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Estimating the frequency of volcanic ash clouds over northern Europe

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A B S T R A C T

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) $\geq$ 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).

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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