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Spatial variability of tephra and carbon accumulation in a Holocene peatland

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ABSTRACT

Microscopic tephra layers ('cryptotephras') represent important age-equivalent stratigraphic markers utilised in many palaeoenvironmental reconstructions. When used in conjunction with proximal records of volcanic activity they can also provide information about volcanic ash cloud fallout and frequency. However, the spatial distributions of tephra layers can be discontinuous even within the same region. Understanding the deposition and post-depositional redistribution of tephra is vital if we are to use cryptotephras as records of ash cloud occurrence and chronostratigraphic markers. The discrete nature of tephra layers also allows for detailed study into processes of deposition and reworking which affect many palaeoenvironmental proxy records.

We undertook a multi-core study in order to examine the historical tephrostratigraphy of a raised peatland in Northern Ireland. Three tephra layers originating from Iceland (Hekla 1947, Hekla 1845 and Hekla 1510) are present in 14 of the 15 cores analysed. This suggests that in areas not influenced by snowfall or anthropogenic disturbance at the time of tephra delivery, the presence or absence of a tephra layer is generally consistent across a peatland of this type. However, tephra shard counts (per unit area) vary by an order of magnitude between cores. These intra-site differences may confound the interpretation of shard counts from single cores as records of regional ash cloud mass/density. Bootstrap resampling analysis suggests that total shard counts from multiple cores are required in order to make a reliable estimate of median shard counts for a site. The presence of three historical tephras in 14 cores enables a spatio-temporal analysis of the long-term apparent rate of carbon accumulation (LARCA) in the peatland. Substantial spatial and temporal variations in LARCA are identified over the last ~450 years. This high variability needs to be taken into account when designing studies of peatland carbon accumulation.

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1. Introduction

Tephra layers preserved in European peatlands provide both a valuable geochronological tool (e.g. Davies, 2015; Dugmore et al., 1995; Lane et al., 2013) and a record of past volcanic activity and ash dispersal events (Swindles et al., 2011b). Tephra deposited onto a peat surface far from the volcanic source is typically fine-grained (<125 μm in size) and accordingly called 'cryptotephra'. It is mostly considered to be primary air fall material (Davies et al., 2007; *contra* Swindles et al., 2013a) and is not thought to be subject to the vigorous reworking processes in the water column and/or the soft sediment which may distort tephra records in lacustrine and marine sediments (Davies et al., 2007; Griggs et al., 2014; Pyne-O'Donnell, 2011). Although tephra layers in peatlands can occasionally span a depth of a few centimetres, the peak is most often confined to a narrow horizon in thickness (Swindles and Plunkett, 2011). These factors suggest that peatlands should act as an excellent archive of past volcanic ash fallout, and that peat records can be used to map the spatial distribution of past fallout events on a continental scale (Swindles et al., 2011; Lawson et al., 2012).

One major issue with this approach is that cryptotephra layers in peatlands can be discontinuous even over small distances

(hundreds of metres to kilometres: (Bergman et al., 2004; Langdon and Barber, 2004)), which requires an explanation. At a regional scale some spatial variation in tephra horizons can be attributed to fluctuation of the volcanic plume height during the eruption, wind speed and direction variability, atmospheric processes (e.g. clouds and ice) and precipitation (Fig. 1), which can influence ash cloud density (Schumann et al., 2011), alter ash cloud trajectory and in the case of rainfall, increase the fallout of particles (Mattsson and Vesanen, 1988). At a local scale, the interaction of wind and vegetation may produce localised airflow patterns which result in the uneven delivery of tephra to the ground surface (Boygle, 1999; Pouget et al., 2014).

Even once the tephra has been deposited on the peat surface, the peat is unlikely to act as a straightforward, passive archive. Peatlands are complex ecosystems with dynamic topography, hydrological regimes, accumulation rate and vegetation composition (Swindles et al., 2012). Therefore peatland processes are likely to exert some control over the redistribution of tephra (and other paleoenvironmental proxies) both vertically and laterally, across the peatland surface (Fig. 1) – albeit probably to a lesser extent than in lacustrine or marine environments.

Previous studies of regional tephra occurrence have focused predominantly on single cores from different sites (Langdon and Barber, 2004). Inconsistent tephra records in two cores from Klocka bog, Sweden, suggest that tephra occurrence may vary at much smaller scales. In this instance tephra fell onto a prolonged snowpack (ca. 7 months) and was subsequently re-dispersed by wind and meltwater, leading to intra-site variation (Bergman et al., 2004). The majority of Holocene European tephra studies have been carried out in mid-latitude peatlands (Lawson et al., 2012), which are less likely to have been affected by prolonged snow cover. A study of two cores from Fallahogy bog in Northern Ireland comparable to the study by Bergman et al. (2004) found much less within-site dissimilarity, raising the possibility that, where prolonged snow cover is rare, tephra stratigraphies may be more consistent (Rea et al., 2012).

Tephra shards are commonly counted in order to determine the depth of peak shard concentration in the vertical profile. Recently, these counts have been used to infer ash cloud fallout over a region (Rea et al., 2012). Understanding the spatial variation in tephra shard concentrations in peatlands is important if it is to be assumed that they represent a record of ash density during an eruption event (Davies et al., 2010). The assumption that reworking has a negligible impact on total tephra shard counts within a given layer, and therefore that tephra shard counts represent a record of ash cloud density, is fundamental when attempting to use counts from one core per site to compare ash cloud fallout across many sites in a region (e.g. Langdon and Barber, 2004; Rea et al., 2012).

The main aim of this study is to assess the spatial variability in the total number of tephra shards relating to a given eruption and carbon accumulation across multiple cores from one site and to consider the implications for the interpretation of results from single core studies.

1.1. Tephra preservation in peatlands

Much of our current understanding of tephra preservation in peatlands is based on experimental evidence rather than detailed study of naturally-deposited tephra. Laboratory and artificial field experiments indicate that although the majority of tephra shards remain at the palaeo-surface during incorporation into the peat matrix, some migrate vertically (both upward and downward) (Payne and Gehrels, 2010; Payne et al., 2005). This would support the common assumption that the peak in tephra shard concentrations, rather than the first occurrence of shards, coincides with

the timing of the ash fall event.

Shards are also likely to move laterally across a peatland on a variety of scales. Tephra shards may be deposited differently and/or moved to such an extent that the number of shards in some areas of the peatland becomes too low to be detected and analysed using current methods (Payne and Gehrels, 2010). Our understanding of cryptotephra redistribution on peatlands extends only to the lateral movement of tephra by wind at microtopographical scales. Experiments suggest that only a small proportion of tephra is transported over the short distance (<3 m) from hummock to hollow (Payne and Gehrels, 2010). There is evidence that tephra may move at even smaller scales (a few centimetres or less). Simulated rainfall onto thin (1 mm) tephra layers has been shown to generate patches of high and low tephra concentration across a peat surface (Payne and Gehrels, 2010). These experiments suggest that reworking does occur at small scales, but they do not address the possibility of tephra shard movement at larger scales (metres, to hundreds of metres).

Although these studies offer valuable information on the reworking on tephra in peatlands, they are experimental and represent both a simplification of reality and a compression of time. Evidence from naturally-deposited tephras which have been subject to peatland processes over a period of hundreds of years is needed to understand the interaction and overall impact of these processes on tephra redistribution in 'real world' scenarios.

Research into the spatial variation of other palaeoenvironmental proxies found in peatlands, specifically pollen and charcoal, suggests that two or more cores taken in close proximity usually display the same general trends in reconstructions but show minor differences which might affect detailed interpretation (cf. Edwards, 1983; Innes et al., 2004; Lawson et al., 2005; Turner et al., 1989). The resolution of these studies is restricted by the dating methods available. In a more recent study, Blaauw and Mauquoy (2012) used wiggle-match radiocarbon dating, which offers a more precise chronological framework, and identified variation in arboreal pollen records from four cores across the same peatland over centennial timescales, although trends were more consistent over millennial timescales. Within-site variation in peatland proxy records over centennial timescales may limit the temporal resolution of palaeoenvironmental studies.

Unlike palaeoecological proxies, historical tephra layers are unique in representing a discrete depositional event rather than a continuous influx, allowing for easier identification of reworking processes (Housley et al., 2013). By improving our understanding of the deposition and redistribution of tephra layers, we will also gain insights into how other palaeoenvironmental proxies may be reworked as they enter the stratigraphic record (cf. Irwin, 1989; Turner et al., 1989).

1.2. Carbon storage in European peatlands

Peatlands represent an important global carbon store and as such the accumulation of carbon in peat has been the focus of large-scale studies (e.g. Charman et al., 2013; Turunen et al., 2004; van der Linden et al., 2014). Although regional climate is often the major control on carbon accumulation rates (Magnan and Garneau, 2014), internal peatland processes can also exert an influence. Spatial differences in carbon accumulation within a peatland could lead to unrepresentative estimates based on one core being extrapolated over a large area.

There has been only limited investigation into variation in long-term apparent rate of carbon accumulation (LARCA) within one peatland site, the majority of studies focussing on high-latitude peatlands (e.g. Belyea and Clymo, 2001; Ohlson and Økland, 1998; Turunen et al., 2004). For example, Turunen et al. (2004)
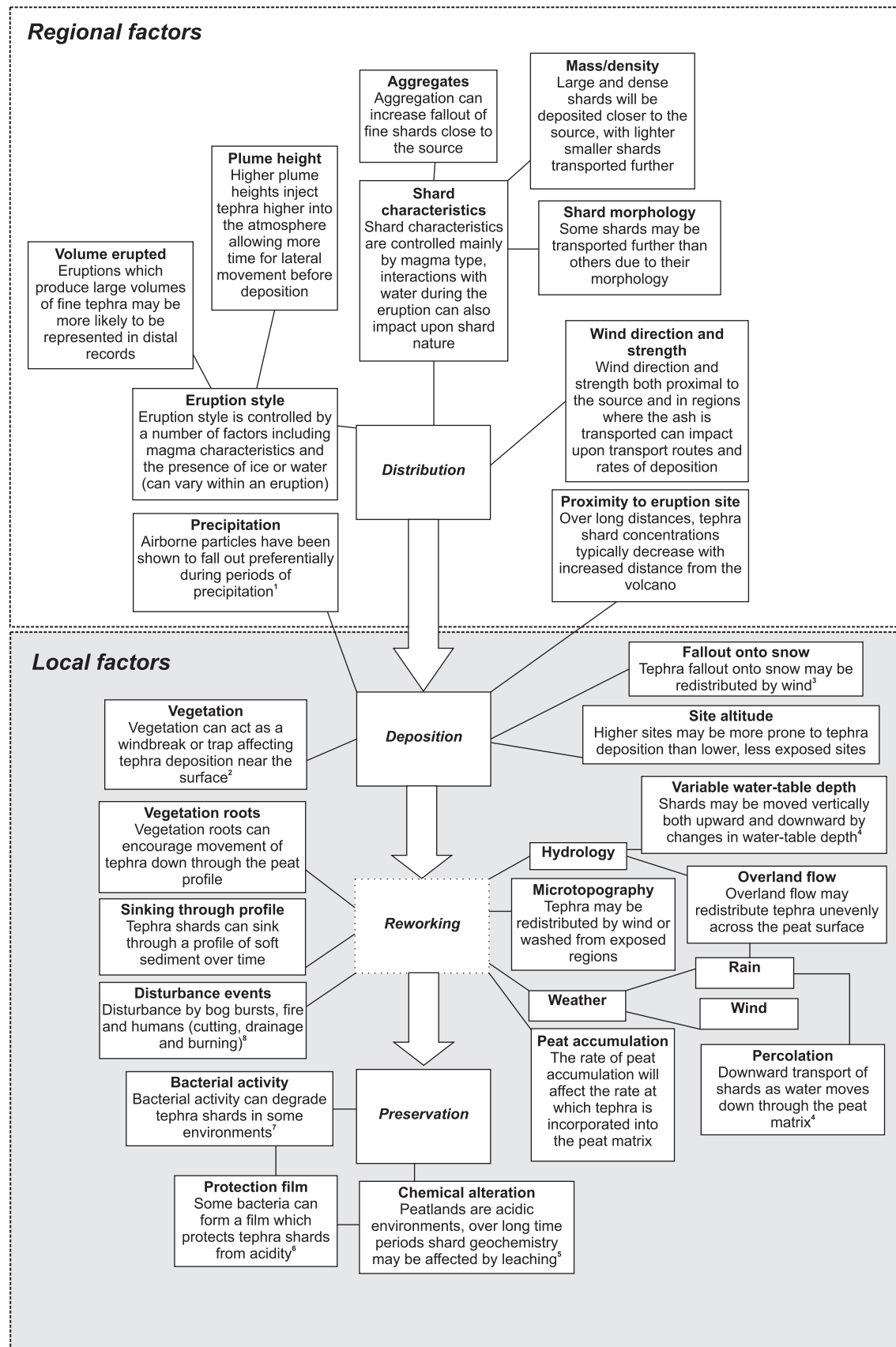
Regional factors

Aggregates
Aggregation can increase fallout of fine shards close to the source

Mass/density
Large and dense shards will be deposited closer to the source, with lighter smaller shards transported further

Plume height
Higher plume heights inject tephra higher into the atmosphere allowing more time for lateral movement before deposition

Shard characteristics
Shard characteristics are controlled mainly by magma type, interactions with water during the eruption can also impact upon shard nature

Shard morphology
Some shards may be transported further than others due to their morphology

Volume erupted
Eruptions which produce large volumes of fine tephra may be more likely to be represented in distal records

Wind direction and strength
Wind direction and strength both proximal to the source and in regions where the ash is transported can impact upon transport routes and rates of deposition

Eruption style
Eruption style is controlled by a number of factors including magma characteristics and the presence of ice or water (can vary within an eruption)

Distribution

Precipitation
Airborne particles have been shown to fall out preferentially during periods of precipitation[1]

Proximity to eruption site
Over long distances, tephra shard concentrations typically decrease with increased distance from the volcano

Local factors

Fallout onto snow
Tephra fallout onto snow may be redistributed by wind[3]

Vegetation
Vegetation can act as a windbreak or trap affecting tephra deposition near the surface[2]

Deposition

Site altitude
Higher sites may be more prone to tephra deposition than lower, less exposed sites

Variable water-table depth
Shards may be moved vertically both upward and downward by changes in water-table depth[4]

Vegetation roots
Vegetation roots can encourage movement of tephra down through the peat profile

Hydrology

Overland flow
Overland flow may redistribute tephra unevenly across the peat surface

Sinking through profile
Tephra shards can sink through a profile of soft sediment over time

Microtopography
Tephra may be redistributed by wind or washed from exposed regions

Reworking

Rain

Disturbance events
Disturbance by bog bursts, fire and humans (cutting, drainage and burning)[8]

Weather

Wind

Peat accumulation
The rate of peat accumulation will affect the rate at which tephra is incorporated into the peat matrix

Percolation
Downward transport of shards as water moves down through the peat matrix[4]

Bacterial activity
Bacterial activity can degrade tephra shards in some environments[7]

Preservation

Protection film
Some bacteria can form a film which protects tephra shards from acidity[6]

Chemical alteration
Peatlands are acidic environments, over long time periods shard geochemistry may be affected by leaching[5]

Fig. 1. Flow chart indicating the main factors which might be expected to (or have been shown to) have an effect on tephra distribution, deposition, reworking and preservation in peatland environments. This study will focus on the influence of local factors. Key references (1) Mattsson and Vesanen, 1988; (2) Pouget et al., 2014; (3) Bergman et al., 2004; (4) Payne and Gehrels, 2010; (5) Hodder et al., 1991; (6) Techer et al., 2001; (7) Thorseth et al., 1995; (8) Swindles et al., 2013a.

identified spatial variation in carbon accumulation within Canadian peatlands dated using ^{210}Pb and [14]C: hummocks had significantly higher carbon accumulation rates than hollows over the last 150 years. However, the large uncertainty in radiometric age estimates, and their cost, is a limitation to this approach. Another line of research has used the 'pine method' of Ohlson and Dahlberg (1991) to estimate peat LARCA: young pine trees growing on a peatland are removed, their age is calculated by counting annual rings, and the original growing point (depth at which the stem meets the root) and the thickness of peat subsequently accumulated are determined. Peat LARCA estimated using this approach varied by a factor of five (over 125 years of peat growth) in 151 different cores from the same 20 m^2 area of a boreal bog (Ohlson and Økland, 1998). However, this technique can only be used on forested peatlands. The presence of three historical tephra layers at our study site (see below for description) offers the opportunity to examine spatial variation in carbon accumulation rates in a mid-latitude, unforested peatland within a secure chronological framework. The same approach could be applied at many other peatlands where there is a well-resolved cryptotephra record.

1.3. Hypotheses

Using data from 15 cores from an ombrotrophic bog, we tested the following null hypotheses:

- Tephra layers show no spatial variation within the peatland in terms of:
  - Presence/absence
  - Total shard counts relating to a given eruption (TSCs, defined as the total number of shards > 10 μm associated with each tephra layer in a column of peat with surface area 1 cm^2)
- Tephra layers from different eruptions recorded in the same peatland do not have significantly different TSCs.
- LARCA shows no spatial variation.

2. Study site

Fallahogy peatland is an ombrotrophic lowland raised bog located north of Portglenone, Northern Ireland (54.912°N, 6.562°W). The peatland is located in the Lower Bann valley, a low-lying area with a mean annual rainfall of ~1000 mm (average from 1941 to 1970) (MetOffice, 1976). The main dome of the peatland is intact, although there has been a limited amount of cutting on the lagg. Plant communities range from *Sphagnum magellanicum* and *Sphagnum rubellum* dominated hollows, to hummocks dominated by Ericaceae and *Eriophorum* sp. The site has been the focus of several palaeoecological studies (e.g. Barber et al., 2000; Rea et al., 2012; Roland et al., 2014).

3. Methods

3.1. Field sampling

A Russian-type corer (Jowsey, 1966) with a 50 cm-long barrel was used to retrieve 15 short cores. Random sampling locations were selected using a random number generator, entered into a handheld GPS, and located in the field (Fig. 2). Samples were taken as close to the pre-selected point as possible (maximum 5 m distant), whilst accounting for the need to extract from areas of similar micro-topography; in this instance *Sphagnum* lawns were sampled (De Vleeschouwer et al., 2011).

To investigate movement of shards on a microtopographical scale three transects from hummock to hollow were investigated. Each transect was surveyed, the dominant vegetation was described and three 50 cm-long cores were extracted from different microtopographical zones. Only the FAL_1 tephra (later identified as Hekla 1947 tephra see Section 4.3) was investigated in these cores.

3.2. Tephra analysis

In the laboratory, samples were prepared using the 'quick burn' method (Pilcher and Hall, 1992; Swindles et al., 2011a). 1 cm^{-3} contiguous samples were ashed at 550 °C and treated with 10% HCl. To aid shard identification, samples were gently sieved at 6 μm to remove finer silt and clay fractions, and the coarse fraction mounted onto slides. Absolute tephra counts cm^{-3} (shards >10 μm) were conducted at 200× magnification on a standard Leica binocular microscope. Spheroidal Carbonaceous Particles (SCPs) were counted in the tephra slides and are reported as counts cm^{-3}. Total shard counts (TSCs) for each tephra layer cm^{-2} (total deposition per square centimetre of peatland surface) were calculated by summing the absolute tephra counts for all the depth samples within that layer.
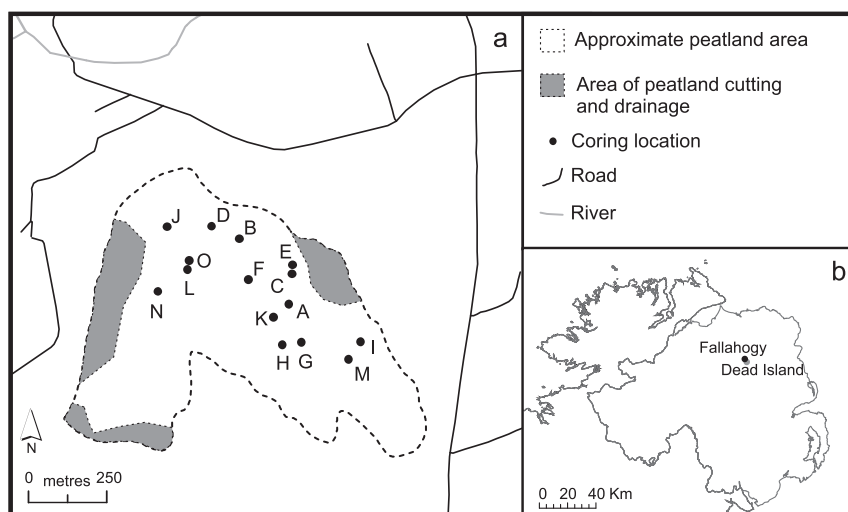

Fig. 2. Map indicating a) the location of the 15 core sampling sites in Fallahogy peatland b) the location of Fallahogy and Dead Island peatlands within Northern Ireland. Some evidence of peat cutting and drainage is evident around the edges of Fallahogy peatland as illustrated.

Samples for geochemical analysis were extracted from core A which showed three distinct peaks of tephra (Fig. 3). An additional sample was extracted from FAL_3 in core K in order to confirm the high accumulation rate which was later identified in this core (see Section 4.9.1.). Due to the abundance of roots in the top of the peat profile and low shard concentration in the second peak (14–15 cm), density separation following the method of Blockley et al. (2005) was unsuccessful. Instead, extraction for geochemical analysis for
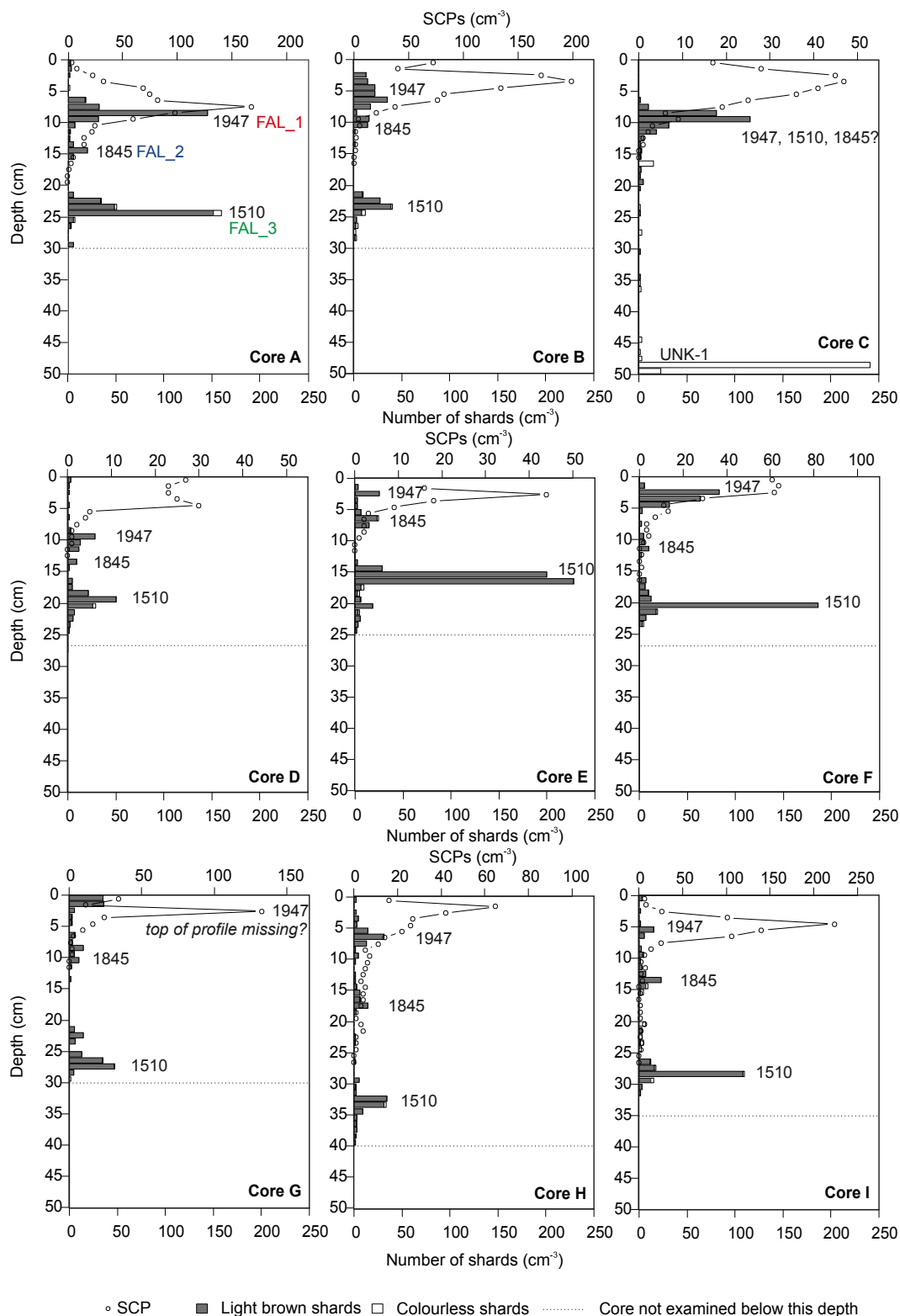
Fig. 3. (2 Panels) Diagrams showing tephrostratigraphy and Spheroidal Carbonaceous Particle (SCP) profiles for the 15 peat profiles. Note horizontal scales for SCP profiles vary. Labels indicating the source event (Hekla 1947, Hekla 1845 and Hekla 1510) have been placed next to peaks in tephra shard concentration. Core C contains a peak of colourless tephra shards which have not been geochemically analysed (UNK-1). Geochemical samples were obtained from tephra peaks in Cores A and K (labelled FAL_1, FAL_2 and FAL_3).
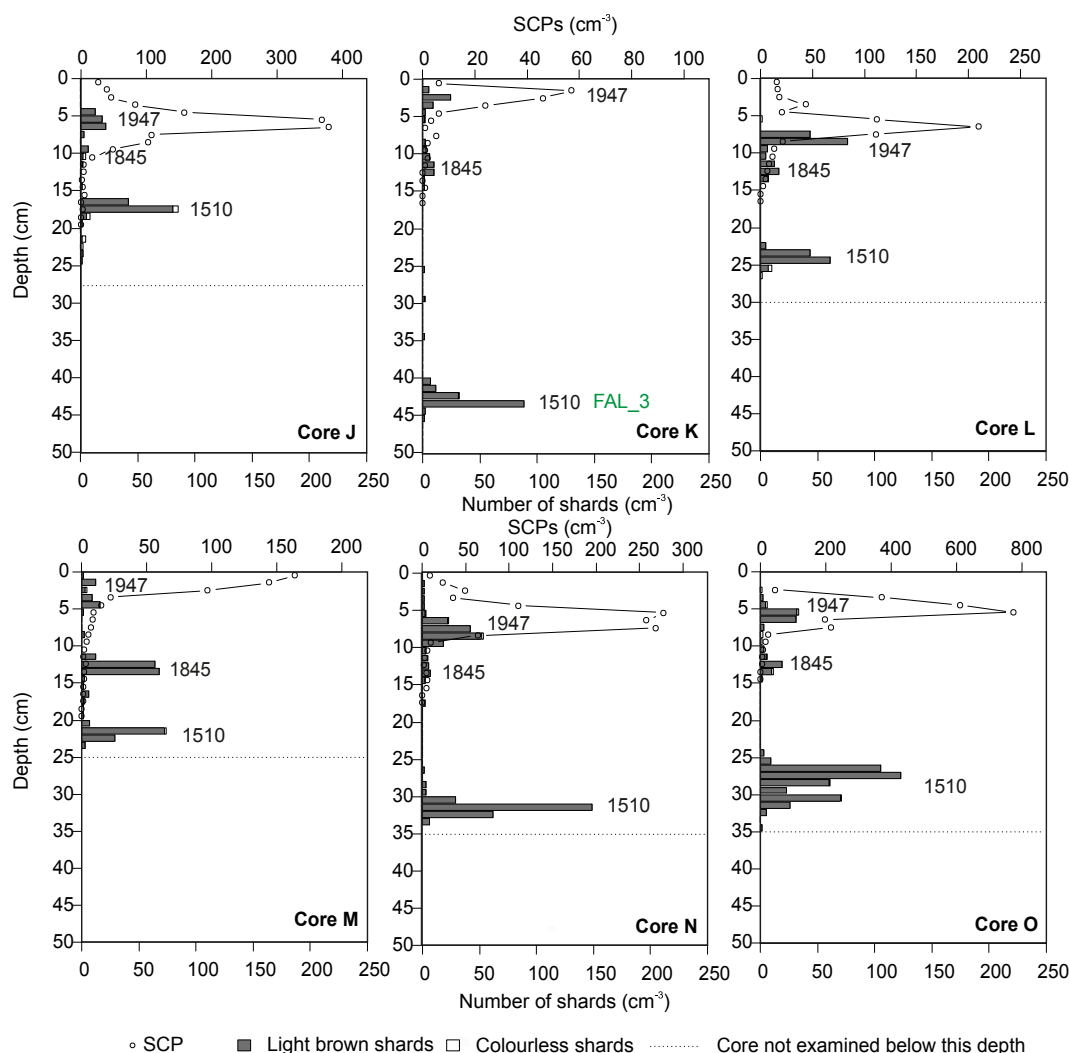
Fig. 3. (*continued*).

3.3. Carbon accumulation

all samples followed the acid digestion method (Dugmore et al., 1992). Samples were treated with hot conc. HNO_3 and H_2SO_4 acids, diluted with water and sieved at 10 μm. The coarse residue was rinsed thoroughly with clean water. There is experimental evidence that exposure to acidic and particularly alkaline treatments for the removal of diatoms can alter tephra geochemistry (Blockley et al., 2005). In this instance the risk of geochemical alteration was reduced as alkaline treatment was not necessary and acid treatment was short (<2 h). Recent work has shown that rhyolitic shards extracted using the acid digestion method and then analysed using Electron probe micro analysis (EPMA) are geochemically indistinguishable from shards extracted using density separation (Roland et al., 2015). This suggests that chemical alteration during the acid digestion method is minor and unlikely to affect the assignment of a tephra to an eruption event.

Samples were mounted onto glass slides using EpoThin resin, ground to expose the shards (cf. Dugmore et al., 1992) and polished to a 0.25 μm finish. EPMA was conducted at the Tephra Analytical Unit, University of Edinburgh. All analyses were conducted with a beam diameter of 5 μm, 15 kV and beam currents of 2 nÅ (Na, Mg, Al, Si, K, Ca, Fe) or 80 nÅ (P, Ti, Mn) (Hayward, 2012). Secondary glass standards, basalt (BCR-2G) and rhyolite (Lipari) were analysed before and after EPMA runs of unknown glass shard analyses.

It was assumed that the peak of each tephra layer represented the year of the eruption (cf. Payne and Gehrels, 2010). Bulk density was calculated on 1 cm^3 samples taken contiguously between the tephra peaks of layers which were subsequently identified as those from the eruptions of Hekla in 1510 and 1947 (see Section 4.3). Samples were oven dried at 105 °C and dry weight was divided by volume to determine bulk density.

Carbon content was estimated using loss-on-ignition (LOI) which offers an approximation of organic matter content. The equation of Bol et al. (1999) was used to convert LOI into % Carbon. This equation was developed from UK moorland soils and has been successfully applied in studies of carbon content on blanket peatlands in the UK (Garnett et al., 2001; Parry and Charman, 2013). Furthermore, % Carbon results obtained for Fallahogy using this equation were in line with typical organic carbon contents in northern peatlands (Charman et al., 2013). LARCA (g C m^{-2} y^{-1}) was calculated by dividing the cumulative carbon mass over a given period by the number of years (Clymo et al., 1998). Apparent total carbon accumulated (ATCA) was calculated as the sum of the total carbon accumulated in each 1 cm^3 interval between the peak shard concentrations of the FAL_1 and FAL_3 tephras.

3.4. Plant macrofossils

In order to reconstruct the microtopography at the coring location at the time of tephra deposition, plant macrofossil analysis was conducted on samples corresponding to peak tephra shard concentrations for the 1510 and 1947 eruptions of Hekla (see Section 4.3). Samples of c. 3 cm^3 of peat were sieved at 125 μm, floated in a petri-dish and examined at 10–50× magnification using a standard binocular microscope. Volume percentages were assigned using a modified version of the quadrat leaf count method of Barber et al. (1994). Moss leaves and epidermal tissues were picked and mounted onto slides for identification at higher magnification. *Sphagnum* was identified to section or species when possible.

3.5. Statistical methods

Cluster analysis with bootstrap resampling (Suzuki and Shimodaira, 2006) and PCA were applied, but did not help greatly to discriminate between the three tephras (Supplementary File, Figs. S1, S2).

4. Results and discussion

4.1. Stratigraphy

The tephrostratigraphic and SCP profiles for 15 cores (named A-O) are displayed in Fig. 3. Although there is some variation in the depth of the tephra layers, all but one of the cores contain three peaks in tephra abundance. The three tephra layers are more distinct in some cores than others. This is most likely due to differences in local accumulation rate and vegetation composition. In some instances the FAL_1 and FAL_2 tephras show a degree of merging toward the tails of their vertical distribution. This suggests that the time between these two events may represent the minimum temporal resolution of eruption events which can be recorded, at least in areas of this peatland where peat accumulation is slower.

Some cores (D and G) show slight deviations from the majority of profiles. In core G, the top of the FAL_1 tephra peak was not recovered, and there is also a rise in SCPs in the uppermost sample indicating that the true SCP peak in this profile may be missing. Therefore we suggest that the top of core G is absent; this is taken into account in subsequent analyses.

Core D appears to have experienced a high rate of accumulation between FAL_1 and the present surface when compared to other cores. However, the assignment of the FAL_1 tephra is supported by its position in line with the rapid increase in SCPs c. 1950 and the FAL_1 and FAL_2 tephra layers are separated by a sample containing no tephra shards. Plant macrofossil analysis indicates that core D may have been a pool or low hollow in the past. There is abundant *Menyanthes trifoliata* 'bog bean' epidermis corresponding with the FAL_3 tephra layer and *Sphagnum* section *Cuspidata* corresponding

with the FAL_1 tephra. All cores were extracted from lawn microforms at the time of coring, therefore a transition between pool or low hollow and lawn microform appears to have occurred in this core between the FAL_1 tephra and the time of coring. The high accumulation rate post FAL_1 in this core might be attributed to a rapid increase in the rate of peat accumulation related to the temperature rise during the twentieth century.

Unlike the majority of cores, core C shows only two peaks in tephra shard concentration. Furthermore, the tephra in core C at a depth of 48–50 cm is distinct from those detected in other cores both in terms of colour and morphology. The anomalous tephrostratigraphy of core C might be attributed to a post-depositional disturbance in peat accumulation. Disturbance events, such as fire and bog bursts, can occur naturally (e.g. Caseldine and Gearey, 2005). However, core C is in close proximity to an area of drainage and peat extraction (Fig. 2). This is likely to be the cause of the anomaly in peat accumulation. For this reason core C was excluded from subsequent analyses.

4.2. Shard morphology

Shards from all three tephras are predominantly light brown and morphologically similar (Fig. 4). Shard size ranges from 15 to 155 μm indicating that relatively large shards can be transported long distances, particularly if shard terminal velocity is low due to a high degree of vesicularity (Stevenson et al., 2015).

4.3. Shard geochemistry and assignment to eruptive event

The major element geochemistry of the three tephra layers detected at Fallahogy is similar. They have bimodal character and include a minor rhyolitic component, as well as dominance of the dacite-andesite composition (Fig. 5; full geochemical dataset is provided in the Supplementary File, Table S1). The geochemistries closely resemble those of tephra from the Hekla (H) eruptions in 1510 and 1947 (Dugmore et al., 1995; Hall and Pilcher, 2002; Larsen et al., 1999; Pilcher et al., 1996; Swindles, 2006). There is good evidence, supported by ^{14}C dating, as well as geochemistry, that the tephras of H1510 and H1947 reached the UK and have been found in many peatlands in Northern Ireland (Lawson et al., 2012). Distinguishing between FAL_1 and FAL_3 based on co-variation major element diagrams proved difficult (Fig. 6), although some discrimination can be observed between the geochemistry of FAL_2 and the other tephras (Fig. 6c, d). FAL_2 generally has a higher TiO$_2$, FeO$_t$ and P$_2$O$_5$ content than FAL_1 and FAL_3.

4.4. SCPs as a method of distinguishing between historically-deposited tephras

Where shards from different tephras are not easily distinguished by their geochemistry, in some instances SCP profiles can be used to complement geochemical data (Swindles and Roe, 2006). SCPs provide a chronological marker for the last ~150
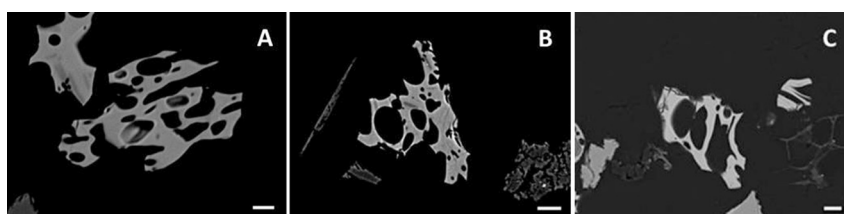

Fig. 4. Scanning electron microscope images of typical tephra shards exposed for geochemical analysis (a) Hekla 1510 (b) Hekla 1845 (c) Hekla 1947. White scale bars are 10 μm.
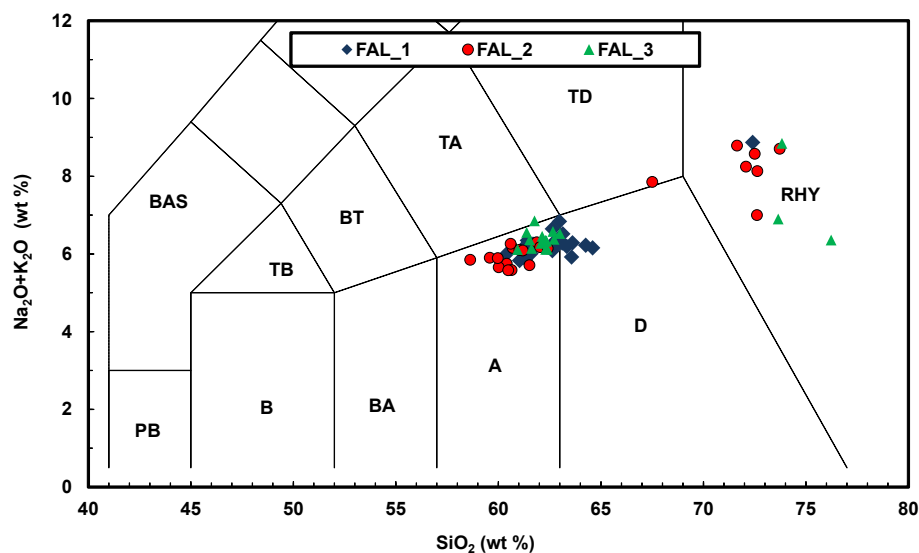
Fig. 5. Total Alkali Silica (TAS) Diagram showing the three tephras detected in core A at Fallahogy (raw data). Shards are mainly of andesitic-dacitic geochemistry. Annotations follow standard terminology e.g. RHY = Rhyolite, D = Dacite, A = Andesite (Le Maitre et al., 1989).
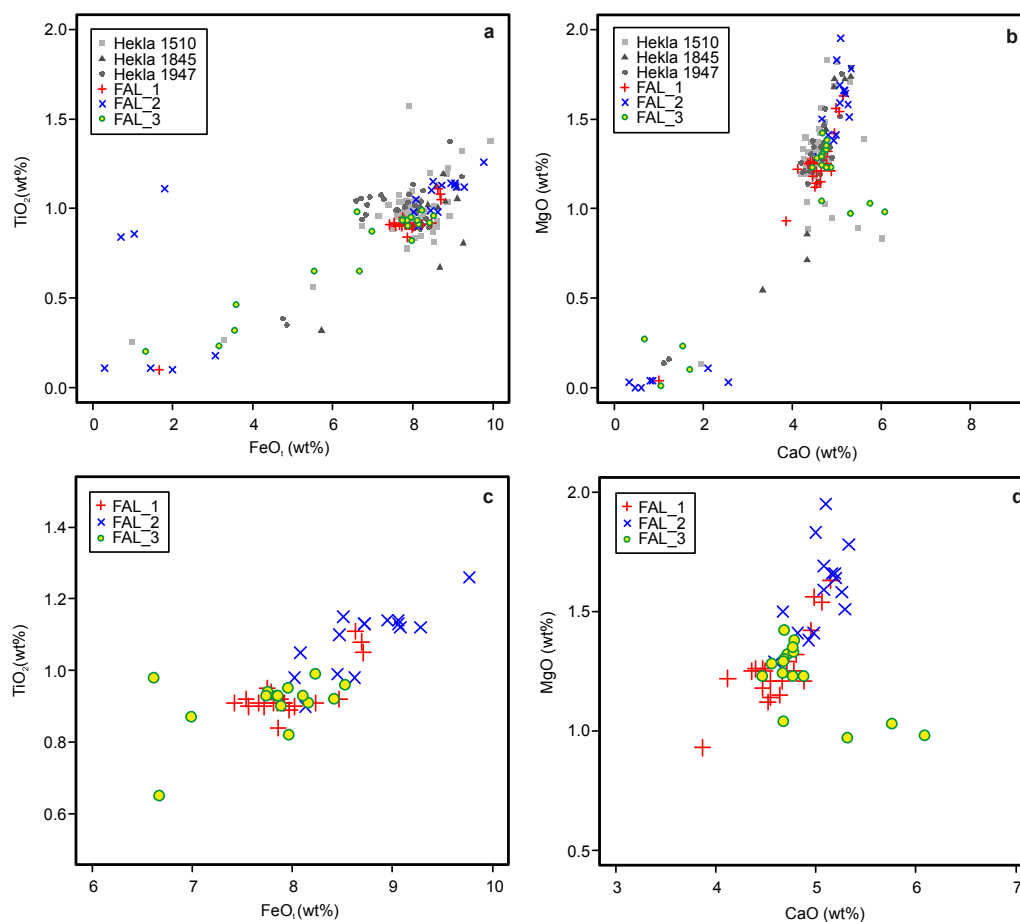

Fig. 6. Tephra geochemistry co-variation diagrams for (a–b) full range of FeO_t(wt%), TiO_2(wt%), CaO(wt%), MgO(wt%) values for the three tephra horizons in core A at Fallahogy plotted against type data for the Hekla eruptions of 1510, 1845 and 1947 from Tephrabase (Newton et al., 2007). (c–d) a restricted range of FeO_t(wt%), TiO_2(wt%), CaO(wt%), MgO(wt %) values for the three tephra horizons in core A at Fallahogy to show in more detail the overlap between the geochemical distributions, all data are normalised.

years (Renberg and Wik, 1984), appearing in this region c. AD 1850 and reaching peak abundance AD 1978 ± 6 years (Rose and Appleby, 2005). The FAL_3 tephra occurs before SCPs appear in the profiles at Fallahogy suggesting a date prior to 1850. The

increase in abundance of SCPs corresponding with the FAL_1 tephra in the majority of cores suggests a date around AD 1950. In the majority cores from Fallahogy, FAL_2 occurs just after the appearance of SCPs in the peat profile, suggesting a date around the time

of the first appearance of SCPs in this region (c. 1850 AD).

Although SCP profiles offer further information for the dating on peat profiles, they must be interpreted with caution because SCPs are themselves subject to movement in the peat matrix. In some instances it appears that the peak in SCPs (AD 1978 ± 6 years) coincides with the peak in tephra concentration for the FAL_1 event. Given that there were no large eruptions of silicic tephra in Iceland in the 1970s or 1980s (Larsen et al., 1999) and given that no claims of cryptotephra layers in Irish peatlands later than Hekla 1947 tephra have ever been made in the literature, we infer that the apparent coincidence of the SCP and tephra peaks is an artefact of either: i) slow rates of peat accumulation between 1947 and c. 1978, or ii) the differential vertical movement of tephra and SCPs. Such differential movement might result from differences in the deposition (continuous vs. one event), morphology, density or size of SCPs and tephra.

4.5. Possible sources for FAL_2

Although FAL_2 has a slightly different major element geochemistry (e.g. slightly higher TiO_2 and FeO_t) to FAL_1 and FAL_3, it shows some similarity and therefore may be derived from the same volcanic system. Furthermore, the Hekla volcano has produced the majority of widespread mid to late Holocene cryptotephras, many of which are of a bi-modal composition. There were five recorded eruptions from Hekla between 1510 and 1947 which produced silicic tephra. Many eruptions produced low tephra volumes or had dominant fallout pathways toward the north of Iceland (Larsen et al., 1999, 2014). Apart from H1845 there is no solid documentary or geochemical evidence that any of these tephras reached northwest Europe. However, there is documentary evidence for the fallout of tephra on the Faroe Islands during AD 1845, suggesting that tephra from the H1845 eruption travelled some distance in a south-easterly direction (Connell, 1846). A report of tephra on the Orkney Islands, dated by interpolation to ca. AD 1800 and with a similar geochemistry to that of H1947 and H1510, has also been tentatively linked to the eruption of H1845 (Wastegård, 2002). To further support assignment to H1845, FAL_2 was plotted against the major element geochemistry of all tephras dated to between 1510 and 1947 AD in the Tephrabase geochemical database (Supplementary File, Fig. S3). There was no clear match with any of these tephras. We therefore correlate the FAL_2 tephra to the eruption of Hekla 1845.

It appears that H1845 may be an under-recognized tephra in N. Ireland. The shard count totals for this tephra at Fallahogy are generally low (<40 shards cm^{-2}). Low shard concentration and a similar geochemistry to other historical Hekla tephras may have prevented detection in some previous research, particularly in peatlands with lower accumulation rates where the tephra peaks for H1947 and H1845 may be challenging to distinguish. The H1845 tephra corresponds to, and provides a dating isochron for palaeoenvironmental studies concerned with the end of the Little Ice Age as well as the Irish famine of 1845–1849, which was a period of great hardship, economic and social importance in Irish history (O'Rourke, 1994).

Based on the SCP profiles, information about tephras previously identified in this region and geochemical data the tephra layers are assigned to the Hekla eruptions of 1947 (FAL_1), 1845 (FAL_2) and 1510 (FAL_3). We suggest that SCP stratigraphies may be valuable for distinguishing tephra shards from the eruption of H1845 (FAL_2) which occur at the beginning of the SCP profile in this region.

4.6. Do cryptotephra layers in peatlands reflect fallout concentrations?

4.6.1. Within-site variation

The same sequence of three tephras was found in 14 of the 15 cores at Fallahogy (Fig. 3). The presence of three peaks indicates three distinct historical ash fallout events. This suggests that in small, unforested, undisturbed peatlands like Fallahogy, where there is a low chance of snow cover at the time of tephra deposition, the presence or absence of tephra from a given eruption can be highly consistent from one core site to another. The extraction of almost any single core from an undisturbed area of the Fallahogy peatland would have been sufficient to determine the presence or absence of all three tephras. However, total shard counts for each tephra layer differ between the cores. The total number of shards for H1510 (total deposition per square centimetre of peatland surface) ranges from 97 to 508 shards cm^{-2} (median 143). Shard counts for H1947 and H1845 also show an order-of-magnitude variation in different cores, with counts of 21–236 cm^{-2} and 10–156 shards cm^{-2} respectively (Fig. 7). Some small variation in TSCs might be expected as a result of analytical uncertainty. However, differences of this magnitude between cores are most likely due to real spatial variation. A Mantel test of the null hypothesis that there is no spatial autocorrelation in the TSCs for the H1510 tephra indicated that, over scales of tens to hundreds of metres, there is no spatial autocorrelation in shard counts ($p = 0.82$). This suggests that any systematic sorting of shards is predominantly occurring at smaller or larger scales. Variation in the total number of tephra shards relating to a given eruption across different cores in a peatland may plausibly be due to three sets of processes: i) uneven deposition from the atmosphere; ii) lateral movement of tephra over the surface of the peatland prior to its incorporation in the peat; iii) loss of tephra through processes such as hydrolysis and dissolution to different extents in different places.

The latter appears unlikely, as although it has been suggested that tephra may dissolve in acidic environments, dissolution is slow, and based on the results of laboratory experiments, rhyolitic shards are predicted to survive for more than 4500 years at a pH of 4 (conversely, mafic tephras deteriorate more rapidly) (Wolff-Boenisch et al., 2004). The tephras detected at Fallahogy are of intermediate composition and have been deposited in the last 450 years, therefore although loss of shards due to dissolution cannot be ruled out, it is unlikely. No visible signs of damage to tephra (e.g. silica gel layer formation or pitting: cf. Blockley et al., 2005) were identified during microscope analysis.

Following deposition, any lateral transport of tephra is likely to occur relatively quickly because there is evidence that tephra is rapidly incorporated into the peat matrix. Experiments indicate that tephra deposited onto a peatland can percolate downward by up to 6 cm in less than 2 years (Payne et al., 2005). Even allowing for subsequent decomposition, long term peat accumulation at Fallahogy over the last c. 5000 years has been relatively rapid in comparison to northern peatlands in general (11 years cm^{-1}; (Roland et al., 2014)). Therefore tephra is likely to be incorporated into the peat more quickly than in peatlands where accumulation rates are lower, which is typically the case at higher latitudes. Variation in TSC across the peat surface at the peatland (macro) scale might be facilitated during periods when the water-table is at or above the surface, resulting in surface flow and therefore the transport of shards from higher to lower areas of the peatland by water, or by preferential deposition of tephra on areas of higher ground, where the dominance of relatively tall vascular plants might encourage interception of airborne shards. However, there is no correlation between the elevation of the core location (at time of coring) and the total number of shards for any of the three

Fig. 7. Maps showing the spatial distribution of cores alongside total shard counts (cm^{-2}) for Hekla 1510, 1845 and 1947 eruptions. Apparent total carbon accumulated between 1510 and 1947 is also shown. Circle sizes are proportional to total shard counts per unit area or apparent total carbon accumulated.

eruptions.

Similarly, there is no relationship between total shard count for the H1510 and H1845 tephras and distance from the edge of the peatland (Spearman's rank correlation (SRC) Supplementary File, Table S2). However, for the most recent eruption (H1947) there is a weak relationship between TSC and distance from the edge of the peatland (SRC r = 0.65, p = 0.016). Shard counts are higher toward the centre of the peatland, suggesting that tephra was either preferentially deposited onto the cupola or preferentially lost from the rand slope.

Either a change in peatland topography or in the processes operating at the macro scale over time might explain why the most recent tephra layer shows a weak non-random pattern of distribution, whilst the earlier two tephras do not. There is no evidence at Fallahogy that the peatland topography at the macro-scale has changed substantially over the last 500 years. However, there is some evidence of a change in water-table depth. Fig. 8b shows the reconstructed water-table depth at Dead Island bog, just 1.2 km south of Fallahogy (Swindles et al., 2010). During the Little Ice Age (LIA, c. 1400–1850 AD), a period characterised by wet and cold conditions which has been identified across multiple sites in Europe (Blundell and Barber, 2005; De Vleeschouwer et al., 2009; Turner et al., 2014) and Ireland (Swindles et al., 2013b), the Dead Island Bog reconstruction suggests the water-table was at or above the peat surface (Swindles et al., 2010). Between 1845 and 1947 the water-table dropped considerably, which could have reduced the potential for redistribution of tephra from the middle of the peatland towards the edges by surface flow.

Given that systematic differences in the total shard count per unit area only appear for one tephra layer, evidence for movement of tephra at a macro scale is inconclusive. Our results also indicate that the movement of tephra shards over the peat surface is variable between events. There are no cores which consistently show higher or lower than average counts for each event. This may reflect the differences in water-table (at or below the peatland surface) during each tephra fall, or the complex interactions of different reworking processes under slightly different environmental conditions.

Hummock and hollow microforms are common on many peatlands. Fallahogy has a well-defined hummock, hollow and lawn microtopography (see Section 2). Hummocks represent raised features where vascular vegetation types dominate and might therefore be expected to preferentially trap airborne particles; however, tephra might also be delivered to hollows during periods of surface water flow. Previous research into pollen concentrations across hummock and hollow microforms identified higher pollen concentrations in hollows (Irwin, 1989). However, the continuous deposition of pollen can make it difficult to decipher whether the differences in concentration are attributable to differential deposition, post-depositional redistribution or dissimilarities in accumulation rates.

All cores in this study were extracted from lawn microforms. However, peatland microforms have been shown to migrate or alter over time (Kettridge et al., 2012). A different microtopography at the coring location at the time of tephra deposition might explain the differences in shard counts. It was initially suggested that the cyclic regeneration of hollows into hummocks was self-regulating, driven by faster rates of peat accumulation in hollows (Osvald,
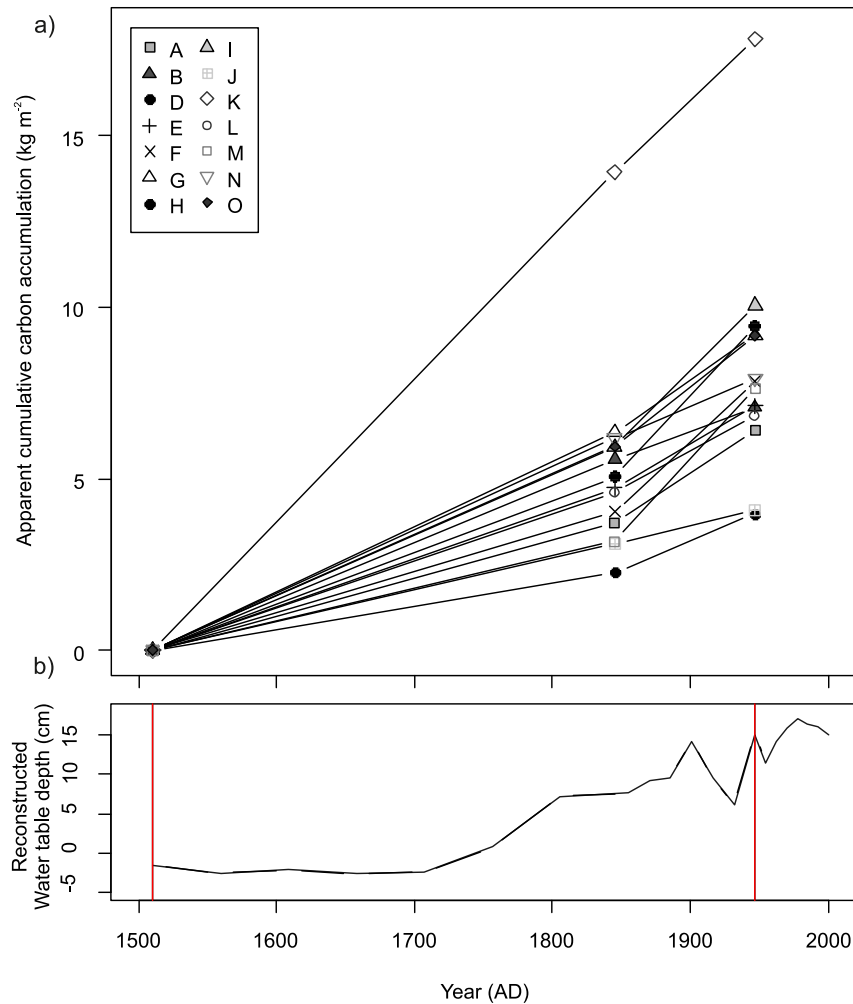
Fig. 8. (a) Graph showing the apparent cumulative carbon accumulation between AD 1510 and AD 1947 in 14 cores at Fallahogy. The peak shard concentrations for tephra from the eruptions of Hekla 1510, Hekla 1845 and Hekla 1947 are used as chronological tie points. (b) Water-table depth reconstruction data from Dead Island bog (~1.2 km from Fallahogy) (Swindles et al., 2010) based on the transfer function of Charman et al. (2006). Red lines indicate tephra horizons identified in both sites and used as chronological tie points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1923; Von Post, 1910). Following increasing evidence that hummocks are long-term features controlled mainly by changes in bog surface wetness, the theory of cyclic regeneration has largely been disregarded (Barber, 1981; Svensson, 1988; Walker and Walker, 1961). Hummocks are now considered long-term features linked to climate, rather than the product of autogenic peatland processes. However, there is no simple sequential or transitional relationship of hummock to hollow microforms with time (Ohlson and Økland, 1998).

Plant macrofossil analysis was conducted on the 14 randomly distributed cores at depths corresponding to the peak shard concentration in the FAL_1, FAL_2 and FAL_3 tephra layers to assess whether the microtopography at each coring location had changed significantly since the FAL_3 tephra layer. The results suggest that the majority of cores had been extracted from areas where the microtopography had not changed dramatically (from a lawn community) in the last 450 years. Core D contained some unambiguous indicators of very wet conditions corresponding with the H1510 tephra layer (see Section 4.1). However, there does not seem to be an exceptionally large or small TSC for the H1510 tephra in this core.

On the three hummock-to-hollow transects (labelled HH 1, 2

and 3), tephra was more abundant in cores where the surface vegetation type at the time of coring was at least partly composed of *Sphagnum* (Fig. 9). The vegetation appears to be more important than the downslope movement, in that, where *Sphagnum* appears in the vegetation community on the mid-slope (e.g. HH3), the presence of *Sphagnum* deters further downslope movement. Our results are in agreement with those of an experimental study into the trapping of SCPs in *Sphagnum* peat, which found that the majority (>99%) of SCPs were trapped by the *Sphagnum* (Punning and Alliksaar (1997).

The redistribution of tephra shards may also be occurring at even smaller scales (sub-micro-topographical). Surface water flow is likely to be affected at these scales by the interplay between vegetation composition and small changes in gradient.

4.6.2. Within site vs. between site variation

In order to make valid inferences about regional ash cloud fallout based on TSC measurements in single cores, the variation in the total number of tephra shards relating to a given eruption within a site must be lower than the variation between sites. Tephra from the eruption of H1947 has been identified in 12 peatlands across Northern Ireland (Rea et al., 2012), with TSCs appearing to
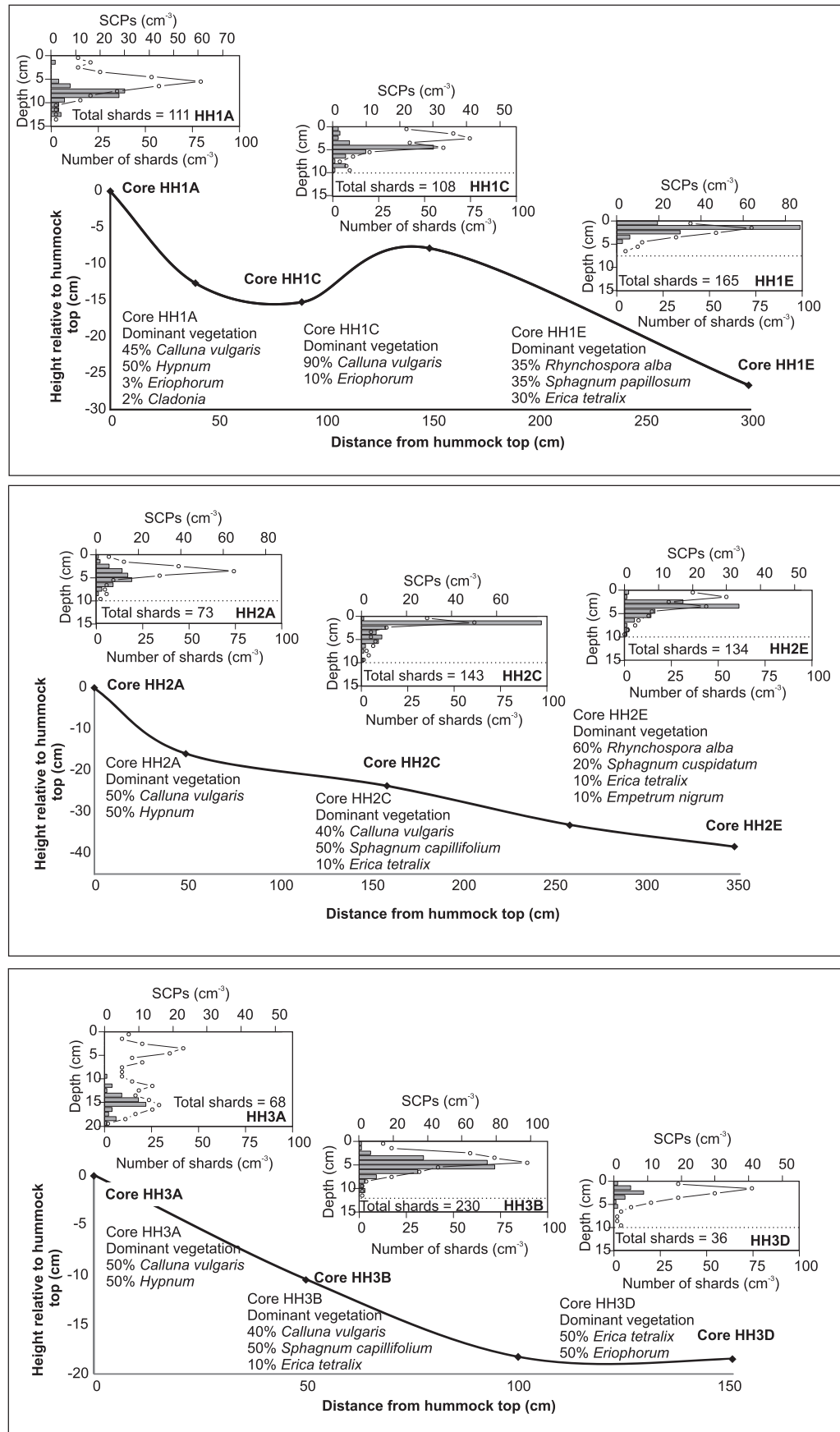
Fig. 9. Diagram indicating shard counts and surface vegetation at time of coring at various points along three transects taken from hummock to hollow on Fallahogy peatland.

vary along a West to East gradient. Higher concentrations in western sites were interpreted as reflecting higher ash fallout in this region (Rea et al., 2012). The range of TSCs was smaller in the 15 cores at Fallahogy than the range of TSCs across the 12 different peatlands in Northern Ireland (Fig. 10). This suggests that, in this instance, regional-scale factors such as precipitation and ash cloud density had a greater influence on the spatial distribution of TSCs than local (within-site) processes.

Nevertheless, using the TSCs from one core to infer ash fallout concentration over the entire peatland is not advisable due to a large degree of internal variation in TSCs within a site. In order to estimate how many cores would be required to establish a reliable median value we conducted a bootstrap analysis (10,000 iterations, random sampling with replacement) of shard counts for each of the tephra layers (Fig. 11). The number of cores required to estimate the median value adequately is subjective. However, multiple cores would have been advisable for any of the three tephra layers detected at Fallahogy peatland.

4.7. Variation in shard counts for different events

Shard counts vary in different tephra layers within a single core as well as the same event from multiple cores. Mann–Whitney tests indicated a significant difference between each pair of events ($p < 0.05$, $n = 14$ [$n = 13$ for H1947]). H1510 has the highest shard counts, followed by H1947 and H1845 (Fig. 12). The same pattern of relative abundance has been found in many other Northern Irish peatlands (Rea et al., 2012; Swindles, 2006).

The higher TSCs for H1510 may reflect the nature of the eruption which had a much larger recorded tephra volume (0.32 km^3) when compared with H1947 (0.18 km^3) and H1845 (0.23 km^3) (Larsen et al., 1999, 2014). The eruption of H1510 is also inferred (on the basis of its deposits in Iceland) to have had a more intense Plinian phase than H1947 (Larsen et al., 2014), perhaps resulting in more intense distal tephra transport. Less information is available about the nature of the eruption of Hekla in 1845, although it is described as having wide tephra dispersal within Iceland (Larsen et al., 2014). The estimated tephra volume for H1845 is similar to (within error) that of H1947, which is not reflected in the TSC for these eruptions at the Fallahogy site. This suggests that there is no simple relationship between tephra volume and the total number of tephra shards relating to a given eruption in cores from distal peatlands.

4.8. Spatial trends in spheroidal carbonaceous particle (SCP) concentration

Tephra is not the only palaeoenvironmental proxy to be deposited onto a peatland from the atmosphere. SCPs, which are a product of the combustion of fossil fuels, are often used as a proxy for atmospheric pollution, with an assumption that the concentration or accumulation rate of SCPs is related to the magnitude of pollution (i.e. the concentration of SCPs in the atmosphere) at the time of deposition. For example, the concentrations of SCPs in lakes have been used to infer differences in the degree of atmospheric pollution in different regions (Rose et al., 1999; Rose and Harlock, 1998). Our results suggest that SCP concentrations within a peatland can be highly spatially variable (the total number of SCPs in our cores range from 97 to 2268 (summing all samples containing SCPs)). Therefore any inference of pollution levels based on SCP counts from one core in a peatland should be undertaken with caution.

To determine whether different microparticles are reworked in the same way we tested the hypothesis: Tephra shard concentrations are positively correlated with SCP concentrations across a peatland. If the two different types of microparticle are deposited and reworked in the same way, we might expect cores with higher than average tephra shard concentrations to also contain higher than average SCP concentrations. Two tests for correlation were conducted: i) between total tephra shard counts and total SCP counts in the whole core; ii) between total shard counts at one point in the core and total SCP counts at the same depth (1947 tephra peak). In both cases there was no significant relationship between the counts of SCPs and tephra shards at the 5% level.

Although this suggests that tephra shards and SCPs are reworked differently on a peatland it is not conclusive. It is difficult to compare microparticles which have been continuously deposited (SCPs) with microparticles which are the result of a single event and have been deposited over a number of days or weeks (tephra). However, it is possible that the microparticles are reworked differently due to differences in their morphology, density or size. Different weather conditions and water-table depth at the time of deposition may also affect reworking.

4.9. Implications for studies of carbon accumulation

4.9.1. Spatial trends in apparent carbon accumulation
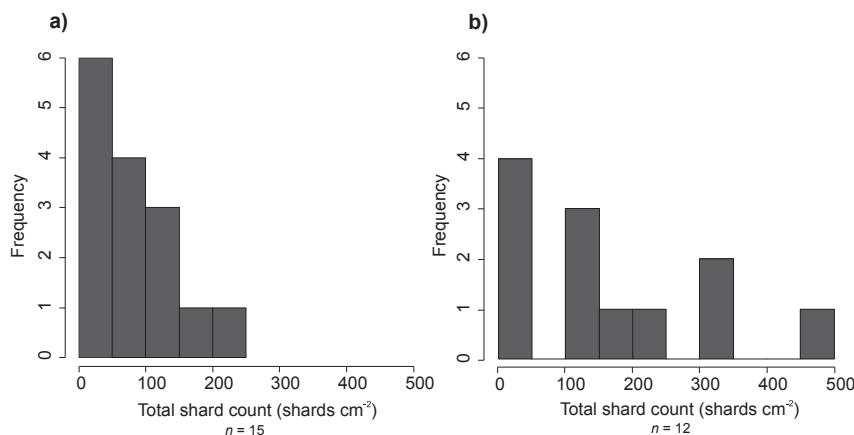Carbon accumulation in peatlands is controlled by the balance

Fig. 10. Histograms showing the total shard counts for the a) Hekla 1947 eruption in 15 cores at Fallahogy (13 cores from this study and 2 cores examined by (Rea et al., 2012)) and b) at 12 other sites across Northern Ireland (Rea et al., 2012).
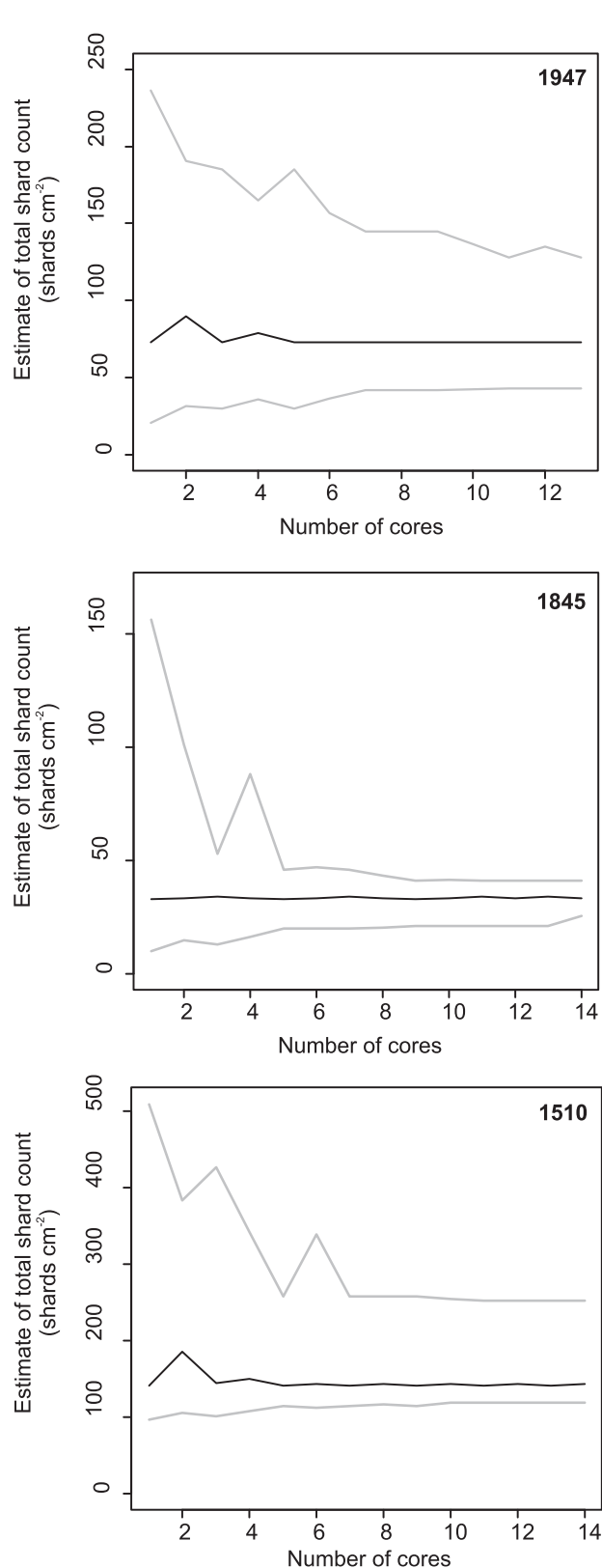
Fig. 12. Boxplots showing the total shard counts for Hekla 1947, Hekla 1845 and Hekla 1510 eruptions in 13 cores at Fallahogy. Boxplot convention is as follows: boxes indicate the interquartile range; the central line through each box indicates the median. The far extent of the upper and lower lines from each quartile indicate the maximum and minimum.

Fig. 11. Results of a bootstrap analysis (10,000 simulations) estimating median shard concentration with different amounts of cores for the three Hekla eruptions. The 0.025 and 0.975 boundaries are indicated by light grey lines. Although the number of cores required for a robust estimate of median shard concentration is subjective, this analysis suggests that multiple cores are required to adequately assess median total shard counts for these three events.
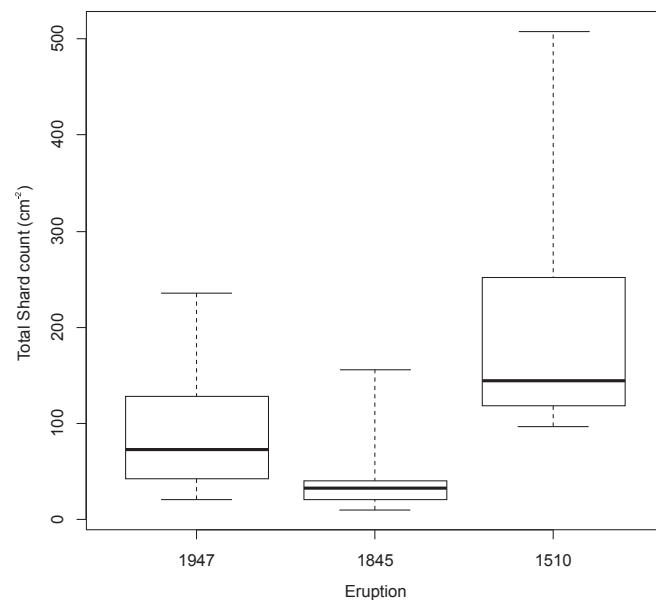
between organic matter production and decay (Clymo, 1984). Rates of production and decay vary according to peatland microtopography due to differences in vegetation community and water-table position (Belyea and Clymo, 2001).

The average peat accumulation rate at Fallahogy between 1510 and 1947 (20 years cm^{-1}) was in the range of 10–40 years cm^{-1}, which is typical for peatlands in Northern Ireland (Swindles and Plunkett, 2011). Peat accumulation rate and apparent total carbon accumulation (ATCA) varied spatially (Fig. 7). The ATCA between 1947 and 1510 ranged from 4.0 to 17.8 kg C m^{-2}, although ATCA in the majority of cores was around the average of 8.6 kg C m^{-2}.

These results indicate that ATCA in this peatland is spatially variable over scales of tens to hundreds of metres. There is no spatial autocorrelation in ATCA at these scales, suggesting that any spatial trends are occurring over larger or smaller scales (Mantel test, p-value 0.60). There is also no relationship between ATCA and elevation or distance from the peatland edge (SRC, Supplementary File, Table S2). Instead, differences in accumulation might be occurring on a microform scale.

Plant macrofossil analysis suggests that there has been no significant change in the microform (lawn) at the majority of the core locations over the last 450 years. However, core D contains indicators of wet conditions, symptomatic of the LIA, corresponding with the H1510 tephra (see Section 4.1). Core D has the lowest ATCA of all the cores between 1510 and 1947 (4.0 kg C m^{-2}), although the accumulation rate increases post 1947. The low ATCA in Core D in the period between 1510 and 1845 might be attributed at least in part to localised very wet conditions during the LIA.

Core K is of particular interest as it shows a much higher LARCA than the other cores. As a check, the FAL_3 tephra in core K was analysed to exclude the possibility that the shards are from a different tephra. Geochemical analysis and SCP chronology confirm assignment to H1510 eruption (Supplementary File, Fig. S4) and therefore we can be confident in the high rate of peat accumulation between 1510 and 1845 (0.094 cm year^{-1}). It would appear the cause is localised as other cores located nearby do not show elevated peat accumulation rates. Large proportions of

unidentifiable organic material in plant macrofossil samples from core K suggest high levels of decay. High rates of peat accumulation have been shown to occur where the balance between production and decay is optimal (Belyea and Clymo, 2001). We suggest that a high rate of litter productivity by vascular plants (*Calluna vulgaris* roots were abundant in plant macrofossil samples) has resulted in high peat accumulation at this coring location, despite a relatively high rate of decay.

4.9.2. Temporal trends in apparent carbon accumulation rate

When considering recent temporal changes in the rate of carbon accumulation, it is important to note that apparent carbon accumulation rates would be expected to increase towards the surface, because younger peats have undergone relatively less decomposition than older peats. Consideration must also be given to the position of the oxic zone (or active layer), where decay rates are higher than in the anoxic zone below. Although none of our cores display a clear boundary, recent carbon accumulation (between 1947 and present) is not included in our analysis as the peat is likely to be undergoing particularly rapid decomposition in the oxygenated zone.

As would be expected, the majority of cores (11 out of 14) show lower peat accumulation rates between 1510 and 1845 when contrasted against the period between 1845 and 1947, with average peat accumulation rates of 0.04 cm yr^{-1} and 0.06 cm year^{-1}, respectively (Fig. 8). The difference in peat accumulation is reflected in LARCA values of 16.6 (1510—1845) and 28.9 g C m^{-2} y^{-1} (1845—1947). The slower peat accumulation during the period 1510 to 1845 might be attributed to a reduction in primary productivity due to the LIA (Charman et al., 2013), however it is difficult to untangle the possible climatic link from the impact of increased time for decomposition to occur in the deeper peats. Three cores show (slightly) higher rates of accumulation during 1510—1845 than during 1845—1947, perhaps indicating some degree of autogenic variation in the balance of primary production and decay.

5. Conclusions

1. Using geochemistry and SCP profiles we have detected 3 tephra layers that correlate to the Hekla eruptions of 1510, 1845 and 1947 in 14 cores from the same peatland, suggesting that in small, largely undisturbed, mid-latitude peatlands, the presence or absence of tephra from a given eruption can be determined, with a high degree of certainty, by analysing a single core.
2. Shard counts for a given eruption showed an order-of-magnitude variation between cores from the same site, suggesting differential deposition or lateral post-depositional movement of tephra. No spatial autocorrelation was identified over the scale investigated (tens to hundreds of metres), indicating that any differential deposition or reworking occurs at different scales.
3. Studies comparing tephra shard concentration across multiple sites must consider the differences in shard concentration within a single site. Bootstrap analysis suggests that multiple cores are required in order to ascertain a reasonably reliable median shard count for a site.
4. There was a significant difference in the TSCs for the tephras from the 3 Hekla eruptions, suggesting that in some cases shard counts might be a useful proxy for ash cloud density. However, owing to the influence of meteorological conditions, results must be interpreted with caution.
5. The three historical tephra layers detected in the 14 cores at Fallahogy allowed us to establish a chronological framework within which to examine spatial differences in carbon

accumulation within a site. We find differences in the apparent total carbon accumulation between 1510 and 1947 AD.
6. Further work is required on (i) the impact of microtopography on tephra distribution, and (ii) tephra dissolution processes and rates in acidic low pH environments.

Acknowledgements

Appendix A. Supplementary data

Supplementary file related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2015.07.025.

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