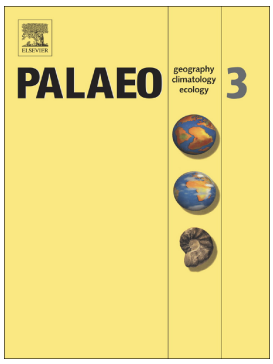

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The role of vegetation cover and slope angle in tephra layer preservation and implications for Quaternary tephrostratigraphy

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Abstract

Our aim is to understand the significance of slope position, slope angle and the interplay between slopes and vegetation in influencing the ways in which tephra layers may be preserved, thickened or thinned within the Quaternary stratigraphic record. This matters because tephra layers are used to reconstruct volumes of past volcanic eruptions and assess both past and future risks, hazards and impacts. This study uses modern data to better understand the formation of the palaeoenvironmental record and evaluates a data set of > 5,500 tephra layer thickness measurements across a range of slopes and vegetation types in Iceland and Washington State, USA. We measured tephra layers formed in October 1918, March 1947, May 1980, April 2010 and May 2011 across moderate slopes (< 35 °). Holding vegetation communities constant, location on slope had no systematic impact on mean tephra layer thickness. Holding slopes constant (< 5 °), we observed systematic modifications of initial fallout thickness in areas of different vegetation types, with layers both thinning and thickening in areas of partial vegetation cover, and thickening within taller vegetation. This has implications for the interpretation of Quaternary environmental record and the reconstruction of past volcanic fallout across areas of varied relief and strong vegetation gradients, where vegetation structure is patchy and topography is variable. Sloping sites with a consistent vegetation cover may produce the most reliable stratigraphic records of fallout whereas flat sites with varied vegetation might not.

Highlights (3-5 bullet points, max 85 characters per point)

- Tephra layers 1–10 cm thick are stable on vegetated slopes < 35 °
- Uniformly vegetated slopes < 35 ° produce consistent stratigraphic tephra records
- Differences in vegetation type affect the thickness of preserved tephra layers
- Tephra layers formed below tall shrubs may be 36 % thicker than the original fallout
- Strong regional vegetation gradients can systematically modify tephra isopach maps

1. Introduction

The overall aim of this paper is to refine the reconstructions of Quaternary volcanic eruptions through a better understand the role that slopes and surface vegetation play in the preservation of tephra layers, and thus how the thickness of tephra layers may be modified as they transition from surface fallout deposits to layers within the Quaternary stratigraphic record. We focus on layers that are 1–10 cm thick that may cover very large areas. Understanding why the thickness of tephra layers may change after their initial deposition is important because layer thickness is used to reconstruct the volume of past volcanic eruptions, and thus potential risks, hazards and impacts (de Silva and Zielinski 1998, Larsen et al. 2001, Lowe 2011, Óladóttir et al. 2014, Bonadonna

and Costa 2012). The accurate measurement of tephra layers within the Quaternary stratigraphic record presents three major challenges. Firstly, how many measurements are necessary to determine the thickness at a particular place; secondly, how many sampling sites are needed to map the fallout accurately, and thirdly, what parts of the landscape to measure-or avoid because they contain a modified record of the original fallout. The question of how to select sampling sites is crucial; the measurements at each sampling site may be accurate and the overall density of sampling points apt, but if there is some systematic bias in the points chosen (for example, they are all sites in basins where fallout is concentrated), then the final result will be flawed.

In this paper, we focus on the influence of slopes on the development of the tephrostratigraphic record in mid-latitude areas, while developing our analysis of the influence of vegetation on tephra layer preservation (Cutler et al. 2016a, b). This paper complements a recent study by Blong et al. (2017) who use a contrasting methodology to report tephra measurements from sites in Alaska, Washington State and Papua New Guinea. Engwell and others (2013, 2015) have addressed the question of how best to measure thicknesses of tephra metres thick (m-scale) but not questions of site selection. We extend their fundamental analysis on how to best measure layers with data on much thinner (and potentially much more extensive) layers, ca. 10 cm thick. We then focus on the quite different question of the effects of different slope locations and vegetation types on the thickness of preserved tephra layers used in palaeo-environmental reconstruction.

Tephra layers between 1–10 cm thick are particularly important because of the continental-scale areas they can cover and the proportion of the total volcanic fallout they may represent (Table 1). They are, for example, the typical scale of deposits found across the Indian sub-continent from the youngest (ca. 74,000 yr BP) Toba Tuff (Acharyya and Basu 1993) and the fallout from ca. 7,700 yr BP Mount Mazama eruption found across Nevada, the Pacific Northwest and parts of southern Canada (Lidstrom 1971). They also indicate the spatial extent of comparatively low concentrations of volcanic ash within the atmosphere, a hazard that can have a wide range of impacts from increased human mortality to the massive disruption of air travel (Davies et al. 2010, Grattan et al. 2003).

The tephra layers from some modern eruptions were measured soon after they were formed (e.g. Thorarinsson 1954, Sarna-Wojcicki et al. 1981, Scasso et al. 1994, Gudmundsson et al. 2012). These records provide accurate data on fallout that stress the importance of thin tephra layers for reconstructing the volumes of past volcanic eruptions. The 1991 AD Cerro Hudson eruption, for example, created an onshore tephra layer > 1cm thick over an area of more than 75,500 km^2; 95 % of this area was covered by ash fall 1–10 cm deep, accounting for more than a third of the total volume on land (Scasso et al. 1994). When offshore estimates are included, the area of tephra deposition 1–10 cm thick may have covered ca. 160,000 km^2, possibly accounting for more than 98 % of the total fallout zone receiving more than 1 cm of deposition and about 55 % of the total volume (Scasso et al. 1994).

(Insert Table 1 here)

As a layer of tephra stabilises, compacts and becomes part of the enduring stratigraphic record, Earth surface processes can drive a range of changes: 1) the tephra layer may be buried with comparatively little modification; 2) the deposit may be partially eroded to produce a thinner tephra layer, or 3) the site of initial fallout may receive further inputs of tephra, re-mobilised from elsewhere, generating a thicker layer (Fig. 1).

(Insert Fig. 1 here)

1.1 Scientific Context

Tephra layers are a very important source of palaeoenvironmental data for reasons that are well-established and include the estimation of past eruption volumes (Pyle 1989, Engwell et al. 2015), identifying volcanic impacts, reconstructing past atmospheric circulation patterns (Larsen et al. 2001, Huang et al 2001), and establishing the isochrons which form the basis of tephrochronology (Thorarinsson 1944, Lowe 2011). Tephrochronology has uniquely powerful applications in palaeogeography that extend from local (e.g. Dugmore and Erskine 1994, Streeter and Dugmore 2014) to continental scales (e.g. Davies 2015) and include methodological developments (e.g. Kirkbride and Dugmore 2001). New uses of tephra layers include the utilisation of layer morphology as a source of data on surface resilience and proximity to threshold crossing events (Streeter and Dugmore 2013).

Observations following recent eruptions in Iceland and Chile reported by Lui and others (2014) show that tephra may remain mobile long after its initial deposition. Freshly deposited tephra layers — especially those with a fine particle sizes —may be highly erodible and subject to wholesale movement where the potential for erosion by Earth surface processes such as wind, rain splash and flowing water is high (Collins et al. 1983). Soil profiles, peat sections or other sub-aerial sequences may avoid the sediment focussing effects of topographic basins and while they usually preserve shorter and less complete palaeoenvironmental records than lakes, they are much more widespread and thus of key importance for the accurate mapping of fallout. Where sub-aerial sequences are used, a key recording principle (especially in areas of m-scale thicknesses of fallout) is to avoid measurements on slopes and to gather thickness data from flat, geomorphologically stable areas which should not receive either an exaggerated input from surrounding areas, or suffer from surface erosion (e.g. Engwell et al. 2013). In landscapes with variable local relief (such as the major mountain chains) it can be difficult to find a sufficiently widespread and frequent occurrence of stable depositional environments for accurate mapping. This problem complicates our understanding of tephra stratigraphy in mountainous areas, e.g. southern Chile and Argentina (Fontijin et al. 2014). Do we have to avoid all slopes when seeking to reconstruct primary tephra layers, or are there circumstances when slopes can produce data representative of the original fallout? On the one hand, it is imperative to find sites that best reflect the original fallout, both in terms of layer thickness/mass loading and internal stratigraphy; on the other hand, given the limitations of the

terrestrial record, it is important not to ignore sites that could contain good data, because fallout reconstruction gains accuracy with more data points.

Where tephra is deposited on steep slopes and left exposed to sub-aerial processes, disturbance is likely to result in down-slope movement due to well understood slope processes (e.g. Selby 1982). On 25 ˚ slopes, for example, 95 % of particles dislodged by rain splash will move down-slope, and in arid conditions dry flows of unconsolidated sand may also occur (Summerfield 2014). In persistently wet conditions, compacted deposits of tephra may become saturated and move down shallow slopes as a result of creep or flow, and when precipitation exceeds surface infiltration rates, sheet wash or rill action may occur and move grains down-slope (Summerfield 2014).

Wholesale movement of Viking Age tephra on slopes has occurred at Stóramörk in southern Iceland, where there is significant down-slope thickening of the Katla 920 AD tephra (Mairs et al. 2006). Locally the tephra layer is typically about 20 mm thick, but in mid-slope locations it thickens by an order of magnitude and the layer can reach thicknesses greater than 500 mm at the slope foot. These slopes were wooded before the late 9th century AD Norse settlement of Iceland and were abruptly cleared in the early 10th century shortly before the tephra deposition (Mairs et al. 2006; Vickers et al. 2011). The instabilities related to the major ecological changes contemporaneous with the ash fall could account for this extensive down-slope tephra movement (Mairs et al. 2006). In contrast, uniform tephra layers that reflect our best understanding of initial fallout thickness formed in areas that did not experience major contemporaneous

changes in surface vegetation (Streeter and Dugmore 2014). This implies that in some circumstances, such as across scales of tens to hundreds of metres within homogenous, short vegetation cover, tephra deposits can exhibit a noticeable uniformity of thickness, even in contexts where the long-term gradual accumulation of aeolian sediment is significantly greater down-slope and reduces away from localised sediment sources (Dugmore et al. 2009).

The comparatively limited occurrence of down-slope thickening of tephra layers observed in soil sections across southern Iceland suggests that slope processes can be moderated by other factors. In most areas of the world this is likely to be the influence of vegetation cover which moderates slope processes by modifying near-surface winds and altering rainfall intensity at the surface (e.g. Furbish et al. 2009; Bochet et al. 2000). We have identified a landscape-scale relationship between vegetation type and tephra thickness (Cutler et al. 2016a, 2016b), emphasising the importance of vegetation structure in the preservation of tephra deposits on level ground, but leaving unresolved the relative importance of vegetation and slope. It is possible that controls exerted by vegetation structures and ground cover may counteract the influence of slope processes and topographic location.

1.2 Research Objectives

Focussing on surfaces not subject to wholesale disturbance by a ground dwelling fauna (such as termites or gophers), we hypothesise that in the case of fine-grained (silt-gravel grade) tephra layers 1–10 cm thick, the principal

controls over the extent to which the thickness of a tephra layer is modified are ecological factors (e.g. vegetation architecture, percentage cover and biocrust formation) and these factors will outweigh the effects of slope angles and locations on slope (geomorphological processes).

In the case of fine-grained tephra layers < 10 cm thick, we pose the following question: *Does surface vegetation cover at the time of tephra deposition have a greater effect than slope locations on which areas may preserve, thicken or lose the initial fallout?*

The task of mapping extensive tephra layers is simplified if data from sloping sites can be used reliably, especially in areas of varied local relief. On the other hand, the task is made more complex if understanding the vegetation cover at the time of the eruption becomes important. Selecting areas with the same vegetation cover will make thickness data consistent, but knowing whether that cover has led to a simple preservation, thickening or thinning of the tephra layer becomes important.

2. Approach and methods

An analysis of modern eruptions with contemporaneous tephra measurements is the best way to refine our understanding of Quaternary stratigraphic records and palaeoenvironments.

2.1 Sampling locations

We focus on tephra layers 1–10 cm thick within the stratigraphic record formed by five separate eruptions between 1918 and 2011 AD. The tephra layers are distributed across six different locations in two very different tree-less environments (Table 2, Fig. 2). In the case of our two 21st century examples (the layers from Grímsvötn in May 2011 (G2011) and Eyjafjallajökull in April 2010 (Ey2010)) we made thickness measurements when the layers had stabilised within the root zone of the surface vegetation. Despite the 35 years that elapsed between the initial deposition of the Mount St Helens eruption in May 1980 (MSH1980) and our distal measurements of thickness the stabilised tephra was still very close to the surface, lying below a thin (3–25 mm) biological soil crust (biocrust). Rates of aeolian sediment deposition in southern Iceland are rapid (in the order of 1 mm yr^{-1}) so that the tephra layers from Hekla in March 1947 (H1947) and Katla in October 1918 (K1918) are now buried up to 400 mm below the surface.

(Insert Table 2 here)

Secondary data on the tephra layers from H1947, MSH1980 and Ey2010 came from thickness measurements made on surface deposits soon after their initial formation (Thorarinsson, 1954 and Sarna-Wojcicki et al., 1981, Gudmundsson et al., 2012, respectively). The thickness of the fallout from Katla in 1918 was not measured in detail at the time, but it has been identified at many sites since then (e.g. Kirkbride and Dugmore 2008, Streeter and Dugmore, 2014). There is a general understanding of the proximal thickness and the axis of fallout

(Larsen 2010), but as yet, no detailed isopach map of the K1918 tephra layer has been produced.

(Insert Fig. 2 here)

We are confident there has been no change in the broad categories of surface vegetation communities we have defined for our study sites (moss heath, low shrub heath, sagebrush scrub, tall shrubs; Table 3, Fig. S1) between the time of tephra fall and our surveys. In southern Iceland, against a backdrop of eroding soils, there has been a long-term stability in vegetation cover as a result of a consistent land management strategy of rangeland grazing over multi-century timescales (Vickers et al. 2011, Streeter et al., 2012, 2015). In Washington State we sampled the tephra in a ca. 300 m wide strip of unmanaged and undisturbed scrubland between the Interstate highway I-90 and a minor local road running parallel to it, east of the intersection with Route 21 (Fig. 2, Table 2).

Our study sites in Southern Iceland experience a cool maritime climate with about 2000 mm of precipitation a year, average July temperatures ca. 10 °C and average January temperatures just below freezing (Einarsson, 1984). In the 21st century, data annual precipitation totals from local weather stations at Skogar and Kirkjubæjarklaustur (Fig. 2) have varied between 1206-2640mm and about one month a year has average temperatures below zero centigrade (Veðurstofa Íslands 2017). Our sampling area in Washington State, near to the town of Ritzville, is semi-arid, with an average annual precipitation of ca. 300 mm and an average July temperature of ca. 20 °C (US Climate Data 2017).

(Insert Table 3 here)

We measured tephra thickness using two methods, the creation of exposed sections and collecting short cores with a gouge auger. Exposed cross-sections of the tephra layers were created by digging a shallow trench with a sharp spade and cleaning vertical faces with a long serrated knife that could cleanly slice through the root mat; where necessary a fine saw was used to cut thicker roots. Thickness measurements were made at right angles to the base of the layer to an accuracy of ± 1 mm. In the case of the K1918 tephra (Site He, Table 2) its burial up to 400 mm below the surface made the excavation of open sections unrealistic, so these measurements were made from multiple cores extracted using a 3 cm wide gouge auger. At these depths within the andosol profile measurements of narrow fine grained tephra layers from the gouge are consistent with measurements from exposed sections, although this is not the case when tephras are close to the surface either within the O horizon, or at the O-A horizon boundary. Tephras were identified with reference to well-known regional tephrochronologies based on their stratigraphic location, layer and grain colours, particle composition, grain size and shape (e.g. Dugmore et al, 2009; Dugmore and Erskine 1994; Kirkbride and Dugmore 2008; Waitt and Dzurisin, 1981).

We used four complementary sampling strategies:

1) *Measurement replication* tests. Two 4 – 5 m long, open section transects with measurements of tephra thickness at 15 mm horizontal intervals to assess

sample size effects combined with a meta-analysis of data from other sampling efforts listed below (Table S1).

2) *Slope transects* created from multiple (up to 10) measurements of tephra thickness from 25 cm x 25 cm open sections within similar vegetation communities at intervals of 5 – 15 m along the dip of slopes. When coring was used to measure tephra layer thickness, it took place on a grid of 30 cores located at 6 m intervals across and down the slope (Table S2).

3) *Slope plots* created from sets of 50 tephra thicknesses measurements from 75 cm long open sections on different angle slopes, haphazardly located within a small area (Table S3).

4) *Vegetation plots* created from sets of 50 thickness measurements from 75 cm long open sections on flat areas located within different vegetation types (Table S4).

2.2 Measurement replication

Two transects (Ha_t1, Ha_t2) of H1947 tephra thickness were recorded at neighbouring locations near the Ha study site (Fig. 2, Table 2). The Ha_t1 transect was set within a flat area of moss heath. Ha_t1 transect was 4.8 m long and comprised 320 thickness measurements of the H1947 tephra taken at 15 mm intervals. Ha_t2 was 5.16 m long and comprised 344 thickness measurements of H1947, also taken at 15 mm intervals. This transect was close to Ha_t1 and had a similar vegetation type but a sharply contrasting, uneven land surface where frost hummocks had broken open to expose bare soil and create a variable mosaic of vegetation and eroding patches of bare soil. We performed

bootstrap sampling of these datasets to assess the effect of sample size on the precision of the thickness estimate, based on 95% confidence intervals. Our findings informed our sampling strategies for other open sections.

2.3 Slope transects

S*lope transects* assessed the effect of slope angle and relative slope position. Transects were recorded at five locations (F, L, R, Ha, He, Fig. 2, Table S1, 2). Vegetation types ranged from low shrub heath to moss heath (Sites F, L, Ha, He: Table 3), and the sparsely vegetated ground surfaces within a sagebrush scrub (Site R). Within each transect the vegetation type was constant and slope angles recorded.

Transects were selected to avoid 'edge effects', i.e. intersections between vegetated and non-vegetated slope sections without a topographic break (this would create the potential for unconsolidated tephra to move rapidly down-slope from initial deposition on the barren area and form a thickened secondary deposit within the vegetation). For the H1947 and K1918 tephra layers (Sites Ha and He: Fig. 2, Table 2) the thickness of overlying aeolian sediment was also measured. This enabled us to compare geomorphic processes acting gradually over months and years (e.g. fine sediment added over a period of decades at a rate of ca. 0.3 – 1 mm yr^{-1}), and the near instantaneous addition of tephra over hours or days (Dugmore et al., 2009).

2.4 Slope plots

At site K (Fig. 2, Table 1, S3), 54 slope plots were recorded. These assessed the effect of slope angle and the area of vegetation cover on tephra layer thickness. Plots consisted of 50 measurements of tephra thickness taken at 15 mm intervals from 0.75 m long open sections located parallel to the slope. This generated 2700 measurements. Plot characteristics (slope angle and percentage vegetation cover based on the DOMIN scale) were recorded and all plots were located within an area of 1 km radius, well within the fallout zone (Fig. 2) so initial deposition (from a high-altitude plume originating over 50 km away and with a low gradient of fallout change) was assumed to be similar. Linear regressions were performed to determine if slope angle predicted the thickness of the tephra at a site in sites with either low (< 66 %) or high (> 66 %) levels of vegetation cover.

2.5 Vegetation plots

Vegetation plots at Langanes and Fossdalur (Sites L and F, Fig. 2, Table 2) were used to assess the impact of vegetation type on tephra layer formation. We selected a total of 29 geomorphologically stable locations where slope angles were low (< 5 ^{o}) (Table S2). At each of the 29 plots, at least 50 measurements of tephra thickness were made across an open section at horizontal intervals of 15 mm. This generated 1656 measurements. Botanical surveys of the plots recorded vascular and bryophyte species. Three ecological communities were defined. These communities were widespread and could be consistently identified across the region; we are also confident these broad groupings are temporally robust

because long-term patterns of land use have not changed significantly over the period of consideration. The ecological communities were characterised as (a) moss heath, (b) low shrub heath and (c) tall shrubs. Summaries of these vegetation types are presented in Table 3. We assigned each vegetation plot to one of these three communities based on visual inspection. At Langanes (Site L) we were able to compare our thickness measurements with the detailed Ey2010 isopach map based on measurements of the surface deposit (Gudmundsson et al., 2012).

3. Results

3.1 Measurement replication

Ha_t1, taken across a moss heath, produced a mean H1947 thickness of 9.3 mm (SE ± 0.2 mm). Ha_t2, where eroding frost hummocks had created an uneven mosaic of similar vegetation and eroding patches, had a mean thickness of 9.5 mm (SE ± 0.8 mm). Repeated areas with no surviving tephra from 1947 (thickness = 0mm) occurred within Ha_t2, and only when these were included did the means converge (SI. Fig. 2). The results of a bootstrap resampling exercise to assess the effect of sample size on these transects was plotted against selected tephra measurements from slope transects and vegetation plots also conducted for this study (Fig. 3). Accuracy of the mean increased with sample size, but there was a limited gain for increasing sample numbers beyond ca. 30 for most measurements, and ca. 50 for disturbed sections such as Ha_t2 (Fig. 3).

(Insert Fig. 3 here)

3.2 Slope transects and initial fallout thickness

The results from the slope transects (Fig. 4, Fig. S3) show that when the surface vegetation type is similar along a slope, position on slopes up to 35 ° makes no systematic difference to tephra layer thickness. This finding applies to tephra layers less than 10 cm thick whose grain sizes range from silts to coarse gravels and includes examples deposited in March, April, May and October (i.e., at different stages of the growing season).

(Insert Fig. 4 here)

In Iceland at Langanes (Site L, Table 2; Fig. 5), where Ey2010 fallout data is available (Gudmundsson et al., 2012), the thicknesses derived from the tephra layers preserved on slopes are similar to the interpolated thickness of the consolidated fallout. Differences in thickness between stratigraphic measurements of the tephra layer on slopes and estimated fallout at Langanes are minor, amounting to 0.2 – 3.6 mm, or 0.6 – 9.6 % of layer thickness. In cases where the layer thicknesses were ca. 10 % thinner than the fallout estimates (La_st8 and La_st9, Table S1) the measured sections lie 150 – 220 m west from the nearest interpolated fallout point, which is closer to the main axis of fallout, in an area where the tephra deposition thinned rapidly towards the margins of the plume.

In Washington State at site R (Fig. 2) our MSH1980 thickness data indicates an effective preservation of the tephra from 1980. The closest contemporary fallout measurement at the junction of Route 21 and I90 (< 1 km) records a thickness of 42 mm (Sarna-Wojcicki, et al, 1981). Initial fallout was loosely packed and bulk density soon increased twofold, implying a significant reduction in thickness. Our slope transect thickness means are 27 mm for Ritz slope A (Fig. 4) and 29 mm for Ritz slope B (Fig. S1), representing a 'consolidated' tephra layer thickness between about 67 –73 % of the thickness of freshly fallen tephra. No systematic variation in thickness occurs down the slopes.

3.3 Slope plots

The G2011 tephra thickness averaged 42 mm across all the 54 separate slope plots, with a range of 13 – 124 mm for plot means. Figure 5 shows the slope plot mean tephra thickness against slope angle. A linear regression of mean tephra thickness in slope plots with > 66 % vegetation cover showed no increase in mean tephra thickness with increasing slope angle ($R^2 = 0.02$, $p = 0.47$). On plots with lower levels of vegetation cover (0 - 66 %) there was a weak positive correlation of slope angle and tephra depth ($R^2 = 0.21$, $p = 0.04$) but no significant correlation with increasing variability ($R^2 = 0.14$, $p = 0.11$).

(Insert Fig. 5 here)

3.4 Vegetation Plots

We identified three consistent and widely distributed vegetation types in Iceland; tall shrubs, low shrub heath and moss heath (Table 3, Fig. S1). Tephra thickness varied with vegetation type (Table 4, Fig. 6). The lowest median thickness across the Fossdalur sites was found in moss heath. The median of thicknesses measured under low shrub heath was greater but with more variability across the data set; under tall shrubs median thickness was greatest but variability was significantly less that that found under low shrub heath. Near Eyjafjallajökull, sites were clustered to form the groups Langanes A and Langanes B; the clusters are 400–500 m apart and are assumed to have received similar amounts of fallout from the 2010 eruption. In both cases, tephra thicknesses were greatest under tall shrubs, less under low shrub heath and lowest in moss heath. When the thickness data from Langanes A and B were combined, moving from moss heath vegetation type to low shrub heath led to a consistent increase in thickness of 12 - 14 %; the transition from moss heath to tall shrubs was associated with an increase in thickness of 27 – 30 % (Table 4, Fig. 6).

(Insert Fig. 6 here)

3.5 Comparisons between vegetation plots and initial fallout

We can compare our Ey2010 tephra thickness data at the Langanes site with the surface measurements of fallout published by Gudmundsson and others

in 2012 (Table 4, Fig. 6). This data was supplied in an interpolated grid from original thickness measurements. The grid spacing was 0.5 km.

(Insert Table 4 here)

Despite the limitations of the Ey2010 fallout dataset, we can still draw out some consistent patterns. Tephra layers preserved within moss heath exhibited a similar thickness (86 – 106 %) to the initial fallout measurements. Tephra layers within low shrub heath were slightly thicker, with values 99 – 119 % of the assumed initial deposit. Tephra layers within areas of tall shrubs were consistently thicker than the initial fallout, with values 113 – 136 % of assumed initial thickness.

3.6 Comparisons between slope transects and vegetation plots on flat ground

At site F where slope transects Fd1 and Fd2 (Table S1) are located nearby to vegetation plots (Fv_7 – Fv_26, Table S2), there is close correspondence between thicknesses recorded on slopes and level sites. A t-test showed there was no significant difference between tephra thickness at slope transect Fd1 (mean = 31.9 ± 4.8 mm) and moss heath vegetation sites (mean = 31.1 ± 6.9 mm, t = — 1.3, df = 145.9, p = 0.17). No significant difference was observed between slope transect Fd2 (mean = 57.6 ± 13.8 mm) and low shrub heath sites (mean = 61.5 ± 29.3 mm, t = 1.39, df = 164.4, p = 0.16).

4. Discussion

Our evaluation of tephra layers 1-10 cm thick shows that comparable thickness data can be acquired from discrete slopes with a consistent vegetation cover, regardless of position on slope. Vegetation cover and plant architecture (stem widths, morphology, height and density per unit area) will, however, influence the preservation of the tephra layer, and may lead to significant layer thickening. Our replication experiments (Fig. 3) help constrain uncertainty and we are confident of the accuracy of mean thickness estimates on slope transects ($n <= 10$) and very confident in our mean thickness estimates from individual slope plots and vegetation plots ($n = 50$).

Freshly fallen tephra will experience differing degrees of compaction as grains pack closer together, with different rates of change for fine and coarse-grained material. This consolidation is likely to be swift, occurring over days rather than weeks, and will be accelerated by rainfall. Experimental data from Mt Hagen in Papua New Guinea show that in humid tropical conditions, freshly deposited tephra layers can be compacted to half of their initial thickness after 16 days, forming layers that are essentially the same thickness 750 days later (Blong et al. 2017). Measurements of surface deposits are often taken in the weeks-months after the eruption (eg Gudmundsson, et al. 2012), and in the case of the Ey2010 tephra, these surface measurements reflect consolidated thicknesses comparable to our stratigraphic measurements.

The influence of the vegetation cover and surface ecological processes on thin (1 – 10 cm thick) tephra layers (as opposed to the impact of tephra on the ecology) has rarely been considered (but see Cutler et al. 2016a, 2016b, Blong et al. 2017). Our data confirm that in certain circumstances vegetation cover influences the thickness of the layer that finally becomes part of the stratigraphy, through capturing more or less tephra than initially fell. Furthermore, ecological processes can act to stabilise tephra layers rapidly. Data from Washington State indicated that biocrusts can form rapidly enough to effectively stabilise cm-scale thicknesses of fine grained tephra on slopes up to 17 °.

If the thickness of shallow tephra layers varies with slope position this could be a reflection of changing patterns of vegetation, rather than the effect of topographic location.

At our sites in Iceland, the initial tephra fall blanketed the surface but its thickness did not exceed the total height of the vegetation as defined by the vertical distance from the average stem height to the soil surface. The implication is that in these cases the stem and leaf architecture of the ground cover trapped tephra and enabled it to stabilise rapidly. The ubiquitous presence of moss is likely to have aided the process of sediment stabilisation, as could the irregular surface texture of grains and their resultant ability to lock together.

We found a similar consistency of MSH1980 tephra thickness across slopes, even though the vegetation cover was quite different. The degree of preservation observed in the MSH1980 tephra was remarkable: around 75 % of

the initial deposit thickness was retained. In order to retain so much fine material, stabilisation of the tephra must have been rapid. In obviously vegetated areas (i.e. under sagebrush clumps, *Artemisia* sp., up to ca. 1.5 m high.), vegetation structure probably provided shelter, reducing wind speed and disrupting the effects of rainfall. The stabilisation of tephra in open areas with sparse vascular plant cover is best explained by the presence of a thin biocrust composed of mosses and lichens. Biocrusts are familiar features in many arid and semi-arid regions, including eastern Washington State (Johansen, 1993; Ponting and Belnap, 2012) and they are known to stabilise fine sediment (Belnap, 2001). A thin biocrust was present on all the sites we sampled and was clearly capable of capping-off the underlying deposit. Cyanobacteria and green algae can colonise suitable substrates in a matter of days to initiate biocrust formation; the development of biocrusts on fine substrates (like fine tephra) is much faster, and more homogeneous, than it is on coarse grains (Rozenstein et al., 2014). Rainfall shortly after the deposition of the MSH1980 layer promoted rapid colonisation by green algae (Rayburn et al., 1982). The formation of an abiotic crust after wetting may also have facilitated microbial colonisation. Thereafter, biological succession occurred, with increasing cover of bryophytes and lichens likely to have been important (Belnap and Lange, 2001).

Taller vegetation has the potential to trap tephra that is mobile in the weeks and months following an eruption. Our Icelandic slope plots demonstrate that in a cool maritime climate where vegetation cover is low (< 66 %) tephra layer thickness can be variable and can be both much thicker and thinner than in comparable areas with high vegetation cover. The implication is that sparsely

vegetated areas could provide a crucial role in providing sources of mobile tephra for areas covered with deeper vegetation to trap. The data from Site L (Fig. 6) indicates that even short vegetation is effective at trapping the majority of tephra fallout, although on average there was some loss of thickness. The fact that we observe in most cases a greater thickness of tephra under tall vegetation than the initial fallout thickness suggests that taller vegetation is consistently better at trapping re-mobilised tephra moving laterally across the landscape. As a result, measurements of tephra thickness may systematically under- or over-estimate the initial fallout thickness as vegetation cover varies across the landscape. We can explore the implications of this on a regional scale with a simple conceptual model (Fig. 7). The variations we propose should apply in mid-latitude environments with modest to low precipitation (annual totals <2000mm) and where there is a lack of bioturbation. Blong and others (2017) note the absence of the 15th century Mt St Helens tephra layer Wn from Alpine meadows on the slopes of Mt Ranier where northern pocket gophers (*Thomomys talpoides*) are very active. Distinct tephra layers may also be absent beneath tropical forest canopies because of ground level obstacles combined with very high rates of cycling and turnover (Blong et al. 2017).

(Insert Fig. 7 here)

While the volumes of past eruptions may be inferred from the extrapolation of proximal deposits (Burden et al., 2013) detailed maps are best produced from direct field measurement of fallout thickness. Some isopach maps have been produced for modern eruptions based on measurements of the initial

fallout (e.g. Thorarinsson 1954, Thorarinsson and Sigvaldason 1973, Scasso et al. 1994, Sarna-Wojcicki et al. 1981, Waitt and Dzurisin 1981). However, most data for estimating the size of past eruptions come from measurements of tephra layer thicknesses within surface stratigraphy (e.g. Thorarinsson 1967, Lowe 2011, Larsen et al. 1999).

Depending on the vegetation gradients around a volcano (and along the axis of fallout) surface ecology may modify the fallout record and present a misleading impression of either a more uniform fallout pattern (with proximal thinning and distal thickening of the record) or vice versa. The practical implications of this can be demonstrated with reference to the mid-Holocene Monte Burney 2 eruption (Fig. 8).

(Insert Fig. 8 here)

In Figure 8, proximal areas of fallout 1 – 10 cm occur across vegetation communities that are structurally similar to those we have studied in this paper, along with forested zones with much taller trees. In the areas characterised by tall trees and a landscape mosaic that permits tephra re-working, we would expect to find an exaggerated version of the Icelandic woodland results: where the tephra layer is preserved it should be somewhat thicker than the initial fallout, providing there is a landscape mosaic with unstable areas to provide re-mobilised tephra. In addition, the tephra deposits in the forested zones are likely to be quite uniform as fallout is homogenised below the canopy, provided that there are a limited number of ground level obstacle such as fallen trees, and

turnover of the forest floor is limited (Zobel and Antos 1991, Cutler et al. 2016b, Blong et al. 2017). Beyond the areas of low shrubs, we would expect fallout to be thinned in areas where biocrusts could not form rapidly. Thus, the choice of sampling sites could make a significance difference to both the thicknesses mapped and the shape of the inferred fallout footprint.

In addition, understanding more about how ecological processes and the type and quality of surface vegetation affects tephra layer morphology could add important new dimensions to the suite of approaches already used to infer environmental data from tephra deposits. The morphology of the Dawson tephra in Alaska, for example, has been used to infer the seasonality of the eruption (Froese et al., 2006). Tephra morphology has also been used to examine solifluction and cryoturbation (Dugmore and Buckland 1991; Kirkbride and Dugmore 2005), and as an Early Warning Signal (EWS, Scheffer et al. (2012)) of upcoming land surface transitions (Streeter and Dugmore 2013). Thicker tephra layers can preserve characteristics and even the vegetation of a land surface for long periods (at least 25 kyr, e.g. Froese et al. (2006)). These approaches can complement more widely used palaeoenvironmental techniques, and can provide spatial data which cannot be gathered in any other way (Zazula et al. 2006; Dugmore and Newton 2012).

4.1 Recommendations for tephra layer measurement

1. Thickness measurements of tephra layers on discrete slope units can be representative of fallout thickness where:

- a minimum of three averaged site measurements down-slope (with a spacing of metre-scale) are taken and the thicknesses are consistent;
- there is a consistent vegetation community or biocrust formation on the slope unit;
- the slope unit is morphologically distinct and isolated such that tephra cannot flow onto the slope unit from adjacent slopes;
- tephra is not intercepted prior to reaching the ground surface, for example by snow cover or other ground level obstacles.

2. Different vegetation communities at the time of fallout can introduce systematic and measurable differences in the preserved thicknesses of tephra, either increasing thickness variability or systematically reducing the volume of stabilized tephra. Where a tephra plumes crosses vegetation communities, this effect can steepen or reduce the apparent gradient in tephra fallout thinning from source.
3. Tephra layer thickness can often be highly variable at sub-metre scales but when sampled adequately over m-scale can produce thicknesses which are consistent and representative of initial fallout.
4. Tephra thickness can be uniform in thickness over m-scale but the average thickness may not be representative of the original fallout where:
    - tephra has been intercepted and removed from the location prior to contact with the ground surface;
    - tephra has been displaced from surrounding areas and the deposition focused.

Therefore, uniformity of tephra thickness, even over multiple m-scales, is not necessarily a reliable indicator of representativeness. This can be checked by having sites which are distributed between multiple topographic settings and comparable vegetation communities.

5. Conclusions

On discrete slopes up to 35 °, measurements taken under similar vegetation communities can produce similar estimates of tephra thickness for tephra layers 1–10cm thick, regardless of position on slope. Thus, sloping locations can produce accurate data on layer thicknesses and need not be shunned in mapping exercises.

Differences in vegetation cover can significantly affect the thickness of tephra preserved in stratigraphic sequences. Tephra layers formed below tall shrubs may be 36 % thicker than the original fallout. Therefore, vegetation cover at time of eruption should be taken into account when producing estimates of fallout volume, especially if the fallout crosses strong vegetation gradients where individual plant communities are patchy and there is scope for localised tephra re-mobilisation.

Biocrusts appear to have great potential to stabilise thin (1 – 10 cm thick), fine-grained tephra layers. Given the ubiquity of biocrust cover in arid and semi-

arid areas, biocrust formation could be of great significance in volcanically active regions such as Central and South America, in addition to the interior of the American West. The early stages of biocrust formation on new tephra substrates are, however, unstudied.

The identification of circumstances when the architecture of surface vegetation exerts a greater influence than topography in the reduction, conservation or augmentation of tephra layers < 10 cm thick is important because such layers are found across very large parts of the Earth's surface. These types of tephra layers also typically make up over half the volume of fallout of a plinian eruption. This data also show that the morphology and thickness of visible tephra layers within stratigraphic sequences can also form an important environmental archive in addition to their value as isochrons.

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Figure list

Fig.1
Possible transformations of a tephra layer after its initial deposition on a land surface, and the changes that may result as a layer becomes preserved in the stratigraphy.

Fig. 2 (Colour)
Map showing sampling locations (red points) and 1cm thickness isopachs from studied eruptions whose locations are indicated by the larger triangles. Isopachs in a) are from G2011 (Thordarson and Höskuldsson, 2014); Ey2010 (Gudmundsson et al., 2012); Hekla 1947 (Thorarinsson, 1954). Arrow shows main axis of fallout from Katla 1918; the isopach from this eruption is not well defined (Larsen, 2010). Isopach in b) is from the 1980 eruption of Mt St Helens (Sarna-Wojciki et al., 1981). Sites are as follows: in a) Hamragardur (Ha), Langanes (L), Heidarsel (He), Kalfalfell (K) and Fossdalur (F). In b) Ritzville (R). In a) glaciers are white areas against the grey of the land. In b) state boundaries are dotted lines and interstate highways are solid lines

Fig. 3 (Colour)
The accuracy of measurements of tephra thickness based on number of measurements of tephra thickness observed. The stars indicate our range of sample sizes.

Fig. 4 (Colour)
Tephra layer thickness from selected down-slope transects from five eruptions in the last 100 years. Closed circles show mean thickness for each location and bars show 1 SE. In b) the shaded area shows the fallout thickness range at this location from Gudmundsson and others (2012). The overall slope angle is the calculated slope angle based on the start and end locations of the transect. These data show circumstances under which the thickness of tephra layers does not vary according to position on slope. At these sites (Table 2) the K1918(Site He), MtStH 1980 (Site R), Ey2010 (Site La) and G2011 (Site F) are all fine grained; H 1947 (Site Ha) is a coarse sand-fine gravel; the Icelandic tephra deposits occurred in different months and stages of vegetation growth; H1947 fell in March, Ey2010 in April and G2011 in May; K1918 fell in October.

Fig. 5
Relationship between slope angle and mean Grímsvötn 2011 tephra thickness at Kalfafell, southern Iceland. Solid points indicate locations where vegetation cover was low, and a regression (solid line) shows a trend of increasing tephra thickness with increasing slope angle. Semi-vegetated sites show a greater range of mean tephra thickness — with areas that are both thinner and thicker than those of neighbouring vegetated sites.

Fig. 6
Tephra thickness from areas of differing vegetation cover at sites F and La. Bold bars show median thickness, notches indicate 95% confidence intervals, and the

ends of the dashed lines indicate the highest and lowest measurements. Initial fallout thicknesses are on the uncompacted layer

Fig. 7
Tephra re-mobilisation and re-deposition in relation to vegetation type and the implications for preserved tephra thickness when volcanic fallout across major ecotones.

Fig. 8 (Colour)
An illustration of a tephra layer that spans a large range of ecological conditions. Isopachs are as shown in Stern (2008) and show the >10cm, >5cm and >1cm thicknesses for the mid-Holocene Monte Burney 2 eruption. Vegetation cover is from MODIS 2001 and classification is based on a simplification of the International Geosphere Biosphere Programme Land Cover Classification (IGPB) (Belward. 1996) categories to best reflect vegetation categories used in this paper.

Tables

Table 1: Examples of selected tephra layers where 49-89 % of the total fallout occurred as tephra layers 1-10 cm thick

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Eruption	V_{tot} (km^3) [1]	V_{1-10} (km^3) [2]	V_{1-10} (%)	Source
Mt Burney 2 (ca. 3830 BP)	2.8	2.5	89	Stern (2008)
Huaynaputina (1600 AD)	19.2	14.6	76	deSilva & Zielinski (1998)
Quizapu (1932 AD)	9.5	5.6	59	Hildreth & Drake (1992)
Cerro Hudson (1991 AD)	7.6	4.2	56	Scasso *et al*. (1994)
Quilotoa (ca. 800 BP)	18.3	8.9	49	Mothes & Hall (2008)

[1] Vtot = total fallout volume (the published value);

[2] V1-10 = volume of tephra in deposits 1 – 10 cm thick, calculated following Fierstein & Nathenson (1992)

Table 2: Details of sampling locations and measurements taken.

Site	Location	Tephra measured	Year of measurement	Original fallout thickness known?	Data collected
Fossdalur (F)	63.98° N, 17.48° W	G2011	2013	N	17 open sections in differing vegetation cover, 3 slope transects
Kalfafell (K)	63.96° N, 17.66° W	G2011	2012	N	54 open sections
Langanes (L)	63.67° N, 19.74° W	Ey2010	2013	Y	16 open sections in differing vegetation cover, 5 slope transects
Ritzville (R)	47.09° N, 118.66° W	MSH1980	2015	Y	2 slope transects
Hamragardur (Ha)	63.62° N, 19.94° W	H1947	2015	Approximately	1 slope transect and 2 transects on flat ground
Heidarsel (He)	63.80° N, 18.18° W	K1918	2014	N	Coring at 6m intervals on a 30 x 18m grid

Table 3: Vegetation groups used in this study

Vegetation type	Sites	Vegetation characteristics
Moss heath	F, K, L, Ha, He	Ground cover dominated by mosses; abundant *Racomitrium* spp. and feather mosses (notably *Hylocomium splendens)*; occasional graminoids. Max. vegetation height 0.2 - 0.3 m.
Low shrub heath	F, L	Patchy vegetation cover with abundant dwarf shrubs (*Betula x pubescens* and *Vaccinium uliginosum*, occasional *Empetrum nigrum*), with ground cover of moss (abundant *Racomitrium lanuginosum*, frequent *Hylocomium splendens*), occasional graminoids. Max. vegetation height 0.5m.
Sagebrush scrub	R	Patchy vegetation dominated by clumps of sagebrush (*Artemisia* sp.) up to ~1.5 m high; areas between sagebrush patches either covered with grass or lacking in vascular plants; the apparently bare areas were covered with a thin (0.3 - 2.5 cm) biocrust composed of mosses and lichens.
Tall shrubs	F, L	*Betula x pubescens* and/or *Salix phylicifolia* canopy ; understory comprising frequent graminoid species (*Agrostis, Poa* and *Festuca* spp., typically) and patchy moss cover; occasional forbs. Vegetation height varies from 0.5 - 4 m.

Table 4. Stratigraphic measurements of Eyjafjallajökull 2010 tephra layer thickness compared to thickness of initial fallout.

Site	Vegetation type	Tephra layer thickness as a percentage of fallout observed by Gudmundsson et al., 2012	Tephra layer thickness as a percentage of that found in moss heath vegetation type
Langanes A	Moss heath	106	100
	Low shrub heath	119	112
	Tall shrubs	136	127
Langanes B	Moss heath	86	100
	Low shrub heath	99	114
	Tall shrubs	113	130

Captions for SI Tables

Table S1 - Location and details of measurement replication test sites.

Table S2 - Location and details of slope transects.

Table S3 - Location and details of slope plots. All sites record G2011 tephra thickness and were measured in June 2012.

Table S4 - Location and details of vegetation plots.

Captions for SI Figures

Fig. S1 (Colour) - Vegetation types considered in this study (Table 2, Fig. 2). Photographed in June: a) Moss heath with three open sections visible at Site F: b) Low shrub heath on a slope transect at Site F; c) tall shrubs at Site F: d) Trench through low shrub cover showing G2011 tephra (Site F), base of tephra shown with dashed line. Photographed in May (before start of growing season): e) Tall shrubs, moss heath and shrub heath at Site L. Photographed in August, f) Sagebrush scrub at Site R.

Fig. S2 – Thickness measurements of Hekla 1947 tephra at Site Ha; a) transect Ha_t1 over continuous moss heath b) transect Ha_t2 over partially eroded area of moss heath. Dashed lines indicate mean thickness estimates.

Fig. S3 (Colour) - Slope transects of tephra layer thickness (Fig. 2, Table S1); a) and b) show G2011 thickness from Site F, c)-f) show Ey2010 thickness transects from Site L, with the nearest fallout thickness from Gudmundsson and others (2012) shown as a grey dashed line. g) Shows a slope transect of layer thickness data from MSH1980, Site R.

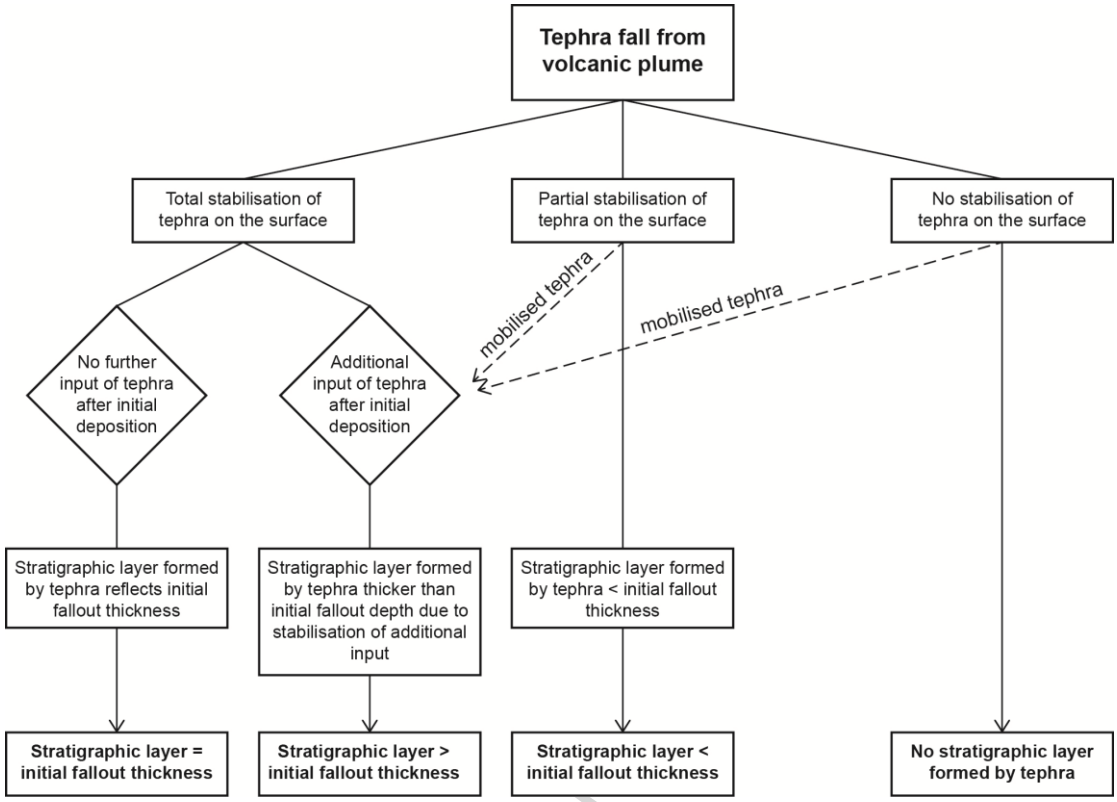

Fig. 1

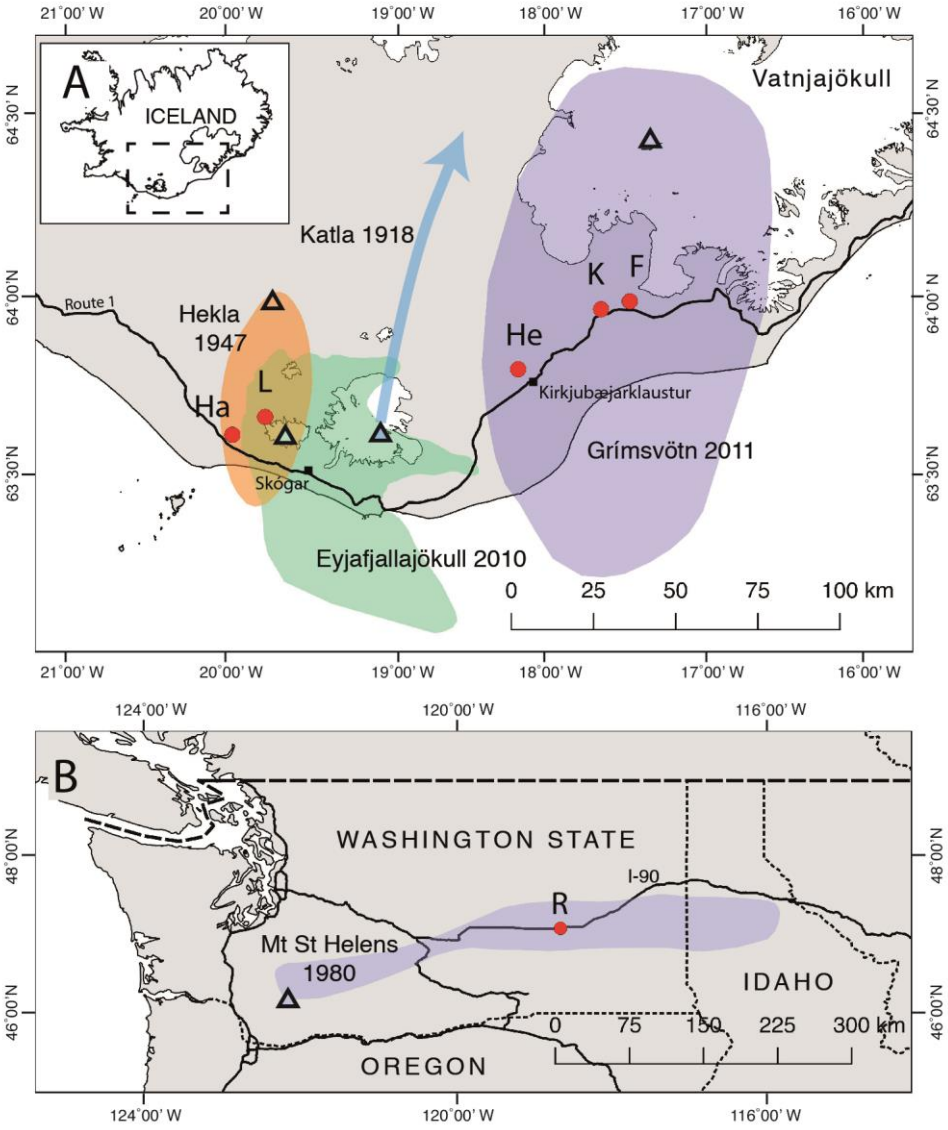

Fig. 2

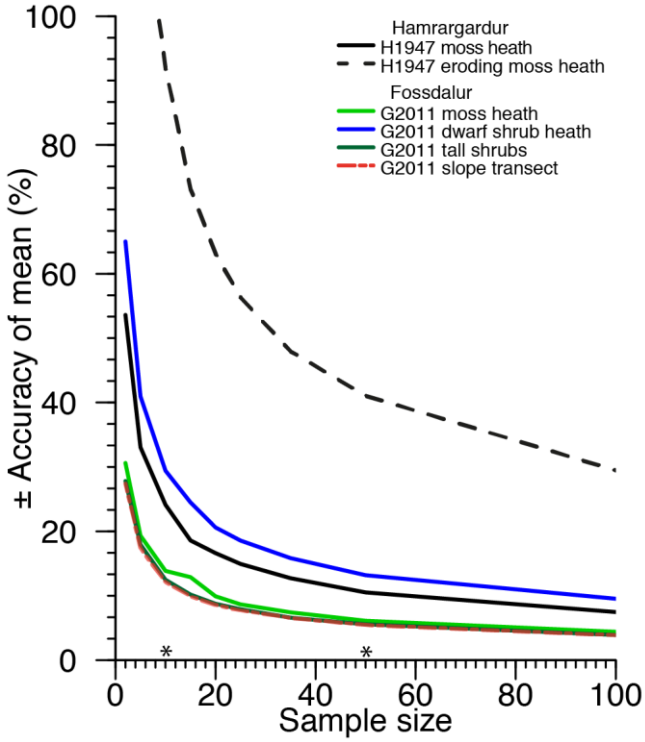

Fig. 3

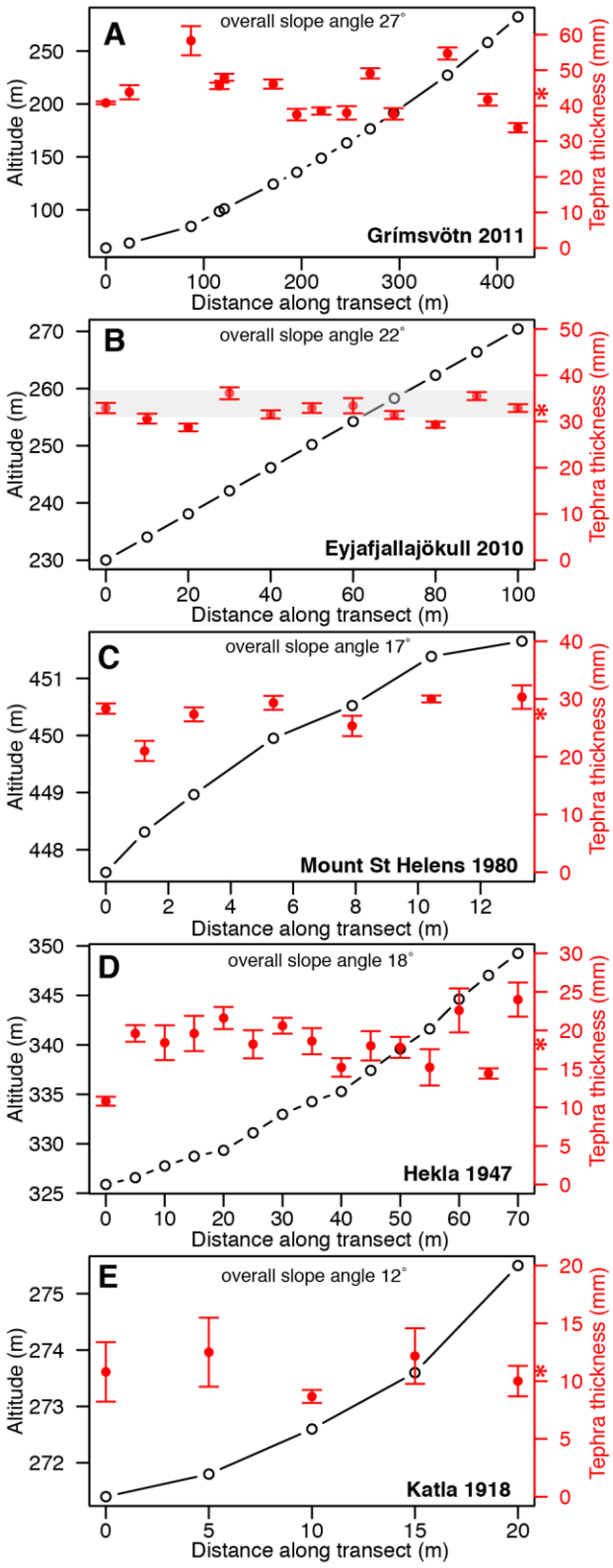

Fig. 4

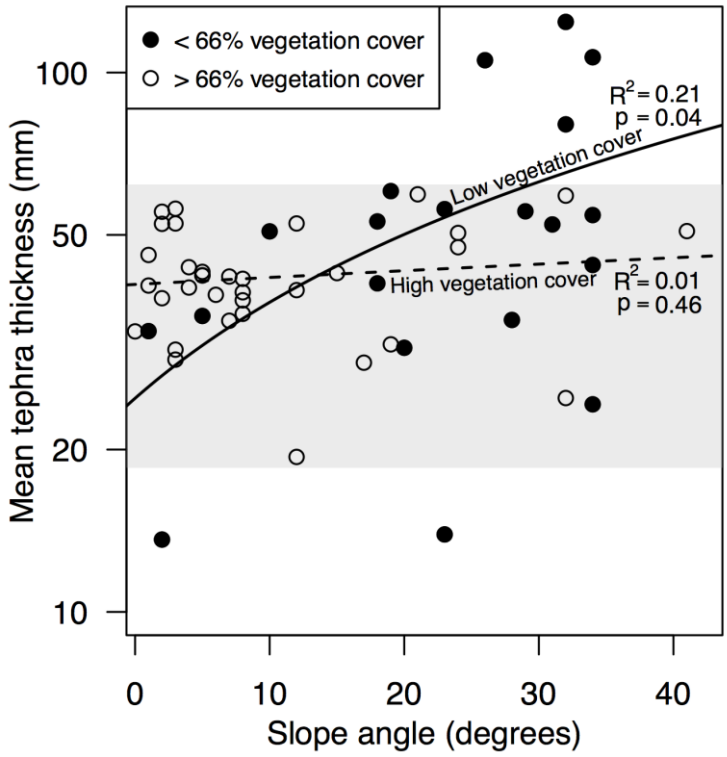

Fig. 5

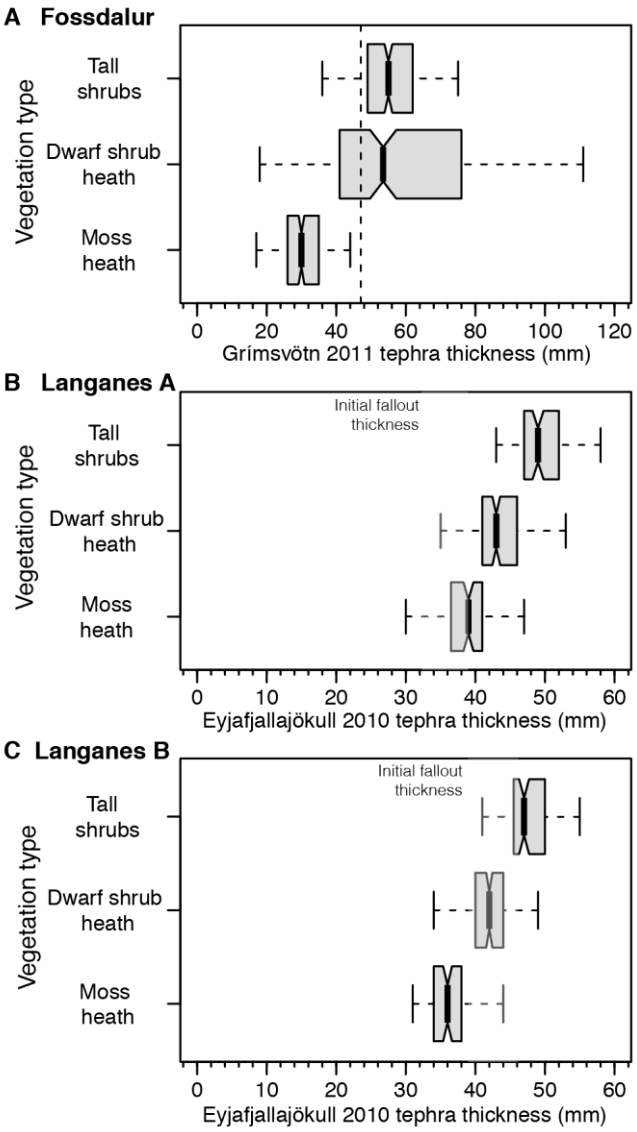

Fig. 6

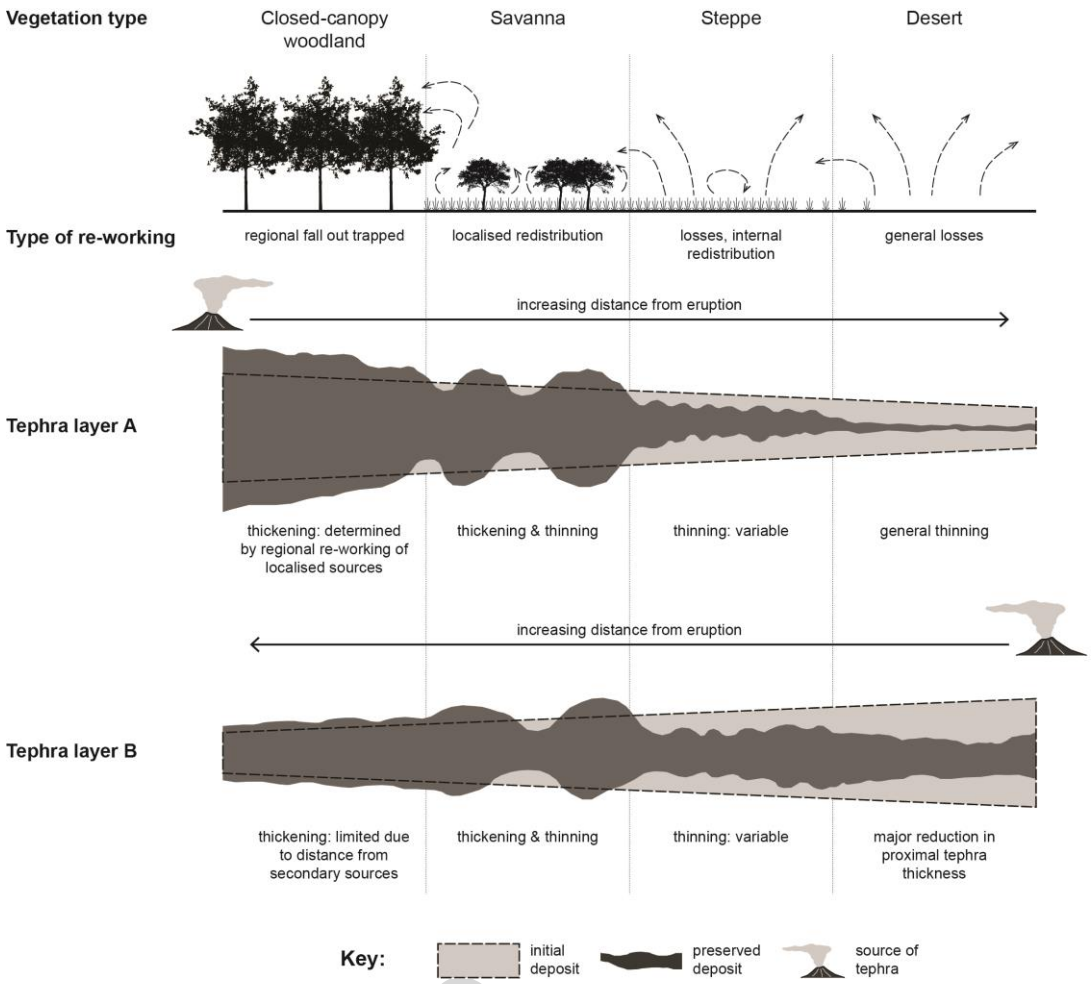

Fig. 7

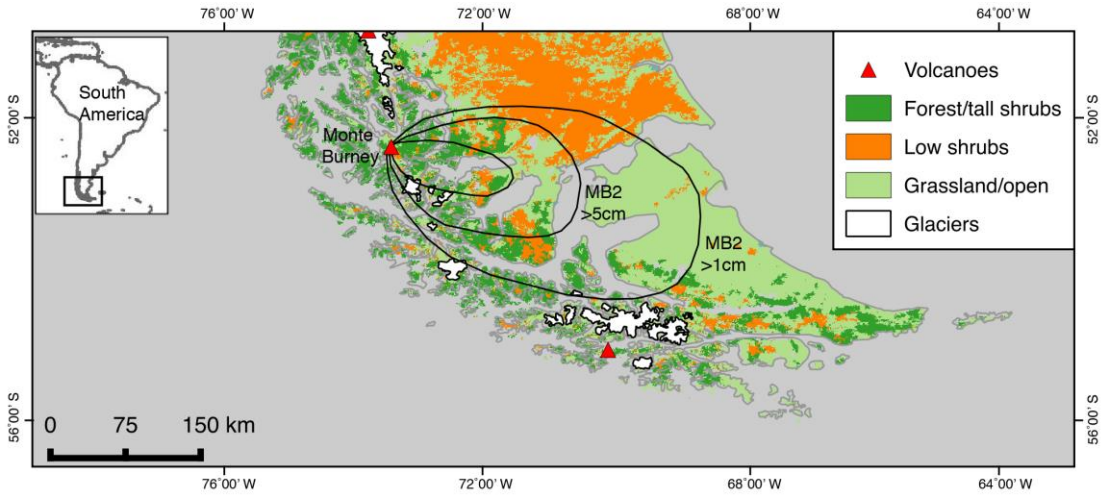

Fig. 8