 6,500±500 years. All pumice layers have some organic matter including humus jackets, twigs, oleo-resin, seeds, chitin, toffee coloured wax, oxalic acid, resin, and even a diatom. Phytoliths, whewellite, opal and gypsum also occur. Toffee-like wax and resin are abundant at the top and bottom of the pumice pile.

Beneath the pumice is a basal layer of coarse rhyodacite ash with only 1-5 % of heavy minerals. This unit is about 9,000 years old and partially weathered and rusty in appearance. Its total thickness is unknown as it was severely eroded after deposition. The minimum thickness is 7 m. It contains toffee wax, lignin, humus jackets, amber, resin and tar.

The source of the dacite and rhyodacite tephra is unknown but the pumice probably came from the summit of an adjacent trachyandesite flow dome at 990 m which later exploded boulders and mud from the pit to form part of the top tephra layer. The basal rhyodacite ash came from the east, probably from Mount Manna and a volcano marked D in Figure 1.

The pumice fragments are well rounded, like the "hurricane" pumice found near Lake Taupo, New Zealand, in contrast to the air fall pumice at Cape Hoskins in New Britain, which has similar sized but highly angular fragments. Nuée deposits usually have an Inman's sorting coefficient of over 2. Bua pumice with a coefficient of 1.70 is close to that of ash at the Mount Lamington crater rim (1.60). The pumice could be either an ash flow or an ash fall (Table 7). "Hurricane" type material with rounded fragments would undergo better sorting in great winds and turbulence than normal ash flow deposits. The facts are best explained by seven separate episodes of ash flow phenomena and temperatures of about 200°C, just melting oxalic acid crystals (160-180°C see below). The ash flows at Mount Lamington were also at 200°C (Taylor, 1958). A "glowing" cloud eruption would tear the leaves and branches from the trees releasing sap, resin and wax. Heating would harden the resin and melt the wax forming toffee wax which would drain 1-2 cm down into the soil. Local hot spots would cause longer smouldering producing the soot which is incorporated in the soft melted wax. A possible problem with this ash flow model is that the entire pumice layer is near uniform in size, but then so is the whole pile of Mount Lamington ash.

The top and bottom layers of the pumice unit contain tar, signifying forest fires. The two hiatuses at the top and bottom of the pumice pile are also marked by abundant toffee wax because of the time lag between rhyodacite ash at 9,000±1,000 years, Bua Pumice at 6,500±500 years and basalt mud at 600 years. Layering of the whole tephra is shown by variations in the heavy mineral content. Basalt ash has 15% heavy minerals, mud 27%, pumice 8-15%, and rhyodacite 1-5%. Very weathered rocks have a high content of opaques in the whole fraction and in the heavy fraction and the content of 27% in the mud would come from thoroughly weathered trachyandesite.

Silver mineralisation is recorded in the Bua region and the silver observed in the feldspar grains may have a common origin. For example, a shear zone in the older volcanics on the Gerewu River 2 km northeast of Bua contains mineralisation with 1,250 ppm Cu, 700 ppm Pb 870 ppm Zn and 48 ppm Ag.

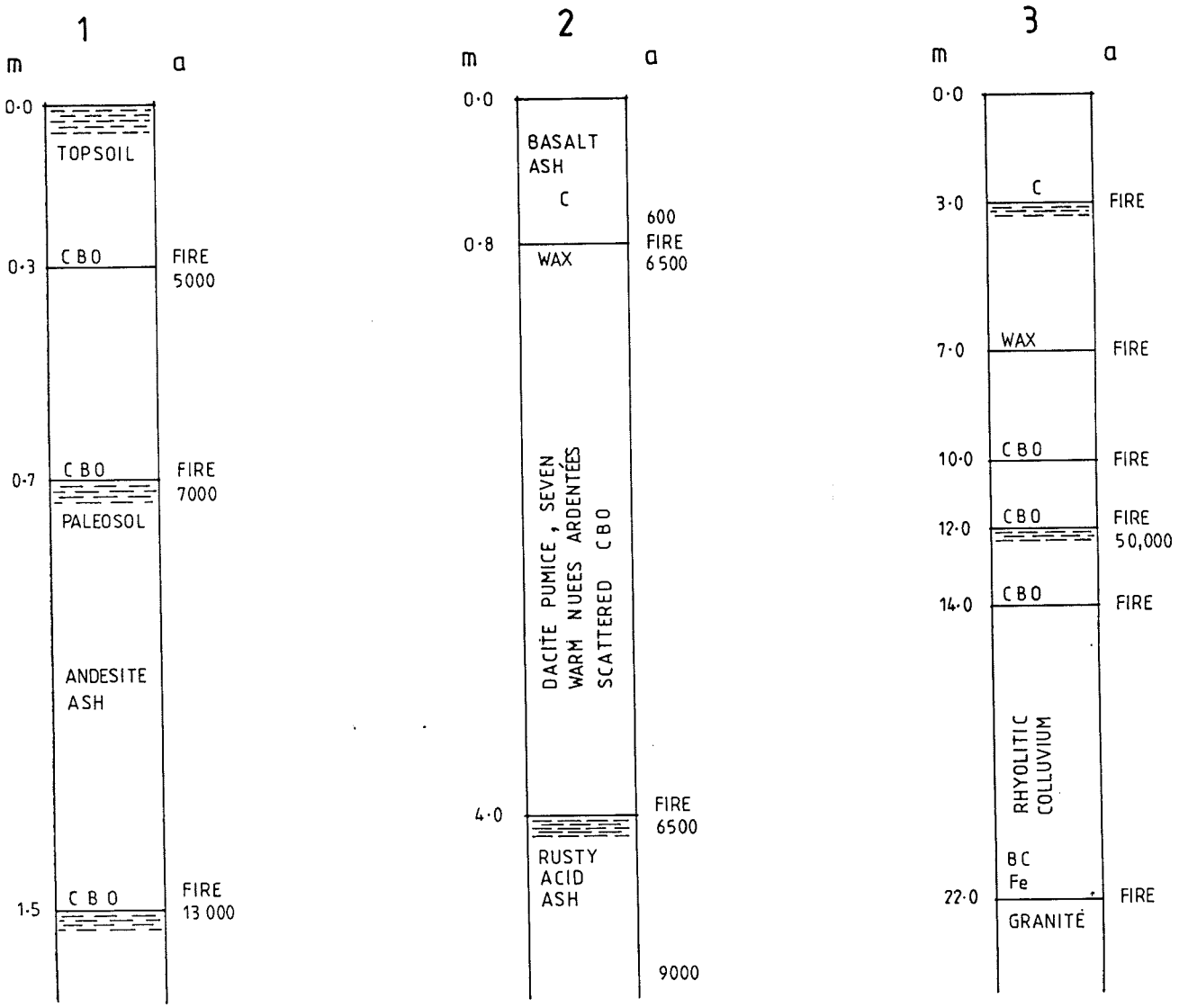

Fig. 2. Profiles of the three sites studied in detail, Guava (1), Bua (2) and Hong Kong (3). C=charcoal, B=bitumen (tar), O=melted wax (commonly sooty), and Fe=ferruginisation.

Hong Kong Island, Site 3

Site 3 is on the flanks of Victoria Peak on the western end of Hong Kong Island (Fig. 3). Here rhyodacite and dacite volcanic tuffs are thermally metamorphosed by an intrusive granite. New metamorphic minerals include almandine, andalusite, cordierite, and sillimanite. Repeated landslides since the Late Pleistocene have caused thick deposits of colluvium on the slopes (Ruxton, 1994). Climates were probably similar to present for the last 10,000 years, however continentality may have caused cooler climates during the last glacial maximum as suggested by the Mid-Levels report (Anon., 1982).

Little is known about the tropical rainforest in South China as it was cut down 800 years ago leaving log slide scars on the shoulders of the hills around Hong Kong. Since the Second World War thick forest has grown up in sheltered spots.

The site examined is a borehole (ML 112) on a ramp seepage slope (15-25°) beneath a debris slope (38°) and cliffs (Figs 2 and 4). The borehole intersected several landslide (colluvial) units and then penetrated *in situ* weathered granite at 22.5 m. The colluvium contains 40-60 % boulders, now very weathered, and much pre-weathered clay.

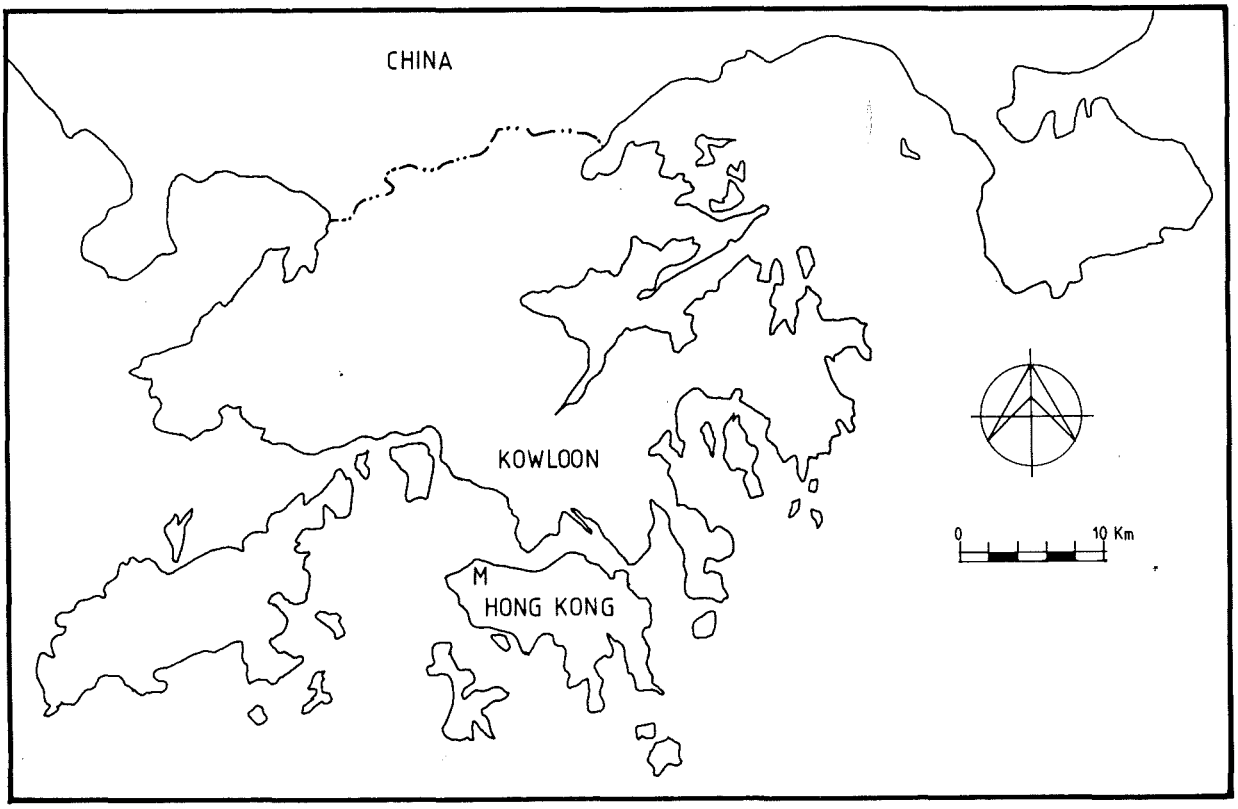

Fig. 3. Location map of Hong Kong showing Mid-Levels Site 3 (M).

Former landslides in Hong Kong were of debris flow type and in the form of spreads or lobes, generally 2-5 m thick, with boulders up to 4 m in diameter (Plate IIa). Movement was probably triggered by fire, torrential rain or seismic shocks or all three (Ruxton, 1985). Internal layering indicates that laminar flow was common and laminae also formed at boundaries due to frictional shear as masses skidded to a halt.

It is difficult to pick colluvium boundaries but water ponds up at them after heavy rain. A more refined approach is to use the particle size distribution of the well graded matrix and diagnostic heavy minerals to distinguish units. The source of material is partly to wholly recrystallised rhyolite tuff which has been metamorphosed by intrusive granite and so mineralogy includes garnet, andalusite, cordierite and even sillimanite (Ruxton, 1994).

Records were not obtained between 0 and 6 m in the borehole so a nearby pit to 4 m is described first (Table 3). Charcoal and bitumen prove fire and a hiatus at 3.5 m. Thus rainforest grew up between the two colluvial units. Being at sea level with a mean annual temperature of 23°C organic matter rapidly decomposed and profiles can attain 0.93% organic carbon. Very little plant material has been seen in the colluvium but only a tiny fraction of the colluvium is ever exposed.

Table 3. Test pit profile at Mid-Levels, Hong Kong.

0.5 to 1.5 m	Worm worked colluvium, fungal spores, roots, channels, argillans, neoferrans, reddish ferruginous mottling, diffuse ferruginous nodules.
1.5 to 3.5 m	Undisturbed landslip material with abundant entrapped air. Isotropic.
	HIATUS
3.5 to 4 m	Paleosol, worm activity, cellular plant material, much iron and clay movement. Whewellite (CaC_2O_4), charcoal, bitumen in cracks of enclosed rock fragment. Waterlogged at times.

Other hiatuses with fire are found at 6.5, 9.5, 12, 14.5 and 22.5 m. The clearest example is at 12.1-12.2 m where hydrated glass is dated at 50,000 years (Ruxton, 1994). The detailed stratigraphy of this break is given in Table 4. The interval between debris flows was probably several hundred years and gave time for erosion of laminated ferruginous cemented grains to be transported to the coast and for material to be blown in from the beach.

Table 4. Detail of the main hiatus around 12 m depth in ML-112 borehole Mid-Levels, Hong Kong.

Colluvium 40% Decomposed Boulders

12.1 m HIATUS

Iron oxide cemented grains, rounded quartz, rounded pumice, ferruginous pisolites, tiny flowers, stomata, ferruginised plant debris, argillans, whewellite, pyrite, charcoal, bitumen, fungi filament covered euhedral quartz grain (Plate IIb), very rare rhyolite glass.

12.2 m HIATUS

Extremely finely laminated clay slope-wash of halloysite kaolin cemented by sesquioxides.

12.3 m HIATUS, WATER PONDS UP AFTER RAIN

Colluvium 60% Decomposed Boulders

The soil on the sedentary weathered granite at 22.5 m has charcoal, tar, corundum and manganese phases but no wax. Aluminium, iron, silica and manganese are stored in some plants and may accumulate in the soil (Lovering, 1959).

In summary fire and fire heating were episodic in Hong Kong rainforest with at least six burns in 90,000 years producing wax, waxy humin, humified lignin, charcoal and tar.

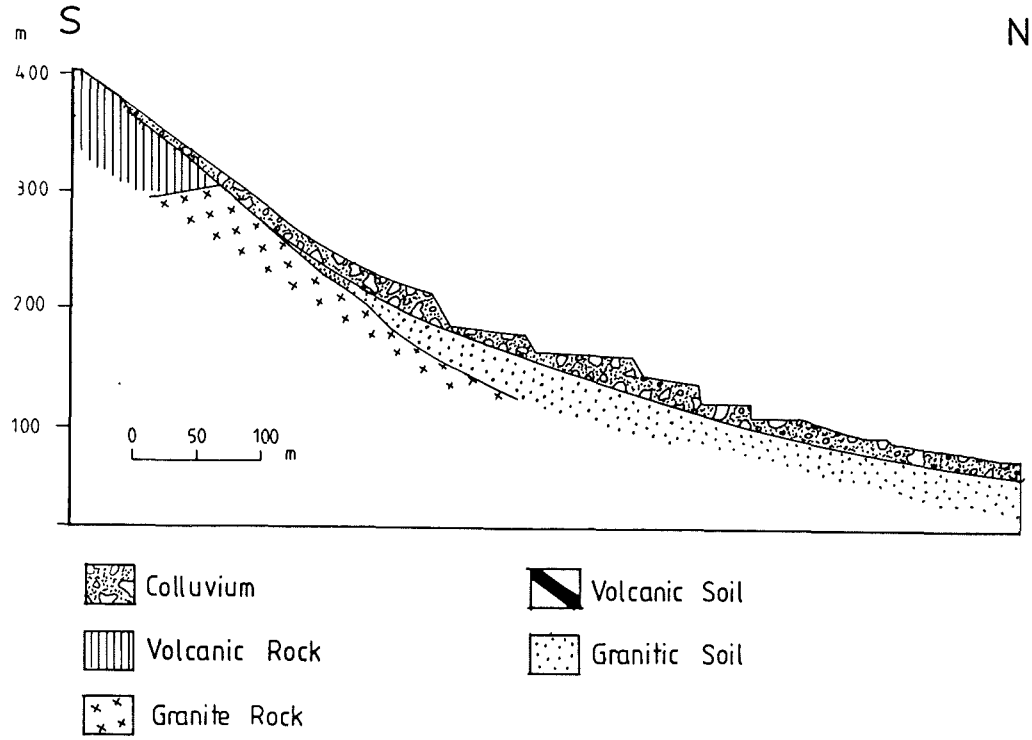

Fig. 4. Slope profile at the Mid-Levels Hong Kong adjacent to Site 3. Roads are cut into the colluvium and the lowest road cutting is close to Borehole ML 112 (profiled).

Organic Matter

In maturation without fire fresh plant debris is entombed and broken up and then, depending on rate of burial, it is partly destroyed by micro-organisms, oxidation and leaching. The macerated debris is blackened around the edges and broken down to sugars and amino acids and polymerised up to humus. The humus at first skin-hardens causing difficulty in distinguishing it from humified lignin and even brown bitumen. Maturation with fire involves melting, and chemical changes as shown in Table 5 with some knowledge of the chemistry indicated in Table 6.

Heat maturation from rainforest fires can produce plant-derived debris with brilliant red colours, which in terms of burial maturation interpretation are equivalent to a hundred degrees centigrade and several hundred metres depth. There are two pathways: (1) cold incorporation in soil which produces humus kerogen (organic source) commonly aromatic, followed by burial in an oil window, (2) local maturation in forest fires. In both cases pyrolysis, sometimes occurring as low as 300°C but more usually above 500°C, causes cracking and distillation leading to tar and ozocerite. In soils soot and charcoal may be end products.

An important discovery of this study has been the recognition of the presence of much wax under tropical rainforests. Wax phytoliths are common in the leaves of some palm trees, which are fire resistant, and many cuticles of other trees are coated with wax. At Guava (Site 1) fresh wax is grey and spongy and on heating by fire melts and turns brown. An active basalt cone south of Bua (Site 2) has ash and scoria on its flanks and wax in the soil (1.5m depth) is scorched black with remelted holes, suggesting that it was subjected to high temperatures. Resin originates as oleo-resin; the sap and exudates from trees. There may even be particles of natural rubber in the regolith at Bua (Site 2). This rubber-like material is tacky and brownish and binds sand grains together.

Plant residues in order of decreasing rate of decomposition are sugars, starches, simple proteins, complex proteins, hemicellulose, cellulose, fats, waxes, lignins and resins (Brady, 1990). Up to 2% nitrogen accumulates in the leaf litter partly due to microbial decomposition of wood where lignin absorbs NH_4^+ ions released from plant proteins. The process continues in the topsoil where up to 0.6% nitrogen may be present (King *et al.*, 1983).

Smouldering of leaf litter occurs at temperatures from 500°C to 650°C (Crutzen and Goldammer, 1993) whereas forest fires may burn at over 1000°C (Ollier and Ash, 1983). In an ash soil, 60 to 90 minutes are required to heat the 25 cm depth level to 250°C (Campbell *et al.*, 1995). Maghemite, widely believed to form by the heating of goethite and hematite in fires (e.g. Fitzpatrick, 1988), was not detected in the profiles studied but is not expected to survive in wet humid conditions. A sort of steaming like cooking is present in damp soils during fire on the surface mainly affecting the wax. Lower water content allows the temperature to rise and a baking process causes maturation. At even higher temperatures scorching and sintering occurs which may delay weathering of silicate minerals.

For each vegetation type there is a definite time period for the accumulation of the optimal biomass which favours burning. Fire reduces the organic carbon content of the biomass four or five times, a factor not always taken into account in carbon cycling of forests. Soil carbon cycling is rapid at 0-2 cm depth (Bird *et al.*, 1996) and decreases exponentially downwards.

Table 5. Melting points (MP) of some organic materials and some likely natural temperatures.

MATERIAL	TEMPERATURE	REMARKS
Tar (from lignin) MP	40°C	Very fluid at 200°C drips down profile.
Paraffin wax MP	50 - 60°C	Residue of light oil, similar to candle wax.
Canada balsam MP	70 - 80°C	Mounting medium.
Palm tree wax MP	82 - 86°C	Some edges frayed.
Oxalic acid MP	160 - 180°C	Dripping and droplets.
Fats to esters	175 - 190°C	Oil skin hardening.
Nuée 1951	200°C	Mount Lamington.
Charred wood	Less than 350°C	Mount Lamington crater.
Corundum (and graphite).	400 - 500°C	Down to 330°C in presence of iron oxides.
Humus degradation	240 - 500°C	240°C functional groups, 500°C nuclei.
Phosphorus vaporisation	550°C	Inorganic.
Pyrolysis	Above 500°C	Down to 300°C at higher pressure ?
Smouldering	500 - 650°C	No wind.
Forest fire	Above 1000°C	Up to 1700°C.
Dry soil 25 cm depth	250°C	60 to 90 minute fire at surface in volcanic ash.

In the geological record fire is indicated by charcoal and silt sized corundum. Harriss (1981) interpreted charcoal fern impressions in the Wealden of England as an indication of fire. The results of his experiments on burning of ferns show that most species glow away whereas others give charcoal.

Identification of organic components is a problem. Amber with trapped insects can be used to prove resin; insect carapace proves chitin; phytolith wax is proved by geometry and banding; cuticle, bee and wasp waxes by enclosed soot; tar by pouring threads; charcoal by a cuboidal microform; lignin by woody structure; and humus by cloudy encasing form. Allophane gel is typically in the clay fraction which only contains 0.07% organic carbon.

Table 6. Some organic residues found in soil and regolith.

MATERIAL	STATE	CHEMISTRY
Ozone	Gas	Ground surface above 40°C, fire, breaks up humus to simple organic acids.
Humus	Liquid-solid	Typical humus kerogen in Staplin (1982).
Oleo-Resin	Liquid emulsion	Thick vegetable oil.
Fat	Low melting point	Glyceride, fatty acid.
Rubber	Tacky	Butadiene.
Chitin	Solid	Glucosamine.
Phytolith wax	Solid	Ester, long chains acid and alcohol.
Cuticle wax	Solid	Long chain, prevents evaporation.
Ozocerite	Solid	Paraffin series up to C29.
Resin	Solid	Polymers, terpenoids, hardens to amber with age or heat.
Lignin	Solid	Hemicellulose, cellulose, polyphenol.
Bitumen	Tacky	Tar, aliphatic aromatic hydrocarbon, sterane, terpane.
Charcoal	Solid	Mostly carbon, low volatiles.
"Amorphous" graphite	Solid	Finely crystalline, pure carbon.

Discussion

The chemistry of organic matter in sediments is well known and that in soils is the subject of humus studies. Fire introduces a new element from rainforests where burning may occur every few centuries or millennia. At Bua it may be regrowth that is torn and heated every 10 to 30 years explaining the high content of wax and resin.

All three profiles examined in this study have developed accumulating soils and have been buried by later deposits. There is little disturbance except for the odd burrowing animal but irregularities can be detected. Such thick deposited regolith in the vadose zone, or with ephemeral perched water tables, is unusual under tropical rainforest and clear boundaries between units are defined by periods of burning.

Resin is a substage organic end product being mined in southeast Asia in the soils beneath *Araucariaceae*_where it originates in the sap of the bark, twigs and leaves. In tephra it may persist many metres below the surface (Eglinton and Murphy, 1969). The main end point of carbon in soil and sediment is tar and charcoal, though the ultimate product is graphite.

Upper regolith steaming, baking and sintering releases some elements from combination and may in places concentrate them. Accumulator plants may aid this process. Organic metal complexes are decomplexed by fire in a sudden way and the residual ash bed causes forest blooms (Humphreys and Lambert, 1965). The fulvic acid structure is now roughly known and two carboxylate sites may accommodate metals (Shin and Moon, 1996). When present in the bedrock and weathering profile gold may accumulate in some plants, and through the litter in humus and resulting ash (cf. Rankama and Sahama, 1950; Butt, 1989). At Bua, silver and chromium (up to 1.5% Cr) occur in or associated with the pumice and in Hong Kong minor gold flakes have been found in two small pits into colluvium derived from rhyolitic tuff.

Studies of organic matter and fire processes in accreting regolith are not only important for understanding geochemical cycling but also have implications for interpreting landscape evolution (Cleveland, 1972) and general regolith development. The nearest other equivalents to the sites described in this study are fanglomerates, loess, and alluvium where accreting sediment may develop paleosols and mollisols with high organic matter. Lateral sequences of colour in alluvium (Bown and Kraus, 1987) are equivalent to vertical changes of colour in the ash at Guava (Site 1).

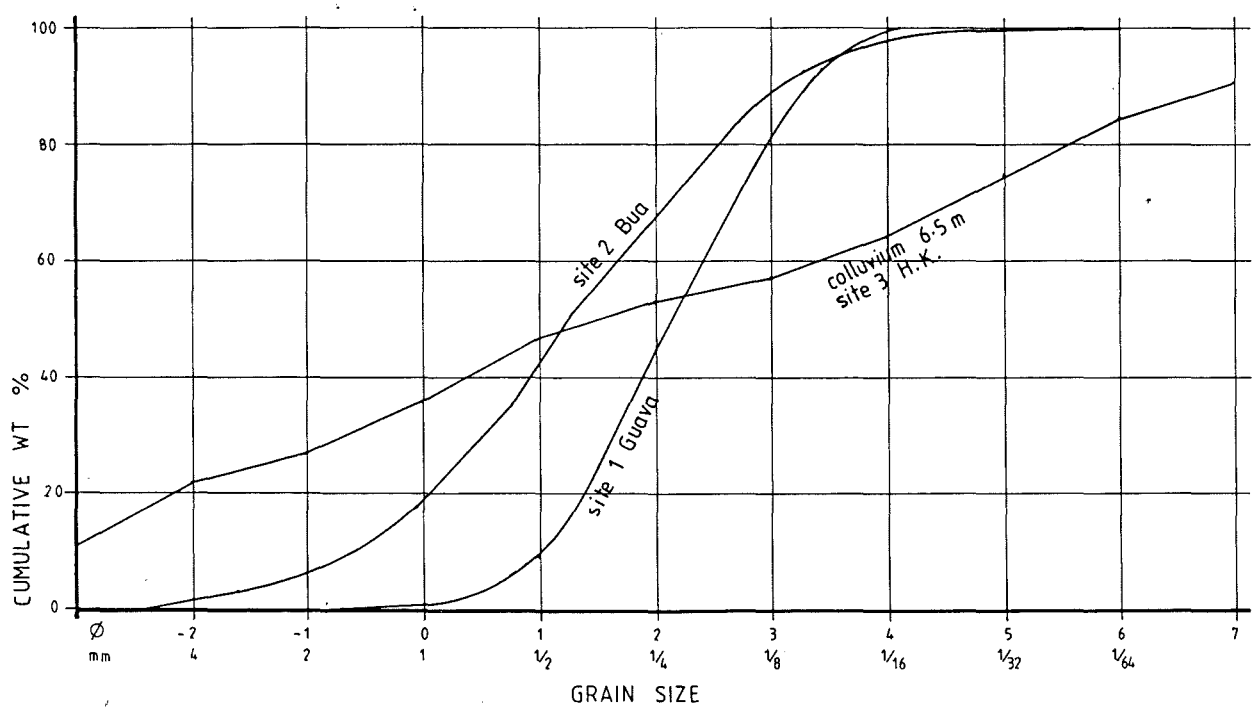

Fig 5. Particle size distribution at the three sites, plotted as cumulative wt% against phi units. The coarsest pumice fragments at site 2 (Bua) are 3 phi units coarser than the maximum shown.

Table 7. Inmans coefficients of tephra from Papua New Guinea, (A) Mount Lamington ash, (B) Bua pumice, (C) Hong Kong colluvium.

DISTANCE FROM CRATER	MEDIAN DIAMETER mm	SORTING $\sigma\phi$	REMARKS
A 150 km	0.15	0.46	Extreme value
A 20 km	0.25	1.0 - 1.2	Well sorted, Guava
A 0 km	0.22	1.60	Crater rim
B 2 km	1.76	1.70	Nueés
C 1 km	0.4	4.3 - 5.8	Trask sorting, similar to boulder clay

Fractal analysis has been applied to studies of soil structure to help understand processes (e.g. Feder, 1989). Fractal values of some relevant soil/regolith components from the literature and the authors own measurements are listed in Table 8. Relative fractal dimensions can be used to predict the distribution of added organic-derived materials. For example, ash and pumice show high fractal values reflecting porosity and indicating a high ability to absorb carbon compounds.

Table 8. Some fractal dimensions of soil/regolithic materials.

OBJECT	PROPERTY	D	ATTRIBUTE
Quartz etching	Pattern	1.6	Dendritic, allometric
Coconut charcoal[1]	Microscopic porosity	2.67	Cusp-like
Kaolinitic soil[1]	Microscopic porosity	2.92	Soil fabric
Ash and Pumice[2]	Fragmentation	3.54	Coarse, spiky
Pumice	Surface area*	2-5 m^2g^{-1}	Vesicular, spiky

D = (fractal dimension), * measured by chemically reactive surface.
1 Feder, 1989.
2 Korvin, 1992.

Measures other than fractal dimensions can also be used to predict behaviour and properties, for example surface roughness by ruggedness, deviation from plane, surface area, and other parameterisations.

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Plate Ia. Typical lowland rainforest with many dead trees (standing organic matter), Putei area, Papua New Guinea.

Plate Ib. Outcrop near Guava (Site 1) showing coarse pumiceous ash (top) overlying finer grained ash. Matchbox is 5.3 cm long. Lineations are spade marks. Reproduced with permission from the Journal of the Geological Society of Australia 13(1), pp. 41-52.

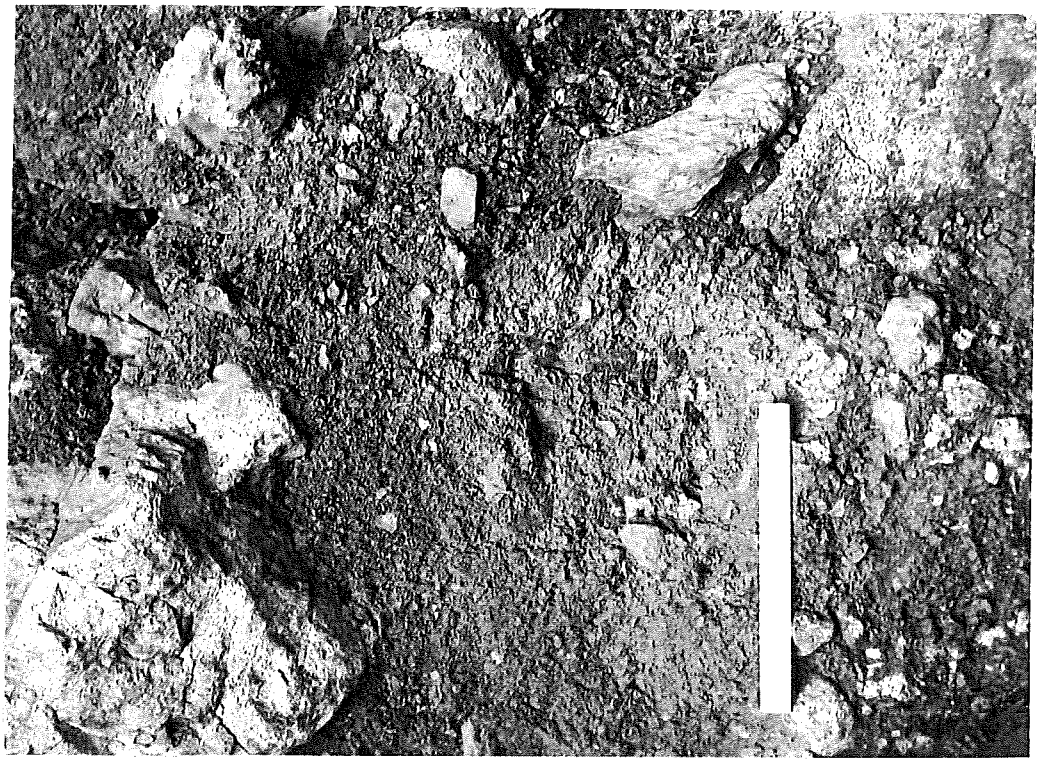

Plate IIa. Boulder colluvium at Mid-Levels, Hong Kong. A swirl structure related to material flow (screw) can be seen adjacent to the rule. Rule is 30.5 cm long.

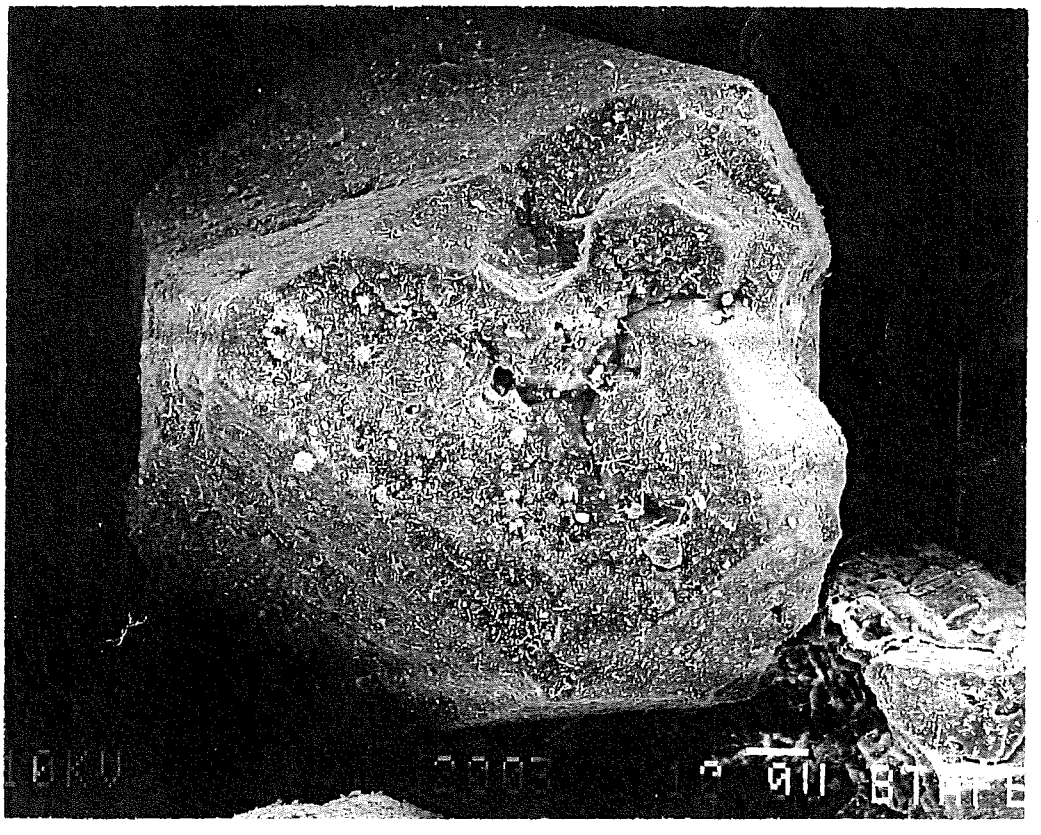

Plate IIb. Scanning electron photomicrograph of a euhedral quartz grain sheathed in fungal filaments. A fracture face also shows etching (see Appendix 1). Scale bar (lower left) is 10 μm. Sample from Mid-Levels, Hong Kong.

APPENDICES

APPENDIX 1

Etching of quartz grains

Observations of quartz grains from the various profiles suggest the following sequence of quartz grain etching:

1. Original euhedral quartz grain (Plate IIb).
2. Coating with fine fungal filaments.
3. Partial fracturing of quartz grain.
4. Fungal filaments distort plastically.
5. Organic acids attack fractured face.
6. Dendritic etch pattern fractal D = 1.6
7. 830 μg SiO_2 dissolved (13.8 μmole) from a cross sectional area of 200 μm^2 of face.

The time frame is uncertain. There is a maximum of 50,000 years but debris flows are spaced at about 240 years at Mid-Levels (Ruxton, 1994) and seepage is the unknown factor. At 40°C the solubility of powdered quartz in distilled water is $10^{-16.55}$ moles cm^{-2} sec^{-1} and increases with humic acids. If the fungi is responsible silica ester could have been formed in solution (Bennett and Siegel, 1989). This raises the question of some wax in this study being made very durable by partial combination with silica which is released in copious amounts from volcanic glass on weathering. In fact the fungal filaments may be silicified.

APPENDIX 2

The major element chemistry of the bedrock (ashes and tuffs) at the three studied sites is given in Table 9. Normative corundum is a good measure of degree of weathering and correlates well with total water. The dacites from Bua are pumice lumps and whole samples. The high MgO in sample 4 is due to contamination by synchronous basalt ash. Trace elements are given in Table 10 and base metal values in Table 11. Chromium values in andesite near Bua are concentrated in the pyroxenes and the biotites (e.g. Table 11). There is no chromium in the amphiboles though some of these are alkali-rich with over 3% K_2O.

Samples in Papua New Guinea weather to allophane, vermiculite and imogolite whereas Hong Kong samples weather largely to halloysite and kaolin.

Humic substances may complex metals (Wood, 1996) and fulvic acids may have chelates in their structure. Organic transportation of metals in tropical rainforest is claimed though analytical data is scarce. Thus certain species may accumulate gold or silver and certain derived humuses transport them.

Table 9. Major element compostions of ashes from Mount Lamington, pumice from Bua, and tuff from Hong Kong.

Wt%	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	58.90	59.80	63.60	63.50	61.50	61.00	61.40	62.30	66.10	73.91	75.37	75.58	73.61
TiO_2	0.38	0.44	0.81	0.52	0.86	0.60	0.68	0.31	0.34	0.19	0.26	0.11	0.36
Al_2O_3	18.20	18.10	15.40	15.40	15.50	19.00	18.10	17.80	16.00	12.63	12.17	13.10	12.59
Fe_2O_3	2.91	2.97	1.55	1.55	2.20	2.80	2.65	2.20	1.79	0.60	0.20	0.69	1.19
FeO	2.52	2.95	3.32	1.59	3.68	0.88	1.08	0.94	0.79	1.39	1.73	0.89	1.77
MnO	0.11	0.09	0.15	0.06	0.15	0.07	0.07	0.03	0.05	0.08	0.05	0.06	0.06
MgO	2.96	2.74	1.48	2.55	1.91	1.69	1.71	0.73	0.94	0.17	0.13	0.05	0.73
CaO	6.45	5.85	3.74	2.65	4.30	2.75	2.90	1.86	2.20	0.63	1.17	0.58	2.65
Na_2O	5.25	4.58	4.55	3.60	4.15	3.70	3.75	3.80	4.00	3.05	3.17	3.70	1.80
K_2O	1.98	1.98	2.70	2.90	2.45	2.60	2.55	2.30	2.55	5.39	5.16	5.62	4.77
P_2O_5	0.33	0.31	0.29	0.17	0.27	0.03	0.04	0.04	0.08	0.04	0.06	0.01	0.07
H_2O^+	0.28	0.12	1.91	3.25	2.35	2.70	3.00	3.90	2.45	0.97	0.34	0.33	0.74
H_2O^-	0.34	0.31	0.17	1.58	0.49	1.20	1.08	2.10	2.21	0.23	0.10	0.12	0.09
CO_2	ND	ND	0.01	0.14	0.08	0.04	0.01	0.20	0.10	ND	-	ND	ND
Organic C	ND	ND	-	0.28	-	0.65	0.71	1.29	0.13	ND	ND	ND	ND
TOTAL	100.61	100.24	99.69	99.74	99.89	99.71	99.73	99.80	99.73	99.28	99.10	100.84	100.43
Normative Corundum			0	2.3	0	5.3	4.0	5.1	3.1				

ND = not determined, - = below detection. Analyses by wet chemical methods, EMS and AAS, 10-13 by ICP OES.

1-2. Andesite ash, Mount Lamington (Taylor, 1958).
3-7. Slightly weathered dacite pumice, Bua (Amdel).
8. Weathered lower rhyodacite ash, Bua (Amdel)..
9. Weathered upper rhyodacite ash, Bua (Amdel).
10-13. Rhyolitic tuffs, Hong Kong (Addison, 1986; Strange and Shaw, 1986).

Table 10. Trace element analyses (ppm) of andesite from Mount Lamington (1-2) and rhyolitic tuff from Hong Kong (3-6).

	1	2	3	4	5	6
V	124	107	30	-	60	-
Rb	47	41	249	204	298	220
Sr	913	981	123	50	147	106
Y	16	15	26	50	29	37
Zr	151	151	151	202	211	295
Nb	3.5	3.5	8	20	11	15
U	-	-	8	8	7	8
Ba	660	675	530	190	700	430
La	18	20	30	60	30	60
Ce	44	48	80	130	80	130

- = below detection. Analysis 1-2 by XRF; 3-6 by ICP OES.

Analyses from Arculus *et al.* (1983) and Addison (1986).

Table 11. Base metal values (ppm) for Mount Lamington rocks and a nearby stream sediment.

Element	**Lamington Rocks** (range for 13 samples) (Arculus *et al.*, 1983)	**Stream Sediment Sample and Other Materials Managalase Plateau**
Cr	58-169	Up to 1.5% in phenocrysts of biotite
Ni	23-68	30
Cu	6-40	15
Zn	64-103	ND
Pb	28-40	20
Co	ND	40
Mo	ND	5
V	99-166	500
Ag	ND	48 (in vein material)
Analysis	XRF	EMP and solid spectrographic

ND = not determined

APPENDIX 3

A 38 cm thick topsoil with 16% humus at the Hydrographers site has formed in the last 1,700 years (based on carbon dating, Ruxton, 1988) giving 3.6 mg humus $cm^{-2}a^{-1}$ (Table 12). Rates are minimal because of the dynamic equilibrium of growth and decay, and net excess is measured. Bulk density varies from 1.2 to 0.5 g cm^{-3} and for convenience is taken as 1.0. The base of the humus layer is commonly sharp and it must extend slowly down or is depleted by micro-organisms, leaching, oxidation and mineralisation. The resistates of the humus lower down (humified lignin and charred wood (0.01%), in concentrations of 1 to 6%) decay at about 0.002 mg $cm^{-2}a^{-1}$.

Table 12. Rate of formation of humus in topsoil in Papua[1].

Rate mg $cm^{-2}a^{-1}$	**Altitude m**	**Remarks**
4.0	2500	Forest on rock
2.0	2000	Grassland
3.6	1830	Forest
3.1	1355	Forest
0.87[2]	1525	Forest
0.98	980	Grassland
1.25[3]	900	Forest

1 Top few cms not measured because of abundant roots.
2 10 cm root mat 40% organic matter.
3 Carbon dating brackets topsoil at several sites.