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# The influence of burial rate on variability in tephra thickness and grain size distribution in Iceland

Polly I.J. Thompson [a,*], Andrew J. Dugmore [a], Anthony J. Newton [a], Nick A. Cutler [b], Richard T. Streeter [c]

[a] School of GeoSciences, University of Edinburgh, EH8 9XP, UK
[b] School of Geography, Politics and Sociology, Newcastle University, NE1 7RU, UK
[c] School of Geography & Sustainable Development, University of St. Andrews, KY16 9AL, UK

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ABSTRACT

We explore whether the rate at which a tephra deposit is buried influences the variability (thickness and grain size distribution) within the tephra layer subsequently preserved within the stratigraphic record. This has important implications for understanding how processes of soil formation interact with the creation of a volcanic record. To assess the relationship between soil formation and the preservation of tephra layers, the thickness and grain size distribution of the Katla 1918 tephra in Iceland and the rate at which it was buried (inferred from the thickness of the overlying soil) was measured 1620 times at six locations. Tephra layer thickness does not correlate with rate of burial, but the proportion of original deposit retained does, and variations in grain size distribution are correlated with burial rate. Our results indicate that whilst medium term (i.e. years-decades) burial processes may contribute less to tephra layer variability than environmental processes operating immediately after deposition, rapid burial facilitates better preservation of the original fallout characteristics with important implications for the accurate reconstruction of past volcanic eruptions based on tephra layer characteristics. There are two key implications: firstly, sites need to be chosen where surface characteristics minimise the initial alterations of tephra deposits, and secondly sites with rapid burial will produce the best quality data, although workable data can be gathered elsewhere if areas of uncertainty are acknowledged.

## 1. Introduction

Tephra is defined as any particulate material erupted from a volcanic vent, regardless of particle size or shape (Thorarinsson, 1944). Tephra can be preserved in many different sedimentary archives (e.g. lacustrine sediments and ice cores) in terrestrial areas of the earth surface, but the main way in which tephra layers are preserved is within soils (Boygle, 1999; Plunkett et al., 2020). In this study, we focus on volcanic ash layers (<2 mm grain size) 1–11 cm thick preserved within andosol soil in Iceland. Many factors have the potential to influence the transformation of tephra deposits on the surface as they become enduring tephra layers within the stratigraphy, one of which is the rate at which tephra is incorporated into the soil profile and how soil formation influences the preservation of tephra layers. Earth surface processes may mean an accurate preservation of a tephra deposit is not possible. Instances where the initial tephra deposit on the surface is not fully preserved in the stratigraphy tells us something about the processes occurring during that transition. Rapid burial may lead to more accurate preservation of the initial deposit, if burial protects the tephra from alteration by surface processes. As enduring tephra layers are used to infer the parameters of explosive volcanic eruptions, it is important to understand the potential impact burial rate has on the fidelity of the tephra record (Cutler et al., 2020; Bonadonna and Houghton, 2005; Pyle, 1989). Therefore, the overall aim of this paper is to determine how the rate at which a tephra deposit is buried impacts on the thickness, morphology and grain size distribution of the preserved layer.

Once a volcanic eruption has deposited tephra across the landscape, the deposit is vulnerable to reworking by surface processes (Dugmore et al., 2020; Dominguez et al., 2020; Hobbs et al., 1983). For example, the finer grain size fractions may be lost through erosion, the morphology may be disturbed by trampling and patches may become thicker or thinner as the tephra is remobilised in different parts of the

* Corresponding author.
*E-mail addresses:* Polly.Thompson@ed.ac.uk (P.I.J. Thompson), Andrew.Dugmore@ed.ac.uk (A.J. Dugmore), Anthony.Newton@ed.ac.uk (A.J. Newton), Nick.Cutler@newcastle.ac.uk (N.A. Cutler), rts3@st-andrews.ac.uk (R.T. Streeter).

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landscape (Blong et al., 2017; Cutler et al., 2018). Compaction of deposits also occurs as part of the preservation process, reducing the initial deposit thickness, sometimes significantly (Blong et al., 2017; Williams et al., 2021). The longer the deposit is exposed at the surface, the greater the potential for reworking. Although tephra layers in the soil profile may also be disrupted (by burrowing animals, for example), the potential for reworking should be much reduced once the deposit is buried. Therefore, it is logical to assume that tephra layers which are buried rapidly should more closely resemble the original deposit than those that were buried more slowly.

The type of soil formed is a function of five factors: climate, biology, relief, parent material and time (Jenny, 1941). Soils of volcanic origin (as are found in Iceland) contain many of the same characteristics as other soil types – a mixture of organic remains, clay, and rock particles, with the key difference being that the rock particles and parent material are volcanic (Delmelle et al., 2015). Burial rates are therefore determined by the interaction of biotic and abiotic factors and certain conditions will favour rapid burial of tephra deposits. For example, plants can rapidly stabilise tephra deposits and cover them with organic matter, although plant colonisation and growth may be constrained by circumstances and the surface environment created by thick tephra deposits (Cutler et al., 2016a). Establishing vegetation cover is a method used to aid tephra clean-up in urban settings and stabilise deposits after a volcanic eruption, as is soil capping to bury the deposit (Hayes et al., 2015). Environmental conditions that favour biocrust formation on the surface of tephra deposits may also have a stabilising effect (Cutler et al., 2018).

Burial can be rapid where there are substantial inputs of allochthonous sediment (Arnalds, 2015). Work by Wilson et al. (2011) following the 1991 Hudson eruption in Chile found that tephra deposits that were stabilised most rapidly were in areas of high rainfall as this enhanced vegetation growth and compaction, whereas stabilisation was slower in windy and arid areas. Agricultural areas where tephra stabilisation occurred slowly after this eruption and the 2008 Chaitén, and 2011 Cordón Caulle eruptions, were negatively impacted by the tephra fall (Craig et al., 2016). Long term monitoring of the 1980 Mount St. Helens tephra has found that much of the tephra has been preserved, attributed to a combination of soil development, plant litter accumulation and vegetation providing a stabilising effect (Collins and Dunne, 2019). It is therefore important for us to understand how tephra burial effects its preservation. As far as we are aware there are no previous studies examining the relationship between burial rate and tephra layer preservation. Here, we refer to burial as the preservation of a tephra deposit into a preserved layer.

Iceland is particularly suited to a study of this type as tephra-producing eruptions are common and many of the resulting tephra layers are precisely dated (Schmid et al., 2017; Thórarinsson, 1975; Thorarinsson, 1967). It is estimated that environments across Iceland experience 25–250 g $m^2$ $a^{-1}$ of dust deposition, which results in high sediment accumulation rates (SeAR) (Arnalds et al., 2012). Soil generation in volcanic areas can be rapid, and especially so in Iceland, because of high rates of late Holocene and contemporary soil erosion which proceeds as a loss of area and results in high fluxes of aeolian sediment. Additionally, rapid SeAR clearly separate tephra layers, that in turn provides a robust means to determine burial rate. Icelandic soils postdate the final retreat of the last ice sheet in the early Holocene, low level soils may preserve sediments from soon after deglaciation, but at higher elevations (above 400 m), andosols usually date from the later Holocene, and times when soil cover was expanding (Ólafsdóttir and Guòmundsson, 2002). In contrast to Iceland, volcanic areas like Japan that have not be subject to complete inundation by Quaternary glaciers have old soils that reach maturity in 4000–7000 years (Wada et al., 1986). In general, volcanic andosol soils generally take longer to form in dry, cold environments (Delmelle et al., 2015), and so we would expect burial rates to be slow in those environments.

In this study, we consider the terms SeAR and burial rate to be synonymous. Vegetation cover across the island immediately before people arrived for the first time in the 9th century CE was 54–65 %, but is now 28 %, and woodland cover that was up to 40 % is now just 1 %. Previously, vegetated land that is now eroded is estimated to be 15–30000 $km^2$ (Arnalds et al., 2013; Arnalds, 2015), and this erosion has generated a significant mobilisation of sediments, some of which falls on existing vegetation and so thickens existing soils. While SeAR in general are high, there is also considerable variation, even between sites located within tens of metres of each other (Dugmore and Buckland, 1991; Streeter and Dugmore, 2014; Dugmore and Erskine, 1994; Sigurðardóttir et al., 2019). Therefore, the rate at which tephra layers are buried and'locked in' to the stratigraphy also varies, meaning that tephra from the same eruption will be exposed to earth surface processes for longer in some areas than others.

### 1.1. *Rationale and hypothesis*

We assumed that the longer a tephra deposit is exposed and active on the surface, the more it is altered. Hence, better preservation of the initial deposit properties should be positively correlated with increased burial rate. Variation in SeAR creates ideal conditions for a natural experiment based on single tephra layer that has experienced varying burial rates. By limiting variation in other factors such as slope, aspect and vegetation cover, we can, in principle, establish how burial rate impacts on tephra layer preservation. This has important implications for interpreting volcanic records and also what alterations to tephra layers can tell us about earth surface processes operating as tephra deposits are preserved.

We focused on tephra layer properties which should have been invariate initially, but which might vary in a landscape subject to varying burial rates (i.e. variability in tephra layer thickness and grain-size distribution (GSD) on relatively small 10–100 s of metres). As tephra from a high altitude eruption plume mantles a landscape, the initial deposit should have a consistent thickness (low variability) at a scale of metres to tens of metres. Surface re-working will lead to local variations in tephra thickness, which become more pronounced with time. Hence, at a metre scale, the parts of a tephra deposit that are buried rapidly should exhibit relatively low variability in thickness, whilst those buried more slowly should have higher variability. Similarly, the GSD of an exposed tephra layer is likely to change over time (due to the loss of grain size fractions more vulnerable to remobilisation, or the addition of re-worked material from elsewhere), but will stabilise when the deposit is buried. Hence, spatial variations in burial rate should result in systematic differences in GSD across a landscape, even if GSD were initially similar. Our study focused on the tephra layer produced by the 1918 eruption of the Icelandic volcano, Katla (K1918 hereafter) (Fig. 1). We therefore propose the following hypotheses:

- H1: Higher rates of SeAR will preserve a greater proportion of the K1918 fallout deposit.
- H2: Variability in tephra layer thickness will be inversely proportional to burial rate.
- H3: Sections with high SeAR will retain more of the grain size fraction of tephra vulnerable to aeolian remobilisation.

## 2. Methods

Our goal was to survey a tephra layer in locations where the main variable was burial rate. Once sampling locations were established, tephra layer thicknesses were measured and samples were collected for grain size analysis. The thickness of soil overlying the tephra layer was recorded to calculate SeAR, which we considered a proxy for burial rate.

### 2.1. *Site descriptions*

At each site, slope and vegetation cover were kept more-or-less

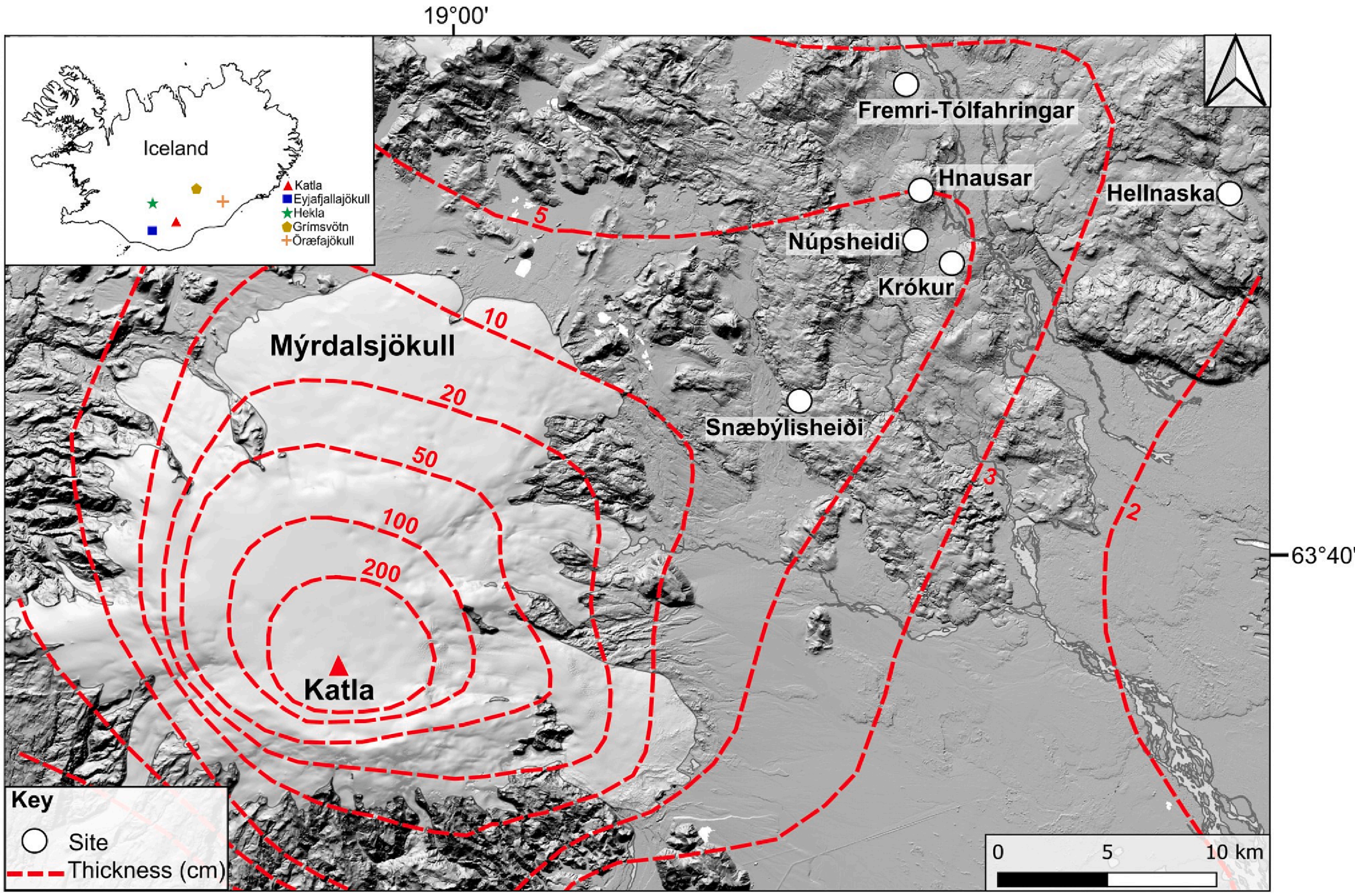


**Fig. 1.** Location plan of the six sites within Skaftártunga, used in this study, and the iopach map of the fallout from the Katla 1918 eruption. Isopaches adapted from Larsen et al. (2021), base map was obtained from ArcticDEM using 2 m resolution (Porter et al., 2018).

constant, whilst burial rate (SeAR) varied. The K1918 layer has a number of desirable features for our study. It is extensive enough that it was possible to select sites where SeAR is the main factor that varies. The layer is buried deep enough in the soil to permit accurate determinations of SeAR, but not so deep that it is inaccessible. Finally, at our study sites the tephra layer is continuous and the boundaries with the overlying and underlying soil are clear and sharply defined. These sites were selected as they contained all of the desirable factors and in particular, the K1918 layer had no more recent tephra layers overlying it, making the calculation of SeAR rates straightforward as measurements of soil thickness were taken from the top of the tephra layer to the top of the soil (the ground surface). Details about each site are summarised in Table 1.

The K1918 eruption (VEI 4) began on the 12th October 1918 and lasted for 23 days (Larsen, 2010). It was a subglacial basaltic eruption, taking ~2 h to melt through the overlying ice, causing a large jökulhlaup (glacial outburst flood) and ash plume (Owen et al., 2019; Gísladóttir et al., 2021). The ash plume reached an altitude of 14–15 km high and dispersed an estimated 1.1–1.2 $km^3$ of tephra (Larsen et al., 2021; Gudmundsson et al., 2021). There were two primary tephra production phases during the eruption, with less activity in between (Gudmundsson et al., 2021). Tephra was largely deposited to the north-east of the volcano. Visible layers are present around Katla, identifiable as a fine-grained black ash layer (Larsen et al., 2014; Óladóttir et al., 2008). Recent work by Larsen et al. (2021) has collated existing K1918 tephra thickness data along with new measurements to create an isopach map of the tephra fallout from the eruption, which we use here to estimate original fallout thicknesses at our sites (Fig. 1).

**Table 1**
Summary of sampling locations. Number of measurements refers to the number of individual measurements taken from each section within each site.

| Site | Location | No. Sections | No. measurements per section | Tephra samples collected | Slope |
|---|---|---|---|---|---|
| Hellnaska | 63.82353N<br>18.28685W | 12 | 20 (10 tephra, 10 soil) | 0 | 2.8° |
| Fremri-Tólfahringar | 63.87039N<br>18.58788W | 12 | 20 (10 tephra, 10 soil) | 0 | 4.4° |
| Núpsheiði | 63.82473N<br>18.57507W | 12 | 20 (10 tephra, 10 soil) | 0 | Approx. 0° |
| Krókur | 63.79404N<br>18.54223W | 12 | 20 (10 tephra, 10 soil) | 0 | 5.5° |
| Hnausar | 63.80362N<br>18.57748W | 12 | 20 (10 tephra, 10 soil) | 0 | 8.7° |
| Snæbýlisheiði | 63.73149N<br>18.68867W | 21 | 20 (10 tephra, 10 soil) | 21 | Approx. 0° |

### 2.2. Data collection

A survey of the K1918 tephra layer was conducted in June and August 2019. At each of the six study sites we established 12 open sections (21 in Snæbýlisheiði) and measured the thickness of a) the K1918 layer and b) the soil overlying the K1918 tephra, taken from the top contact of the tephra layer to the ground surface. A total of 81 sections were measured. Sections were between two and 186 m apart. Each section had continuous vegetation cover (Fig. 2). Due to the high erosion rates in Iceland, eroding edges and eroding features (such as the Icelandic'rofabard' – see Arnalds (2000)) are common. Rofabards are a distinctive erosion feature in Iceland and are formed in areas which contain thick andosols overlying a more cohesive (less erodible) material such as lava or till. As erosion patches deepen and widen, escarpments of bare soil (rofabard) are formed (Arnalds, 2000). A well-developed rofabard will affect vegetation development close to the eroding front and thus its ability to trap and preserve tephra deposits, which can become more variable at small spatial scales (Streeter and Dugmore, 2013a). As a function of distance from the sediment sources represented by a rofabard, SeAR can decline into a vegetated area (Dugmore and Erskine, 1994), but this effect is limited to small spatial scales (i.e. thinning occurs over a distance of just a few metres from the rofabard edge). If the erosion continues, eventually all of the soil will be eroded away, leaving a barren landscape (Dugmore et al., 2009). We collected our measurements from such eroding edges (detailed in C and D, Fig. 2), as it allowed the K1918 tephra layer to be accessible whilst minimising environmental disturbance. SeAR and tephra thickness are likely affected by proximity to eroding edges, however we sampled at the same point on the eroding edges, the boundary between fully vegetated areas and partially or not vegetated areas, so that they were still comparable.

Tephra thickness measurements were made to the nearest millimetre. A total of 10 measurements were made of each strata in each section, at horizontal intervals of ~10 cm. Random resampling of the tephra thickness dataset showed that mean thickness stabilised with ~40–80 measurements, indicating that our sample size of 120 was sufficient to establish a reliable mean (Dugmore et al., 2018). The initial K1918 tephra thickness at each site was estimated from the thickness between isopachs presented in Larsen et al. (2021). A comparison of the measurements presented in Larsen et al (2021) and our data was used to estimate how much of the deposit has been retained as a preserved tephra layer at each of our sites.

### 2.3. Grain size analysis

We took samples of the K1918 tephra to assess its grain size characteristics. In total, 21 tephra samples of around 2 $cm^3$ were collected from the Snæbýlisheiði sections. Samples were collected from the full thickness of the layer (from the top to bottom contact) so that GSD was representative for the layer as a whole. Prior to particle size analysis, samples were oven dried at 60 °C, organic matter was then removed through digestion using 30 % concentration $H_2O_2$ (following a standard methodology, see Blott et al. (2004)). The samples were sieved prior to laser diffraction analysis to remove particles beyond the maximum size range of the device we used to measure grain size, i.e. 1000 μm. The GSD of samples was measured, using a Beckmann Coulter LS230 with a PIDS detector, based on a Fraunhofer diffraction model and measuring particles ranging from 0.04 to 1000 μm (Blott et al., 2004). The fraction of the sample >1000 μm in diameter was retained and weighed. This coarse portion was subsequently combined with the results of the laser diffraction analysis. This was done by calculating the proportions of the sample above and below 1000 μm, and scaling the results appropriately. Key descriptive statistics of the GSD in the subsequent analysis (mean, median, standard deviation and coefficient of variation) were obtained using the Excel plugin GRADISTAT (Version 9.1), see Blott and Pye (2001).

### 2.4. Statistical analysis

Descriptive statistics of soil and tephra thickness (coefficient of variation, mean, standard deviation) were calculated for each section within each site. The SeAR (mm $a^{-1}$) was calculated by dividing

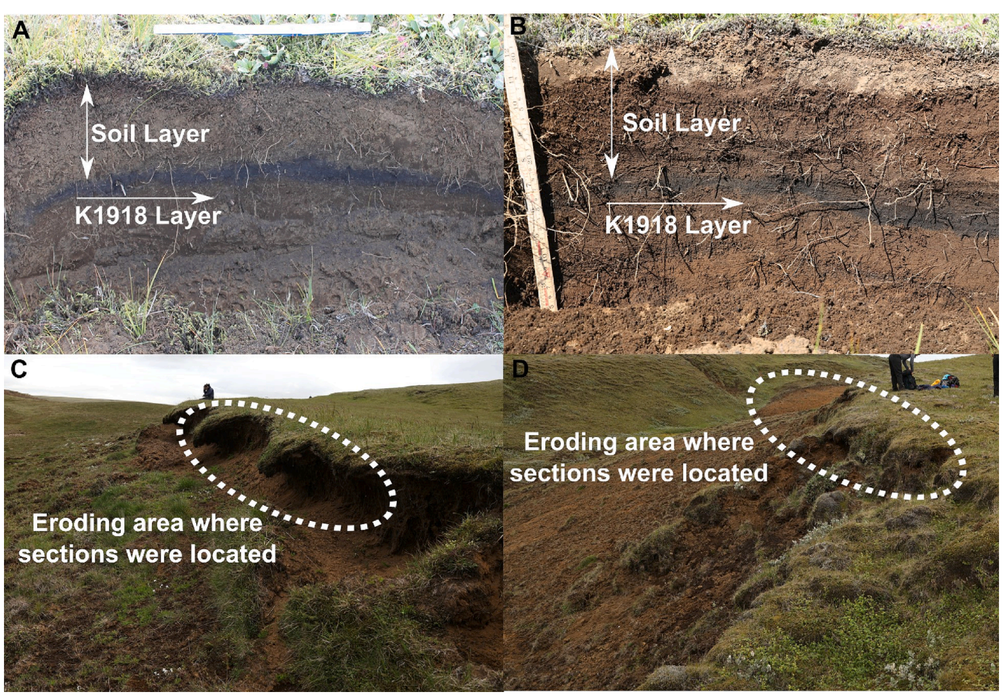


**Fig. 2.** Photographs of example sections and of sites where sections were located. A) is an exposed section from the Snæbýlisheiði site. B) is an exposed section from the Hnausar site. C) is an example of an eroding soil slope or rofabard where sections were located at the Hellnaska site and D) is an example edge where sections were measured Fremri-Tólfahringar site.

measured soil thickness by the period of burial (101 years). The coefficient of variation in K1918 layer thickness was calculated as follows: **CV** $= s/x$ where $s$ is the estimated standard deviation of the sample and $x$ is the estimated mean of the sample. Statistical modelling was used to establish the relationship between SeAR and 1) tephra layer thickness and 2) mean grain size. To assess the relationship between tephra layer thickness variability and SeAR a linear mixed effects model was used as there was non-independence in the data set (i.e. site-level confounding effects that influence the model). The model used coefficient of variation in tephra thickness as the response variable, SeAR as the fixed effect and site identity as the random effect. SeAR and coefficient of variation were log-transformed prior to the analysis, which was conducted using the lme4 package in R (Bates et al., 2015). The significance of the model was assessed by comparing it to a null model (i.e. removing the fixed effect) using ANOVA. Outliers were not removed for analysis, but the data was normalised using log-transformation where necessary.

## 3. Results

Within sites, SeAR was high but variable, confirming that it can vary even when distance between sections is low (<100 m). All but one site lost material from the initial fallout tephra deposit thickness, but again there was variability among sections. There was a correlation between SeAR rates and tephra retention, with higher SeAR correlated with a greater proportion of the initial deposit retained.

### 3.1. Soil thickness

Table 2 shows the soil thickness data. Overall, the soil cover to the K1918 tephra was thick and variable. For example, mean soil thickness (and, as a consequence, SeAR) varied by a factor of 3 among sites (79.5–254.9 mm). Mean soil thickness values were high, with four out of the six sites exhibiting mean thicknesses >150 mm. This variability is illustrated in Fig. 3, which shows the section level detail of thicknesses measured. Krókur and Snæbýlisheiði both contain high soil thickness values and also show the greatest range in values; Krókur: 78–569 mm, Snæbýlisheiði: 100–515 mm. The range in the other three sites is much smaller.

### 3.2. Tephra thickness

Tephra thickness was variable both within and among sites (Fig. 4, Table 3). The range in CV values was greater across all sites than it was for soil thickness. Mean tephra layer thickness varied between 17 and 38 mm, but the CV for the six sites was similar (around 20 %) as shown in Table 3.

### 3.3. Initial tephra fallout and preserved thickness

Tephra deposit thicknesses reported on the surface in Skaftártunga in 1918 were between 65 and 100 mm, with measurements of the preserved layer taken in 1970 being 5–60 mm (Larsen et al., 2021). Table 4 shows the calculated loss or gain of tephra at each site, based on the initial fallout thickness that were obtained from the isopachs in Larsen et al. (2021).

The percentage of tephra retained for all 81 sections was calculated based on the initial deposit thicknesses taken from the isopach in Larsen et al. (2021) in Table 3. These data were plotted against SeAR to examine if SeAR influences the percentage of the initial deposit retained in the layer (Fig. 5). There was a significant positive correlation between SeAR and percentage of tephra retained (Spearman rank: $r_2$: 0.40 [53154], p = <0.001).

Out of the 81 sections, 30 have tephra retention >90 %. Based on these sections, the minimum SeAR measured to enable >90 % deposit retention was 0.5–5.1 mm $a^{-1}$. Assuming that retention does not fully occur in the first year post deposition, but after approximately three years, using these SeAR's the lower limit of soil required on top of a deposit to faithfully preserve it as a layer is 1.5–15.2 mm. For 50–60 % deposit retention, 0.7–1.6 mm $a^{-1}$ accumulation is required, equating to 2.2–4.9 mm soil over three years. For <30 % retention, 0.6–1.4 mm $a^{-1}$ accumulation is required, equating to 1.9–4.1 mm soil over three years.

### 3.4. Relationship between SeAR and tephra variability

Across the six sites, SeAR varied by a factor of three (0.8–2.5 mm $a^{-1}$). Our model indicated that there was no significant relationship between variability in tephra layer thickness (CV) and SeAR ($X^2$ (1) = 0.19, p = 0.66) (Fig. 6).

### 3.5. Grain size distribution

Results of the grain size analysis from the Snæbýlisheiði site show that the K1918 tephra is fine-grained, <2 mm (fine sand – clay sized grains). It also exhibits a bimodal GSD with a primary peak at 4 φ and a secondary peak at 1 φ (Fig. 7). There is a strong positive skew (i.e. a fine tail). The mean particle size for all sections combined is 1.5 φ (354 μm) the standard deviation is 3.1 φ (125 μm). The median particle size and SD were 2.6 (177 μm) φ and 3.6 φ (88 μm), respectively. The grain size distributions of all sites are displayed in Fig. 7, which highlights the variability among sections. Panels A and B highlight GSD curves in sections which have a SeAR greater or <1.5 mm $a^{-1}$. The SeAR threshold of 1.5 mm $a^{-1}$ was selected because it divides the sampling locations into two groups of approximately equal size (nine sections <1.5 mm $a^{-1}$, 12 > 1.5 mm $a^{-1}$), so that any notable difference should be visible once plotted.

There was a significant negative correlation between tephra layer thickness and mean particle size (Spearman rank: $r_s$: 0.44 [866.56], p = 0.047). This indicates that coarser layers tended to be thinner than finer layers. There was a significant positive correlation between burial rate and mean grain size: as burial rate increases the K1918 tephra layer becomes coarser (Fig. 8, ($r_2$ = 0.15, F(1, 19) = 4.61, p = 0.04).

There was no significant difference between mean grain size (φ) in samples with SeAR < 1.5 mm $a^{-1}$ and samples with SeAR > 1.5 mm $a^{-1}$ (Two sample *t*-test: $^t$1.8 = 19, p = 0.09), nor was there any difference between the amplitude of the coarse and fine peaks according to SeAR (Two sample *t*-test of mean % volume in coarse peaks [$^t$0.15 = 19, p = 0.88]; Two sample *t*-test of mean % volume of fine peaks [$^t$0.89 = 19, p = 0.38]). Dominguez et al. (2020) identified that the total range of tephra that can be reworked by wind is between 0.4 and 500 μm (11.2–1 φ) and the most vulnerable size fraction to aeolian remobalisation is 63–125 μm. A large proportion (85.5 %) of the total grain size distribution of K1918 tephra falls above 1 φ. All sections with SeAR < 1.5 mm $a^{-1}$ have <12 % volume in the vulnerable fraction above 1 φ, whereas five out of twelve sections with SeAR > 1.5 mm $a^{-1}$ have >12 % volume in the vulnerable fraction >1 φ.

**Table 2**
Table summarising descriptive statistics for soil thickness above the K1918 tephra for all sites.

| Site | Mean SeAR mm $yr^{-1}$ | Mean soil thickness (mm) | Standard deviation (mm) | CV (%) |
|---|---|---|---|---|
| Snæbýlisheiði | 1.8 | 183.3 | 12.1 | 6.6 |
| Krókur | 2.5 | 254.9 | 14.9 | 5.8 |
| Hnausar | 1.9 | 187.0 | 10.9 | 5.8 |
| Hellnaska | 1.5 | 154.1 | 16.7 | 10.9 |
| Fremri-Tólfahringar | 0.9 | 95.2 | 14.3 | 15.0 |
| Núpsheiði | 0.8 | 79.5 | 7.8 | 9.8 |

## 4. Discussion

Burial rate appeared to influence the characteristics of the K1918

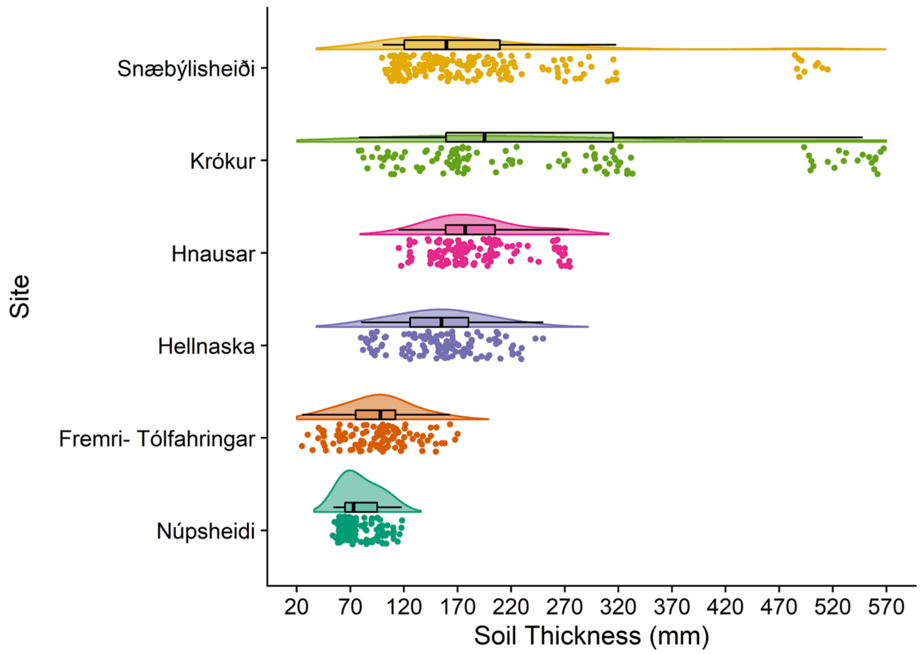


**Fig. 3.** Soil thickness above the K1918 tephra for all sites. Variability in the measurements collected from the sections within the sites is highlighted by the individual point measurements and boxplots, showing median values. Plots were created using the'raincloud' visualisation method on R (Allen et al., 2019).

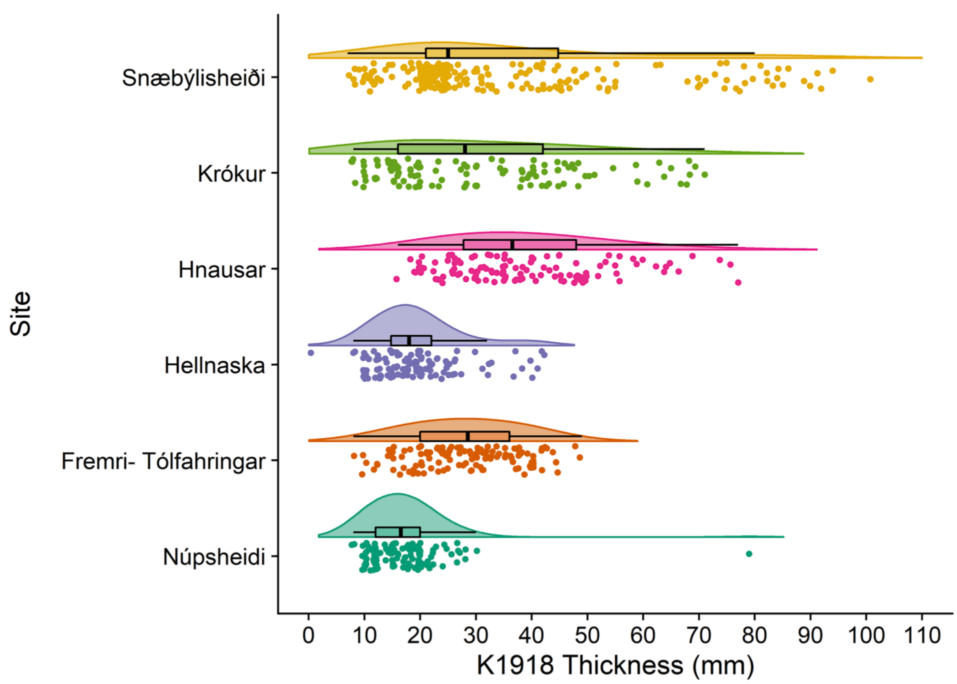


**Fig. 4.** Plot summarising the tephra thickness in all sites. Variability in the measurements collected from the sections within the sites is highlighted by the individual point measurements and boxplots, showing median values. Plots were created using the'raincloud' visualisation method on R (Allen et al., 2019).

layer, as there was a significant positive correlation between retained thickness and SeAR: the higher the SeAR, the greater the proportion of the initial deposit preserved in a tephra layer. SeAR also appears to have an impact on GSD, albeit not in the way hypothesised. SeAR has little to no effect on overall variability in tephra layer thickness. Our results suggest that whilst SeAR is a factor in tephra layer preservation, it should be viewed as one of many interacting factors that will vary in importance in different locations and for different tephra layers. These factors include the weather at the time of deposition, surface conditions and human and animal influences (Arnalds et al., 2016), which are not captured in our dataset.

### 4.1. SeAR and tephra deposit retention

The preserved K1918 tephra layer has undergone some alterations from the fallout deposit isopach map from Larsen et al. (2021). Effective preservation of tephra is critical for its use in tephrochronology and eruption reconstruction (Schmid et al., 2017). Although remobilisation is often viewed as an unhelpful complication, modified units can preserve important attributes of the eruption, such as grain size (Buckland

**Table 3**
Table summarising descriptive statistics for K1918 tephra thickness for all sites. Sites are ordered in increasing distance from Katla, with Snæbýlisheiði closest.

| Site | Mean tephra thickness (mm) | Standard deviation (mm) | CV (%) | Number of individual measurements |
|---|---|---|---|---|
| Snæbýlisheiði | 34.9 | 5.6 | 16.0 | 210 |
| Krókur | 30.4 | 8.4 | 27.5 | 120 |
| Hnausar | 38.8 | 6.8 | 17.4 | 120 |
| Hellnaska | 19.3 | 5.1 | 26.2 | 120 |
| Fremri-Tólfahringar | 28.1 | 7.0 | 24.9 | 120 |
| Núpsheiði | 17.1 | 3.8 | 22.5 | 120 |

**Table 4**
Table showing the loss (−) or gain (+) of tephra at each site between the initial fallout thickness and our measurements, based on mean tephra thicknesses presented in Table 3.

| Site | Initial fallout thickness (mm) | Difference in man measured thickness from fallout (mm) |
|---|---|---|
| Snæbýlisheiði | 50 | −16 |
| Krókur | 50 | −20 |
| Hnausar | 30 | +8 |
| Hellnaska | 20 | −1 |
| Fremri-Tólfahringar | 30 | −2 |
| Núpsheiði | 50 | –33 |

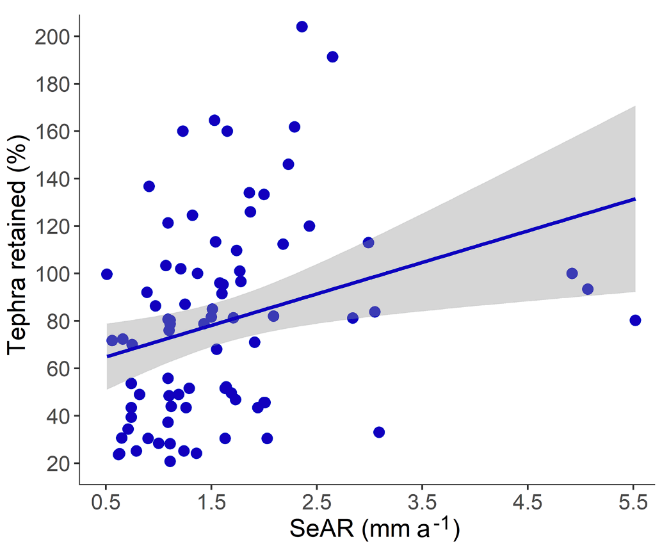


**Fig. 5.** Scatter plot illustrating the relationship between SeAR and the percentage of tephra retained from the initial fallout. Values over 100% indicate sections where the tephra layer thickness measured in 2019 was greater than the initial deposit thickness, i.e., addition material was gained from elsewhere after deposition. Shaded area represents the 95% confidence interval.

et al., 2020). Cutler et al. (2018) found that the degree of tephra preservation is highly dependent on the local environmental conditions at the time of deposition, particularly the earth surface processes and vegetation coverage. This aligns with other studies that show that vegetation cover is important for tephra preservation (Cutler et al., 2016; Dugmore et al., 2020). Cutler et al. (2018) also note that tephra layers did not thin in predictable manner during preservation. Furthermore, experimental work by Blong et al. (2017) concluded that compaction occurs very rapidly after deposition, which should be accounted for in tephra thickness and bulk density estimates. It is likely that some of the 'loss' of material measured here is due to compaction of the deposit, rather than actual loss of material via wind and water. Compaction will reduce the thickness of the fresh deposit as it is preserved as a layer.

Tephra preservation also depends on factors such as eruption intensity, the volume of tephra produced and weather conditions at the time of deposition (Óladóttir et al., 2012). The eruption of Katla in 1918 occurred during min-autumn in October. Oral records and reports from the time of the eruption that are referred to in Larsen et al. (2021) do not mention snow on the ground at the time of the eruption, but they do say that the tephra on the ground was covered by snow from 20th October onwards (Larsen et al., 2021). Climate records from Stykkishólmur (the closest station to the sites in this study) exist from 1918. These records indicate that winter 1918 was very cold in comparison to the years before and after (between −2 and −5 °C), meaning the ground was quite likely to be frozen at the time of the eruption (Icelandic Met Office, 2023). The presences of snow and/or ice on the soils surface will have influenced tephra preservation by enhancing the reworking potential, as well as potentially limiting burial by soil, as there would have been less mobile aeolian sediment if the ground was frozen (Óladóttir et al., 2012). Thus, because the K1918 eruption occurred during October, the time of year and the landscape conditions associated with this time of year (with vegetation die-back at the end of the growing season and the start of winter) may have affected aspects of preservation of the tephra deposit but are likely to have affected all our sites in similar ways.

Statistical tests indicated that as SeAR increases, so does the retention of the initial deposit thickness, although there is considerable variability among measured sections. A third of them had a reduced thickness, the rest maintained the same thickness or, in one instance, became thicker. The K1918 tephra is likely to have compacted by around 20 % since deposition (Gudmundsson et al., 2021; Larsen et al., 2021). Scaling-up to account for compaction indicated that retention of tephra was better than site measurements suggest, with all but one site losing less material than predicted and retaining a great portion of the initial deposit thickness. Retention across all sections measured within the sites was between 20 and 210 %, with 21 sections (26 %) exhibiting a gain in overall thicknesses, reflected in percentages >100 (Fig. 5). As distance from the volcano increased, the original tephra thickness decreased but the thinnest tephra layers we measured were at Núpsheiði, which was not the most distant site from Katla, emphasising the importance of rapid burial in preserving a greater proportion of the deposit.

Similarly, we have demonstrated that a higher SeAR means the tephra layer appears to more closely reflect the original deposit, probably because of the shorter time available for reworking. However, an alternative explanation is that at sites where SeAR is higher, it indicates a location in the landscape which is better than average at accumulating sediment (or one is particularly close to a sediment source). These sites may preferentially accumulate tephra which has been remobilised immediately after an eruption. Thus, a percentage of tephra within the preserved layer which is in the size fraction vulnerable to aeolian movement may be remobilised tephra from elsewhere in the landscape, rather than in-situ material which has not been eroded.

Higher levels of SeAR are required to retain a certain percentage of the tephra deposit. There are however, uncertainties when trying to quantify how rapidly a deposit is buried and changes in SeAR rates, particularly where other factors such as biocrust formation may occur (Cutler et al., 2018). This variability could be explored in further work examining how rapidly soil seals the surface of a fresh tephra deposit and preserves it. This indicates that while SeAR may not be important in terms of absolute variation in thickness, it is a factor enabling deposit retention. Therefore, hypothesis 1 (higher rates of SeAR will preserve a great proportion of the K1918 fallout deposit) cannot be rejected. To determine if it is the preservation of the layer or addition and retention of remobilised material, sub-samples of the tephra layer are required.

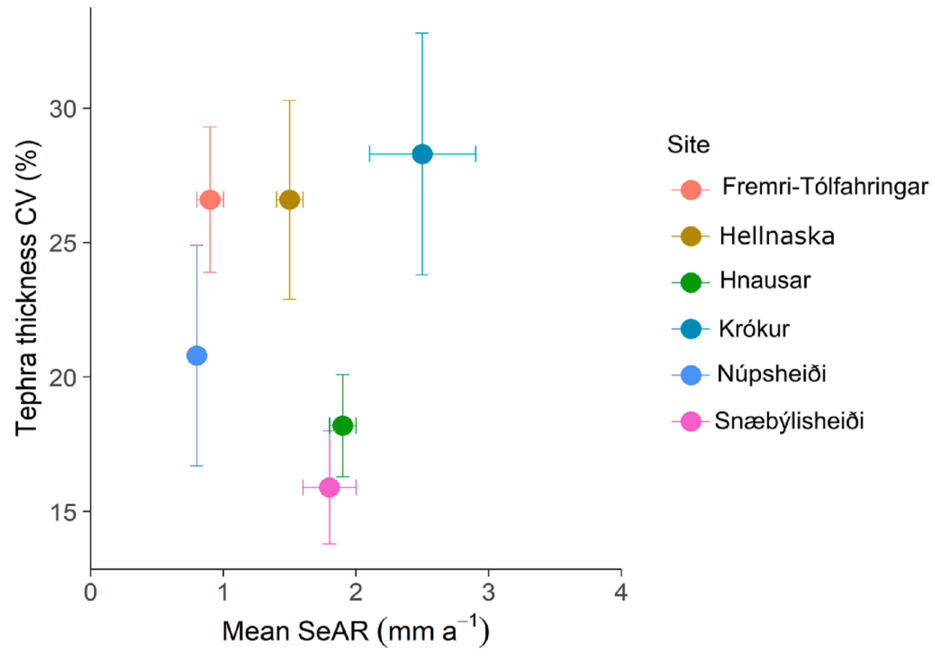


**Fig. 6.** The relationship between tephra thickness variability and SeAR for all six sites. ±1 SE are indicated for each site.

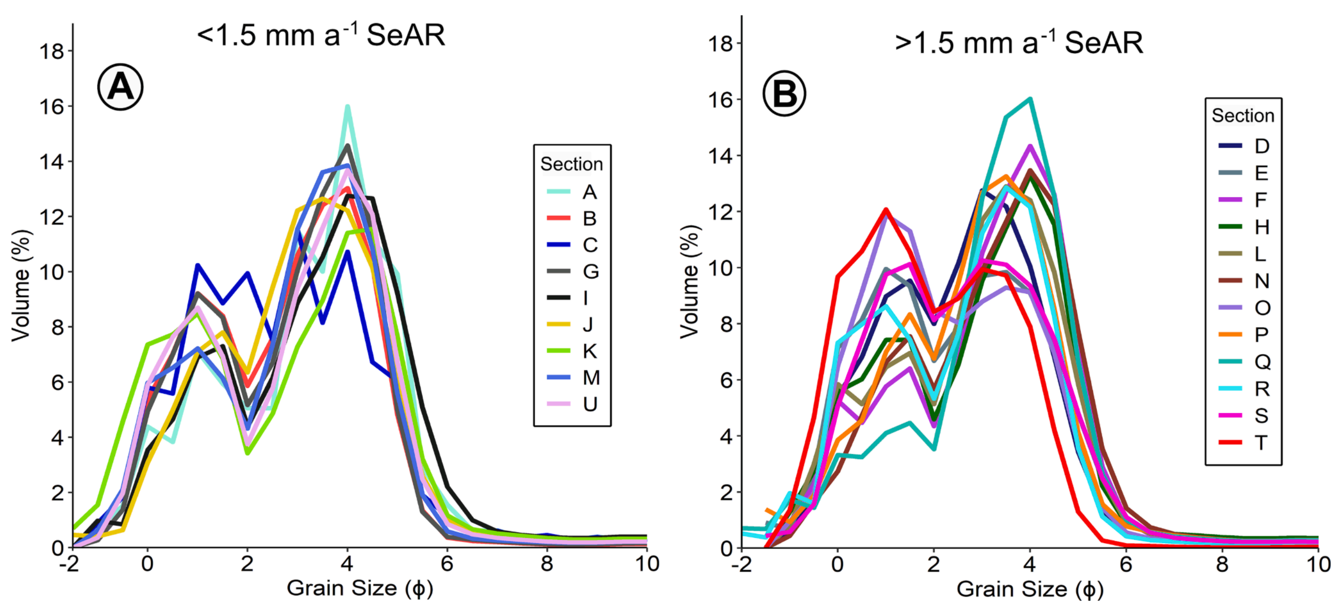


**Fig. 7.** Grain size distribution of the K1918 tephra in our study sections, split according to mean SeAR. A. indicates a subset of grain size distribution curves from sections which have <1.5 mm a$^{-1}$ SeAR (n = 9) and B indicates a subset of grain size distribution curves from sections which have >1.5 mm a$^{-1}$ SeAR (n = 12). All sections have a bimodal distribution, but sections with >1.5 mm per year SeAR have much greater variability around the 1φ peak than sections with lower SeAR rates.

### 4.2. SeAR variability and the burial process

The rate at which a stabilised tephra deposit is buried depends on multiple factors, such as local microclimate, and vegetation change, which in turn will vary across the region (Streeter and Dugmore, 2014; Dugmore et al., 2009). In Iceland, there is evidence that tephra can be remobilised and active on the landscape for long periods of time, especially in areas where soil accumulation is slow (Arnalds, 2015; Arnalds et al., 2016). Burial of a tephra layer may begin soon after an eruption, as vegetation grows through it and helps to trap aeolian sediment. In the weeks-months after the eruption, a fresh tephra deposit will compact, may be eroded, and /or have organic or inorganic material from elsewhere added (Cutler et al., 2016a; Cutler et al., 2018). Eventually, this will result in burial and the formation of a new tephra layer, which will have undergone a degree of transformation (Dugmore et al., 2020). Work by Liu et al. (2014) also suggests that modification of tephra deposits from processes such as erosion, compaction and redeposition can alter tephra particles and thus subsequent reworking, as eroded grains move differently.

In southern Iceland, soil accumulation occurs mainly due to the deposition of wind-blown sediment. The quantity of sediment available for aeolian deposition - and, to a large extent, SeAR – is driven by soil erosion. Icelandic soils are particularly susceptible to wind erosion, due to the lack of cohesive phyllosilicates, coarse texture and high

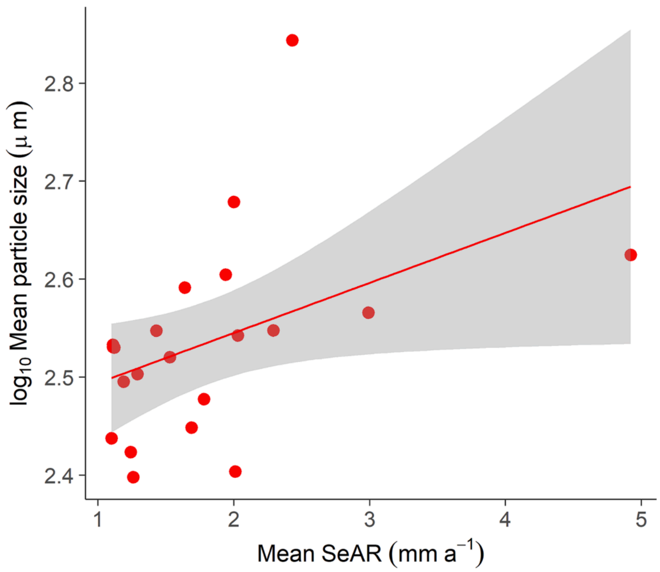


**Fig. 8.** Scatter plot illustrating the relationship between K1918 tephra grain size distribution and SeAR. Shaded area represents the 95% confidence interval of the line.

infiltration capacity, which can make SeAR rates very high (Arnalds, 2015). Weathering of basaltic tephra is the main parent material for Icelandic soils. Enhanced erosion occurs due to human influence over the last 1000 years outpaces the contribution from weathering of basaltic tephra (Arnalds, 2005; Dugmore and Erskine, 1994; Streeter and Cutler, 2020). When soil erosion occurs in Iceland it is patchy at a range of scales, as it develops from erosion spots to the propagation of eroding fronts and a loss of area (Arnalds, 2000). Thus where the soil is not eroding it can accumulate, enhanced by the influx of sediment from erosion elsewhere, either locally or regionally.

Through our calculation of SeAR, we assume that it has been constant since 1918. However, it will have varied through time and some sites may have had lower SeAR at the time of the eruption, but are now higher because they are more proximal to the erosion edge (which has moved laterally back over the intervening 100 years). This means our estimates likely overestimate the minimum SeAR required to ensure good preservation of the deposit. However, biases relating specifically to our choices of sampling locations on an eroding face are minimal, as all sites were in a similar geomorphic situation. There are therefore multiple factors that are potentially responsible for varying SeAR rates across our sites, but the differences in tephra preservation we observe must have developed prior to the burial by aeolian sediment.

Mean SeAR by site (km-scale) varied by an order of magnitude, and similar variability was observed within sites, at a scale of metres. For example, the greatest distance between two sites is 22 km (Snæbýlisheiði to Hellnaska) and the shortest is 2.1 km (Núpsheiði to Krókur, Fig. 1). Variations in SeAR appear to have an impact on the proportion of tephra retained, but do not have a direct impact on local variability in tephra layer thickness. In southern Iceland, soil erosion varies temporally as well as spatially. Streeter and Dugmore (2014) found that SeAR in Skaftártunga increased from the 16th century until the present day, with the highest levels post 1918. This change was observed alongside increased indicators of instability such as evidence of slope wash. Since the 19th century, SeAR in Skaftártunga has been estimated at 2.2 mm $a^{-1}$, on average, so rates measured here (1–3 mm $a^{-1}$) are within this range (Streeter and Dugmore, 2013b, 2014). However, overall averages conceal a lot of spatial variability in SeAR.

Our work concentrates on the impact of burial rate (and, by implication, soil development processes) have on tephra preservation. But it is likely that tephra deposition also impacts soil development (Bonatotzky et al., 2021). In between volcanic eruptions, andosol soil production and development continues as normal through top-down weathering of volcanic parent material. However, these processes are slowed or halted when the ground surface is sealed under a fresh tephra deposit (Delmelle et al., 2015). The buried soil becomes a palaeosol and new soil will begin to form on top of the tephra deposit, aiding its burial (Delmelle et al., 2015; Arnalds et al., 2012).

### *4.3. SeAR and tephra thickness variability*

We anticipated that SeAR would be negatively correlated with variability in tephra layer thickness, as rapid burial would limit reworking of the freshly deposited tephra (Hypothesis 2). However, there was no relationship between SeAR and variability in tephra layer thickness (Fig. 6). As burial rate has little or no impact on the variability of tephra layer thickness, this indicates the importance of other factors in determining tephra layer morphology. Vegetation cover at the time of deposition is likely to be important, such as coverage, height, stem architecture and packing (Cutler et al., 2016a, 2016b; Dugmore et al., 2018).

### *4.4. SeAR and grain size distribution*

In our third hypothesis we state sections with high SeAR will retain more of the fraction vulnerable to aeolian demobilisation. The overall GSD of the K1918 tephra exhibits a bimodal distribution, regardless of burial rate. Eychenne et al. (2012) found that the bimodal distribution of the Tungurahua (Ecuador) 2006 tephra was partly due to different transport processes operating on differing size fractions. Phreatomagmatic eruption phases can also be responsible for creating bimodality in GSD (Costa et al., 2016). Most eruptions from Katla are phreatomagmatic because they are sub-glacial and the eruption in 1918 was no exception, as it took place on the southeast rim of the Katla caldera, beneath ~400 m of ice (Sturkell et al., 2010). This is very likely to have caused the.

bimodal GSD distribution presented here (Gudmundsson et al., 2021). Vertical sub-sampling the K1918 tephra layer to measure the GSD of would have provided additional stratigraphic information about the bimodal grain distributions however, because of the shallow depths of fallout considered in this study the cause of any vertical variations in GSD could be the result of two quite different processes. Grain sizes could vary through the course of the eruption, and this variation might be faithfully preserved, or the primary fallout may have been sorted by frost action which could move particle of different sizes through the profile. As a result material in this study was sampled from the top contact of the layer to the bottom of the layer in each section. This was mixed together to give one sample per section. Data collection was done this way because the main aim of this research was to examine if burial rate by soil affects the GSD of the layer as a whole, rather than individual phases or sections of the preserved layer potentially altered by post depositional processes. As it is apparent that K1918 has a bimodal GSD, an important avenue for future studies would be to examine this in more detail to determine how this develops within a vertical section through the tephra.

Fig. 7 shows that GSD appears to vary with SeAR. Sections with a higher rate of SeAR (>1.5 mm $a^{-1}$) retain more of the total vulnerable fraction range 0.4–500 μm (11.2–1 φ) than sections with lower rates of SeAR, consistent with Hypothesis 3. Additionally, variability in the GSDs appeared to be related to SeAR. Higher SeAR was associated with coarser layers; it also appeared to lead to more variable coarse fractions, although this relationship was not statistically significant. It is usually assumed that the GSD in a tephra layer is representative of the initial deposit, however a study of the Mount St Helens 1980 tephra by Cutler et al. (2021) found that although the overall grain size characteristics of the preserved tephra layer were similar to the original deposit, there was a loss of finer material, attributed to'winnowing'. Fine tephra grains (>4 φ, 62.5 μm) are more cohesive which enables them to resist remobilisation from wind - particularly when wet - meaning that coarser grains are actually more susceptible to movement by wind (Del Bello et al., 2021; Dominguez et al., 2020).

The positive correlation found between SeAR and proportion of the GSD in 'vulnerable' grain size fractions indicates that rapid burial locks-in the initial GSD, with all sections with SeAR < 1.5 mm $a^{-1}$ having <12 % volume above 1φ (0.5 mm), whereas five out of twelve sections with SeAR > 1.5 mm $a^{-1}$ have >12 % volume. This is consistent with our hypothesis that higher SeAR will result in the retention of more of the tephra size fraction that is vulnerable to aeolian remobilisation (Hypothesis 3). Thus, the relationship between SeAR and GSD shows that rapid rates of burial retain more of the vulnerable fraction, but tephra layer thickness also has an influence on the GSD of the tephra layer. Further work to identify whether this is the case at other sites and for other tephra layers would help to constrain whether this is a site specific variability or a pattern of tephra layer preservation that occurs elsewhere with high rates of SeAR. An alternative hypothesis is that sites which are better at accumulating sediment (higher SeAR) are also likely to be better at accumulating the fraction of the GSD which is vulnerable to aeolian remobilisation, i.e. they may contain more of the fraction because they have had additional material added, not because the material has not been eroded. To reliably test this GSD samples from the time of the eruption would be required to compare against samples collected post preservation.

Our results highlight the complexity of the different factors impacting tephra preservation. Based on field observations, Dominguez et al. (2020) identified that remobilisation of tephra by wind can occur at grain sizes up to 1 φ (0.5 mm). This is consistent with the idea that the longer tephra remains active on the surface, the more it is transformed (in terms of GSD). As there are no measurements of the GSD in the initial K1918 deposit, we are unable to compare how the distributions have altered through time. However, it is clear that there are many factors that influence the modification of GSD of initial tephra deposits, such as earth surface processes (wind, water, snow), vegetation coverage, slope of land surface and disturbances by other factors (humans and animals). We have observed a correlation with SeAR, but we cannot prove which of the two potential scenarios is more important – GSD is better preserved because it is on the surface for a shorter period, or GSD is more altered at high SeAR sites because these sites are good at collecting aeolian sediment, which will include remobilised tephra. Overall, the rate of burial does influence the resulting GSD of the preserved tephra layer.

Other surface processes, such as the effect of rainfall and snow melt, are also likely to alter the GSD of tephra deposits over time, and lead to differences between freshly deposited tephra and layers preserved in the soil (Fig. 9) (Thompson et al., 2021). Surface processes that impact GSD may only affect the top portion of the layer, so variation in GSD may not be throughout the entire layer and may vary from top to bottom in thicker layers. Rainfall will move nonconsolidated material such as tephra on slopes and redistribute deposits on flat ground, which can alter the preserved GSD, because tephra deposited across a landscape may decrease the infiltration capacity and increase overland flow, washing away parts of the deposit (Major and Yamakoshi, 2005). The impact of these processes will vary with grain size. Coarser grains are susceptible to mobilisation by rainsplash; finer material is more likely to be moved by wind (Jones et al., 2017). A reduction in the length of time the tephra is exposed on the surface therefore reduces the ability of these factors to alter the GSD of the tephra.

### 4.5. Experimental design

This study successfully captured spatial variability in tephra layer properties. As SeAR varied across the landscape, we were able to test

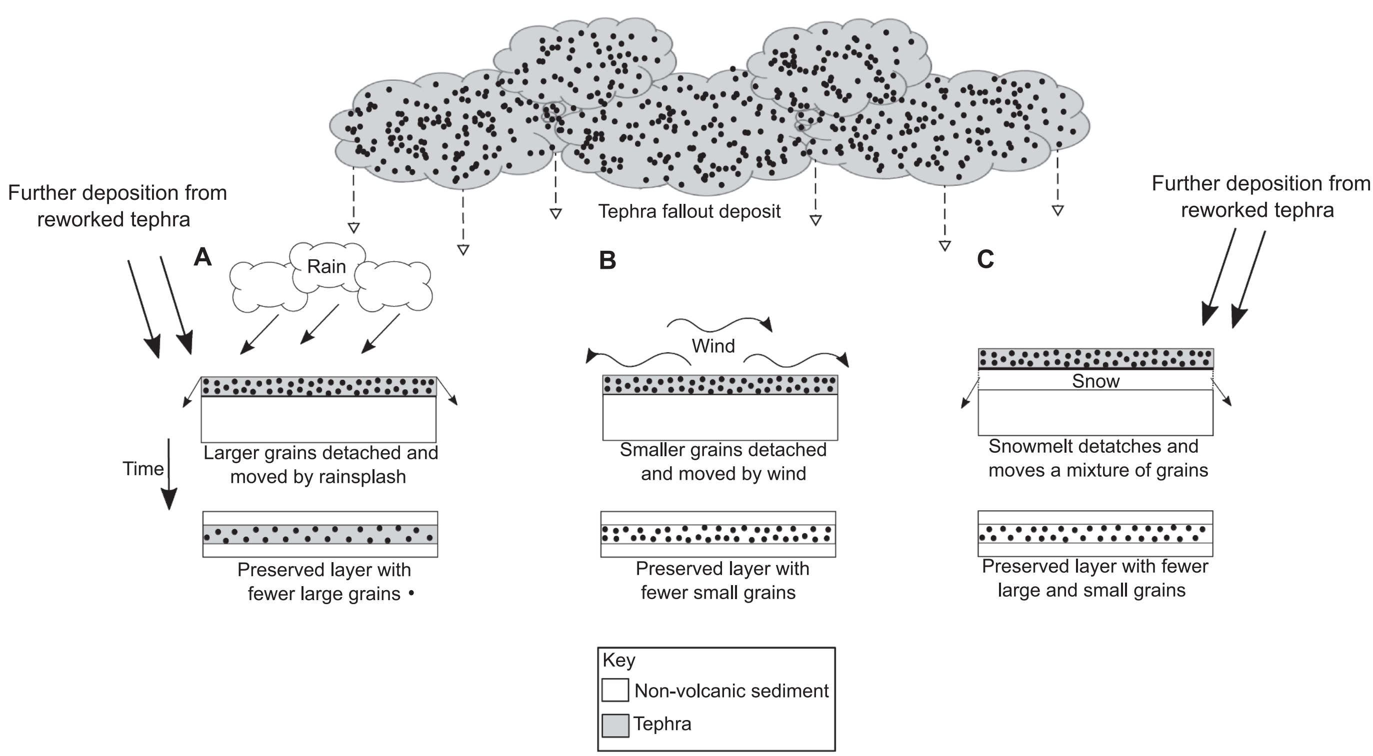


**Fig. 9.** Schematic summary of surface processes and our inferred impact on GSD of cm-scale thickness of tephra. A. the effect of rain, B. the effect of wind and C. the effect of tephra deposited on snow. Large grains are size fractions <1 φ and small grains are >1 φ (Dominguez et al., 2020). There will be a net loss and gain of grains, so areas that have lost grains may gain them from elsewhere. When these processes operate on thicker tephra deposits they could create internal variation within the tephra layer.

whether it has an impact on tephra layer preservation. An avenue for further study would be to examine areas of the landscape that have an even larger range of SeAR rates and especially areas with very low SeAR rates. Low SeAR are likely to lead to very poor preservation, resulting in a thin, patchy and variable tephra layer or one completely absent from the local record. However, in some instances stabilisation (and preservation) of a tephra may be driven by factors other than burial, for example the Mount St Helens tephra in eastern Washington State was found near the surface and had only been minimally altered below a protective biocrust, indicating factors such as climate and biological activity are important (Cutler et al., 2021). High rates of aeolian soil accumulation occur in Iceland (Arnalds et al., 2012). Soil accumulation rates in Gran Canaria (which also has volcanic parent material) have been measured as 17–79 g m $a^{-1}$ in comparison to Iceland's 25–250 g m $a^{-1}$ (Roettig et al., 2017). Volcanic areas with low SeAR and few stabilisation mechanisms will have limited capability in preserving an accurate tephra record, impacting volcanic reconstruction in that area. This is true for east of the Andes in South America, as it has a minimal tephra record despite numerous tephra producing eruptions locally (Fontijn et al., 2014). Soil production and accumulation are therefore important in determining the fidelity of tephra stratigraphy as a record volcanic activity. Additionally, vertical sub-sampling tephra layers to give GSD curves for stratigraphic units (when different units are present and visible in the preserved layer) could provide additional insight into potentially informative patterns, attributable to either volcanic processes or post depositional modifications.

A wider range of SeAR might have allowed a subtle relationship to have been detected, rather than the null relationship presented here. For more comprehensive exploration, tephra layers from different volcanic areas such as New Zealand, Japan and Alaska, would need to be investigated. An experimental study to test how burial rate influences tephra thickness, morphology and GSD could provide a means to test this, as factors such as initial deposition can be controlled and processes acting on the surface can be monitored. It is important to further understand this as reconstructing past volcanic eruptions relies on tephra layers being representative of what was deposited at the time and any alterations will influence our interpretations.

## 5. Conclusion

We have demonstrated that there is a significant positive correlation between SeAR and the proportion of cm-scale thicknesses of the K1918 fallout that is preserved in similar environments. The higher the SeAR, a greater proportion of the initial thickness is preserved, but SeAR is not directly correlated with overall thickness variability in tephra layers. There is a positive correlation between burial rate and mean grain size, and as burial rate increases the preserved layer has a higher proportion of larger grains preserved. This indicates that the more rapidly a deposit is buried, a greater proportion of the GSD is also preserved. This has important implications for volcanic reconstruction, as areas that preserve fallout more faithfully are desirable for this. When overlying soil thickness is 1.5 mm after three years, 90+% of the original deposit thickness was preserved; in contrast, 0.6 mm of soil accumulation in the same period only resulted in <30 % preservation, based on our measurements of SeAR, assuming that that SeAR has been constant since 1918. Thus, there seems to be a potentially sharp falloff in preservation with low rates of soil accumulation.

Burial rate factors will act upon the variability that may develop in tephra deposits on the surface before entrainment, as a result of their deposition across varying types of surface. This study considered areas with similar vegetation, thus avoiding a complication that will occur with variation surface conditions. Highly vegetated areas or areas with other tall vegetation, with densely packed stems, will rapidly stabilise a cm-scale thickness of tephra. Climate and the time of year when an eruption occurs is also an important determinant of how a tephra layer is preserved. Thus, the best records of past volcanic activity in distal tephra layers will be found in these areas where there is also a rapid accumulation of soil- and swift burial of the tephra deposit. Whilst this work highlights burial rate is an important factor in the preservation process of tephra deposits as enduring stratigraphic layers, examining slower rates of burial in other volcanic areas would usefully extend this research. This would also enable us to further quantify how much burial is required to minimise the loss of a freshly deposited tephra and refine the thresholds identified in this study for the minimum amount of soil required to begin the preservation process.

**Data availability:**

The data used in this manuscript has been uploaded as supplementary material.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Attached data in the attach file step

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2023.107025.

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