Reviewed research article

Isochrons and beyond: maximising the use of tephrochronology in geomorphology

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Abstract – *This paper reflects on the application of tephrochronology in geomorphology. A common use of tephra layers is to define isochrons and use them to date environmental records. Applications of tephrochronology with the greatest practical utility, however, involve both classic isochrons (layers with an extensive distribution, distinctive well-characterised properties and good independent dating) and all other tephras present, including poorly-identified, unprovenanced and re-mobilised units that define time transgressive horizons. The effective use of this 'total tephrochronology' requires replication across multiple sites, the clear identification of primary tephra deposits and re-mobilised deposits, combined with a good understanding of when tephra deposits truly define isochrons. Large scale replication of tephra stratigraphy is possible (and desirable) with terrestrial sequences, and can offer a detailed understanding of both geomorphological processes and human interactions with the environment. It is possible to use sequences of unprovenanced tephras as a 'barcode' to undertake local correlations and refine the application of well-known marker horizons to environmental records. High frequency and high resolution measurement of both the units between tephra layers and the tephra layers themselves can identify subtle shifts in landscape stability and land use.*

INTRODUCTION

Tephrochronology is based on the utilisation of isochrons defined by tephra layers formed by the undisturbed fallout from volcanic eruption clouds (Thórarinsson, 1944). The identification of the tephra produced by a specific eruption permits the correlation of separate tephra deposits formed at the same time, the recognition of a contemporaneous surface and the definition of an isochron. This isochron may be traced to the most suitable location or source for dating. Tephra isochrons have great utility as they provide precise and accurate correlation between different records. They are especially useful if their age is also known with both accuracy and precision. While the utilisation of distinctive widespread isochrons is perhaps the best known aspect of tephrochronology, there are other very useful attributes of tephras and different ways in which they may be used to gain a better understanding of past environments (Lowe, 2011). In this paper we focus on some of the less-commonly utilised uses of tephra layers in environmental reconstruction and different ways of thinking about tephrochronology that go beyond the straightforward identification and utilisation of well-constrained isochrons. Figure 1 shows the location of places mentioned in the text.

BUILDING BLOCKS: TEPHRA LAYERS AND ISOCHRONS

There is a hierarchy of importance amongst individual tephra deposits when it comes to their use in tephrochronology. At the pinnacle sit the tephra layers that have four key characteristics; extensive spatial distribution in a short period of time, distinctive properties that are well-characterised, good independent dating and an occurrence at times of widespread interest. In Iceland, this group of tephras is epitomised by the Vatnaöldur c. 870 AD tephra also known as the Settlement Layer (a tephra that marks the settlement of Iceland by the Norse (Larsen, 1984)), and includes major silicic tephras of Hekla (e.g. Hekla 4), Öræfajökull 1362 AD and Askja 1875 AD (e.g. Thórarinsson, 1958, 1967; Larsen and Thórarinsson, 1977; Larsen and Eiríksson, 2008). While all of these tephras are well-dated, distinctive in isolation and have been described in detail, they vary in their use in archaeology and palaeoenvironmental studies because of contrasting spatial distributions and their differing relevance to contemporary research agendas. Today the Settlement Layer (also referred to as the Landnám tephra after the Norse term for 'land-taking') is arguably the most significant marker horizon in Iceland, because of both its stratigraphic relationship with initial phase of human settlement and its widespread distribution across the island (and beyond) (Figures 1 and 2b). These characteristics combined with ice-core dating (Grönvold *et al.*, 1995; Zeilinski *et al.*, 1997) create a truly iconic marker horizon. The contrasting status of tephras such as Hekla 4, Öræfajökull 1362 AD and Askja 1875 AD comes from a combination of their age and distribution: Hekla 4 occurs at a time of widespread archaeological and environmental change across the British Isles (e.g. Gear and Huntley, 1991; Blackford *et al.*, 1992), covers much of Iceland (Larsen and Thórarinsson, 1977), but falls when the island is uninhabited and forms an isochron of rather more limited Icelandic interest compared to Vatnaöldur c. 870 AD. While Hekla 4 can be found across much of Iceland, Öræfajökull 1362 AD and Askja 1875 AD have comparatively restricted Icelandic dis-

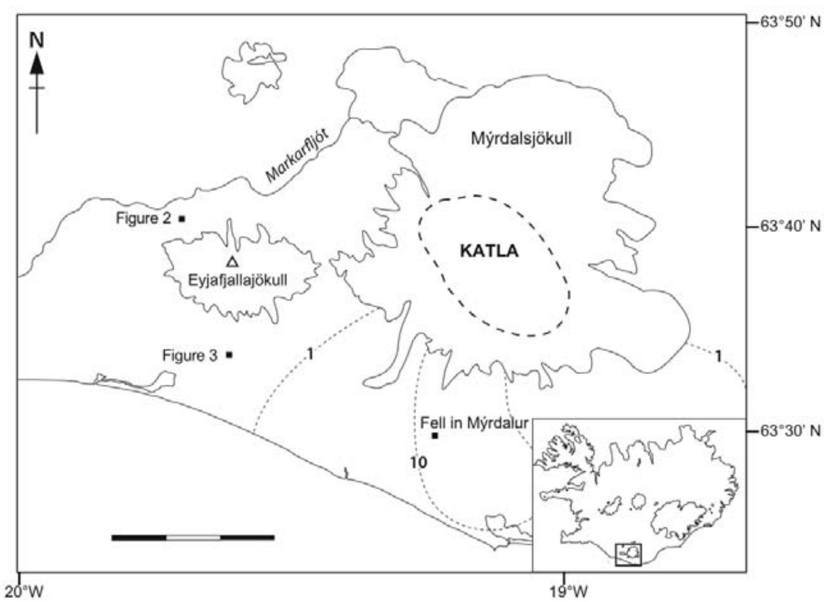

Figure 1. Key locations mentioned in the text. The limits of 1 cm and 10 cm thick fallout from the Katla eruption of c. 1357 AD are taken from Einarsson *et al.* 1980. – *Staðsetning öskulagasniða á 2. og 3. mynd ásamt þykktargeira öskufalls úr Kötlu 1357 samkvæmt Þ. Einarssyni og fl. 1980.*

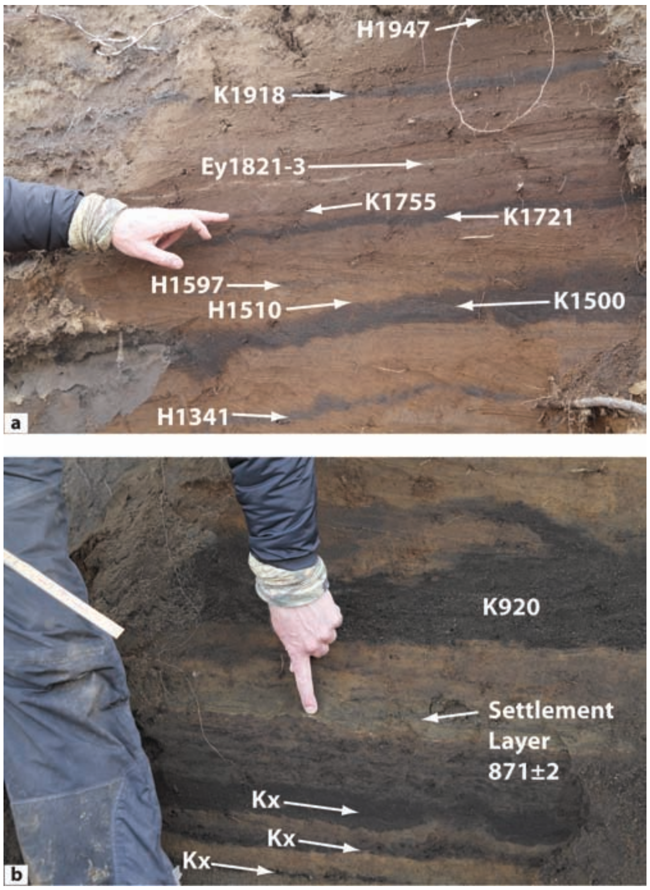

Figure 2a. Profiles on the south side of the Markarfljót valley, north of Eyjafjallajökull (Figure 1) contain a frequency of recent tephra layers typical of many part of the south. The basaltic layers of Katla have very similar major element characteristics and the constituent grains in isolation are indistinguishable in the field. In section and in context different tephra layers can be firmly identified: in this section, for example, K1918 can be identified by its position between H1947 and Ey1821; K1755 and K1721 by their co-occurrence and K1500 either by its very close association with H1510, or its more general location between H1597 and H1341. Figure 2b. The Settlement Layer tephra effectively marks the first human settlement (Landnám) of Iceland. This tephra is a distinctive layer with a lower silicic part (by the finger tip) and an upper olive grey/green layer that includes a crystal fraction. The Katla layers below Landnám form isochrons as precise as those above, but their calendar or sidereal dates are not known with the same accuracy or precision. Even though the basaltic tephras from Katla may be indistinguishable in isolation they can form a distinctive and diagnostic bar code of thicker and thinner layers.

Mynd 2a. Í jarðvegssniðum á svæðinu norðan Eyjafjallajökuls og sunnan Markarfljóts er fjöldi gjóskulaga í jarðvegi dæmigerður fyrir mörg svæði á Suðurlandi. Basaltgjóskulögin frá Kötlu hafa mjög svipaða efnasamsetningu og eru það lík útlits að þau þekkjast ekki sundur í felti. Í sniði og í samhengi við önnur gjóskulög má þekkja Kötlulögin í sundur: Í þessu sniði má t.d. þekkja K1918 af legu þess milli gjóskulaganna H1947 og Ey1821; K1755 og K1721 finnast saman og þekkjast þannig, og K1500 má annað hvort þekkja af fylgni þess við gjóskulagið H1510 eða legu þess milli gjóskulaganna H1597 og H1341. Mynd 2b. Landnámslagið féll um svipað leyti og landnám hófst á Íslandi. Hér er þetta gjóskulag auðþekkt af neðri hluta úr ljósri, súrri gjósku (við fingurgóminn) og efri hluta úr basískri, ólífugrárri/grænni gjósku með kristöllum. Kötlulögin neðan við Landnámslagið mynda jafntímafleti sem eru jafn nákvæmir og þeir sem gjóskulögin ofar í sniðinu mynda, en aldur þeirra í almanaksárum eða stjörnuárum er ekki þekktur af sömu nákvæmni og Landnámslagsins. Jafnvel þótt ekki sé hægt að þekkja einstök Kötlugjóskulög geta þau myndað einkennandi og auðþekkta röð af þykkri og þynnri lögum, líkt og strikamerki.

tributions, despite their large scale and extensive distal spread (Thórarinsson, 1956, 1981a). In general, the years of their formation (1875, 1362 and c. 2,250 BC) have somewhat less general historical, ecological or archaeological interest than the Landnám period, although the eruptions themselves are of volcanological significance.

Although the context and the research questions being asked will ultimately determine the immediate worth of any tephra layer, those that are identified with less certainty, not effectively correlated or inaccurately dated will generally have less individual value. Tephrochronology can, however, be far more than the utilisation of a limited number of outstanding isochrons, and the sum of parts combined may be much greater than the tally of individual components. Collective worth can be developed in two ways; firstly through the local utilisation of whole tephra stratigraphies, including poorly provenanced layers, re-deposited tephras, patchy deposits, notable absences and cryptotephras. Secondly, environmental data may be extracted from the form and local distribution of tephra layers themselves. This development of 'added value' to tephrochronology is most straightforward when dealing with visible traces of multiple tephra deposits that can be mapped in the field.

In NW Europe, where Icelandic tephras are mostly present as cryptotephra deposits (and thus not visible in the field), tephrochronology has tended to focus on a limited number of key marker horizons (e.g. Dugmore *et al.*, 1995; Pilcher *et al.*, 1996; Turney *et al.*, 1997; van den Bogaard and Schmincke, 2002; Wastegård and Davies, 2009). This is the logical development of tephra studies that began with the convincing demonstration that identifiable tephra deposits were present, even though they were hidden from view (Persson, 1971; Thórarinsson, 1981a; Dugmore, 1989a). The significant effort required to isolate and identify cryptotephras has meant that their principal contribution has been to provide a limited number of unambiguous and key dates within palaeoenvironmental sequences. While this has produced very effective and high profile developments of tephrochronology, such as the identification of the Vedde and Saksunarvatn tephras within the last glacial-interglacial transition of the British Isles (Turney *et al.*, 2006), it represents a fraction of the potential richness of interpretation made possible through Thórarinsson's original vision (Thórarinsson, 1944). To explore the development of this vision in more detail, this paper will focus on geomorphological applications in the birthplace of modern tephrochronology, and, we hope, pay tribute to Thórarinsson's enduring scientific legacy.

When isochronous tephra layers do not necessarily define isochronous surfaces

When a tephra layer is formed by in-situ fallout from an eruption cloud, the contact surface between the tephra and the underlying landscape forms an isochron (Figure 2). There are times, however, when this temporal relationship between the tephra and the landscape it covers may not be that simple. It is the surface that is the isochron; the materials that form the surface may or may not be of the same age. For example, a landscape formed by patches of eroding soil, river terraces and exposed glacial sediments will have a surface that is a mosaic of different aged materials, but has a common exposure at a moment in time (i.e. the moment the tephra fell).

This provides the single biggest contrast between the landscape applications of tephrochronology in geomorphology and archaeology and its more restricted use in dating sedimentary sequences, such as lake sediments or peat cores. We have established that the surface on which a tephra falls may be composed of materials of quite different ages, but the surface exposed to tephra fall is isochronous. This can, however, change after the deposition of the tephra layer, even if the stratigraphic location of the tephra within the sediment sequence remains unchanged. A common example of this is cryoturbation of near-surface sediments, leading to frost hummock (thufur) formation (Figure 3). In these circumstances, the tephra layers affected by the hummock formation still define isochrons, but it may be that neither the underlying materials in contact with an individual tephra layer, nor the surface defined by the base of the tephra layer are of a similar age; after disturbance the age of the tephra will not be the same as the cryoturbation structures they define.

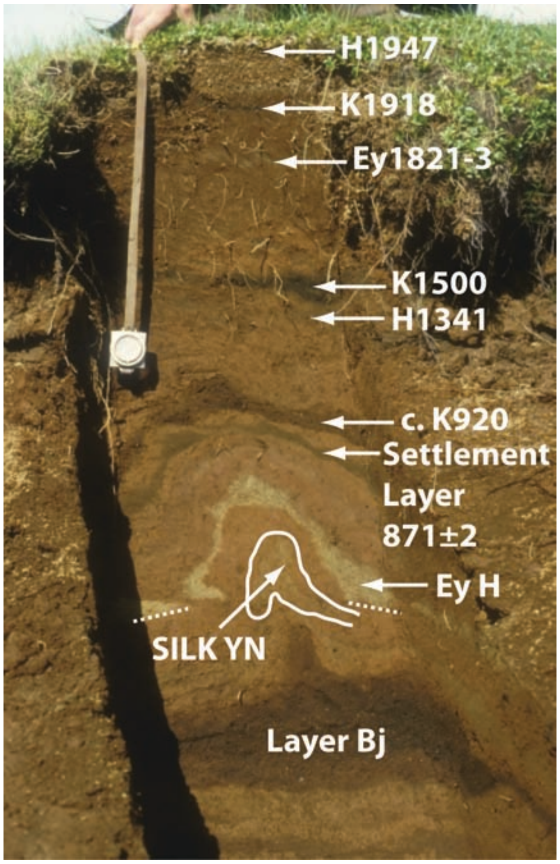

Figure 3. The surface covered by the pre-historic tephra layer Bj defines an isochron of the same age as the overlying tephra (location shown in Figure 1). The silicic tephra Ey H is also an isochronous primary tephra deposit, but in this case the surface in contact with the base of the layer is not all of the same age. The dotted lines highlight places where the surface is most probably the same as the tephra. In the centre of the profile, however, the layer has been distorted by post-depositional frost hummock formation and to the left of centre the layer has been over folded. Thus, the hummock form post-dates the deposition of the tephra and the surface defined by the tephra as a whole is not isochronous. The early 5th century SILK-YN tephra has also been distorted after deposition to form a vertical finger of sediment in line with the hummock peak, and so in this case too the surface defined by the tephra is not the same age as the tephra. – *Yfirborð jarðvegsins sem forsögulega gjóskulagið Bj féll á er jafntímaflötur af sama aldri og gjóskulagið. Yfirborðið sem súra, ljósleita gjóskulagið Ey H féll á er hins vegar ekki allt af sama aldri þar sem gjóskulagið hefur aflagast vegna frostverkunar eftir að það féll. Þúfan sem frostlyftingin myndaði er yngri en gjóskulagið og flöturinn undir gjóskunni er ekki alls staðar af sama aldri. Punktalínurnar sýna staði þar sem yfirborð jarðvegsins er af sama aldri og gjóskan. Gjóskulagið SILK-YN frá 5. öld aflagaðist einnig eftir að það féll en bútur úr því er lóðréttur innan í þúfunni.*

Other examples of post depositional morphological modification of tephra layers occur in glaciers where ice flow distorts and relocates tephra layers, changing their geometry as well as changing their location, but leaving their stratigraphical setting unaltered. Tephra layers currently outcropping around the margins of Vatnajökull were originally deposited in different locations above the snowline (Larsen *et al.*, 1998). They have been moved many kilometres by ice flow and have been subject to complex sequences of morphological modifications. The stratigraphical relationships of the tephra and the frozen water exposed at the time of tephra deposition does, however, remain the same, even though the tephra fell on snow and that snow has been transformed to glacier ice, which has flowed from the accumulation areas of the glacier to its ablation zone.

Tephra melting from a glacier may create a secondary isochron, one unrelated to the age of the tephra itself. For example, in the North Atlantic during the last glacial-interglacial transition the distribution of Icelandic tephra along the southern margin of the melting sea ice created an extensive ocean-floor stratigraphic marker horizon, but one with a tenuous relationship to the age of the eruption that created the tephra (e.g. Ruddiman and McIntyre, 1973; Brendryen *et al.*, 2011).

A second and even more extensive secondary dispersal of tephra has been achieved by ocean-transported pumice of Icelandic origin during the Holocene (e.g. Binns, 1972; Newton, 1999). These pumice forming eruptions created comparatively little atmospheric fallout (Larsen *et al.*, 2001), but large volumes of cobble-grade pumice. This was delivered into the ocean and dispersed by ocean currents to be deposited along contemporaneous high water lines and storm beaches around the North Atlantic. Some pumice survives as linear deposits on the strandlines of Svalbard (e.g. Salvigsen, 1984) and Norway (e.g. Undås, 1942; Newton, 1999); in Scotland, rising sea levels have overwhelmed many of the original deposits, but pumice is a frequent find in archaeological sites from the Mesolithic to modern times (e.g. Newton, 2001; Newton and Dugmore, 2003).

In all of these cases it is important to recognise that isochron status may only apply to undisturbed primary deposits of tephra - that is material produced, distributed and deposited in a very short period of time, and thus effectively defining that moment of time. It may also apply to the surface the tephra overlies and the sediment in direct contact with the tephra, but even when a tephra does not define a surface the same age as the tephra-forming eruption, this still provides a valuable environmental record of process; for example, the creation of frost hummocks, glacier flow or ocean circulation.

DEVELOPING THE USE OF ISOCHRONS

The NW European focus on the identification of isochrons within palaeoenvironmental records has parallels with the use of tephrochronology in Icelandic glacial geomorphology (e.g. Thórarinsson, 1956; Dugmore, 1989b; Kirkbride and Dugmore, 2001a, 2008). A common theme between NW Europe and Iceland is the identification of isochrons in relation to environmental changes and the correlation of key marker horizons between different environmental records. The greater abundance of tephra layers in Iceland means that more nuanced interpretations are possible, but these may require an approach to tephrochronology and a use of tephra deposits which is quite different to those employed with the key international marker horizons (e.g. Kirkbride and Dugmore, 2001b, 2005, 2006).

In most Icelandic stratigraphic sequences formed within the last 1200 years, all of the tephra layers present may be identified and dated to very high levels of precision. This capability is built on Thórarinsson's pioneering work and in particular the clear understanding he developed of the post-Settlement eruptions of Öræfajökull, Hekla and Katla (Thórarinsson, 1958, 1967, 1975, 1980). In some sequences, however, the patchy occurrence of tephra layers towards the margins of their distributions can introduce ambiguity. In the Markarfljót valley north of Eyjafjallajökull, for example, the 18th century stratigraphy can include thin black tephra layers formed by Katla eruptions in 1755 and 1721 (Larsen, 2000, Kirkbride and Dugmore 2008) (Figure 2a). Where both tephra layers are present, identification is unambiguous. Where only one tephra layer is present, it could be from either of the 18th century Katla eruptions, because they have very similar major and minor element compositions. Moving to the west of the Markarfljót valley certainty is re-gained because only the 1755 fallout is present around Stóramörk.

Within these Markarfljót valley sequences a secure 19th century isochron is formed by the silicic fallout from the 1821–1823 eruption of Eyjafjallajökull, and effective 16th century markers are formed by the chemically distinct tephra from Hekla 1597, and the couplet formed by the tephras from Hekla 1510 and Katla c. 1500 (Haraldsson, 1981). Thus, while some parts of a stratigraphic record may be secure other, intervening parts may vary in the confidence of their identification, chronological accuracy or precision.

Trace element data can go a long way to resolve tephra layer identification (e.g. Óladóttir *et al.*, 2011a), but there are still circumstances where current knowledge of trace elements abundances is unable to resolve tephra identifications (e.g. the eight tephra layers with ambiguous plots reported by Óladóttir *et al.*, 2011a). A similar problem of chemical equifinality exists with other layers of quite different chemical composition, such as the Hekla silicic tephras from 1510 and 1947 (Larsen *et al.*, 1999), but again stratigraphic associations are definitive; for example the combination of Hekla 1510 and Katla c. 1500 is diagnostic and has been used in field mapping (Haraldsson, 1981; Dugmore *et al.*, 2009; Figures 2, 3).

Across the soil-covered lands of Iceland, the potential for the repeated analysis of the local tephra sequence in many different stratigraphic sections makes a vitally important contribution to the rigor of tephrochronological applications. Not every soil profile will contain every tephra layer to have fallen in a region; so ideally profiles are added to the analysis until it can be shown that adding more profiles does not add more new primary tephra deposits; at that point it is possible to be confident that all possible tephras have been identified and the potential omissions from any individual profile can be established.

Lake cores can preserve a much more detailed tephra record than surrounding terrestrial deposits (e.g. Björck *et al.*, 1992; Haflidason *et al.*, 1992; Caseldine *et al.*, 2003; Hardardóttir *et al.*, 2009). There can, however, be significant stratigraphical variation across a lake bed, sediments may be reworked by currents, the record affected by earthquakes and tephra deposits may be so thick that successful coring represents a real challenge (Boygle, 1999). While lakes can preserve excellent multiple proxy indicators of environmental conditions and a homogenised record of catchment processes, they are one step removed from the landscapes that people interact with on a daily basis. Within a catchment-scale lake record, geographical patterns of the environment at a moment in time cannot be resolved with accuracy and it is not possible to differentiate between different in-catchment landholdings, or components of the landscape (e.g. Mairs *et al.*, 2006). It is notable that recent key works on the volcanic histories of Katla, Grímsvötn, Bárdarbunga and Kverkfjöll have utilised terrestrial sites (Óladóttir *et al.*, 2005, 2011a, 2011b).

Isochrons and primary tephra deposits

To be confident that all significant episodes of volcanic fallout across a specific area have been identified, it is necessary to clearly identify primary tephra deposits, remobilised layers that still define isochrons and reworked tephra that form time-transgressive deposits. This is not always a straight-forward task, especially when seeking to utilise tephrochronology in fields such as geomorphology, environmental reconstruction and archaeology. In these applications, the stratigraphy under consideration is often complex, present in short vertical sequences and spatially fragmented; tephra layers are often intercalated with many other types of deposit, from cultural materials such as midden and artificial structures to natural features such as fluvial deposits and glacial till. Tephra layers often lie within soils formed from aeolian sediments, but they may also lie within very different materials such as cultural deposits or diamictons. Complex sequences produced by a shifting interplay of episodes of deposition, transport and erosion may contain both tephra deposits that have been disturbed in situ, yet still define an isochronous horizon, and tephra deposits that have been remobilised, lost their isochronous status and yet appear to be primary deposits because of their lack of exotic admixtures, limited grain modification and the presence of ambiguous sedimentary structures. Where there has been a limited or non-existent contemporaneous movement of other sediments, redistributed deposits of tephra may be essentially similar in character to those of primary undisturbed fallout. The presence of exotic materials or distinctive sedimentary structures can be definitive evidence of remobilisation and re-working of tephra (Óladóttir *et al.*, 2011a); but their absence does not necessarily mean that there has been no mobilisation and post-eruption thickening of the tephra layer. Likewise, reworked layers may have both sharp upper and lower contact and laterally continuous sedimentary structures. This may, for example, happen when tephra layers are re-deposited across snow beds – and so be a key concern when considering upland areas or winter eruptions. In these circumstances, the key field observations of tephra layer colour and contacts, grain size and shape, and layer thickness identified by Óladóttir *et al.*, (2011a) can be usefully expanded to include an assessment of the spatial distribution and regional stratigraphic patterns. Detailed mapping of each tephra layer in relation to the geomorphology, probable contemporaneous vegetation cover and land use can show the degree to which modification is likely, or not. This can effectively identify both isochrons defined by internally modified layers and tephra deposits that may be uncontaminated.

Vegetated plateau and terraced areas are likely to contain the best indication of fallout thickness, slopes are likely to have experienced either erosion of the primary fallout thickness, or thickening due to tephra mobilisation down-slope. Sediment traps such as well-vegetated basins are likely to have the most complete tephra records and if their catchments are stable, they are unlikely to contain multiple layers of reworked tephra (e.g. Kirkbride and Dugmore, 2001a). Lowland, ecologically-favoured areas are likely to recover more rapidly from the impacts of tephra fall than upland, ecologically marginal areas, and as a result lowland tephra sequences are likely to have less disturbance. Crucially, if a tephra layer is found in multiple profiles in contrasting geomorphological settings, then it is not likely to be the product of localised tephra re-mobilisation and is likely to define an isochron.

Tephra deposits will experience varying degrees of reworking and redistribution while they are exposed to the surface environment. Original observations of the season-by-season changes to the fallout from the 2010 AD eruption of Eyjafjallajökull show that the small-scale variability of tephra layer thickness (a good indication of the cumulative amount of post-depositional change) is a reflection of landscape stability and the completeness and depth of vegetation cover. The mobilisation of a tephra deposit - and its potential movement across the landscape - will be minimised if the full thickness of the tephra layer is rapidly stabilised by a spatially continuous vegetation cover. Redistribution will result in areas stripped of primary tephra deposits. This process has been observed happening to Ey2010 in the un-vegetated forelands of the southern margin of Eyjafjallajökull ice cap, and also to the fallout of the c. 1357 eruption of Katla on vegetated surfaces at Fell í Mýrdalur (Figure 1). The stripping of unconsolidated tephra from exposed, unvegetated surfaces affected by winds, water and frost action is to be expected. The reasons for the near-complete removal of tephra from grass-covered, slopes of aggrading soil are less obvious. Fell í Mýrdalur lay beneath the principal axis of fallout in 1357 AD, was comparatively close to the eruption site and received coarse (sand-grade) fallout (Einarsson *et al.*, 1980; Figure 1). If, as is likely, hill slopes of around 30° near to the farm were covered by a well-grazed sward, there would have been little opportunity for a decimetre-scale deposit of coarse-grained tephra to stabilise, especially as this is one of the wettest parts of Iceland. In contrast, the accumulation of a continuous 'rain' of silt-grade aeolian sediment did take place, as did the discrete episodes of silt-grade, mm-thickness fallout from both Hekla 1300 and 1341 eruptions; the crucial difference being that the fine-grained silts could work into the vegetation mat and thus be incorporated into the stratigraphy, whereas the coarse grained tephra from c. 1357 AD evidently did not.

THE USE OF POORLY PROVENANCED TEPHRA STRATIGRAPHIES

In contrast to the generally well-known tephrochronology of the last 1200 years, pre-Landnám tephra stratigraphies may contain many unidentified layers. The basic framework is secure and built around one of Thórarinsson's great legacies, knowledge of the great silicic layers from Hekla; Hekla-S, Hekla 3, Hekla 4 and Hekla 5 (Thórarinsson, 1944; Larsen and Thórarinsson, 1977), now supplemented with a thorough understanding of the volcanic history of Katla (Larsen *et al.*, 2000, 2001; Óladóttir *et al.*, 2005), Grímsvötn, Bárdarbunga and Kverkfjöll volcanic systems (Óladóttir *et al.*, 2011b). These studies have identified over 550 Holocene tephra layers, established their chemical characteristics and revealed the eruption frequency of key volcanic systems, but despite these monumental achievements the spatial distributions of most Holocene layers is yet to be established. As a result, local details can be usefully added using a 'barcode' approach that replicates recognisable stratigraphic sequences over short distances (Figure 2b).

The key to the 'barcode' approach is that it uses the thicknesses and stratigraphic order of layers to make very short range correlations typically over distances of 10–100m. This approach is unlikely to work over longer (km scale) distances because of the effects of different tephra plume orientations. Even if a short stratigraphic sequence of tephra layers are all from the same source, it is most unlikely that the fallout was of the same scale and blown in the same direction and distance for every eruption; as a result the thicknesses of the layers will change in different ways across the landscape. Add layers from other volcanic sources and the relative variations in tephra thicknesses across a landscape will become more pronounced. Over very short distances, however, fallout will remain roughly similar and the thickness within each profile will be exaggerated or inhibited depending on the geomorphological setting, and the relative thicknesses will show common patterns. A profile may, for example, have a short sequence of basaltic layers that are in order thin, thick, thicker, thin and thick; although the absolute thicknesses will change with variations in slope position and vegetation, over short distances the ratio of thicknesses is likely to remain similar. As a result, the barcode they define may be used in local correlations even when the provenance of the tephra is uncertain.

Pre-Landnám rates of non-tephra aeolian sediment accumulation are much lower, than those of the recent past, so there is less stratigraphic separation between individual tephra layers. Non-tephra aeolian sediment accumulation rates (SeAR) are greater in recent times because of the soil erosion triggered by human impacts - a key point first proved by Thórarinsson (1961) in an early application of tephrochronology. In southern Iceland, the post-Landnám SeAR generally increase by more than an order of magnitude, but it does have great local variation (Dugmore and Buckland, 1991; Dugmore *et al.*, 2000, 2009; Streeter *et al.*, 2012). This means that closely-spaced pre-Landnám eruptions can produce tephra layers that have little, if any, intervening aeolian sediments. In addition, lower aggregation rates in pre-Settlement stratigraphies allow pedological processes to generate weathered profiles, a phenomenon that is rare in historical times post-1500, because of the very rapid rates of profile aggradation.

In contrast to aeolian sediment sequences and minerogenic soils, peat sequences may contain far clearer pre-Settlement tephra records than they do now - and for essentially the same reason. Low levels of aeolian sediment flux are associated with the growth of peats with very high organic contents. In favoured areas in pre-Settlement time these peats did grow rapidly, and so provided clear stratigraphic separation for tephra layers. In recent centuries, peats have been affected by both high levels of non-tephra minerogenic input derived from soil erosion and the effects of artificial drainage, both of which make the identification of tephra layers more difficult. Physical contrasts between the tephra and the surrounding materials are reduced, while episodic waterlogging can result in profile weathering and associated colour changes.

Weathering can change the macroscopic features of a tephra layer, most noticeably by turning the colour of basaltic layers from black into shades of red/brown and creating consolidated, indurated layers that are more resistant to erosion than the surrounding sediment. Profile weathering that transforms tephra layers can be distinguished from the red/brown colouring of dark basaltic tephra caused by oxidation during eruptions, because profile weathering affects both the tephra layers and the intervening sediments. Importantly, the stratigraphic patterns, defined by stratigraphic order, layer thicknesses and particle sizes, remain unaltered, and so even when there is uncertainty about provenance, the 'barcode' defined by the stratigraphy can still be used with confidence.

Rapid sediment accumulation in the surviving areas of vegetation cover mean that pre-Landnám layers frequently lie below the depths easily reached by pits manually-dug from the surface. As a result, access to early Holocene sections usually relies on natural sections such as eroding river banks and gully walls (e.g. Óladóttir, 2011b). Naturally eroding sections within post-Landnám sediments will tend to form near-vertical faces as the greatest resistance to erosion is provided by the surface vegetation; in pre-Landnám sequences the presence of more resistant layers mean that, in the absence of erosion focussed at the base, sloping exposures will tend to form. This combination of more and less easily eroded sediment gives rofabards (eroding slopes of soil) their characteristic concavo-convex profile (Arnalds, 2000).

Soil cover in early Holocene times was patchy and became more extensive until the onset of post-

Landnám erosion. Some areas have truncated sequences of Holocene soils because of episodes of erosion driven by geomorphic processes such as glaciation and fluvial action, but in areas where a high density of soil sections have been dug through to the underlying substrate (such as south of lake Mývatn, close to Öræfajökull and around Eyjafjallajökull), it is apparent that this is not a complete explanation (Guðmundsson, 1998; Dugmore, 1987; Ólafsdóttir and Guðmundsson, 2002). Within the surviving areas of soil cover, basal ages show that soil cover has become more extensive through the course of the Holocene, and indicates an increasing cumulative total of superficial fine sediment across the island as a whole. Tephra production through the Holocene is likely to have been a major driver of this change, especially the very large tephras (such as Hekla 3 and Hekla 4) that were deposited across the sparsely vegetated central highlands (Larsen and Thórarinsson, 1977; Óladóttir, 2011b). In the uplands, cubic kilometres of tephra would have remained potentially mobile for decades to centuries after their initial deposition. This would have provided large-scale sediment banks that could be winnowed-out to create a fine-grained flux of aeolian dust over the surrounding lowlands, and the raw material for soil formation. With the eruption of more tephra, more extensive soils could form. Modern analogues for this process can be observed with both the 2010 Eyjafjallajökull and 2011 Grímsvötn tephras. The consequence for tephrochronology is that older records are more spatially-fragmented because with increasing age the soils necessary to preserve tephra are more limited in extent and increasingly patchy.

Despite impressive recent progress identifying a very large number of the Holocene pre-Settlement tephra layers from the Katla, Grímsvötn, Bárdarbunga and Kverkfjöll volcanic systems that have dispersed into the lands around the icecaps, only a small proportion of pre-Landnám tephra layers have been mapped in detail (Larsen *et al.*, 2000, 2001; Óladóttir *et al.*, 2005, 2011b). When a lack of time, resources or inclination mean that it is not possible to analyse the major, minor and trace element compositions of all the tephra layers encountered in a study, one response is to effectively ignore the problematic tephras and concentrate on the well-known marker horizons such as Hekla 3 and Hekla 4; this may provide sufficient resolution to tackle the questions being posed, and so be entirely justified. There may, however, be significant gains to be made from using the less straight-forward deposits. For example, a prominent pre-Little Ice Age 'Eystriheiði' high stand of Sólheimajökull can be constrained using the 871±2 AD Settlement tephra layer, which lies on top of the outermost moraine and the SILK YN tephra that is buried beneath it (Dugmore, 1989b; Dugmore *et al.*, 2000; (Figure 3). The use of well-known marker horizons alone would date the glacier high stand to between c. 410 AD and c. 871 AD. It is however possible to achieve a better resolution because around Sólheimajökull, SILK YN is overlain by a basaltic tephra, both of which underlie the moraine, and Landnám lies above a narrow black tephra both of which overlie the moraine (Dugmore 1989). Although these two black tephras have only been mapped in a limited area around Sólheimajökull, their distribution across different geomorphological settings shows that they are primary tephra deposits and despite their unknown provenance (and indeed, poorly known individual ages), they can be used to narrow the likely age of the Eystriheiði stage to the 6th-7th centuries AD (Dugmore *et al.*, 2000).

The comparatively stable, non-tephra, aeolian sediment depositional regimes that existed before Settlement mean that aggradation rates can be used to successfully interpolate dates, an approach that has been tested with independent radiocarbon dating (Dugmore 1987, 1989b; Óladóttir *et al.*, 2005, 2011b). In the case of the Eystriheiði stage, non-tephra sediment accumulation rates alone could have been used to estimate the moraine ages. However, because of the variable contact between the moraine and the underlying sediments onto which it was emplaced and the uneven surface of the boulder moraine that was later covered by soil, the uncertainties of such age estimates would have been considerable. The unprovenanced tephras lying stratigraphically close to the moraine do, however, give a very good guide to where effective applications of accumulation rate age estimates can be made.

3-D ENVIRONMENTAL RECONSTRUCTION

A novel use of tephrochronology in Iceland has been the detailed mapping of the spatial variation of sediment accumulation. This has been facilitated by the predominantly aeolian origin of soils and the generally high rates of sediment accumulation that have resulted in rapid (decadal) formation of stratigraphic units that may be mapped in the field (e.g. Streeter *et al.*, 2012).

Following on from Thórarinsson's pioneering studies of soil erosion (e.g. Thórarinsson, 1961), others have used the presence of multiple isochrons to define the variation of soil accumulation across landscapes developed during discrete periods of time (e.g. Dugmore and Buckland, 1991; Dugmore and Erskine, 1994; Dugmore *et al.*, 2000, 2009; Simpson *et al.*, 2001; Ólafsdóttir and Guðmundsson, 2002; Mairs *et al.*, 2006; Streeter *et al.*, 2012). Spatial variation of sediment accumulation has been used to infer the scale of first settlement impacts, vegetation change, land use and climate change. A key question is how to best combine data from multiple profiles. Useful patterns have been revealed through the combination of profiles in similar landscape units (e.g. Mairs *et al.*, 2006). When large numbers (>30) of high resolution measurements (within 1mm) are made in individual profiles, then in-profile variation becomes a powerful indicator of change (Streeter *et al.*, 2012).

CONCLUSIONS

The most common use of tephra layers is to define isochrons and use them to date environmental records. Of all the Holocene tephras produced in Iceland, few form 'classic' isochrons with four key characteristics; a known extensive spatial distribution, distinctive properties that are well-characterised, good independent dating and an occurrence at times of widespread interest.

The most detailed applications of tephrochronology, and those with the greatest practical utility in geomorphology, involve the use of all tephras within a deposit, including unprovenanced and remobilised units; the effective use of 'total tephrochronology' requires multiple stratigraphic sections and the clear identification of primary and re-mobilised deposits even in complex stratigraphic sequences that record geomorphological, environmental and archaeological change.

Terrestrial sequences, despite their generally poorer individual quality than lake cores, offer the greatest potential for understanding spatial variations in the lived environment. Spatially extensive, large scale replication of stratigraphic sequences through the use of multiple profiles is possible (and desirable) with terrestrial sediments and peats, and can offer detailed understanding of land surface and environmental processes.

An undisturbed layer of primary tephra fallout will be isochronous and the surface it covers will also be isochronous. Post-depositional modification of the geometry of the tephra can, however, mean that although stratigraphical relationships may remain unaltered, the new surface defined by the tephra may not relate to the time of the tephra-forming eruption. Reshaped tephra horizons, while presenting chronological complications, can contain key records of environmental processes.

Despite current limits to our knowledge of the spatial distribution of pre-Landnám tephras in Iceland and the inherent spatial and temporal variability of the surviving record, it is possible to use local stratigraphic sequences of unprovenanced tephras as a 'barcode' to enhance local correlations and refine the application of well-known marker horizons to environmental records.

High frequency and high resolution measurement of both the units between tephra layers and the tephra layers themselves can give valuable insight and identify subtle shifts in landscape stability and land use. An enduring legacy of Thórarinsson's great vision of tephrochronology is its utility within geomorphology and human-environment interactions and uses that go beyond the identification of isochrons (Thórarinsson, 1944, 1981b).

In Iceland, tephra layers in deep stratigraphic sequences created by near continuous sediment accumulation and exhibiting little if any re-mobilisation have been used to develop remarkable insights into volcanic history and eruption frequency (e.g. Larsen, 2000; Óladóttir *et al.*, 2005, 2008, 2011a, 2011b). Geomorphological, palaeoenvironmental and archaeological applications, however, additionally require engagement with poorly developed tephra sequences, complex stratigraphies, isochrons, time transgressive horizons and the consideration of a wide range of deposits. When this is done, it can illustrate the power of tephrochronology, even in less than ideal settings. The same approaches to tephrochronology have potentially wide ranging applications in other volcanically active regions.

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ÁGRIP

Gjóskutímatal er mikilvægt í rannsóknum á landmótun svæða. Gjóskulögin eru almennt notuð til að skilgreina jafntímafleti og tímasetja umhverfið sem þau finnast í. Gjóskutímatal kemur að mestum notum þegar bæði vel þekktir jafntímafletir eða leiðarlög (útbreidd gjóskulög með greinileg og vel skilgreind einkenni ásamt traustri aldurgreiningu) og önnur gjóskulög á svæðinu eru notuð í sameiningu. Þar með teljast gjóskulög af óþekktum uppruna og einnig lög sem eru endurflutt, en slíkt lag verður ekki endilega til á sama augnabliki á hverjum stað (er "time transgressive") og er því ekki af sama aldri alls staðar þar sem það finnst. Gjóskutímatal sem tekur til allra þessa þátta nýtist best þar sem fjöldi sniða er mældur en gera þarf skarpan greinarmun á óhreyfðum gjóskulögum, sem mynda raunverulega jafntímafleti, og endurflutt-um lögum. Með mörgum mælingum á gjóskulagaskipan í jarðvegi á tilteknu svæði má fá betri skilning á landmótunarferlum og á áhrifum mannvistar á umhverfið. Röð gjóskulaga af óþekktum sem þekktum uppruna og aldri getur myndað eins konar "strikamerki"("barcode") sem nýtast bæði til að treysta tengingar milli jarðvegssniða og til að fá nákvæmari upplýsingar um aðstæður í umhverfinu en þegar eingöngu eru notuð strjálli leiðarlög. Nákvæmar mælingar á gjóskulögunum og jarðveginum á milli þeirra í fjölda sniða geta leitt í ljós fíngerðar breytingar á stöðugleika landslags sem og breytingar á landnýtingu með tíma.

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