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The spatial distribution of Holocene cryptotephras in north-west Europe since 7 ka: implications for understanding ash fall events from Icelandic eruptions

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ABSTRACT

We present distribution maps for all cryptotephras (distal volcanic ash layers) younger than 7 ka that have been reported from three or more lakes or peatlands in north-west Europe. All but one of the tephras originates from Iceland; the exception has been attributed to Jan Mayen. We find strong spatial patterning in tephra occurrence at the landscape scale; most, but not all of the tephra occurrences are significantly spatially clustered, which likely reflects atmospheric and weather patterns at the time of the eruptions. Contrary to expectations based on atmospheric modelling studies, tephras appear to be at least as abundant in Ireland and northern Scotland as in Scandinavia. Rhyolitic and other felsic tephras occur in lakes and peatlands throughout the study region, but andesitic and basaltic tephras are largely restricted to lake sites in the Faroe Islands and Ireland. Explanations of some of these patterns will require further research on the effects of different methodologies for locating and characterizing cryptotephras. These new maps will help to guide future investigations in tephrochronology and volcanic hazard analysis.

1. Introduction

The use of Icelandic tephras as a dating tool for lake sediments and peats in north-west Europe has become well established over the last two decades, following the pioneering work of Dugmore and colleagues (Dugmore, 1989; Dugmore and Newton, 1992; Dugmore et al., 1992, 1995) and Hall et al. (1993) among others (see Swindles et al., 2010 and Lowe, 2011 for recent reviews of the method). The eruption of the Icelandic volcanoes Eyjafjallajökull in 2010 and Grimsvötn in 2011, which led to high concentrations of ash in the airspace over the eastern North Atlantic and much of Europe for several days on each occasion and which substantially disrupted air transport and the global economy (Birtchnell and Büscher, 2010), have prompted a re-evaluation of the scientific value of geological records of past eruptions (Davies et al., 2010).

Swindles et al. (2011) compiled all existing published and some unpublished reports of tephra in lake sediments and peats from north-west Europe to examine the temporal distribution of ash fall events during the mid- to late Holocene. They showed that, in any given decade within the last millennium, the probability of an ash fall event large enough to leave a detectable deposit was approximately 0.16. The analysis was limited to the last 7000 calendar years because (i) there have been relatively few finds of older Holocene tephras in European lakes and peatlands, and (ii) there is evidence that Icelandic volcanoes were atypically active in the early Holocene, due to unloading of the mantle as the Icelandic ice cap retreated (Jull and McKenzie, 1996; Pagli and Sigmundsson, 2008). Our analysis also excluded the very limited number of marine records as they are taphonomically very distinct from terrestrial records.

The present article extends the analysis of the same dataset to explore the spatial patterning of ash fall events across north-west Europe. We present new maps for all 22 tephras that occur at three or more sites and discuss the distribution patterns that they show, adopting a robust methodology for interpreting absence of evidence. We discuss how these patterns can inform our understanding of the atmospheric transport of volcanic ash. We also critically review the quality of the present dataset and make recommendations for future analyses of distal tephras.

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2. Methods

All available published and unpublished records of tephra occurrences in peat and lake sediments younger than 7 ka throughout north-west Europe (specifically, in the Faroe Islands, the British Isles, Scandinavia, Germany, and Estonia) were catalogued (Swindles et al., 2011). In the resulting database, the identification of the tephra made by the original authors of the source publications was accepted. Some additional unpublished data (by G. T. Swindles) were included in the database. In a few instances we inferred that one or more tephras called by different names by different authors in fact represented the same ash fall events. For example, "OMH-185 Population 2" (Hall and Pilcher, 2002; Plunkett et al., 2004), "BGMT-3" (Langdon and Barber, 2001, 2004), and "DOM-6" (van den Bogaard and Schminke, 2002; van den Bogaard et al., 2002) are all likely on stratigraphic, geochemical, and petrological grounds to represent the same tephra, known more widely as the "Microlite tephra". A full list of tephras identified and their equivalences is given in the supplementary information to Swindles et al. (2011).[1] All but one of the tephra layers recorded is believed to originate from Iceland; the exception, PMG-5/MOR-T2, has been attributed to Jan Mayen (Chambers et al., 2004).

In total, 22 tephras were found to occur at three or more locations. These occurrence events were mapped in ArcGIS 9.3.1 (Fig. 1). The database contains a further 84 tephras which were only found at one or two sites.

As well as mapping positive identifications of tephras, we were concerned to identify cases where there was strong evidence for genuine absence of a tephra – that is, where there was evidence that it would have been possible to find it, had it been present, given the stratigraphic length of the sequence and the degree of investigator effort. Both of these factors are often difficult to determine on the basis of published reports. We took the presence of tephras both younger and older than a given missing tephra as an indication that, if the missing tephra had been present at the site, it would likely have been found (age estimates for all of the tephras reported here are given in Table 1). We labelled these missing tephras as "absent". The presence of bracketing tephras was taken as a strong indication both that the sequence encompassed the period when the tephra in question was produced, and that efforts had been made to locate tephras in this part of the sequence. Additional checks were made and sites were removed from the list if, for example, a hiatus had been identified by the original authors. We took the conservative approach of assuming that our youngest mapped tephra, Hekla 1947, would not have been detected anywhere, owing to the various difficulties of sampling uppermost lake sediments and the unspoken tendency of many workers to neglect the topmost part of lake sediment or peat sequences. In the case of our oldest mapped tephra, Lairg A (also known as Hekla 5), we looked for evidence of older tephras (not included in our database) in the original publications. We acknowledge that some tephras marked as "absent" may actually have been present in the sequences but were not reported, perhaps because the original investigators did not search for tephras systematically or thoroughly throughout their sequences, or because small concentrations of tephra shards were deliberately ignored.

The number of tephra layers found at each site was mapped (Fig. 2a); the count only includes those tephras found at three or more sites, to avoid the possibility of including layers of reworked ash. The numbers of tephras of each of three geochemical types was also plotted (Fig. 2b–d). In these figures, the circles are proportional in area to the number of tephras found.

The total number of tephra layers identified in each of five regions (following Swindles et al., 2011) was summarized using box-plots (Fig. 3). Two sites in Estonia were included in the "Scandinavia" region for reasons of brevity.

The observed spatial patterns were further subjected to spatial point pattern analysis, with an empirical approach comparable to the neighbourhood density function of Condit et al. (2000) and Perry et al. (2006). The neighbourhood density function is a non-cumulative variant of Ripley's K (Ripley, 1976) that is simpler to interpret in this context. For each tephra in turn, each sampling site was marked as to whether the tephra was "present" or "absent" (as defined above), and the great-circle distance between each pair of sites where the tephra was present was calculated. These distances were binned into 100 km intervals and their frequency distribution was plotted as the solid black line in Fig. 4. The great-circle distance between each point where the tephra was "present" and each point where the tephra was "absent" was also calculated. This frequency distribution was found as before and the sum of the two frequency distributions was plotted as the dashed black line in Fig. 4. A randomisation test was conducted, with Monte Carlo simulations undertaken by iteratively randomly re-assigning the marks on the sampling sites (in the original proportion) and the frequency distribution of pairs of points marked as "present" being re-computed. For each Monte Carlo simulation, i.e., for each randomisation test, 9999 iterations were conducted. The grey envelope in Fig. 4 shows the 0.025 and 0.975 quantiles of the resulting frequencies in each bin. The test for significant departure from the null hypothesis of random assignment of marks was carried out by calculating, for each simulation, the sum of squares of deviations from the median simulated frequencies (cf. Diggle, 1983; Perry et al., 2006). The probability of achieving a sum of squares greater than the actual sum of squares is reported in Table 1 for tephras where there were a reasonably large number (five) of marks of both types. Statistical analysis was undertaken using R 2.11.1.

3. Results

The tephra distribution maps are shown in Fig. 1. The maps show strong spatial patterning in most cases. Only three tephras appear to have occurred widely across all regions: these are AD 860 B, Hekla 4 and Lairg A. Three tephras show a markedly Scandinavian distribution, with occasional occurrences in Germany, the Faroes and Shetland. Askja 1875 is perhaps the archetype of these northern ash falls, its distribution matching closely that of the ash fall recorded at the time (Thorarinsson, 1981; Carey et al., 2010). The only identification of this tephra in Germany is based on just two geochemical analyses (van den Bogaard and Schminke, 2002) and is doubtful. The Askja 1875 tephra distribution pattern presumably represents an eruption taking place during a period of strongly zonal airflow (cf. Leadbetter and Holt, 2010). Older tephras showing a similar distribution include Hekla 3 and Hekla-Selsund. One tephra, Mjáuvøtn A, has only been reported from the Faroe Islands; the Landnám and Tjørnuvík tephras are found only in the Faroe and Lofoten Islands (and, too recently to have been included in the dataset of Swindles et al., 2011, in north-west Scotland: Cage et al., 2011). By far the majority of the tephras (ten) are restricted to the northern and western British Isles, particularly to Ireland. There are three tephras (Glen Garry, Microlite, Lairg B) which do not fall into any of these groups; the most striking of these distribution patterns is that of the Glen Garry tephra, found very commonly at sites in Great Britain and Germany, but not in Ireland, the Faroes or Scandinavia.

On a finer spatial scale the distribution pattern of individual tephras can vary substantially. For example, although Hekla 1510 is

[1] Available at http://www.geosociety.org/pubs/ft2011.htm.