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Do peatlands or lakes provide the most comprehensive distal tephra records?

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ABSTRACT

Despite the widespread application of tephra studies for dating and correlation of stratigraphic sequences ('tephrochronology'), questions remain over the reliability and replicability of tephra records from lake sediments and peats, particularly in sites >1000 km from source volcanoes. To address this, we examine the tephrostratigraphy of four pairs of lake and peatland sites in close proximity to one another (<10 km), and evaluate the extent to which the microscopic (crypto-) tephra records in lakes and peatlands differ. The peatlands typically record more cryptotephra layers than nearby lakes, but cryptotephra records from high-latitude peatlands can be incomplete, possibly due to tephra fallout onto snow and subsequent redistribution across the peatland surface by wind and during snowmelt. We find no evidence for chemical alteration of glass shards in peatland or lake environments over the time scale of this study (mid-to late- Holocene). Instead, the low number of basaltic cryptotephra layers identified in distal peatlands reflects the capture of only primary tephra-fall, whereas lakes concentrate tephra falling across their catchments which subsequently washes into the lake, adding to the primary tephra fallout received in the lake. A combination of records from both lakes and peatlands must be used to establish the most comprehensive and complete regional tephrostratigraphies. We also describe two previously unreported late Holocene cryptotephras and demonstrate, for the first time, that Holocene Icelandic ash clouds frequently reached Arctic Sweden.

1. Introduction

Tephrochronology can be defined as the use of tephra (volcanic ash) layers for the dating and correlation of stratigraphic profiles. The technique was initially developed using visible tephra layers in Iceland (Thorarinsson, 1944), but the discovery of Icelandic tephra layers on the Faroe Islands and in Scandinavia allowed the extension of tephrochronology into regions further away from source volcanoes (e.g. Persson, 1966, 1968). The potential of distal tephrochronology was further advanced by the discovery of microscopic layers of volcanic ash ('cryptotephras') in peatlands, lakes, ice and marine cores across the North Atlantic and northern Europe (Dugmore et al., 1995; Gudmundsdóttir et al., 2011). Widespread tephra and cryptotephra layers can now be used to correlate stratigraphic sequences in different depositional environments and provide tie points for climate reconstructions across regions (Davies et al., 2012; Lane et al., 2013).

Despite the widespread application of cryptotephras for the dating and correlation of stratigraphic sequences, and more recently as a record of ash cloud frequency (Swindles et al., 2011, 2013b), there remain a number of questions over the chronostratigraphic reliability of cryptotephra layers in terrestrial archives. There is evidence for the gradual in-washing, within-basin focussing and re-deposition of cryptotephra layers in lakes (Davies et al., 2007; Pyne-O'Donnell, 2011). In peatlands, which have been proposed to record primary tephra-fall material, patchy tephra distribution patterns can occur due to fallout onto snow (Bergman et al., 2004), and there is evidence for the movement of tephra-derived glass shards across the peat surface by wind or water (Payne and Gehrels, 2010; Swindles et al., 2013a; Watson et al., 2015). Furthermore, despite the dominance of basaltic over silicic volcanism in Iceland and the potential for phreatomagmatic eruptions which have been shown to distribute fine ash over long distances, only five cryptotephras of basaltic composition have

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been detected in N. European sites over the last 7000 years, mostly in lake sediments (Lawson et al., 2012). This is in contrast to ~80 silicic cryptotephras which have been widely identified in both peatlands and lakes (silicic > 63% SiO_2: Dugmore et al. (1995)).

In this paper we investigate Holocene tephra records from lakes and peatlands in close proximity to one another (<10 km apart). Based on the assumption that both lake and peatland have received the same primary tephra-fall deposits, we aim to evaluate whether they record the same or different tephrostratigraphies. In addition, we evaluate the differential preservation of glass (tephra) shards in lakes versus peatlands.

2. Site description

Four pairs of sites in northern Europe (each comprised of one lake and one peatland) were identified using the following criteria: 1) close proximity (<10 km apart); 2) coverage of a range of meteorological conditions (e.g. high-latitude sites where tephra might be more likely to fall out onto snow, see Fig. 1); and 3) coverage of a range of different peatland and lake types (spanning a range of preservation conditions including acidic peatlands and alkaline lakes). Sites were favoured if prior information on basal age or outline chronology was available. A brief description of each site is given below; sites are listed according to their location on a south-west to north-east transect. Detailed information on site characteristics can be found in Table 1 and photos of each site can be found in Fig. S1.

2.1. Site 1: Claraghmore, Northern Ireland

Claraghmore bog is an intact raised bog. Previous palaeoecological studies suggest the site contains a peat record spanning much of the Holocene (Plunkett, 2006, 2009). Claraghmore Lake is one of two small lakes which lie at the bottom of a shallow slope immediately adjacent to the peatland. The lake is approximately 100 m in length, with a maximum water depth of 3.5 m at the time of sampling, and is bordered by *Quercus* and *Corylus* woodland. The lake margins are characterised by fens containing *Cyperaceae* and *Poaceae*. Lake sediments are composed of gyttja. To the best of our knowledge this study represents the first palaeoenvironmental investigation of this lake.

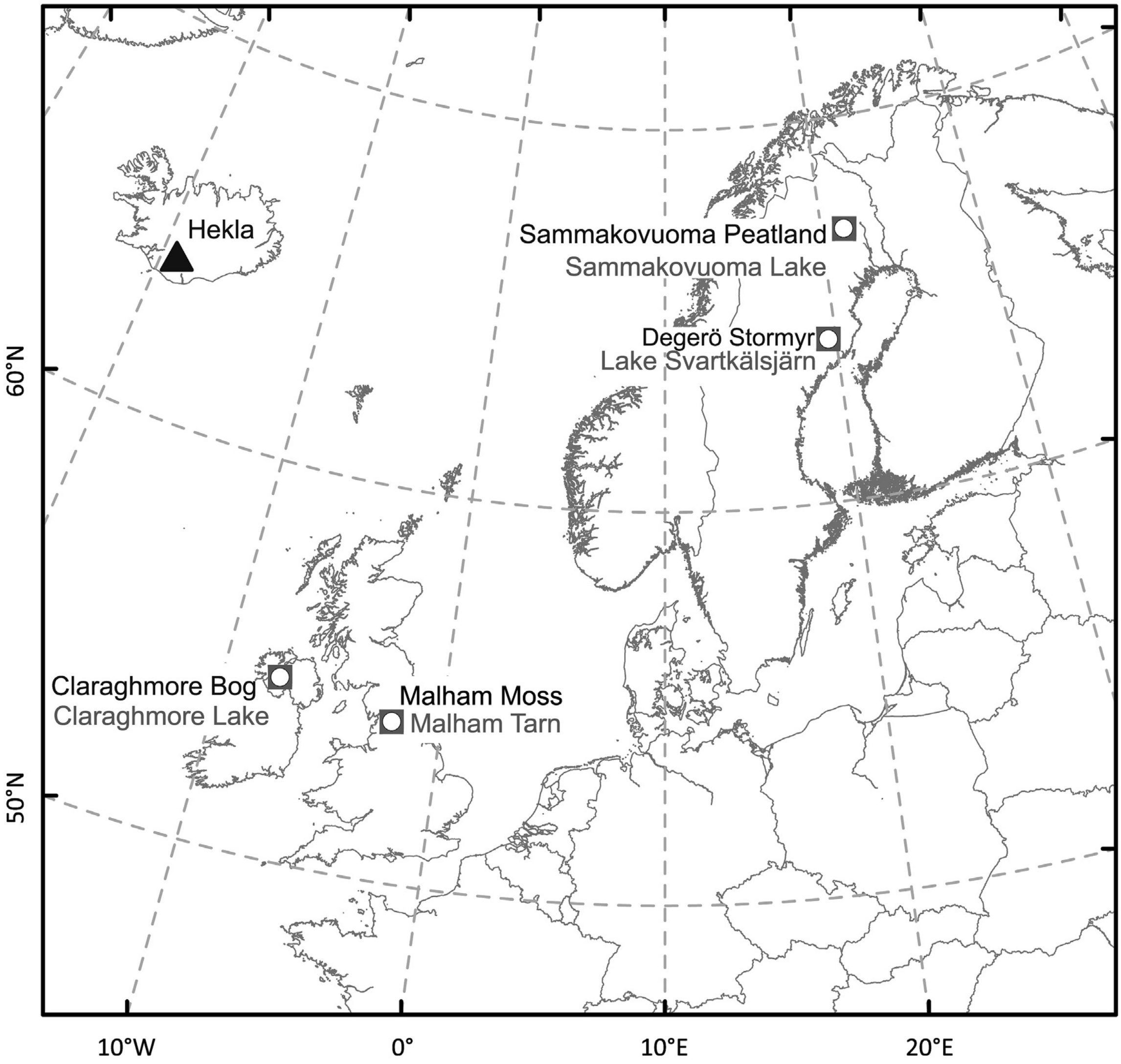

Fig. 1. Map showing the location of lake (grey square) and peatland (white circle) sites sampled in this study. The black triangle indicates the location of the Hekla volcano, the source for the majority of widespread late Holocene tephras in northern Europe.

Table 1
Location and characteristics of each of the lake and peatland sites included in this study. Shading indicates the pairing of peatland and lake sites. The climatic data refer to the following periods and sources: 1 = 1951–1980 (Sweeney, 1997); 2 = 1961–2000 (Burt and Horton, 2003); 3 = 1959–2000 (Burt and Horton, 2003); 4 = 1961–1990 (Alexandersson et al., 1991); 5 = 1961–1990 (Norwegian Meteorological Institute, 2015); 6 = 1961–1990 (Tveito et al., 2000).

Site	Lake or peatland (L/P)	Location (decimal degrees)	Elevation (m a.s.l.)	Site type	pH (at time of sampling)	Mean annual precipitation (mm y^{-1})	Mean annual temperature	Water depth at coring location (cm)	Length of core (cm)	Distance between lake and peatland
Claraghmore Lake	L	54.631°N, 7.450°W	78	Small lake	6.5	1000–1200^{1}	4 °C in January 15 °C in July^{1}	350	450	0.3 km Bearing of 310°
Claraghmore Bog	P	54.633°N, 7.454°W		Raised bog	N/A			NA	910	
Malham Tarn	L	54.096°N, 2.165°W	380	Small marl lake	8.2	1502^{2}	6.9°C^{3}	250	310	0.5 km Bearing of 282°
Malham Moss	P	54.097°N, 2.173°W		Raised bog	N/A			NA	640	
Lake Svartkälsjärn	L	64.264°N, 19.552°E	260	Small lake	6.7	520	2 °C with average temperatures of −12 °C in January and 15 °C in July^{4}	312	203	~9 km Bearing of 176°
Degerö Stormyr	P	64.181°N, 19.564°E	270	Acid bog complex	4.3			NA	440	
Sammakovuoma Lake	L	66.992°N, 21.500°E	237	Small lake	7.0	480^{5}	−2 to −3 °C^{6}	350	240	1.9 km Bearing of 280°
Sammakovuoma Peatland	P	66.995°N, 21.457°E		Acid bog complex	5.9		−1.5 °C^{5}	NA	440	

2.2. Site 2: Malham, England

Malham Moss is an ombrotrophic raised bog adjacent to Malham Tarn (lake). Over the last c. 8000 years *Sphagnum* peat has accumulated in Malham Moss up to a depth of up to 6 m (Pigott and Pigott, 1963). Malham Tarn is ~600 m in length and the lake sediments, which span more than 6 m, are composed mainly of *Chara* marls. The average water depth is ~2.5 m. The lake is fed by springs and its waters are alkaline (pH = 8.2: Pentecost (2009)). Previous palaeoecological research suggests a basal age for the lake sediments of c.12 000 cal yr BP (Nuñez et al., 2002).

2.3. Site 3: Lake Svartkälsjärn and Degerö Stormyr, Sweden

Degerö Stormyr and Lake Svartkälsjärn are located in the Västerbotten region of northern Sweden. Degerö Stormyr is an acid peatland complex with an area of 6.5 km^2 and peat depth of 3–8 m. The deepest peat has an age of c. 8000 cal yr BP (Nilsson et al., 2008). Lake Svartkälsjärn is a small lake with a total area of c. 0.05 km^2, catchment area of c. 2.5 km^2 and a water depth of 3.1 m at the time of sampling. Lake sediments are composed mainly of gyttja. Previous paleoecological research suggests the lacustrine sediment record (2.2 m) spans the period from 10,000 cal yr BP to present (Barnekow et al., 2008).

2.4. Site 4: Sammakovuoma, Sweden

The Sammakovuoma sites in northern Sweden represent the most northerly locations in this study. Radiocarbon dating suggests a peatland age of 9260 cal yr BP (depth 4.6 m) (Matts Nilsson, personal comm). Lake Sammakovuoma is a small lake (c. 400 m in length) with a water depth of 3.5 m at the time of sampling. Lake sediments are composed mainly of gyttja. The catchment vegetation comprises forest dominated by *Pinus*. The lake catchment also contains areas of bog and fen. To the best of our knowledge this study represents the first palaeoenvironmental investigation of this lake.

3. Methods

3.1. Field sampling

Where possible, cores from peatlands were extracted from areas containing the deepest peat. Lake cores were extracted from the middle of each lake in an attempt to minimise the risk of obtaining sediments exposed to reworking during previous lake level fluctuations. Samples were taken either from the peatland surface or from a small boat using a Russian D-section corer with either a 50 or 100 cm barrel length (sample diameter 5 cm and 9 cm respectively) following the parallel hole method (De Vleeschouwer et al., 2011).

3.2. Organic matter content

Organic matter content was determined through loss-on-ignition (LOI) which was conducted on adjacent 5–10 cm intervals on all cores. Samples were oven dried at 105 °C for 24 h, weighed and combusted in a furnace at 550 °C for 4 h following procedures described in detail in Chambers et al. (2010).

3.3. Tephra analysis

All cores were sub-sampled at 5–10 cm intervals, then combusted at 550 °C and treated with 10% HCl (Hall and Pilcher, 2002; Swindles et al., 2010). Samples containing mineralogical material or biogenic silica required sieving at 10 μm in an ultrasonic bath (no coarse sieving e.g. 125 μm required) and, in some instances (all lake sites and the Swedish peatlands), separation using heavy liquid floatation (Blockley et al., 2005). All residues (including heavy fractions) were examined to ensure extraction had been successful. Residues were rinsed thoroughly in deionised water, mounted onto glass slides using Histomount and examined on a Leica binocular microscope at ×200 and ×400 magnification. Where glass shards were identified, subsampling was repeated at 1 cm intervals. Comparing the number of shards (n shards g^{-1}) in the peak sample identified in a lake and peatland is not possible due to the difference in dry bulk density between peat and lake sediments. However, in order to give some indication of the relative concentrations of glass shards in peatlands and lakes, the total shard counts for each cryptotephra layer per cm^2 (total tephra deposited per square centimetre of peatland/sediment surface) were calculated by summing the numerical glass shard counts for all the depth samples within that layer (Table 2).

Tephra shards from peatlands with low minerogenic content were extracted for geochemical analysis using the acid digestion method (Dugmore et al., 1992). Samples were treated with conc. HNO_3 and H_2SO_4 before sieving the residue at 10 μm and rinsing with deionised water. Samples containing minerogenic material

Table 2
Cryptotephra layers detected in peatland and lake sites as part of this study.* = based on the age-depth model of Barnekow et al. (2008). Ages shown in Italics are based on age depth model (linear interpolation) from other dated tephras, median probability age given in brackets.† = Tephras extracted for geochemical analysis by the acid extraction method alone (c.f. Dugmore et al., 1992), or acid extraction followed by density separation. All other tephras were extracted using density separation only, following Blockley et al. (2005).

Site	Depth in sediment/ peat (cm)	Sample ID	Tephra(s)	Age	Geochemical composition	Total shards (cm^{-2})	Total shards analysed (n)	References
Claraghmore bog	44–48	CLA-B1†	Öræfajökull 1362 Hekla 1510?	c. AD 1362	Rhyolitic 1 Basaltic shard	30	7	Dugmore et al. (1995); Hall and Pilcher, (2002); Larsen et al. (1999); Pilcher et al. (2005); Pilcher et al. (1995, 1996)
	58–61	CLA-B2†	Unknown#4 Mix?	*721–726 cal yr BP (724 BP)*	Mixed composition	75	20	n/a
	73–77	CLA-B2a†	Hekla 1104	AD 1104	Rhyolitic	21	4	Hall and Pilcher (2002); Larsen et al. (1999); Pilcher et al. (2005); Pilcher et al. (1995, 1996)
	87–90	CLA-B3†	MOR-T4	c. AD 1000	Rhyolitic-Dacitic	20	20	Chambers et al. (2004)
	108–110	CLA-B4†	AD860B	AD 846–848	Rhyolitic	51	12	Hall and Pilcher (2002); Pilcher et al. (1995); Swindles (2006)
	241–244	CLA-B5†	Microlite GB4-150	2705–2630 cal yr BP 2750–2708 cal yr BP	Rhyolitic Dacitic-Trachydacitic	13	17	Hall and Pilcher (2002); Swindles (2006)
	415–418	CLA-B6-B7†	Hekla 4 Silk N2	4345–4229 cal yr BP 4345–4229 cal yr BP	Rhyolitic-Dacitic Dacitic-Trachydacitic	73	29	Dugmore and Newton (1992); Pilcher et al. (2005); Pilcher and Hall (1996); Plunkett et al. (2004); Zillen et al. (2002)
	868–870	CLA-B8†	Lairg A	6947–6852 cal yr BP	Rhyolitic	79	4	Dugmore et al. (1995); Hall and Pilcher (2002); Pilcher et al. (2005); Pilcher et al. (1996)
Claraghmore lake	110–113	CLA-L1	Unknown#3	Post AD 1000	Basaltic	141	19	n/a
	145–149	CLA-L2	MOR-T4	c. AD 1000	Rhyolitic-Dacitic	42	2	Chambers et al. (2004)
	206–208	CLA-L3	Hekla 4	4345–4229 cal yr BP	Rhyolitic-Dacitic	26	1	Dugmore and Newton (1992); Pilcher et al. (2005); Pilcher and Hall (1996); Zillen et al. (2002)
	328–331	CLA-L4	Lairg B	6724–6627 cal yr BP	Rhyolitic	275	21	Dugmore et al. (1995); Pilcher et al. (1996)
	332–338	CLA-L5	Lairg A	6947–6852 cal yr BP	Rhyolitic	723	20	Dugmore et al. (1995); Hall and Pilcher (2002); Pilcher et al. (1996)
Malham Moss	123–125	MM-1†	Glen Garry	2210–1966 cal yr BP	Dacitic-Rhyolitic	131	12	Dugmore et al. (1995); Dugmore and Newton (1992); Pilcher and Hall (1996)
	323–328	MM-2†	Hekla 4	4345–4229 cal yr BP	Rhyolitic-Dacitic	221	10	Dugmore and Newton (1992); Pilcher et al. (2005); Pilcher and Hall (1996); Zillen et al. (2002)
	577–580	MM-3†	Lairg B	6724–6627 cal yr BP	Rhyolitic	23	4	Dugmore et al. (1995); Pilcher et al. (1996)
	595–598	MM-4†	Lairg A	6947–6852 cal yr BP	Rhyolitic	152	10	Dugmore et al. (1995); Hall and Pilcher (2002); Pilcher et al. (1996)
Malham Tarn	135–145	MT-1	Glen Garry	2210–1966 cal yr BP	Dacitic-Rhyolitic	85	15	Dugmore et al. (1995); Dugmore and Newton (1992); Pilcher and Hall (1996)
Degerö Stormyr	42–44	SV-B1†	Askja 1875	AD 1875	Rhyolitic	103	16	Larsen et al. (1999); Oldfield et al. (1997); Pilcher et al. (2005)
	71–74	SV-B2†	Hekla 1158 Hekla 1104	AD 1158 AD 1104	Dacitic Rhyolitic	186	15	Hall and Pilcher (2002); Larsen et al. (1999); Pilcher et al. (2005); Pilcher et al. (1995, 1996)
	152–154	SV-B3†	Hekla 3	3037–2956 cal yr BP	Dacitic-Rhyolitic	51	21	Lawson et al. (2007); Zillen et al. (2002)
	180–183	SV-B4†	Hekla-S/Kebister	*4053–3886 cal yr BP (3968 BP)*	Dacitic-Rhyolitic	42	5	Dugmore et al. (1992); Wastegård et al. (2001); Zillen et al. (2002)
	190–193	SV-B5†	Hekla 4	4345–4229 cal yr BP	Rhyolitic-Dacitic	35	16	Dugmore and Newton (1992); Pilcher et al. (2005); Pilcher and Hall (1996); Zillen et al. (2002)
	237–240	SV-B6†	Lairg A	6947–6852 cal yr BP	Rhyolitic	50	23	Dugmore et al. (1995); Hall and Pilcher (2002); Pilcher et al. (2005); Pilcher et al. (1996)
Svartkälsjärn lake	11–18	SV-L1	Hekla 1104 Hekla 1158	AD 1104 AD 1158	Rhyolitic Dacitic	246	21	Hall and Pilcher (2002); Larsen et al. (1999); Pilcher et al. (2005); Pilcher et al. (1995, 1996)

(*continued on next page*)

Table 2 (*continued*)

Site	Depth in sediment/ peat (cm)	Sample ID	Tephra(s)	Age	Geochemical composition	Total shards (cm^{-2})	Total shards analysed (*n*)	References
	41–44	SV-L2	QUB 570 Group 2 (c. AD 650)? (Unknown#2)	c. 2500–2000 cal yr BP*	Dacite-Andesite	147	20	Pilcher et al. (2005)
	79–82	SV-L3	Hekla 4	4345–4229 cal yr BP	Rhyolitic-Dacitic	303	21	Dugmore and Newton (1992); Pilcher et al. (2005); Pilcher and Hall (1996); Zillen et al. (2002)
	108–113	SV-L4	Unknown#5	c. 6000–5000 cal yr BP*	Rhyolitic-Dacitic	16	7	n/a
	123–128	SV-L5	Lairg A?	c. 6500–6000 cal yr BP*	Rhyolitic	40	10	Dugmore et al. (1995); Hall and Pilcher (2002); Pilcher et al. (2005); Pilcher et al. (1996)
Sammakovuoma peatland	46–49	SB-1[†]	Hekla 1104	AD 1104	Rhyolitic	109	20	Hall and Pilcher (2002); Larsen et al. (1999); Pilcher et al. (2005); Pilcher et al. (1995, 1996)
	67–70	SB-2[†]	SN-1 (Unknown#1)	1232–1226 *cal yr BP (1229 BP)*	Trachydacite	193	26	Larsen et al. (2002); Holmes et al. (2016)
Sammakovuoma lake	15–17	SL-1	Hekla 1104	AD 1104	Rhyolitic	539	8	Hall and Pilcher (2002); Larsen et al. (1999); Pilcher et al. (2005); Pilcher et al. (1995, 1996)
	39–42	SL-2	SN-1 (Unknown#1)	*1781–1721 cal yr BP (1752 BP)*	Trachydacite	285	19	Larsen et al. (2002); Holmes et al. (2016)
	109–113	SL-3	Hekla 4	4345–4229 cal yr BP	Rhyolitic-Dacitic	828	35	Dugmore and Newton (1992); Pilcher et al. (2005); Pilcher and Hall (1996); Zillen et al. (2002)

were extracted using heavy density liquids (cleaning float 2.25 g cm^{-3}, retaining float 2.50 g cm^{-3}) (Blockley et al., 2005). Information on the extraction method and ID code for each tephra sample is given in Table 2.

Glass shards were mounted onto glass slides (Dugmore et al., 1992) or into blocks (Hall and Hayward, 2014). All samples were polished to a 0.25 μm finish. Major element geochemistry for all samples excluding those from Malham Moss was analysed using a Cameca SX100 electron probe micro analyser (EPMA) at the University of Edinburgh. Small shard sizes necessitated the use of narrow beam sizes (3–5 μm) and the beam current was varied during each analysis to limit volatile element (Na and K) loss (Hayward, 2012). Glass shards from cryptotephra layers identified in Malham Moss were analysed using a 10 μm beam on the JEOL JXA8230 EPMA housed at the University of Leeds. In both locations, analyses were conducted at 15 kV (full analytical conditions are listed in Table S1). Secondary glass standards (Lipari obsidian and BCR-2G: Jochum et al. (2005)) were analysed before and after EPMA runs of unknown glass shard analyses. Assignments to specific eruptions were based on stratigraphy and visual comparison of tephra geochemistry with the Tephrabase database (Newton et al., 2007) and published literature using bi-plots of oxides.

3.4. *Radiocarbon dates*

Five radiocarbon dates were obtained for peatland sites on above-ground vegetation macrofossils which were picked from sieved samples (>125 μm) under a low power microscope. One radiocarbon date was obtained for Claraghmore lake. In this instance the lack of plant macrofossils in the lake sediment necessitated the extraction of a bulk sample. Samples of lake sediment and peat were pre-treated using the standard acid-alkali-acid treatment, digested in hot (80 °C) 1 M HCl for 2 h, hot (80 °C) 0.5 M KOH for a further 2 h and then re-treated with 1 M HCl. Samples were rinsed thoroughly with de-ionised water between each acid/alkali stage and were submitted to Direct AMS, Seattle, USA for ^{14}C dating. All dates were calibrated using Calib 7.1 (Stuiver and Reimer, 1993) and the IntCal13 atmospheric curve (Reimer et al., 2013).

4. Results and discussion

4.1. *Tephra correlations*

4.1.1. *Site 1: Claraghmore*

Claraghmore bog contains tephra from nine eruptions in the form of eight cryptotephra layers (CLA-B6-B7 contains tephra from two eruptions) (Figs. 2 and 3). The majority of the cryptotephra layers identified at Claraghmore bog are silicic, of Icelandic provenance, and have previously been documented at other sites across Ireland. A small number of light brown shards in the top few centimetres of peat at Claraghmore bog were too sparse for geochemical analysis (3 shards cm^{-3}). These shards are similar in morphology and colour to shards from the eruption of Hekla 1947, which have previously been identified at multiple sites across Northern Ireland (Rea et al., 2012). Spheroidal carbonaceous particles (SCPs) were identified alongside these shards, suggesting that they were deposited after the Industrial Revolution which supports tentative assignment to the AD 1947 eruption of the Hekla volcano (Swindles and Roe, 2006; Swindles et al., 2015).

CLA-B1 contains glass shards which show geochemical similarity to those from a mixture of different Icelandic eruptions including Öræfajökull 1362 and Hekla 1510. CLA-B2 could not be matched to previously recognised cryptotephra layers based on glass geochemistry. The age of CLA-B2 (~720 cal yr BP) is constrained by bracketing cryptotephra layers CLA-B1 and CLA-B2A (=Hekla 1104) to between AD 1104 and AD 1362. The glass major element analyses for CLA-B2 are not a complete geochemical match to any of the five northern European cryptotephras identified during this period, although some individual analyses show similar geochemistry to the analyses of shards from Hekla 1158, BGMT1, GB4-57 and QUB-385 (Fig. 4(a–b)). It is possible that CLA-B2 is a

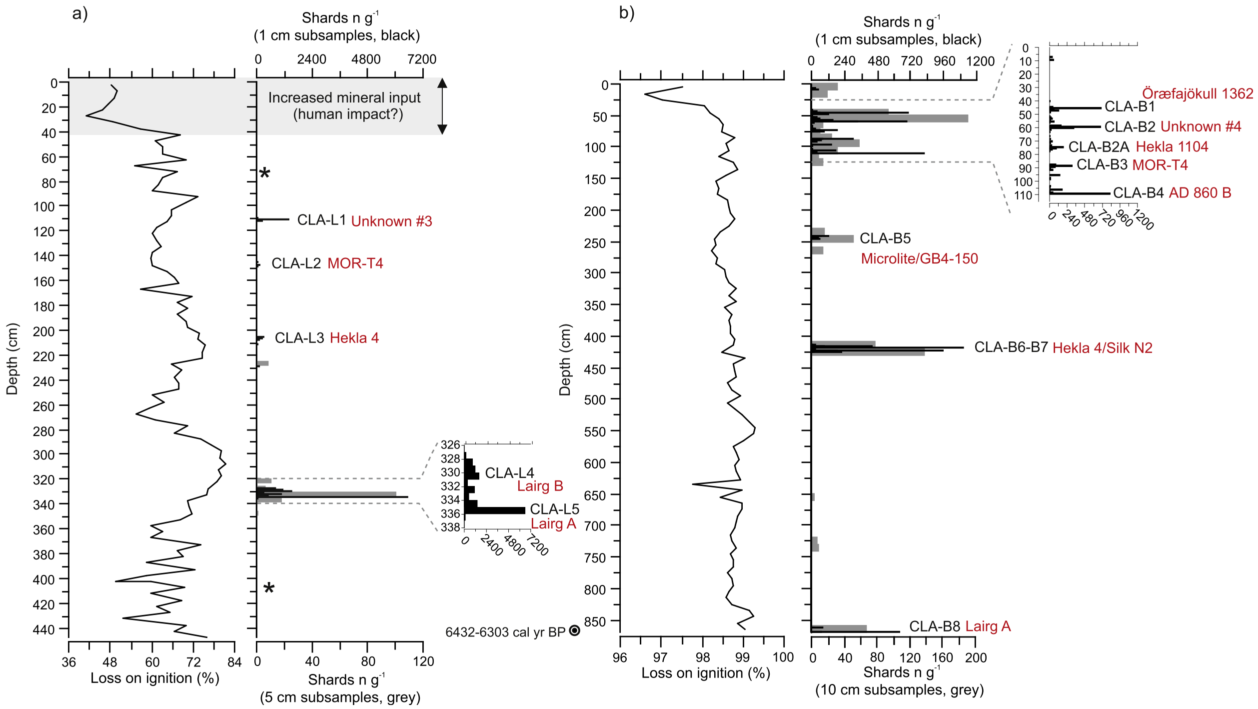

Fig. 2. Diagram showing the tephrostratigraphy and loss-on-ignition values at Claraghmore a) lake and b) bog. Tephra codes are indicated in black. Where assignments to a known tephra isochron have been made based on glass geochemistry and stratigraphy, these are indicated in red beside the tephra code. Tephras which could not be assigned to a known tephra isochron are marked as 'Unknown' and numbered. Samples containing traces of shards (<5 shards) are indicated by an asterisk. An area of increased mineral input has been highlighted at the top of the lake profile. Radiocarbon dates are reported as the calibrated 2σ range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

previously undiscovered tephra; however, given the diversity in glass geochemistry and the low resolution of the peatland record, CLA-B2 may represent a mixture of shards from two or more of the tephras listed above.

Analyses of glass shards in sample CLA-B3 indicate a rhyolitic-dacitic major element geochemistry similar to that of glass shards from the MOR-T4 tephra layer (c. AD 1000) previously identified at one site in Ireland (Chambers et al., 2004). The position of CLA-B3 above CLA-B4 (=AD 860 B) supports correlation to the MOR-T4 tephra. CLA-B4 contains shards matching the geochemistry of

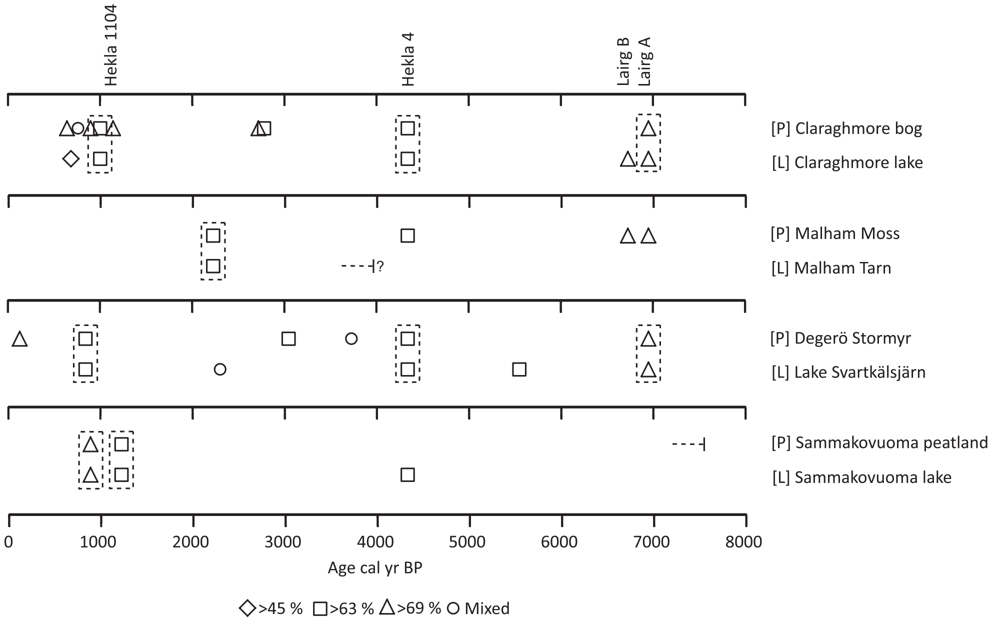

Fig. 3. Diagram summarising the tephras identified at each lake and peatland pair. [P] and [L] mark peatland and lake sites, respectively. Tephras identified in both the lake and the peatland are enclosed in dashed lines. The style of the point reflects the SiO_2 content (wt %). Ages plotted are midpoint ages. Where the basal age of the core has been ascertained using ^{14}C dating this has been marked by a dashed line. One basal date was estimated using less secure methods (sedimentation rate/pollen analysis) and is indicated with a question mark. The most common tephra deposits in this study have been named.

glass shards from the AD 860 B tephra, recently correlated to a volcano in Alaska (Jensen et al., 2014). The 17 analyses on glass shards from the CLA-B5 tephra indicate that this cryptotephra layer contains shards with major element glass geochemistry matching analyses on glass from both the Microlite and GB4-150 tephras.

The CLA-B6-B7 tephra is correlated to Hekla 4 (4345-4229 cal yr BP), as the majority of shards show geochemical similarity to those of tephra from this eruption. However, the CLA-B6-B7 cryptotephra layer contains a number of glass shards which do not match the geochemistry of glass shards from the Hekla 4 eruption (Table 2) (Fig. 4(c–d)). These shards show geochemical similarity to glass shards most likely from an eruption of Katla volcano in Iceland (Silk-N2) which occurred at around the same time as Hekla 4 (Larsen et al., 2001; Plunkett et al., 2004).

Only a small number of geochemical analyses were possible on glass shards from the CLA-B8 tephra. These analyses show some similarities to the glass geochemistry of the Lairg A tephra (6947-6852 cal yr BP). Assignment to the Lairg A tephra, a product of the Hekla volcano, is supported by a ^{14}C age of 6432–6303 cal yr BP above the CLA-B8 tephra. Previous research has also identified the Hekla 3 (3037–2956 cal yr BP) and BMR 190 (2655-2535 cal yr BP) tephras in Claraghmore bog (Plunkett, 2009). We find no evidence for the presence of these cryptotephras in our core. Conversely, we identify cryptotephras in the Claraghmore bog that correlate with MOR-T4 (CLA-B3), Öræfajökull 1362 (CLA-B1) and Hekla 1104 (CLA-B2A), cryptotephra layers which were not identified in the previous study (Plunkett, 2009).

The Claraghmore lake core contains five cryptotephra layers (Table 2, Fig. 4(e–f)); most have previously been recorded in Ireland. Three of the cryptotephra layers (MOR-T4 (=CLA-L2), Hekla 4 (=CLA-L3) and Lairg A (=CLA-L5)) are present in both the lake and peatland (Fig. 5). MOR-T4 and Hekla 4 form sparse glass shard horizons in the lake and therefore correlation is based on a small number of glass geochemical analyses combined with stratigraphic position. CLA-L4, correlated to the eruption of Lairg B (Torfajökull volcano) is present in the lake, but not in the peatland. CLA-L1 predominantly contains glass shards of a basaltic geochemical composition, which do not match the geochemical composition of glass from any previously identified cryptotephra deposits (Table 3). Glass shards from this tephra are of a different geochemical composition to glass shards from two basaltic tephras identified in western Ireland: the Veiðivötn 1477 tephra found at An Loch Mór (Chambers et al., 2004) and the BRACSH-1 (c. AD 1800) tephra identified at Brackloon (Reilly and Mitchell, 2015). They are also not a geochemical match with glass shards from the ‘Unknown Basaltic’ tephra (1060–1094 ± 75 cal yr BP) identified at Lake Tiefer See, Germany (Wulf et al., 2016) (Fig. 4j–k). CLA-L1 represents the third Holocene basaltic tephra horizon to be identified in Ireland and most closely matches the geochemistry of glass derived from the pyroclastic eruptives of the Grímsvötn volcano. Given the highly similar geochemistry of glass from cryptotephra layers from the Grímsvötn volcanic system, which can make attributing tephra to a specific eruption based on geochemistry difficult, ^{14}C dating was conducted on a bulk lake sediment sample from below CLA-L1. Analysis suggested that CLA-L1 is younger than 2517–2750 cal yr BP. However, there are no widespread tephra layers from the Grímsvötn volcanic system between 6000 cal yr BP and 1800 cal yr BP. Furthermore, tephra from the eruption of Grímsvötn in AD 150 (1800 cal yr BP) has been found in only one lake in the north of Iceland, suggesting it was not widely distributed toward Europe (Haflidason et al., 2000). The ^{14}C age obtained also suggests an age reversal as it lies above the CLA-L2 cryptotephra layer which has been geochemically assigned to the MOR-T4 tephra (c. AD 1000, 950 cal yr BP). MOR-T4 was also identified in Claraghmore bog (CLA-B3) and contains glass with a distinct geochemical signature, not easily confused with other European cryptotephras. Given the problems with bulk sediment samples in lakes (e.g. carbonate contamination – Barnekow et al., 1998), and possible contamination of the lake with older carbon eroded from the catchment and washed into the lake, we suggest that the ^{14}C age below CLA-L1 is unreliable and indicates an age which is too old for the CLA-L1 cryptotephra. For this reason it is not possible to assign CLA-L1 to a specific eruption, but this cryptotephra is most likely the product of an eruption of the Grímsvötn volcanic system after AD 1000. CLA-L1 does not match the geochemistry of glass from the most explosive eruption of the Grímsvötn volcano during this period (AD 1783 – Reilly and Mitchell, 2015). The eruptions of AD 1354, 1659 and 1774 are all possible sources for this tephra based on geochemistry despite their relatively low explosivity (1659 and 1774 VEI 2, 1354 VEI unknown) (Global Volcanism Program, 2013).

4.1.2. Site 2: Malham

There is evidence of four silicic tephra fallout events in the core taken from Malham Moss (Figs. 3 and 6). All four tephras, Glen Garry (MM-1), Hekla 4 (MM-2), Lairg B (MM-3) and Lairg A (MM-4), have previously been recorded at sites in Great Britain and Ireland. We identify the Lairg A and Lairg B tephras for the first time in England. Only one cryptotephra layer in Malham Tarn contained sufficient shards for geochemical analysis (MT-1) and was identified as the Glen Garry tephra (1966–2210 yr BP) (Fig. 7).

It is likely that the Malham Tarn core does not extend far enough to ascertain whether the Hekla 4 (4345–4229 cal yr BP), Lairg B (6724–6627 cal yr BP) and Lairg A (6947–6852 cal yr BP) cryptotephra layers were also deposited in the lake. Dating of marl sediment is extremely difficult and radiocarbon dating of charcoal and macrofossils from Malham Tarn has proved problematic in the past (Barber et al., 2013). Pollen analysis on a basal sample from our core (depth 315–320 cm) is consistent with an age no earlier than the Elm decline 6347–5281 cal yr BP (Parker et al., 2002) and perhaps much younger. The absence of the Hekla 4, Lairg A and Lairg B tephras may due to the length of the sediment core which was recovered.

4.1.3. Site 3: Lake Svartkälsjärn and Degerö Stormyr

The tephra record at Degerö Stormyr comprises six silicic cryptotephra layers including tephra from Askja 1875 (SV-B1), Hekla 1104 and Hekla 1158 (SV-B2), Hekla 3 (SV-B3) and Hekla 4 (SV-B5) (Fig. 8). The SV-B4 cryptotephra layer was deposited between SV-B3 (Hekla 3 = 3037-2956 cal yr BP) and SV-B5 (Hekla 4 = 4345-4229 cal yr BP). The geochemical analyses of glass from SV-B4 suggest a match with the Hekla-S/Kebister tephra (3750-3700 cal yr BP) which corresponds to the stratigraphic age interval for the SV-B4 cryptotephra and has been recorded widely across Scandinavia (Wastegård et al., 2008). SV-B6 is correlated to Lairg A (6947–6852 cal yr BP) based on glass geochemistry and its stratigraphic position above peat with a radiocarbon age of 7143–6806 cal yr BP.

The sediment core recovered from Lake Svartkälsjärn contains five cryptotephra layers from six distinct Icelandic eruptions (Fig. 9). Three of these tephras can be linked based on glass geochemistry and stratigraphy to Hekla 1104/Hekla 1158 (SV-L1) and Hekla 4 (SV-L3) (Fig. 8). However, the lake core also contains two cryptotephra layers (SV-L2 and SV-L4), the glass analyses from which do not match the glass compositions of established cryptotephras in northern Europe. Approximate ages for these cryptotephras can be ascertained according to their depth and the age-depth model on a core from a different study of the same lake. Although correlations to an existing profile must be made with caution, the core of Barnekow et al. (2008) was recovered from a

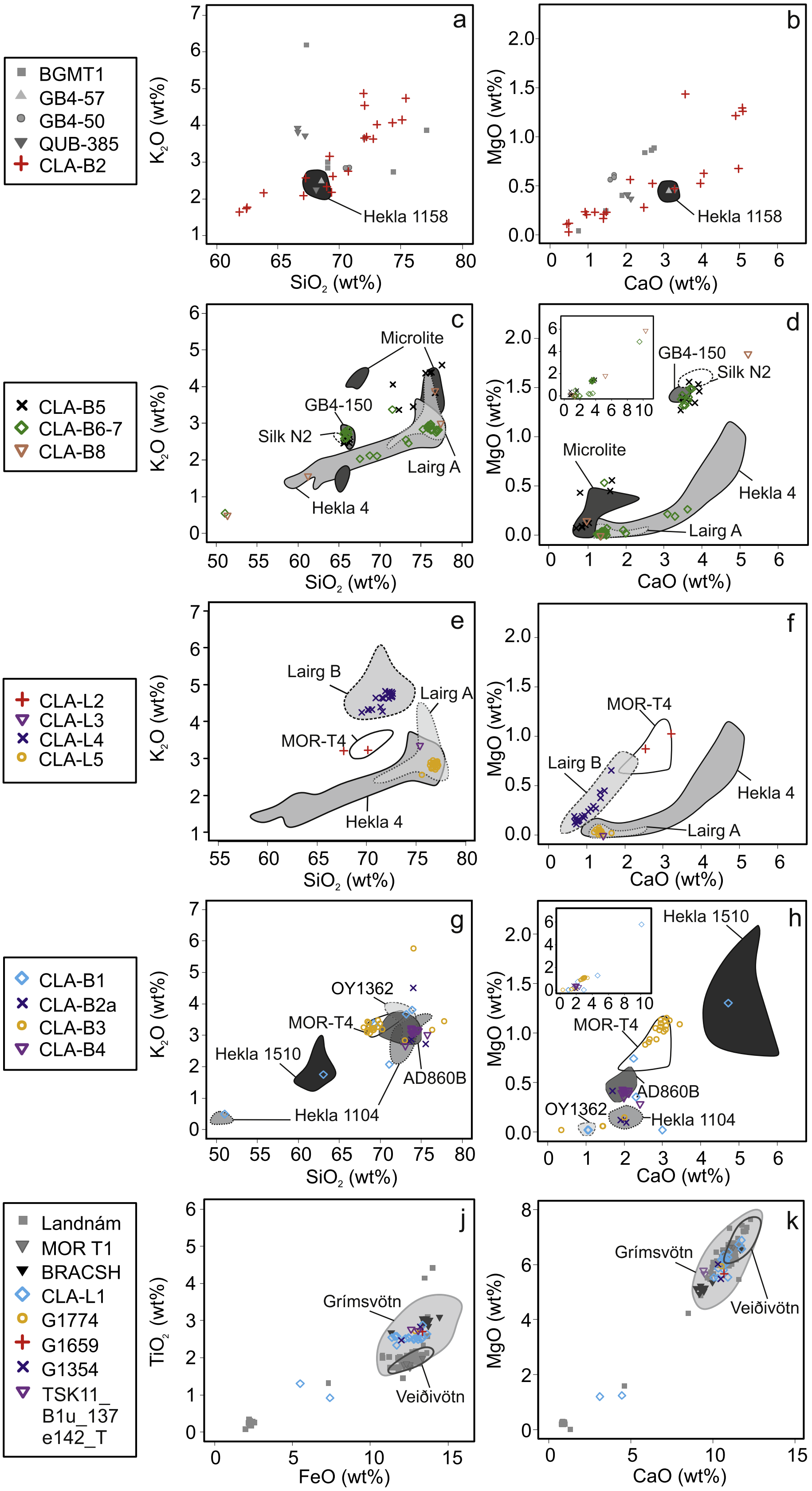

Fig. 4. Geochemical bi-plots of major elements of glass from Claraghmore sites plotted against envelopes for the glass geochemistry of known tephras based on type data from the Tephrabase database (type data references in Table 2). All data have been normalised. (a–b) Claraghmore bog sample CLA-B2 is an unidentified tephra or mix of tephras dating between AD 1104 and AD 1362 plotted against northern European cryptotephras from this period. (c–d) Claraghmore bog cryptotephra layers prior to AD 860; inset plots show the full range of the data. (e–f) Claraghmore lake cryptotephra layers and suggested sources. (g–h) Claraghmore bog cryptotephra layers from AD 860 to present. The main plots

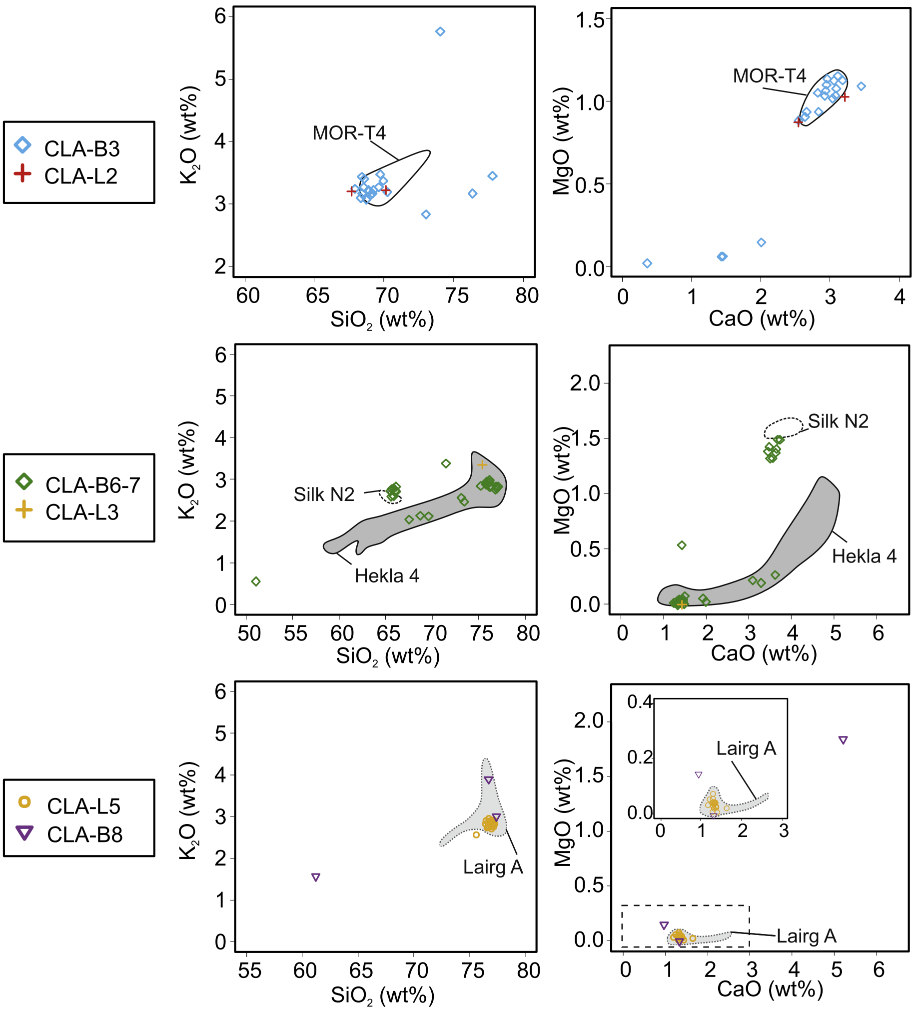

Fig. 5. Geochemical bi-plots of major elements of glass found in both Claraghmore lake and peatland plotted against envelopes for the glass geochemistry of known tephras based on type data from the Tephrabase database (type data references in Table 2). All data have been normalised. Inset plots show zoomed in view.

similar location within the basin and the record between surface sediment and basal clay is 1.92 m (similar to that of our core = ~1.9 m). Based on the age-depth model of Barnekow et al. (2008), the SV-L2 and SV-L4 tephras have approximate ages of 2500–2000 and 6000–5000 cal yr BP, respectively. SV-L2, which is not present in the Degerö Stormyr peat sequence, is most similar in glass geochemistry to glass shards of the QUB 570 Group 2 (~1300 cal yr BP) tephra, which has been identified at Lofoten, Norway (Pilcher et al., 2005). There is also some geochemical similarity with the glass of the BMR-190 tephra (~2595 cal yr BP), although this tephra has not been identified outside Ireland. Given the uncertainty associated with the dating of SV-L2, we tentatively suggest a correlation with the QUB 570 Group 2 tephra. No geochemical match was identified for shards from SV-L4, which contains glass shards with a range of major element geochemistry and may represent a mixture of tephras deposited onto snow in the lake catchment and then washed into the lake during snowmelt events. Of the ten successful geochemical analyses conducted on glass shards from SV-L5, two indicate geochemical similarity to the glass composition of shards from Lairg A (6947-6852 cal yr BP), which was also identified in the Degerö Stormyr peat sequence. An approximate date of 6500–6000 BP for SV-L5 based on interpolation suggests that at least some of the shards in SV-L5 are from the Lairg A tephra. The eight remaining geochemical analyses do not match the geochemical analyses for any established cryptotephra layers of a similar age.

4.1.4. Site 4: Sammakovuoma

Cryptotephra layers (SL-1, SB-1) containing glass shards with major elemental geochemistry identical to glass shards from the eruption of Hekla AD 1104 were identified in both Sammakovuoma peatland and lake. A second cryptotephra layer (SL-2, SB-2) containing glass shards of trachydacite geochemistry, was also present in both the peatland and lake at Sammakovuoma (Figs. 10 and 11). Glass geochemistry from the SL-2/SB-2 tephra does not match the geochemistry of glass from any published northern European

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illustrate the geochemical variation among silicic to intermediate shards; inset plots show the full range of the data, including basaltic shards. (j–k) Claraghmore lake tephra ClA-L1, which contains glass shards of a basaltic composition; also shown are geochemical envelopes of glass data for eruptives from the Veiðivötn (dark grey) and Grímsvötn (light grey) volcanoes. Envelopes are based on geochemical data from Streeter and Dugmore (2014); Lawson et al. (2007); Chambers et al. (2004); Wastegård (2002); Wastegård et al. (2001); Haflidason et al. (2000); Dugmore and Newton (1998); Thordarson et al. (1996); Mangerud et al. (1986) and references therein. TSK11_B1u_137_e142_T tephra data from Wulf et al. (2016).

Table 3
Non-normalised major element geochemical analysis data for glass shards from the CLA-L1 and SB-2/SL-2 (=SN-1) cryptotephras identified at Claraghmore (CLA-L1) and Sammakovuoma peatland and lake (SB-2/SL-2).

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
CLA-L1	67.30	1.30	14.25	5.50	0.18	1.21	3.12	4.99	2.81	0.30	100.96
Claraghmore Lake	63.78	0.92	14.96	7.42	0.18	1.24	4.46	4.53	1.87	0.33	99.70
110–113 cm	50.71	2.34	14.85	11.70	0.19	5.54	10.92	3.02	0.38	0.28	99.92
Unknown eruption of Grímsvötn volcano	50.70	2.54	13.76	11.39	0.19	6.73	11.59	2.51	0.45	0.25	100.10
	50.69	2.52	13.12	12.83	0.20	6.18	10.66	2.68	0.41	0.27	99.56
	50.54	2.65	13.69	13.29	0.22	5.86	10.33	2.81	0.40	0.28	100.08
	50.53	2.53	13.26	13.36	0.19	5.80	10.67	2.66	0.37	0.29	99.67
	50.48	2.52	13.68	12.26	0.21	6.07	10.85	2.68	0.38	0.26	99.41
	50.46	2.56	13.72	13.02	0.20	6.06	10.79	2.60	0.36	0.29	100.06
	50.37	2.49	13.37	12.81	0.19	6.23	10.73	2.73	0.39	0.25	99.56
	50.34	2.58	13.50	11.59	0.18	6.89	11.75	2.65	0.38	0.29	100.15
	50.29	2.49	13.63	13.07	0.20	6.18	10.80	2.57	0.35	0.28	99.87
	50.16	2.63	13.47	13.65	0.24	5.52	10.32	2.72	0.38	0.29	99.37
	49.89	2.57	13.44	11.70	0.20	6.57	11.76	3.10	0.38	0.27	99.88
	49.85	2.87	12.92	13.36	0.20	5.52	10.06	2.70	0.48	0.32	98.29
	49.63	2.52	13.18	12.50	0.19	6.18	10.53	2.57	0.38	0.28	97.96
	49.21	2.50	13.44	13.25	0.21	6.35	10.66	2.55	0.41	0.26	98.83
	49.18	2.55	13.26	12.47	0.17	6.45	10.95	2.76	0.46	0.28	98.52
	49.07	2.53	13.01	12.98	0.21	6.26	10.91	2.90	0.39	0.29	98.55
SB-2	70.59	0.20	15.20	2.98	0.14	0.11	1.04	5.60	4.86	0.02	100.75
Sammakovuoma peatland	67.75	0.38	15.75	4.46	0.16	0.27	1.81	6.16	4.19	0.07	100.98
67–70 cm	67.39	0.40	16.60	4.21	0.19	0.33	1.87	6.43	4.18	0.06	101.65
SN-1	67.16	0.47	16.04	4.55	0.18	0.41	2.22	6.25	3.90	0.09	101.27
	66.92	0.41	16.03	4.15	0.19	0.35	1.95	5.98	4.04	0.07	100.10
	66.69	0.43	16.74	4.34	0.20	0.33	2.12	6.45	4.00	0.07	101.37
	66.44	0.45	16.46	4.40	0.19	0.34	2.03	6.18	4.08	0.81	100.64
	66.39	0.40	16.44	4.13	0.18	0.33	1.90	5.99	4.06	0.07	99.90
	66.34	0.43	16.81	4.29	0.17	0.34	2.12	6.06	3.98	0.07	100.60
	66.32	0.45	16.66	4.67	0.17	0.34	2.03	6.08	4.06	0.07	100.84
	66.15	0.64	15.85	5.63	0.21	0.57	2.01	5.79	4.41	0.14	101.40
	65.65	0.57	17.25	5.17	0.20	0.55	2.52	6.06	3.73	0.12	101.82
	65.58	0.45	18.12	4.18	0.15	0.36	3.00	6.85	3.19	0.09	101.97
	65.52	0.42	16.02	4.46	0.16	0.28	1.90	6.06	4.04	0.05	98.92
	65.15	0.58	16.46	5.28	0.17	0.51	2.64	6.00	3.63	0.14	100.58
	65.14	0.59	16.68	5.28	0.21	0.58	2.77	6.26	3.63	0.13	101.26
	65.11	0.57	17.10	5.37	0.17	0.53	2.55	6.30	3.72	0.12	101.58
	64.82	0.62	16.17	5.72	0.19	0.61	2.55	5.78	3.83	0.13	100.42
	64.70	0.58	16.57	5.03	0.21	0.61	2.48	6.05	3.73	0.14	100.10
	64.44	0.58	16.52	5.28	0.22	0.55	2.71	5.80	3.63	0.11	99.86
	64.44	0.60	16.10	5.46	0.21	0.52	2.56	6.14	3.72	0.15	99.89
	64.42	0.58	16.44	5.42	0.21	0.55	2.52	6.56	3.92	0.11	100.71
	64.28	0.60	16.62	5.08	0.21	0.63	2.59	6.16	3.66	0.13	99.97
	64.22	0.60	16.56	5.27	0.23	0.56	2.50	6.28	3.74	0.11	100.06
	63.86	0.60	16.64	5.35	0.22	0.61	2.61	5.91	3.79	0.13	99.72
	63.54	0.56	15.98	5.28	0.21	0.60	2.52	6.11	3.80	0.11	98.72
SL-2	70.21	0.17	14.71	2.85	0.12	0.07	1.19	5.61	4.73	0.01	99.69
Sammakovuoma Lake	66.44	0.40	15.08	4.26	0.17	0.33	1.88	5.57	4.04	0.06	98.22
39–42 cm	66.31	0.47	15.38	4.55	0.19	0.39	2.15	5.45	3.87	0.09	98.86
SN-1	66.12	0.42	15.12	4.53	0.17	0.32	1.99	5.63	4.00	0.06	98.36
	65.87	0.56	15.80	5.12	0.21	0.55	2.49	5.45	3.72	0.12	99.90
	65.81	0.57	16.15	5.45	0.21	0.56	2.62	5.67	3.52	0.13	100.69
	65.61	0.58	15.69	5.06	0.19	0.58	2.61	5.47	3.97	0.12	99.88
	65.54	0.59	15.68	5.54	0.22	0.63	2.48	5.38	3.86	0.14	100.06
	65.47	0.57	15.90	5.42	0.20	0.62	2.47	5.64	3.72	0.11	100.13
	65.43	0.59	15.77	5.29	0.23	0.61	2.61	5.40	3.68	0.13	99.73
	65.25	0.45	15.68	4.61	0.16	0.46	2.80	5.81	3.44	0.11	98.78
	65.18	0.54	15.92	5.18	0.21	0.53	2.63	5.47	3.80	0.12	99.57
	65.15	0.60	15.33	5.16	0.21	0.62	2.53	5.46	3.86	0.13	99.05
	65.10	0.55	15.98	5.35	0.22	0.58	2.62	5.73	3.85	0.12	100.11
	64.95	0.57	15.84	5.18	0.20	0.57	2.62	5.65	3.78	0.13	99.49
	64.89	0.57	15.78	5.40	0.22	0.52	2.42	5.51	3.89	0.12	99.32
	64.24	0.60	15.26	5.22	0.20	0.64	2.58	5.28	3.71	0.14	97.87
	63.73	0.50	15.30	4.98	0.19	0.60	2.38	5.49	3.55	0.10	96.83
	61.97	0.56	15.20	5.08	0.21	0.57	2.55	5.61	3.61	0.14	95.50

cryptotephra layer (Fig. 10). However, the glass composition is highly similar to that of the SN-1 tephra from the Icelandic Snæfellsjökull volcano. The age of 'peaty soil' below the SN-1 tephra layer in Iceland indicates a maximum age for the SN-1 tephra of 1860–1520 cal yr BP (Larsen et al., 2002). Interpolation between two closely spaced radiocarbon dates in Sammakovuoma peatland suggests SB-2 has an age of between 1183 and 1147 cal yr BP, more recent than the previous age suggested for the SN-1 tephra

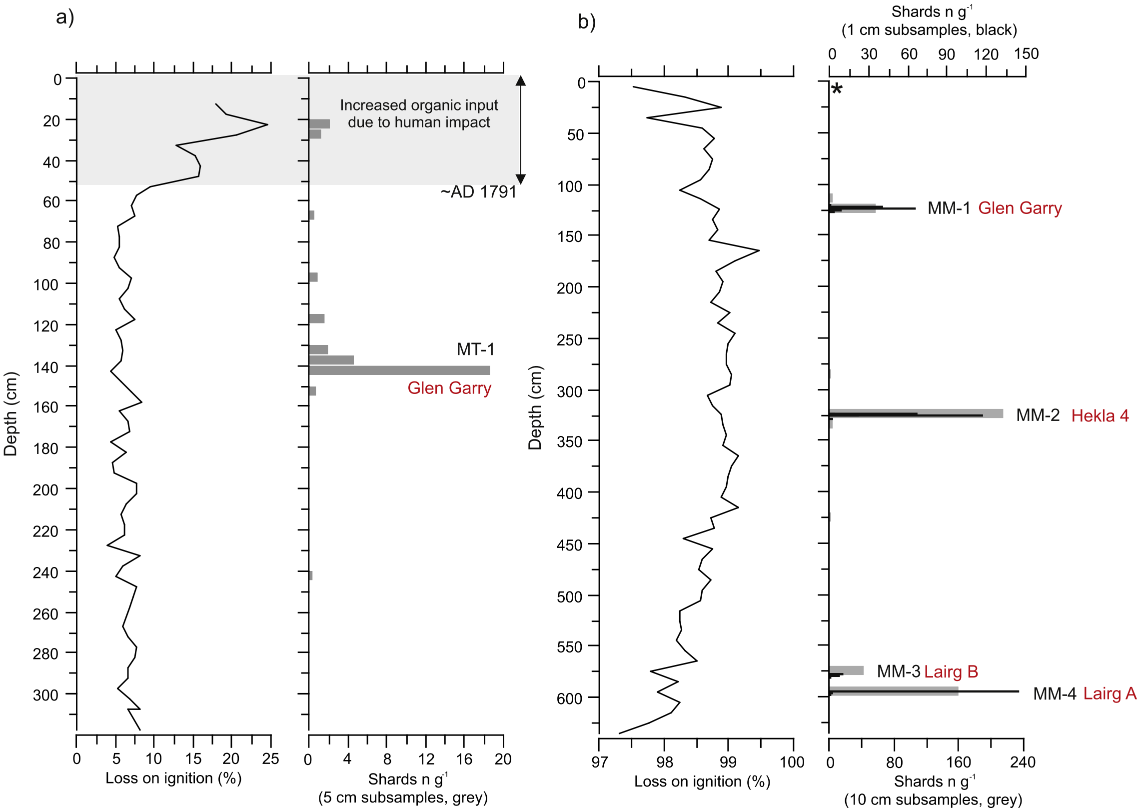

Fig. 6. Diagram showing the tephrostratigraphy and loss-on-ignition values at Malham a) Tarn, b) Moss. Tephra codes are indicated in black. Where assignments to a known tephra isochron have been made based on glass geochemistry and stratigraphy these are indicated in red beside the tephra code. An area of increased organic input has been highlighted at the top of lake profile.

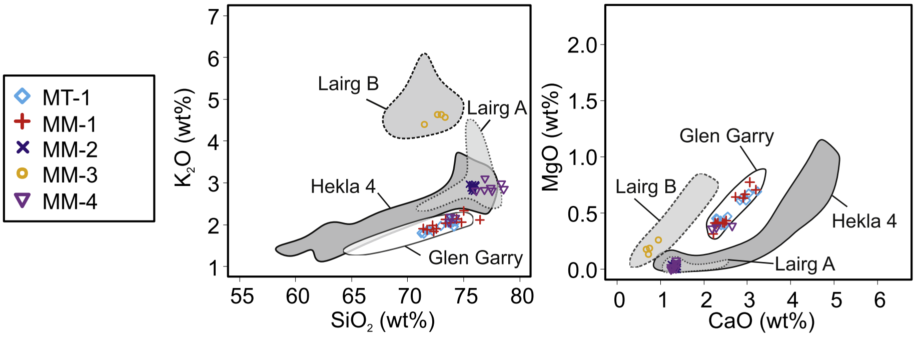

Fig. 7. Geochemical bi-plots of major elements of glass from Malham Tarn and Malham Moss plotted against envelopes for the glass geochemistry of known tephras based on type data from the Tephrabase database (type data references in Table 2). All data have been normalised.

(Table 4). However, given that there are no known explosive eruptions of Snæfellsjökull after SN-1, we correlate SL-2/SB-2 to the SN-1 tephra and conclude that a previous age of 1860–1520 cal yr BP for the SN-1 tephra should be considered a maximum age. The SN-1 tephra has been identified on the island of Svalbard (D'Andrea et al., 2012), but our identification in Sweden constitutes the first identification of this tephra in continental (northern) Europe. A third cryptotephra layer (SL-3), correlated to the Hekla 4 eruption, was also identified in the lake but was absent from the peatland.

4.2. Peatland vs. lake archives

Assuming that ash cloud occurrence is homogenous on scales of <10 km and that one core is representative of an entire peatland or lake, we would expect to find the same cryptotephra layers in peat and lake cores from two sites in close proximity. However, despite instances where the same cryptotephra layer was identified in both the peatland and lake records, the overall tephrostratigraphic records in peatlands and lakes differ considerably. There appears to be no consistent difference in the number of cryptotephra layers recorded in lakes and peatlands. In some records localised precipitation patterns or human disturbance (e.g. Claraghmore Lake or Malham Tarn) might account for differences in the tephrostratigraphic records. However, in other instances differences in the number of cryptotephra layers recorded in lakes and peatlands may have been caused by processes of reworking and redistribution (e.g. catchment erosion or intra-lacustrine reworking).

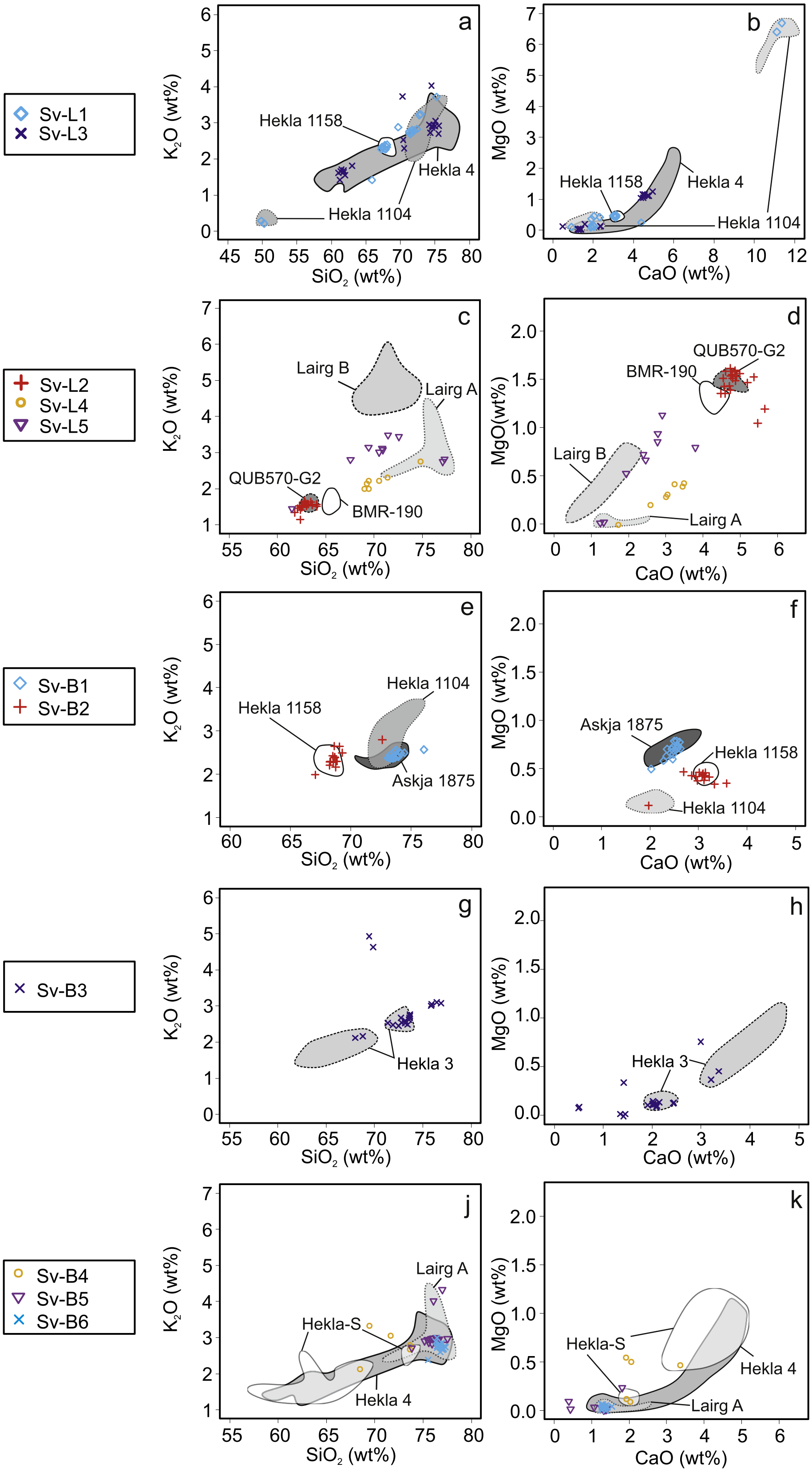

Fig. 8. Geochemical bi-plots of major elements of glass from Lake Svartkälsjärn (a–d) and Degerö Stormyr (e–k) plotted against envelopes for the glass geochemistry of known tephras based on type data from the Tephrabase database (type data references in Table 2). All data have been normalised.

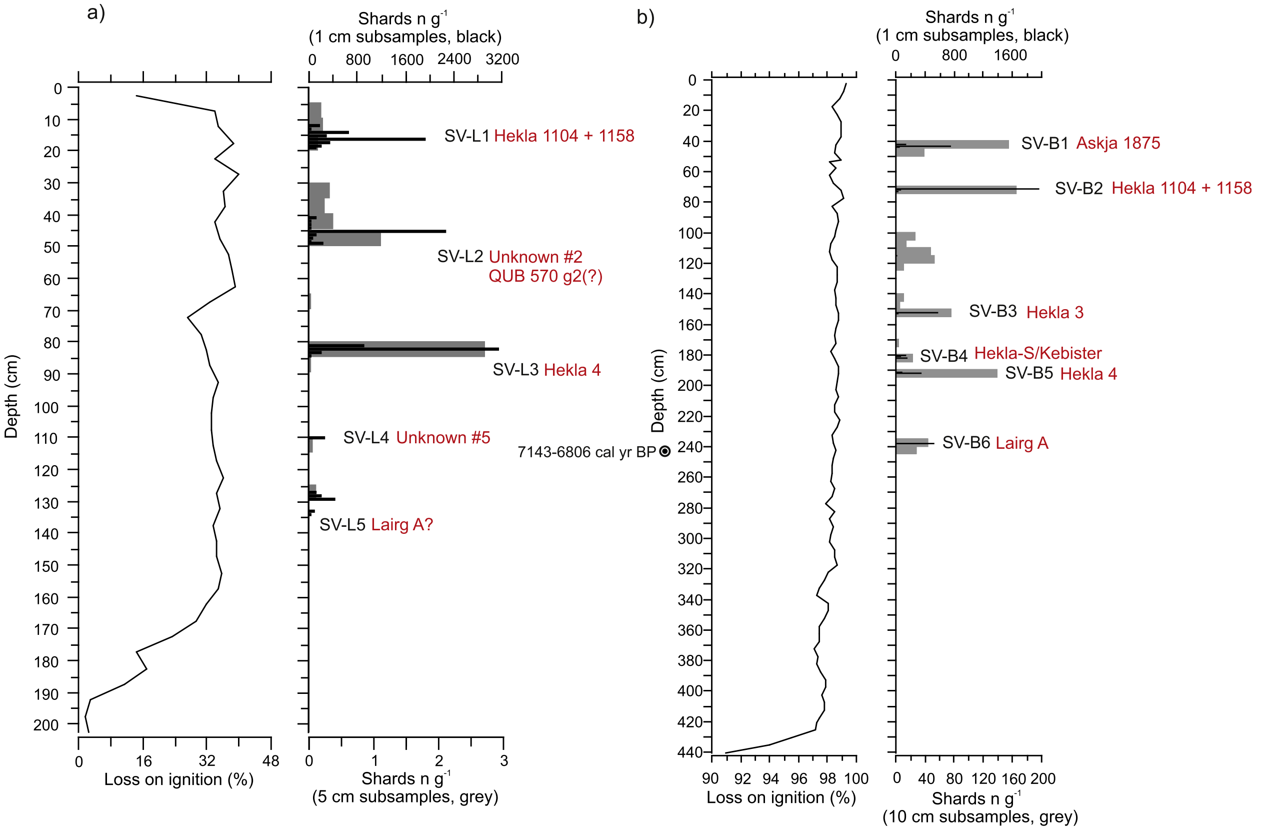

Fig. 9. Diagram showing the tephrostratigraphy and loss-on-ignition values at a) Lake Svartkälsjärn, b) Degerö Stormyr. Tephra codes are indicated in black. Where assignments to a known tephra isochron have been made based on glass geochemistry and stratigraphy these are indicated in red beside the tephra code. Radiocarbon dates shown are the calibrated 2σ range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2.1. *Cryptotephra layers absent from peatland records*

Loss-on-ignition data can be used to indicate the influence of minerogenic inputs on peatlands. Decreases in loss-on-ignition (% loss) values indicate an increase in minerogenic content. The loss-on-ignition values for all our peatlands exceed 92% (95% in 3 out of 4 cases, excluding basal sections where no cryptotephra deposits were identified) (Figs. 2, 6, 9 and 11). Our results indicate that the peatlands in this study have a high organic content and have received very low mineral input. We therefore suggest that all of our peatland sites are ombrotrophic and thus have only received tephra from the air (direct fallout) and that there is no evidence for material being washed into the peatland.

In three of our peatland-lake pairs, at least one of the cryptotephra layers identified in the lake was not present in the peatland. This might be expected as lakes receive tephra in-wash from a wide catchment area, as opposed to ombrotrophic peatlands which record only primary tephra-fall (Bramham-Law et al., 2013; Bertrand et al., 2014). The core at Sammakovuoma peatland has a basal age predating 7500 cal yr BP and peat would have been present at the site during tephra fallout from the Hekla 4 eruption (4345-4229 cal yr BP). Cryptotephra shards from the Hekla 4 eruption were identified in Sammakovuoma Lake (SL-3). However, the Hekla 4 tephra was not identified at Sammakovuoma peatland. Cryptotephra layers in northern peatlands and lakes can be affected by tephra fall onto snow cover and subsequent redistribution (Bergman et al., 2004; Davies et al., 2007). Sammakovuoma peatland and lake are covered in snow and ice for prolonged periods during the winter. It is conceivable that the Hekla 4 tephra might have been deposited onto snow and then reworked from the more exposed peatland by wind and water. Although tephra shards in the lake catchment would have been subject to reworking, they may have been washed into the lake from the wider catchment during snowmelt. In high-latitude regions the impact of tephra fallout onto snow and subsequent redistribution by wind and/or water might explain the absence of some cryptotephra layers from peatlands. However, prolonged snow cover is less likely at Claraghmore bog.

At Claraghmore lake we identified two cryptotephra layers which are absent from the peatland (CLA-L1 = ‘Unknown’ and CLA-L4 = Lairg B). In this instance we suggest that the peatland has failed to capture sparse cryptotephra layers; glass shards from which have been focussed into the lake from the wider catchment, bringing them above levels of detection in lake sediments. The impact of catchment in-wash on increasing tephra concentrations in lakes is indicated by the total shard counts for some tephras found in both lakes and peatlands in this study. Total shard counts must be interpreted with caution, given the sensitivity to sample volume. However, in some instances total shard counts for the same cryptotephra layer differ greatly in lakes and peatlands. For example, the total shard number for the Lairg A tephra in Claraghmore lake was 723, an order of magnitude more than identified in the peatland (79 shards). A similar order of magnitude difference was apparent in Hekla 4 shard counts in Degerö Stormyr peatland and Lake Svartkälsjärn ($n = 35$ and $n = 303$, respectively). Research on visible tephra layers at lake and bog sites in the Waikato area of North New Zealand identified more visible tephra layers in lakes, perhaps owing to in-wash of tephra from the catchment (Lowe, 1988a, b). Invisible cryptotephra layers containing low concentrations of shards have been identified in subsequent studies of the same bogs (Gehrels et al., 2006).

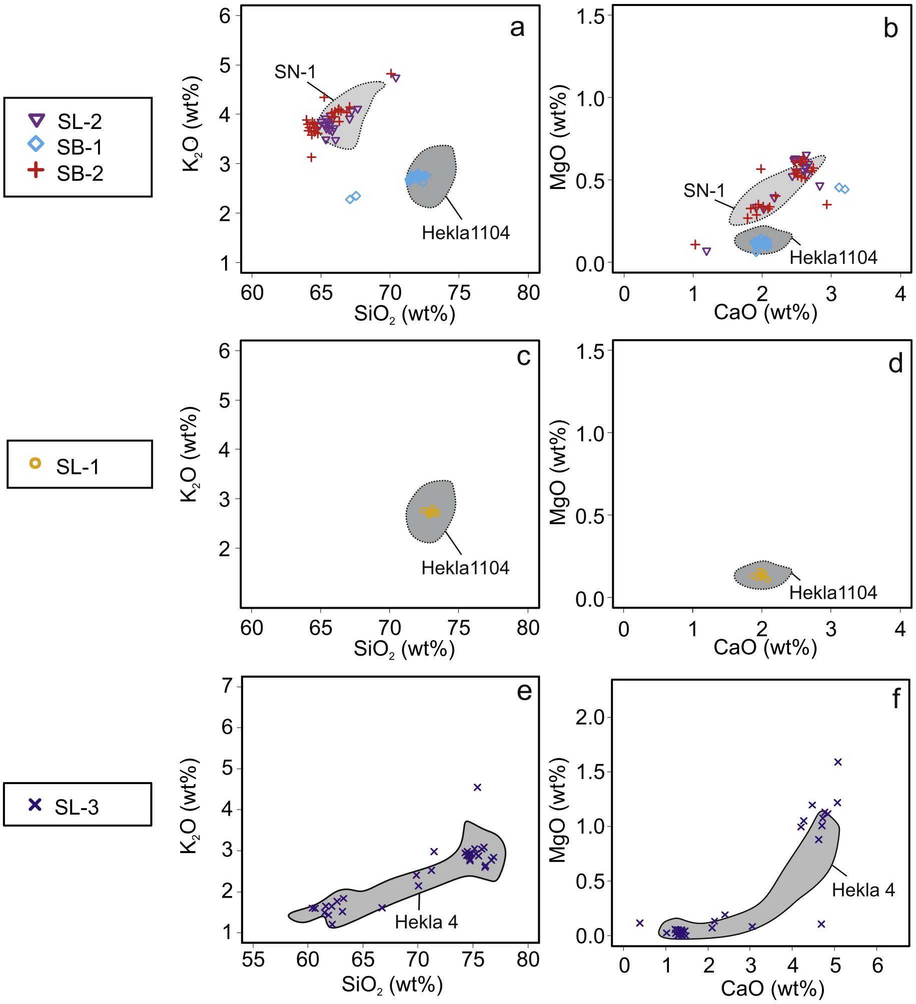

Fig. 10. Geochemical bi-plots of major elements of glass from cryptotephra layers from Sammakovuoma peatland and lake plotted against envelopes for the glass geochemistry of known tephras based on type data from the Tephrabase database (type data references are listed in Table 2). All data have been normalised. (a–d) cryptotephra layers which were found in both the lake and the peatland, inset plots show SL-1 tephra which is obscured in the larger plot by SB-1. Both tephras are a geochemical match for the Hekla 1104 tephra, type data for the SN-1 tephra from Larsen et al. (2002) and Holmes et al. (2016) (e–f) cryptotephra layer found in Sammakovuoma lake and identified as the Hekla 4 tephra.

4.2.2. Cryptotephra layers absent from lake records

At Malham Moss, Claraghmore and Degerö Stormyr, we identify more cryptotephra layers in the peatland than in the lake. A number of tephras identified toward the top of cores at peatland sites were not identified in nearby lake sites – at Claraghmore Lake and Lake Svartkälsjärn, for example. Possible reasons for the absence of tephras in the top of lake records include: 1) the top of the record was characterised by the soft sediment-water interface and was not recovered in its entire volume during sampling; 2) site specific factors: at Claraghmore and Malham there is sedimentological evidence (LOI) that land management and/or disturbance in the lake catchment (i.e. human factors) may have resulted in a large sediment influx, disturbing the lake sediments and 'diluting' the tephra record in the upper part of these cores; and 3) the cryptotephra layers may have contained insufficient shards to be detected in the lake sediments. Some loss of shards during density separation extraction is inevitable and therefore cryptotephra layers which consist of low concentrations of shards may be undersampled in lake sediments.

Although care was taken to capture the sediment-water interface at all sites, incomplete recovery of surface sediment cannot be discarded as the reason for missing cryptotephra layers at the top of lake cores. An alternative explanation for the missing cryptotephra layers in the top of Claraghmore lake is the impact of humans on the recent sediment influx to the lake. LOI data for the lake sediments indicates increased mineral input in the top 50 cm of sediment at Claraghmore lake. Conversely, there is no sedimentological evidence for human disturbance at Lake Svartkälsjärn. Instead the apparent absence of the Askja 1875 tephra identified in the nearby Degerö peatland (SV-B1) from the tephra record at Lake Svartkälsjärn might be explained by poor recovery of the water-sediment interface.

Recent disturbance and problems with sampling soft sediments at the top of lake profiles cannot account for the missing tephras in the older lake records. Other tephras found in Degerö peatland but not identified in the nearby Lake Svartkälsjärn (SV-B4, SV-B3) lie between tephras which are identified in both lake and peatland records, suggesting that their absence from the lake record is not an artefact of sampling. Similarly, as both the MOR-T4 (CLA-B3/CLA-L2) and Hekla 4 (CLA-B6-B7/CLA-L3) tephras are identified in Claraghmore lake and peatland, we might expect the Microlite and GB4-150 tephras (2705-2630 cal yr BP and 2750-2708 cal yr BP, respectively) which are present in the peatland between MOR-T4 and Hekla 4 to also to be present in the lake. However, there are no glass shards during this interval in the Claraghmore lake record. One possible explanation is that these tephras were present in lake

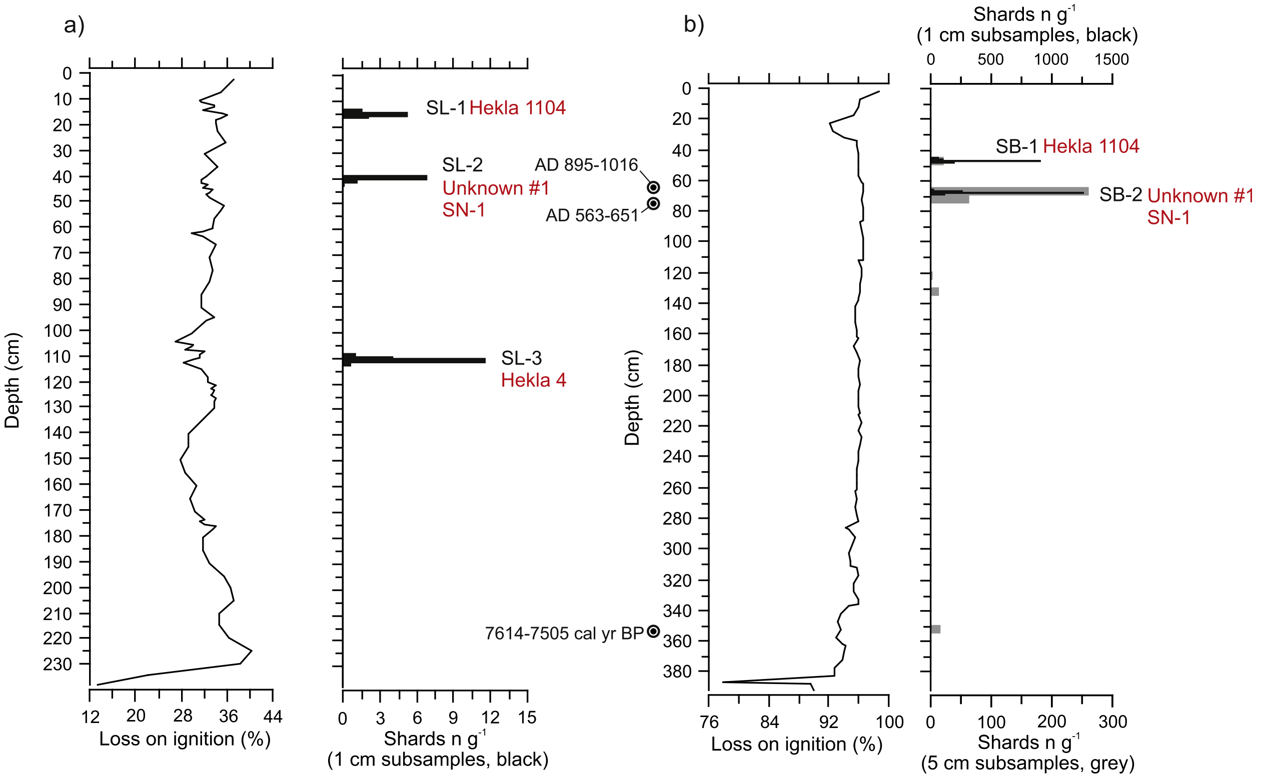

Fig. 11. Diagram showing the tephrostratigraphy and loss-on-ignition values at Sammakovuoma, a) lake and b) peatland. Tephra codes are indicated in black. Where assignments to a known tephra isochron have been made based on glass geochemistry and stratigraphy these are indicated in red beside the tephra code; tephras which could not be assigned to a known tephra isochron are marked as 'unknown', and each unknown tephra is numbered. Radiocarbon dates shown are calibrated 2σ ranges. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Radiocarbon dates obtained on samples from sites in this study. The CLA-L1^{14}C date indicated in italics would imply an age reversal with the MOR-T4, (c.AD 1000) cryptotephra from the same core. Given the problems with bulk sediment samples in lakes (carbonate contamination – Barnekow et al., 1998), and possible contamination of the lake with older carbon from the neighbouring peatland, we suggest that the ^{14}C date below CLA-L1 is unreliable.

Sample ID	Laboratory ID	Site	Depth (cm)	^{14}C age BP ± 1σ	δ^{13}C per mil	Calibrated range (2σ)	Material
SBRC1	D-AMS 012524	Sammakovuoma Peatland	64–68	1083 ± 24	−32.2	AD 895–1016	*Sphagnum* leaves/stems
SBRC2	D-AMS 012525	Sammakovuoma Peatland	70–73	1449 ± 29	−27.2	AD 563–651	*Sphagnum* leaves/stems
SBRC3	D-AMS 012526	Sammakovuoma Peatland	352–356	6692 ± 31	−37.6	7614–7505 cal yr BP	*Sphagnum* leaves/stems *Eriophorum* spindles
CLARC1	D-AMS 012527	Claraghmore Bog	855–860	5587 ± 29	−34.1	6432–6303 cal yr BP	*Sphagnum* leaves/stems, seeds
SVRC1	D-AMS 012528	Degerö Stormyr	240–243	6077 ± 29	−31.8	7143–6806 cal yr BP	*Sphagnum* leaves/stems, seeds
CLAL1	*D-AMS 013414*	*Claraghmore Lake*	*113–116*	*2551 ± 22*	*−29.3*	*2517–2750 cal yr BP*	*Bulk sediment*

sediments as very sparse concentrations of shards but were not identified because the shard concentrations were below detection levels. The concentration of shards for the Microlite tephra in Claraghmore bog is lower than the concentrations of glass shards of other tephras also identified in Claraghmore lake (e.g. Hekla 4 and MOR-T4 tephras), and therefore the lake sample may have contained insufficient shards for extraction by density separation.

An alternative reason for the apparent lack of some cryptotephras from lake records is within-basin focussing and redistribution which might reduce shard counts below levels of detection in some areas of the lake. Relatively large with-in basin differences (e.g. 23 cm – 5 cm) in the thickness of visible tephra layers provide evidence of the degree to which tephra can be differentially deposited or moved within lake basins (Mangerud et al., 1984). In small shallow lakes such as those investigated in this study, small particles can be remobilised by wind-induced currents (Mackay et al., 2012). Once tephra has been delivered, within-basin focussing and preferential deposition near stream inlets might result in the concentration of shards from some cryptotephra layers into certain areas of the lake. Conversely, internal redistribution might also result in some tephras being reworked to below detection levels in some parts of the basin. Where shards are present in low concentrations, within-basin focussing in lakes provides a natural means of concentrating a small number of shards. However, this process does not appear to concentrate shards to the same location consistently over time resulting in a patchy distribution of different tephras deposited at different times in different areas of the lake basin. For example, the Lairg A and Hekla 4 tephras have very similar total numbers of shards in Claraghmore bog (79 and 73), but show very different total shard concentrations in the lake (723 and 26 shards). Although the peatland record is not unaffected by redistribution (Watson et al., 2015), such a difference in the concentrations of shards for these two cryptotephra layers in the same lake would appear to suggest internal reworking or redistribution. This hypothesis would also appear to be supported by the range of ash concentrations identified in late glacial micro-tephra layers in Scottish lakes; proximity to catchment inlets was identified as an important factor in determining the concentration of tephra glass shards across the lake basin and spatial ash concentration maxima for different tephra layers varied over time (Pyne-O'Donnell, 2011). The 'patchy' nature of the black basaltic component of the Vedde ash, which varied from visible, to apparently absent (to the naked eye) in different cores from the same Scottish lake also suggests that processes within the catchment and lake can greatly impact on tephra shard concentrations within a lake basin (Davies et al., 2001). The consequences of within-basin redistribution are two-fold: firstly the retrieval of one core from the centre of a lake may not result in the recovery of the complete record of tephra which has fallen out over that lake site. Secondly, the re-distribution of shards by within-basin processes might act to favour the detection of ash cloud events depositing only a small number of tephra glass shards by concentrating shards toward one area of the lake thus bringing them above detection levels of current extraction techniques. Our results support the suggestion of previous studies of proximal tephra layers in lakes and catchments (e.g. Boygle, 1999) that a combination of records from both lakes and peatlands must be used to establish the most comprehensive and complete regional (crypto-) tephrostratigraphies.

4.3. Preservation of mafic tephras

Prior to this study, tephra from only five basaltic eruptions had been identified in terrestrial Holocene records in northern Europe, the majority in lakes in the Faroe Islands or Ireland (Wastegård et al., 2001; Chambers et al., 2004). The apparent lack of basaltic tephras in peatlands cannot be easily explained by the different extraction methodologies used to conduct initial scans for tephra on samples from peatlands and lakes. The extraction method commonly applied to lake samples, density separation, can result in the loss of basaltic shards which are not always recovered at a standard float density of 2.5 g cm^{-3} (Davies et al., 2001). Conversely, peatland samples are commonly extracted by igniting the surrounding peat (Hall and Pilcher, 2002) a process which involves limited use of chemical treatment or handling and should result in the loss of very few shards of any chemical composition. Three explanations have been proposed for the dominance of felsic tephras in the distal geological record, and in particular the apparent scarcity of basaltic tephras in peatlands:

1) There is experimental evidence that basaltic glass is more prone than silicic glass to hydration, alteration and even complete dissolution in acidic environments (Pollard et al., 2003; Wolff-Boenisch et al., 2004);
2) Basaltic glass shards are more dense than silicic shards (2.5–2.9 and 2.3 g cm^{-3}, respectively), and therefore glass shards of basaltic composition are likely to fall out of the atmosphere earlier than silicic shards of the same size (Stevenson et al., 2015), and arrive over northern Europe in lower concentrations in the air.
3) Eruptions of basaltic magma are typically less explosive and therefore generally produce less tephra, which is released at a lower height, than eruptions of more silicic magmas. Unlike raised peatlands, lakes concentrate shards from the wider catchment, perhaps increasing the probability of cryptotephra layer detection in lake sediments when fewer glass shards have been deposited at a distal location during an eruption.

Claraghmore lake contains the only basaltic cryptotephra layer identified in this study (CLA-L1) which has a relatively high concentration of shards ($n = 141$) when compared with those of other cryptotephra layers identified in this lake. No basaltic cryptotephra layers were identified in Claraghmore bog. The presence of large concentrations of basaltic shards in Claraghmore Lake, while the layer was apparently completely absent from the adjacent peatland, suggests that basaltic cryptotephra layers are not recorded representatively when compared to silicic cryptotephra layers in peatlands. Our findings would appear to support the hypothesis that the low numbers of basaltic tephras in the European record may be partly due to the dominance of peatland records, which appear to provide unfavourable conditions for the preservation and/or concentration of basaltic glass shards. There have been many more cryptotephra studies on peatlands in Ireland than have been conducted on lakes. This is not reflected in the number of basaltic cryptotephra layers identified in lakes and peatlands in the region ($n = 2$ and $n = 0$, respectively).

As no basaltic cryptotephra layers were identified in both peatland and lake sites it was not possible to compare geochemical data for tephra of mafic composition recovered from peatlands and lakes. However, Hekla 1104 and SN-1 in Sammakovuoma peatland and lake are geochemically indistinguishable (Figs. 10 and 7) suggesting that rhyolitic (Hekla 1104) and trachydacitic (SN-1) tephras undergo either the same chemical alteration, or a negligible amount of chemical alteration in lake and peatland environments with different pH conditions (lake pH = 7.0, peatland pH = 5.9). Similarly, there is no discernible difference between the major element glass geochemistry of the Glen Garry tephra found in both Malham Tarn and Malham Moss (1966–2210 cal yr BP). This suggests that prolonged exposure to acid (Malham Moss) or alkaline conditions (Malham Tarn, pH = ~8) has not impacted on the tephra geochemistry as determined by EPMA. Samples from both Malham Tarn and Sammakovuoma Lake were extracted for geochemical analysis using density separation, whereas samples from Malham Moss and Sammakovuoma peatland were extracted using acid extraction. In this instance neither the depositional environment nor the method of extraction had a significant impact on the major element geochemistry of glass shards from the Hekla 1104, SN-1 or Glen Garry cryptotephra layers.

Given that we only identified one basaltic cryptotephra layer in the lake and peatland sites examined in this study and therefore had only a small sample size, we reviewed tephra records from published literature over the last 7000 years (Fig. 12). There are some examples of basaltic tephras identified in peatlands. The Hov (6190-5720 cal yr BP) and Landnám (AD 871 ± 2) tephras have been identified in peatland records on the Faroe Islands (Hannon et al., 2001; Wastegård, 2002). Given the close proximity of the Faroe Islands to Iceland, the glass shards at these sites were most likely larger and more numerous than those delivered to peatlands further away from Iceland. Although larger shards have a smaller surface area to volume ratio and are therefore less prone to chemical alteration, we suggest that given the longevity of these shards in peatlands, and given that we identify no evidence of dissolution in tephras of rhyolitic and mixed composition; preservation alone is unlikely to explain the lack of Holocene basaltic tephras in peatlands. Instead, we suggest that, due to differences in eruption style and tephra density, basaltic tephra shards fall out more quickly than rhyolitic tephra shards; therefore fewer shards reach sites far from the volcano. Raised peatlands record only primary tephra fall material and small concentrations of shards may be below detection levels, whereas lakes focus tephra from across the catchment into a small basin and concentrate the tephra, raising the numbers of shards above detection levels. As previously discussed, this process is complicated because tephras are then subject to additional within-basin redistribution, which can act to bring the number of shards above/below detection levels in areas of the lake basin. This idea is supported by the recent discovery of basaltic tephra from the Laki eruption of 1783 in a small (30 × 15 m) woodland hollow in Ireland. We suggest that similar processes of runoff and the concentration of glass shards might operate in small

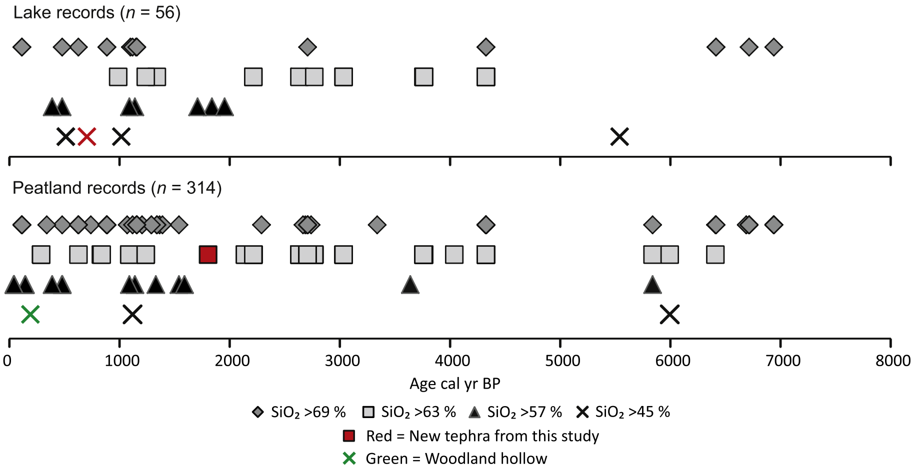

Fig. 12. Diagram indicating the age and geochemistry of glass from cryptotephra layers deposited in peatland and lake sites in northern Europe over the last 7000 years. Silica values (in wt %) are based on the TAS classification system. Age displayed is the mid-age estimate for each tephra. Basaltic tephras have been found in both lakes and peatlands. The two new tephras described in this paper are added in red. Ages of these new tephras are based on interpolation from radiocarbon dates or age depth models and are given in Table 2. The basaltic tephra indicated in green was identified by Reilly and Mitchell (2015) in a woodland hollow but is included here in the 'peatland' category. References: Swindles et al. (2011) database and references therein and Wulf et al. (2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

woodland hollows as operate in small lakes.

5. Conclusions

1. We present evidence that lakes and peatlands provide contrasting records of volcanic ash deposition; the dominance of peatland records of ash fallout in northern Europe may bias our current understanding of ash cloud reoccurrence.
2. In general, we identify more cryptotephra layers over the same time period in peatlands than lakes. However, there is evidence of incomplete tephra records in both peatlands and lakes. A combination of records from both lakes and peatlands must be used to establish the most comprehensive and complete regional tephrostratigraphies.
3. We find no evidence for chemical alteration to any of the glass shards which were analysed in this study. We suggest that glass shards do not undergo significant chemical alteration in peatland or lake environments (pH range: 4.3–8.2) over the time scale of this study. Instead, we suggest that the low number of basaltic cryptotephra occurrences in peatlands is most likely related to peatlands capturing only primary tephra fall events. This is in contrast to lakes which concentrate tephra fallout from a wider area.
4. We also find no evidence for the chemical alteration of shards extracted by different extraction processes (density separation vs. acid extraction). We clearly illustrate that acid digestion is a suitable extraction method for glass shards of rhyolitic and trachydacitic composition from ombrotrophic peatlands and does not result in a significant degree of chemical alteration.
5. We identify a new basaltic tephra at Claraghmore Lake in Ireland (CLA-L1). The geochemistry of glass from this tephra suggests it is derived from an eruption of the Grímsvötn volcano, Iceland, post AD 1000. This basaltic tephra is not present in the adjacent peatland.
6. We identify a new trachydacitic cryptotephra (SN-1) and extend the existing spatial coverage of cryptotephras in northern Europe to sites in Arctic Sweden. SN-1 is tightly dated to 1183-1147 cal yr BP in one of our peatland sites suggesting an earlier age (1860–1520 cal yr BP: Larsen et al. (2002)) on peaty soil underlying SN-1 in Iceland should be considered a maximum estimate. The cryptotephra deposits we describe may provide important marker horizons for palaeoclimatological research in the vulnerable Arctic region.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2016.03.011.

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