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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 > 5500 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.

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, 2016b). 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 et al. (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

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

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

[a] V_{tot} = total fallout volume (the published value).
[b] $V_{1–10}$ = volume of tephra in deposits 1–10 cm thick, calculated following Fierstein and Nathenson (1992).

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 and 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 subcontinent from the youngest (ca. 74,000 yr BP) Toba Tuff (Acharyya and Basu, 1993) and the fallout from ca. 7700 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 CE Cerro Hudson eruption, for example, created an onshore tephra layer > 1 cm thick over an area of > 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 > 98% of the total fallout zone receiving > 1 cm of deposition and about 55% of the total volume (Scasso et al., 1994).

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).

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 Liu et al. (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 (Fontijn 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 CE 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 > 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,