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# The interpretative value of transformed tephra sequences.

Short running title: Transformed tephra sequences

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## ABSTRACT

We explore developments in tephra science that consider more than chronology, using case studies. Volcanic processes and prevailing weather conditions determine the distribution of tephra deposits immediately after an eruption, but as these freshly fallen tephra become part of the stratigraphic record, the thickness, morphology and definition of the layers they form changes, reflecting the interplay of the tephra, Earth surface processes, topography and vegetation structure, plus direct or indirect modification caused by people and animals. Once part of the stratigraphic record, further diagnostic changes can happen to the morphology of tephra layers, such as the creation of over folds by cryoturbation. Thus, tephra layers may contain proxy evidence of both past surface environments and subsurface processes. Transformations of tephra deposits can complicate the reconstruction of past volcanic processes and make the application of classical tephrochronology as pioneered by Thorarinsson (Sigurður Þórarinnsson in Icelandic) challenging. However, as Thorarinsson also noted, novel sources of environmental data can exist within transformed tephra sequences that include the spread or removal of tephra, variations in layer thickness and internal structures, the nature of contact surfaces and the orientation of layers.

Key words: tephrochronology, solifluction, cryoturbation, bioturbation, isochron

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## 1. Introduction

This paper has two overall aims: 1) to evaluate the transformation of tephra when they are exposed as deposits at the surface of the Earth, and later when they form discrete layers within the terrestrial sedimentary record and 2) to consider the ways in which these varied transformations can be used in Quaternary science. These aims are significant because distinctive modifications driven by specific environmental processes offer a little-used source of proxy environmental data and provide insights unobtainable by other means. In addition, modifications to tephra deposits complicate their use in both volcanology and chronology, and so a better understanding of the changes can improve our confidence in two major applications of tephra studies in Earth and Quaternary sciences. We illustrate our points with Icelandic examples of visible tephra layers < 20 cm thick. Original observations reported here are combined with a critical synthesis of previous work on the modifications of tephra deposits in many different settings (e.g. Thorarinsson 1951, 1981b; Dugmore and Buckland, 1991, Hildreth and Drake, 1992; van Vliet-Lanoë et al., 1998; Kirkbride and Dugmore, 2005, Cutler et al. 2016a,b: Table 1).

In volcanology, the reconstructions of past eruption columns/plumes and hazard assessments rely on accurate measurements of visible tephra layer thickness, internal stratigraphy, particle size distributions and tephra composition in terms of lithic fragments, crystals, and glass (e.g. Koyaguchi and Ohno, 2001; Connor et al., 2001; Bonadonna and Houghton 2005; Erlund et al., 2010; Engwell et al., 2013). If there are significant changes in the characteristics of the tephra deposit as it becomes a layer in the stratigraphic record, these need to be understood so that we can make correct inferences about volcanic processes.

In Quaternary science, recent decades have seen the emergence of tephra studies focussed on cryptotephra, the very fine-grained tephra not visible to the naked eye (Lowe and Hunt, 2001; Lowe, 2011; Davies, 2015). The global scales of cryptotephra distribution means that they offer the greatest spatial scales of correlation, enabling the linkage of primary palaeoenvironmental archives, which has greatly furthered our understanding of global change (Thorarinsson, 1981a; Davies, 2015). Thus, a key aim of tephra studies in Quaternary science is the identification of an isochron defined by the tephra in question (regardless of whether the tephra is visible to the naked eye or not) (e.g. Shane, 2000; Abbott et al., 2011; McCulloch et al., 2017). It is recognised that where a) tephra deposits within the stratigraphic record have undergone morphological transformations; b) the surfaces defined by tephra horizons have been modified, or c) tephra grains have migrated into different stratigraphic settings, then the original chronological relationships between the tephra and the material context or surface defined by the tephra will have changed (e.g. Dugmore and Newton, 2012). When the focus of a study is chronology, the modification of tephra deposits and layers can be a problem, although it may also be an opportunity to use the characteristics of transformed tephra layers to reconstruct the physical structure of the vegetation communities onto which the tephra fell, post depositional earth surface processes and subsequent movements of sediments encompassing the tephra.

Table 1 : A summary of studies that have used transformed tephra layers to infer environmental processes taking place in both marine and terrestrial environments.

Type of Transformation	Tephra layer	Evidence of:	Source
Reworking	Laacher See	<sup>1</sup> Solifluction, <sup>2</sup> Fluvial processes	<sup>1</sup> Nyssen et al., 2016. <sup>2</sup> Schmincke et al., 1999.
Deformation, dislocation, disrupted	<sup>1</sup> Multiple Icelandic tephra layers; <sup>2</sup> V1717, V1477, Ö1362, LTL, H3 and H4	Solifluction	<sup>1</sup> Veit et al., 2011. <sup>1</sup> Hirakawa, 1989. <sup>2</sup> Kirkbride & Dugmore, 2005.
Reworking	Laacher See	Erosion	Andres et al., 2001.
Reworking, redepositing	Multiple Icelandic tephra layers	Erosion in lakes and lake catchments	Boygge, 1999.
Convolved, overturned	'PA tephra' found in Alaska	Solifluction & cryoturbation	Matheus et al., 2003.
Increasing variation morphologically towards a critical threshold	Ey2010 & G2011 (Iceland)	Cryoturbation	Streeter & Dugmore, 2013a.
Reworking, distortion	Sheep Creek K tephra, Yukon, Canada	Cryoturbation	Sanborn et al., 2006.
Reworking in a marine environment	Nine Icelandic tephra layers	Bioturbation/oceanographic processes	Gudmundsdóttir et al., 2011.
Reworking, patchy preservation, diffusion of layer	<sup>1</sup> 3.6 Ka Aniakchak cryptotephra; <sup>2</sup> Various experimental cryptotephra deposits; <sup>3</sup> Pinatubo 1991 tephra; <sup>4</sup> 7.7 cal Kyr B.P Mt Mazama tephra; <sup>5</sup> Okataina Volcanic Centre & Taupo Volcanic Centre tephra; <sup>6</sup> Various New Zealand tephra; <sup>7</sup> 1883 Krakatau tephra; <sup>8</sup> Suksunarvatn 10 180 ± 60 cal. yr BP tephra, <sup>9</sup> Taupo, Waimihia, Rerewhakaaitu, Kawakawa tephra, <sup>10</sup> Simulated ashfall events to quantify bioturbation; <sup>11</sup> Tephra from Katla and Tindfjallajökull volcanoes, Iceland	Bioturbation	<sup>1</sup> Pearce et al., 2017. <sup>2</sup> Griggs et al., 2015. <sup>2</sup> Cassidy et al., 2014. <sup>3</sup> Wetzel et al., 2009. <sup>4</sup> Walther et al., 2009. <sup>5</sup> Shane et al., 2006. <sup>6</sup> Roering et al., 2004. <sup>7</sup> van den Bergh et al., 2003. <sup>8</sup> Andrews et al., 2002. <sup>9</sup> Carter et al., 1995. <sup>6</sup> Barns & Shane, 1992. <sup>10</sup> Todd et al., 2014. <sup>2</sup> Aalto & Miller, 1999. <sup>11</sup> Lacasse et al., 1996.
Fracturing, reworking	Multiple tephra found in southern Italy	Slope processes	Lucchi et al., 2013.
Layers vertically offset	Multiple tephra in New Zealand	Earthquakes	Delange & Lowe, 1990.
Disturbed, moved vertically	Eight well defined tephra layers from Hekla and Katla (H1636-K1918)	Ice-wedge polygons & palsa formations	Friedman et al., 1971.
Impressions formed in the surface of a freshly fallen tephra deposit	<sup>1</sup> Masaya Triple Layer Tephra, Nicaragua, <sup>2</sup> Multiple, global distribution reviewed, <sup>3</sup> Pleistocene Roccamonfina volcanic ash, Italy, <sup>4</sup> Tuff 7, Ngorongoro, Tanzania,	<sup>1</sup> 2.1 ka human footprints, <sup>2</sup> Footprints of Hominids, other mammals and birds, <sup>3</sup> Oldest known human footprints <sup>4</sup> 3.6 million year old hominin footprints,	<sup>1</sup> Schmincke et al., 2009, <sup>2</sup> Houck et al., 2009, <sup>3</sup> Mietto et al., 2003 <sup>4</sup> Musiba 2012, <sup>4</sup> Leakey & Hay 1979
Normal vs inverse grading	7.6 cal ka BP Tuhua Tephra	Paludal vs lacustrine environment of deposition	Newham et al., 1995.

Research in tephrochronology *sensu stricto* continues to gather pace (e.g. Davies, 2015; Lowe, 2018). Our aim is to balance these developments in tephra science with a focus on visible layers in exposed terrestrial sequences. These layers can be studied in the field, giving novel insights beyond chronology. In this way, we seek to develop classic tephrochronological studies as pioneered by Thorarinsson in Iceland through the mid to late 20<sup>th</sup> century CE (e.g. Thorarinsson 1944, 1956, 1958, 1961, 1967, 1981a, b). We draw mainly on Icelandic case studies. For clarity, we use the term tephra *deposit* to describe an accumulation of tephra lying on the surface, and tephra *layer* to describe a visible horizon of tephra bounded by other sediments and lying within the near-surface stratigraphic record. We consider potential transformation of primary and secondary tephra deposits over multi-century timescales in two broad categories of Late Holocene surface terrestrial environment: 1) on geomorphologically stable surfaces, with a spatially heterogeneous capability to retain tephra, and 2) on geomorphologically unstable surfaces with a similar spatially heterogeneous capability to retain tephra, combined with ephemeral surface characteristics that vary after tephra deposition.

We illustrate our points with mainly Icelandic examples because it is the location we are most familiar with, but also because of the richness of the tephra record in general, and the frequency of layers < 20 cm thick in particular (e.g. Thorarinsson, 1967, 1981b; Larsen, 2000). Whilst we focus on Iceland, we believe that the processes and factors we discuss here can be recognised more widely, with caveats. For example, the relatively restricted diversity of Icelandic biota and the island's cool temperate climate limit bioturbation, and aeolian sediment fluxes are high, particularly in recent centuries, leading to rapid burial of stable tephra deposits in vegetated areas (Arnalds, 2015). In southern Iceland, for example, pre-human settlement sediment accumulation rates were typically about 0.3 mm per year; these rates frequently increased up to an order of magnitude following the Norse settlement of the 9<sup>th</sup> century CE (Dugmore et al., 2000, Streeter et al., 2015). While we focus on accessible terrestrial sequences, we also recognise that reworking and alteration of tephra deposits can be a common feature of lacustrine and marine environments, with a similar potential to produce novel sources of environmental insight.

Visible tephra layers 1-10 cm thick are chosen because we believe they offer the best chance of extracting proxy records of past environmental conditions and their spatial extent is often large. Surface deposits 1-10 cm thick are likely to be incorporated into the sedimentary record without precipitating catastrophic ecological change, i.e. they are commonly subsumed within, rather than totally burying, all but the lowest-growing plant communities (Dugmore et al., 2018). In Iceland, Thorarinsson and others have studied the impacts of historical eruptions and concluded that while the extent of damage is dependent upon the season in which the eruption occurs, a tephra deposit has to be at least 8-10 cm thick to produce farm abandonment (Einarsson et al., 1980). In a farming system based on animal husbandry and rangeland grazing, tephra 15-20 cm thick have stopped farming for 1-5 years, while layers 20-40 cm thick have prevented farms being occupied for more than a decade (Thorarinsson, 1979). Thorarinsson's historical analysis from Iceland is broadly consistent with the abandonment of pastoral ranching seen in the steppe lands of South America following the 1991 eruption of Cerro Hudson (Wilson et al., 2012). Fig. 1 summarises the zone we are particularly interested in. This zone lies outside the thick tephra deposits (>D) that create new surfaces, force settlement abandonment and are primarily modified by the interplay of earth surface processes and topography with the sedimentological characteristics of the tephra deposit. Our zone of interest extends as far as the deposits of tephra are visible, and where discrete layers are thick enough (>d) for variation to show in open sections, which in practice is c1 cm thick.

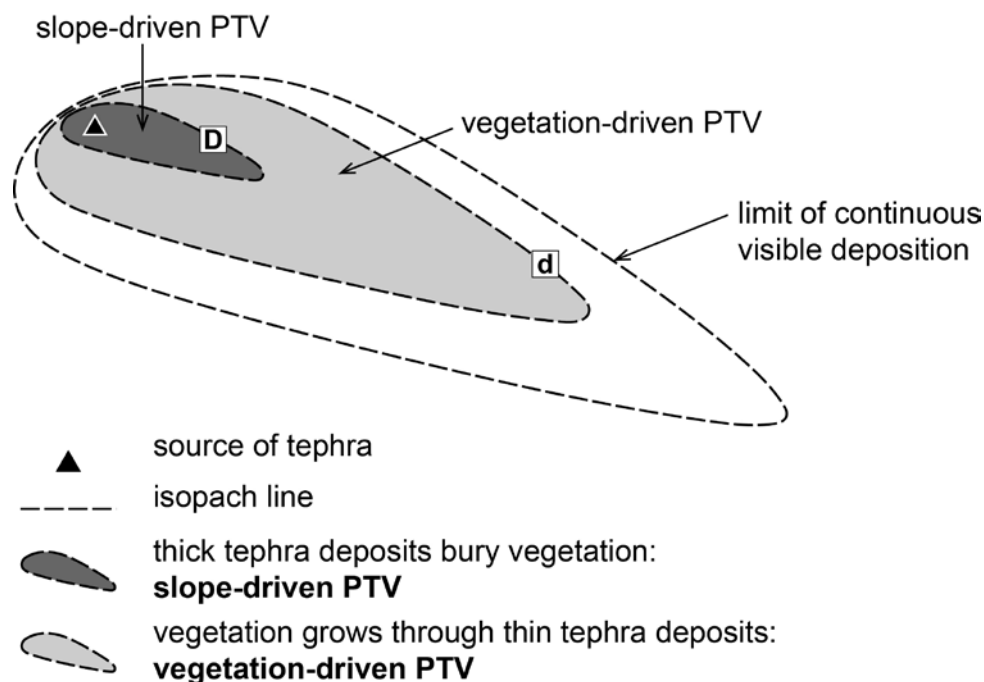


Fig. 1 : The factors influencing the preservation of a tephra deposit vary with the initial thickness of the tephra. In proximal areas, thick tephra deposits (thickness  $> D$ ) bury vegetation, creating an entirely new landscape from unconsolidated sediment, and force farm abandonment. The pattern of tephra variation (PTV) in this zone is determined by the interplay of Earth surface processes, topography and tephra sedimentology. As the tephra deposit thins with distance from the source, vegetation cover will become increasingly important. In the zone of thin deposits ( $d < \text{deposit thickness} < D$ ), vegetation can grow through the tephra, stabilising the sediment, limiting remobilisation and trapping remobilised grains. Trapped, stabilised tephra is eventually incorporated into the sedimentary record. In this zone, tephra layer thickness will reflect local variations in vegetation cover on slopes  $< \text{approx. } 35^\circ$ . The thickness of  $D$  and  $d$  will vary depending on the structure of ground level vegetation communities and the time of year. In Iceland  $d < 1\text{cm}$  and  $D > 25\text{cm}$ , as historically tephra falls  $>25\text{cm}$  have laid farms to waste for more than 5 years (Thorarinsson 1979)

The spatial extent of tephra layers 1-10 cm thick is often large. For example, an onshore tephra layer  $> 1$  cm thick was spread over an area of  $> 75,500 \text{ km}^2$  by the eruption of Cerro Hudson in CE 1991, and 95% of this area was covered by ash fall 1–10 cm deep (Scasso et al., 1994).

## 2. The transformation of tephra deposits

Earth surface processes and bioturbation can affect tephra immediately after their initial deposition. Deposits will settle and compact; people can clear field systems and settlements, animals can churn surface layers; wind, and water in the form of precipitation, snowmelt or overland flow, will remobilise particular fractions or entire deposits (Wilson et al., 2013; Blong et al., 2017; Cutler et al., 2018). This phase of reworking may persist for as long as the tephra remains on the surface and can last for years-decades, particularly in parts of the world where vegetation cover is limited, such as Iceland (Liu et al., 2014) and elsewhere, e.g. in Patagonia (Panebianco et al., 2017). Once tephra has been buried, forming a tephra layer, sub-surface processes such as cryoturbation, solifluction and bioturbation can affect the tephra. These processes can cause major alterations to both the thickness and morphology of layers *in situ*

(Grab, 2005; Kirkbride & Dugmore, 2005; Pearce et al., 2017) and differ from the impacts of surface erosion by natural processes or human agency (Church et al., 2007, McGovern et al., 2007).

Tephra exposed at the surface may be primary deposits (i.e., the product of the first deposition of tephra from a volcanic plume), or secondary deposits, where tephra accumulations are formed by the remobilisation of primary deposits (Fig. 2). Distinguishing between primary and secondary tephra deposits is not always a straightforward task, especially if the tephra has experienced differing degrees of transformation, disruption, and re-deposition. There are, however, several possible approaches to the identification of secondary deposits. Firstly, the presence of exotic materials or distinctive sedimentary structures can provide definitive evidence of remobilisation and re-working of tephra (Óladóttir et al., 2011); but their absence does not necessarily mean that there has been no mobilisation and post-eruption deposit thickening (Boyle, 1999; Dugmore and Newton, 2012). Secondly, observations of tephra layer composition and stratigraphic contacts, internal bedding structures, geochemical coherence, grain shape and size, combined with an assessment of the spatial distribution of each layer, and regional stratigraphic patterns can effectively distinguish between primary and secondary deposits. Finally, if a tephra layer occurs in multiple profiles in contrasting geomorphological settings, then it is unlikely to be the product of localised tephra remobilisation and is likely to define a consistent isochron (Dugmore and Newton, 2012). Primary tephra deposits that incorporate additional, secondary, tephra deposition may still define an isochron contemporaneous with the eruption that formed them both. Thus, they may have utility for tephrochronology in Quaternary science, and although the combined deposit may have lost much, if not most of its volcanological significance, it may have acquired additional environmental meaning.

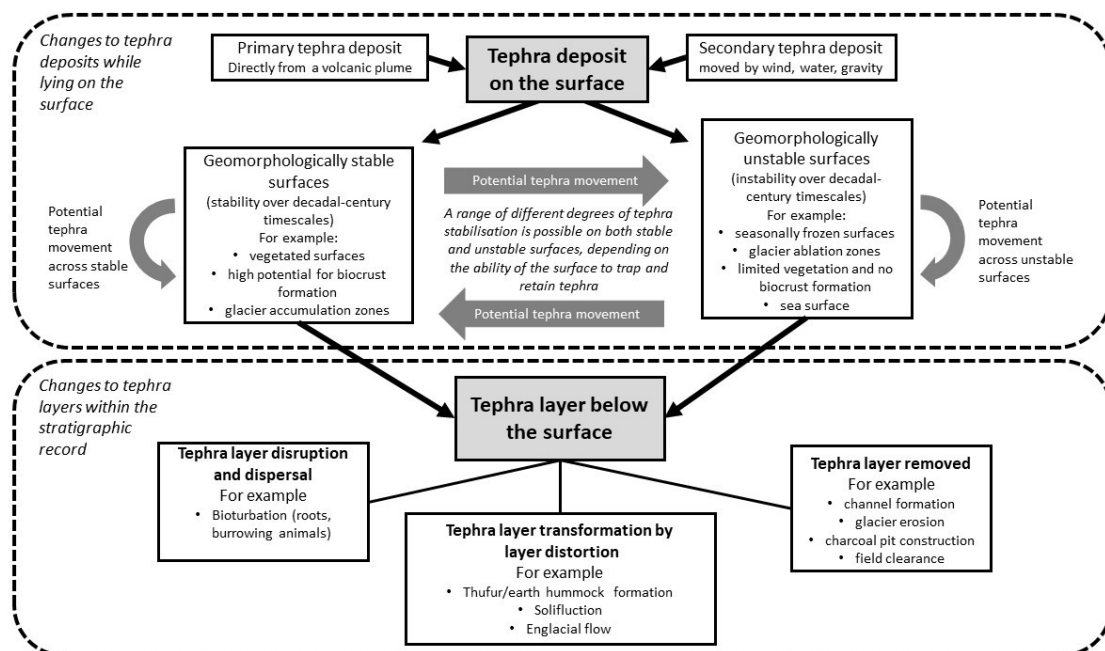


Fig. 2: Tephra deposits on the surface and tephra layers within stratigraphic sequences may undergo differing degrees of transformation, and the legacies of these transformations can provide diagnostic palaeoenvironmental records that can usefully compliment tephrochronology.

In terms of terrestrial landscapes, it is useful to draw out the fundamental contrasts between modifications of tephra deposits that lie on geomorphologically stable and unstable surfaces (Fig. 2). We define geomorphologically stable areas as those where net aggradation of the surface takes place over decadal timescales, so tephra deposits can stabilise to greater or lesser extents, form layers within the stratigraphy, and a near continuous sedimentary record develops. Stable surfaces can be vegetated in differing ways with total or partial vegetation cover, simple or complex canopy levels and a great range of vegetation types. Stable surfaces may lack cover of higher plants, and/or be permanently frozen. Whilst the surface itself may be geomorphologically stable, its capacity to stabilise tephra deposits will vary spatially and temporally, and depend on the thickness, particle size and chemistry of the tephra deposit, as well as the timing of the deposition and prevailing surface conditions.

### **3 Tephra deposition on geomorphologically stable surfaces**

By working with recent tephra deposits such as Eyjafjallajökull 2010 and Grímsvötn 2011 in the years following their formation, we have directly related the characteristics of vegetation communities (plant height, density, etc.) to the formation of tephra layers (Cutler et al., 2016a, b; Dugmore et al., 2018).

At a broad scale, vegetation community composition can be a surrogate for vegetation structure, but when considering the variations in the mosses and vascular plants of the heathlands of southern Iceland, the relationship between community variability (Shannon diversity, multivariate inertia) and variability in the Grímsvötn 2011 tephra layer was weak (Cutler et al., 2016b). Whilst plant community composition and vegetation structure are related on a fundamental level, growth variations within species are likely to obscure this relationship. A few species can have a dominant effect on the physical structure of the community due to their size, whilst many other species will make minimal contributions. For example, at one site in Iceland a single willow species drove major changes in the thickness of the Grímsvötn 2011 tephra (Cutler et al., 2016b).

Vegetation structure can be measured photogrammetrically when a narrow strip of vegetation bordering a shallow trench is photographed in front of a white backdrop, rendered into a two tone, black and white image and the cumulative percentage of black pixels (vegetation) are calculated from the ground level upwards (Cutler et al., 2016a). Work of this sort shows that primary controls on the movement of tephra and modification of deposits, are leaf shape and size, vegetation height, architecture, stem thickness, and density, all of which will be affected by seasonal variation. Vegetation community structure interacts with meteorological processes (e.g. wind speed, ambient temperature, precipitation), and tephra characteristics (e.g. thickness of deposit, particle size and shape).

Areas with high potential for preserving tephra deposits, such as those supporting a tall, dense matrix of vegetation with minimal disturbance from animals or people, have the capacity to both retain tephra fall that does not bury it, and trap additional tephra that is subsequently reworked from elsewhere (Cutler et al., 2016a, 2016b) (Fig. 3, 1-3).

While exposed on the surface the centimetre-scale tephra deposits of the Eyjafjallajökull 2010 eruption have been reworked by the wind. Whereas layers forming within dwarf shrub heath have thickened and become more locally variable (99-119% of the original thickness: Dugmore et al., 2018), those in moss heath have generally thinned in relation to the original fallout to 86-106% of the original thickness (Dugmore et al., 2018). Within moss heath, vegetation structure



and thickness of the Grímsvötn 2011 tephra are correlated, and beneath tall shrubs the Eyjafjallajökull 2010 tephra layer has thickened to 113-136% of the original thickness (Dugmore et al., 2018).

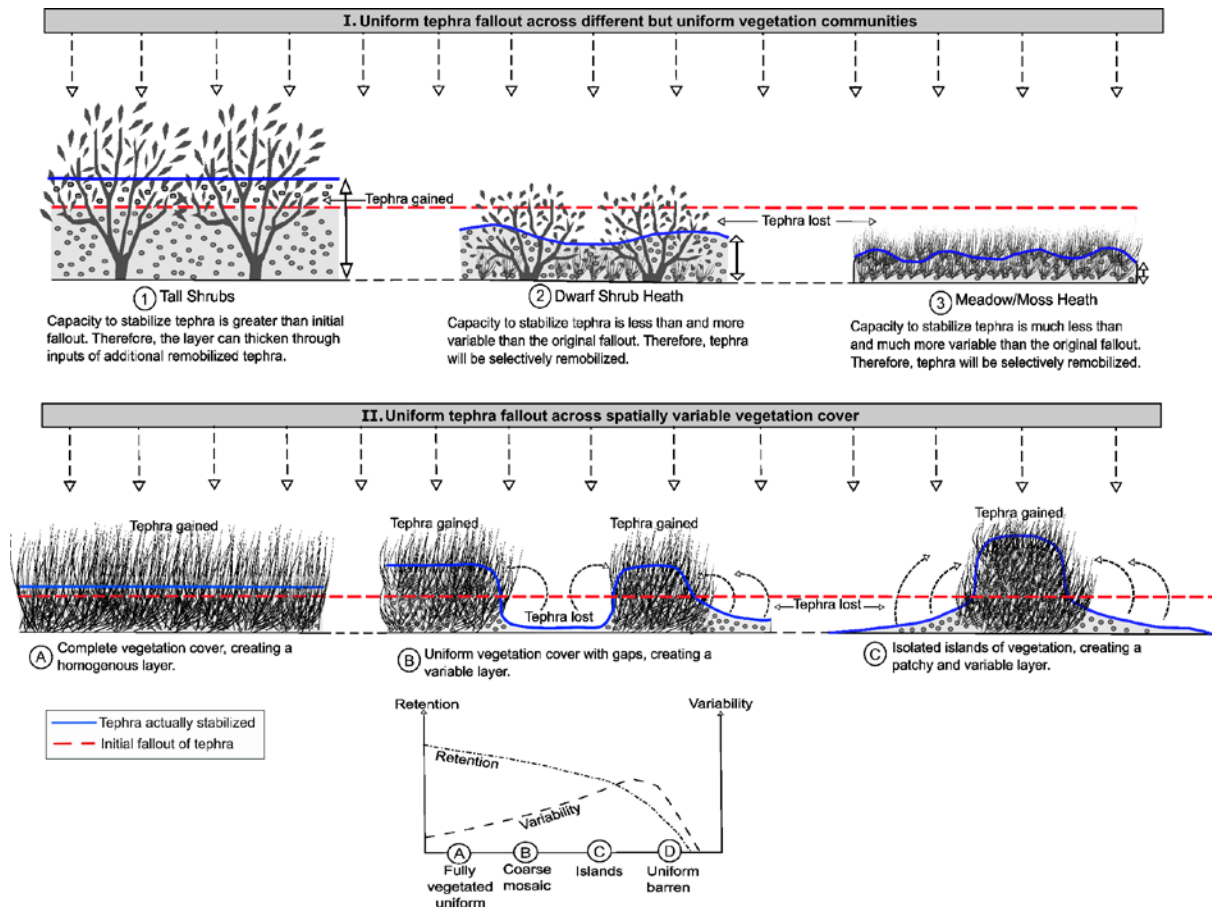


Fig. 3: Vegetation structures can have a significant influence on the surface preservation of tephra deposits 1-10cm, and thus the thicknesses of the layers they subsequently form within the stratigraphic record. The scale of tephra deposit transformation may be driven either by variations in the quality of a uniform vegetation cover (e.g. tall shrubs, dwarf shrub heath, meadow/moss heath), or the quantity of vegetation cover (e.g. the surface area covered and fragmentation of that cover).

When there is a vertical layering of vegetation structure, such as a ground cover and an overarching canopy, then the relationship between tephra stabilisation and ground cover decouple as the deposit becomes less spatially variable. The Grímsvötn 2011 tephra has limited spatial variability over metre scales, where it lies in birch woodland (Cutler et al., 2016a). This is most probably because vegetation reduces the wind speed at the near-surface and thus reduces tephra remobilisation (Cutler et al., 2016b).

The existence of relationships between vegetation community structure and tephra layer morphology suggests that tephra layers can complement well-established methods of reconstructing past landscape (e.g. based on pollen, phytoliths, spores, plant macrofossils and insects).

Perhaps surprisingly, topography seems to have a minimal effect on landscape-scale variability in tephra deposits 1-10 cm thick that have been partially or wholly subsumed within the pre-existing vegetation cover. Measurements of the Grímsvötn 2011, Eyjafjallajökull 2010, Hekla 1947 and Katla 1918 tephra layers all show that the influence of vegetation structure on the preservation of tephra deposits is more important than slope (up to angles  $< 35^\circ$ ) or, indeed, position on a slope (Dugmore et al., 2018). Locally, the rapid development of biocrusts can stabilise a tephra deposit in the absence of macroscopic vegetation with significant vertical relief (Dugmore et al., 2018). We have observed this on fine grained deposits of the 1980 Mount St Helens tephra in eastern, semi-arid areas of Washington State. These examples from contrasting locations indicate that although the mechanisms which stabilise tephra deposits are likely to vary from region to region, the end result, that tephra layers do not vary as a result of slope angle/position, may be the same.

A decoupling of vegetation patterns and tephra stabilisation may occur if snow covers the vegetation, because melting provides an opportunity for the tephra to be remobilised before it comes into contact with the vegetated surface. Supranival tephra deposition (tephra deposited on the surface of snow) can result in the complete removal of a tephra from an area if the tephra is blown or washed off the snow before it fully melts. A similar outcome may also occur due to the actions of wind and water when they are capable of moving an unconsolidated tephra deposit but not eroding the underlying surface, such as a well-grazed sward.

Habitat fragmentation (e.g. deforestation) will intensify contrasts in tephra layer preservation as it is mobilised and lost from some areas, captured and stabilised in others that have a 'retention capacity' greater than 100% of the initial fallout. (Fig. 3, a-c). In broad terms, a coarse mosaic of more and less well-vegetated patches is likely to retain less tephra (preserve less of the original tephra deposit) than a uniformly well vegetated area because some of the remobilised tephra is likely to be lost from the local system, e.g. as it is washed out of the fallout zone by streams and rivers.

In addition to creating variability from initial uniformity, the interactions of surface vegetation and tephra can result in a reduction of thickness variability. For instance, where fallout varies across spatially extensive and comparatively uniform plant communities, thickness variations due to uneven patterns of fallout can be reduced, or lost, resulting in a spatially homogeneous deposit (Fig. 4). This is a possible explanation for areas of consistent mass loading from the tephra layer produced by the 1947 Hekla eruption that can be observed today (Cutler et al., 2018). The mass loading data were obtained from sites with different deposit thicknesses some 20–40 km south of the volcano. They show there has been a significant loss of tephra since 1947 (Cutler et al., 2018; Thorarinsson, 1954); the losses have been variable so that sites that were initially quite different now exhibit a widespread uniformity (Cutler et al., 2018). Both aspects of deposit modification have significant implications for volcanological studies that rely on accurate reconstructions of initial fallout to estimate the volume of eruptions and height of eruption columns (Cutler et al., 2018; Dugmore et al., 2018).

The extensive remobilisation of tephra deposits  $< 20$  cm thick can result in the multi-decadal persistence of tephra  $> 50$  cm thick in topographically favoured locations. In the same area of Iceland where deposits of the 1947 Hekla tephra have been thinned to become more uniform, tephra deposits many times thicker than the initial fallout can be observed along

geomorphologically stable margins of stream courses, forming deposits that were (in 2019) free of soil cover or surface vegetation (Fig. 4 a-c).

The re-mobilisation and re-deposition of tephra on stable surfaces can complicate the reconstruction of past eruptions, but because the distribution and structures of surface vegetation heavily influence these processes, this problem can become an opportunity. Spatial patterns in vegetation cover can act as a proxy for ecosystem resilience, and as an early warning sign of imminent ecological collapse, for example the transition from a landscape that is mostly vegetated, to one that is eroded (Scheffer et al. 2009). If the patterns in the vegetation influence the retention of tephra deposits (e.g., there are patches with different vegetation height, or stem density), then local variability in tephra layer thickness might be an indicator of past ecological resilience (Streeter and Dugmore, 2013a).

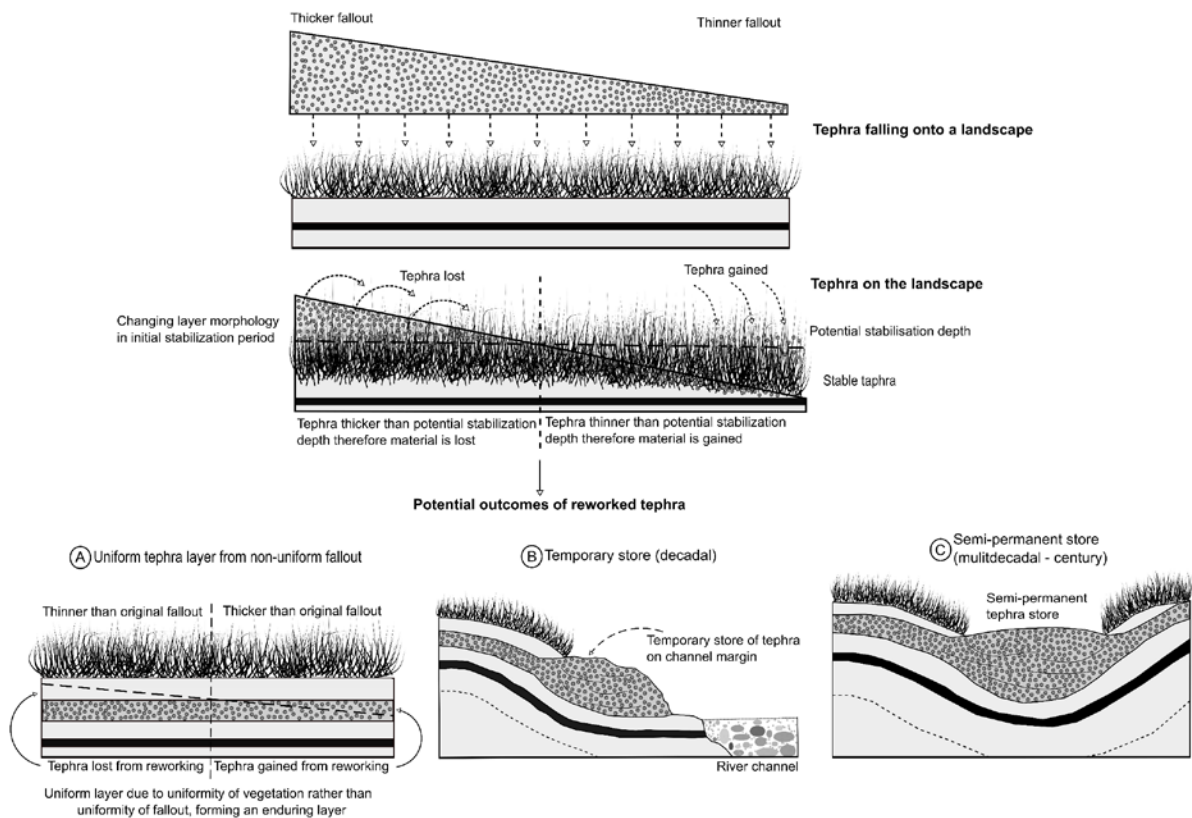


Fig. 4: (A) Vegetation cover may act to homogenise variable thicknesses of tephra fallout, creating a more even distribution; in some areas the vegetation may not stabilise the full thickness of fallout, and so the enduring record may be of a deposit thinner than the original fallout. In southern Iceland this has happened in areas with fallout from the 1947 eruption of Hekla > 10cm (Cutler et al., 2018). In other areas the vegetation may be able to stabilise a thicker layer than the original fallout, and thus may trap additional tephra re-mobilised in the aftermath of the eruption, and thus the enduring record may be thicker than the original fallout. This has happened in areas of tall shrubs on the northern side of Eyjafjallajökull that received <10cm of fallout from the 2010 eruption (Dugmore et al., 2018). (B & C) Semi-permanent stores of remobilised tephra may persist in topographically suitable parts of the landscape.

#### 4 Tephra deposition on geomorphologically unstable surfaces

In general, geomorphologically unstable surfaces, such as migrating dunes systems, actively braiding river floodplains and ploughed fields will not preserve primary tephra deposits, and

secondary deposits are likely to suffer from extreme forms of transformation, disruption, dispersal and re-deposition. They may also be removed in their entirety from the area covered by initial fallout. In very different environments to Iceland, Blong and Pain (1978) used the variable preservation of tephra mantles in the highlands of Papua New Guinea to infer patterns of slope instability over the last 50Ka. In Iceland and other high latitude or high altitude areas, a common form of unstable surface is produced by seasonally frozen materials, be they formed from soil, snow or ice. There has, however, been comparatively limited work on the immediate post-eruption transformations that occur after tephra is deposited on ice and snow (e.g. Hunt, 1994; Kirkbride and Dugmore, 2003; Richardson and Brook, 2010; Nield et al., 2013; Barr et al., 2018).

The extent and speed of changes to a tephra deposit on snow and ice surface is highly variable, being dependent on a complex interplay of factors with the key influence of thermal processes exaggerating initial spatial variations in deposit thickness. For example, as the April-May 2010 Eyjafjallajökull eruption in Iceland occurred just before the ablation season, and later the same year we observed tephra deposited across a variety of frozen substrates, including snow over ground, snow over impermeable glacier ice, and exposed glacier ice. In this range of circumstances we infer that, mass loading of tephra and substrate permeability are key controls on the developmental pathway of tephra reworking.

#### ***4.1 Supranival tephra deposit transitions***

When tephra covering snow is thin, it increases melting by absorbing short-wave radiation. Just 2-3 mm of the 1980 St Helens tephra almost doubled snowmelt (Driedger, 1981). Conversely, when tephra thickness exceeds c. 25 mm it acts as an insulating blanket, which can preserve seasonal snow for weeks or months until the protective layer is disaggregated or thinned by wind or water erosion (Kirkbride and Dugmore, 2003). Metre-scale tephra covers may preserve snow and ice for many years, especially at high latitudes (Muller and Coulter 1957).

Supranival tephra covering permeable spring snow is not easily reworked. Moisture from the snow dampens the tephra (presumably by upward capillary action) and meltwater percolates downwards into the snowpack, so that few tephra grains are removed and an intact layer remains for many weeks. Such deposits may be pock-marked by small “craters” (collapse pits) where meltwater cavities develop within the snowpack. Drying of the surface of thicker supranival tephra provides cohesion and brittle-style failure where slumps occur, with a characteristic blocky fracture. Permeability seems to be the key property that allows tephra to be let down onto the ground surface when the snow finally melts, though this might not be in the first summer after tephra deposition. Final fragmentation of the snowpack associated with ablation cone development disrupts tephra deposit continuity at the metre-scale, and leaves parts of the ground free of tephra while concentrating tephra into “sinks” of meltwater flow concentration.

## **5.0 Subsurface tephra layer modification**

The distortion of subsurface tephra layers can show that the enclosing sediment moved after the formation of the tephra layer. Thus, tephrochronology provides both evidence of past subsurface processes and, potentially, the ability to date these events too. We evaluate these phenomena by considering tephra distortion in situ (by cryoturbation); distortion in a flowing medium (ice); post-interment dispersal (by bioturbation), total removal of tephra from the stratigraphic record (erosion events) and wholesale displacement of layers.

### 5.1 Tephra layers distortion within soils and peat

Folded and convoluted tephra layers can provide independent evidence for freezing conditions and characteristic sediment displacement. Sanborn et al. (2006) assessed perennially frozen loess deposits in the Klondike goldfields (Alaska) formed in full-glacial environments. They used the undulating pattern of Sheep Creek K tephra layers (evidence of reworking and distortion by cryoturbation processes), combined with lateral separations of the Dominion Creek tephra, to assess environmental conditions. They concluded that processes such as cryoturbation and ice-wedge formation reduced as the conditions became drier. In central Alaska, the PA tephra is found in ice-wedge clasts and solifluction deposits, and its occurrence in the form of highly convoluted, and even overturned layers, has been used as evidence for the oldest permafrost in region (Matheus et al., 2003). In Iceland, the distortion of tephra layers can also record later episodes of cryoturbation and solifluction (e.g. van Vliet-Lanoë et al., 1998, Kirkbride and Dugmore, 2005, Veit et al., 2011), but despite the presence of well-dated tephra layers, the precise timing of these episodes is harder to pin down.

While horizontal tephra layers of even thickness are clear evidence that solifluction and cryoturbation have *not* taken place, differing degrees of tephra layer unevenness, relative relief or disturbance have various implications for the timing of episodes of sediment movement in relation to the age of tephra (Fig. 6). If a tephra layer includes overfolds, then distortion due to sediment movement has to have taken place sometime after the formation of the deposit and incorporation into the sediment profile (Kirkbride and Dugmore, 2005; Veit et al., 2011). Where sections of the tephra are vertical, or very steep, the layer must also have undergone distortion after burial, with similar chronological implications. The more extensive the vertical relief, the more likely it is that post-depositional distortion has occurred. In contrast, undulating tephra layers can form through the deposition of tephra across uneven ground, such as on well-vegetated earth hummocks (*thúfur*), that may be actively growing (Dugmore and Buckland 1991). In the following discussion, we use the Icelandic term *thúfur* or *Púfur* (singular *thúfa* or *Púfa*) to describe small-scale vegetated earth mounds formed by cryoturbation processes that generally occur in clusters (Grab 2005). This is to acknowledge the pioneering work of Icelandic scholars (e.g. Jónsson (1909), and Thoroddsen (1913)) and their terminology, which later became synonymous with the term ‘earth hummock’ Washburn (1956: 830).

To illustrate how tephra can be used to understand sediment deformation in some detail, a section including *thúfur* from the southern flanks of Eyjafjallajökull in southern Iceland is shown in Fig. 5 (Dugmore and Buckland 1991). The flat base of tephra Layer Bj (shown in the detailed cross section of a *thúfa* on the right hand side of Fig. 5) shows that before 500 CE tephra fell on a smooth ground surface lacking *thúfur*. After tephra Layer Bj formed, sediment movements created a ‘finger’ of tephra projecting vertically from the upper surface of the deposit. Related sediment movements produced uplifted vertical faces and over folding in the SILK YN and Ey Ha tephra layers, and must have post-dated c 500 CE and the deposition of these tephra layers. The 877 CE Landnám tephra layer may have fallen over an established *thúfur* because its cross profile mirrors the form and scale of modern *thúfur*, but as some parts of the layer are also near vertical it seems likely that the individual *thúfa* grew after 877 CE (Schmid et al., 2017). While somewhat irregular, the Katla 920 CE tephra fall could be *in situ* as it lacks the vertical or near vertical sections of the others. Certainly, by the turn of the 16<sup>th</sup> century CE and the deposition of tephra from Katla in 1500 CE and Hekla in 1510 CE, there were no *thúfur* on the site, a situation that has persisted to the present day.

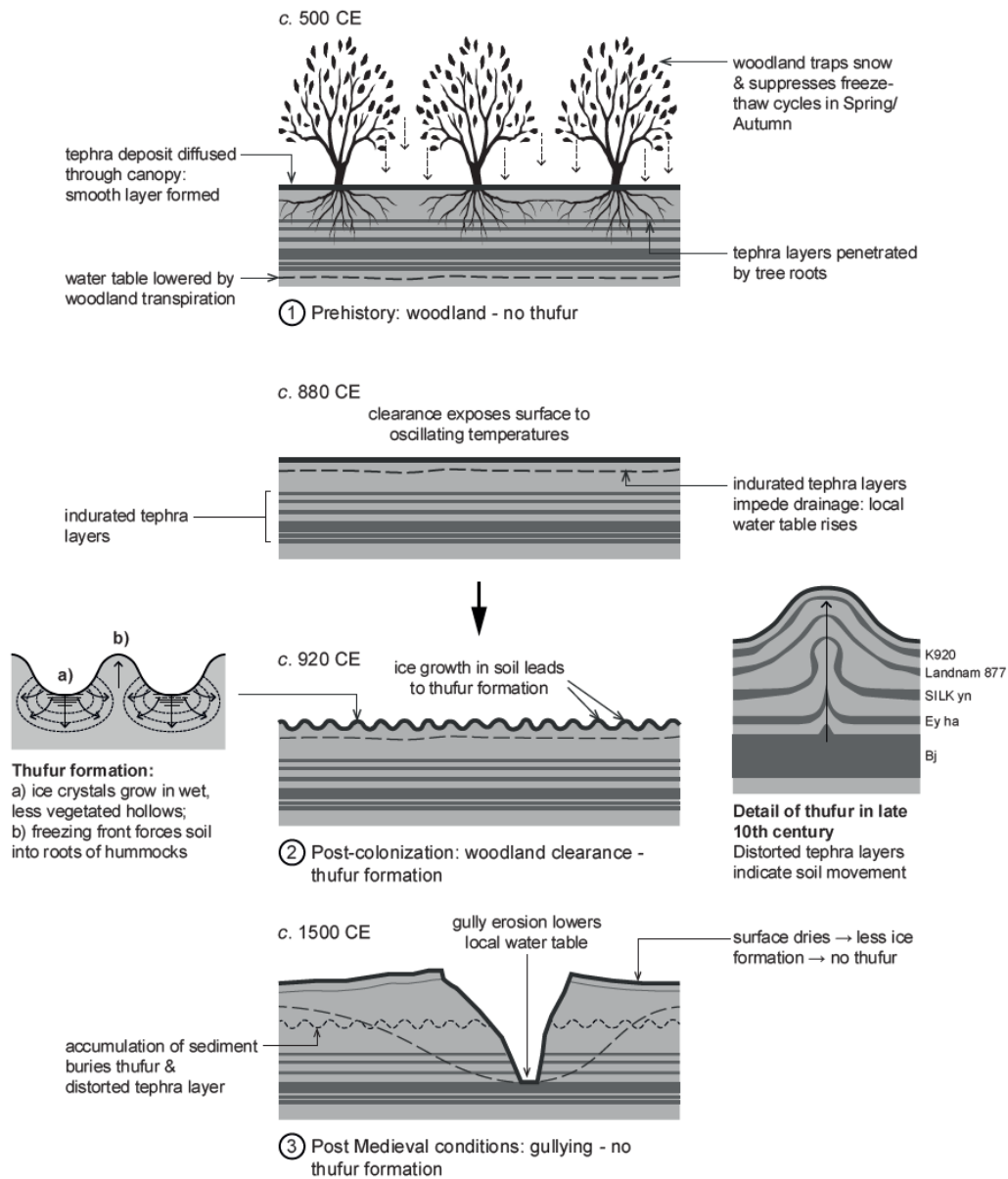


Fig. 5: Episodic changes in landscape maybe recorded in the morphology of tephra layers. In this example snapshots of landscapes in southern Iceland are defined by tephra deposition around 500, 880, 920, and 1500 CE. The morphology of the tephra layers can be used to identify different landscape conditions with and without thufur formation. Tephra layers are shown as dark layers; Layer Bj >15cm thick, all younger tephra layers are < 5cm thick.

In addition to providing a record of surface processes have occurred in the past, the distortion of tephra layers can also provide insights into the operation of the processes themselves. For example, a variety of different seasonal displacements of sediment caused by frost action are likely to lead to the formation of thufur (e.g. Lundqvist 1969, Mackay, 1980; van Vliet-Lanoë and Seppälä, 2002; Grab, 2005; Killingbeck and Ballantyne, 2012). Thus, our preferred

explanation for this sequence involves changes to 1) the surface exposure to temperature variation due to vegetation change and 2) ground water levels due to erosion. A simple connection to regional climate change seems unlikely because thúfur at this site did not form until medieval times, and disappeared by the Little Ice Age. Shrub cover at the site before the Norse settlement could have stabilised snow cover, and so provide a thermal buffering against the oscillating cycles of freezing and thawing that could promote sediment movement. Shrub clearance could have exposed the ground surface to a wider range of temperature change and so triggered earth hummock formation. As climate conditions deteriorated into the Little Ice Age, soil erosion created gullies that lowered water table, moving it away from the aggrading surface. Lowering of the water table dried out the surface and inhibited thúfur formation. Thus it is possible to use the distortion of tephra layers within the stratigraphy of an earth hummock, or other solifluction or cryoturbation features, to infer the direction and nature of sediment displacements and, by extension, the likely drivers of change (e.g. van Vliet-Lanoë et al., 1998; Kirkbride and Dugmore, 2005).

The example illustrated in Fig. 5 (and others, e.g. Veit et al., 2011) demonstrates that high resolution tephra stratigraphy can be used to uncover a nuanced relationship between the formation of miniature cryogenic mounds and periods of temperature decline. This shows that while Icelandic case studies could be developed to understand *process* that form thúfur and other solifluction features in Iceland, and thus better understand common geomorphological phenomena from other high latitude and montane environments (Grab, 2005), they also illustrate distinctive aspects of the Icelandic *tephra record* that make it quite special. The key methodological point being the need to seek out areas where a range of well-dated, suitably-sized, stratigraphically separated and temporally spaced tephra layers are present and to use these areas to understand processes operating both there and elsewhere (Dugmore and Newton, 2012). The Icelandic study was facilitated by frequently occurring and well dated tephra layers a few cm thick, combined with rapid rates of sediment accumulation that separate out a sequence of near-surface changes in a stratigraphic sequence. Similar conditions may well apply in other locations, e.g. New Zealand.

Delange and Lowe (1990) noted vertical offsets of tephra layers in the Kopouatai peat bog (New Zealand), which were created by earthquake-related faulting. As with other forms of tephra layer distortion, this evidence must be closely bracketed with evidence for a lack of earthquake activity in order to produce dating precision. However, the disrupted layers do provide diagnostic evidence of environmental processes that might not be apparent in other records. Similarly, the distribution of hummocks and pools on a bog surface may be inferred from highly-localised concentrations of cryptotephra in ombrotrophic (rain-fed) peat records that can be seen on x-ray images (Dugmore and Newton, 1992). Reconstructing the morphology of former bog surfaces through tracking localised concentrations of grains within undulating tephra horizons is a more straightforward option than sampling other palaeoenvironmental indicators, such as plant macrofossils, at a similarly detailed, yet extensive resolution.

## ***5.2 Englacial tephra layer distortion***

Tephra falling onto glacier accumulation zones will be buried by the snow falling during the winter after the eruption. Its incorporation into the glacier creates an isochronous layer within the glacier's stratigraphy. Snow and ice recrystallise under strain to form metamorphic foliation, destroying the original stratigraphic layering within a glacier. Where an englacial

tephra isochron is present, the form of the deformed stratigraphic surface is preserved throughout. Thus, the geometry of an englacial tephra layer records the total strain experienced by the ice since the tephra fall. This is expressed as folding of tephra layers within the ice, ranging from broad warping in gentle sloping ice cap areas (Lliboutry, 1957; Larsen et al., 1998), to tight accordion-like folds developed under intense longitudinal compression in icefalls. Fig. 6 illustrates this with a schematic long profile of the distribution of the Hekla 1947 tephra in the former tongue of the Gígjökull glacier, Iceland. This is inferred from outcrops of tephra on the glacier surface and in the walls of crevasses before the rapid glacier retreat of the early 21<sup>st</sup> century (Kirkbride and Dugmore 2003, Gudmundsson et al., 2011). The non-surging outlet glaciers of Mýrdalsjökull and Vatnajökull have received fallout from Katla and/or Grímsvötn, and it is common to see tephra outcrops oriented convex-downstream, the two-dimensional expression of a three-dimensional form in which the layer forms a broad syncline with an upstream dipping hinge. In such cases the tephra remains in stratigraphic sequence with primary ice stratification. Such a form has consequences for the interaction of the emerging tephra layer along its outcrop and the spread of emerging debris over the glacier surface, and consequently for influencing the surface melt rate.

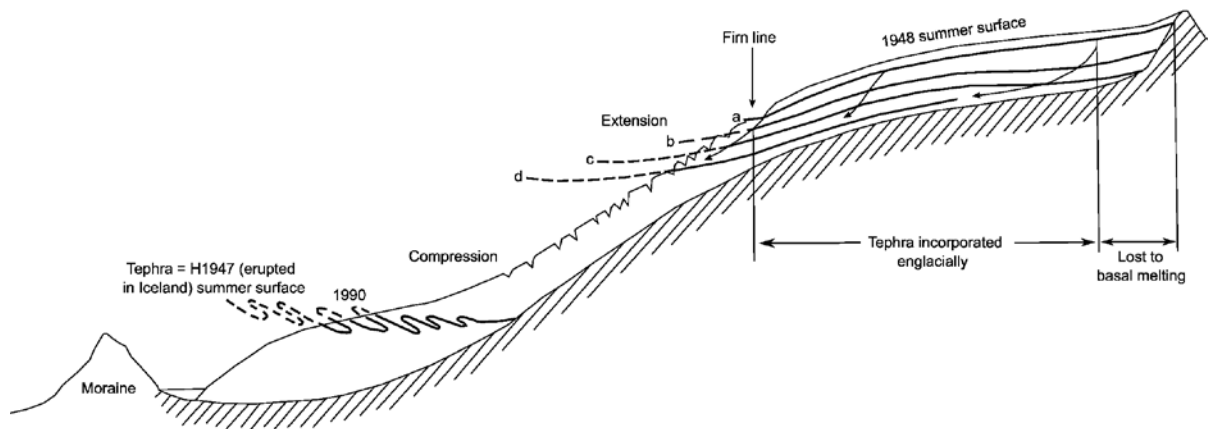


Fig. 6: The changing morphology of the Hekla 1947 tephra layer within the Gígjökull outlet glacier of Eyjafjallajökull during the latter half of the 20<sup>th</sup> century, as inferred from a combination of aerial photographs (1960-1984), and field observations of outcrops of tephra on the glacier surface and within crevasse walls (1990-2010). The tephra outcrops at the terminus of the glacier record the total strain experienced by the ice since the tephra layer was deposited in the accumulation zone. Line (a) represents the extent of the tephra layer buried in the accumulation zone the year after the eruption. The arrows indicate ice flow. As the tephra layer is buried and flows toward to base of the glacier the uppermost part will be lost from the ice due to basal melting. Below the firn line surface melting of the ice will remove the lowest part of the entrained tephra layer, a process that continues in each melt season as the ice containing the tephra flows downhill. This is represented by the lines tephra will (b-d) that represent the progressive movement of the tephra layer through the glacier and its gradually reducing extent. As the tephra passes through the ice fall in the central part of the glacier it is distorted and its changing morphology records the cumulative changes it experiences.

Fig. 7 schematically represents the Katla 1918 tephra emerging from Sólheimajökull glacier, Iceland. Here, a subglacial ridge has created a double-syncline form, with dip angles increasing from the hinge axes to the very steep limbs. Relationships between tephra geometry, glacier thinning and flow velocity (Kirkbride and Deline, 2013) explain two main outcomes of such a situation. First, outcrops of low-angle tephra layers migrate rapidly across the local surface as the tephra emerges by surface melting, but form a supraglacial deposit only slightly thicker than the true thickness of the englacial layer. In other words, little concentration of tephra



occurs at the glacier surface. Conversely, steeply-angled tephra outcrops migrate only slowly as the surrounding ice lowers, focussing the emerging debris into thick, localised accumulations and effectively insulating the underlying ice. These effects may be seen on aerial imagery of Sólheimajökull in the 1980s, 1990s and 2000s, in which the Katla 1918 outcrop is seen as a thin continuous line, with clean ice upstream (accumulated after 1919), and the glacier downstream is thinly tephra-covered. As Fig. 7 demonstrates, this thin cover over pre-1918 ice is the surficial residue of the emerged tephra layer that has rapidly been washed from the glacier. The Katla 1918 outcrop has migrated across all of this area to deposit the tephra (by primary dispersal, *sensu* Kirkbride and Deline, 2013), rather than the tephra washing across the glacier from the outcrop. Along the glacier margins, a thick continuous tephra cover parallels the ice margins where steeply-dipping fold limbs emerge, and maintain their position.

Schematic geometry of an exposure of folded Katla 1918 tephra on the surface (Sólhimajökull)

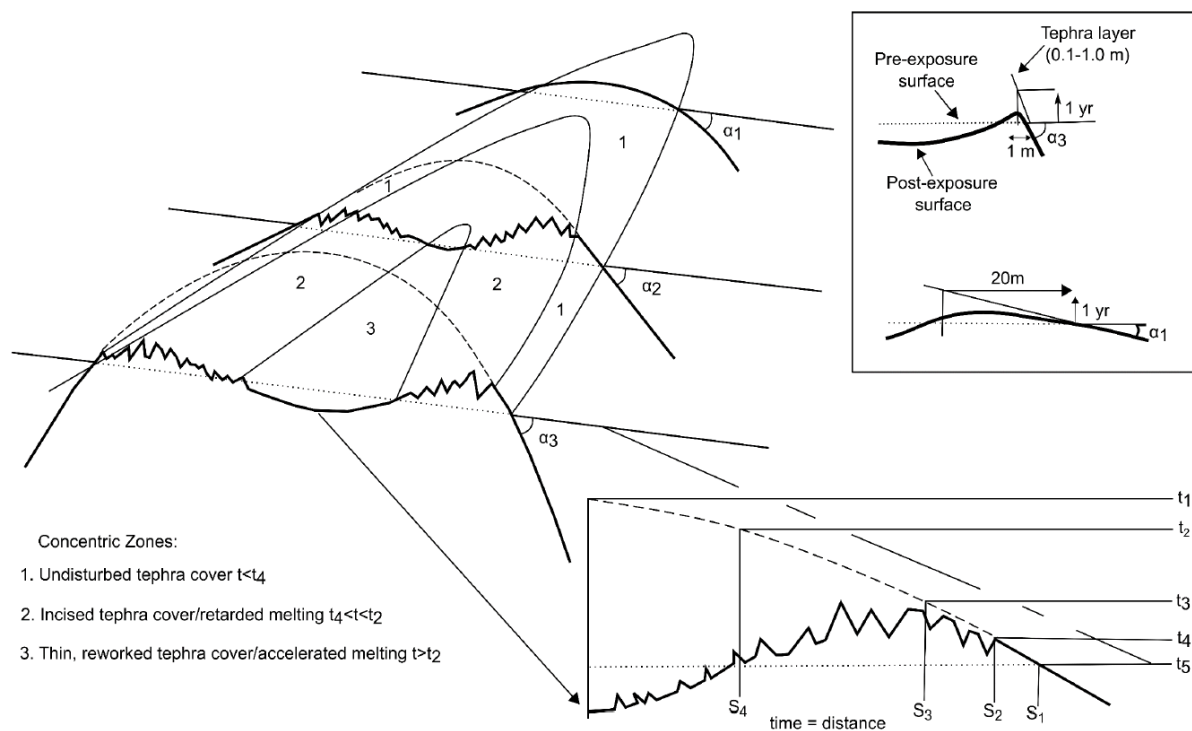


Fig.7: Relationships between an emerging anticlinal englacial tephra layer and a melting glacier ice surface. The shape of the upstream-plunging anticline is such that the tephra layer emerges at gentler angles towards the emergent hinge ( $\alpha_3$  to  $\alpha_1$ ). The upper inset shows that steeper tephra bands ( $\alpha_3$ ) migrate horizontally over shorter distances than gentler bands ( $\alpha_1$ ) for a given rate of glacier thinning. Thus, supply a thicker tephra cover to the glacier surface, reducing melt by more, but over a smaller area and with a slower rate of migration (see Kirkbride and Deline 2013). Concentric zones relate to the progressive stripping of the exposed tephra layer: Zone 1 is thick undisturbed tephra, zone 2 is incised by melt streams to give tephra-capped plateaux and sharp-crested ridges, and zone 3 comprises residual thin cover of low albedo and increased melt rate. The lower inset shows how these zones migrate over space ( $S_1$  to  $S_5$ ) as the glacier thins over time ( $t_1$  to  $t_5$ ). In the main diagram, the cross-profiles show how surface relief is modified by the outcropping and reworking of the tephra band using the dotted line as the reference surface.

## 6.0 Post-interment dispersal of tephra layers

In addition to the flexing, stretching and compressing of tephra layers by solifluction and cryoturbation, the disruption of the layer itself by processes such as bioturbation and the movement of water through a profile can spread particles of tephra into new stratigraphic contexts. The bioturbation of tephra is a phenomena most commonly associated with marine sediments (e.g. Carter, et al., 1995; Andrews et al., 2002; van den Bergh et al., 2003; Todd et al., 2014), but it also occurs in terrestrial deposits and can be identified through its effects on tephra layers. Earthworms have the ability to mix fine-grained tephra with enclosing sediments, as do larger burrowing animals such as the Mazama pocket gopher (*Thomomys mazama*) that are currently remobilising near surface layers of the 1980 Mt St Helens tephra across Washington State. Mixing of tephra with the surrounding soil may occur because of root penetration, and this is thought to be responsible for modifications to the 7.7k cal BP Mt Mazama tephra (Walther et al., 2009). Cryptotephra may be particularly prone to movement within a profile, because of their generally small particle size and sparse occurrence (Dugmore and Newton, 1992), although experiments have observed little movement of tephra through peat (Payne and Gerhals, 2010). Tephra grain counts on contiguous samples are a particularly effective method of quantifying layer diffusion and re-mobilisation and can produce some novel insights, such as the potential impacts of peat burning (Swindles et al., 2013). Within-profile movements of tephra grains can result in cryptotephra layers losing their coherence as discrete horizons related to atmospheric fallout and their original stratigraphic contexts, and can present both interpretative challenges and opportunities. The latter stem from the enduring potential to identify source area and even eruption through the chemistry of the glass shards. X-ray tomography is an emerging method of identifying and visualising the disruption of tephra layers by processes such as bioturbation (see Griggs et al., 2015 and Evans et al., 2017). This is a non-destructive technique, that uses CT scanning to reconstruct and visualise the three-dimensional structure of objects. Griggs et al (2015) identified the potential of using this technique through analysing marine sediment cores containing tephra layers. The results highlighted the diffusion of tephra into the surrounding sediments and burrowed channels, identified as the result of bioturbation by marine organisms. An identifiable (and ideally dated) re-mobilised tephra can thus form a *tracer* of environmental processes, which is discussed below.

### **6.1 Absent tephra layers**

The extreme manifestation of tephra remobilisation is the complete removal of a tephra deposit. Definitive evidence of absence, for example where a tephra layer abruptly terminates within a stratigraphic record, can identify and date incision events both natural (e.g. channel formation, Kirkbride and Dugmore, 2008) and anthropogenic (e.g. the excavation of pits for charcoal making, Church et al., 2007). For this to be useful, it is important that researchers report the absence of tephra layers “expected” to be found in particular locations. This is rarely done and we recommend that this should become common practice because it would also assist in the creation of better isopach maps of fallout (Engwell et al., 2013).

On a sub-metre scales, narrow gaps c. 1-10 cm wide are often apparent in tephra layers. In southern Iceland, we have observed that since the late 9<sup>th</sup> century CE Norse settlement tephra layers < 3 cm thick are more often seen as being more ‘patchy’ in section than thicker layers. Patchiness also occurs in layers formed before the Norse colonisation, where it is more frequently observed and also commonly affects thicker layers. One possible explanation for both these sets of observations is the changing presence of woody stems or the growth of woody roots, combined with different capacities for tephra to infill of voids within their stratigraphy. Patchy tephra in both pre and post-settlement sediments frequently occur in areas that are

within the ecological limits of woodland, and so may represent the disruption of tephra layers that either fell around a woody plant stem or were penetrated by woody roots after the tephra layer was deposited. When these plants died and rotted away, movement of the enclosing sediment to fill the resulting voids can lead to gaps forming in the tephra layer. In pre-settlement Iceland, woody vegetation was more extensive, and in lowland areas individual stems were likely to be thicker, because they could grow to maturity without anthropogenic disturbance.

## 7.0 Tephra tracers

All tephrae preserve a basic record of atmospheric circulation at the time of the eruptions which formed them. A single lobe shows that a single wind direction affected the volcanic plume; multiple lobes indicate a range of different dispersal axes; calm conditions can result in a lack of any distinct lobes of fallout and elongated lobes can indicate strong atmospheric circulation (e.g. Larsen et al., 2001, Gudmundsson, et al., 2012). At a larger scale, the distribution pattern may have a seasonal significance, as for example with the distribution of the YTT ash from the 74ka Toba eruption which includes sites in the South China Sea and thus provides strong evidence for activity during the summer monsoon (Oppenheimer, 2002).

Where isolated grains of tephra are attributable to a specific source area or eruption through their glass chemistry alone, they may act as a tracer of environmental processes, regardless of particle size. At the macroscale, cobble-grade pieces of pumice may be swept into the oceans, if their sources are close to the sea or the pumice is transported by rivers or floods. Once in the marine system, buoyant pumice may be transported by currents across oceans. A proportion of the pumice (in some cases the majority) will become saturated with seawater and sink, but some may be deposited on nearby or distant shorelines. It may then be reworked, buried in coastal sediments, incorporated into raised beach deposits or collected and used by people. Holocene eruptions in Iceland have produced ocean-transported pumice that was deposited on coastlines in the Canadian Arctic, western Greenland, Iceland, Svalbard, the British Isles and Scandinavia (Binns, 1972; Larsen et al. 2001). Along the Norwegian coast, pumice is found on raised shorelines (e.g. Undås, 1942), as well as at archaeological sites, ranging from the Mesolithic to modern times (Newton, 1999a). In the British Isles, pumice has been found in over 150 archaeological sites ranging from early Holocene Mesolithic to modern (e.g. Newton, 1999b, 2001, 2013). People have utilised pumice deposits across the North Atlantic region because it can be used as a tool to prepare animal hides and sharpen wood, bone and antler. It can also be formed into fishing floats, sharpeners, smoothers, rubbers and jewellery, resulting in distinctively shaped, flattened and grooved pieces (e.g. Carver et al., 2016). In the western North Atlantic (Denmark Strait, Labrador Sea, Davis Strait, Baffin Bay) sea ice may limit the spread of floating pumice. The occurrence of pumice in the Ellesmere Island is therefore particularly noteworthy, and is either evidence for sea ice minima or the actions of people, collecting, moving and then discarding pumice, or both (e.g. Blake, 1970, 1975). The presence of pumice can also provide alternative records of volcanic activity, and may represent a significant proportion of the tephra produced by individual eruptions. For example, the Katla SILK eruptions which produced most of the Holocene pumice deposits found on shorelines

around the North Atlantic basin, only generated modest volumes of atmospheric fallout, to form terrestrial layers of a limited regional extent (Larsen et al., 2001).

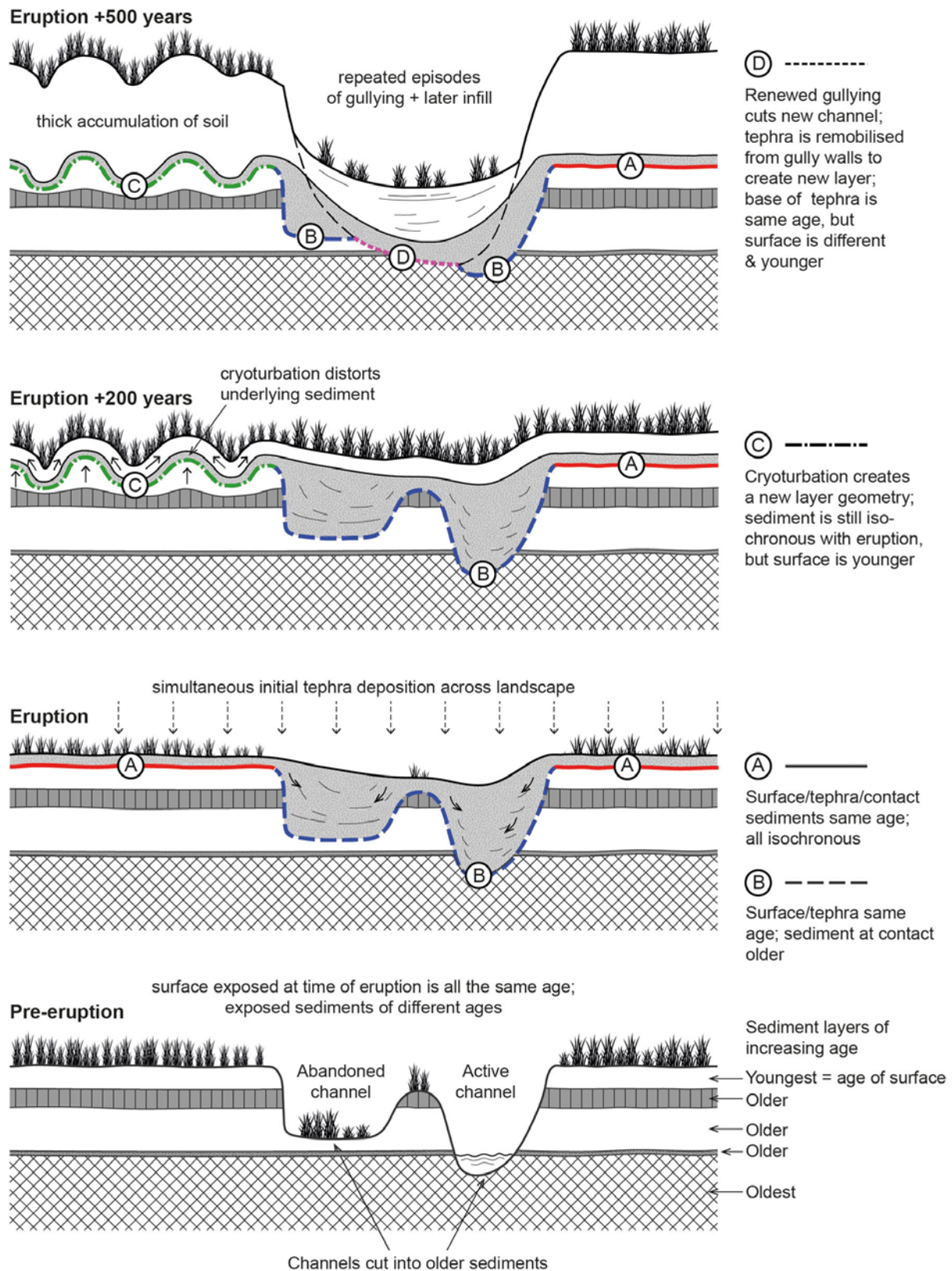


Fig. 8 :The chronological relationship between the surfaces defined by tephra layers and the sediments that compose them can be very varied due to erosion and change through time as a result of sub surface movements of tephra layer. (A, B). On burial a tephra layer may be distorted (cf Fig. 5) and the age relationship between the

*tephra and the surface it defines changes (C). Later incision and reworking can create yet more different age relationships (D).*

## **8.0 Isochrons, dating surfaces and sediments.**

Quaternary science makes an extensive use of isochrons defined by tephra deposits (Lowe, 2011, Dugmore and Newton, 2012, Streeter and Dugmore 2014). The relationship between a tephra layer, the surface it defines and the sediments with which it is in contact can change through time as a result of erosion, sub-surface sediment movements or re-deposition of tephra (Fig. 8). Many of the soil-covered, vegetated landscapes in Iceland have experienced episodes of erosion, ranging from the formation of small erosion spots to the development of rofabards (eroding escarpments of bare soil) and gullying (Arnalds 2000, Dugmore et al. 2009). As a result, exposed surfaces can be formed of sediments with a range of ages. When the exposed surface is covered by tephra, differences may occur between the age of the tephra and the age of the sediments in contact with it; while the sediments may or may not be the same age as the tephra layer, both may form surfaces that are the same age (Fig. 8, a - c). A change in environmental conditions after tephra incorporation within the stratigraphy may result in cryoturbation that distorts the original form of the tephra layer (Fig. 5), while sometimes retaining the same stratigraphic order of sediments (Fig. 8, c). Thus, while the sediments in contact with the tephra layer maybe the same age, the shape of the surfaces the tephra defines are not. Incision and re-mobilisation of tephra deposits can also create a situation where neither the sediment in contact with the tephra layer nor the surface defined by it are the same age (Fig. 8, d). As a result, changes that take place after tephra burial within the stratigraphic record create both potential interpretative problems and opportunities when it comes to palaeoenvironmental inference.

## **8.1 Data recording**

When tephra layers are being used to construct a tephrochronology, stratigraphic relationships such as the depth of a tephra in a core (e.g. Cassidy et al., 2014), or a relationship of a tephra layer to a stratigraphic unit (e.g. Kirkbride and Dugmore, 2008) are key. Quantitative descriptions of primary tephra deposits for both tephrochronology and the reconstruction of volcanic processes are often recorded with a single representative measurement for a unit's thickness at a particular location. These may indeed be based on a single measurement, but an average figure derived from a number of individual measurements is also common (e.g. Engwell et al., 2013).

Harnessing the potential of transformed tephra layers for environmental reconstruction requires additional data capture. Qualitative, descriptive data on distortions of tephra layers and distinctive structures such as overfolds, can be collected using photographs (e.g. Veit et al., 2011) and sketches (e.g. van Vliet-Lanoë et al., 1998). More sophisticated, but much smaller scale data capture can take place with 2D X-ray analysis (e.g. Dugmore and Newton 1992) and 3-D X-ray tomography (e.g. Griggs et al., 2015), which will create both graphical and digital outputs. Photography can be used to both capture quantitative data on layer thickness variation (e.g. Streeter and Dugmore 2013b) and create a data archive. Layer thickness variations and variability are straightforward to quantify through multiple measurements (Streeter and Dugmore, 2013b, 2014) that can be structured in different ways to capture different scales of change depending on the research question being addressed (Cutler et al., 2016a, 2016b). Tephra layers <20 cm thick can be usefully recorded to a resolution of 1 mm (e.g. Streeter and Dugmore 2013b). Measurements of tephra layer thickness (taken at right angles to the surface

of the deposit) may take place at horizontal intervals of 1-10 cm and in groups of 3-5 measurements as clusters, (e.g. Cutler et al., 2018), along short transects less than 1 m in length (e.g. Dugmore et al., 2018), or longer transects of 5-20 m (Cutler et al., 2016a, 2016b). Whilst quantification and related statistical analysis are essential to tease out potential relationships between land surface cover and tephra layer characteristics other relevant data also includes notes on structures within a layer, presence or absences of tephra, the nature of contact surfaces and the orientation of layers. Online databases, such as Tephabase (Newton et al., 2007), provide a means of collating such data and allowing comparisons to be made, if they share common standards.

## 9.0 Conclusions

Morphological and stratigraphical transformations of visible tephra units may occur while the primary deposit is lying on the surface and may begin, continue or cease after it has been incorporated into the stratigraphic record. There may be single episodes of transformation or complex sequences of transformation that vary in terms of process, timing and intensity.

Most uses of tephra in Quaternary science and volcanology focus on primary deposits, where the characteristics of the deposit reflect those of the source eruption and the tephra lies in its original stratigraphic context (e.g. Larsen, 2000, Carey et al., 2010, McCulloch et al., 2017). There may be good criteria for identifying (and potentially discounting) remobilised, or re-worked tephra deposits, such as the presence of distinctive bedding structures or exotic materials (Óladóttir et al., 2011). However, the absence of tephra layers in individual sections, where they may be expected to be found, could be due to remobilisation and reworking, rather than a lack of primary fallout. Greater clarity can be achieved through detailed mapping, and the identification of coherent spatial patterns and anomalies (Dugmore and Newton, 2012). Obviously, modified deposits are often considered as unreliable and frequently ignored. However, we argue that they may be valuable sources of information, acquired through qualitative description (Kirkbride and Dugmore, 2005) or detailed measurement, for example by photogrammetry (Streeter and Dugmore, 2013b).

In order to understand in detail the processes that alter surface tephra deposits in the period after deposition, high-resolution measurements are required. The timing of volcanic eruptions is not predictable, requiring experimental approaches, where tephra is deliberately deposited on a surface and regularly monitored. A limited number of such studies have taken place (e.g. Payne and Gerhals, 2010, Todd et al., 2014, Blong et al., 2017), but we suggest experiments which cover a wider range of environments and tephra characteristics may give valuable insights into the processes that alter tephra while it is on the surface.

Classical tephrochronology has made many important contributions to our understanding of volcanic eruptions, past environments and societies, and tephra deposits, identified tephra layers and the isochrons they define are used in a variety of ways to understand chronology and other aspects of the past. The environmental processes that affect the tephra record can make the application of classical tephrochronology challenging. However, novel sources of environmental data exist within tephra sequences which have experienced post-depositional transformations which can be used to create new perspectives of past processes, land surface conditions and trajectories of change. As well as developing a wider tephra science for past environments, understanding the processes that transform tephra deposits contributes to a better understanding of the correct interpretation of tephra layers to reconstruct eruption parameters.

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