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Citation for published version:
Dugmore, A, Newton, A, Smith, K & Mairs, K-A 2013, 'Tephrochronology and the late Holocene volcanic and flood history of Eyjafjallajökull, Iceland' Journal of Quaternary Science, vol 28, no. 3, pp. 237–247. DOI: 10.1002/jqs.2608

Digital Object Identifier (DOI):
10.1002/jqs.2608

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Journal of Quaternary Science

DOI: 10.1002/jqs.2608

Tephrochronology and the late Holocene volcanic and flood history of Eyjafjallajökull, Iceland

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Tephrochronology and high resolution environmental reconstruction

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Abstract

High resolution records of sediment accumulation are necessary to evaluate subtle temporal and spatial variations in sediment flux, especially in the context of decadal-scale human-environment interactions. Tephrochronology provides a uniquely powerful way of constraining 3-D change. Digital photography using consumer grade cameras may be used to gather thousands of stratigraphic measurements to ± 1 mm (potentially equivalent to ± 2 years of accumulation) and provides data amenable to statistical manipulation. This new approach is illustrated with an evaluation of 15th century landscape change in Iceland. High resolution measurements show that apparent 'spikes' in accumulation after episodes of plague are an artefact of lower resolution measurements (± 2.5 mm) over decadal periods. Regional records show little change in sediment accumulation rates after the plagues but key local records made possible using this new methodology reveal that the period AD 1389-1416 (encompassing the plague outbreak of AD 1402) had some of the lowest sediment accumulation rates since settlement of the island. This new approach to landscape assessment indicates that in this pastoralist community the aftermath of human mortality rates of 50-60% saw no development of feral sheep populations or a switch to less labour intensive wool production. The implication is that cattle production was maintained and the relative easing of landscape impacts could explain the lag between 14th century climatic deterioration and 18th century increases in landscape change.

Keywords: Tephrochronology, Iceland, plague, soil erosion, photogrammetric, late Holocene

A. Introduction

This paper presents a new approach to high resolution environmental reconstruction using tephra layers. Rather than basing interpretation on a limited number of vertical measurements, which has been the general practice to date, this paper uses thousands of high resolution vertical measurements, obtained directly in the field or through the analysis of digital photographs. The individual measurements are to the highest realistic precision (± 1 mm) and large numbers of measurements have been combined to provide more accurate indications of environmental changes and their spatial pattern. This approach is illustrated with an assessment of the impacts of plague-induced depopulation on landscape in medieval Iceland and has wide ranging applications in regions of the world affected by volcanic fallout.

Tephrochronology offers remarkable chronological control due to the isochronous nature of tephra layers which form extensive time parallel marker horizons (Thórarinsson, 1944, 1981, Lowe, 2011). The surface buried by a tephra layer represents a moment in time so it provides outstanding potential for palaeoenvironmental reconstruction. Tephra layers can precisely connect records formed at the same time in different places and so permit the detailed exploration of past environmental patterns (e.g., Dugmore *et al.,* 2009). Geomorphological records may, for example, be correlated with precision over both small and larger scales (Kirkbride and Dugmore 2001, 2003, 2005, 2008), pollen records may be used to reconstruct details of past ecologies (Hallsdóttir, 1987; Erlendsson, 2007; Erlendsson *et al.,* 2009) and the presence of multiple tephra layers enable spatial patterns in rates of aeolian sediment accumulation between tephra layers to be measured over decadal and century time scales (Dugmore and Buckland, 1991; Gisladóttir, 2001). Open sections provide opportunities to take many measurements of accumulation rates between tephra layers but rarely are these measurements produced in great numbers, so although very good data can be produced (e.g., Mairs *et al.,* 2006) it is rarely of a form amenable to statistical analysis. Where detailed measurements are made particularly good (sub-decadal) dating can be achieved (Church *et al.,* 2007), so new approaches to making multiple repeat measurements between tephras that boost data collection are of potentially great utility and value.

There is considerable potential for the development of tephra-related methodologies as maturing archaeological and environmental datasets enable new research questions to be tackled (e.g., McGovern *et al.,* 2007). For example, some well-established approaches devised for the development of tephrochronology as a dating tool (e.g., Thórarinsson, 1958, 1967), can be refined when the research focus switches from the identification, correlation and dating of tephra layers to the application of tephrochronology to problems of environmental change. In Iceland, for example, the mapping tephra layers over hundreds of square kilometres, when individual sections of Holocene stratigraphy are routinely several metres deep and contain several dozen tephra layers has used measurements to within 0.25 cm (e.g., Larsen *et al.,* 2001). Greater precision is not necessary for the measurement of deposits on these scales or to tackle fundamental questions of tephrochronology, such as the source of a tephra, its volume, dispersal pattern and visible extent (e.g., Larsen and Thórarinsson, 1977). Once a regional chronology is established, however, there is scope for the development of far more detailed measurement of both the intervals between tephra layers and the tephra layers themselves.

The transformation of tephra layers after their initial deposition presents a challenge for the reconstruction of past volcanic events, but it is a potential source of valuable environmental data. Examples of this include downslope re working (Mairs *et al.,* 2006), the formation of frost hummocks (thúfur) (Dugmore and Buckland, 1991) and solifluction lobes (Kirkbride and Dugmore, 2005). In these cases the deformation of tephra layers contains key environmental data but the richness of the environmental record is a challenge to capture from a limited number of profile measurements and drawings, while producing an excellent visual record, lack the potential for statistical analysis. Likewise, although the presence of multiple tephra layers means that spatial variation of the sediments between the tephras can be mapped over entire landscapes, the separation of clear spatial signals from the noise of local variation is currently more of an art than a science.

To develop more rigorous applications of tephrochronology this paper presents new field and photogrammetric based approaches to data collection and illustrates their application in southern Iceland.

A. Tephra layers and the formation of isochrones

The measurement of sediments between tephra layers relies on the clear definition of both the upper and lower surfaces of a tephra. In the time that elapses between their initial deposition and the formation of a long-term stratigraphic record tephra layers may be transformed on a series of different scales. For instance tephra layers which fall onto snow may be reworked when the snow melts (Manville *et al*., 2000; Froese *et al*., 2006). These effects can create significant variability in the form of the tephra layer over centimetre-scale horizontal distances, and in practice the depth between tephra isochrones can vary substantially over short (50-100 cm) distances (Figure 1). A crucial sampling problem is therefore to determine representative measurements of both the tephra and the sedimentary units bounded by tephras. This can be tackled by using multiple measurements to quantify the variability in distance between tephra layers.

Insert Figure 1 around here

A. Resolution, spatial scales and the understanding of landscapes of human-environment interaction

Key issues in studies of human-environment interactions are scale matching, in both the spatial and temporal resolution of environmental records and written sources and the correct attribution of cause and effect (Caseldine & Turney, 2010). Human pandemics, for example may spread rapidly over large areas, but their resultant environmental impact may have significant spatial patterning. This is a problem because although the overall, aggregate picture may be appear to show one pattern of change, this may conceal localized impacts. Population decline in medieval Sweden because of plague resulted in a heterogeneous pattern of abandonment with high levels of abandonment (70%) in marginal areas, but only low levels (10%) in productive areas (Lagerås, 2007). Therefore while regional pollen chronologies from large lakes show a pattern of no or little change a combination of local pollen diagrams show a clear signal of agricultural abandonment (Lagerås, 2007). This is clearly also an issue when considering geomorphological change. Statistically robust multiple measurements can boost confidence that the data from stratigraphic sections is representative and can be correctly attributed to specific environmental processes. The use of photogrammetric techniques provides a pragmatic way to achieve this without thousands of time consuming manual field measurements.

The combination of multiple vertical measurements of accumulation from different sections located in both similar and contrasting parts of the landscape has helped to reveal important patterns of landscape change in Iceland (e.g., Dugmore *et al.,* 2009). Regional sediment signals from > 250 m away from a recorded section can be distinguished but the record is usually dominated by sediment mobilised from < 250 m (Dugmore and Eriskine, 1994). Although the process of aeolian erosion of soils in Iceland is driven by wind, rain and frost, and the intensities of these natural processes vary across the landscape, it is apparent that major differences in landscape instability and triggers of change are driven by landuse (Arnalds A, 1987; Arnalds O, 1999, 2004; Arnalds O *et al.,* 2001a, 2001b; Gísladóttir, 1998, 2001). Broad patterns can be distinguished using comparatively low resolution measurements, typically ±2.5 mm, if they are considering periods of century-scale duration and accumulations of tens of centimetres of sediment. The frequency of volcanic eruptions in Iceland and the utility of the tephrochronological record mean that more subtle variations taking place at decadal scales may also be considered. These are crucial because the nature of geomorphic change which involves sediment moving short distances within a landscape; if the record is homogenised key patterns of change may be lost. At higher resolutions, critical for the rigorous examination of human-ecodynamics, a crucial question is how best to identify environmental signals that may be localised and not visible in either single cores or low resolution regional synthesis.

Insert Figure 2 around here

Multiple measurements provide measures of the central tendency of the sediment accumulation data which can be considered representative for the measured period. Many manual measurements can be recorded to ±1 mm, with typically 50 measurements per layer. This approach gives data amenable to statistical analysis, however it is time consuming. Using photogrammetric techniques potentially thousands of precise (<±1 mm) measurements may be collected per profile. Typically 200-500 measurements of sediment accumulation rate can be made per layer, compared to one using conventional logging techniques, or 50-200 using labour intensive manual field measurement techniques. This expansion in number and density of measurements is significant, allowing greater confidence in the identification of subtle variations in landscape trajectories that either go unnoticed or are masked by inaccuracies in manual recording techniques (Figure 2).

A. Consumer-grade cameras and photogrammetric techniques in geomorphology

Photogrammetric techniques are used to provide accurate spatial 2-D and 3-D data in geomorphology at long and short distances (Chandler, 1999; Pike, 2000). The availability of high specification, consumer level digital cameras means that these have replaced the more expensive calibrated cameras for many applications where cost, convenience and portability are issues. Although generally not as accurate or stable as calibrated metric cameras, consumer grade cameras have been used successfully in many scientific applications (Ahmad and Chandler, 1999 ;Wackrow *et al*, 2007; Rieke-Zapp *et al.,* 2009). They are also typically smaller and more portable which is useful in remote field areas where large metric cameras and their rigging can be hard to transport (Rieke-Zapp *et al.,* 2009). Self calibration packages allow the quantification of unknown internal camera geometry (Beufort, 2000). Precision depends on the application but is generally <± 1mm for close range images.

A. A new methodology in tephrochronology

B. Field Collection of Images

Soil sections to be photographed were prepared present a flat and vertical surface at least 50 cm wide to the camera. Exposed roots were cut away. The tripod and camera was located perpendicular to the section face 1-2 m away from the face of the profile. A spirit level attached to the top of the camera ensured that it was level. 10 cm square plastic targets provided scale for each photograph. At least two targets were attached to the face of the profile to check the scale was constant over the image. A field recording of the profile was made to a resolution of ±2.5 mm, for the identification of tephra layers. For a subset, more detailed measurements to a precision of ±1 mm were recorded for direct comparison with measurements obtained from the photographs (Figure 2).

The camera used was a Canon EOS 1000D digital single-reflex (DSLR) camera, with a Canon EF 28mm f/2.8 lens and mounted on a tripod. This lens allowed the photographing of a 50 cm wide section of soil at a distance of less than 3 m from the profile, a key requirement given the practical access constraints to soil sections. Lenses with short focal lengths (< 24 mm) were not used because of their increased radial distortion. A DSLR cameras was chosen because it produces high quality photographs and can capture more light than a digital compact camera. A fixed focal length lens was prefered because any distortion produced is more predictable than that of a zoom lens, but they can be used effectively if care is taken to quantify the internal geometry (Chandler *et al.,* 2005).

B. Camera calibration and measurement of accumulation rates

The Camera Calibration toolbox for MATLAB (Bougent, 2000) was used to calibrate the camera and lens used in the field. This software runs a form of self-calibrating bundle adjustment to determine the internal geometry of the camera and the lens distortion based on a series of calibration images (Bougent, 2000). The mean pixel error for this camera and lens combination was x ± 1.12, y ± 1.29, with greater distortion at the edges of the image than the centre. As a result measurement were not taken at the edge of the image. At the scales in this study (2-4.5 pixels/mm) there is a horizontal (x) distortion uncertainty of ±0.26-0.60 mm and a vertical (y) uncertainty of ±0.27-0.64 mm. The internal characteristics of the camera set up used in this paper are capable of resolving features to a precision of <±1 mm at 2 m from the profile face.

Photos were taken at 3906 x 2602 resolution and adjusted for contrast and white balance. In some cases they were sharpened with imaging software to enhance visible contrast between layers. After initial processing measurements were taken using the imaging software ImageJ (http://rsbweb.nih.gov/ij/). A plugin was written for ImageJ which allows the user to trace the edges of a tephra layer visible in the photo (plugin code included in supplementary material). The x_1y_1 coordinates were saved for all points along this line, along with the base of the next tephra layer, saved as x_2y_2 coordinates. The difference between y coordinates in pixels was calculated for each coordinate where $x_1 = x_2$ The scale was determined from the mean of 10 measurements of plastic scale targets in pixels. Scale was calculated individually for each image, as the distance between the camera and section varied dependant on site conditions.

B. Comparing measurement techniques in the field

Insert Figure 3 around here

27 stratigraphic profiles in Skaftártunga, south Iceland (Figure 3) were recorded using standard logging techniques, repeated measurements (typically 15 per layer) and

photographic techniques. These profiles are a subset of a much larger (200 profile) data collection from the region (Streeter *et al.,* 2012). The stratigraphy of this area over the post settlement period (AD c870) is well known (Larsen, 2000) and is summarised in Figure 4.

Insert Figure 4 around here

To compare the methods an example is presented of measurements from one profile using three different techniques: a single standard measurement, many detailed measurements and photographic measurement (Table I). Based on over 100 comparisons of measurements between layers using both standard and photographic techniques there is no indication of systematic increases in difference between measurements recorded by the three techniques with increasing depth of stratigraphic measurement. Increasing variability in sediment accumulation between layers does not increase differences in the depth recorded by each technique. Thin and uniform layers are measured to the same level of accuracy as thicker and variable layers. The average difference between standard and photographic measurements was ±22% of the measured distance. The average difference between detailed measurements and photographic measurements is ±15.4 % of the mean distance, this decreases to <10% when over 50 measurements were taken. Making many measurements in the field is time consuming but produces figures which are close to those generated using photographic techniques, which we believe indicates that both measurements produce results close to the true sediment accumulation.

Insert Table I around here
Insert Figure 5 around here

An application of the central limit theory was used to calculate the minimum number of measurements required so that the measured mean accumulation depth falls within the 95% confidence interval (CI) for actual mean accumulation depths. Mean standard deviation for all depth measurements using photogrammetric techniques was ±5.83 mm, based on measurements of 132 sediment and tephra units. Based on the standard deviation recorded 22 measurements are required to have 95% confidence in the mean to ±2.5 mm, and 150 measurements to have a 95% confidence interval of ±1 mm. This figure is an approximation because typically the distribution of measured thickness was not normally distributed (Figure 5). In practice single measurements are not randomly selected so accuracy can be higher, but in the samples here 17.5% of single measurements fall outside the 95% CI of the corresponding photographic measurement. This shows the range of variability that the single measurement is trying to measure, which can also be seen when measurements are plotted as histograms (Figure 5).

If a single measurement is collected with skill it could be representative, however there is a high probability that it isn't. Therefore multiple measurements offer a more robust approach. For short time intervals and depths of 5-50 mm the errors produced by only single measurements may alter calculated sediment accumulation rates (SeAR) by enough to change the interpretation, especially where trying to correlate human events of brief duration with a record that is precise but unevenly spaced. Detailed measurements reduce the likelihood of measurement artefacts occurring in the data, for examples where there are sudden 'spikes' where SeAR changes by more than 25% for short (<50 year) periods. These spikes were visible in the standard measurements of several profiles but did not exist in the photographic measurements (Figure 7). This is of importance when trying to correlate changes in SeAR with external events, which may be expected to only produce relatively small changes, compared to the very large landscape changes seen in upland areas in the 16-20th centuries (e.g., Thórarinsson 1961; Dugmore and Buckland, 1991; Mairs *et al.,* 2006). By combining measurements across several profiles (e.g., Mairs *et al.,* 2006) it is possible to build up an accurate SeAR regional picture, but for detailed comparisons of relatively small changes across smaller numbers of profiles many measurements are needed.

A. A Case Study of landscape and population change

B. Long term drivers of landscape change

Soil erosion over the last 1,200 years has affected large areas of Iceland, stripping ~20,000km^2 of pre-settlement soil cover (Thórarinsson, 1961; Arnalds *et al.* 1997). General patterns of erosion through time can be distinguished (Figure 6, part c). Surviving areas of soil cover generally show an increasing trend of sediment accumulation through time and while early peaks are not unusual recent centuries (post AD 1500) invariably contain the greatest rates of aggradation (Thórarinsson, 1961; McGovern *et al.,* 2007; Dugmore *et al.,* 2009). Within southern Iceland broad pattern of erosion from early peaks in the uplands through late medieval increases of SeAR in the pre-Landnám woodland zones to recent peaks at low levels can be distinguished (Figure 6, Dugmore and Buckland, 1991). Locally SeAR can reflect the scale of ecological transformation as forest clearance is associated with temporary increases in sediment accumulation (Mairs *et al.,* 2006). The converse is also apparent. In Þórsmörk long term woodland conservation and medieval settlement movement are associated with reduced levels of SeAR (Dugmore *et al.,* 2006). In general the inability of management systems to track unpredictable climatic changes from AD 1300 onwards, coupled with socio-political change and a shift to wool production increased rangeland degradation (typically areas above 300 m) (Simpson *et al.,* 2001). Modern rates of land cover loss, despite being associated with peak levels of SeAR are insufficient to explain the cumulative loss of soil cover since Landnám (Dugmore *et al.,* 2009). The explanation of the contrast between early peaks in land cover loss and later peaks in SeARs probably lies in contrasting depths of soil cover. It is likely that threshold crossing events before AD 1500 resulted in the stripping of soil cover from large areas particularly in the uplands but as the soils were comparatively thin a limited amount of sediment was mobilised. Later erosion in ecologically less marginal zones resulted in a reduced rate of land cover loss but involve the erosion of much deeper soils and the generation of high sediment fluxes (Dugmore *et al.,* 2009).

B. The plague and environmental change

Pandemics in human populations can have continental scale environmental effects (Nevle & Bird, 2008; Dull *et al.,* 2010). Medieval plagues in Europe produced major demographic changes, as they repeatedly killed between 25-50% of the human population (Herlihy, 1997).

The environmental impact of the 14th Century plagues on mainland Europe is visible in the pollen record as a widespread decline in cereal pollen and rise in indicators of secondary woodland growth such as *Betula sp.* and *Corylus* (Yeloff and van Geel, 2007; Lagerås, 2007). In Ireland Hall *et al.,* (2003) find a reduction in cereal pollen coinciding with the AD 1362 Oræfajökull tephra layer. In northern England secondary woodland (*Betula spp.)* rises significantly after AD c1350 (Yeloff *et al.,* 2007) and there is evidence of increasing landscape stability in upland areas (Chiverrell *et al.,* 2007) but in the main these records are limited by the resolution of radiocarbon dating. Environmental records are consistent with written records that show a reduction in arable and increase in woodland (Poos, 1991).

In a pre-industrial context a reduction of arable production following periods of population decline is not surprising because of the close dependency of cultivation on labour. In regions with a primarily pastoralist based agriculture such as Iceland the relationship between population decline and landscape is not as clear; fewer people could mean fewer animals and a ubiquitously reduced environmental impact, alternatively, a reduced human population may have consolidated on the best landholdings and so changes in environmental impact may have been spatially uneven. A third possibility is that while some areas could have seen an overall reduction of grazing impact because of fewer animals, it may also been significantly increased in others areas; labour shortages could have resulted in less fodder production and as a result winter grazing could be increased to cover the short fall — and so produce greater environmental impacts in discrete areas of the landscape (e.g., Simpson *et al.,* 2004). Un-managed grazing by feral sheep would also increase environmental impacts, as would a switch from more labour intensive cattle rearing to less labour intensive wool production with its increased utilisation of rangeland grazing. To test these hypotheses we can use tephrochronology to date and quantify rates and episodes of landscape change which may be compared to plague records and inferred changes in land use.

Two episodes of plague in the 15th century had major impacts on the population of Iceland, with mortality estimates for AD 1402-1404 of 50-60% and between 30-50% for the plague in AD 1494 (Karlsson, 1996). Contemporary written sources note that in AD 1444 c20% of farms were still deserted (Karlsson, 1996). Skaftártunga in South Iceland (Figure 3) has well-dated tephra layers from the eruption of Hekla in AD 1341 (H1341) and AD 1389 (H1389), Katla AD 1416 (K1416), Veiðivötn AD 1477 (V1477), Katla AD 1500 (K1500) and Hekla AD 1597 (H1597), covering the period before, during and after these major population events (Figure 4). This allows high temporal resolution record of changes in sediment accumulation rate to be generated for key time periods. Extra details can be gained from two mid 15th Grímsvötn tephras produced between AD 1416-1477. Although the calendar dates of these layers are unknown, they provide precise and accurate relative dating controls that can be traced across the landscape.

B. Geomorphic change in Skaftàrtunga over the last 1200 years

The silicic Katla layer SILK-YN dated at 2660±50 ^{14}C BP (Larsen *et al.,* 2001) was recorded in 12 profiles and indicates a mean pre human settlement SeAR of 0.28±0.05 mm/yr (mean±1 SD). After the settlement of Iceland in AD c870, dated by the Landnám tephra later (AD 871 ±2 Gronvöld *et al.,* 1995) SeAR increases to 0.6 ±0.5 mm/yr; this large increase in SeAR and variability is seen in other areas of south Iceland and is associated with the introduction of grazing animals and vegetation change (Dugmore and Buckland 1991; Dugmore *et al*. 2000). These initial impacts are greater in the north of Skafártunga where average altitude is higher and growing season shorter (Figure 6, part B). The environmental impact of the Eldgjá eruption (ice core dated to AD 935 ±2, Zelinski *et al.,* 1995) was considerable in this area because air fall tephra depths averaged 21 cm and in five sections recorded in this study it exceeded 50 cm. This depth of tephra smothers herbaceous and low lying vegetation and 43% of the 139 recorded instances of this layer show continued reworking centuries after the eruption. This instability is reflected in the high SeAR seen in the 10th to 13th centuries. Between the 13th century and the 18th century SeAR declines to 0.5 ±0.3 mm/yr with lower variability.

Insert Figure 6 around here

The aggregate mean SeAR between AD 1389-1416 is 0.42 ±0.19 mm/yr (±1σ), significantly lower than the post-Landnám mean but not distinguishable from mean SeAR over the period AD 1206-1755. In the 22 profiles where accumulation between H1389 and K1416 was recorded photographically (it was not recorded at 5 profiles), 63% had the lowest sediment accumulation rate in the post-Landnám period. Over the whole data set 25% of sections recorded either the lowest or second lowest post-Landnám SeAR in the period AD 1389-1416, significantly more than the 5% probability of this occurring by chance.. In profile 27 the H1389-K1416 SeAR of 0.4 ±0.1 mm/yr (±1σ) is comparable to the pre-Landnám figure of 0.42 mm/yr at this site these two periods are the lowest sedimentation rates over the last 2600 years. Profiles from one lowland area (Hrífunes farm) and two upland areas (Snæbyli and Búland farms) show that in the early 15th century SeARs are significantly lower than the post Landnám average, and the preceding period bounded by Katla AD 1262 and Hekla AD 1389 (Figure 7). Two tephra layers from Grímsvötn which, based on SeAR, are dated to AD c1430 and AD c1460, show that SeAR's return to mean post-Landnám values by the mid 15th century. There is no apparent SeAR change related to the second plague in AD 1494. This plague had a lower mortality rate that the first episode (and so is likely to have had an inherently smaller effect). In addition, 120 years separate the formation of the bounding tephra layers V1477 and H1597, so short lived impacts could be masked by a rapid recovery in SeAR.

Insert Figure 7 around here

The 18th century starts of a period of greatly enhanced SeAR levels and indicators of local geomorphic instability is seen in many profiles. This probably reflects both the worsening climatic conditions of the 'Little Ice Age' and the release of large volumes of sediment from the migration of erosion fronts into deep lowland soils (Dugmore *et al.,* 2009).

A. Discussion

Written records contain details at changes at the resolution of individual settlements and households, for specific days, weeks, months and years. Environmental data rarely achieves this degree of temporal resolution, but with frequent, well dated tephra falls, and rapid rates of sediment accumulation there is a possibility of scale-matching at sub-metre spatial resolutions for both the specific times of the tephra deposition and for decadal-resolution time periods in between. As a result it is possible to use high precision measurements of the environmental record and the ability to collect large, spatially-referenced data sets to explore rapid changes, where a detailed knowledge of the interaction of peoples and landscapes is crucial to understanding the process at work and their consequences.

Grazing by domestic animals is the principal trigger of erosion in southern Iceland (Dugmore *et al.,* 2009) so the low levels of SeAR seen in the period AD 1389-1416 are consistent with a reduced livestock pressure on the landscape related to population collapse caused by the plague in AD 1402. Sheep cannot be over wintered easily in Iceland without feed supplement in the form of fodder: this has a large labour requirement and it would have been difficult to maintain stocking levels with a smaller population. Increased winter grazing could be a response to reduced labour availability, as would the development of a feral sheep population, or a switch to more sheep in relation to cows but these changes would have resulted in increased upland erosion (Adalsteinsson, 1990; Simpson *et al.,* 2004). Increased SeARs are not apparent in Skaftártunga, and so these possibilities do not appear to have happened here.

Benign climatic conditions cannot explain unusually low SeARs because temperature and storminess proxies indicate less favourable weather conditions than during the 10-13th centuries where overall SeAR was higher (Figure 7). It therefore seems likely that the landscape responded to a short period of reduced landscape pressure before returning to average post-Landnám SeAR by the mid 15th century.

When seen in aggregate the SeAR signal indicates 'business as usual' through the plague years, but at the local level there is evidence of a reduction in intensity of landscape use, relating to the first and most lethal plague in AD 1402, but not after the second somewhat smaller-scale plague in AD 1494. Multiple photogrammetric measurements increase confidence that these changes are real. Mean SeAR values averaged from multiple profiles are necessary to prevent measurement artefacts in the record but can obscure localised changes. The observed easing in landscape pressure in the 15th century could have been achieved through reduced overall stocking levels, a maintenance of cattle numbers and no increase in relative numbers of sheep. This would have increased landscape resilience and contributed to the lag between degradation and the climatic deterioration that began in the late 14th century and intensified in the 16th century (Geirsdóttir *et al.,* 2009; Ran *et al.,* 2011). These climate changes were only associated with large increases in sediment erosion from the mid-18th century onwards (Thórarinsson, 1961; Dugmore *et al.,* 2000, 2009; Gísladóttir *et al.* 2010).

High frequency, high resolution photogrammetrically based measurements of both tephra layers and intercalated sediments can offer methodological and practical insights. The variable margins of tephra layers seen in cross section could be argued to be of such a scale that measurement to within 5 mm can be representative and accurate. The data presented here shows that measurement to within 1 mm (or c. 2 years of sediment accumulation) produces consistent and replicable results, and when this is done a smoother variation of sediment accumulation is apparent, averaging out apparent spikes in SeAR which are measurement artefacts. This strengthens the argument put forward by Dugmore and Erskine (1994) that individual profiles of aeolian sediment in Iceland are gathering an environmental signal from a catchment extending tens to hundreds of metres from the profile location.

It is apparent that the quality of the tephra record is variable. Some parts of the record are particularly suitable to high resolution analysis (such as the 10^{th}-17^{th} centuries) but other parts are not — in this study the post 17^{th} century record and the pre-settlement record. This is due to an increasingly variable expression of tephra layers that become patchy and irregular with diffuse margins. In the post 17^{th} century record root penetration can be significant and comprise more than 10% of the profile. Roots create variability in tephra layers that could go in time as profiles aggrade, root frequency reduces and existing roots decay. In pre-settlement sequences aeolian sediment accumulation rates are lower, sediments exhibit weathering profiles and woody vegetation with substantial roots and stems was more frequent. In these cases representative measurements to within 5 mm are as precise as the record will probably stand without the generation of a spurious sense of accuracy, but it should be borne in mind that this can still achieve a temporal resolution equivalent to less than seven years of sediment accumulation.

B. Wider implications

This study has considered sediment accumulation rate in primarily aeolian sequences, however there are other situations where a high resolution approach could provide improved data. Where tephra layers are not accurately dated or there are intercalated archaeological remains such as charcoal pits (Church *et al.,* 2007) photogrammetric techniques could be used to constrain the age of these deposits based on a more accurate measurement of the stratigraphic location between known layers and sediment accumulation rates for well constrained time periods. There are other characteristics of the tephra layer that give clues to the depositional environment and also post-depositional reworking. Thúfur (frost heave hummocks) indicate changes in climate and processes acting on the sedimentary record. Events such as earthquakes which shear tephra layers can be observed and dated using photographic techniques. Accurate measurement of these features could provide additional on post-depositional processes.

A. Conclusions

High resolution multiple measurements of sediment accumulation are possible and give unique insight. Although a single measurement may be representative of a stratigraphic unit, local (10-100 cm) variability is such that repeated high resolution measurements are a more certain way of capturing a representative thickness. Where multiple tephra deposits form coherent layers that are separated by visible layers of intercalated sediment measurements to within 1mm (or < 2 years) accuracy are possible both in the field and through the use of photogrammetric techniques using consumer-grade cameras.

Large numbers of measurements (in sets of 50-100 readings) can be acquired from each stratigraphic section either in the field, or through the analysis of photographs. These data can then be subjected to statistical analysis. This can produce both accurate and precise measurements of sediment accumulation rates on decadal scales that can be replicated at many sites across the landscape, and comparisons between sites made with higher levels of confidence. This data provides robust information on local variation that is a key scale for testing hypothesis of landscape change.

Abrupt episodes of depopulation in Iceland produced by plague did not produce similarly abrupt changes in landscape change at a regional scale; there was neither a reduction nor an increase of sediment mobilisation across the landscape as a whole. At the local scale, however, some easing of pressure is indicated by the lowest sediment accumulation rates since the settlement of Iceland despite deteriorating climatic conditions. This data enables different models of response to demographic shocks to be evaluated. The people of Skaftártunga did not lose control of their livestock and allow sheep to go feral. Neither did they follow developments elsewhere in Iceland and switch to wool production with a related increase in rangeland pressure. Instead they focussed on their traditional cattle-orientated mix of livestock. This strategy would explain the delayed impact of the subsequent climate changes of the Little Ice Age.

A. Acknowledgements

This work was supported by the Natural Environment Research Council (NE/F00799X/1), the Leverhulme Trust (F/00152/Q) and US National Science Foundation (OPP Arctic Social Sciences grants 0732327 and 1042951). We would also like to acknowledge the help of numerous field assistants with the collection of field data.

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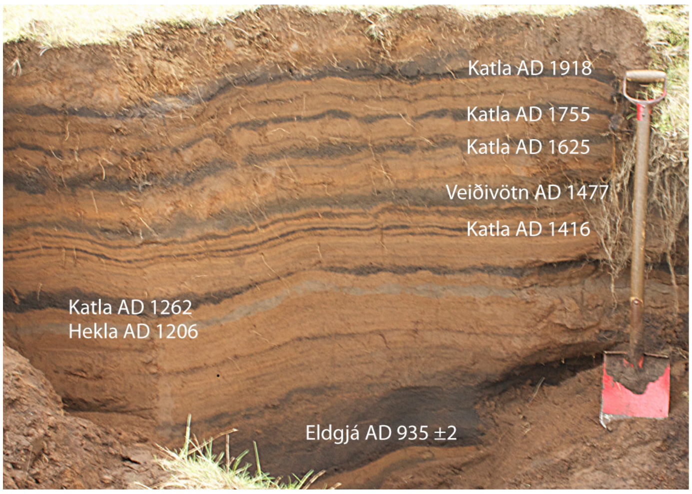

Figure 1. Photograph of post Landnám (AD c870) soil section and tephra layers, south Iceland (Profile 27, Figure 3). Spade is 1 m in size. The thick (20-30cm) black tephra layer at the base is from Eldgjá AD 935 ±2 (Zeilinski *et al.,* 1995) and the diffuse top of this layer indicates multiple centuries of disturbance. Main tephra layers are annotated.

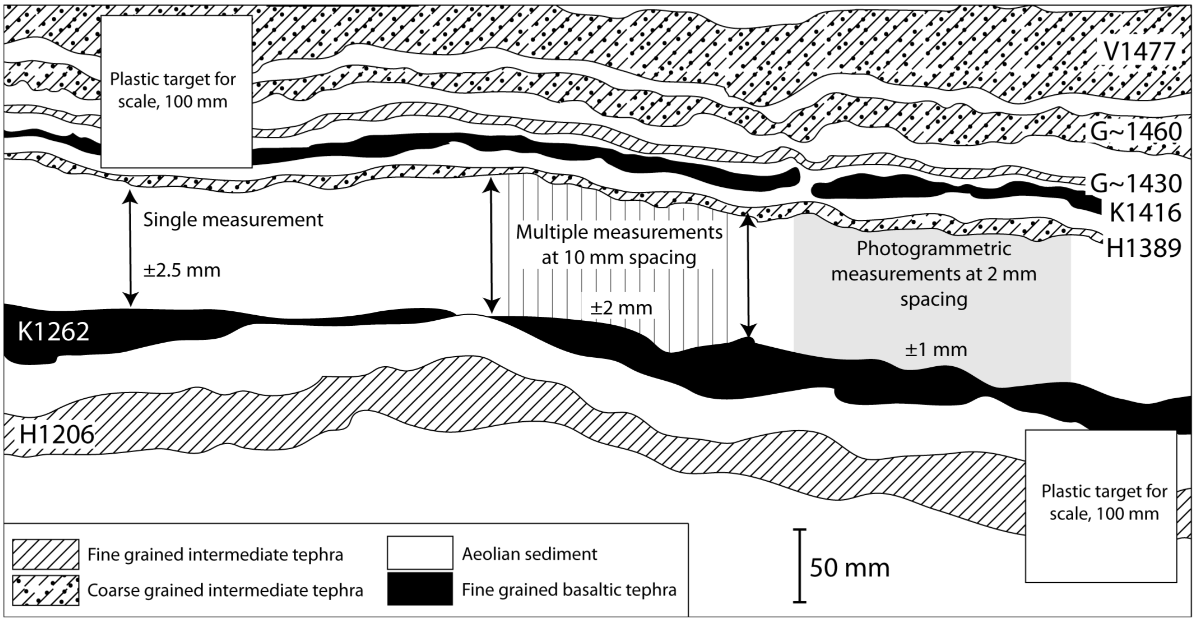

Figure 2. Traced photograph of soil section (Profile 27, Figure 3), south Iceland, showing large variations in sediment accumulated between tephra layers and illustrating the different recording techniques used in this paper. Tephra layers are identified by H: Hekla, K: Katla, V: Veiðivötn, G: Grímsvötn, followed by the year AD of eruption.

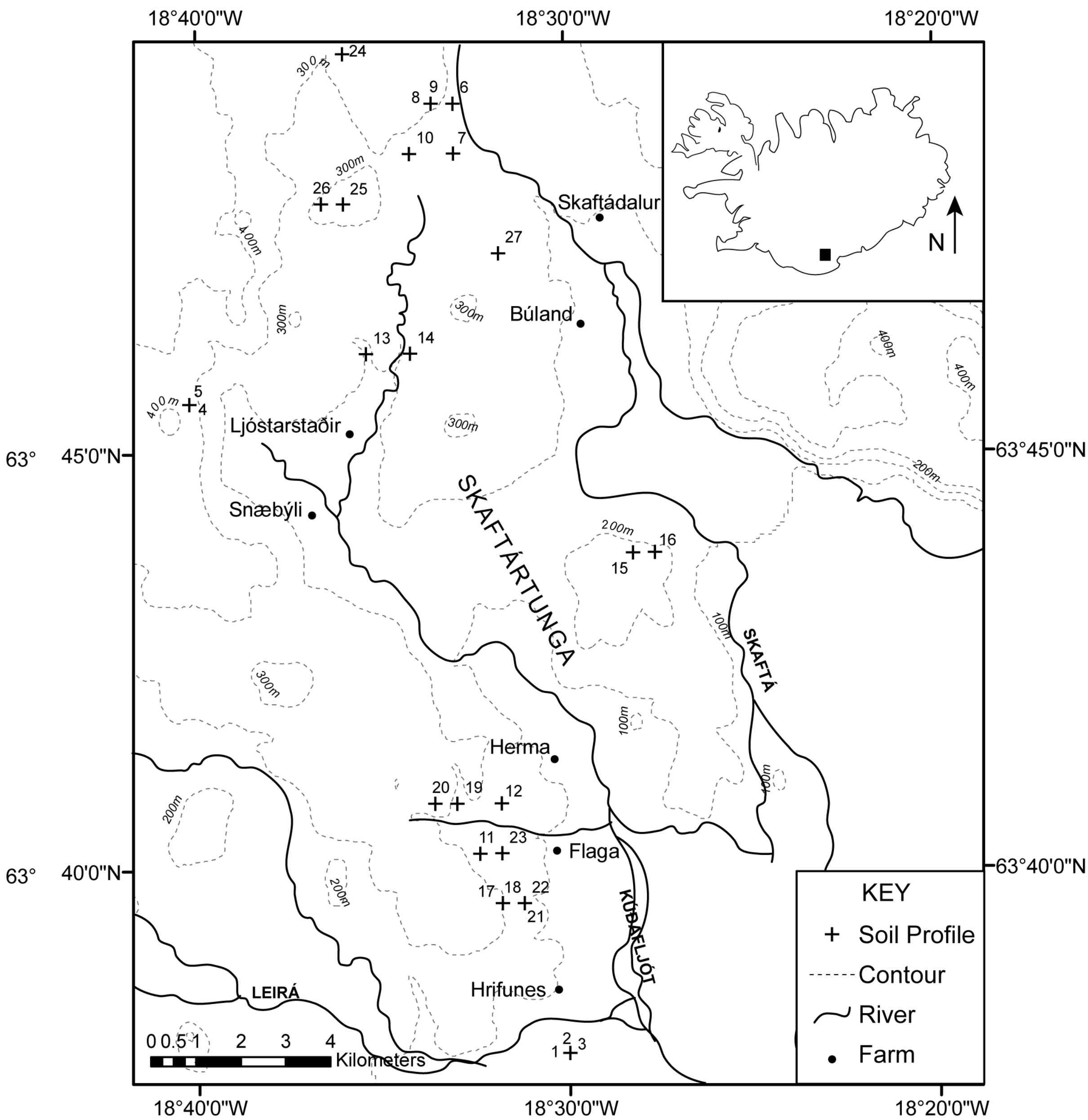

Figure 3. Study area, Skaftártunga, south Iceland, showing profiles measured photogrammetrically.

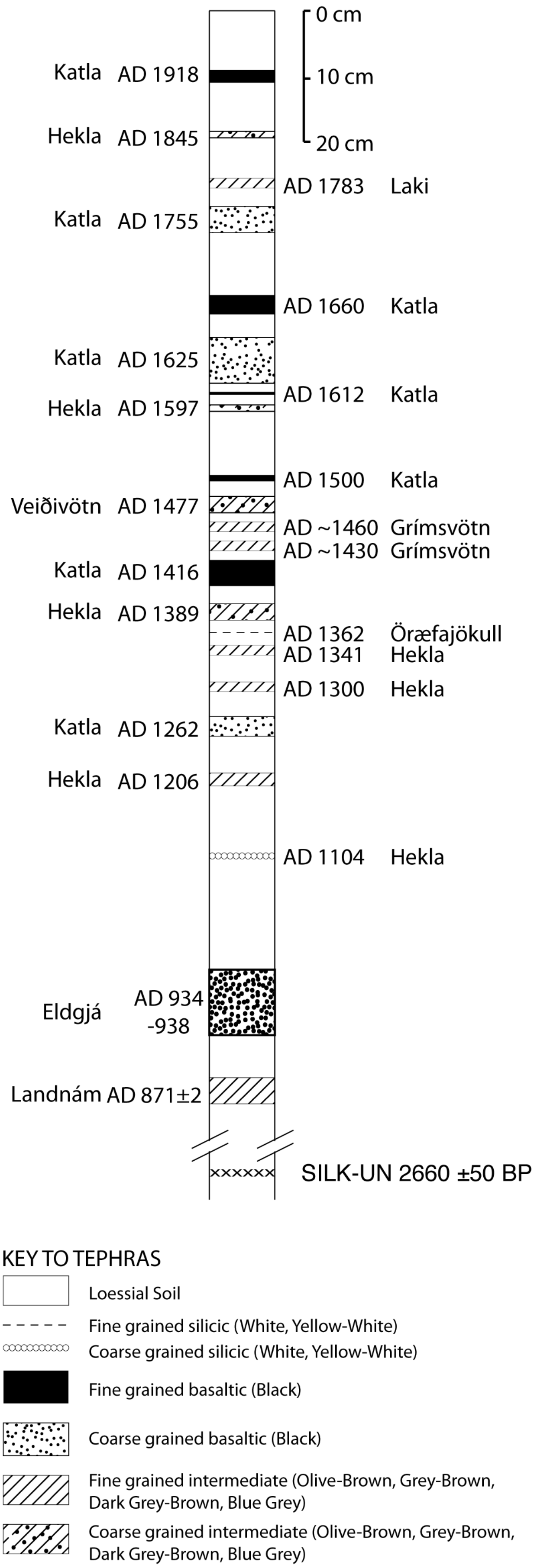
0 cm
10 cm
20 cm
Katla AD 1918
Hekla AD 1845
AD 1783 Laki
Katla AD 1755
AD 1660 Katla
Katla AD 1625
AD 1612 Katla
Hekla AD 1597
AD 1500 Katla
Veiðivötn AD 1477
AD ~1460 Grímsvötn
AD ~1430 Grímsvötn
Katla AD 1416
Hekla AD 1389
AD 1362 Öræfajökull
AD 1341 Hekla
AD 1300 Hekla
Katla AD 1262
Hekla AD 1206
AD 1104 Hekla
Eldgjá AD 934 -938
Landnám AD 871±2
SILK-UN 2660 ±50 BP
KEY TO TEPHRAS
Loessial Soil
Fine grained silicic (White, Yellow-White)
Coarse grained silicic (White, Yellow-White)
Fine grained basaltic (Black)
Coarse grained basaltic (Black)
Fine grained intermediate (Olive-Brown, Grey-Brown, Dark Grey-Brown, Blue Grey)
Coarse grained intermediate (Olive-Brown, Grey-Brown, Dark Grey-Brown, Blue Grey)

Figure 4. Composite tephrochronology for east of Mýrdalsjökull, south Iceland. Tephras on the left found most frequently, those on the right found infrequently. Modified from Larsen, 2000.

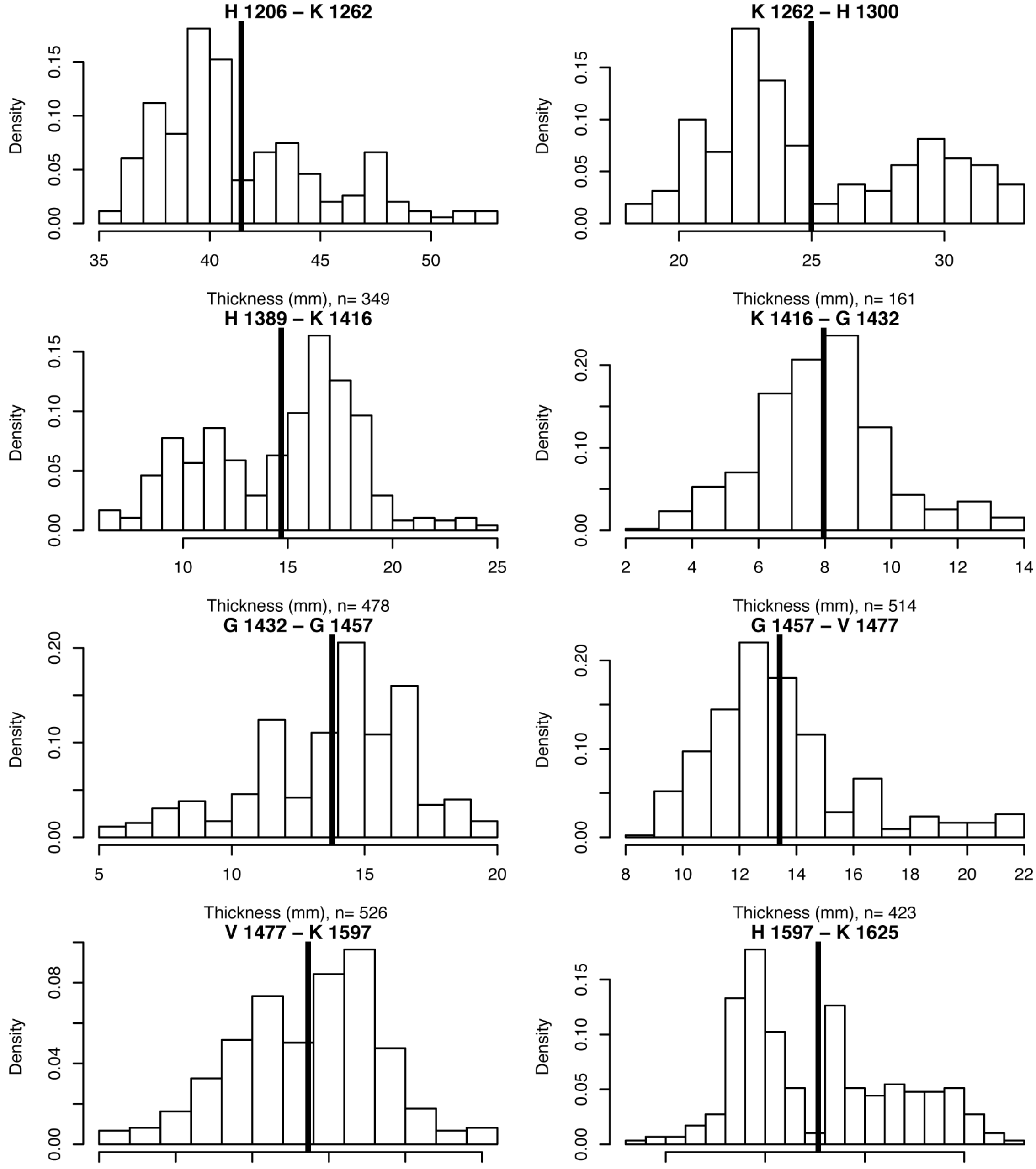

Figure 5. Density histograms of accumulated sediment between 11 tephras identified in profile 20. Mean accumulation thickness is indicated by the bold vertical line. Most measurements of accumulated sediment do not show a normal distribution and there is a wide range of thicknesses measured, showing the difficulty in using single measurements as representative thicknesses. Tephra layers are identified by H: Hekla, K: Katla, V: Veiðivötn, G: Grímsvötn, followed by the year AD of eruption.

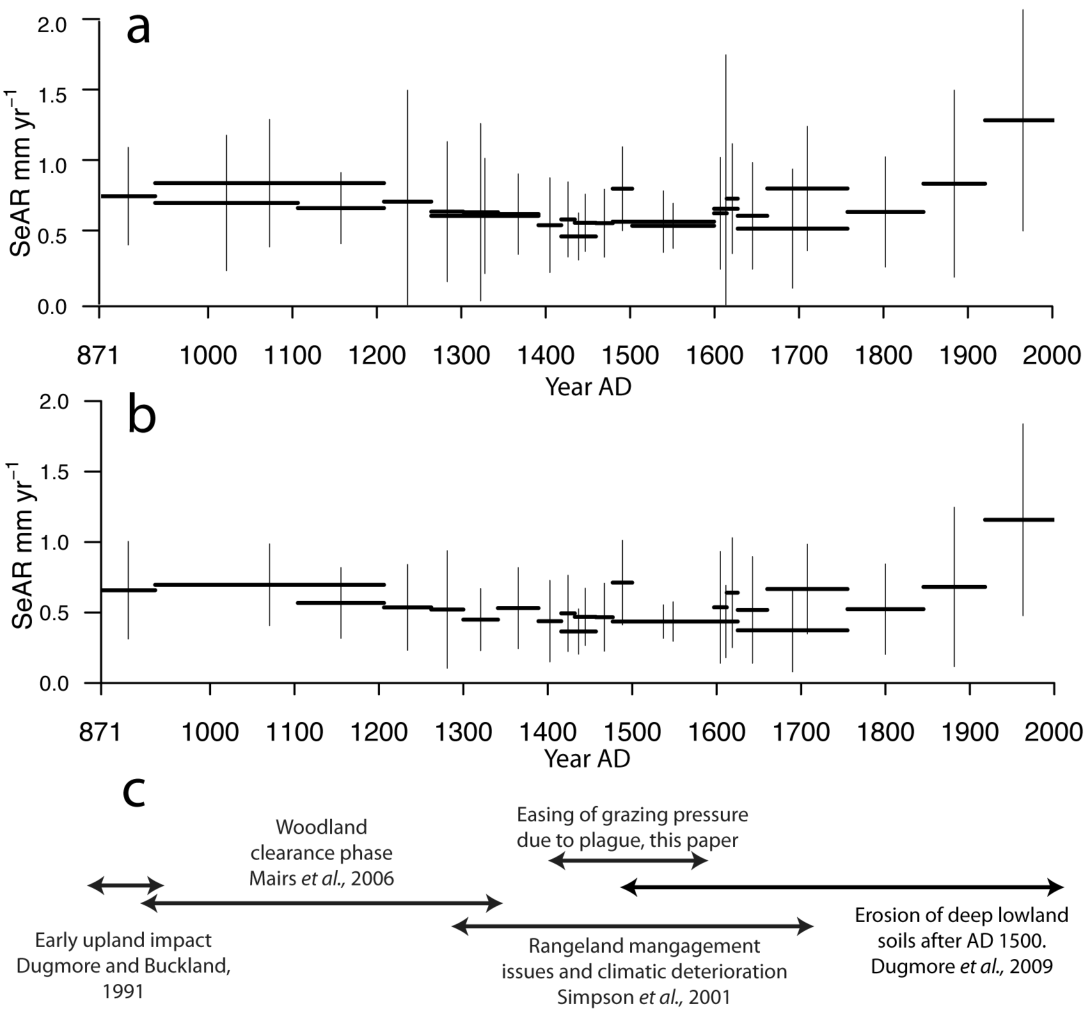

Figure 6. Aggregate SeAR in Skaftártunga over the period of human settlement (post AD 870) for >250 m elevation (A) and < 250 m elevation (B). Thin vertical lines indicate one standard deviation from mean SeAR. C indicates previously identified trends in landscape change in Iceland.

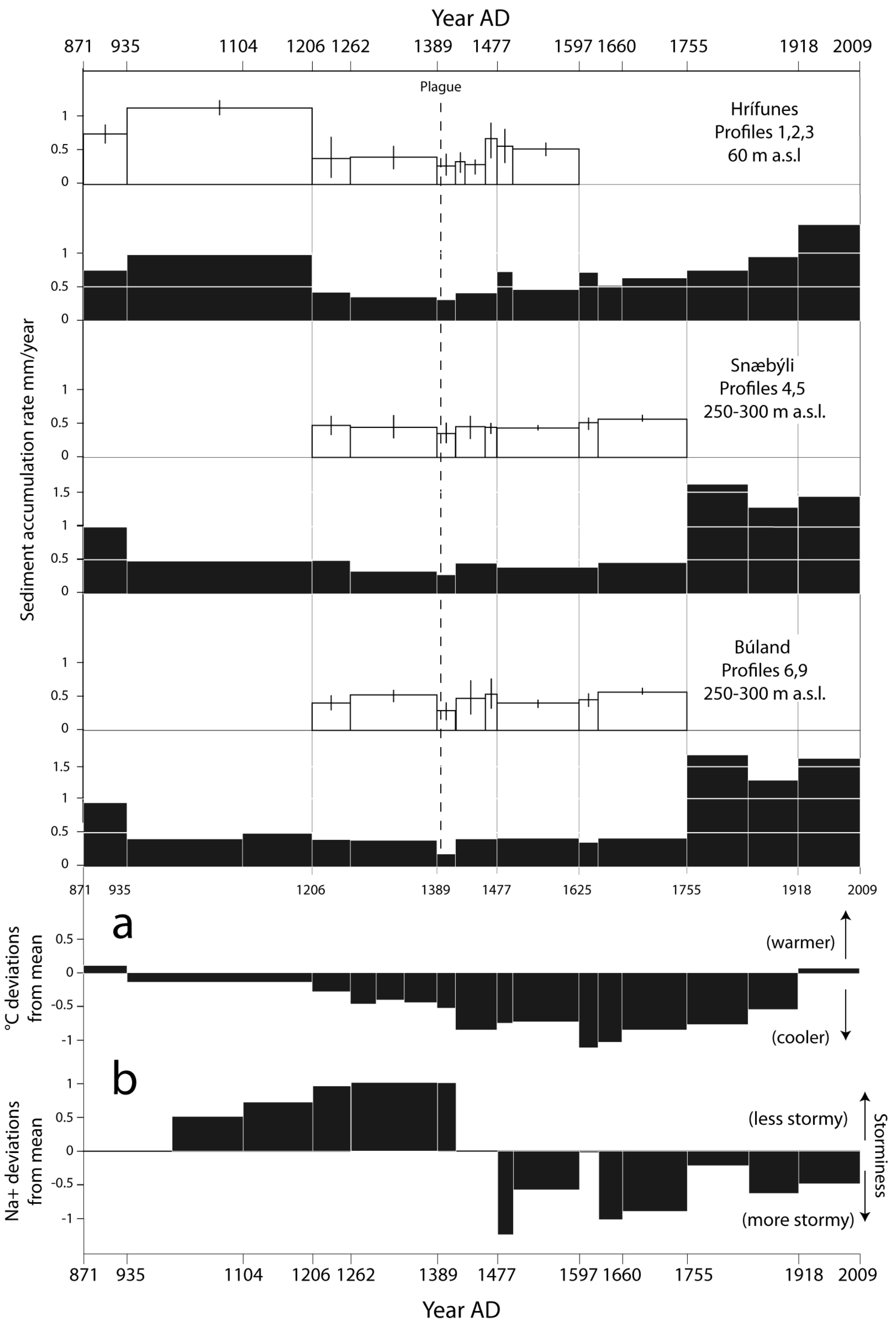

Figure 7. Sediment accumulation rates for selected groups of profiles in Skaftártunga showing mean sediment accumulation rates from photographic measurements (open bars) with 1 standard deviation shown and sediment accumulation rates from standard measurements (black filled bars) and (A) temperature deviations from the mean (AD 500-2000) from the Mann *et al.,* 2009 reconstruction of North Atlantic region sea surface temperatures and averaged over periods matching tephra layers. (B) shows a proxie of

storminess in the north Atlantic based upon deviations from the mean of Na+ concentrations in the Greenland Ice Sheet Project (GISP) ice core (Meeker and Mayewski, 2002) averaged over periods bounded by identifiable tephra layers.

Table I. Comparison of different measurement techniques for sediment accumulation between Hekla AD 1389 and Katla AD 1416 at profile 27.

	n	Mean measurement (mm)	Measurement resolution (mm)	1 standard deviation	2 standard deviations	Mean standard error (MSE) (mm)	% er Se
Single	1	15.00	5	-	-	2.19	2
Multiple	141	10.83	2	2.14	4.28	0.18	1
Photogrammetric	454	10.82	1	2.19	4.38	0.10	0

* Sediment accumulation rate

A. Supplementary Information

Measurement of sediment accumulation on a photograph using ImageJ

Firstly the photograph is loaded into the software ImageJ. ImageJ is an open source imaging software and is available from http://rsbweb.nih.gov/ij/index.html. Its inbuilt measurement tools are used to measure the plastic targets created for scale. The plug in “My_Plugin.class” is selected by selecting Plugins —> Compile and Run and then navigating to the folder where the file is stored. For uneven tephra layers the Freehand line selection tool (selected by right clicking on the line selection toolbar button) is used. It is then possible to trace the tephra for measurement and the output of xy coordinates will appear in a Log window. These results can then be copied and analysed in a suitable program. In this paper the LOOKUP function of MS Excel was used to ensure that only pairs of coordinates where the x coordinates matched were selected and used as measurements.

My_Plugin.class code

```
import ij.*;
import ij.plugin.filter.PlugInFilter;
import ij.process.*;
import ij.gui.*;
import java.awt.*;
import java.awt.event.*;
import java.util.*;

	/**
	Richard Streeter
	September 2010


	This JAVA plugin for the ImageJ software implements the MouseListener and 
MouseMotionListener interfaces
	and listens for mouse events generated by the current image. When the user traces a 
line on the image
	the xy coordinates are recorded and stored in a Log dialoge box, these can then be 
copied into another program
	or saved.


	It extends already the exising classes mouseListener() and MouseMotionListener() 
and  which are open source and available at
	http://rsbweb.nih.gov/ij/plugins/index.html

	*/

	public class My_Plugin implements PlugInFilter, MouseListener, 
MouseMotionListener {
		ImagePlus img;
		ImageCanvas canvas;
		static Vector images = new Vector();
```

```
	public int setup(String arg, ImagePlus img) {
		this.img = img;
		IJ.register(Mouse_Listener.class);
		return DOES_ALL+NO_CHANGES;
	}

	public void run(ImageProcessor ip) {
		IJ.showMessage("My_Plugin","This plug in is for the measurement of tephra
layers \n It records the xy coordinates as you drag the mouse along. \n");
		Integer id = new Integer(img.getID());
		if (images.contains(id)) {
			IJ.log("Already listening to this image");
			return;
		} else {
			ImageWindow win = img.getWindow();
			canvas = win.getCanvas();
			canvas.addMouseListener(this);
			canvas.addMouseMotionListener(this);
			//int tool = Toolbar.getInstance().addTool("Test Tool");
			//Toolbar.getInstance().setTool(tool);
			//images.addElement(id);
		}
	}

	public void mousePressed(MouseEvent e) {
		int x = e.getX();
		int y = e.getY();
		int offscreenX = canvas.offScreenX(x);
		int offscreenY = canvas.offScreenY(y);

	}

	public void mouseReleased(MouseEvent e) {
	//	IJ.log("nothing ");
	}


// Logs movement when the mouse is dragged

	public void mouseDragged(MouseEvent e) {
		int x = e.getX();
		int y = e.getY();
		int offscreenX = canvas.offScreenX(x);
		int offscreenY = canvas.offScreenY(y);
		IJ.log(offscreenX+","+offscreenY);
	}

	public static String modifiers(int flags) {
		String s = " [ ";
```

```
            if (flags == 0) return "";
            if ((flags & Event.SHIFT_MASK) != 0) s += "Shift ";
            if ((flags & Event.CTRL_MASK) != 0) s += "Control ";
            if ((flags & Event.META_MASK) != 0) s += "Meta (right button) ";
            if ((flags & Event.ALT_MASK) != 0) s += "Alt ";
            s += "]";
            if (s.equals(" [ ]"))
                s = " [no modifiers]";
            return s;
        }

        public void mouseExited(MouseEvent e) {}
        public void mouseClicked(MouseEvent e) {}
        public void mouseEntered(MouseEvent e) {}
        public void mouseMoved(MouseEvent e) {}


}
```