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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.

Keywords: Iceland, Jan Mayen, tephra, peat, lake sediment, volcanic ash, Eyjafjallajökull, tephrochronology, 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 (2011) compiled all existing published and some unpublished reports of tephra in lake sediments and peats from north-west Europe to examine the temporal distribution of ash fall events during the mid- to late Holocene.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, 2009). 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.

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 (Figure 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 (Figure 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 (Figures 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 (Figure 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. (2002) 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 Figure 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 Figure 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 Figure 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 Figure 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 Hort, 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 found at several sites (all in Ireland), there are several sites within the current mapped limits of its distributions from which it is apparently absent. Hekla 3 has a much wider distribution, occurring at sites across north-west Europe, from Ireland to Sweden and Germany, yet it is also absent from many sites within that range. Conversely, some ash layers, such as the Glen Garry tephra, have been found at every suitable site within the mapped limits of their distributions.

Figure 2a shows the spatial distribution of the number of tephras deposited within the last 7000 calendar years at each site (only including those tephras mapped here). There is strong variation in this number – the range is from one to 11 – but there is no clear spatial pattern in this variation (Figure 3). A handful of sites contain large numbers of tephra layers which are not known elsewhere (and which we have not mapped). A study at Borge in Norway (Pilcher et al. 2005), for example, found a total of 30 tephras, at least 20 of which could not be correlated to tephras elsewhere.

Figures 2b-d show the number of recorded tephras at each site, broken down by tephra chemistry. Rhyolitic tephras are the most abundant and are found everywhere. Other types of felsic tephras (mostly dacites and trachytes) are slightly less common, but are also widely distributed. More mafic (less silica-rich) tephras have a much more restricted distribution, with finds only in Ireland, the Faroe islands, and the Lofoten islands. In fact, most of the more mafic tephras known from Ireland are rather intermediate in composition. Strictly basaltic tephras are largely confined to the Faroe Islands (the Tjørnuvík, Mjáuvøtn A and one stage of the Landnám tephra, although as noted above the latter, including its basaltic phase, has recently been identified in north-west Scotland (Cage et al., 2011). Only one basaltic tephra has been found further afield: the Veiðivötn 1477 tephra has been identified at two sites (and thus is not mapped here), Getvaltjärnen in Sweden (Davies et al., 2007) and An Loch Mór in Ireland (Chambers et al., 2004).

4. Discussion

4.1 Spatial patterning of tephra occurrences

Our mapping exercise suggests that past ash plumes have shown a wide range of behaviour. They can be dense and widespread (e.g. Hekla 4); spatially patchy but widespread (e.g. Hekla 3); restricted to one region but found at practically all sites within its bounds (e.g. Glen Garry); or restricted to one region and patchily distributed within it (e.g. Hekla 1510). Figure 4 allows us to examine more closely the spatial scaling of tephra distributions. The plot for Askja 1875, for example, can be interpreted as showing that occurrences of the Askja 1875 ash are strongly more clustered at scales of < 1000 km than we would expect if the occurrences were distributed among the sites at random, as the black line (frequency of distances between sites where the tephra is present) is usually above the shaded area (the envelope of 95% of simulations of random distribution) for distances < 1000 km. Conversely, distances between sites where the tephra is present are less frequent than we would expect at scales > 1200 km. For most tephras where the frequency of distances is greater than the upper limit of the shaded area, this occurs at distances < 500 km, which reflects the fact that most of the clusters visible in Figure 1 are smaller than 500 km in extent. (Peaks in a few cases at ~1100 km are due to the large number of tephras found at German sites; this is probably a reflection of the small sample size and the large separation of the German sites from other sites, and perhaps an indication that these particular sites were investigated with exceptional thoroughness.) As a result of this local clustering, most of the tephras plotted in Figure 4 showed significant departures from a random distribution (p-values are listed in Table 1). The exceptions, for reasons discussed below, are Öræfajökull 1362, AD 860 A, Hekla 4 and Lairg B.

The results of space-, air- and ground-based monitoring and research reported following the Eyjafjallajökull 2010 event, which took place during a period of low wind speeds, provided a striking demonstration that tephra distribution can be spatially patchy (e.g. Schumann et al., 2011): mixing in the atmosphere can be a slow process and parcels of air can maintain their identity for relatively long periods, which means that the ash is not necessarily spread as a uniformly thin layer over a wide region, as suggested (not necessarily intentionally) by the smooth contour lines drawn in many previous tephra-mapping exercises (e.g. Thorarinsson, 1981; Wastegård and Davies, 2009; Carey et al., 2010; Davies et al., 2010). This can explain the distribution pattern of tightly-bounded tephras such as Glen Garry, and also tephras such as Öræfajökull 1362, AD 860 A, and Lairg B, which have large ranges but are only found at some sites within those ranges. In the few cases where uniform and wide dispersal *is* found (e.g. Hekla 4, Lairg A, Askja 1875), it may indicate that the eruption lasted for a long time, or that it consisted of several stages, leading to tephra being spread widely over several days or weeks of varying atmospheric conditions. The latter point is illustrated by the apparent absence of the dacitic phase of Hekla 4 from Ireland, which indicates a change in the atmospheric circulation or local weather patterns during the course of the eruption.

Hekla 4 is found unusually widely across the study region. It seems likely that the limits of the distribution of Hekla 4 have not yet been reached by the present dataset, except possibly in western Ireland; it may yet be found at more distal sites.

4.2 Variation in the number of tephras recorded at each site

The distribution of the number of tephras at each site (Figure 2a) and the average number of tephras per region (Figure 3) are likely to reflect in large part the degree of investigator effort: for example, the sites in Germany, all the work of one group (van den Boogard and Schminke, 2002; van den Bogaard et al., 2002), contain some of the largest numbers of tephras despite being among the most distant from the Icelandic source area. Another important factor may be the length of sequences: many English and Scottish sequences, for example, are relatively young blanket mire peats in which we would not expect to find many of the older tephras. It is also well known that small-scale depositional and post-depositional processes can cause variation in the abundance of a tephra in cores taken from the same site (Boygle, 1999; Payne et al., 2005; Pyne-O'Donnell, 2011). Even with these limitations in mind, it is surprising that there are, for example, on average more tephras at sites in Ireland (35 sites, mean number of tephras per site = 3.46) than in Scandinavia (22 sites, mean number of tephras per site = 2.32), although a two-sample Wilcoxon test suggests that the difference may not be significant ($p = 0.188$). That cryptotephras should be at least as common in Ireland as in Scandinavia is inconsistent with our present understanding of how Icelandic tephras are likely to be dispersed. In a systematic analysis of a numerical atmospheric transport model using meteorological data for the period 2003–2008, Leadbetter and Holt (2010) calculated the probability of tephra occurrences across Europe following a typical eruption of Hekla. They found that the most heavily-affected region by far would be Scandinavia. Although at least some tephra deposition was probable (typically with a probability of 0.3–0.4 during any particular event) over the British Isles, northern France, the Netherlands, Germany and Scandinavia, there was no suggestion in their study that Ireland would be more likely to see tephra deposition than other areas. This discrepancy could be important in terms of risk analysis, because ash brought southwards from Iceland is likely to be more disruptive to air travel than ash plumes restricted to north of 60°N and could, alongside SO_2 and other aerosols, pose a health risk to a larger number of people (Horwell and Baxter, 2006; Oman et al., 2006; Newnham et al., 2010). Clearly, more and better data on past tephra occurrences would help to test the robustness of this observation (as discussed below), but we would also like to see modelling studies focused more closely on ground-level deposition and on critical parameters such as grain-size distribution and mass loading which could be more closely related to the empirical data, following Lacasse (2001).

We tested for a difference in the number of tephras recorded in lakes and peatlands. The result (Wilcoxon test, $p=0.637$) suggests there is no significant difference, although the number of lakes in the database is small (13 out of 99 sites in our dataset).

4.3 Differences in distribution according to tephra chemistry

There is a clear tendency for more mafic tephras to occur towards the north-western margins of our study area. However, basaltic tephras have so far been reported only from studies of lake sediments. Many workers use density concentration techniques (e.g. Turney, 1998) that, by design, concentrate rhyolitic tephras preferentially, and which may result in basaltic tephras being missed, but most peat sequences have been analysed using alternative approaches (ashing or chemical digestion) that would be expected to preserve basaltic tephra if it were present. This suggests that the relative scarcity of basaltic tephras in Holocene sequences in Europe is possibly related to differential preservation rather than to analytical biases or transport processes alone (contra Dugmore et al., 1995; cf. Pollard et al., 2003; Wolff-Boenisch et al., 2004; Swindles et al., 2011). Basaltic glass is readily dissolved and hydrated to various weathering products in soils and sediments, although the rate at which it does so varies depending on the depositional environment (Schiffman et al., 2000). Other factors, such as eruption style, may also be involved. Basaltic eruptions can be explosive but they are more likely to be effusive than Plinian and thus less likely to inject material high into the atmosphere, which would limit their potential to disperse ash. Furthermore, basaltic eruptions often produce denser, less vesicular tephra particles than less mafic eruptions; these may be more likely to sediment out from the atmosphere before reaching the continent. Further searches for basaltic tephras in lake sediments, where conditions for preservation seem to be more favourable, may help to clarify the true frequency of basaltic ash fall events in north-west Europe.

4.4 Recommendations for future work

The data synthesized by Swindles et al. (2011) and mapped here were not usually collected for the purpose of mapping tephra distributions, and using the dataset for this purpose reveals some of the limitations of cryptotephra studies more generally. One of the more striking findings of this study is that there are a large number of tephras which have not yet been identified at more than one or two sites. There are several possible explanations for this (cf. Dugmore et al., 1995). Some investigators may not have been able to find a match for every tephra in the literature, although a match may exist, because (i) geochemical data are not always published in full; (ii) geochemical and stratigraphical data from a tephra layer do not always make an unambiguous correlation possible; (iii) some identified tephra layers may actually represent layers of reworked tephras, rather than primary deposition; and (iv) the geochemistry of some tephras may also have altered over time, making them impossible to match. On the other hand, this apparent abundance of rare tephras may indicate that there have been many more ash fall events since 7000 cal BP than the 22 that we have mapped in this exercise. If this is the case, few of them have left clear traces in the geological record, either because they deposited only a sparse layer of tephra, or because they only affected small regions, or because the tephra grains were too small to be identified and/or analysed, or because the grains were lost through chemical alteration. There are several other important limitations of the present dataset. There are large spatial gaps, notably in southern Britain, Poland, Latvia, Lithuania, Finland, Norway, and much of northern Sweden, and the intensity of research in those regions for which we do have data has been far from uniform. The spatial variability of tephra occurrences may also be explained by methodological inconsistencies. For example, some researchers have routinely sieved their samples, which may have removed many of the smaller shards. Until recently it was not commonly possible to analyse the geochemistry of tephra shards smaller than about 20 μm, so only more recent studies include fine-grained tephras (and even then, very small grains may be missed). We suggest that researchers should use standard published protocols for extraction and identification as far as practicable (Swindles et al., 2010; Lowe, 2011). Any deviation from such protocols should be reported, including full details of sieving (including mesh sizes) and density separation (including the density of the liquid used).

As well as variation in techniques for concentrating tephras, there has been variation in the methods used to prepare them for geochemical analysis. In order to ensure meaningful comparisons with existing data, we strongly recommend that future workers adhere to the most well-established method, acid digestion (cf. Swindles et al., 2010). Although it is clear that this does lead to some chemical alteration of shards (Blockley et al., 2005), the effect has not been shown to impede geochemical matching of unknown tephras with reference material, and ‘like-with-like’ comparisons with existing data depend on methodological consistency. Geochemical data should also be published in full and/or lodged on databases such as Tephrabase (Newton et al., 2007) to allow cross-correlation between sites and reconsideration of published identifications in the light of new data.

Another issue is the inconsistency in researchers’ views about what constitutes a tephra ‘layer’: low concentrations of tephra may have been analysed by some groups and ignored by others. Nonetheless, the strong coherence of many of the mapped distributions presented here suggests that genuine differences in distribution of these tephras do emerge from the data. Future workers should consider presenting data on tephra shard concentrations (or tephrostratigraphy) across the whole profile, rather than just reporting individual tephra layers. This would give a clearer indication of where tephras are genuinely absent and begin to provide information on the variation in the abundance of tephras, rather than simple presence/absence. Researchers should also indicate where they have looked for tephra shards in sequences and found none. Finally, colour, particle morphology, particle sizes, vesicularity and any other characteristics of individual shards, if recorded routinely, could assist identification, correlation and understanding of ash-fall dynamics.

5. Conclusions

1. The new maps presented here indicate which tephra isochrons typically occur in a given region, which will help to guide future tephrochronological investigations. For example, certain tephras, such as Hekla 4, are likely to be found even in very distal locations.

2. The new maps indicate substantial spatial gaps in the available information, especially in northern Scandinavia and the western Baltic and in southern Britain.

3. We find strong differences in the spatial distribution of many tephras on large (≥ 500 km) scales. Some, but not all tephras are significantly spatially clustered, which likely reflects atmospheric and weather patterns at the time of the eruptions.

4. Although we expected on the basis of previous modelling studies to find cryptotephras most frequently in Scandinavian lakes and peatlands, comparable sites in Ireland and northern Britain typically contain at least as many tephras. More work is needed to explain this discrepancy, as it has implications for our understanding of past and, by extension, future Icelandic ash distribution patterns and their potential impact on the aviation industry, public health and the economy.

5. Rhyolitic and other felsic tephras occur throughout the study region, but more mafic (andesitic and basaltic) tephras are largely restricted to the Faroe Islands and Ireland. Basaltic tephras have thus far been reported only from lake sediments, suggesting that their under-representation in peat sequences may be at least partly due to differential preservation rather than simply more limited dispersal.

6. The under-representation of basaltic tephras strongly suggests that the record of past tephra falls preserved in European lakes and mires is by no means a complete record of past ash fall events. Estimates of past ash fall frequency based on these records are therefore likely to be underestimates. This has implications for volcanic hazard analysis based on these and similar records.

7. We emphasize the usefulness for future research of adopting standardized approaches to searching for and analysing tephra; of reporting tephra concentrations and genuine absences; and of using existing community tools such as Tephrabase (Newton et al., 2007) to make geochemical data available and assist the correlation of tephras.

Footnote

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

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Tables

Table 1. List of tephras mapped. Key to dating methods: H, historically recorded; I, interpolated between radiocarbon dates; W, dated by wiggle-matching of ^{14}C dates. The p-value indicates the degree to which the distribution of points approaches a random distribution; values < 0.05 (marked with an asterisk) are judged to be significantly non-random.

Tephra name	Reported date (cal. yrs)	Dating method and reference	Source	Number of sites	Geochemical type	p-value
Hekla 1947	AD 1947	H	Hekla	11	Dacitic-Andesitic	-
Askja 1875	AD 1875	H	Askja	13	Rhyolitic	0.000*
Hekla 1510	AD 1510	H	Hekla	13	Dacitic-Andesitic	0.003*
PMG-5/ MOR-T2	c. AD 1400	I (Chambers et al., 2004)	Jan Mayen?	3	Trachyte	-
Öræfajökull 1362	AD 1362	H	Öræfajökull	9	Rhyolitic	0.181
Hekla 1104	AD 1104	H	Hekla	21	Rhyolitic	0.001*
Landnám	AD 871±2	GRIP ice core (Grönvold et al., 1995)	Veiðivötn/ Torfajökull	3	Basaltic	-
Tjørnuvík	9th century AD	I (Hannon et al., 2001)	Hekla	4	Andesitic-Rhyolitic	-
AD 860 B	AD 776-887	W (Pilcher et al., 1995; Wastegård et al., 2003)	?	20	Rhyolitic	0.006*
AD 860 A	AD 776-887	W (Pilcher et al., 1995; Wastegård et al., 2003)	?	5	Rhyolitic	0.111
GA4-85	c. AD 700-800	I (Hall and Pilcher, 2002)	Katla?	4	Dacitic-Trachydacitic	-
Glen Garry	16-260 BC	W (Barber et al., 2008)	?	26	Dacitic-Rhyolitic	0.000*
BMR-190	705-585 BC	W (Plunkett et al., 2004)	Hekla	7	Dacitic	0.000*
Microlite	755-680 BC	W (Plunkett et al., 2004)	?	20	Rhyolitic	0.003*

GB4-150 (~SILK-UN)	800-758 BC	W (Plunkett et al., 2004)	Katla	8	Dacitic-Trachydacitic	0.003*
Hekla 3	1087-1006 BC	W (van den Bogaard et al., 2002)	Hekla	13	Dacitic-Rhyolitic	0.008*
Hekla-S/ Kebister	1800-1750 BC	W (Wastegård et al., 2008)	Hekla	19	Dacitic-Rhyolitic	0.002*
Hekla 4	2395-2279 BC	W (Pilcher et al., 1995)	Hekla	44	Rhyolitic	0.135
Mjáuvøtn A	c. 3550 BC	I (Wastegård et al., 2001)	?	3	Basaltic	-
Hoy	4620-4230 BC	R (Dugmore et al., 1995)	Torfajökull	3	Rhyolitic	-
Lairg B	4774-4677 BC	W (Pilcher et al., 1996)	Torfajökull	10	Rhyolitic	0.093
Lairg A	4997-4902 BC	W (Pilcher et al., 1996)	Hekla	13	Rhyolitic	0.032*

Figure captions

Figure 1. Maps showing the distribution of tephras identified in peat and lake sediments across north-west Europe since 7000 cal BP. Maps are not shown for tephras which occur only at one or two sites. Occurrences of tephras in Iceland are not shown. Black circles indicate sites where the tephra has been identified; white circles indicate sites where there is strong evidence for the absence of the tephra, i.e. where other well-dated tephras both younger and older than this tephra were found in the sequence. Grey circles indicate other sites in the database. The grid lines are at 10° intervals.

Figure 2. (a) The spatial distribution of the number of tephras younger than 7000 cal BP recorded at each site. Symbol size is proportional by area to the number of tephras. Only the 22 tephras mapped in this study were included in the counts; some sites contain additional tephra layers (see Swindles et al., 2011, supplementary data). (b-d) The number of tephras recorded at each site as in Figure 2a, broken down according to tephra chemistry: (b) rhyolitic; (c) other felsic tephras (dacitic, dacitic-rhyolitic, dacitic-trachydacitic, trachytic); (d) mafic and part-mafic tephras (andesitic-rhyolitic, dacitic-andesitic, basaltic).

Figure 3. Box-plot showing the mean number of tephras at each site, split by region. The counts only include the 22 tephras mapped as part of this study. The median of each distribution is marked by the solid black line in the middle of each grey box; the lower and upper limits of the box mark the first and third quartiles of the data, respectively; and the dashed lines extend to the extremes of the data. The number of sites represented by each box is, from left to right: 9, 4, 29, 35, 22.

Figure 4. Plots of distances between tephra events. Black lines: distances between events where both are marked as the tephra being “present”. Dashed black lines: distances between all “present-present” and “present-absent” pairs of events. Grey shading: envelope containing 95% of simulations under random re-labelling.

Fig. 1a

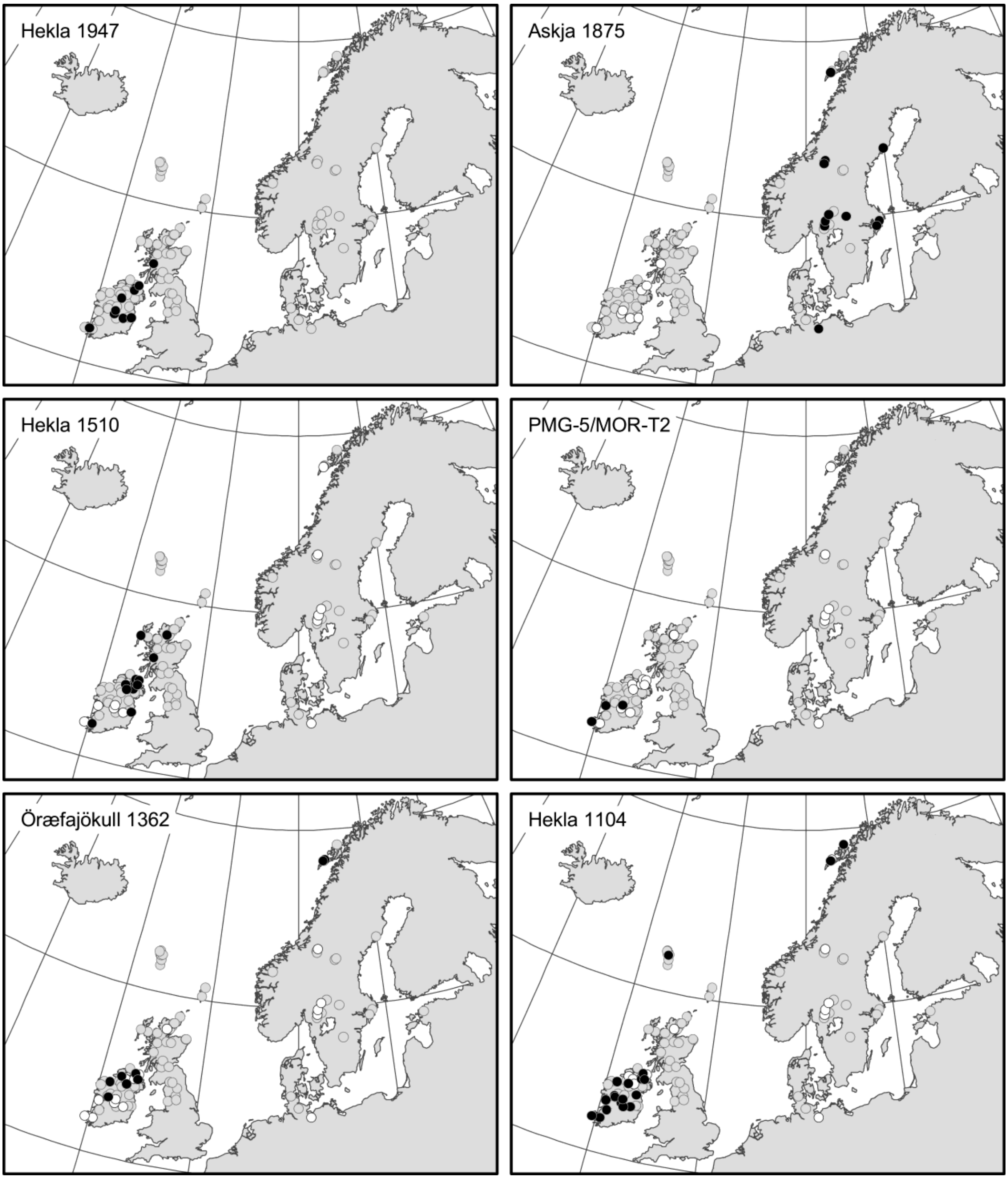

Hekla 1947
Askja 1875
Hekla 1510
PMG-5/MOR-T2
Öræfajökull 1362
Hekla 1104

Fig. 1b

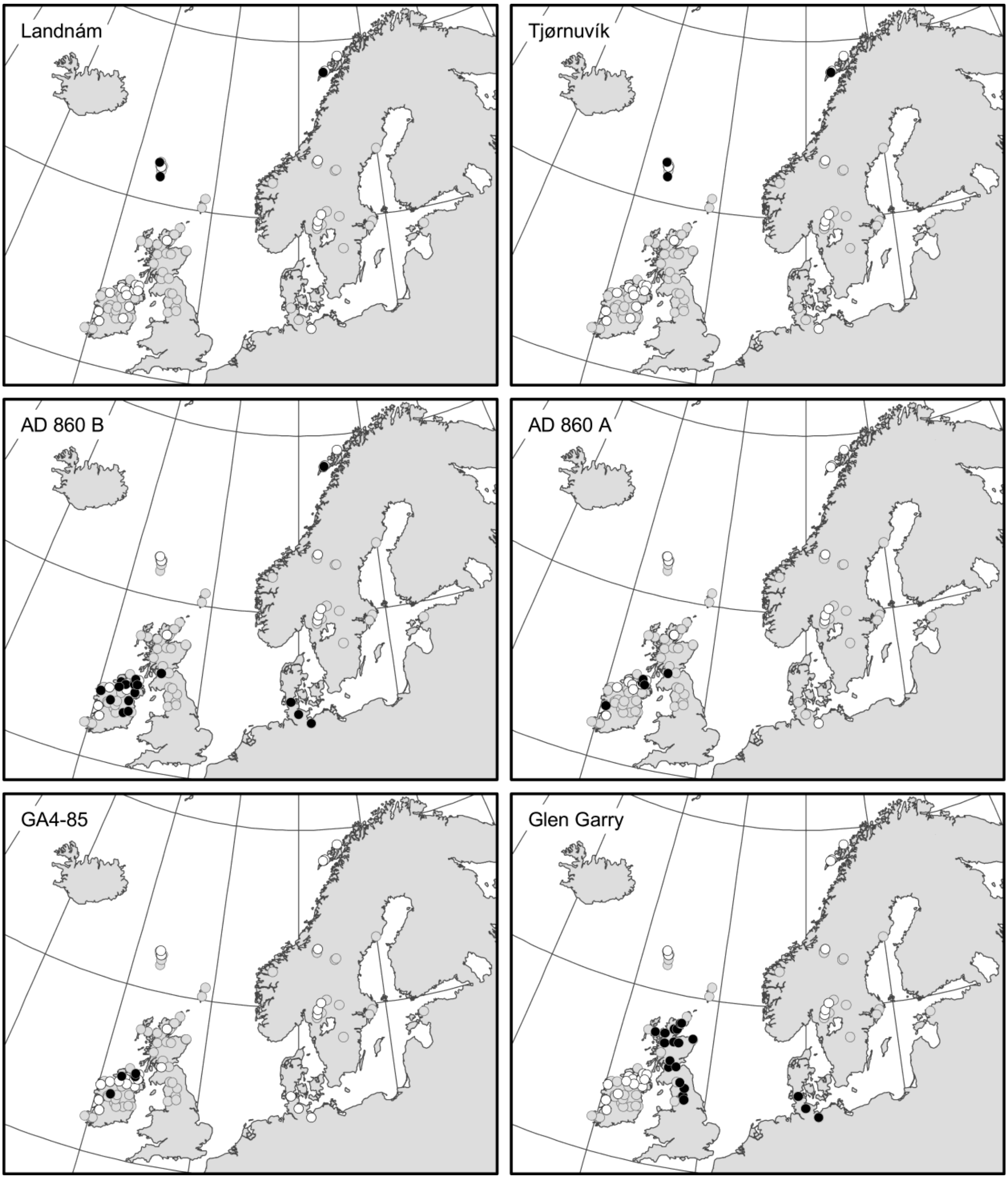


Fig. 1c

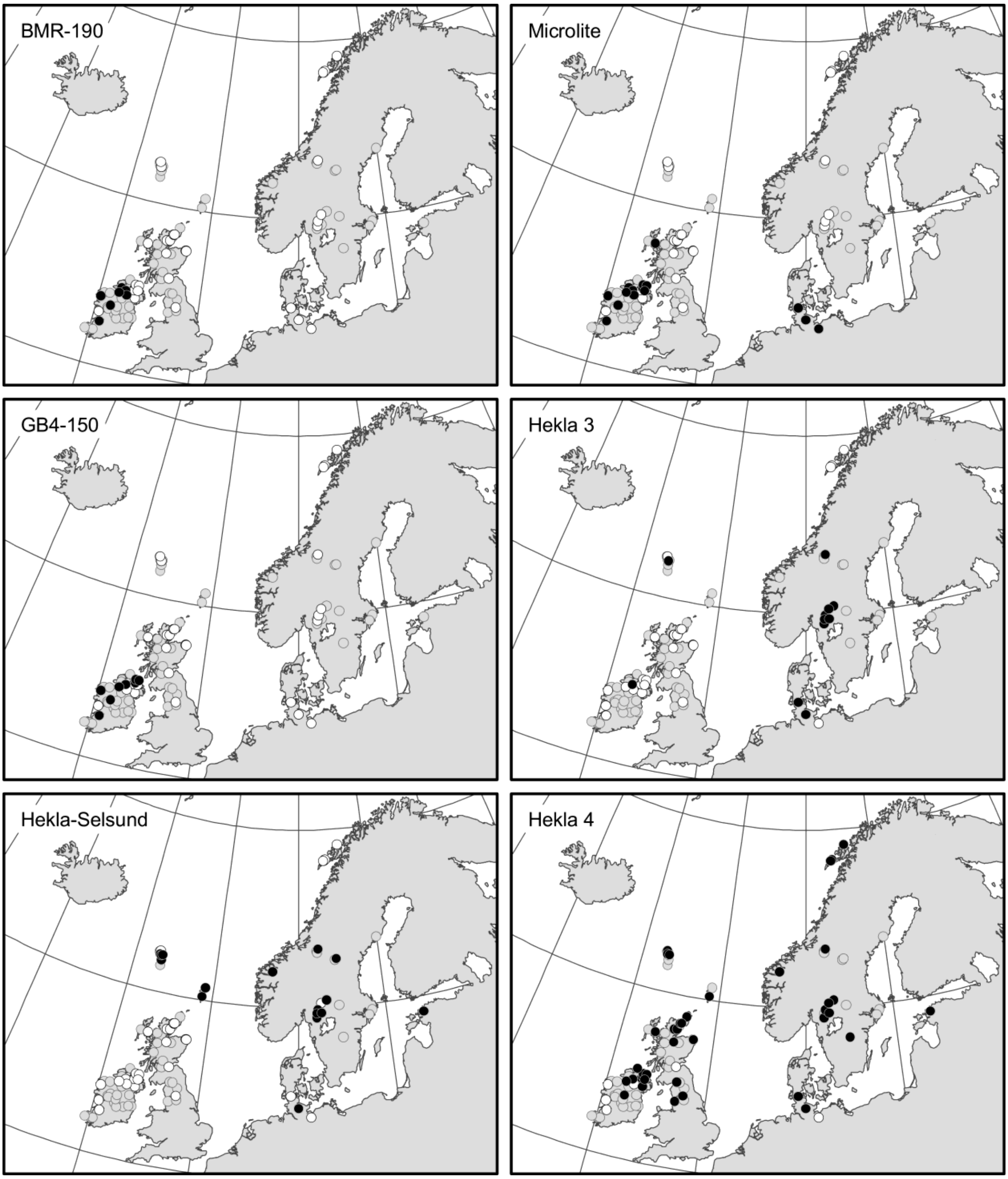


Fig. 1d

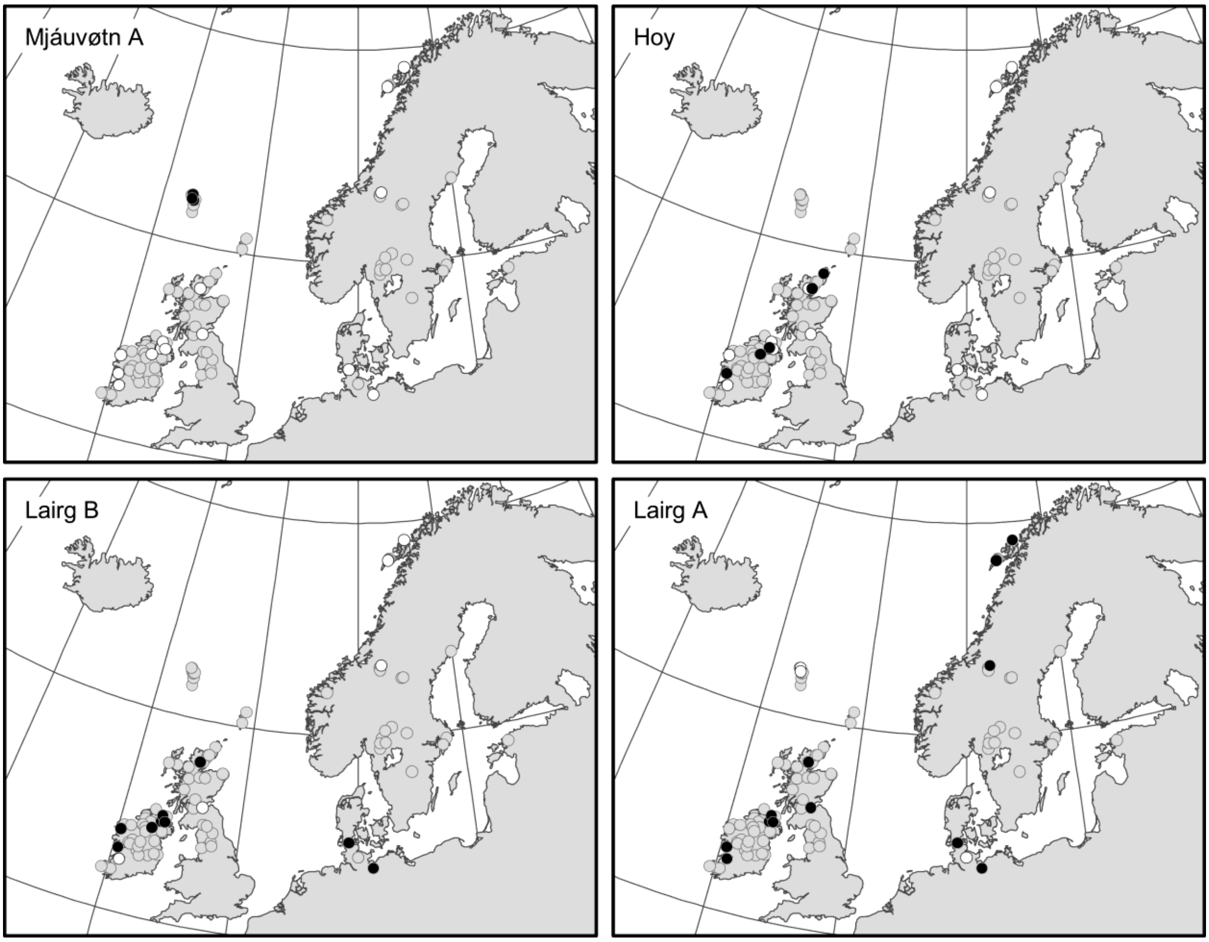
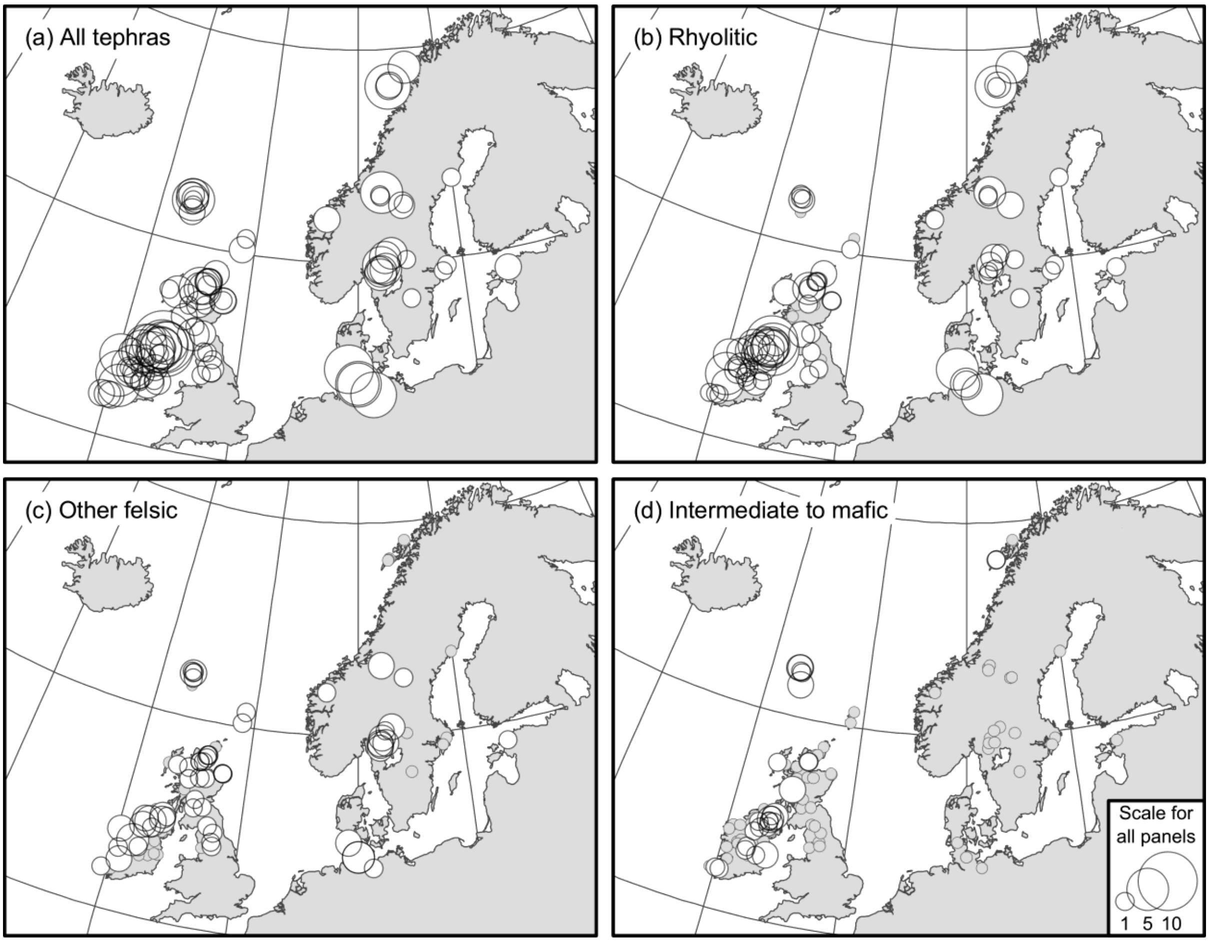
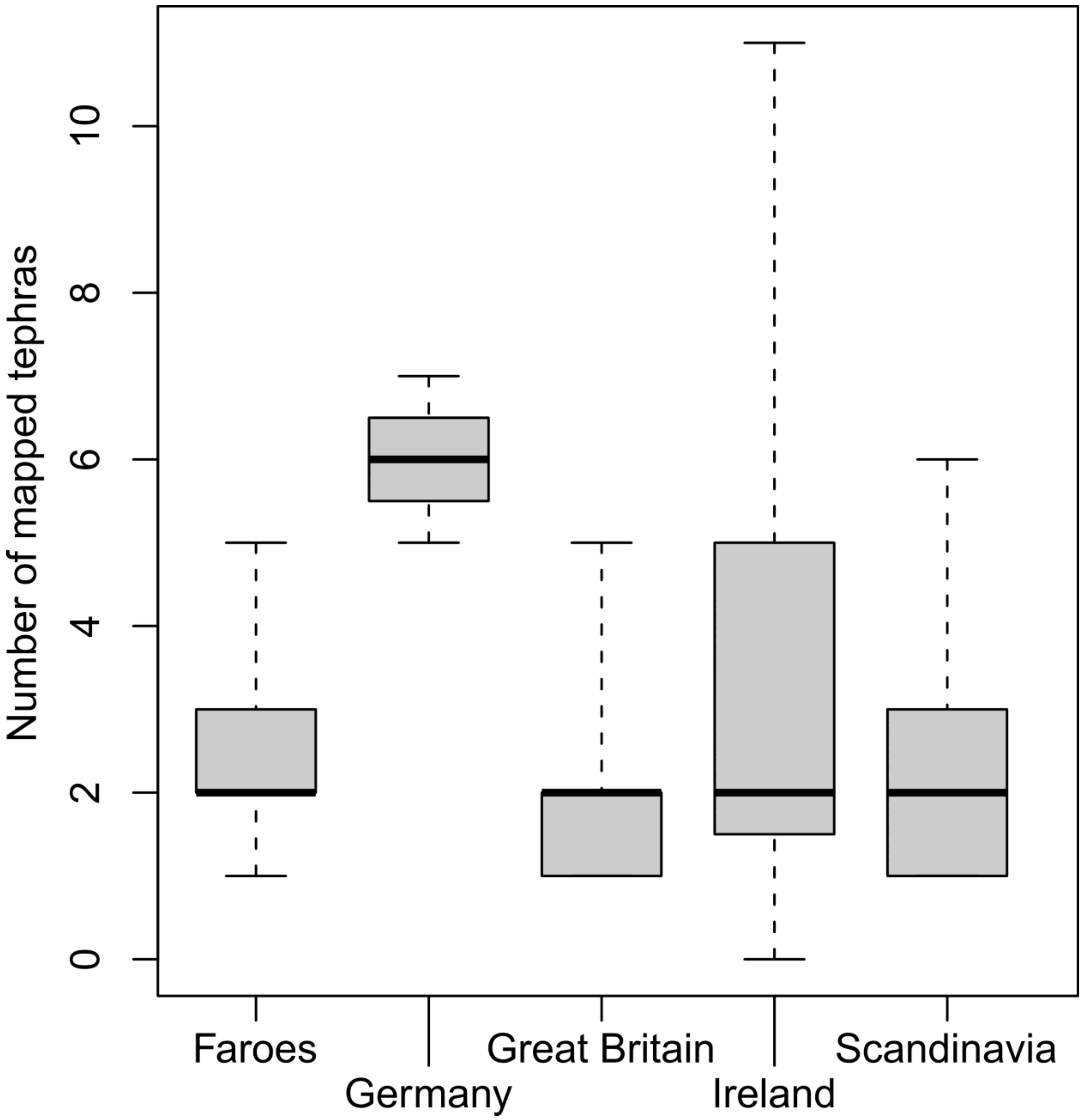


Fig. 2



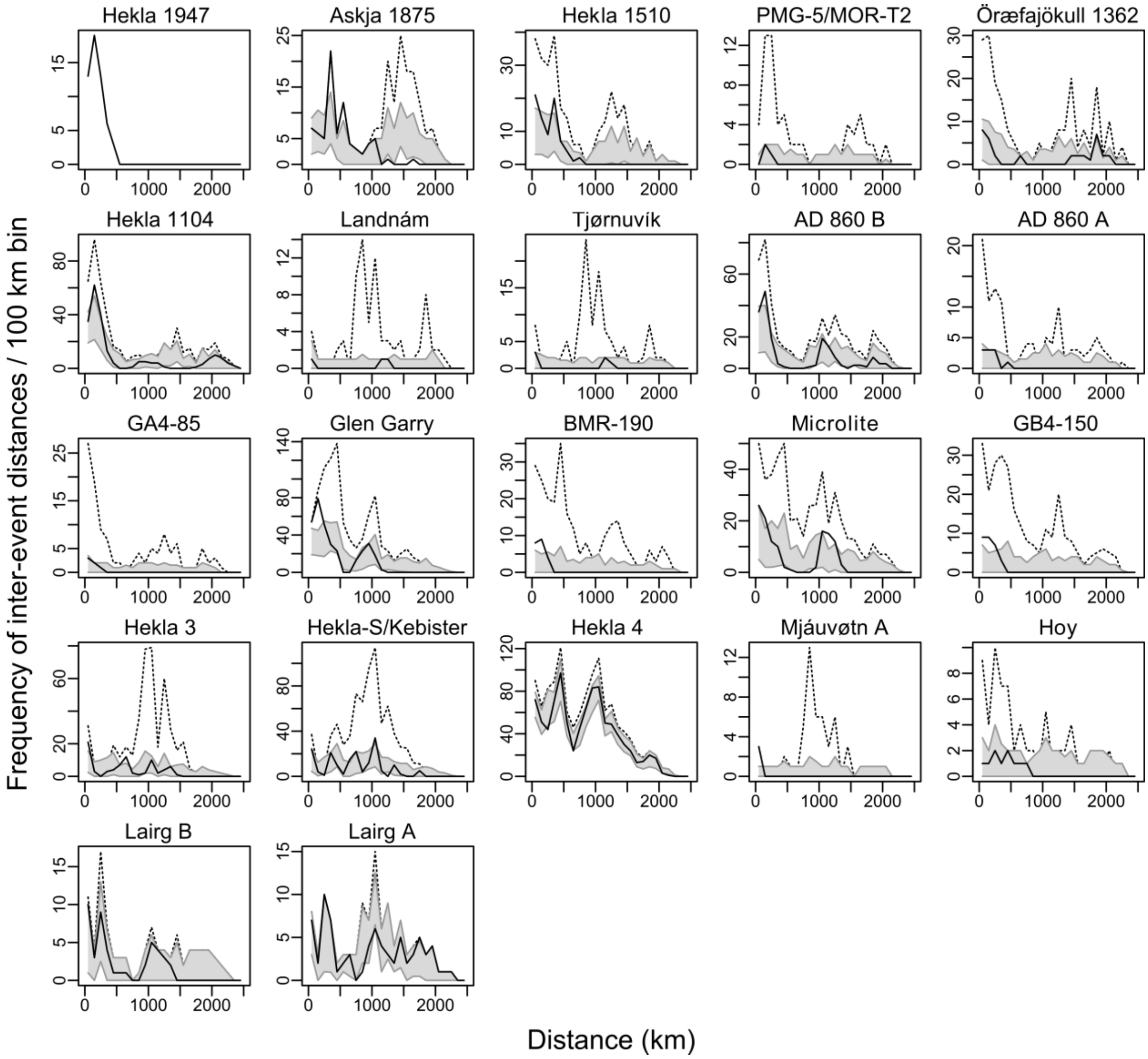
(a) All tephras
(b) Rhyolitic
(c) Other felsic
(d) Intermediate to mafic
Scale for all panels
1 5 10

Fig. 3



Number of mapped tephras
0
2
4
6
8
10
Faroes
Germany
Great Britain
Ireland
Scandinavia

Fig. 4


Hekla 1947
Askja 1875
Hekla 1510
PMG-5/MOR-T2
Öræfajökull 1362
Hekla 1104
Landnám
Tjørnuvík
AD 860 B
AD 860 A
GA4-85
Glen Garry
BMR-190
Microlite
GB4-150
Hekla 3
Hekla-S/Kebister
Hekla 4
Mjáuvøtn A
Hoy
Lairg B
Lairg A
Frequency of inter-event distances / 100 km bin
Distance (km)