Earth and Planetary Science Letters 460 (2017) 41–49

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Estimating the frequency of volcanic ash clouds over northern Europe

E.J. Watson[a,*], G.T. Swindles[a], I.P. Savov[b], I.T. Lawson[c], C.B. Connor[d], J.A. Wilson[d]

[a] School of Geography, University of Leeds, Leeds, LS2 9JT, UK
[b] School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK
[c] Department of Geography and Sustainable Development, University of St Andrews, St Andrews, KY16 9AL, UK
[d] School of Geosciences, University of South Florida, Tampa, FL 33620-5550, USA

ARTICLE INFO

Article history:
Received 1 June 2016
Received in revised form 26 November 2016
Accepted 29 November 2016
Available online xxxx
Editor: T.A. Mather

Keywords:
cryptotephra
reoccurrence
survival analysis
hazards
eruptions
Iceland

ABSTRACT

Fine ash produced during explosive volcanic eruptions can be dispersed over a vast area, where it poses a threat to aviation, human health and infrastructure. Here, we focus on northern Europe, which lies in the principal transport direction for volcanic ash from Iceland, one of the most active volcanic regions in the world. We interrogate existing and newly produced geological and written records of past ash fallout over northern Europe in the last 1000 years and estimate the mean return (repose) interval of a volcanic ash cloud over the region to be 44 ± 7 years. We compare tephra records from mainland northern Europe, Great Britain, Ireland and the Faroe Islands, with records of proximal Icelandic volcanism and suggest that an Icelandic eruption with a Volcanic Explosivity Index rating (VEI) ≥ 4 and a silicic magma composition presents the greatest risk of producing volcanic ash that can reach northern Europe. None of the ash clouds in the European record which have a known source eruption are linked to a source eruption with VEI < 4. Our results suggest that ash clouds are more common over northern Europe than previously proposed and indicate the continued threat of ash deposition across northern Europe from eruptions of both Icelandic and North American volcanoes.

1. Introduction

Explosive volcanic eruptions release large volumes of fine ash which can be transported long distances (thousands of kilometres) downwind of the volcano (Pyle et al., 2006). Volcanic ash is a hazard for human health and even in moderate concentrations can cause engine failure in jet aircraft. Reliable estimates of the frequency of volcanic ash events would help society, governments and business to mitigate for the social and economic losses incurred during future ash clouds. One approach to understanding the frequency of future volcanic ash fallout in Europe is to use information on past events to forecast future hazard (Connor et al., 2015; Mason et al., 2004).

Over the last few centuries a number of ash clouds such as those during the eruptions of Askja in 1875 and Hekla in 1947 have been witnessed and recorded (Mohn, 1878; Thorarinsson, 1954). However, historical records of ash over northern Europe only extend over a short period of time (none before 1600) (Swindles et al., 2013). The only evidence of pre-historic ash clouds are traces of ash ('tephra') which are eventually deposited and incorporated into ice sheets, peatlands, marine and lake sediments (Lowe, 2011; Watson et al., 2016). In locations far from the volcano, tephra shards may form horizons so sparse in concentration they are not visible to the human eye ('cryptotephra'). Records of past ash fallout have been identified as cryptotephra layers in many regions of the world, including those remote from active volcanoes (Ponomareva et al., 2015; Smith et al., 2016). Cryptotephra layers are typically used for dating the stratigraphic records in which they are found. However, we examine the extent to which cryptotephra layers present an opportunity to understand the frequency of the ash clouds which produce them. Here, we focus on northern Europe, as the region boasts one of the most well studied cryptotephra stratigraphies in the world. However, our approach might be easily applied to other regions where cryptotephra have been identified. Iceland is one of the most volcanically active regions of the planet, and lies in the North Atlantic close to the path of trans-Atlantic air traffic (Thordarson and Hoskuldsson, 2008). The principal transport direction for volcanic ash from Iceland is easterly to south-easterly toward northern Europe, directly towards some of the busiest airports in the world (Wastegård and Davies, 2009). The eruption of the Icelandic volcano Eyjafjallajökull in 2010 caused widespread disruption to travel and major financial losses. Just a year later, the eruption of Grímsvötn also led to minor travel disruption in Scotland (Stevenson et al., 2013).

* Corresponding author.
E-mail address: gy08ejw@leeds.ac.uk (E.J. Watson).

http://dx.doi.org/10.1016/j.epsl.2016.11.054

The examination of peatlands and lake sediments spanning the last 7000 years across northern Europe has led to the identification of multiple cryptotephra layers, each representing ash fall from a different eruption (Lawson et al., 2012).

The past recurrence rate of ash fallout events can be estimated using data on past event frequency. This can then be used to forecast the likelihood of future eruptions based on an estimated recurrence rate. The first estimate for the average return interval of volcanic ash fallout over northern Europe was made by Swindles et al. (2011). They combined data on the ages of cryptotephra layers with the ages of observed ash clouds recorded in historical documents and calculated an average return interval for volcanic ash clouds over northern Europe of 56 ± 9 years, which equates to a 16% chance of an ash cloud over northern Europe that produces a recognizable cryptotephra layer in any 10 year period.

A forecast of the likelihood of future eruptions based on an estimated past recurrence rate from geological records, such as cryptotephra layers, will always represent a minimum estimate because there is the possibility that some events have not been preserved (or yet identified) in the geological record. Satellite images of the ash clouds produced during recent Icelandic eruptions indicate that volcanic ash distribution in the atmosphere is patchy, and transport trajectories are dependent on wind direction (Folch et al., 2012). Cryptotephra deposits are equally patchy, with different cryptotephra layers displaying different spatial distributions throughout northern Europe (Lawson et al., 2012). The cryptotephra data utilised by Swindles et al. (2011) was not collected for the purpose of calculating the frequency of past ash clouds and contained temporal, and spatial gaps. Spatial gaps in European cryptotephra distribution may represent the true margins of the distribution of Icelandic tephra, or they may be an artefact of sampling density. Should they be the latter, these 'gap' regions offer the most promise for identifying new, previously undiscovered tephra layers. As more research is conducted to address spatial and temporal gaps in cryptotephra records, there is a probability that evidence for more volcanic eruptions will be identified, directly affecting the model of Icelandic ash cloud frequency over northern Europe.

The majority of cryptotephra layers in northern Europe are of Icelandic origin. However, there has been no detailed comparison of Icelandic eruption records and cryptotephra records of ash clouds in northern Europe (mainland northern Europe, Great Britain, Ireland and the Faroe Islands). Understanding the characteristics of the Icelandic eruptions which have resulted in ash fall over northern Europe during the last 7000 years may allow for improved estimation of a range of estimates (minimum and maximum) for the frequency of the frequency of ash clouds reaching northern Europe.

In this paper we:

- Report new data on tephra layers extending the coverage of cryptotephra layers across northern Europe and utilising these new data to present a new recurrence model for volcanic ash clouds over northern Europe.
- Compare data from the European geological record and historical observations with data on Icelandic volcanism in order to refine our understanding of the type of Icelandic eruption which poses the greatest risk of producing an ash cloud reaching northern Europe.
- Model the frequency of Icelandic eruptions with various geochemical compositions and explosivity. Using these models, and information on which Icelandic eruptions are most likely to produce ash clouds over northern Europe, we suggest a range of estimates for the return interval of volcanic ash clouds over northern Europe.

2. Methods

2.1. Addressing spatial gaps in existing cryptotephra records

We focused our research on the spatial gaps in northern European tephra records which offered the most promise for identifying previously undiscovered cryptotephras: northern Sweden, Wales and southern England. These regions are far from existing cryptotephra finds, and contain peatlands and/or lakes with the potential to record cryptotephra fallout over the last 7000 years. We curtail our analysis at 7000 years as there is evidence for an increase in the frequency of Icelandic volcanism following glacial unloading at the end of the last glacial (Jull and McKenzie, 1996). Therefore, records of ash cloud frequency from before 7000 yr BP may not reflect the frequency of ash clouds under current and future conditions.

Details of sampling strategy and tephra identification for sites in northern Sweden, Wales and Southern England have been published elsewhere (Watson et al., 2016). Stordalen peatland in Sweden (68.35°N, 19.04°E) was sampled using a Russian-type peat corer (De Vleeschouwer et al., 2011). Samples from all sites were combusted to remove organic material and the residue rinsed in 10% HCl before mounting onto slides (Hall and Pilcher, 2002) or, where large quantities of biogenic silica or minerals were present, following the density separation technique of Blockley et al. (2005). Tephra shards were identified under a high power microscope. Samples which contained tephra were re-extracted for geochemical analysis following either the acid digestion method of Dugmore and Newton (1992) (excluding NaOH treatment) or the density separation technique of Blockley et al. (2005). Tephra shards were mounted onto glass slides (Dugmore and Newton, 1992) or into blocks (Hall and Hayward, 2014). All samples were polished to a 0.25 μm finish. Major element geochemistry was analysed using an electron probe micro analyser (EPMA) at the University of Edinburgh. Analyses were conducted using wavelength dispersive spectroscopy at 15 kV, beam diameters 3–5 μm, beam current varied for different elements following Hayward (2012). Secondary glass standards (Lipari obsidian and BCR-2G: Jochum et al., 2005) were analysed before and after EPMA analysis of unknown glass shards. Assignments to specific eruptions were constrained by stratigraphic position and comparison of tephra geochemistry with the Tephrabase database (Newton et al., 2007) and published literature.

2.2. Estimating recurrence rates

The new northern European cryptotephra reoccurrence database (Supplementary File 1) includes new tephra layers from geological records and observations. Each geochemically homogenous and stratigraphically distinct cryptotephra layer is assumed to represent an ash fall event. There is limited evidence for the transport and redistribution of glass shards by wind following initial deposition, particularly in arid climates (Folch et al., 2014). However, cryptotephra layers included in this study were stratigraphically and geochemically distinct and therefore although wind redistribution must be considered as a possible cause of uncertainty in cryptotephra studies, we are confident that each cryptotephra layer in this study represents one ash fallout event. Data on Icelandic eruptions, VEI and geochemistry were drawn from the Smithsonian Holocene Volcano Database (Global Volcanism Program, 2013). Eruptions were grouped according to geochemistry into mafic and silicic eruptions (silicic >63% SiO_2). Return intervals were calculated using the methods described by Connor et al. (2003, 2006). The empirical survivor function (in uncensored data as here = Kaplan–Meier estimate, by Dzierma and Wehrmann, 2012) was calculated using the repose intervals (taken as the time between

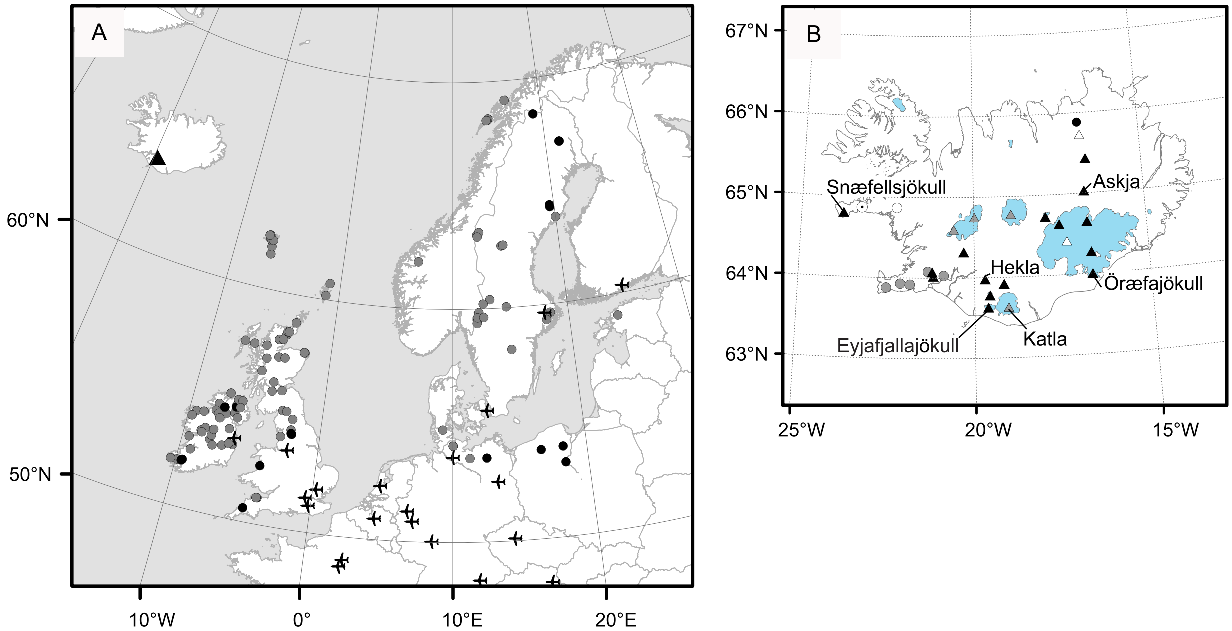

Fig. 1. A) map indicating the location of sites in northern Europe where cryptotephra layers have been identified, grey circles indicate sites included in the original database compiled by Swindles et al. (2011), black circles indicate new sites added to the database, from this and other studies, see Supplementary File 1 for references. Aeroplane symbols indicate the locations of airports which are included in a list of the thirty busiest European airports (2006), data from the Eurostat geographic databases GISCO (Eurostat, 2006). B) Map of Iceland indicating Holocene volcanoes and the location of large ice sheets (blue shading). Data on Holocene volcanoes from the Smithsonian Database (Global Volcanism Program, 2013). Volcanoes are indicated as follows: white triangle = caldera, white circle = fissure vent, white circle with point = pyroclastic cone, black circle = shield volcano, black triangle = stratovolcano, grey triangle = sub-glacial, grey circle = crater.

the onset of two successive eruptions). In cases where the start time for an eruption had not been historically recorded, start time was assumed to be the mid-age. In this instance the survivor function $S(t)$ gives the probability (P) that an observed repose interval T, exceeds a given time interval (t) (Cox and Oakes, 1984):

$$S_T(t) = P[T > t]$$

The Kaplan–Meier survival function for each repose interval was calculated as below:

$$S(t_i) = \frac{N - i}{N} \quad i = 1, \ldots, N,$$

where N is the total number of observed repose intervals and i refers to the ith repose interval in an ordered list from shortest to longest observed repose interval. In order to forecast likely repose interval duration given this observed dataset, a parametric model of survival function was fit to the empirical, Kaplan-Meier survival function. All datasets were first tested for stationarity over the last 1000 years using a Kolmogorov–Smirnov (KS) goodness-of-fit test, then the Kaplan–Meier survival function calculated, and finally the parametric model fit to these data. All datasets excluding 'all Icelandic eruptions' were stationary at the 95% confidence interval. The 'all Icelandic eruptions' dataset was found to be stationary over the last 450 years and parametric models were applied to this time period only. We applied the Kolmogorov–Smirnov (KS) goodness-of-fit test to aid in the selection of the parametric model of best fit. Examples of commonly used parametric models of survival function for natural hazard modelling include the Exponential (Swindles et al., 2011); Weibull (Dzierma and Wehrmann, 2012) and Log Logistic distributions (Connor et al., 2006). We fitted each of the above parametric models to our datasets using maximum likelihood (using package Flexsurv in R version 3.1.0). For each dataset, the model which offered the best fit to the Kaplan–Meier estimate was used to forecast the return interval of events.

The frequency of known Icelandic eruptions or tephra deposition in northern Europe is not expected to be stationary over longer periods of time because of variability in reporting and identification of older units, greater uncertainty in the age determinations of individual units, and likely variable rates of volcanic activity in this longer time frame. To examine the variation in recurrence rate of both Icelandic eruptions and ash clouds over the last 7000 years we apply an algorithm to estimate the recurrence rate during a specific time period based on Monte Carlo simulation of the timing of past eruptive events that produce tephra layers. Each known event (tephra layer or eruption age) has an uncertainty associated with it. We draw a random sample from that age distribution to construct a set of ages for the entire data set. The local recurrence rate is calculated for each eruption time in this set by averaging the repose time between the eruption and its previous and successive eruptions, corresponding to a window of $n = 2$ during which time the repose interval is considered to be constant. This allows us to plot the change in estimated recurrence rate with time. Successive Monte Carlo simulations re-sample eruption age from the age distributions for each unit, ultimately producing a confidence interval for the recurrence rate as a function of time, accounting for the uncertainty in the age determinations. This approach follows those developed by Bebbington and Cronin (2011), Kiyosugi (2012), and Bevilacqua et al. (2015), and uses the code available in Wilson (2016).

3. Results

3.1. The new distal tephra record

We identified evidence for volcanic ash fallout, in the form of at least one cryptotephra layer, at every site studied, suggesting that spatial gaps in cryptotephra records are an artefact of research intensity and do not represent the margins of volcanic ash distribution in northern Europe (Fig. 1). Additional cryptotephra layers and observed eruptions added to the database from this study and other research are listed in Supplementary File 1, and geochemical plots indicating assignments are provided in Supplementary File 2.

Table 1
Table indicating the model used to estimate reoccurrence, average repose interval over the last 1000 years and % chance of an event in any 10 year period.

Dataset	Model	Average Repose	% chance of event in any 10 year period	n of repose intervals	Range of repose intervals (years)
All Icelandic eruptions[a]	Exponential	3.3	95	131	0–19
Ash clouds over northern Europe	Exponential	43.96	20	23	0–111
All Icelandic Eruptions VEI $\geq$ 4	Weibull	25.91	21	35	0–63
Silicic Icelandic Eruptions VEI $\geq$ 4	Weibull	90.63	<1	10	54–148
Silicic Icelandic Eruptions VEI $\geq$ 3	Weibull	50.33	8	18	9–121

[a] Last 450 years (the period for which this dataset is stationary).

Cryptotephra layers identified at sites in northern Sweden, Poland, southern England and Wales have extended the known spatial distribution patterns of widely dispersed cryptotephra layers such as Hekla 4 and Hekla 1104 and less well established isochrons such as Hekla 1158 (previously identified at only one distal site, Pilcher et al., 2005).

Six new cryptotephras, previously not identified in northern Europe, have been added to the database. Two new basaltic cryptotephra layers linked to the Grímsvötn volcano have been identified in Ireland (Reilly and Mitchell, 2015; Watson et al., 2016) and one in Germany (Wulf et al., 2016). The recent identification of more basaltic cryptotephra layers may reflect an increased focus on the analysis of sparse tephra layers (Lake Tiefer See, Unknown Grímsvötn tephra, contained just two shards, Wulf et al., 2016), which has, in part been facilitated by new techniques for the mounting and EPMA analysis of fewer and smaller shards (Hall and Hayward, 2014; Hayward, 2012).

3.2. Repose time distribution fits

Fig. 2 shows the cumulative frequency of ash fallout over northern Europe and Icelandic eruptions over the last 1000 years. The northern European ash fallout record appears stationary at the 95% confidence interval. However, the 'all Icelandic eruptions' dataset is only stationary over the last 450 years and thus parametric models were applied to this time period. On the basis of KS tests, log likelihood and Akaike Information Criterion (Akaike, 1998) we conclude that the majority of proximal Icelandic and distal European eruption frequency data over the last 1000 years are best described by Exponential and Weibull distributions (Table 1, Fig. 3, Supplementary File 3). The Exponential model describes a simple stochastic point process (Poisson process), suggesting that the rate of eruptions is constant over time. The Weibull model also describes a model of simple failure, but indicates that as more time elapses since the last eruption, the next eruption becomes more likely. In datasets for which the Weibull model was the best fit, the data indicated a longer average repose, perhaps indicating that there is a natural limit to the duration of repose between larger eruptions (e.g., VEI $\geq$ 4). Future eruption probabilities were calculated using the model of best fit for each dataset (Table 1).

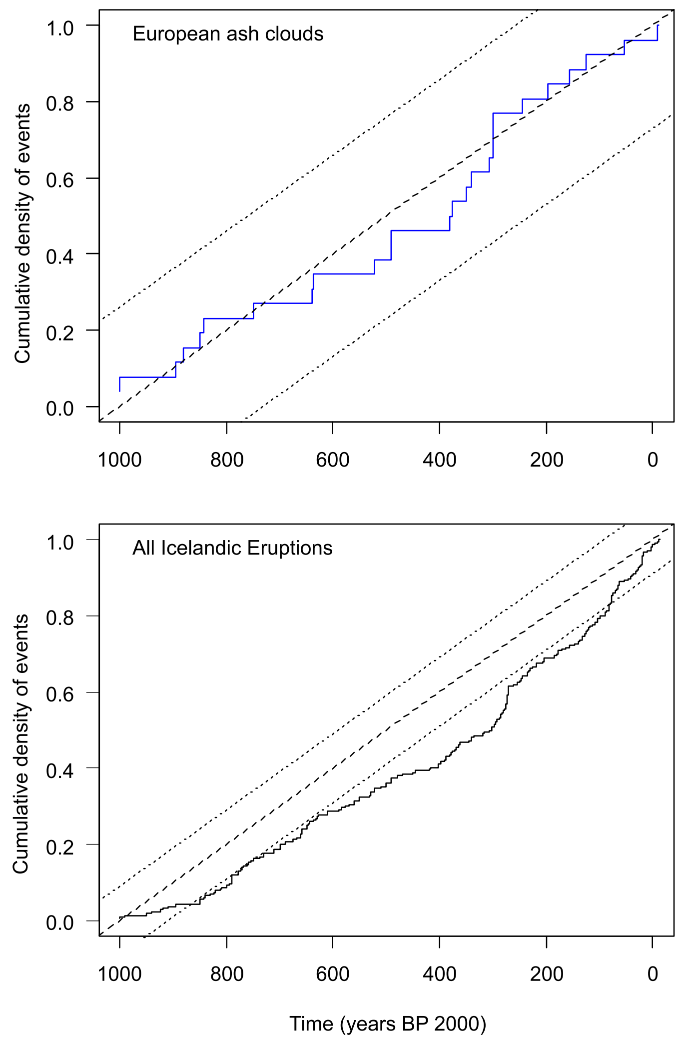

Fig. 2. The cumulative frequency of European ash clouds and Icelandic Eruptions over the last 1000 years. The Kolmogorov–Smirnov test indicates that European ash clouds have not been significantly different from the steady state model over the last 1000 years ($p < 0.05$); Icelandic eruptions show some minor deviations from a steady state. The coarse dashed line indicates the steady state model; finely dashed lines indicate 95% confidence interval.

4. Discussion

The recurrence rate of both Icelandic volcanism and ash clouds over northern Europe has varied over the last 7000 years (Fig. 4, Supplementary File 4). Variation in the frequency of Icelandic volcanism over time can be explained by periodic changes in rifting activity in Iceland and the influence of surface loading (glacier extent) on rates of volcanism (Larsen et al., 1998; Schmidt et al., 2013). The recurrence rate of ash clouds over northern Europe and all Icelandic eruptions shows a general increase in the last 1500 years. This is likely due to the preferential preservation of more recent deposits over older deposits in the geological record, and the increased recording of observed historical events.

A peak in ash clouds over northern Europe is evident ~1000 BP, corresponding to a small increase in Icelandic eruption frequency around this time. However, the median recurrence rate for ash fallout does not exceed 0.11 eruptions year^{-1} (1150 BP), much lower than the recurrence rate for Icelandic eruptions (proximal record) which peaks at 2.2 eruptions year^{-1} (659 BP). Not every Icelandic eruption will result in an ash cloud over northern Europe. This is partly a reflection of the nature of Icelandic volcanism which is dominated by mafic magma compositions (91% of post-glacial eruptions) associated primarily with effusive eruptions which typically produce little or no fine ash (Thordarson and Hoskuldsson, 2008). In addition to being sensitive to changes in the rate of Icelandic volcanism, the frequency of distal ash clouds reaching

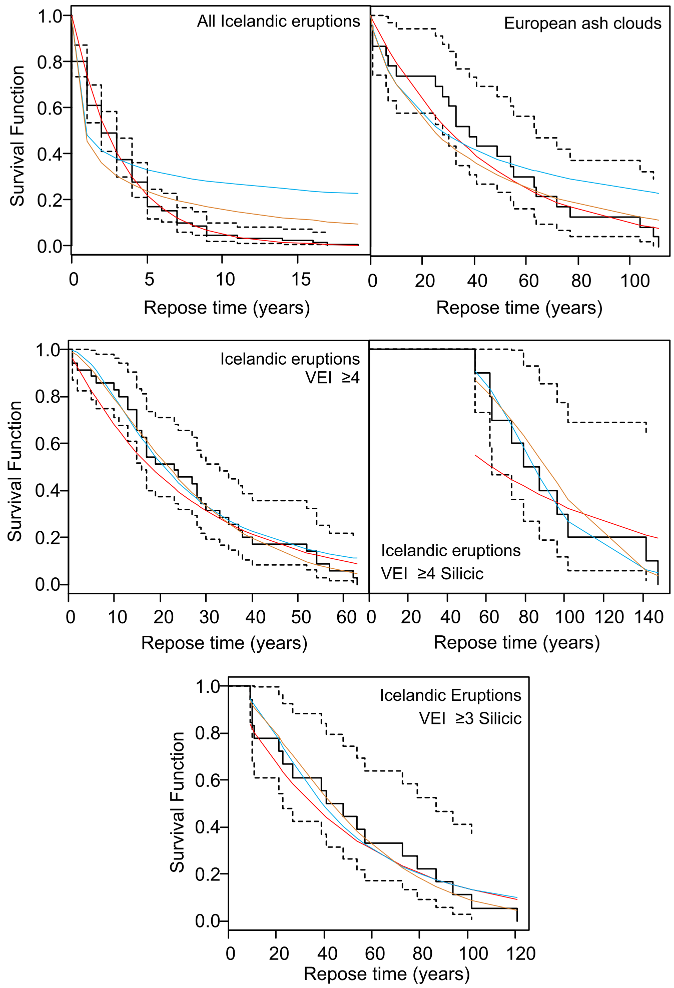

Fig. 3. Kaplan–Meier estimate of the survivor function (last 1000 years, 450 years for All Icelandic Eruptions) with fits for the Exponential (red), Log logistic (blue) and Weibull (orange) distribution functions. Broken lines indicate 95% confidence interval on the Kaplan–Meier estimate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

northern Europe is affected by wind direction, wind speed and rainfall, all of which affect the probability and trajectory of long range ash transport (Davies et al., 2010).

A total of 84 ash clouds have been either observed over northern Europe and/or identified as cryptotephra layers in the last 7000 years. The majority of the ash clouds for which a source volcano or region has been identified ($n = 46$) have an origin in the Eastern Volcanic Zone of Iceland ($n = 35$), which is also the source region for the majority of proximal Icelandic tephra deposits (Larsen et al., 1999) (Fig. 5). The Hekla volcano has been the most prolific volcano for the production of ash fallout over northern Europe during the Holocene (cryptotephra layers and observations, $n = 9$ and $n = 6$ respectively). Over half of the cryptotephra layers identified in northern Europe have not been assigned to a source volcano ($n = 38$), but contain glass shards with a major element chemistry consistent with an Icelandic origin. A minority of cryptotephra layers ($n = 6$) contain glass shards which do not have a chemical affinity toward glasses produced by Icelandic volcanoes and have been linked to eruptions of volcanoes in: Jan Mayen (71.0°N, 8.5°W, $n = 4$) (Chambers et al., 2004), Alaska (61.4°N, 141.7°W, $n = 1$) (Jensen et al., 2014) and the Azores (39.0°N, 28.0°W, $n = 1$) (Reilly and Mitchell, 2015). Although cryptotephra layers demonstrate that ash from distant eruptive centres such as Alaska can reach northern Europe, based on past records, the greatest future risk of ash clouds is posed by eruptions of Icelandic volcanoes, in particular from eruptions of the volcanoes in the Eastern Volcanic Zone, the source region for >80% of Icelandic eruptions during the Holocene (Thordarson and Hoskuldsson, 2008).

Given the changes in the frequency of Icelandic volcanism over the last 7000 years, we focus the majority of our analysis on the last 1000 years, the period for which the most complete records of volcanic activity and ash clouds exist and for which the frequency of volcanism and ash clouds are most stationary. All but one of the ash clouds over northern Europe in the last 1000 years have a glass chemistry consistent with that of the products of Icelandic volcanoes ($n = 22$). The exception is the MOR-T2 (= PMG-5, Hall and Mauquoy, 2005) tephra identified at three sites in Ireland and originally attributed, based on glass chemistry, to an eruption on Jan Mayen (Chambers et al., 2004). However, the lack of trachytic tephras in records from Jan Mayen (Gjerløw et al., 2016) and the identification of trachytic compositions originating from the Azores (Johansson et al., 2016) suggests the latter may constitute a more likely source region.

The average repose interval for ash clouds over northern Europe (from any source region over the last 1000 years) is 44 years, or a 20% chance of ash cloud fallout in any 10 year period (Table 1). However, although stochastic estimates of reoccurrence can provide a basis for estimating future hazard posed by volcanoes and volcanic ash clouds they must be interpreted with caution. According to the exponential model applied to records of past ash clouds over northern Europe the probability of two ash clouds over northern Europe in a 10 year period is <1%. However, the eruption of Eyjafjallajökull in 2010, was followed the next year, by the

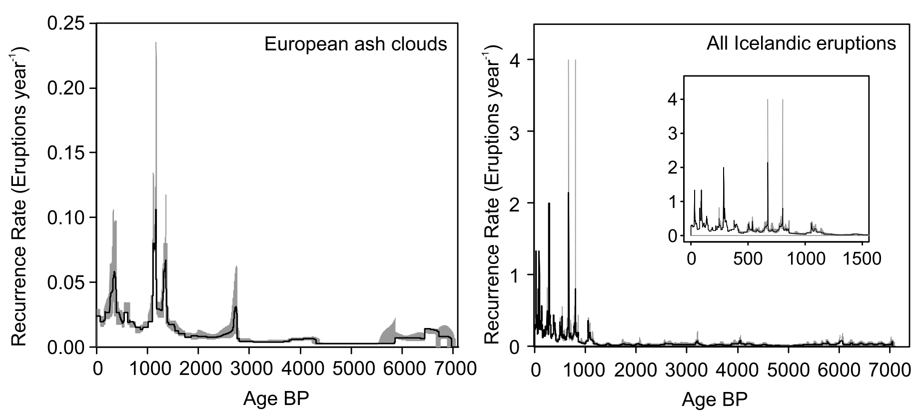

Fig. 4. The Recurrence Rate of ash clouds over northern Europe and all Icelandic eruptions for the last 7000 years. Inset: data for last 1500 years. Black line indicates the median recurrence rate calculated using a moving average recurrence rate window size 4 ($n = 2$). Grey shading indicates 90% confidence interval, based on Monte Carlo simulation of the known ages and uncertainties in tephra layers.

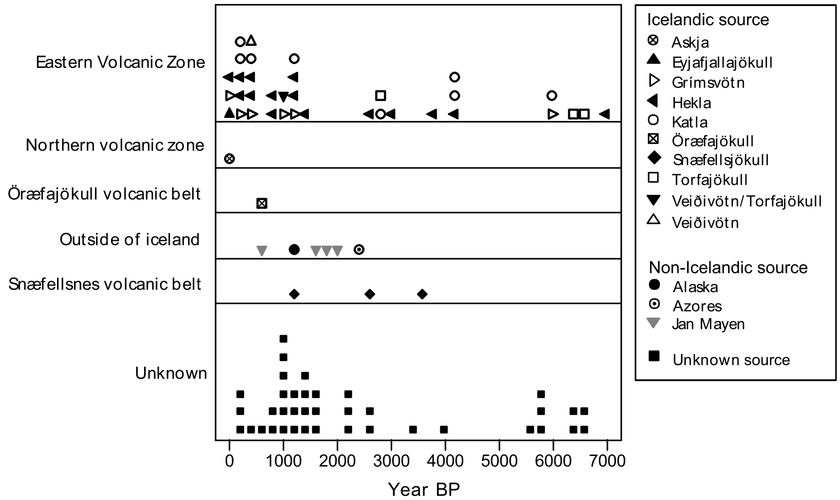

Fig. 5. Diagram illustrating the frequency, source region and source volcano of cryptotephra layers identified in northern Europe over the last 7000 years based on the database of Swindles et al. (2011) which has been updated to include tephras mentioned in Supplementary File 1. The majority of ash clouds are from volcanoes in the Eastern Volcanic zone of Iceland. A small number of tephra layers have been linked to source regions in Jan Mayen (Chambers et al., 2004), Alaska (Jensen et al., 2014) and tentatively to volcanoes in the Azores (Reilly and Mitchell, 2015).

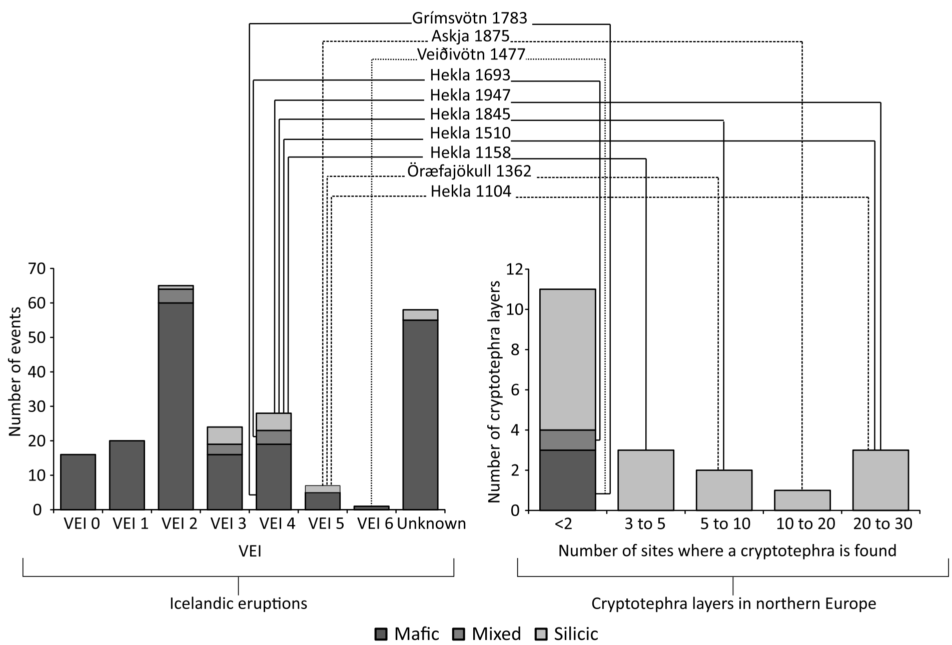

Fig. 6. Diagram showing data on Icelandic eruptions and European ash (cryptotephra layers) for the last 1000 years (Global Volcanism Program, 2013) and the European cryptotephra database of Swindles et al. (2011) updated as of March 2016. All eruptions and cryptotephra layers are grouped by geochemistry. Icelandic eruption data is grouped by VEI. European cryptotephra records are grouped by the number of sites at which they are found. Cryptotephras which have been linked to a source eruption have been indicated and the connections based on geochemistry, VEI and number of sites where a tephra is identified are highlighted. Pattern of connecting lines reflects VEI of the eruption. Note *Y* axes are different scales.

eruption of Grímsvötn. Both eruptions produced ash clouds over northern Europe, highlighting the fact that statistical models of recurrence based on past records must be interpreted with caution.

The magnitude of volcanic eruptions is commonly described according to a rating on the Volcanic Explosivity Index (VEI), a logarithmic scale with a higher rating indicating a more explosive eruption (Newhall and Self, 1982). The VEI of ancient eruptions is subject to a level of uncertainty as tephra records may be eroded over time. It is therefore possible that the VEI of some ancient eruptions is an underestimate of their true magnitude and this must be considered when estimating the frequency of volcanic eruptions in different VEI categories. For this reason, the reoccurrence of a given magnitude of eruption must always be considered a minimum estimate. As it is evident that not every Icelandic eruption produces ash cloud fallout over northern Europe, we aim to identify the minimum VEI of an eruption which has resulted in an ash cloud over northern Europe in the last 1000 years. Ten ash cloud fallout events with known Icelandic source eruptions were either observed and/or identified in the geological record. All of these ash fallout events have been from eruptions with a VEI $\geq$ 4 (Fig. 6). This corresponds to a Plinian eruption, with a plume height $\geq$ 10 km and a volume of ejected tephra $\geq$0.1 km^3 (Newhall and Self, 1982). The average repose interval for Icelandic eruptions with a VEI $\geq$ 4 is 26 $\pm$ 3 years (standard error of the mean, range of repose intervals = 0–63 years) (Table 1).

There have been a total of 36 eruptions with a VEI $\geq$ 4 recorded in Iceland during the last 1000 years, of which 26 have not produced cryptotephra layers which have been identified in the distal geological record and 21 (∼42%) have been neither observed nor identified in the distal geological record. The majority ($n = 18$) of the VEI $\geq$ 4 eruptions which have not been identified in northern European records have been eruptions of mafic magma. Despite the dominance of mafic volcanism on Iceland, the majority of far-travelled cryptotephras are silicic. The dominance of silicic tephras in northern Europe has been well documented and possible reasons for the relative lack of mafic cryptotephra layers in northern Europe are debated (Davies et al., 2010; Lawson et al., 2012; Wastegård and Davies, 2009). Our analysis suggests that even explosive (VEI $\geq$ 4) mafic eruptions that are favourable to having developed high plume heights do not produce ash fallout over northern Europe. In line with this hypothesis, there is no relationship between the eruption VEI and the total number of sites at which a cryptotephra is found in northern Europe ($p = 0.965$). Ash fallout from the largest eruption (VEI 6) in the last 1000 years, Veiðivötn 1477 has been identified at only two sites in northern Europe (Chambers et al., 2004; Davies et al., 2007). Conversely, cryptotephra from the less explosive Hekla 1104 eruption (VEI = 5) has been recorded at 27 sites. The mafic composition of the Veiðivötn 1477 eruption might explain its identification at only two sites when compared to tephras of less explosive eruptions of silicic compositions. Tephra shards of mafic composition are generally less vesicular and more dense than tephra shards of silicic composition, therefore basaltic tephra shards may be transported over shorter distances (aeolian fractionation). Furthermore, magma composition controls magma viscosity which is an important control on the total grainsize distribution of an eruption, with silicic eruptions producing a higher volume of smaller shards with the potential to be transported over long distances (Costa et al., 2016). However, differences in distribution by wind, the degradation of basaltic tephra shards in acidic (peatland) environments (cf. Pollard et al., 2003; Watson et al., 2016) and spatial sampling bias cannot be discounted as reasons for the small number of distal basaltic tephra records identified.

Given an Icelandic eruption VEI $\geq$ 4 of silicic composition there is a 73% chance that ash will be deposited over part of northern Europe. However, in the last 1000 years three Icelandic eruptions of silicic composition have not been identified as cryptotephra layers in northern Europe, the eruptions of Hekla in 1766, 1597 and 1300. There are many possible reasons for the apparent absence of these events in the European geological record. Lacasse (2001) identified wind direction as a significant control of tephra trajectories in the North Atlantic. Above 15 km, wind direction varies seasonally, with strong westerlies dominating in the winter and weaker easterlies dominant in the summer months. Larsen et al. (1999) present maps of the main axis of distribution of tephra from historical age silicic eruptions, based on isopach mapping of tephra layers on Iceland. During the eruptions of Hekla 1300 and 1766 the main axis of transport was away from northern Europe, toward northern Iceland. However, predicting the transport direction of distal ash based on isopach maps can be misleading due to differences in wind direction with height and with distance from the volcano. Wind shear can result in tephra from higher in the plume being transported in a different direction to tephra released lower in the plume. Tephra released higher in the plume is more likely to be transported over long distances and therefore proximal isopachs and distal cryptotephra deposition may appear contradictory. For example, although proximal Icelandic tephra records indicate that the Hekla 1104 tephra was predominantly transported toward the north, the identification of cryptotephra from the Hekla 1104 eruption in Ireland suggests that southerly transport of ash occurred. The eruption of Hekla 1104 had a relatively large erupted volume (∼2.0 km^3), perhaps increasing the chances of a small amount of tephra being transported toward northern Europe, despite a dominant northern trajectory.

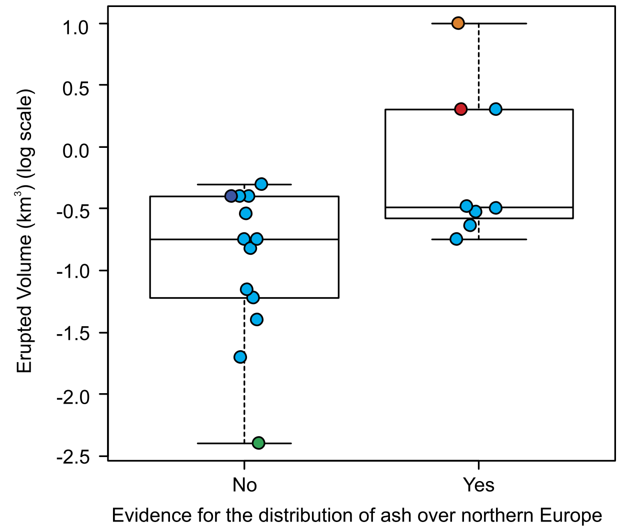

Fig. 7. Boxplots (with overlain jitter plot) showing the total erupted volumes (km^3) for the historic silicic eruptions of Icelandic volcanoes (Hekla (light blue), Askja (red), Öræfajökull (orange), Eyjafjallajökull (green) and Torfajökull (dark blue)), $n = 21$, volume data compiled by Larsen et al. (1999). Data are grouped into eruptions which resulted in evidence for the distribution of ash over northern Europe, and those for which there is no evidence of ash distribution over northern Europe. Boxplot convention is as follows: boxes indicate the interquartile range; the central line through each box indicates the median. The far extent of the upper and lower lines from each quartile indicate the maximum and minimum. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

There is a significant difference in the erupted volumes of historical silicic eruptions of Icelandic volcanoes (Larsen et al., 1999) which have, and have not reached sites in northern Europe (Mann Whitney test, $p = 0.039$). The median erupted volume for eruptions which have and have not been identified in northern Europe are 0.33 km^3 and 0.18 km^3 respectively (Fig. 7). However, some eruptions with lower tephra volumes, but favourable wind conditions have been identified in northern Europe. For example, cryptotephra from the eruption of Hekla in 1947 which had relatively small erupted volume (0.18 km^3), but a dominant transport direction toward the south, has been identified at 22 sites in northern Europe, albeit in a constrained spatial region (Dugmore et al., 1996; Lawson et al., 2012).

Indeed, where available, Icelandic isopach maps of the majority of tephra layers identified in northern European records over the last 1000 years suggest a dominant wind direction toward the south or east rather than the north or west ($n = 5$ and 3 respectively). We suggest that a northerly wind direction, combined with a low erupted volume <1 km^3 (Hekla 1300 = 0.50 km^3, Hekla 1766 = 0.40 km^3: Larsen et al., 1999) may explain the apparent absence of cryptotephra from the silicic eruptions of Hekla in 1300 and 1766 in northern Europe.

However, neither wind direction nor eruptive volume can easily explain the lack of the Hekla 1597 tephra in northern European records as isopach maps suggest the dominant axis of distribution was south–east, toward northern Europe, and the erupted volume (0.3 km^3) exceeded that of the Hekla 1947 eruption, which has been identified in Europe. Despite the (geologically) short interval between the eruptions of Hekla 1510 and 1597 eruption, which resulted in the deposition of tephra at multiple sites in Ireland, it is unlikely that the Hekla 1597 tephra has been miscorrelated to the eruption of Hekla 1510, as the geochemistry of Hekla 1597 is distinct (Dugmore and Newton, 2012). Therefore, it remains unclear why the Hekla 1597 tephra has not been identified in any continental European sites.

According to available data, the average repose interval of a VEI ≥ 4 Icelandic eruption with a silicic composition is 91 years. Given that the newly estimated average return interval for ash clouds in northern Europe is 44 years, it stands to reason that silicic eruptions VEI ≥ 4 have not been the only source of ash clouds over northern Europe. However, from geological and observational records it would appear that the biggest risk of widespread ash clouds over northern Europe is posed by eruptions with a VEI ≥ 4 and a silicic magma composition.

Alongside the distal European tephra layers which have been assigned to a specific Icelandic eruption there are nine cryptotephra layers which contain glass shards with a geochemistry consistent with an Icelandic origin but which could not be traced to an eruptive source and VEI rating (Supplementary File 5). All of these unassigned tephra layers have been identified at fewer than four sites; five have been identified at only one site. By comparison, the majority (seven out of ten) of the tephras which have been assigned to an eruption have been identified at four or more sites. Furthermore, many of the unassigned tephra layers have been identified only in one region; for example the Loch Portain B tephra has not been identified outside of Scotland and the Outer Hebrides (Dugmore et al., 1995), and the MOR-T4 tephra, although identified at four sites, appears to have a fallout region confined to Ireland and Wales (Chambers et al., 2004; Watson et al., 2016). Although issues of reworking cannot be ruled out, the limited spatial distribution of many of these unassigned tephra layers, and the lack of assignment to a major eruptive event, might suggest they were deposited during smaller eruptions producing distal ash over a smaller area during short explosive phases. The proximal geochemistry for smaller magnitude, less explosive eruptions may not have been so well characterised, making correlations between European and Icelandic tephra layers more difficult. The geochemistry of eruptives from some rhyolite Icelandic volcanoes, such as Torfajøkull and Snaefellsnes, has not been well characterised and therefore there is lack of proximal Icelandic data for comparison with the geochemistry of European cryptotephra layers (Haflidason et al., 2000). Cryptotephra layers in northern Europe may even represent a record of Icelandic volcanism which has been eroded from the Icelandic record by subsequent eruptions. It is possible that some eruptions with a VEI $= 3$ did produce ash over Europe, with only limited spatial distribution. The average recurrence rate of VEI ≥ 3 eruptions of silicic composition is 50 years, which equates to a chance of 8% of an eruption of this type in a 10 year period (Table 1).

5. Conclusions

Microscopic cryptotephra layers in sediment records from around the world provide evidence that explosive volcanic eruptions have produced ash fallout over many regions, some thousands of kilometres from active volcanoes. Evidence of ash fallout in the past, can help us to consider future risks. In this paper we focus on northern Europe, which has one of the most well studied regional cryptotephra stratigraphies in the world, spanning the last 7000 years. Nevertheless, there are still spatial gaps in existing northern European cryptotephra records. The discovery of Icelandic cryptotephras in regions previously not examined for cryptotephra records, by this study and other recent work (Wulf et al., 2016) suggests that the spatial gaps in northern European cryptotephra distributions are an artefact of research intensity and do not necessarily represent the margins of ash clouds over northern Europe. However, in some instances sparse numbers of shards may indicate that glass shards from some eruptions are approaching the margins of their detectable range. Although effort was made in this study to address some of the largest spatial gaps in existing cryptotephra records, more gaps do exist, and future research in this regions may identify additional cryptotephra layers, possibly from eruptions previously not identified in northern Europe.

A comparison of Icelandic and European tephra records over the last 1000 years reveals that all ash clouds (identifiable to a source eruption) in the northern European geological record have been produced by highly explosive Plinian eruptions with a VEI $\geq$ 4. According to the geological record, Icelandic eruptions with a VEI ≥ 4 and a silicic magma composition present the most risk of producing an ash cloud over northern Europe. A number of cryptotephra layers in the geological record do not have a known source, and are found in fewer distal sites. These cryptotephra layers might represent ash clouds which were produced by eruptions with a lower VEI. These cryptotephra layers have a major element glass geochemical composition consistent with a source eruption in Iceland, but have not been traced to a specific vent site/volcanic centre. Future research should concentrate on trying to identify a source volcano for these tephra layers. This might involve work on proximal deposits in Iceland, to characterise the geochemistry of tephra derived from eruptions of a smaller magnitude or lesser studied volcanic regions. Cryptotephra layers in northern Europe may even represent a record of Icelandic volcanism which has been eroded from the Icelandic record by subsequent eruptions. The average return interval of a volcanic ash cloud over northern Europe based on the new database is 44 ± 7 years, suggesting that ash clouds are more common over northern Europe than previously proposed (56 ± 9 years; Swindles et al., 2011). Applying an exponential model, our new database suggests a 20% chance of an ash cloud over northern Europe in any 10 year period. Our model represents a minimum estimate for the recurrence rate of ash clouds over northern Europe, but increased spatial coverage of sites within Europe means the new estimate is less likely to be confounded by sampling bias than previous modelling efforts. This study, which included the development of a new cryptotephra database for northern Europe highlights the utility of cryptotephra records in understanding the frequency of volcanic ash fallout. Comparisons between proximal and distal tephra records, such as that conducted in this study hold promise for informing our understanding risk of volcanic ash fallout in other regions of the world.

Acknowledgements

This research was undertaken while Elizabeth Watson held a NERC-funded Doctoral Training Grant (NE/K500847/1). Support for development of the Monte Carlo recurrence rate model was provided by NSF award ACI 1339768 to C.B. Connor. We acknowledge Dylan Young for his assistance in running code in Linux. The authors would like to acknowledge three anonymous reviewers for helpful comments on a previous version of this manuscript.

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2016.11.054.

References

Akaike, H., 1998. Information theory and an extension of the maximum likelihood principle. In: Selected Papers of Hirotugu Akaike. Springer, pp. 199–213.

Bebbington, M.S., Cronin, S.J., 2011. Spatio-temporal hazard estimation in the Auckland Volcanic Field, New Zealand, with a new event-order model. Bull. Volcanol. 73.

Bevilacqua, A., Isaia, R., Neri, A., Vitale, S., Aspinall, W.P., Bisson, M., Flandoli, F., Baxter, P.J., Bertagnini, A., Esposti Ongaro, T., Iannuzzi, E., Pistolesi, M., Rosi, M., 2015. Quantifying volcanic hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: 1. Vent opening maps. J. Geophys. Res., Solid Earth 120, 2309–2329.

Blockley, S.P.E., Pyne-O'Donnell, S.D.F., Lowe, J.J., Matthews, I.P., Stone, A., Pollard, A.M., Turney, C.S.M., Molyneux, E.G., 2005. A new and less destructive laboratory procedure for the physical separation of distal glass tephra shards from sediments. Quat. Sci. Rev. 24, 1952–1960.

Chambers, F.M., Daniell, J.R.G., Hunt, J.B., Molloy, K., O'Connell, M., 2004. Tephrostratigraphy of An Loch Mor, Inis Oirr, western Ireland: implications for Holocene tephrochronology in the northeastern Atlantic region. Holocene 14, 703–720.

Connor, C., Bebbington, M., Marzocchi, W., 2015. Chapter 51 – Probabilistic volcanic hazard assessment. In: Sigurdsson, H. (Ed.), The Encyclopedia of Volcanoes, second edition. Academic Press, Amsterdam, pp. 897–910.

Connor, C.B., McBirney, A.R., Furlan, C., 2006. What is the probability of explosive eruption at a long-dormant volcano? In: Mader, H.M., Coles, S.G., Connor, C.B., Connor, L.J. (Eds.), Statistics in Volcanology. The Geological Society, London, pp. 39–46.

Connor, C.B., Sparks, R., Mason, R., Bonadonna, C., Young, S., 2003. Exploring links between physical and probabilistic models of volcanic eruptions: the Soufriere Hills Volcano, Montserrat. Geophys. Res. Lett. 30, 1701.

Costa, A., Pioli, L., Bonadonna, C., 2016. Assessing tephra total grain-size distribution: insights from field data analysis. Earth Planet. Sci. Lett. 443, 90–107. http://dx.doi.org/10.1016/j.epsl.2016.02.040.

Cox, D.R., Oakes, D., 1984. Analysis of Survival Data: Monographs on Statistics and Applied Probability. Chapman and Hall, London.

Davies, S.M., Elmquist, M., Bergman, J., Wohlfarth, B., Hammarlund, D., 2007. Cryptotephra sedimentation processes within two lacustrine sequences from west central Sweden. Holocene 17, 319–330.

Davies, S.M., Larsen, G., Wastegård, S., Turney, C.S.M., Hall, V.A., Coyle, L., Thordarson, T., 2010. Widespread dispersal of Icelandic tephra: how does the Eyjafjöll eruption of 2010 compare to past Icelandic events? J. Quat. Sci. 25, 605–611.

De Vleeschouwer, F., Chambers, F.M., Swindles, G.T., 2011. Coring and sub-sampling of peatlands for palaeoenvironmental research. Mires Peat 7, 1–10.

Dugmore, A.J., Larsen, G., Newton, A.J., 1995. Seven tephra isochrones in Scotland. Holocene 5, 257–266.

Dugmore, A.J., Newton, A.J., 1992. Thin tephra layers in peat revealed by X-radiography. J. Archaeol. Sci. 19, 163–170.

Dugmore, A.J., Newton, A.J., 2012. Isochrons and beyond: maximising the use of tephrochronology in geomorphology. Jökull 62, 39–52.

Dugmore, A.J., Newton, A.J., Edwards, K.J., Larsen, G., Blackford, J.J., Cook, G.T., 1996. Long-distance marker horizons from small-scale eruptions: British tephra deposits from the AD 1510 eruption of Hekla, Iceland. J. Quat. Sci. 11, 511–516.

Dzierma, Y., Wehrmann, H., 2012. On the likelihood of future eruptions in the Chilean Southern Volcanic Zone: interpreting the past century's eruption record based on statistical analyses. Andean Geol. 39, 380–393.

Eurostat, 2006. GISCO Airports 2006. http://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/transport-networks.

Folch, A., Costa, A., Basart, S., 2012. Validation of the FALL3D ash dispersion model using observations of the 2010 Eyjafjallajökull volcanic ash clouds. Atmos. Environ. 48, 165–183.

Folch, A., Mingari, L., Osores, M.S., Collini, E., 2014. Modeling volcanic ash resuspension – application to the 14–18 October 2011 outbreak episode in central Patagonia, Argentina. Nat. Hazards Earth Syst. Sci. 14, 119–133. http://dx.doi.org/10.5194/nhess-14-119-2014.

Global Volcanism Program, 2013. Volcanoes of the world, v. 4.3.4., in: Venzke, E. (Ed.), Smithsonian Institution.

Haflidason, H., Eiriksson, J., Van Kreveld, S., 2000. The tephrochronology of Iceland and the North Atlantic region during the Middle and Late Quaternary: a review. J. Quat. Sci. 15, 3–22.

Hall, M., Hayward, C., 2014. Preparation of micro- and crypto-tephras for quantitative microbeam analysis. In: Special Publications Geological Society of London, vol. 398, pp. 21–28.

Hall, V.A., Mauquoy, D., 2005. Tephra-dated climate- and human-impact studies during the last 1500 years from a raised bog in central Ireland. Holocene 15, 1086–1093.

Hall, V.A., Pilcher, J.R., 2002. Late-Quaternary Icelandic tephras in Ireland and Great Britain: detection, characterization and usefulness. Holocene 12, 223–230.

Hayward, C., 2012. High spatial resolution electron probe microanalysis of tephras and melt inclusions without beam-induced chemical modification. Holocene 22, 119–125.

Jensen, B.J.L., Pyne-O'Donnell, S., Plunkett, G., Froese, D.G., Hughes, P.D.M., Sigl, M., McConnell, J.R., Amesbury, M.J., Blackwell, P.G., van den Bogaard, C., Buck, C.E., Charman, D.J., Clague, J.J., Hall, V.A., Koch, J., Mackay, H., Mallon, G., McColl, L., Pilcher, J.R., 2014. Transatlantic distribution of the Alaskan White River Ash. Geology 42, 875–878.

Jochum, K.P., Willbold, M., Raczek, I., Stoll, B., Herwig, K., 2005. Chemical characterisation of the USGS reference glasses GSA-1G, GSC-1G, GSD-1G, GSE-1G, BCR-2G, BHVO-2G and BIR-1G using EPMA, ID-TIMS, ID-ICP-MS and LA-ICP-MS. Geostand. Geoanal. Res. 29, 285–302.

Johansson, H., Lind, E.M. Wastegård, S., 2016, Compositions of glass in proximal tephras from eruptions in the Azores archipelago and their links with distal sites in Ireland. Quat. Geochronol. http://dx.doi.org/10.1016/j.quageo.2016.07.006, in press.

Jull, M., McKenzie, D., 1996. The effect of deglaciation on mantle melting beneath Iceland. J. Geophys. Res., Solid Earth 101, 21815–21828.

Kiyosugi, Koji, 2012. Temporal and Spatial Analysis of Monogenetic Volcanic Fields, unpublished Ph.D. dissertation. University of South Florida.

Lacasse, C., 2001. Influence of climate variability on the atmospheric transport of Icelandic tephra in the subpolar North Atlantic. Glob. Planet. Change. http://dx.doi.org/10.1016/S0921-8181(01)00099-6.

Larsen, G., Dugmore, A., Newton, A., 1999. Geochemistry of historical-age silicic tephras in Iceland. Holocene 9, 463–471.

Larsen, G., Gudmundsson, M.T., Björnsson, H., 1998. Eight centuries of periodic volcanism at the center of the Iceland hotspot revealed by glacier tephrostratigraphy. Geology 26, 943–946.

Lawson, I.T., Swindles, G.T., Plunkett, G., Greenberg, D., 2012. The spatial distribution of Holocene cryptotephras in north–west Europe since 7 ka: implications for understanding ash fall events from Icelandic eruptions. Quat. Sci. Rev. 41, 57–66.

Lowe, D.J., 2011. Tephrochronology and its application: a review. Quat. Geochronol. 6, 107–153.

Mason, B.G., Pyle, D.M., Oppenheimer, C., 2004. The size and frequency of the largest explosive eruptions on Earth. Bull. Volcanol. 66, 735–748.

Mohn, H., 1878. Askeregnen den 29de-30–teMarts 1875. Forh. I Videnskapsselskabet I Christiania aar 1877 (10), 89–92.

Newhall, C.G., Self, S., 1982. The volcanic explosivity index (VEI) an estimate of explosive magnitude for historical volcanism. J. Geophys. Res. 87, 1231–1238.

Newton, A.J., Dugmore, A.J., Gittings, B.M., 2007. Tephrabase: tephrochronology and the development of a centralised European database. J. Quat. Sci. 22, 737–743.

Pilcher, J., Bradley, R.S., Francus, P., Anderson, L., 2005. A Holocene tephra record from the Lofoten Islands, Arctic Norway. Boreas 34, 136–156.

Pollard, A.M., Blockley, S.P.E., Ward, K.R., 2003. Chemical alteration of tephra in the depositional 51 environment: theoretical stability modelling. J. Quat. Sci. 18, 385–394.

Ponomareva, V., Portnyagin, M., Davies, S.M., 2015. Tephra without borders: far-reaching clues into past explosive eruptions. Front. Earth Sci. 3, 83.

Pyle, D.M., Ricketts, G.D., Margari, V., Van Andel, T.H., Sinitsyn, A.A., Praslov, N.D., Lisitsyn, S., 2006. Wide dispersal and deposition of distal tephra during the Pleistocene 'Campanian Ignimbrite/Y5' eruption, Italy. Quat. Sci. Rev. 25, 2713–2728.

Reilly, E., Mitchell, F.J., 2015. Establishing chronologies for woodland small hollow and mor humus deposits using tephrochronology and radiocarbon dating. Holocene 25, 241–252.

Schmidt, P., Lund, B., Hieronymus, C., Maclennan, J., Árnadóttir, T., Pagli, C., 2013. Effects of present-day deglaciation in Iceland on mantle melt production rates. J. Geophys. Res., Solid Earth 118, 3366–3379.

Smith, V.C., Isaia, R., Engwell, S.L., Albert, P.G., 2016. Tephra dispersal during the Campanian Ignimbrite (Italy) eruption: implications for ultra-distal ash transport during the large caldera-forming eruption. Bull. Volcanol. 78, 45.

Stevenson, J.A., Loughlin, S., Font, A., Fuller, G.W., MacLeod, A., Oliver, L.W., Jackson, B., Horwell, C.J., Thordarson, T., Dawson, I., 2013. UK monitoring and deposition of tephra from the May 2011 eruption of Grímsvötn, Iceland. J. Appl. Volcanol. 2.

Swindles, G.T., Lawson, I.T., Savov, I.P., Connor, C.B., Plunkett, G., 2011. A 7000 yr perspective on volcanic ash clouds affecting northern Europe. Geology 39, 887–890.

Swindles, G.T., Savov, I.P., Connor, C.B., Carrivick, J., Watson, E.J., Lawson, I.T., 2013. Volcanic ash clouds affecting Northern Europe: the long view. Geol. Today 29, 215–217.

Thorarinsson, S., 1954. The tephra-fall from Hekla on March 29th 1947. In: Einarsson, T., Kjartansson, G.S.T. (Eds.), The Eruption of Hekla 1947–48. Societas Scientarum Islandica, Reykjavik, pp. 1–68.

Thordarson, T., Hoskuldsson, A., 2008. Postglacial volcanism in Iceland. Jokull 58, 197–228.

Wastegård, S., Davies, S.M., 2009. An overview of distal tephrochronology in northern Europe during the last 1000 years. J. Quat. Sci. 24, 500–512.

Watson, E.J., Swindles, G.T., Lawson, I.T., Savov, I.P., 2016. Do peatlands or lakes provide the most comprehensive distal tephra records? Quat. Sci. Rev. 139, 110–128.

Wilson, J.A., 2016. A New Volcanic Event Recurrence Rate Model and Code for Estimating Uncertainty in Recurrence Rate and Volume Flux Through Time with Selected Examples. Unpublished M.S. Thesis. University of South Florida. http://scholarcommons.usf.edu/etd/6435.

Wulf, S., Dräger, N., Ott, F., Serb, J., Appelt, O., Guðmundsdóttir, E., van den Bogaard, C., Słowiński, M., Błaszkiewicz, M., Brauer, A., 2016. Holocene tephrostratigraphy of varved sediment records from Lakes Tiefer See (NE Germany) and Czechowskie (N Poland). Quat. Sci. Rev. 132, 1–14.