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Preservation of thin tephra

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Abstract

The preservation of thin (<300 mm thick) tephra falls was investigated at four sites in Papua New Guinea (PNG), Alaska and Washington, USA. Measurements of the variations in the thickness of: (i) Tibito Tephra 150 km downwind from the source, Long Island (PNG) erupted mid-seventeenth century; (ii) St Helens W tephra (erupted 1479–80 A.D.) on the slopes of the adjacent Mt. Rainier in Washington State; (iii) Novarupta (1912) tephra preserved on Kodiak Island (Alaska, USA); and (iv) an experimentally placed tephra at a site near Mt. Hagen (PNG) allow tentative conclusions to be drawn about the relative importance to tephra preservation of slope gradients, vegetation cover and soil faunal activity. Results for the experimental tephra suggest that compaction occurs rapidly post-deposition and that estimates of tephra thickness and bulk density need to indicate how long after deposition thickness measurements were made.

These studies show that erosional reworking of thin tephra is not rapid even on steeper slopes in high rainfall environments. In Papua New Guinea a 350-year old tephra is rarely present under forest but is well-preserved under alpine grasslands. On Mt. Rainier 500-year old tephra is readily preserved under forest but absent under grasslands as a result of gopher activity. Despite the poor relationship between tephra thickness and slope steepness the thickness of thin tephras is highly variable. On Kodiak Island thickness variability across a few metres is similar to that observed across the whole northeast of the island. The measured variability reported here indicates large sample sizes are necessary to adequately estimate the mean thickness of these thin tephra.

These results have implications for the preparation of isopach maps, estimation of tephra volumes and elaboration of the potential consequences of tephra falls.

Keywords: Tephra fall, Preservation, Compaction, Thickness, Erosion, Vegetation, Fauna, Sample size

Introduction

Tephra thickness is influenced by eruption dynamics, topographic variations, compaction, erosion and deposition, and bioturbation (Engwell et al. 2013). While the relative importance of these influences is rarely examined numerous observations attest to the rapid erosion from hillslopes of recently emplaced tephra. Deep rills and gullies are quickly cut in fresh tephra producing some of the highest recorded erosion rates (Cilento 1937, p47–8; Huggins 1902, p20; Waldron 1967, p11; Ollier and Brown 1971; Higashi et al. 1978; Kadomura et al. 1978; Lowdermilk and Bailey 1946, p286; Collins et al. 1983).

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 Mount St Helens after the 1980 eruption 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). The amount of vegetation remaining on tephra-mantled slopes also influences erosion rates (Collins et al. 1983).

Observations supporting the rapid erosion of tephra have generally been made close to the source volcanoes where the tephra was at least 300 mm thick, and sometimes considerably thicker. Erosional reworking and/or survival of thin deposits (i.e., 10–300 mm) have not been reported in any detail. Although emplacement of thin tephra is usually less destructive of the vegetation cover it is not clear whether erosion of thin tephra is similarly rapid, or whether preservation is more or less likely.

Most studies of thin tephra relate to their use as chronostratigraphic marker beds and are commonly based on tephra preserved in lakes and/or swamp

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deposits. By and large, preservation of thin tephra in terrestrial environments is poorly documented despite the fact that terrestrial areas experiencing relatively thin tephra falls are generally substantially larger than those receiving thicker deposits (e.g., Payne and Symeonakis 2012). Nonetheless, thin tephra are of considerable value in geomorphic, pedologic, geologic and archaeologic investigations as they can form obvious marker horizons and may cover tens of thousands of square kilometres (e.g. Lowe 2011; Arnalds 2013).

The present contribution sets out observations on the preservation of thin tephra 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. In each study, our aims were to determine the variability in thin tephra preservation and to elucidate, so far as possible, the factors that encourage or prevent preservation by recording multiple observations in quite limited areas. While each of these studies was limited in duration they span a variety of geomorphic environments and ecosystems and include one experimental study (at Mt. Hagen), two studies of thin tephra emplaced 350–500 years ago but not recorded in written accounts until the second half of the twentieth century (in the Western Finisterre Ranges, PNG and on the slopes of Mt. Rainier, USA), and one well-documented historic eruption (Kodiak Island, USA).

The study areas

Mt. Hagen

In 1977 seven small experimental plots were established near Mt. Hagen town (5.8°S, 144.25°E) in the Western Highlands Province of Papua New Guinea (Fig. 1) at an elevation of 1500 m. The plots measured 0.12 m^2 and were placed on surfaces with slopes of less than three degrees. Plot surface covers included long (200–350 mm) and short (20–40 mm) grasses providing 100% ground cover 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 6°S, 146.5°E (Fig. 1). In 1979 a study was made of the erosion and preservation of Tibito Tephra, erupted from Long Island (VEI 6) probably around 1660 A.D., in an area of the Finisterre Ranges at an elevation of ~3600 m. In this area, approximately 95 km from Long Island, Tibito Tephra is an olive-green fine-medium sand about 50 mm thick (Blong 1982). Annual rainfall at high altitude in the Western Finisterre Ranges is unknown but evidence elsewhere in

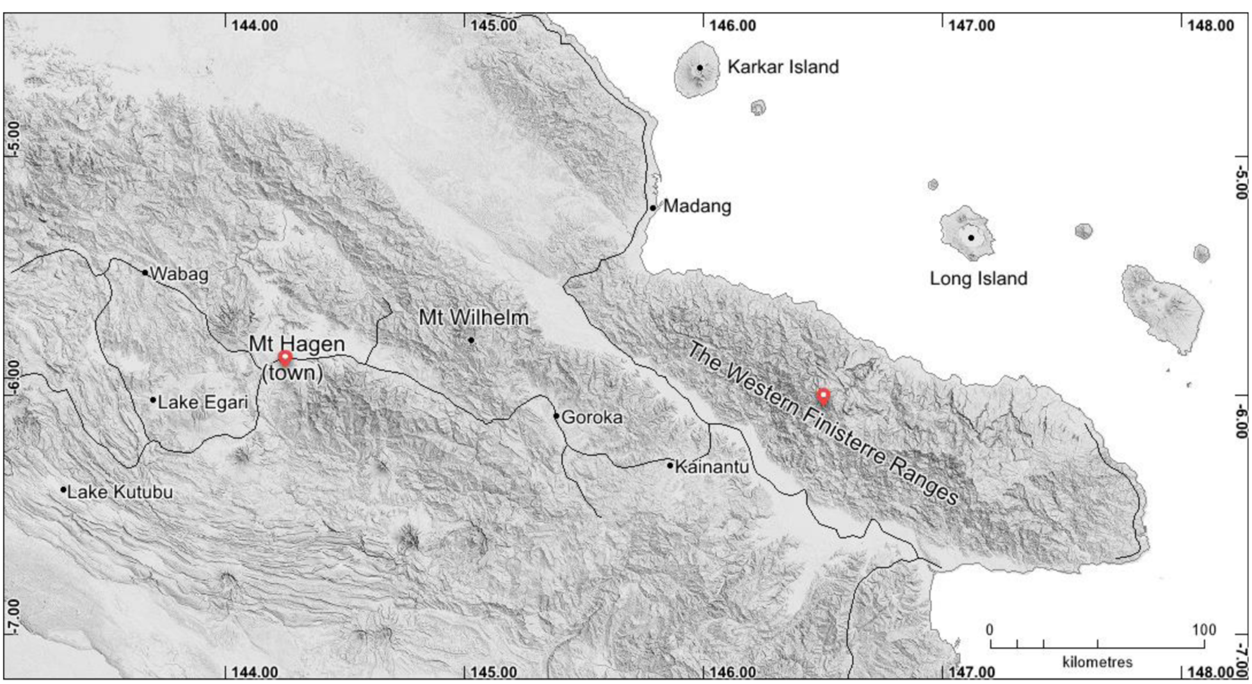

Fig. 1 Part of the Papua New Guinea mainland showing the town of Mt. Hagen where the compaction experiment was conducted and the location of the field sample of Tibito Tephra in the Western Finisterre ranges

Papua New Guinea suggests it is likely to be at least 3000–4000 mm.

In the Western Finisterres 14 sites were selected with up to 14 samples made at each site within a 3 m radius, but with no sample within 40 cm of another. All sites were selected within an area of a few hectares in alpine grassland. Soil cores were taken manually using a 30 mm diameter corer pushed into the ground to the hilt. All cores were taken in moss covered gaps between grass and bromeliad clumps averaging 30 cm height.

Each of the 14 sites was assigned to a geomorphic environment (see Table 3) and broadly grouped as low slope angle crest, steep erosional slope, or low slope angle valley floor. Percent cover for each plant species was estimated visually for 10 × 1 m^2 subunits of a single 10 m^2 quadrat at each site, and the mean value used as the best estimate. Cover data were analysed using a sum of squares agglomerative (SSA) classification (Orloći 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 tephra emplacement.

Mt. Rainier

Sites in the southern and eastern part of Mt. Rainier National Park, Washington, USA were selected for a study of the preservation of Mount St Helens W tephra (Fig. 2). In this area, Mount St Helens W tephra is a 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, dated to 1479–1480 A.D. on the basis of tree ring counts (Yamaguchi 1983), is one of the youngest tephra in this area of Mt. Rainier National Park to form a conspicuous bed. Layer W in Mt. Rainier National Park is the St Helens Wn tephra of Mullineaux et al. (1975, p334). Observations reported here were made in alpine meadows at Sunrise Ridge and Chinook Pass and in forest at Ohanapecosh. Figure 2 shows the distribution of the tephra in the park area (after Mullineaux 1974).

Kodiak Island

Twenty six sites on north eastern Kodiak Island, Alaska (Fig. 3) were investigated in 1978 to determine the influence of slope angle on erosion and preservation of

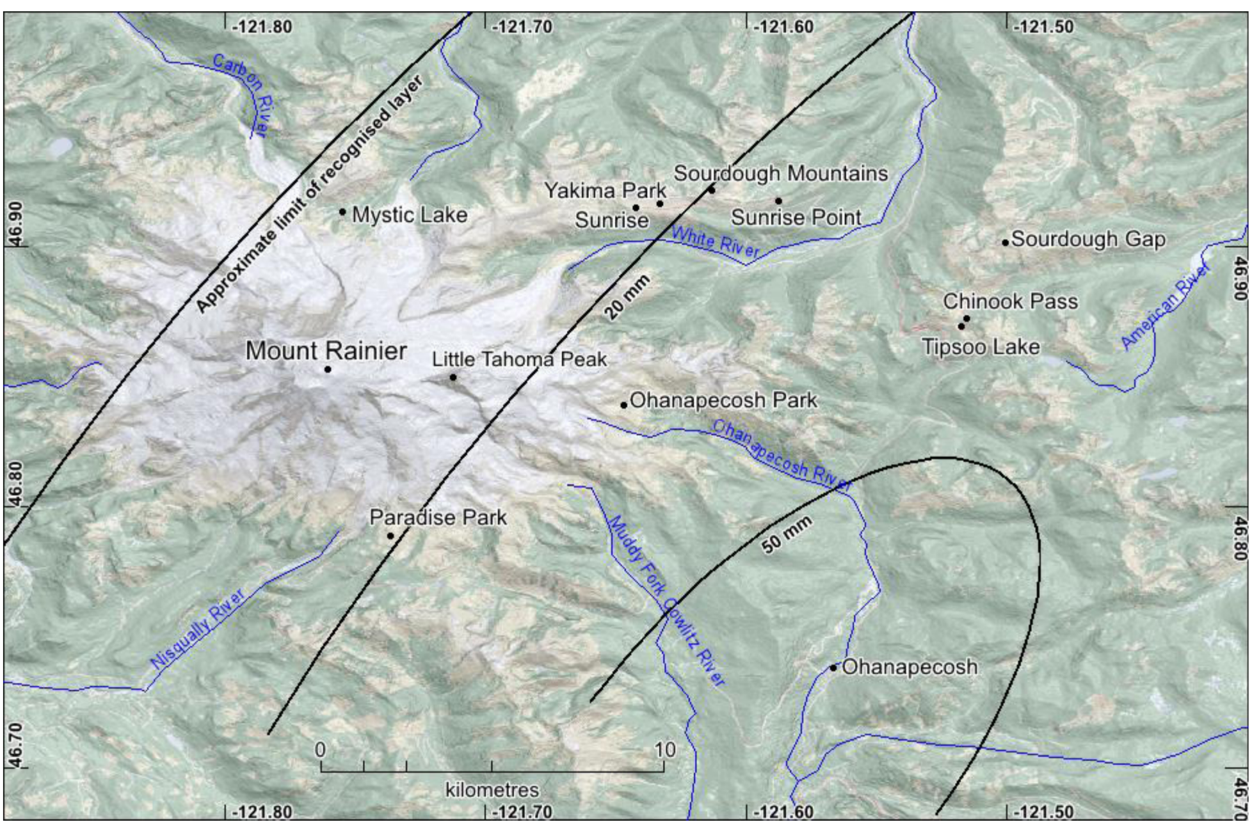

Fig. 2 Distribution of St Helens W tephra in Mt. Rainier National Park area, Washington, USA. (tephra thickness after Mullineaux 1974, p39). The observations referred to in this paper were made near Sunrise, at Chinook Pass and in forest at Ohanapecosh

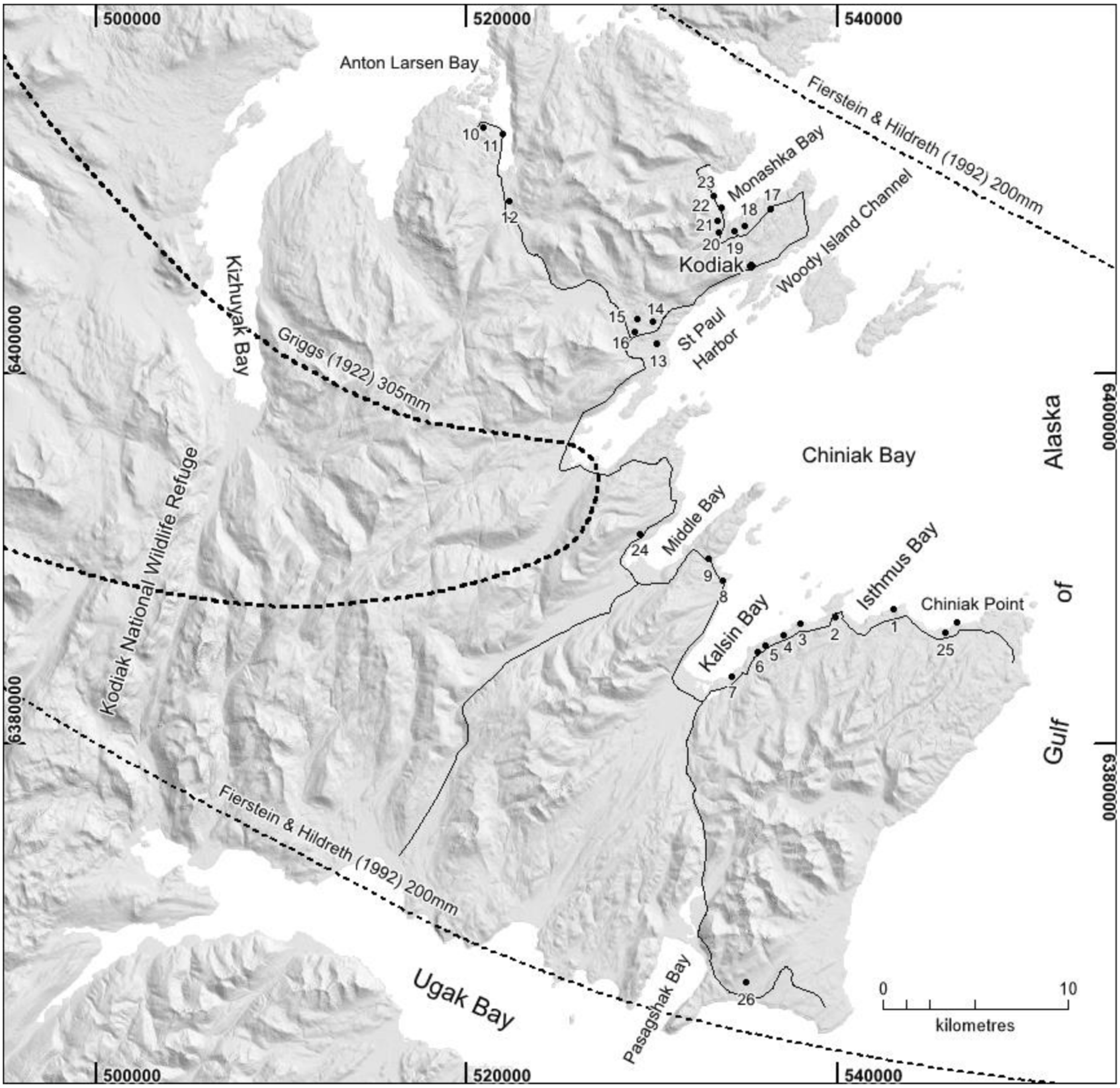

Fig. 3 Locations of the 26 Novarupta tephra (1912) study sites on Kodiak Island, Alaska. The one foot (~305 mm) isopach produced by Griggs (1922) and the 200 mm isopach from Fierstein and Hildreth are also shown. UTM (Zone 5 coordinates have been used on the margins of the image

Novarupta (1912) tephra, the product of the world's most voluminous eruption in the twentieth century (Hildreth and Fierstein 2000). Kodiak town is about 170 km SSE of Novarupta. Tephra fell to a thickness of about 450 mm on Kodiak town, 170 km downwind from the vent, over a period of about 60 h, but rapidly compacted to about 250–300 mm (see below). Our field observations were made before the detailed analysis of Fierstein and Hildreth (1992). While comparison of locations on our Fig. 3 and Fierstein and Hildreth's Fig. 2 suggests we probably examined some of the same field sites, the stratigraphic sequence we followed was the earlier 3-layer division described by Reiger and Wunderlich (1956) (see Fig. 4):

Layer 3 – firm, compact, dacitic, light grey silt loam, 25–50 mm (deposited overnight in Kodiak 8–9 June, 1912).

Layer 2 – yellow-brown dacitic coarse silt loam, 75–125 mm (deposited from noon on the 7th to 1430 h on the 8th June).

Layer 1 – loose, predominantly rhyolitic light yellow-brown loamy fine sand, 25–50 mm grading to grey-

Fig. 4 An exposure of Novarupta (1912) tephra on the eastern side of Kodiak Island. The sharp base of Layer 1 is clearly visible with a diffuse boundary to the overlying yellow-brown Layer 2. The light-grey silt loam of Layer 3 is only visible in some of the exposure

brown loose fine sand, 75–100 mm (deposited from 5 pm on 6th June to 7 am on 7th June).[1]

As the layering of the tephra is still readily observed it is possible to determine whether the tephra is still in situ at specific sites, erosionally reworked, or absent (Fig. 4). In the field, a distinction was made between "essentially in situ" tephra and "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 only partly true.

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).

Factors influencing erosion and preservation of thin tephra

Compaction

The bulk density of freshly-fallen tephra is low but is also highly variable (Table 1). Published values range from 0.23 to 1.23 g cm^{-3} with a mean value of about 0.69 g cm^{-3}, though the time between emplacement and measurement is rarely known. 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).

The changes in density implied by these values also imply a change in thickness: for example, Aramaki (1956, p200) reported changes in thickness at a site 13 km southwest of Asama crater; immediately after the 1783 eruption the alternating layers of pumice and fine ash were reported as 1200 mm thick, with compaction within a few months to 1050 mm. One hundred and seventy years later the layer was recorded as only c.650 mm thick. 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 Mount St Helens (1980) tephra over a period of 12 months, their measurements did not begin until 4 months after the eruption.

Accounts describing the thickness of the tephra deposited at Kodiak on 6–9 June 1912 illustrate the difficulties in sorting out the influences of compaction, erosion and redeposition. 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 ft (600 mm) thick. On 20 June she wrote to her mother again commenting that the tephra was "on the level 14

Table 1 Bulk densities of freshly-fallen tephra as reported in a range of previous studies

Thickness of tephra	*Bulk density g/cm^3*	*Eruption and year*	*Reference*
38 mm	0.23	Soufrière St Vincent, 1902	Anderson and Flett 1903, p475
25–300 mm	0.25	Soufrière St Vincent, 1902	Anderson and Flett 1903, p475
9.5–13 mm	0.35–0.47	Soufrière St Vincent, 1902	HMSO 1903, p33
30 mm	0.93	Shiveluch, 1964	Gorshkov and Dubik 1970, p268
2.5 mm	0.80	Shiveluch, 1964	Gorshkov and Dubik 1970, p269
20 mm	1.23	Bezymianny, 1955	Gorshkov 1959, p86
20 mm	1.12	Bezymianny, 1955	Gorshkov 1959, p87
6 mm	0.58	Bezymianny, 1955	Gorshkov 1959, p80
16.6 mm	0.66	Bezymianny, 1955	Gorshkov 1959, p81
25 mm	0.64	Bezymianny, 1955	Gorshkov 1959
5 mm	0.6–0.8 0.7–0.92	Hekla, 1970	Thorarinsson and Sigvaldason 1972, p273

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 in. (550 mm). Martin (1913, p172) states the thickness as 10 in. (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 in. (450 mm). Wilcox (1959, p416) gives the thickness at Kodiak village as about 10 in. (250 mm). The cumulative ash fall map of Fierstein and Hildreth (1992) shows thicknesses of 200–300 mm in the Kodiak town area on the north eastern part of Kodiak Island. Observations made by the first author 66 years after the tephra fall (i.e. in 1978) indicate that the tephra has compacted to an average thickness of 150–210 mm on those sites where all three layers are present (that is, in the absence of significant erosion or redeposition).

All these observations (both measured and estimated thicknesses) could be substantially correct but made at different times after the eruption and, perhaps, in different parts of Kodiak 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 2 years measurements were made, however, the plots were covered in long grass.

Data from the Mt. Hagen experiment indicate compaction of tephra on the plots over a two-year period (Table 2), however, the most dramatic decrease in thickness for some plots occurred in the first few days. These initial measurements were based on the elevation of markers above the tephra surface while subsequent measurements were determined by digging up portions of the plot. Thicknesses became more variable with time, with some of this variability contributed by upward mixing by soil fauna which increased the apparent thickness of the layer (Table 2). 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), but the layer had not been destroyed by this mixing and new surface layer development.

The experimental tephra deposition plots were established at Mt. Hagen in January, a month with c.250–300 mm rainfall. Two days after plot establishment tephra which had bent blades of grass had been reworked downwards, but on plots with grass 200–350 mm tall 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 rain drops being absorbed by the low-density tephra), but tephra thickness had been reduced by 10 mm or more on three plots (Fig. 5). 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 50–55 mm thick tephra plots 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; that is, the tephra had still not reached the ground. 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 tephra occurs in the first few weeks after deposition, particularly during the rainy season. Clearly, this change in thickness, essentially in the absence of erosion, implies dramatic changes in bulk density of fresh tephra. The results suggest that the apparent ranges of values of

Table 2 Site conditions and tephra thicknesses at the Mt. Hagen, PNG experimental plots

Plot No	*Vegetation*	*Slope angle (degrees)*	*Initial thickness (mm)*	*Subsequent thickness (mm)*				
				7 days	16 days	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

Fig. 5 Part of Plot 2 16 days after the start of the experiment. Compaction by raindrop impact is evident as the taut strings, initially flush with the tephra surface, stand proud. Numerous grass shoots have penetrated the tephra surface. The initial thickness of 50 mm has been reduced to 25–30 mm in just 16 days

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.

Slope angle

The rate of erosion of tephra is assumed to be proportional to the sine of the slope angle (Young 1972). Measurements on Kodiak Island, in the Western Finisterre Ranges, and in Mt. Rainier National Park provide information on this relationship for thin tephra. The Kodiak Island measurements span an length of about 50 km on the north east of the island, the western Finisterres measurements were made in an area of a few hectares, while the Ohanopecosh data were collected from a single exposure at intervals of about 50 mm. A general thinning of the tephra at all three locations with increasing slope angle is apparent but in no case is the relationship strong, with r^2 ranging from 0.17 to 0.29 (Fig. 6). Slope angle – thickness relationships are marginally stronger for the St Helens W and Kodiak tephra than they are for the Western Finisterres (Tibito) tephra.

On Kodiak Island thinning on steeper slopes seems generally to have been accomplished by the removal of Layer 3 and the upper part of Layer 2 but detailed measurements are available at only a few sites. The field data indicate an essentially undisturbed thickness of Novarupta tephra of 150–210 mm on slopes of less than 15°. If we accept that the chosen sites are representative, then Fig. 6 indicates remarkably limited erosion of the tephra from slopes of less than c.30°. Even some slopes of 35° have retained 150 mm tephra cover; i.e., considerably more than half the original cover.

In the Western Finisterres, mean Tibito tephra thickness changes little with slope angle; that is, there is only limited thinning of tephra over a slope angle range of 40°. (Table 3, Fig. 6). Only the alluvial fan and landslide sites (Sites 10 and 13 in Table 3) show significant deposition and reworking of tephra, mean thickness having increased from c. 50 mm (judged from slope crest sites) to 80–110 mm. However, when the standard deviation of thickness values recorded at each site is considered (Table 3) most depositional sites (valley floors and 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 erosional hillslopes so that the data are comparable with that from Kodiak Island the sample is small, but it does not suggest marked thinning of tephra with increasing slope steepness.

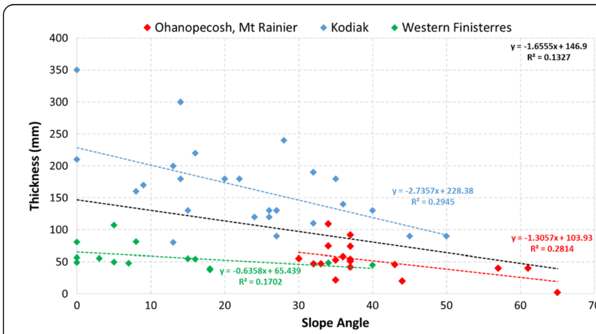

Fig. 6 Slope angles (degrees) versus tephra thickness measured normal to the slope at exposures of St Helens W at Ohanopecosh on Mt. Rainier, Novarupta tephra on Kodiak Island, and Tibito Tephra in the Western Finisterres. The Kodiak Island sites are spread out across about 50 km (see Fig. 3). The Western Finisterre data shows the mean thicknesses recorded at each of the 14 sites (in an area of a few hectares) listed in Table 3. The Ohanopecosh (Mt Rainier) measurements are in a small area with sites only 50 mm or so apart recorded against the local slope angle. At no site is the relationship between tephra thickness and slope angle strong

Table 3 Sample site characteristics and Tibito Tephra thicknesses in the Western Finisterre Ranges, Papua New Guinea. N = no of samples at each site

SITE No.	*Geomorphic environment*	*Vegetation group*	*Slope angle (degrees)*	*Mean Tibito thickness (mm)*	*Standard deviation (mm)*	*N*
1	Planar hillslope	1	~18	39.3	40.7	7
2	2nd order valley floor	2	5	49.6	26.2	13
3	2nd order valley floor	2	15	55.0	30.3	12
4	Crest	1	0	49.2	13.1	12
5	Planar hillslope	2	7	48.2	18.3	11
6	Valley floor	1	16	54.2	23.1	12
7	Crest	1	3	55.5	28.1	11
8	Hillslope spur	1	34	48.8	42.6	8
9	Short sideslope	1	40	45.0	29.5	10
10	Alluvial fan	2	8	81.4	48.0	11
11	Planar hillslope	1	18	37.8	15.6	9
12	Valley basin floor	3	0	80.5	43.7	10
13	Landslide	2	5	107.5	102.5	2
14	Lake margin	3	0	56.7	15.3	3

On a general slope of 20–25° under mature forest of Red cedar, Douglas fir and Western hemlock at Ohanopecosh (location on Fig. 2) on the southern slope of Mt. Rainier, tephra thickness measurements were made at 50 mm intervals along a short exposure and recorded against the local slope angle. Even within a short distance the forest floor has substantial microrelief, presumably 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 stem flow and rain splash 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). There is a general thinning of tephra on steeper slopes but again the relationship is not particularly strong (Fig. 6).

Geomorphic environments

At the Western Finisterres site it is possible to divide the 14 sample sites into three general geomorphic environments – crests, erosional slopes and valley floors. The cumulative thickness of Tibito Tephra recorded in each of the geomorphic environments confirms that mean thicknesses on erosional slopes are thinner than those on valley floor (depositional) sites (Fig. 7). This also shows that Tibito Tephra was absent from 20% of the erosional sites sampled. The full range of thicknesses recorded occurs on both erosional slopes and depositional valley floors (0 to 180–190 mm) while crest environments show a more limited range (0 to 110 mm).

Vegetation

Three distinct vegetation assemblages are recognised at the Western Finisterres study area based on sums of squares agglomerative (SSA) classification of the 14 vegetation sites samples (Table 4). 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, 9, and 11) represents a low, woody shrubland typical of the well-drained upper slopes and ridges. Groups 2 (sites 2, 3, 5, 10, and 13) and 3 (sites 12 and 14) are dominated by herbaceous species occupying wetter valley floor locations. Sites 12 and 14, in particular, are found close to a small tarn on waterlogged ground. The SSA classification also shows that vegetation Groups 1 and 2 are more closely related to one another than they are to Group 3.

The small number of vegetation sample sites does not allow for detailed comparison with a classification of the landscape into geomorphic environments. 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 Groups 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, valley bottoms, $X^2 = 8.04$, $p < 0.01$).

A wide range of Tibito Tephra thicknesses are associated with all three vegetation types though shrublands on well drained slopes (Group 1) has the most cores where tephra is absent and where median tephra

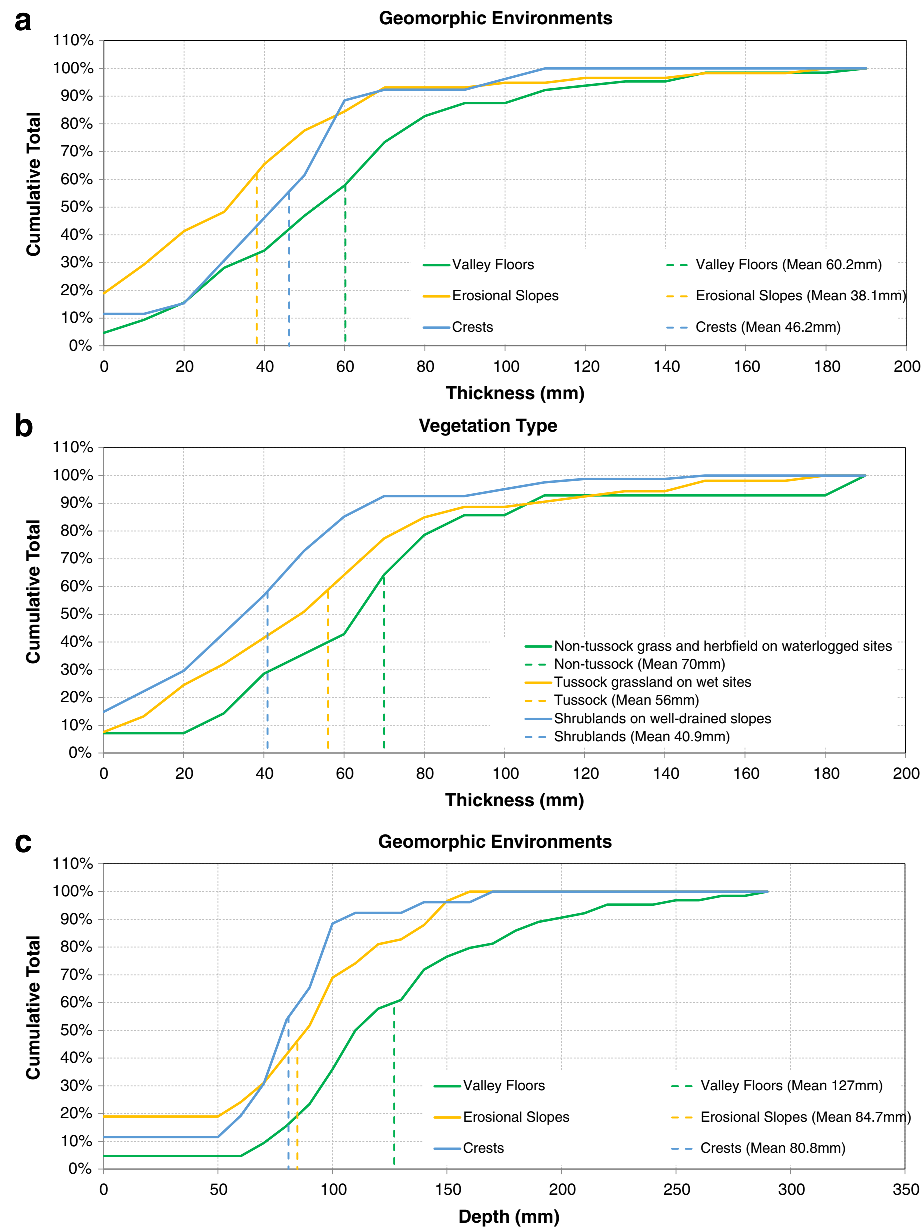

Fig. 7 a Cumulative totals of Tibito Tephra thickness for valley floor, erosional slopes, and slope crest geomorphic environments in the Western Finisterres. Median thicknesses for crest environments lie between those for erosional and depositional environments. Note that Tibito Tephra was absent from 20% of the erosional slope sample cores, 12% of the crest sample cores, and 5% of the valley floor cores; **b** Cumulative thicknesses and mean thicknesses of Tibito Tephra in non-tussock grassland and herbfield (waterlogged) sites, tussock grassland (wet) sites, and shrubland (well-drained) slopes; **c** Depth of burial of the surface of Tibito Tephra recorded in alpine grasslands at elevations around 3600 m above sea level. Cumulative rates of burial for valley floor, erosional slope, and slope crest geomorphic environments are shown. The survey was conducted about 330 years after deposition of Tibito Tephra

thickness is less than on the wetter tussock and non-tussock sites (Fig. 8).

Pollen analysis was carried out on samples taken immediately above and below Tibito Tephra on two short soil cores for key pollen types indicating the presence of either grassland/shrubland (*Poaceae* and *Cyperaceae* pollen), or forest (*Rapanea* and *Dacrycarpus* pollen). Results conform to the findings of Corlett (1984a, 1984b) for Mt. Wilhelm (5.77°S, 145.03°E; see location on Fig. 1) in the nearby Bismarck Ranges, PNG. He describes a major change from forest to grassland/shrubland for 28 sites on Mt. Wilhelm immediately following emplacement of Tibito Tephra. This change is not related in any way to the ash fall; rather, it appears to

Table 4 Dominant plant species associated with each of the three alpine communities identified by SSA classification at the Western Finisterres, Papua New Guinea. 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 Guinea

Group	*Community type*	*Dominant species*
1 *Site Nos: 1, 4, 6, 7, 8, 9, 11*	Shrublands on well-drained slopes (>7 degrees)	*Selliguea sp.*
		Gaultheria mundula
		Styphelia suaveolens
		Coprosma divergens
		Gleichenia bolanica
		Festuca sp. (papuana?)
		Myosotis linearis
2 *Site Nos: 2, 3, 5, 10, 13*	Tussock grassland on wet sites	*Deschampsia klossii*
		Drapetes ericoides
		Astelia papuana
		Potentilla sp.
		Rhododendron womersleyi
3 *Site Nos: 12, 14*	Non-tussock grass and herbfield on waterlogged sites	*Astelia papuana*
		Monostachya oreoboloides
		Trachymene sp.
		Potentilla sp. (fousteriana?)
		Carpha alpina
		Ranunculus sp.

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 (*Ipomoea batatas*) to the New Guinea highlands.[2] 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 PNG which suggests very limited preservation of tephra under forest.

There are several possible reasons for the poor preservation of tephra layers in forested areas of New Guinea (and other rainforest regions). Firstly, the variable thickness of canopy cover, combined with ground layer obstacles such as fallen trees, rotting stems, and the location of living stems, precludes the even distribution of ash on the forest floor.[3] Secondly, various authors have calculated the mean turnover rate of trees within rainforest to range 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 including thin tephra. Thirdly, soil fauna may play an active part in mixing of the soil.

Fig. 8 Gopher trails in an alpine meadow, Chinook Pass, Mt. Rainier National Park

Faunal activity

Experimental plot studies at Mt. Hagen (PNG) illustrate that a relatively even, compacted tephra layer can be expected to develop within a few weeks of ash fall in short (<200 mm) grassland. In grasslands of the lowland tropics, the mixing activities of termites likely preclude survival of thin tephra. Although 350-year old Tibito Tephra has been 'mapped' across tens of thousands of square km on the PNG mainland (Blong 1982) it has been recorded at very few lowland sites away from the coast other than in sites with special preservation characteristics such as in lakes and swamps.

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 layer receives some organic inputs through root decomposition, but is not greatly affected.

Survival of the 500-year old[4] Mount St Helens Wn tephra as a recognisable layer under forest at high altitude near Mt. Rainier, USA, is more difficult to explain. The rate of turnover at these sites may be much lower (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 tephra.

Mount Rainier and the highlands of PNG provide an interesting contrast. In highland PNG Tibito Tephra is preserved under grassland but not under forest, whereas the opposite appears to be the case with Mount St Helens Wn tephra on the eastern slopes of Mount Rainier; slower biological turnover may at least partly explain the presence of Wn tephra under forest at Mt. Rainier while macrofauna appear responsible for destruction of the tephra layer 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 (Fig. 2). In these areas, more than 5 km of exposure was examined. Mount St Helens W tephra is absent in alpine meadow/herbfield 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 single 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 (Fig. 2) indicates that W tephra should be 30–40 mm thick. Except for two small lenses 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 Mount St Helens W tephra is extensive under patches of white bark pine (*Pinus albicaulis*) and yellow cedar (*Chamaecyparis nootkatensis*) forest. 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 influenced by 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 seems more plausible as tephra fall onto snow would still result in at least recognisable lenses of tephra after snow melt.

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 (Fig. 8). 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, despite individual lifespans of only 2–3 years (Johnson and Horwath Burnham 2012), have almost completely reworked 20–40 mm thick layers of W tephra in alpine meadow sites in 500 years or less. This is in accord with the observation of Andersen 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 4 months after the 1980 eruption and with those of Kyoo et al. (2005) where soil turnover in the upper 50 cm by gophers occurs in only 40–100 years on California hillslopes. Despite this apparently rapid turnover of W tephra in alpine meadows, Layer W is well preserved in forest areas.

On the Mt. Hagen experimental plots faunal activity resulted in marked mixing of the tephra and even its destruction on parts of plots in a little more than 2 years. Observations made at 1 month and 8 months (Table 2) 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 8 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 soil fauna but earthworm activity was most evident.

Following Wood and Johnson (1978) two broad soil-forming processes can be recognised – horizonation, represented here by the deposition of a layer of volcanic ash, and homogenization, pedoturbation or soil mixing produced by subsequent burial of the tephra layer. In areas without termites, earthworms are the most widely recognised faunal agent for soil mixing with measured rates in the range 360–9000 kg/ha/y (Wood and Johnson 1978). While the experimental plots in Mt. Hagen at 1500 m elevation showed rates of burial of tephra of up to 5 mm/y the longer-term rates measured in the Western Finisterres at 3600 m elevation averaged only 0.2–0.3 mm/y with valley floors and tussock grasslands on wet sites showing the highest rates (Fig. 7c).

Variability in tephra thickness

In order to determine potential uncertainties surrounding the accuracy and precision of our Western Finisterres sampled data we have followed Engwell et al. (2013) in estimating observational uncertainty, or simply the standard deviation normalised to the average thickness for each sample site. There is significantly more variation within the uncertainty associated with the samples taken on erosional slopes when compared to crests and valley floors (Fig. 9a). There is substantially less spread between the samples taken at the crests and valley floors. The Vegetation type data (Fig. 9b) show for Shrublands on well-drained slopes and Tussock grasslands on wet sites that uncertainty between the observation data is independent of each environment or rather one environment does not provide stability of precision of sampled data over the other. This conclusion cannot be applied to the Non-tussock grass and herbfield sites as there are only two in this category.

Observations made in the four study areas in Papua New Guinea, Washington State and Alaska indicate that the thickness of thin tephra is quite variable over small areas and in time periods spanning a few months to 500 years. Our observations in the Western Finisterre Ranges are of particular interest as they raise questions about the representativeness of isolated measurements of tephra thickness, the number of measurements necessary to determine mean thickness adequately, and attendant inaccuracies in isopach maps of tephra distribution and estimates of ashfall volume.

Measured thicknesses ranged from 1 to 19 cm but Tibito Tephra was missing from 17 cores (11.8% of cores). Mean thickness for all 148 cores was 49.1 ± 36.5 mm, but if only those cores where Tibito Tephra was identified are sampled the mean becomes 55.4 ± 34 mm.

Mean tephra thickness for the 1912 Novarupta tephra sampled on Kodiak Island is about 160 mm with

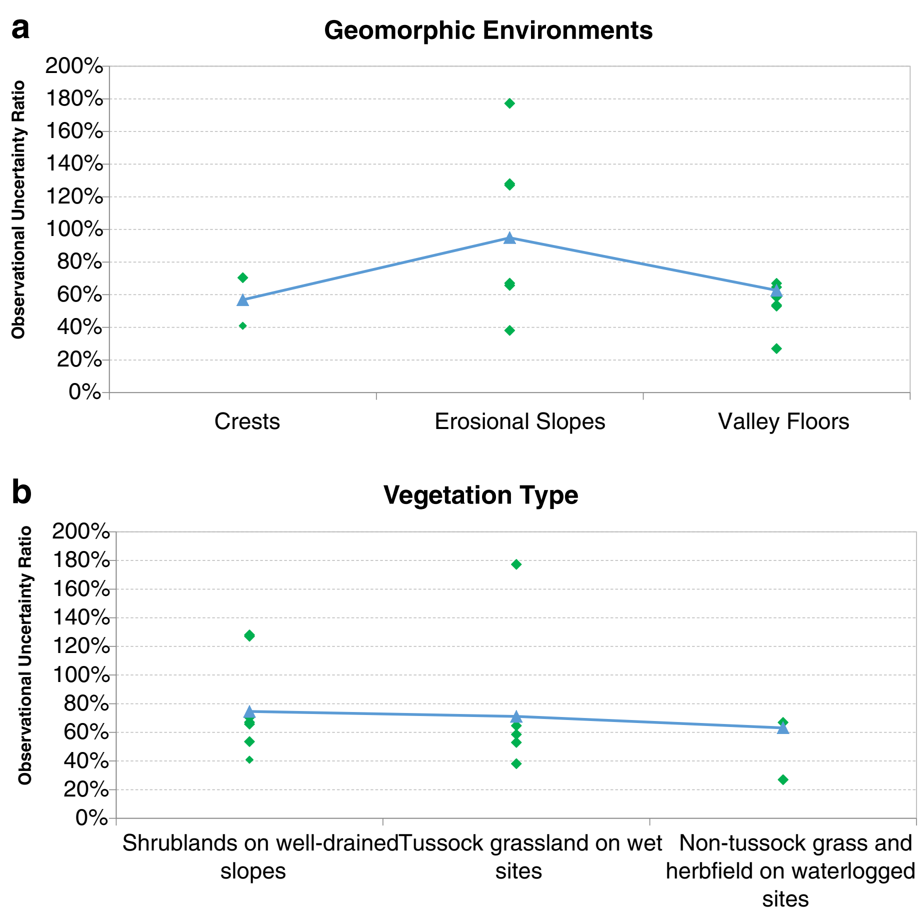

Fig. 9 Observational Uncertainty estimated, following Engwell et al. (2013), for western Finisterre sites. **a** Geomorphic environments; **b** Vegetation types

Standard Deviation (SD) = 63.4 mm (Fig. 10). As for Tibito Tephra, Novarupta tephra thickness also varies markedly over small areas. Figure 10 also shows the variability in thicknesses recorded at just one of the Kodiak sample sites - Site X 7.

Site X 7, near Kalsin Bay (Fig. 3), has a north eastern aspect on an undulating slope of 6–10 degrees 20–30 m above sea level and underlain by about 1 m of brown soil on till. The site was covered with grasses, fireweed, salmonberry, and mosses with part of the site just 20 m from a spruce forest. Tephra cover appeared to be continuous with 24 measurements made at about 5 m intervals along the road cutting. Figure 10 shows the variability in tephra thickness in this essentially homogeneous site. All three layers of Novarupta tephra could be recognised at only 6 of the 24 sites, with Layer 3 present at 7 of the 24 sites. Mixing and diffusion were most common at the top of the tephra and rare at the sharp and regular base (cf. Fig. 4). The range in thickness appeared to result mainly from the surface microrelief of the site before tephra deposition. Interestingly, the mean and SD of the thickness at this one site with all measurements within 120 m or so of one another are essentially the same as the mean and SD for all 26 sites measured on Kodiak Island which are spread out across more than 50 km of the north eastern coast (for 26 sites: Mean = 164 mm; SD = 63.4 mm; for Site X7: Mean = 160 mm; SD = 61.8 mm).

The high variability in tephra thickness shown in the Western Finisterres and the Kodiak sites has implications for how many samples are necessary to confidently determine mean tephra thickness at sites with thin tephra (i.e. less than 200 mm). Table 5 summarises the number of records, mean thickness and the standard deviation of the thickness for the Western Finisterres, Ohanopecosh and Kodiak sites. The 'Confidence' column shows the confidence we have that the mean thickness is correct to within ±10 mm and the last column indicates the number of thickness measurements required at each site to estimate the mean thickness with 95% confidence.

If the sample statistics shown in Table 5 are representative of thin tephra variability within small sample areas, there are few studies where we can be confident that we have adequately assessed mean tephra thickness, and we need many more measurements to be reasonably certain that our conclusions are soundly based.

Conclusions and implications

Based on the Mt. Hagen tephra deposition experiment, compaction occurs rapidly after deposition, primarily, we suspect, as a result of raindrop impact; records of tephra thickness (and of bulk density) may be quite dependent on how long after deposition measurements were made. While much of the evidence is little more than anecdotal, both thickness and bulk density measurements of "freshly fallen tephra" reported in the literature need to be interpreted with care. Careful analyses of freshly fallen tephra across a range of thicknesses, grain sizes, and environmental conditions are required.

While the statement that individual sand and silt-sized tephra grains may be retained on leaves and take weeks or longer to reach the ground surface is of no surprise, the observation that some 1912 Novarupta tephra was still perched on some of the large horizontal branches of spruce trees 66 years after the eruption is more startling. Deposition of these moss-covered lenses of tephra in a stratigraphic soil sequence may not take place until tree fall occurs, perhaps hundreds of years after the tephra fall.

Erosional reworking of thin tephra at the sites examined is not rapid even on steeper slopes. At the high altitude Western Finisterres and the high latitude Kodiak Island sites thin tephra remain well preserved for decades to centuries despite the relatively high rainfalls in both environments. Nonetheless, in the Western

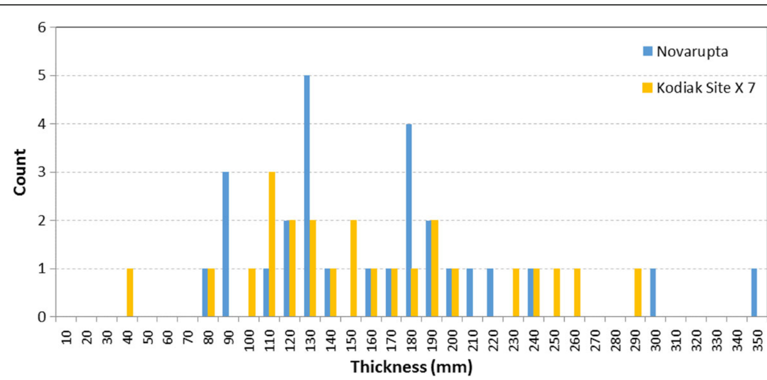

Fig. 10 Variability of Novarupta (1912) tephra thickness at 26 sample sites on the north eastern portion of Kodiak Island and tephra thicknesses at Kodiak Site X 7 (location on Fig. 3), an exposure spanning just 120 m in length. Kodiak Island (26 sites): Mean = 164 mm; SD = 63.4 mm, Kodiak Site X 7: Mean = 160 mm; SD = 61.8 mm

Table 5 Sample sizes, mean thicknesses and standard deviations of tephra thickness at each of the sample sites. Confidence limits for the sample size assuming a 10 mm error in mean thickness is acceptable and the number of samples required to estimate the mean thickness with 95% confidence

Location	n	$\bar{x}$	δ	Confidence; 10 mm Error	n; 95% Confidence Interval
W Finisterres, PNG	148	49.1	36.5	99.9%	52
Crests	*26*	*46.2*	*26.2*	*94.8%*	*27*
Erosional slopes	*58*	*38.1*	*36.2*	*96.5%*	*51*
Depositional sites	*64*	*60.2*	*37.7*	*96.6%*	*55*
Non tussock; waterlogged	*14*	*70.0*	*44.2*	*60.5%*	*76*
Tussock; wet sites	*53*	*56.0*	*39.8*	*93.3%*	*61*
Shrublands; well-drained	*81*	*40.9*	*30.5*	*99.7%*	*36*
Ohanopecosh, WA	19	51.6	24.5	92.5%	24
Kodiak, AK	26	164.0	63.4	57.6%	155
Kodiak Site X7	24	160.4	61.8	57.1%	147

Finisterres, mean and median thicknesses on slope crests lie between those for erosional slopes and depositional valley floors, and the observational uncertainty estimated from the erosional sites is substantially larger than for slope crest and valley floor sites.

On erosional slopes in the Western Finisterres 20% of soil cores recorded no tephra, compared with 12% on slope crests and 5% on valley floors, emphasising that a reasonable number of sites or cores need to be examined to confirm the presence/absence of thin tephra.

Biological activity plays a major role in tephra preservation. In PNG the 350-year old Tibito Tephra is not present under forest but is well-preserved in alpine grasslands. On Mt. Rainier 500-year old tephra is readily preserved under forest where biological turnover is assumed less rapid than in highlands PNG but absent as an identifiable layer under grasslands where gophers thoroughly mix soils, evidently within a few decades of deposition.

The depth of burial of Tibito Tephra by subsequent biological activity is greatest on valley floors, least on slope crests, and intermediate on 'erosional' slopes. The depth of burial of the tephra is least on shrublands on well-drained sites waterlogged non-tussock grass and herbfield sites, and greater on wet tussock grassland sites.

Despite the weak relationship between slope steepness and tephra thickness, variability in thickness is quite high. On Kodiak Island variability across even a few metres is similar to that observed across the whole north eastern end of the island.

The marked variability in thickness for thin tephra suggests that large (even impractically large) samples sizes are necessary to adequately determine mean tephra thickness with reasonable confidence.

Our observations emphasise the importance of rapid initial compaction, vegetative substrate and faunal activity as factors influencing survival and preservation of thin tephra. These conclusions stand in contrast to the emphasis on rapid erosional removal reported for thicker tephra. These observations of thin tephra preservation here are of significance in interpreting tephrostratigraphic sequences, the recording of mean tephra thickness, the construction of isopach maps, and the determination of ashfall volumes and eruption magnitudes. They may also be relevant to the interpretation of archaeological sites and lacustrine sequences.

Endnotes

[1]Fierstein and Hildreth (1992) recognise eight Novarupta (1912) tephra and six colour "zones" of tephra on Kodiak Island. Their rhyolitic plinian layer A and compositionally heterogeneous B appear to correspond to Reiger and Wunderlich's (1956) Layer 1, plinian dacite C + D and fine ash E with layer 2, and plinian dacite F + G and fine ash H with Layer 3, recognising that subunit distinctions fade with distance from the source.

[2]The timing of the introduction of the sweet potato into Papua New Guinea is a matter of debate. See, for example, Ballard et al. (2005)

[3]Griggs (1922, p28 and 38) includes photographs of old forest spruce with moss-covered trunk and branches loaded with ash near Kodiak and comments "moss balls held quantities of the falling ash, which have since been consolidated and bound in place by new growth". In 1978 David Gringrich of Kodiak Island pointed out to the first author that large horizontal branches on some old spruce trees still had 1912 Novarupta tephra on upper surfaces with moss growing on them. Sixty six years after the eruption, some Novarupta tephra had still not reached the ground!

[4]500 years old in 1978 at the time of the investigation reported here.

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Authors' contributions
Fieldwork and data analysis for the Western Finisterres, PNG study was undertaken by NE and RB. RB developed and maintained the experimental plots in Mount Hagen, PNG and performed the field measurements on Kodiak Island and around Mount Rainier. All statistical analysis was completed by PG. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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