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PRESERVATION OF THIN TEPHRAS

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INTRODUCTION

Numerous observations attest to the rapid erosion from hillslopes of recently emplaced tephras. A survey of the literature on Soufrière (St Vincent, 1902), Rabaul (Papua New Guinea, 1937), Paricutin (Mexico, 1943-1945), Irazu (Costa Rica, 1963-64), Usu (Japan, 1977) and Mt St Helens (USA, 1980) together with occasional comments about other tephra-producing eruptions suggest the following conclusions:

1. Deep rills and gullies are quickly cut in fresh tephra especially where the development of an impermeable surface crust increases runoff volumes (Cilento, 1937, p47-8; Huggins, 1902, p20; Waldron, 1967, p11; Higashi et al., 1978; Kadomura et al., 1978; Lowdermilk and Bailey, 1946, p286; Collins *et al*., 1983).

2. Rates of rill and gully erosion are amongst the highest recorded anywhere while sediment concentrations in mudflows or secondary lahars may be as much as 65% by weight (Ollier and Brown, 1971; Waldron, 1967; Higashi *et al*., 1978).

3. Erosion of tephra is frequently proportional to slope steepness with extensive redeposition on valley floors. Rill erosion and shallow landsliding of tephra are important processes on steeper slopes. Topographic position is also important in determining how much tephra remains at a site (Anderson and Flett, 1903, p437; Segerstrom, 1950; 1960; Collins *et al*., 1983; Lehre *et al*., 1983).

4. The amount of vegetation remaining on tephra-mantled slopes influences erosion rates (Collins *et al*., 1983). Tephra erosion facilitates recovery of surviving vegetation (Lawrence and Ripple, 2000) and

vegetation regrowth influences the retention of tephra (Segerstrom, 1950; 1960).

5. As much as one third to one half of the tephra may be removed from the slopes within one year or less of emplacement (Anderson and Flett, 1903, p453; Waldron, 1967, p11), though more detailed studies at Mt St Helens suggest only 11% of tephra was removed in the first year (Collins *et al*., 1983) and that erosion rates declined dramatically with time (Collins and Dunne, 1986).

6. The decline in erosion rate is not produced by revegetation but by increased infiltration capacity, decreased erodibility of the tephra exposed and the development of a stable rill network (Collins and Dunne, 1986).

7. In the long term, stability of the underlying substrate is an important influence on erosional removal of the tephra mantle (Blong and Pain, 1978).

The examples on which the above conclusions are based do not always specify the thickness of the tephra mantle but observations were generally made close to the volcanoes where the tephra was at least 300 mm deep, and sometimes considerably deeper. On the other hand, erosional reworking and/or survival of thin (i.e., 10-300 mm) seems to have not been reported in any detail; although emplacement of thin tephras is usually less destructive of the vegetation cover it is not clear whether erosion of thin tephras is similarly rapid or whether preservation is ensured.

Most studies of thin tephras relate to their use as chronostratigraphic marker beds and are commonly based on tephras preserved in lakes and/or swamp deposits. By and large, preservation of thin tephras in other situations is poorly documented. Nonetheless, thin tephras are of considerable value in geomorphic, geologic and archaeologic investigations as they form obvious marker horizons and cover large areas.

The present contributions sets out observations on the preservation of thin tephras at four sites: near Mt Hagen and in the Western Finisterre Ranges, Papua New Guinea, on the slopes of Mt Rainier, Washington, USA, and on Kodiak Island, Alaska, USA. Each of the four studies was of only limited duration and detail but, collectively, the results provide considerable data on erosion and survival of thin tephras and the factors that influence their preservation.

THE STUDY AREAS

Mt Hagen

In 1977 seven small experimental plots were established in Mt Hagen (Lat. 5.9^{o}S, Long. 144.3^{o}E), Papua New Guinea Figure 1) at an elevation of 1500 m. The plots measured only 0.12 m^2 on low angle slopes. Vegetation covers included long (200-350 mm) and short (20-40 mm) grasses and bare ground. The tephra used for the experiment was formed by crushing a lightly-consolidated 14,000 year old tephra to pass a 2 mm sieve, with approximately half the material finer than 1 mm. This tephra was broadcast by hand from a height of 500 mm, to form layers 10-60 mm thick.

Western Finisterre Ranges

The Western Finisterre Ranges lie in Morobe Province, Papua New Guinea at Lat. 6^{o}S, Long. 146.5^{o}E (Figure 1). In 1979 a study was made of the erosion and preservation of Tibito Tephra, erupted from Long Island about 1665 A.D., in an area of the Finisterre Ranges at an elevation of about 3500 m. In this area Tibito Tephra, an olive green fine-medium sand, is about 50 mm thick (Blong, 1982). Annual rainfall at high altitude in the Western Finisterre Ranges is unknown but experience elsewhere in Papua New Guinea suggests it is likely to be greater than 3-4000 mm.

Fourteen sites representing seven geomorphic environments were selected for study. Ten or more 30 mm diameter cores were collected from random locations on each site between grass and bromeliad clumps, so that all cores were taken from roughly the same level. Tephra thickness and the depth to the tephra surface were recorded.

Percent cover for each species were estimated visually for 10 x 1 m^2 subunits of the 10 m^2 quadrats, and the mean value used as the best estimate. Cover data were analysed using a sum of squares agglomerative (SSA) classification (Orloci, 1978) which provides a classification of both sites and species. Pollen assemblages immediately above and below Tibito Tephra were analysed for two sediment cores to determine both the nature of the vegetation at the time of the tephra deposition and whether vegetational change occurred after this time.

Mt Rainier

Sites in the southern and eastern part of Mt Rainier National Park (Lat. 46.8°N, Long. 121.8°W) were selected for a study of the preservation of Mt St Helens W tephra (Figure 2). In this area Mt St Helens W tephra is 10-80 mm thick, white to light brown layer of loose sand-sized pumiceous and crystal-rich ash. In some exposures dark minerals and lithic fragments are common, giving the tephra a "salt and pepper" appearance (Mullineaux, 1974, p37-38). St Helens W is the youngest tephra in this area of Mt Rainier National Park to form a conspicuous bed. The tephra was deposited in 1479-1480 A.D. on the basis of tree ring counts (Yamaguchi, 1983), and sulphate aerosols in the GISP2 Greenland ice core (Hallet *et al*., 2001). Layer W in Mt Rainier National Park is the St Helens Wn tephra of Mullineaux et al. (1975, p334). Observations of the Mt St Helens W reported here were made in alpine meadows at Sunrise Ridge and Chinook Pass and in forest at Ohanopecosh. Figure 2 outlines the distribution of the tephra in the park area.

Kodiak Island

Twenty six sites on northeastern Kodiak Island (Lat. 57°N, Long. 154°W) were investigated in 1978 to determine the influence of slope angle on erosion and preservation of Novarupta (1912) tephra, the product of the world's most voluminous eruption in the twentieth century (Hildreth and Fierstein, 2000). Tephra fell to a thickness of about 450 mm on Kodiak town, 170 km downwind from the vent, over a period of about 60 hours, but rapidly compacted to about 250-300 mm. The following stratigraphic sequence is readily recognisable (Reiger and Wunderlich, 1956):

> Layer 3 – firm, compact, dacitic, light grey silt loam, 25-50 mm (deposited overnight in Kodiak 8-9 June)
>
> Layer 2 – yellow-brown dacitic coarse silt loam, 75-125 mm (deposited from noon on the 7th to 1430 hours on the 8th)
>
> Layer 1 – loose, predominantly rhyolitic light yellow-brown loamy fine sand, 25-50 mm grading to grey-brown loose fine sand, 75-100 mm (5pm on 6th June to 79am on 7th June)[1].

As the layering of the tephra is readily observed it is possible to determine whether the tephra is still *in situ*, erosionally reworked, or absent. In the field a distinction was made between "essentially *in situ*" tephra and

[1] Fierstein and Hildreth (1992) recognise six "zones" of tephra on Kodiak Island.

“reworked” tephra. The former is generally characterised by the presence of Layer 1 and Layer 2 and the possible absence of Layer 3. Griggs’ (1918, p41) statement that Layer 3 “has almost everywhere blown away, leaving the present surface of the ash composed usually of the middle brown layer”, would seem to be an exaggeration.

Most of the 26 sites examined were covered with low shrubs, grasses, ferns, fireweed (*Epilobium* sp.) and/or salmonberry; only a few sites were under spruce or alder. Most sites were on planar hillslopes, nearly all sites were underlain by 500 mm or more of till on either Cretaceous metamorphic rocks or a variety of Quaternary sediments. Some of the surface processes operating in the Kodiak – Katmai environment have been described by Hilton (2003). The locations of the 26 study sites are shown in Figure 3.

FACTORS INFLUENCING EROSION AND PRESERVATION

Compaction

The bulk density of freshly fallen tephra is quite low but it is also highly variable if the examples cited in Table 1 are to be believed. The values cited range from 0.23 to 1.52 g cm^{-3} with a mean value of 0.69 g cm^{-3}. On the other hand, values for compacted tephra range from about 1.3 to 1.8 g cm^{-3} (Moore, 1967, p19; Waldron, 1967, p5; Duncan and Vucetich, 1970, P Hughes, *pers.comm.*).

The changes in density implied by these values also imply a change in thickness; a change resulting from compaction rather than erosion. For example, Gorshkov and Dubik (1970, p283) report a decrease in thickness on compaction from 100-150 mm to 40-50 mm. Similarly, Aramaki (1956, p200) reported changes in thickness at a site 12 km southwest of Asama crater. Immediately after the 1783 eruption the tephra was reported as 1200 mm thick, with rapid compaction to 1050 mm. One hundred and 70 years later the layer was only c650 mm thick. Again, the decrease in thickness was attributed to compaction and not to erosion. While Collins *et al*. (1983) reported no discernible systematic change in the bulk density of Mt St Helens (1980) tephra over a period of 12 months, their measurements did not begin until four months after the eruption.

Data compiled on the thickness of the Novarupta tephra at Kodiak is also constructive as several accounts describe the thickness of the material deposited on 6-9 June 1912. Nellie Erskine, wife of one of Kodiak’s prominent businessmen, in writing to her mother a few days after the event, described the tephra as about 2 feet (600 mm) thick. On 20 June she wrote to her mother again commenting that the tephra was “on the level 14 inches [350 mm] and in places as high as your head where it is piled up" (Erskine, 1962, p140, p192). Captain K W Perry's account published in the Washington *Sunday Sun* on 2 March 1913 but taken from his earlier official report as the senior government official in Kodiak at the time of the eruption gives the tephra thickness as 22 inches (550 mm). Martin (1913, p172) gives the thickness as 10 inches (250 mm) in September 1912. Griggs (1918, p3) reports that Kodiak was "covered about a foot deep" (300 mm) and H Erskine (1940) gives the thickness at 18 inches (450 mm). Observations made by the first author 66 years after the tephra fall indicate that the tephra has compacted to a thickness of 160-210 mm on slopes of less than 15^o.

All these observations on tephra thickness could be substantially correct but made at different times after the eruption and, perhaps, in different parts of the town. Similarly, the wide range of reported bulk densities of fresh tephra in Table 1 may be partly a function of varying intervals between emplacement and observation.

Experimental plots set up in Mt Hagen provide additional data on the compaction of tephra. Table 2 sets out the tephra thicknesses and plot conditions at the beginning of the experiment. For most of the more than two years measurements were made, however, the plots were covered in long grass.

Although Table 2 shows compaction of the tephra on most plots to about the initial thickness in two years, Figure 4 indicates a dramatic decrease in thickness for most plots in the first few days. These measurements were based on the elevation of markers above the tephra surface while subsequent measurements were determined by digging up portions of the plot surface. Discrepancies in thickness are perhaps contributed to by upward mixing by soil fauna to increase the apparent thickness of the layer. Table 2 suggests that some samples increased in thickness with time as a result of mixing; certainly thicknesses became more variable even in portions of the plots not disturbed by earlier investigations. By the end of the experiment the tephra on most plots was covered by up to 5 mm of organic rich topsoil indicating active bioturbation by soil organisms (cf. Wood and Johnson, 1978).

The plots were installed in Mt Hagen in January, a month with c.250-300 mm rainfall. Within two days of plot establishment tephra which had bent blades of grass had been reworked downwards but on plots with grass 200-350 mm long many grains had still not reached the ground surface. Within a week it became clear that raindrop impact was important in compacting the experimental tephra. There was little evidence that tephra was splashed from the plot (the energy of falling drops being absorbed by the low-density tephra), but tephra surfaces had been lowered by 10 mm or more on three plots (Figures 4 and 5). Thin lines of less-compacted tephra could be observed under the strings across some plots. On plot 2 some areas protected by leaves were still at the original elevation while most of the plot surface had compacted. There was no evidence of surface crusting.

After 16 days puddled surfaces appeared on some plots, minor flow lobes had occurred from the margins of the 50 mm thick tephras and there was evidence of tephra splashed upwards to heights of 150-180 mm on the corner marker pegs. On plots with tall grass some tephra was still as much as 100 mm above the ground surface *en route* to the surface. On these plots there was a tendency for the tephra to form lenses rather than a continuous cover. Tephra thicknesses were not recorded on these plots as undue surface disturbance would have resulted.

The observations made on these experimental plots indicate that much of the decrease in thickness results from compaction and that much of the compaction of thin tephras occurs in the first few weeks after deposition, particularly during the rainy season. Clearly, this change in thickness, initially in the absence of erosion, implies dramatic changes in bulk density of fresh tephra. The results suggest that the apparent ranges of values of bulk density recorded in Table 1 should be interpreted with caution. Similarly, care must be taken that the rapid thinning of deposits by compaction is not interpreted as erosional removal of the tephra.

<u>Slope angle</u>

As indicated earlier there is some evidence in the literature that the rate of erosion of tephra is proportional to slope steepness. This is not surprising as a basic precept of hillslope geomorphology (from simple mechanics) is that the rate of downslope movement is proportional to the sine of the slope angle (e.g. Young, 1972). At Mt St Helens, Collins *et al*. (1983) show that much of the 70% of the removal of 150-300 mm thick tephra on 9^{o} slopes was by rill erosion and that the importance of rill erosion increased with increasing slope gradient. There is also a suggestion that rill erosion is limited on thinner tephras. Studies on Kodiak Island, in the Western Finisterre Ranges, and in Mt Rainier National Park provide information on this relationship.

The locations of Kodiak Island sites are shown on Figure 3. On Figure 6 slope angles refer to general slopes in the vicinity of the exposure; tephra thicknesses were recorded normal to the slope. For many of the 26 sites a range of values has been recorded. A general thinning of the tephra with increasing slope angle is apparent. This thinning on steeper slopes seems generally to have been accomplished by the removal of Layer 3 and the upper part of Layer 2; the description "essentially in situ" on Figure 6 indicates that on many slopes Layer 1 and at least a portion of Layer 2 retain their airfall bedding.

The field data indicate an essentially undisturbed thickness of Novarupta tephra of 160-210 mm on slopes of less than 15^o. If we accept that the chosen sites are representative, then Figure 6 indicates remarkably little erosion of tephra from slopes of less than c.30^o. Only on slopes >35^o is there much removal and even then some sites have retained >160 mm tephra cover; i.e., certainly more than half the original cover.

In the Western Finisterres, for each sample site the mean and standard deviation of Tibito Tephra thickness has been calculated and plotted against general site slope angle (Table 3, Figure 7). Mean tephra thickness changes little with slope angle although Figure 7 suggests that the thickness is more variable on steeper slopes.

Only the alluvial fan site (Figure 7) shows significant deposition and reworking of tephra, mean thickness having increased from c. 50 mm (judged from slope crest sites) to about 90 mm. However, when the range of thickness values recorded at each site is considered (Table 3) it appears that most depositional sites (valley floors and the alluvial fan) have a more varied tephra cover than do the erosional sites (slope crests and planar hillslopes). As depositional areas have numerous sites with tephra thickness <50 mm these sites have clearly also suffered either non-deposition or significant erosion of the tephra.

If we consider only the planar hillslopes so that the data are comparable with that from Kodiak Island (Figure 6) the sample is very small, but it does not suggest marked thinning of tephra with increasing slope steepness.

A set of measurement made under forest at Ohanopecosh (figure 2) on the southern slope of Mt Rainier provide data on the slope-tephra thickness relationship at a microscale. On a general slope of 20-25^o under a mature forest of red cedar, Douglas fir and western hemlock measurements were made at 50 mm intervals along a short exposure. Even within a short distance the forest floor has substantial microrelief, as it had at the time of tephra emplacement. In such an area the tephra fall does not provide a continuous mantle of even thickness as the fall is intercepted by tree branches and reworked by splash and stem flow before arriving at the ground surface. Further reworking can occur after this initial emplacement so that it is sometimes possible to recognise an *in situ* thickness as well as a total thickness (*in situ* thickness + reworked thickness). Careful observation of the fine details of the tephra thickness made it possible to record the thickness to the nearest mm.

A plot of thickness versus slope angle (Figure 8) shows a general thinning of the tephra on the steeper slopes. However, the relationship is not particularly strong.

Faunal activity

At sites in all four study areas there is considerable evidence of the effects of soil microfauna on tephra layer disturbance. These matters will be discussed later; the important point for the present is the role of macrofauna in tephra layer destruction in alpine meadow areas of Mt Rainier National Park.

In the Sunrise – Sunrise Point and Sourdough Trail areas of the park on south-facing slopes at elevations of 1900-2000 m St Helens W tephra should be 20+ mm thick (Figure 2). In these areas, more than 5 km of exposure was examined; exposures need only be 200-300 mm deep as St Helens W tephra occurs just below the surface.

Mt St Helens W tephra seems entirely absent in alpine meadow/herbfields areas even on ridge crests and gentle slopes. Small white pumice grains commonly occur just below the surface and some areas have a "salt-and-pepper" appearance as described by Mullineaux (1974, p37-38). The only alpine meadow exposure of W tephra in the Sunrise area, found near the Sunrise campground, was 350 mm long with an average thickness of 20 mm.

In the Chinook Pass – Tipsoo Lake area at 1600-1800 m the tephra is again absent from the alpine meadows though Mullineaux's map (Figure 2) indicates that W tephra should be 30-40 mm thick. Except in two small spots about 100 mm long where W tephra was 50-80 mm thick no exposures could be found. Nonetheless, loose pumiceous sand, believed to be W tephra was scattered everywhere.

However, in both the Sunrise and the Chinook Pass areas Mt St Helens W tephra is quite extensive under small patches of forest – white bark pine (*Pinus albicaulis*), and/or yellow cedar (*Chamaecyparis nootkatensis*). The stunted trees of these small forest patches are probably at least several hundred years old.

These observations perhaps suggest that the present day distribution of W is dependent on vegetation type but it is also possible that W fell onto snow or that reworking and removal of W under meadow conditions could result from the activity of the northern pocket gopher (*Thomomys talpoides*). The latter hypothesis seems more plausible.

Gopher activity in meadows around Sunrise and Chinook Pass is everywhere in evidence. The pocket gopher remains active in winter forming tunnels through the snow just above the ground. Soil excavated from tunnels 40-200 mm below the surface is placed in the snow tunnels. Spring melting leaves ridges of soil across the meadows. The northern pocket gopher avoids forests, preferring a diet rich in forbs, and living in deep light soils. Wintertime territories are frequently flooded, promoting a seasonal change in territory and distributing the impact of their burrowing activities even more widely (Schamberger, 1971?; Thorn, 1978).

The available evidence suggests that pocket gophers, and perhaps other agents, have almost completely reworked 20-40 mm thick layers of W in alpine meadow sites in 450 years or less. This is in accord with the observation of Anders and MacMahon (1985) that gopher activities had covered up to 2% of the ground surface with pre-Mount St Helens 1980 soil in the first four months after that eruption. On the other hand, Layer W is well preserved in forest areas around Mt Rainier.

It is interesting to note that in the alpine grasslands of Papua New Guinea, Tibito Tephra is well preserved whereas it has largely disappeared as a result of biological activity under montane forests.

On the Mt Hagen experimental plots faunal activity resulted in marked mixing of the tephra and even destruction on parts of plots in a little more than two years. Observations made at one month and eight months (Table 1) indicate an increase in the variability of tephra thickness. On some plots the tephra developed a crumb topsoil-like structure but with little mixing of organic matter. On other plots the tephra formed clods with downward mixing of as much as 50 mm. Earthworm activity was evident. After eight months the tephra layers were surprisingly well preserved even when “sown” as a 10 mm layer onto grasses 300 mm high or even onto a simulated garden surface (Plot 7).

However, after 25 months preservation of the tephra was much less complete. On Plot 6 where tephra had been only 10 mm thick the tephra had virtually disappeared with only a few small balls 3-4 mm in diameter readily visible. Even portions of 50 mm thick layers had vanished on Plot 2. On Plot 7 a diffuse layer of tephra could be recognised in the top 60-70 mm but the tephra was buried by 10-20 mm of topsoil. No doubt mixing was produced by a range of fauna but earthworm activity was most evident.

Vegetation

Sums of squares agglomerative (SSA) classification of the 15 vegetation sites samples at the Western Finisterres study area reveals three distinct vegetation assemblages (Figure 9). All sites were located above the altitudinal tree-line at 3500-3600 m above sea level in alpine shrubland/grassland. Group 1 (sites 1, 4, 6, 7, 8, and 11) represents a low, woody shrubland community typical of the well-drained slopes and ridge crests. Groups 2 (sites 2, 3, 5, 10, 13 and 15) and 3 (sites 12 and 14) are dominated by herbaceous species occupying the wetter valley and tarn locations. Sites 12 and 14, in particular, are found close to a small tarn on waterlogged ground. Dominant species in these communities are listed in Table 3.

The small number of vegetation sample sites does not allow for detailed comparison with a classification of landscape into geomorphic units. However, a correlation between vegetation communities and geomorphology is apparent. All sites in Group 1 were identified as well-drained and relatively dry, while all sites in Group 2 and 3 are wet, and mostly poorly-drained. A strong relationship also exists (not independently from that described above) between vegetation group and erosional vs depositional landscape units (Group 1 = erosional, planar hillslopes plus ridge crests; Groups 2 and 3 = depositional, alluvial fans, landslides, valley bottoms, $X^2 = 8.04$, $p<0.01$). Site 15 was added to the data set since it represents a wet site located on an erosional surface (i.e. a hillside seepage point). In the SSA classification (Figure 9) it is located (vegetationally) with the other wet sites and not with the hillslope sites.

Tibito Tephra was found in all cores taken at the Western Finisterres field site. Degree of preservation (reworking) has been described earlier, as has thickness and relationship to slope angle. The correlation between vegetation and erosional/depositional units suggests further analysis of tephra characteristics according to these criteria. Mean tephra thickness is greatest on depositional units (n = 72, mean thickness 58 mm, versus n = 79, mean thickness = 42 mm), but this difference is not significant. Similarly, the depth of overlying soil is greater for depositional units (124 mm versus 107 mm) but again is not significant due to the large variation between sites. Nevertheless, the direction of differences is as would be expected;

that is, accumulation of both tephra and overlying soil mineral and organic material is greater in depositional environments.

Pollen analysis was carried out on two short soil cores. Samples were taken immediately above and below the tephra layer and only a few key pollen types were counted, these indicating the presence of either grassland/shrubland (*Poaceae* and *Cyperaceae* pollen), or forest (*Raponea* or *Dacrycarpus* pollen). Results conform with the findings of Corlett (1984a, b) for Mt Wilhelm in the nearby Bismarck Ranges, Papua New Guinea. He describes a major change from forest to grassland/shrubland for 28 sites on Mt Wilhelm immediately following the Tibito Tephra event. This change is not related in any way to the ash fall. Rather, it appears to represent a chance correlation with the increasing population of people at high altitude (and their burning of the forest) following the introduction of sweet potato to the New Guinea highlands. Introduction of the sweet potato is thought to have allowed the extension of agricultural activities altitudinally by about 600 m (Corlett, 1984a).

That the tephra has been preserved under grassland in the sites studied agrees with the observational information available for Papua New Guinea which suggests limited preservation of tephra under forest. If forest had persevered at the present study site after the Tibito event, then the tephra may not have survived in an identifiable layer. The reasons for this difference between forest and grassland are worth considering:

(a) Forest

There are several possible reasons for the poor preservation of tephra layers in forested areas of New Guinea (and other rainforest areas). First, the variable thickness of canopy cover, combined with ground layer obstacles such as fallen trees, rotting stems, and the location of living stems, precludes an even distribution of ash on the forest floor. Second, various authors have calculated the mean age of sites (i.e., tree locations within the forest) within rainforest to vary between 40 and 180 years (Hartshorn, 1978, 1980). This rapid rate of cycling implies regular disturbance of the forest soil by treefall and mixing of surface and subsurface soil horizons. Third, soil fauna may play an active part in mixing of the soil.

(b) Alpine grassland

Experimental studies at Mt Hagen, Papua New Guinea, illustrate that a relatively even, compacted tephra layer can be expected to develop within a few weeks of ash fall on a short (<200 mm) grassland. In grasslands of the lowland tropics, the mixing activities of termites would preclude survival of this layer. However, termites are absent from alpine grasslands and there is little mixing activity by the "depauperate" soil fauna. The pattern of grass growth and mortality is also less likely to disturb the tephra. Death of plant parts (i.e. tillers above ground, and roots below ground) is followed by decomposition *in situ*. Thus, organic matter is added to the soil surface, and some is incorporated into the soil profile as roots decompose. The tephra may receive some organic inputs through root decomposition, but is unlikely to be greatly affected.

Below altitudinal tree-line tephra preservation is dependent upon special site conditions such as are provided by lakes and swamps.

Survival of tephra under forest at high altitude near Mt Rainier, USA, is more difficult to explain. The rate of turnover of sites may be much slower (perhaps >300 years) due to the greater longevity (and slower growth rates) of trees typical of montane forests in the middle latitudes of the northern hemisphere. Also, the lower temperatures, especially in winter, at Mt Rainier, compared with tropical montane forest areas may reduce soil faunal activity. These factors could allow longer survival of identifiable tephras.

CONCLUSIONS AND IMPLICATIONS

1. Erosional reworking of thin tephras at the sites examined is not rapid.

2. However, based on experimental plots, compaction occurs rapidly as a result of raindrop impact. Whether these observations are also relevant to changes in thicker tephras (>300 mm) has yet to be determined.

3. Compaction presumably produces significant changes in tephra bulk density over short periods of time after deposition. Bulk density measurements of "freshly fallen tephra" reported in the literature need to be interpreted with care.

4. Although erosion and reworking can occur via raindrop impact and the formation of micro-mudflows, the available evidence suggests compaction is much more important in reducing the thickness of thin tephras.

5. On long grass plots (>200 mm) some tephra grains took some weeks to reach the ground surface and tephra tended to form balls and lenses rather than a continuous cover.

6. The relationship between slope gradient and the degree of reworking of tephra is not strong at the sites examined, even for steeper slopes. At the high altitude Western Finisterres and the high latitude Kodiak Island sites thin tephras remain well preserved for decades to centuries.

7. On Mt Rainier macrofaunal activity appears to have removed virtually all trace of a 500-year old tephra under grasslands while reasonable preservation occurs under stunted timber.

8. While the observations reported here are incomplete and do not constitute a full set of experiments they emphasise the importance of rapid initial compaction, vegetative substrate and faunal activity as the dominant factors influencing survival and preservation of thin tephras. These conclusions would seem to stand in contrast to the emphasis on rapid erosional removal reported for thicker tephras. While substantive investigations are required, these conclusions have considerable relevance to the interpretation of tephra deposits used in tephrostraigraphic, chronostratigraphic and archaeological studies.

AFTERWORD

In 1978 David Gringrich of Kodiak Island pointed out to the first author that the large horizontal branches on some old spruce trees on the island had Novarupta tephra on the upper surface with lichen/moss growing on it. Sixty six years after the eruption, some Novarupta tephra had still not reached the ground!

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Table 1: Bulk densities of freshly fallen tephra

Thickness of tephra	Bulk density g/cm^3	Reference
38 mm	0.23	Anderson and Flett, 1903, p475
25-300 mm	0.25	Anderson and Flett, 1903, p475
9.5-13 mm	0.35-0.47	HMSO, 1903, p33
30 mm	0.93	Gorshov and Dubik, 1970, p268
25 mm	0.80	Gorshov and Dubik, 1970, p269
20 mm	1.23	Gorshkov, 1959, p86
20 mm	1.12	Gorshkov, 1959, p87
6 mm	0.58	Gorshkov, 1959, p80
16.6 mm	0.66	Gorshkov, 1959, p81
25 mm	0.64	Gorshkov, 1959
5 mm	0.6-0.8 0.7-0.92	Thorarinsson and Sigvaldason, 1972, p273

Table 2: Site conditions and tephra thicknesses, Mt Hagen experimental plots

Plot No	Vegetation	Slope Angle (degrees)	Initial Thickness (mm)	Subsequent thickness (mm)				
				7 days	16days	30 days	236 days	767 days
1	Grasses 20-40 mm; <5% Bare ground; dense root mat	5	50	35	25	~20	25	20-30
2	Grasses 20-40 mm; 40-50% bare ground	0.5	50	35	25-30	20-25	20-30	25-30
3	Grasses <20 mm; 40-50% bare ground	2	30	29	~15	10	10-12	15-20
4	Dense tall grasses 200-350 mm; no bare Ground	1	20-30	-	-	-	20	<20
5	Dense tall grasses 200-3000 mm; no bare Ground	1	50-60	-	-	-	40	25-30
6	Grasses 20-40 mm; <5% Bare ground	7	10	-	-	-	5-10	<5
7	Bare soil dug over To spade depth	3.5	25	-	>10	-	~10	~20

Table 3: Dominant plant species associated with each of the three alpine communities identified by SSA classification

Group	Community Type	Dominant species[2]
1	Shrublands on well-dra slopes (>7 degrees)	*Selliguea sp.* *Gaultheria mundula* *Styphelia suaveolens* *Coprosma divergens* *Gleichenia bolanica* *Festuca sp. (papuana?)* *Myosotic linearis*
2	Tussock grassland on wet sites	*Deschampia klossii* *Drapetes ericoides* *Astelia papuana* *Potentilla sp.* *Rhododendron womersteyii*
3	Non-tussock grass and herbfield on waterlogged sites	*Astelia papuana* *Monostatachya oreoboloides* *Trachymene tripartite* *Potentilla sp. (fousteriana?)* *Carpa alpine* *Ranunculus sp.*

[2] Not all plants could be identified to species level since only a small proportion of the flora was in flower at the time of the study. All species were identified by staff of the Lae Herbarium, Papua New Guinea.

LIST OF FIGURES

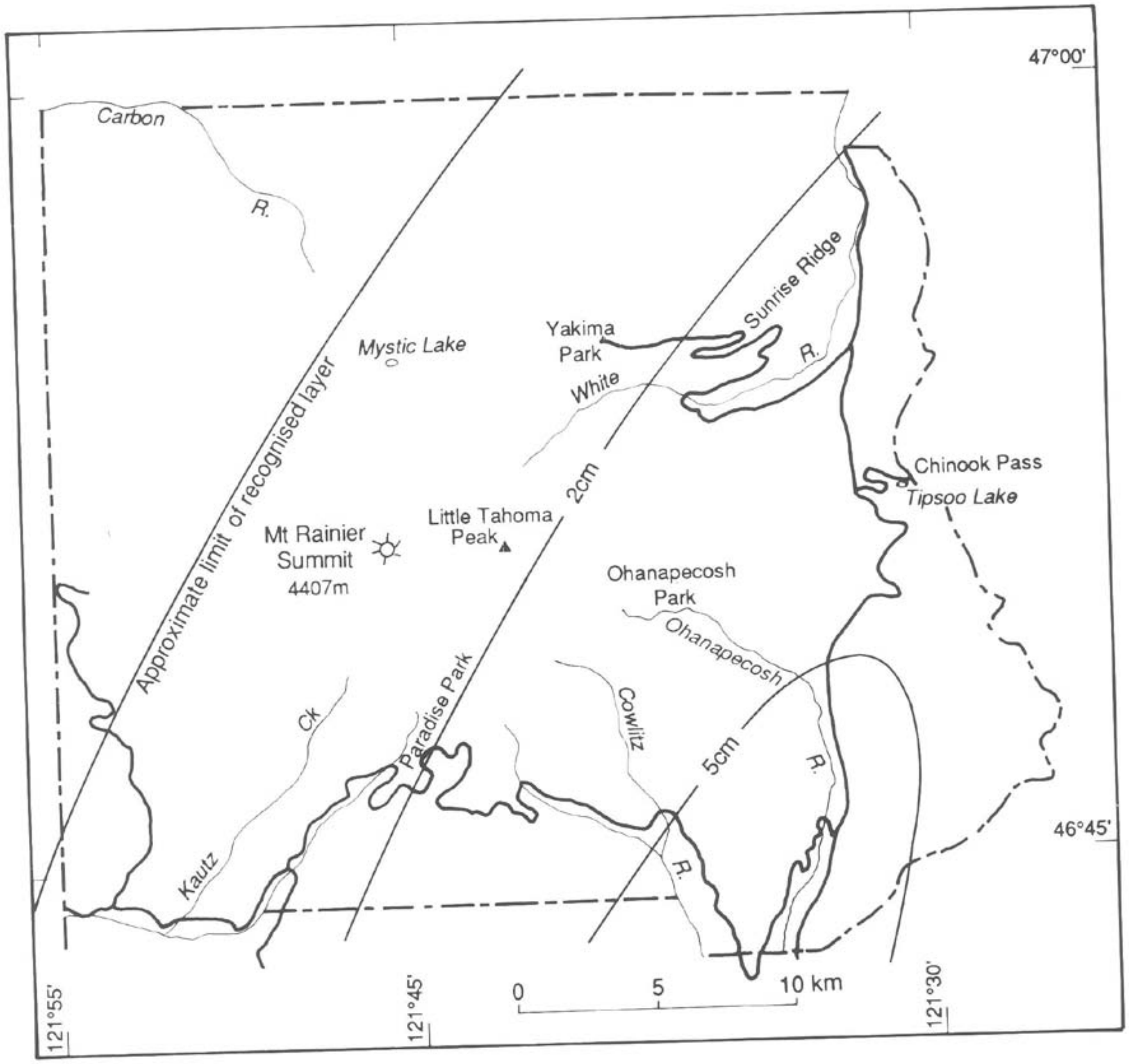

Figure 2: Distribution of St Helens W tephra in Mt Rainier National Park area, Washington, USA. (after Mullineaux, 1974, p39).

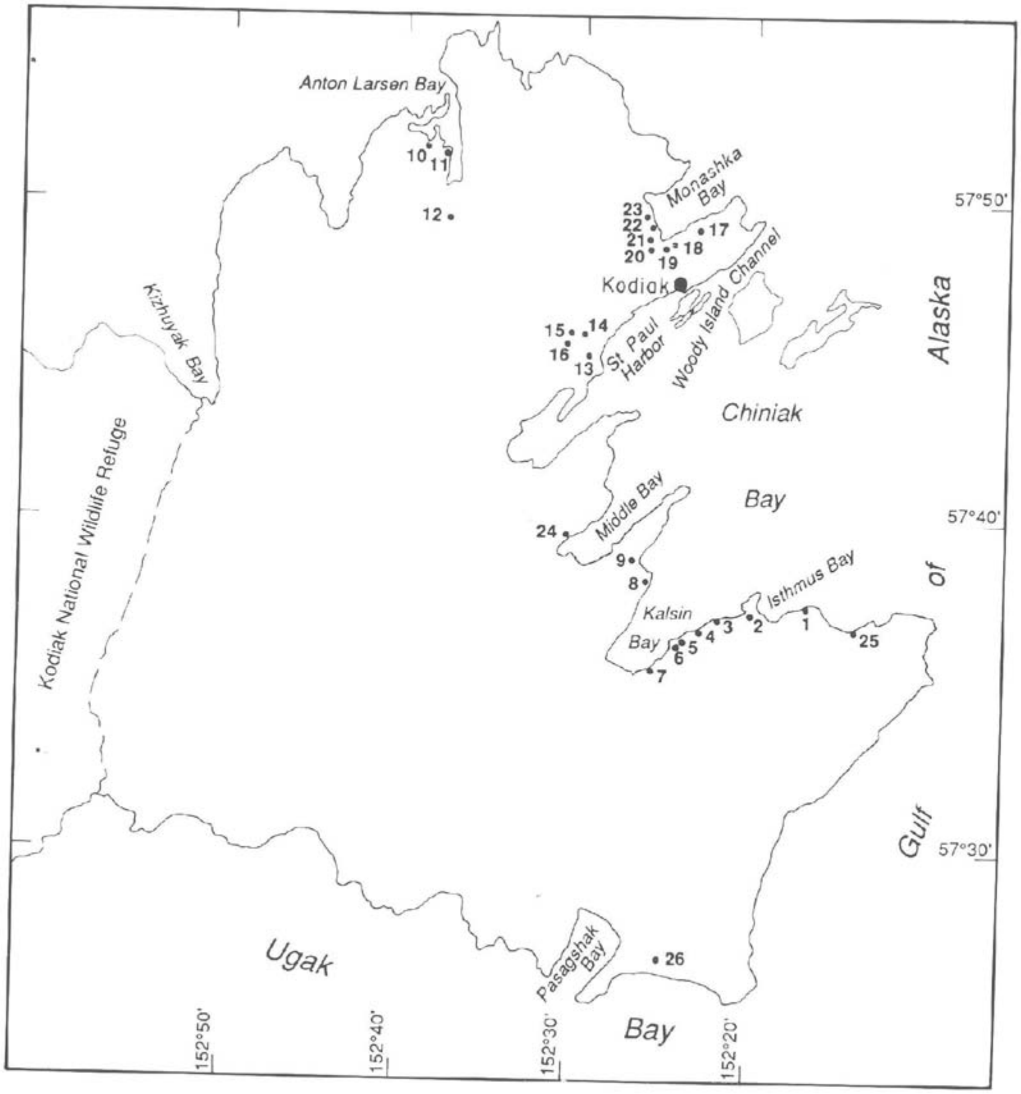

Figure 3: Locations of study sites on Kodiak Island, Alaska.

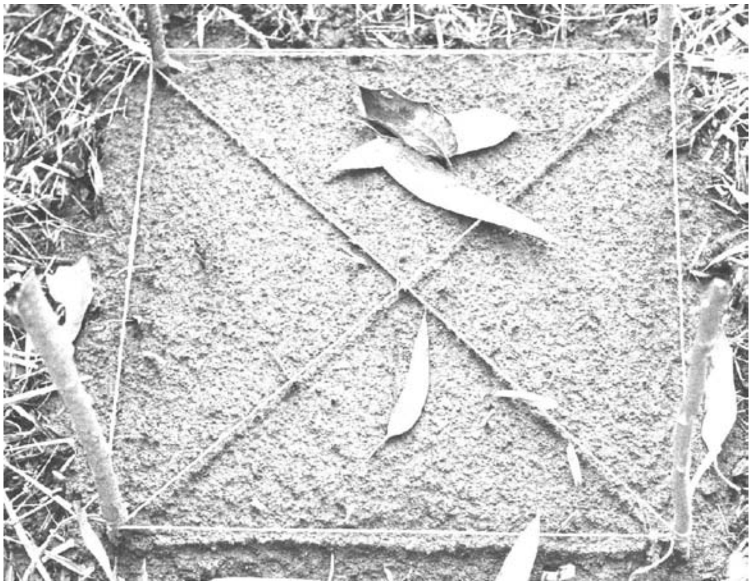

Figure 5a: Plot 2 seven days after the start of the experiment. Tephra was 50 mm thick at the beginning of the experiment.
The taut strings were initially flush with the plot surface.

Figure 5b: Part of Plot 2 16 days after the start of the experiment. Compaction by raindrop impact is evident. Numerous blades of grass have penetrated the tephra surface.

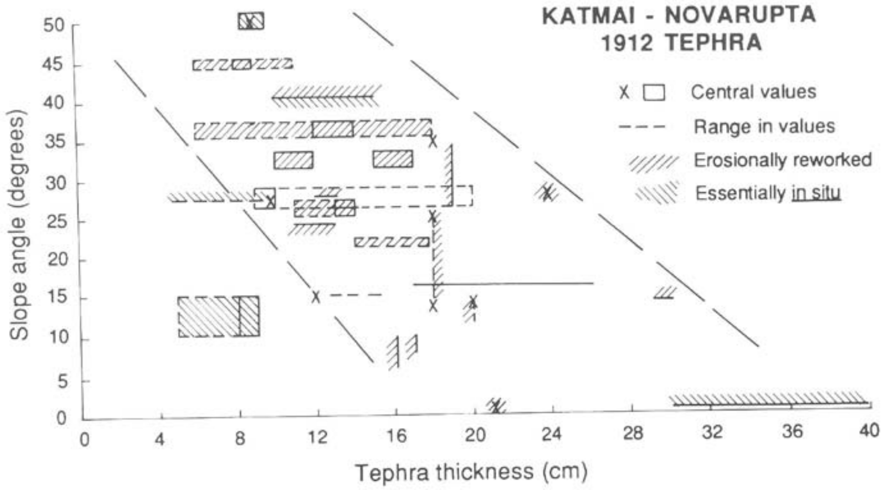

Figure 6: Slope angles (degrees) versus tephra thickness for the Novarupta 1912 tephra, Kodiak Island. Dashed lines indicate boundaries encompassing most observations.

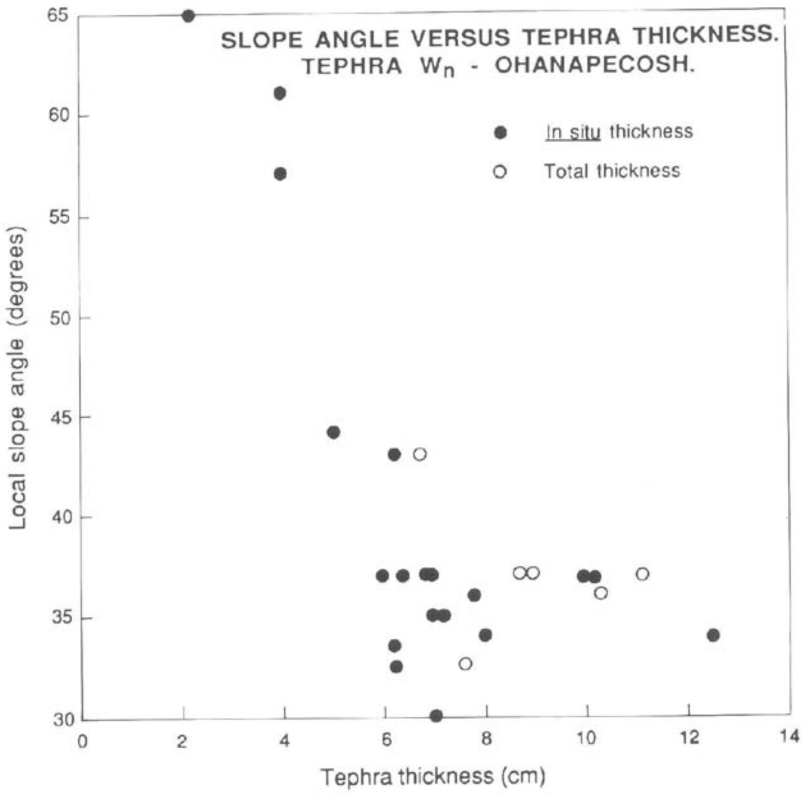

Figure 8: Slope angle versus tephra thickness, Ohanopecosh area, Mt Rainier

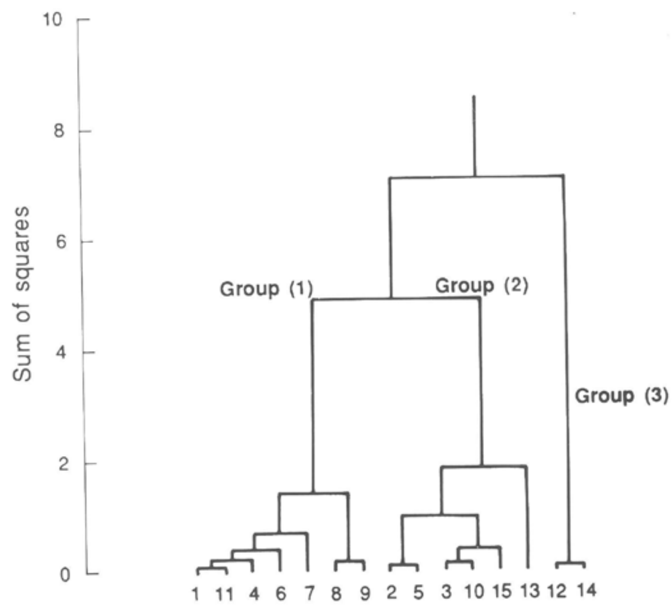

Figure 9: Sum of squares agglomerative classification of vegetation sites in alpine grassland/shrubland, Western Finisterrres, Papua New Guinea.