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Holocene tephra horizons at Klocka Bog, west-central Sweden: aspects of reproducibility in subarctic peat deposits

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ABSTRACT: This paper presents one of the most extensive Holocene tephra records found to date in Scandinavia. Microtephra horizons originating from Icelandic eruptions were recorded in two ca. 2 m thick peat profiles at Klocka Bog in west-central Sweden. Five of the microtephra horizons were geochemically correlated to the Askja-1875, Hekla-3, Kebister, Hekla-4 and Lairg A tephras respectively. Radiocarbon-based dating of these tephras broadly agree with previously published ages from Iceland, Sweden, Germany and the British Isles. The identification of the Lairg A tephra demonstrates a more widespread distribution than previously thought, extending the usefulness of Icelandic Holocene tephrochronology further north into west-central Scandinavia. Long-lasting snow cover and seasonal wind distribution in the lower stratosphere are suggested as factors that may be responsible for fragmentary tephra deposition patterns in peat deposits of subarctic Scandinavian. Copyright © 2004 John Wiley & Sons, Ltd.

KEYWORDS: tephra; tephrochronology; Holocene; Klocka Bog; Sweden.

Introduction

Tephrochronology is a powerful tool for relative and absolute dating of Quaternary deposits (Westgate *et al*., 1992; Sarna-Wojcicki, 2000). The high-resolution Holocene tephrochronology of Iceland is of particular value for constraining and correlating the timing and duration of short-term climatic and palaeoecological events in the North Atlantic region (e.g. Eiríksson *et al*., 2000a, b). Over the past few decades glass particles, originating from Icelandic volcanic systems, have been identified in Holocene peat sequences and lake sediments throughout Scandinavia (e.g. Persson, 1966, 1971; Boygle, 1998; Zillén *et al*., 2002; Wastegård, in press[Q1]). Here we present new evidence from Klocka Bog, an ombrotrophic peat deposit in west-central Sweden. The tephras detected include several of the most important Holocene tephra isochrone in the North Atlantic region.

As part of pioneering tephrochronological investigations in central Scandinavia, Persson (1966, 1971) sampled a peat sequence at Klocka, and detected two ash layers of Icelandic origin that possibly originated from the Öraefajökull (AD 1362) and Hekla-4 or Kebister eruptions (ca. 4200 and 3800 cal. yr BP, respectively). Persson's identifications were made on the basis of refractive index measurements of the glass particles, supported by conventional radiocarbon dating. Our renewed sampling of the site has revealed an unprecedented set of tephras including the Lairg A tephra (Dugmore *et al.*, 1995a[Q2]; Pilcher *et al*., 1996; Hall, 2003), not previously recorded in Sweden. In addition, this paper highlights depositional problems encountered in tephrochronological studies of peat deposits. The results from Klocka Bog contribute to the ongoing mapping of north-west European tephra distributions as chronological marker horizons within Quaternary stratigraphy, and these time markers open new possibilities for comparison and correlation of multi-proxy data from terrestrial, marine and ice-core archives.

Site description

Klocka Bog (63 °18.5′N, 12 °29.0′E, surface area ca. 260 ha) is a gently sloping bog-fen complex protruding into Lake Ånnsjön, situated at 526 m a.s.l. in the province of Jämtland, west-central Sweden (Fig. 1; Lundqvist, 1969). The peat deposit is surrounded by coniferous forest (mainly *Picea*

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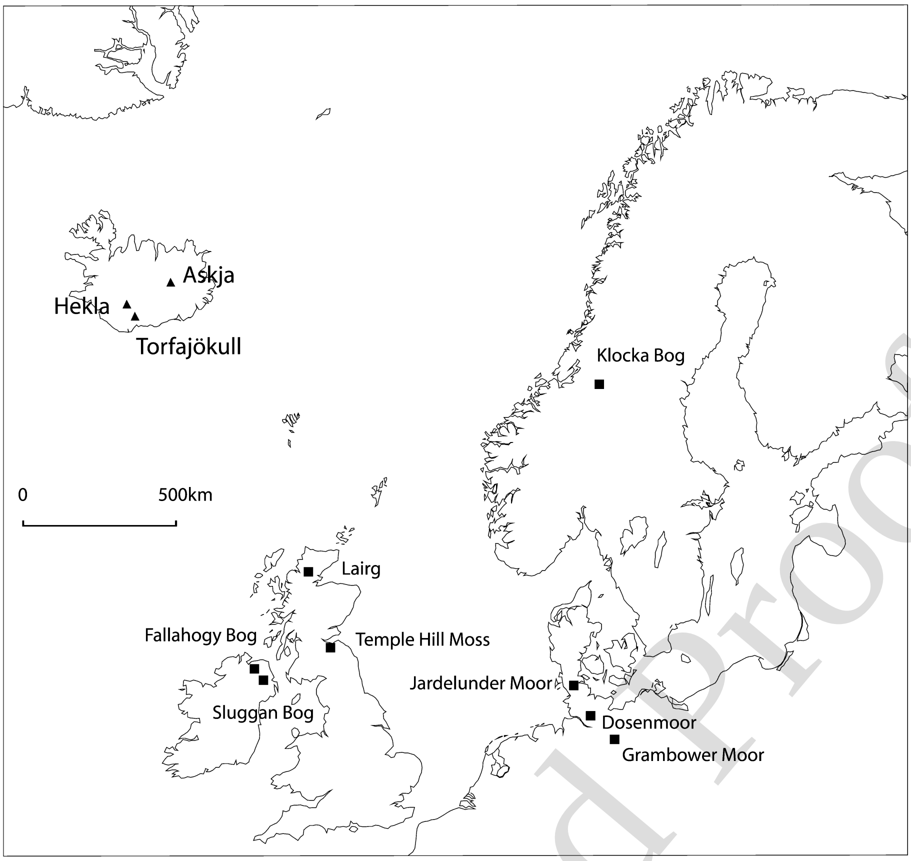

Figure 1 Map of the North Atlantic region showing the location of the Askja, Torfajökull and Hekla volcanoes, and known sites on the British Isles and in northern Germany where the Lairg A tephra has been recorded (e.g. Dugmore *et al.*, 1995a[Q3], Pilcher *et al.*, 1996; Hall and Pilcher, 2002; van den Bogaard and Schmincke, 2002). Only two of the four adjacent sites in Northern Ireland have been included

abies), and is dissected by several small streams. The shoreline of Lake Ånnsjön is actively eroding into the bog, creating a 2.5 m high vertical erosion scarp that facilitates sampling of the peat sequence. Scattered *Betula pubescens* sp. trees occur near the edge. The surface of the deposit is dominated by bog areas, with a vegetation of mainly *Betula nana*, *Vaccinium uliginosum*, *Empetrum nigrum*, *Rubus chamaemorus*, *Sphagnum* sp., and lichens. The wetter fen areas, or pools, are dominated by *Sphagnum* sp., *Eriophorum* sp., *Andromeda polifolia* and *Drosera* sp. The mean annual temperature in the area is 1.1 °C, and monthly mean values for January and July are −7.6 °C and 10.7 °C, respectively. Mean annual precipitation amounts to 628 mm, of which 45% falls as snow (data from 1961 to 1990; Alexandersson *et al.*, 1991).

Methods

The peat sequence was sampled at two locations (profiles 1 and 2) situated ca. 150 m apart along an open section. Profile 1, extending 232 cm in length, was sampled with a 7.5 cm Russian peat corer, and profile 2 (236 cm) was sampled as contiguous monoliths of peat ($20 \times 6 \times 6$ cm) from a freshly cleared section. In both cases, samples were collected ca. 0.5 m inside the erosion scarp. Cores and monoliths were carefully wrapped in plastic before transport and stored at 4 °C. The profiles were dominated by homogeneous *Sphagnum*-peat and contained no visible tephras.

Glassy microtephra particles (shards) were detected using the method described by Pilcher *et al.* (1995). Contiguous sections of 5 cm thickness were taken from each peat profile, ashed for 4 h in a muffled furnace at 550 °C, soaked in 10% HCl for approximately 12 h, and mounted in Canada Balsam for inspection under a polarising microscope at 100–400 × magnification. Samples of 2.0 cm^3 were then resampled at 1 cm resolution from sections containing volcanic glass. Glass shards exceeding 20 μm in size from these samples were counted and tephra concentrations were calculated by the use of added *Lycopodium* spores.

Following location and quantification of tephra horizons, additional subsamples from the same levels were subjected to the acid digestion procedure described in Persson (1971) and Dugmore *et al.* (1992). In order to obtain sufficient concentrations of glass shards for electron probe microanalysis (EPMA), greater volumes of peat (20–45 cm^3) were used than, for example, by Dugmore *et al.* (1995a)[Q3]. Mineral residues were not subjected to sieving or heavy liquid separation, except for the sample at 3–4 cm in profile 1, where the high minerogenic content made separation using sodium polytungstate necessary. The heavy liquid separation method described by Turney (1998), with densities of 2.3 and 2.5 g cm^{-3}, was used in this case. Quantitative geochemical analysis was performed on a wavelength dispersive spectrometer (WDS) electron microprobe at the Department of Geology and Geophysics, Edinburgh University. Further details of EPMA procedures used in this study are given later in Table 3, and, more generally, in Dugmore *et al.* (1995a)[Q3] and van den Bogaard and Schmincke (2002).

Thirteen AMS radiocarbon dates were obtained from 4–20 mm thick peat samples (Table 1). The material dated was predominantly *Sphagnum* and other moss species. Calibrated radiocarbon ages were obtained according to the IntCal 98 calibration data-set (Stuiver *et al.*, 1998).

Table 1 Radiocarbon dates from profiles 1 and 2 from Klocka Bog. Material submitted for analysis contained moss stems and leaves except for LuA-5134, which was composed of *Pinus* sp. wood. The dates were calibrated against the IntCal98 data set Stuiver *et al.* (1998) (and ages are expressed as calendar years BP (before 1950))

Profile	Depth below peat surface (cm)	^{14}C age BP	Calibrated age BP and error estimate (2σ)	δ^{13}C (‰)	Laboratory number
1	25–26	2195 ± 100	2150 ± 300	−25.0	LuA-5140
1	58–59	3010 ± 85	3165 ± 225		LuA-5139
1	106–107	4690 ± 85	5350 ± 300		LuA-5138
1	172–173	6190 ± 80	7035 ± 235	−24.5	LuA-5137
1	193–194	6870 ± 100	7725 ± 215		LuA-5136
1	215–216	8055 ± 95	8950 ± 350		LuA-5135
1	232–234	8390 ± 100	9335 ± 215		LuA-5134
2	27–28	2740 ± 90	2895 ± 185		LuA-5317
2	48–49	3685 ± 85	4025 ± 325		LuA-5318
2	112.8–113.2	4310 ± 40	4900 ± 80		LuA-5536
2	175–176	5555 ± 85	6360 ± 190		LuA-5319
2	194–195	6040 ± 85	6925 ± 275	−26.6	LuA-5320
2	234–236	7490 ± 50	8285 ± 105		LuA-5537

Geochemical results and correlation of tephra horizons

Initial screening indicated that five of the 5-cm contiguous samples from profile 1, and three of the 5-cm contiguous samples from profile 2, contained glass shards (Fig. 2). Initially, all tephra horizons appeared to contain sufficient amounts of shards for microprobe analysis, except for the layer at 26–27 cm in profile 1. Only measurements yielding a sum exceeding 93% were used for identifying tephra horizons. Obtaining analyses with a sum above 95%, as recommended by Hunt and Hill (1993), proved difficult because of the small size (<10 μm) of some shards. However, totals in the range of 93–95% can be of considerable value in studies of distal tephra deposition where the number of shards available for analysis is limited and shards are small. The tephra horizons identified are shown in Table 2 and their major element geochemistry is presented in Table 3. Tephra concentration data and age–depth relationships are shown in Fig. 2. All horizons are dominated by rhyolitic glass shards, with geochemical characteristics that suggest an Icelandic source (Table 3 and Fig. 3).

A tephra horizon with relatively high concentration of glass shards was found at 3–4 cm in profile 1. This layer is geochemically correlated to the Askja-1875 tephra, which is widespread in central Sweden (Fig. 3a, and Table 3; e.g. Mohn, 1878; Persson, 1966; Sigurdsson and Sparks, 1981; Oldfield *et al.*, 1997; Boygle, 1998), but has not been found previously at Klocka Bog (Persson, 1966). The tephra horizon at 26–27 cm in profile 1 contained only a few glass shards and geochemical analysis was not possible. The age–depth model suggests an age of ca. 2200 cal. yr BP, which is close in age to the Glen Garry tephra, found on the British Isles and northern Germany (Dugmore *et al.*, 1995a[Q3]; van den Bogaard and Schmincke, 2002). A recently discovered tephra at Stömyren Bog, south central Sweden, dated by interpolation to ca. 2100 cal. yr BP (Gunnarson *et al.*, 2003), is a possible alternative, as is the slightly older BGMT-3 tephra (ca. 2340 cal. yr BP) identified in Scotland (Langdon and Barber, 2001). However, the Stömyren Bog tephra recently has been shown to be geochemically distinct from the Glen Garry and BMGT-3 tephras (Wastegård, in press[Q1]).

The third youngest tephra horizon at Klocka Bog was found at 27–28 cm in profile 2. Its geochemistry is typical of the Hekla volcanic system (e.g. Larsen *et al.*, 1999), exhibiting CaO contents between 1.8 and 3.2 wt% and MgO contents between 0.1 and 0.4 wt% (Fig. 3c). The most widespread tephra from Hekla dated to this period is Hekla-3 (ca. 3000 cal. yr BP; Dugmore *et al.*, 1995a[Q3]; Boygle, 1998; van den Bogaard and Schmincke, 2002). It is difficult to separate this tephra, based on the geochemistry alone, from the slightly older Kebister tephra (ca. 3750 cal. yr BP; Fig. 3b and c), but the calibrated radiocarbon date of 2895 ± 185 cal. yr BP at the peak tephra concentration suggests a correlation to the Hekla-3 eruption.

The highest concentrations of glass shards were found at two distinct horizons in profile 1. The upper horizon has a peak concentration of ca. 3000 shards >20 μm cm^{-3} at 80–81 cm and the lower contains ca. 2500 shards >20 μm/cm^{-3} at 91–92 cm. Regardless of how the age model is constructed, the ages fall between ca. 3700 and 4700 cal. yr BP for these two layers. The Hekla volcanic system has been identified as their source, based on non-mobile element bi-plots and ratios, e.g. FeO$_{tot}$ versus MgO and CaO versus MgO (Fig. 3b and c). More specifically, these geochemical signatures suggest that the upper layer can be correlated to the Kebister tephra and the lower to the Hekla-4 tephra (Fig. 3b and c). These two tephras are probably the most widespread mid-Holocene tephras in Scandinavia, having been identified in both lacustrine and peat deposits (e.g. Boygle, 1998; Zillén *et al.*, 2002; Gunnarson *et al.*, in press[Q4]). The age difference between the two tephras, calculated from laminated lake sediments, is 400 ± 40 varve years (Zillén *et al.*, 2002), which indicates a mean peat accumulation rate of 0.25–0.30 mm yr^{-1} at Klocka Bog. Only shards from the earliest phase of the Hekla-4 eruption (i.e. FeO$_{tot}$ contents between 1.8 and 2.0%; Fig. 3c) seem to be present (cf. Larsen and Thorarinsson, 1977; Larsen *et al.*, 1999). The Kebister and Hekla-4 horizons were not dated in profile 1, but a tephra horizon at 48–49 cm in profile 2 was dated to 3685 ± 85 ^{14}C yr BP (Table 1). This horizon contained only a few particles and geochemical analysis was not possible. Owing to a plateau in the radiocarbon calibration curve, the radiocarbon age covers a broad calibrated age interval (4025 ± 325 cal. yr BP). Therefore, the tephra at 48–49 cm in profile 2 could be correlated to either Kebister or Hekla-4 (cf. Table 2). Persson (1966) described only one mid-Holocene tephra at Klocka Bog (Fig. 2), dated to 3700 ± 75 ^{14}C yr BP (calibrated age: 4045 ± 215 cal. yr BP; Table 1). Persson correlated this horizon to the Hekla-4 tephra, but a correlation with the Kebister tephra, identified at a later date, as suggested by Boygle (1998) now seems more plausible.

The lowermost tephra horizon identified (Fig. 4), which was found in both profiles (172–173 cm in profile 1; 194–195 cm in profile 2), was dated to 6190 ± 80 ^{14}C yr BP and 6040 ± 85 ^{14}C yr BP, respectively (Table 1). The calibrated age is ca. 6650–7270 cal. yr BP. Two distinct colourless tephras dated to this time span have been found at many sites on the British Isles and in northern Germany (e.g. [Q3]Dugmore *et al.*, 1995a; Pilcher *et al.*, 1996; van den Bogaard and Schmincke, 2002). These deposits, the Lairg B and A tephras, derive from the Torfajökull and Hekla volcanic systems, respectively. The older layer (Lairg A), is dated to 6903 ± 95 cal. yr BP in Northern Ireland (Pilcher *et al.*, 1996), and van den Bogaard and Schmincke (2002) interpret it as a fallout from the Hekla-5 eruption (ca 6100 ^{14}C yr BP; Larsen and Thorarinsson, 1977). Microprobe analyses of the tephra at 194–195 cm in profile 1 point to the Hekla volcanic system as a potential source (Fig. 3b and c) and all analyses agree with those from the Lairg A layer. The geochemical signatures are difficult to separate from the Hekla-4 tephra (e.g. Hall and Pilcher, 2002), and therefore

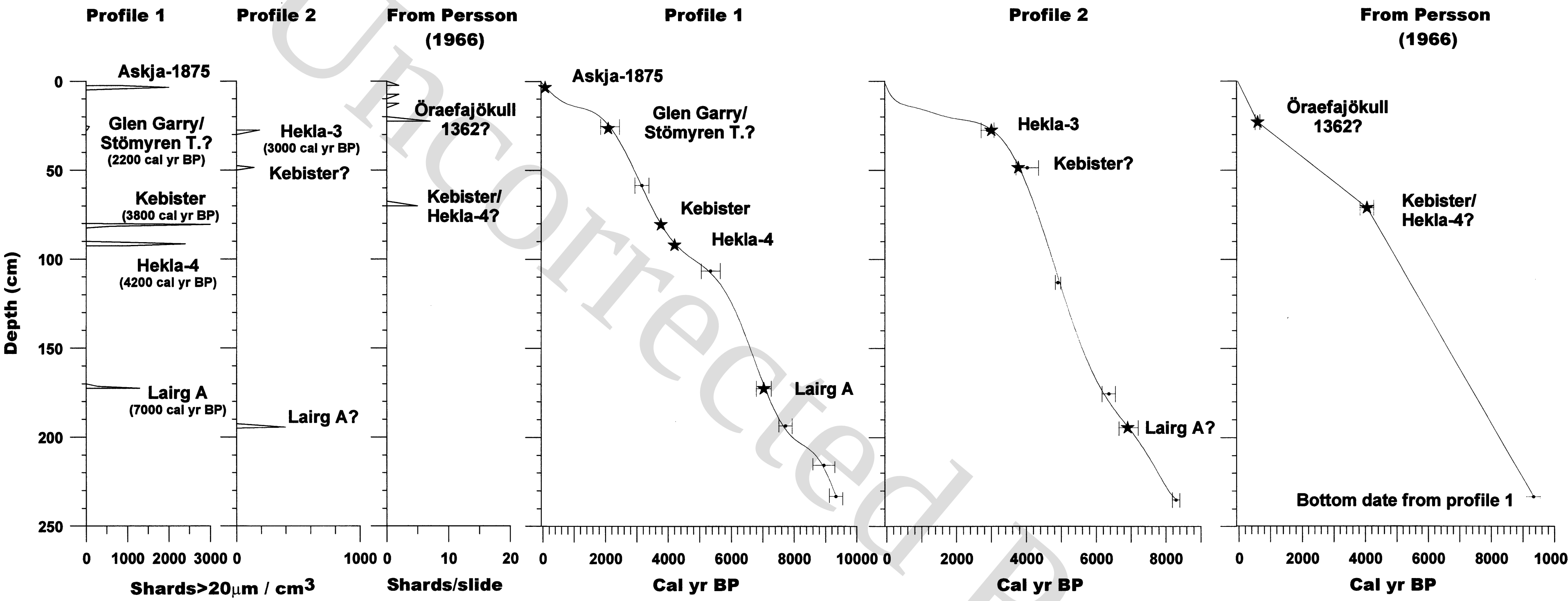

Figure 2 Tephra particle concentrations from Klocka Bog for profiles 1 and 2, and their age–depth curves. Concentration data and age–depth relationships from Persson (1966) are also included. The age–depth curve for profile 1 is fixed to the peat surface (0 cm), Askja-1875, Hekla-4 and all of the radiocarbon dates with a 10th grade polynomial curve fit. For profile 2, the curve is fixed to the peat surface (0 cm) and all of the radiocarbon dates with a 9th grade polynomial curve fit. The tephras investigated by Persson (1966) have an unknown geochemistry and were only correlated to relevant eruptions based on radiocarbon ages; as are the Glen Garry/ Stömyren tephra from profile 1 and the Kebister tephra from profile 2. Tephra horizons are marked with stars, and calibrated radiocarbon ages are expressed as mid-intercepts and 95.4% confidence intervals

Table 2 Tephra horizons identified at Klocka Bog and their age assignments. P1 and P2 refer to profiles 1 and 2, respectively. The tephra horizon at 48–49 cm in profile 2 can be correlated to either Kebister or Hekla-4. * From Persson (1966, 1971); the tephra horizon at 70–72 cm cannot be correlated to Kebister or Hekla-4 solely based on the radiocarbon date, but a best-fit to the age–depth curve suggests a correlation to Kebister. [1]Haflidason *et al.* (2000), [2]Pilcher *et al.* (1996), [3]van den Bogaard *et al.* (2002), [4]Gunnarson *et al.* (2003), [5]Dugmore *et al.* (1995a[Q3]; age for the Glen Garry tephra)

Tephra horizon	Depth below peat surface (cm)	Age (This study) (cal. yr BP; $\pm 2\sigma$)	Published Age (cal yr BP; $\pm 2\sigma$)
Askja-1875	3–4 (P1)	—	AD 1875[1]
Öraefajökull-1362?	22–24 (*)	—	AD 1362[1] AD 1365 ± 75*
Glen Garry/ Stömyren Tephra?	26–27 (P1)	ca. 2200 (P1)	2125 ± 185[5] ca. 2100[4]
Hekla-3	27–28 (P2)	2895 ± 185 (P2)	2997 ± 40[3]
Kebister	80–81 (P1)		3765 ± 135[4]
?	48–49 (P2)	4025 ± 325 (P2)	
?	70–72 (*)		4045 ± 215*
Hekla-4	91–92 (P1)	—	4287 ± 58[2]
Lairg A	172–173 (P1)	7035 ± 235 (P1)	6903 ± 95[2]
?	194–195 (P2)	6925 ± 275 (P2)	

distinction was achieved using the radiocarbon ages obtained. Although Holmes (1998) has found this deposit in Norway, this is the first confirmed record of the Lairg A tephra in Sweden.

Influence of long-lasting snow cover on tephra deposition

The tephra horizons identified at Klocka Bog are discontinuous, implying a patchy tephra distribution at the time of incorporation into the peat sequence. As discussed below, the difficulties of reproducing tephra results from closely spaced sites and the inferred uneven tephra distributions are more likely related to post-depositional effects (e.g. Boygle, 1999; Hunt, 1994[Q4]; Davies *et al.*, 2001) than to eruption plume depositional dynamics (Sparks *et al.*, 1997; Lacasse, 2001). Processes associated with the northerly location of the study site, such as long-lasting snow cover and exposure to strong winds, are believed to be important for tephra studies in Scandinavia, as elaborated on further below.

Lacasse (2001) discussed the influence of climate variability and seasonal wind dynamics on the atmospheric transport of tephra in the subpolar North Atlantic. The transport and subsequent tephra fallout is dependent on strong westerly winds in the lower stratosphere, which are predominantly directed towards Scandinavia during the autumn and winter months (October–March), and towards Greenland during spring and summer (April–September). In addition, investigations on Iceland carried out by Jóhannesson *et al.* (1981), Hunt (1994)[Q4] and Boygle (1999) have shown that snow in combination with strong winds can have a profound effect on local tephra deposition, especially at exposed sites such as bogs and other treeless areas where lack of wind shelter may facilitate tephra redeposition. The tephra distribution at the time of initial fallout is dependent on prevailing weather conditions. Calm, dry conditions produce a blanket-like tephra cover whereas cyclonic events lead to more discontinuous patterns. Aeolian and fluvial activity at the site of deposition may then lead to redistribution of the primary tephra cover (Boygle, 1999). However, the Icelandic studies have focused on proximal tephras, usually several centimetres in thickness, or more. These proximal tephra layers, characterised by considerable mass and grain sizes in the range of ca. 0.06–5 mm, react quite differently to aeolian processes (e.g. snow drift), than microtephra horizons (grain size ca. 10–60 µm) such as those found in Scandinavia.

In the study area the snow cover currently lasts ca. 7 months, from late October to late May, which implies that the site has been covered by snow during a major part of the Holocene. Hence it is probable that some of the pre-19th century tephras were deposited initially on snow cover. Judging from the concentrations presented in Fig. 2, the associated tephras hardly appeared as more than a slight discoloration of the surface, if deposited on snow. The tephra-loaded snow could then have been easily redeposited in aeolian sediment traps, such as pools and small hollows. Even if immediately buried by fresh snow, such tephra deposits remain sensitive to aeolian activity until the spring melt, when meltwater transport may lead to further redeposition across the frozen peat surface (Hunt, 1994)[Q4]. In contrast, tephras deposited on bare peat surfaces would have been incorporated directly into the field layer, usually dominated by mosses, and hence protected from any form of redeposition. As suggested by Hunt (1994)[Q4], these processes are probably of great importance for the spatial distribution of distal tephras in the North Atlantic region.

The only tephra at the study site with a sufficiently well constrained eruption date to allow this hypothesis to be tested is the uppermost tephra in profile 1, correlated to the Askja-1875 eruption. The explosive eruption of Askja in 1875 started on 29th March, followed by tephra fallout over west-central Sweden a day later (Mohn, 1878). During March 1875, the mean temperature was −4.9 °C and the monthly precipitation was 9 mm at Östersund, 100 km east of Klocka Bog (data from SMHI, 2002). It is thus very likely that the site was snow-covered during the tephra fallout. Therefore, it is plausible that the absence of the Askja-1875 tephra horizon in profile 2 is related to post-depositional loss at the sampling site.

When regarding the tephra horizons interpreted as Kebister and Hekla-4 in profile 1 and Hekla-3 in profile 2, it seems even more likely that aeolian and/or fluvial processes have been involved. A complex distribution pattern has been imposed. There are no tephras in profile 1 that can be correlated to Hekla-3, and only one of the two tephras correlated to Kebister and Hekla-4 in profile 1 can be found in profile 2 and in the dataset presented by Persson (1966). The origin of these single horizons remains uncertain, but the radiocarbon ages point to a correlation with the Kebister tephra.

The tephra horizon interpreted as Lairg A in profiles 1 and 2 is not present in the profile investigated by Persson (1966). However, Persson only sampled the profile to a depth of 190 cm, thus possibly omitting Lairg A. Single shards of tephra are reported to occur at levels of 130, 150 and 180 cm, but Persson reported single shards almost throughout the profile, to which little significance were assigned. It is hence possible that some tephras (e.g. Lairg A and possibly Kebister) were deposited during the snow-free season, whereas other tephras (e.g. Askja-1875, Hekla 3 and possibly Hekla-4) were deposited on snow.

In addition, the relatively high concentrations of tephra particles correlated to the Askja-1875, Kebister, Hekla-4 and Lairg A eruptions in profile 1, may suggest that the sampling site was dominated by wet fen conditions during extended periods of the Holocene. This is corroborated by humification data and finds of *Isoëtes lacustris* in the lower part of the sequence (Bergman and Hammarlund, in preparation[Q5]).

Table 3 Results of the geochemical analysis of the tephra horizons recorded at Klocka Bog. Suggested correlations to published geochemical data are in brackets. Electron micro probe analysis was undertaken on a Cambridge Instruments Microscan V microprobe operating at 20 kV accelerating voltage, 5 μm beam diameter, and a 15 nA beam current. Slides were scanned systematically for superficial grains. Two-second energy dispersive spectrometry (EDS) compositional profile checks were obtained for every well polished grains of suitable size (i.e. >5 μm). Quantitative analysis of shards with volcanic glass composition was then undertaken in WDS mode. Before each WDS analysis the beam was centred by 'burning' a hole in the araldite resin and the beam current was determined by the insertion of a Faraday cup into the path of the beam. Nine major elements were measured, with a counting time of 10 s per pair of elements. The beam was covered during spectrometer movement to minimise mobilisation of alkali elements. To assess the degree of sodium mobilisation, this element was measured during the first and final counting period. n = number of shards analysed

Profile: depth	n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TOTAL
P1: 3–4 cm [Askja-1875]	1	74.41	0.71	12.03	2.99	0.10	0.54	2.06	2.92	2.63	98.39
	2	73.09	0.80	12.32	3.43	0.08	0.68	2.50	2.70	2.52	98.12
	3	73.01	0.76	12.51	3.57	0.09	0.76	2.54	2.86	2.44	98.54
	4	72.97	0.80	12.25	3.54	0.08	0.66	2.61	3.21	2.65	98.77
	5	72.72	0.85	12.50	3.64	0.04	0.77	2.69	3.70	2.54	99.45
	6	72.44	0.85	12.24	3.69	0.09	0.79	2.73	3.25	2.48	98.56
	7	72.43	0.72	12.00	3.30	0.06	0.70	2.40	2.52	2.47	96.60
	8	72.05	0.70	12.37	3.80	0.10	0.79	2.85	3.33	2.40	98.39
	9	71.85	0.78	12.12	3.41	0.04	0.71	2.46	3.13	2.32	96.82
	10	71.80	0.85	12.49	4.11	0.12	0.87	2.86	3.44	2.17	98.71
	11	71.56	0.74	12.17	3.48	0.12	0.75	2.31	2.89	2.22	96.24
	12	71.54	0.87	12.73	3.94	0.14	0.83	2.95	3.27	2.16	98.43
	13	71.44	0.83	12.18	3.20	0.11	0.68	2.31	3.11	2.41	96.27
	14	71.16	0.86	12.53	4.25	0.09	0.87	2.77	2.96	2.36	97.85
	15	70.37	0.88	12.49	4.41	0.15	0.93	3.15	3.29	2.33	98.00
Mean (1–15)		72.19	0.80	12.33	3.65	0.09	0.76	2.61	3.11	2.41	97.94
1σ (1–15)		0.98	0.06	0.21	0.39	0.03	0.10	0.29	0.30	0.15	0.99
P2: 27–28 cm [Hekla-3]	1	71.85	0.24	14.21	2.89	0.09	0.15	2.01	3.79	2.46	97.69
	2	71.58	0.17	14.01	3.16	0.08	0.13	1.85	4.29	2.58	97.85
	3	70.84	0.21	14.03	3.09	0.12	0.14	1.94	4.08	2.51	96.96
	4	69.93	0.22	13.97	2.98	0.09	0.16	1.81	3.90	2.37	95.43
	5	69.90	0.30	14.43	3.78	0.08	0.16	2.44	3.76	2.45	97.30
	6	68.00	0.35	14.53	5.29	0.16	0.35	3.04	3.52	2.07	97.31
	7	67.59	0.39	14.70	5.50	0.19	0.39	3.14	3.88	2.20	97.98
	8	67.01	0.45	14.88	5.57	0.15	0.37	3.21	3.84	2.18	97.66
	9	66.85	0.40	14.76	5.24	0.15	0.33	3.10	3.52	2.01	96.36
P1: 80–81 cm [Kebister]	1	71.95	0.17	13.84	2.92	0.12	0.14	2.04	3.91	2.66	97.75
	2	71.26	0.18	13.85	2.95	0.10	0.13	2.00	4.22	2.43	97.12
	3	70.94	0.17	13.66	3.06	0.12	0.16	2.06	3.79	2.51	96.47
	4	70.39	0.20	14.35	4.01	0.12	0.21	2.56	4.31	2.41	98.56
	5	69.85	0.38	14.73	4.91	0.18	0.25	2.99	4.47	2.40	100.16
	6	68.88	0.36	14.72	5.57	0.18	0.41	3.00	2.35	2.12	97.59
	7	68.83	0.32	14.24	4.06	0.16	0.22	2.55	4.34	2.35	97.07
	8	68.07	0.44	14.63	5.69	0.15	0.40	3.06	4.06	2.09	98.59
	9	67.77	0.34	14.57	4.74	0.17	0.37	2.96	3.94	2.26	97.12
	10	67.52	0.40	14.55	5.07	0.16	0.32	2.91	3.93	2.04	96.90
	11	67.20	0.35	14.39	5.14	0.16	0.40	2.96	3.97	1.98	96.55
	12	66.80	0.37	14.32	5.28	0.41	0.40	3.03	3.77	2.01	96.39
	13	65.77	0.36	14.30	5.20	0.24	0.35	3.19	4.30	2.15	95.86
	14	65.70	0.44	14.33	5.48	0.18	0.39	3.19	4.18	1.98	95.87
	15	64.70	0.37	14.70	6.13	0.11	0.60	3.35	3.82	2.12	95.90
	16	69.34	0.13	13.38	3.21	0.11	0.10	1.97	3.74	2.37	94.35
	17	68.02	0.25	13.36	2.89	0.10	0.20	1.97	3.88	2.60	93.27
	18	65.23	0.40	14.02	5.03	0.13	0.34	3.06	4.40	1.88	94.49
	19	64.22	0.35	13.93	5.37	0.16	0.37	2.89	3.85	1.99	93.13
P1: 91–92 cm [Hekla-4]	1	74.10	0.06	12.36	0.63	0.00	0.01	0.81	3.71	2.66	94.34
	2	73.67	0.08	12.99	1.98	0.07	0.02	1.36	3.97	3.33	97.47
	3	72.73	0.12	12.64	1.86	0.08	0.03	1.28	4.20	3.32	96.26
	4	72.69	0.09	12.59	1.95	0.10	0.03	1.24	4.07	2.80	95.56
	5	72.44	0.07	12.50	1.89	0.07	0.02	1.37	3.77	2.72	94.85
	6	72.17	0.07	12.27	2.03	0.10	0.02	1.39	3.25	2.86	94.16
	7	62.04	1.18	13.31	9.43	0.28	1.38	4.53	3.80	1.69	97.64
P1: 172–173 cm [Lairg A]	1	74.77	0.12	12.47	1.69	0.06	0.08	1.27	2.88	2.89	96.23
	2	74.63	0.07	12.36	1.75	0.11	0.05	1.37	3.77	2.83	96.94
	3	73.64	0.14	12.50	1.70	0.08	0.07	1.29	3.87	2.42	95.71
	4	73.33	0.10	12.34	1.53	0.03	0.05	1.26	3.81	2.72	95.17
	5	72.85	0.09	12.14	1.68	0.03	0.05	1.28	3.00	2.57	93.69
	6	72.33	0.09	12.16	1.68	0.04	0.04	1.29	3.24	2.49	93.36
	7	70.72	0.08	14.58	1.97	0.10	0.06	3.02	4.52	2.09	97.14

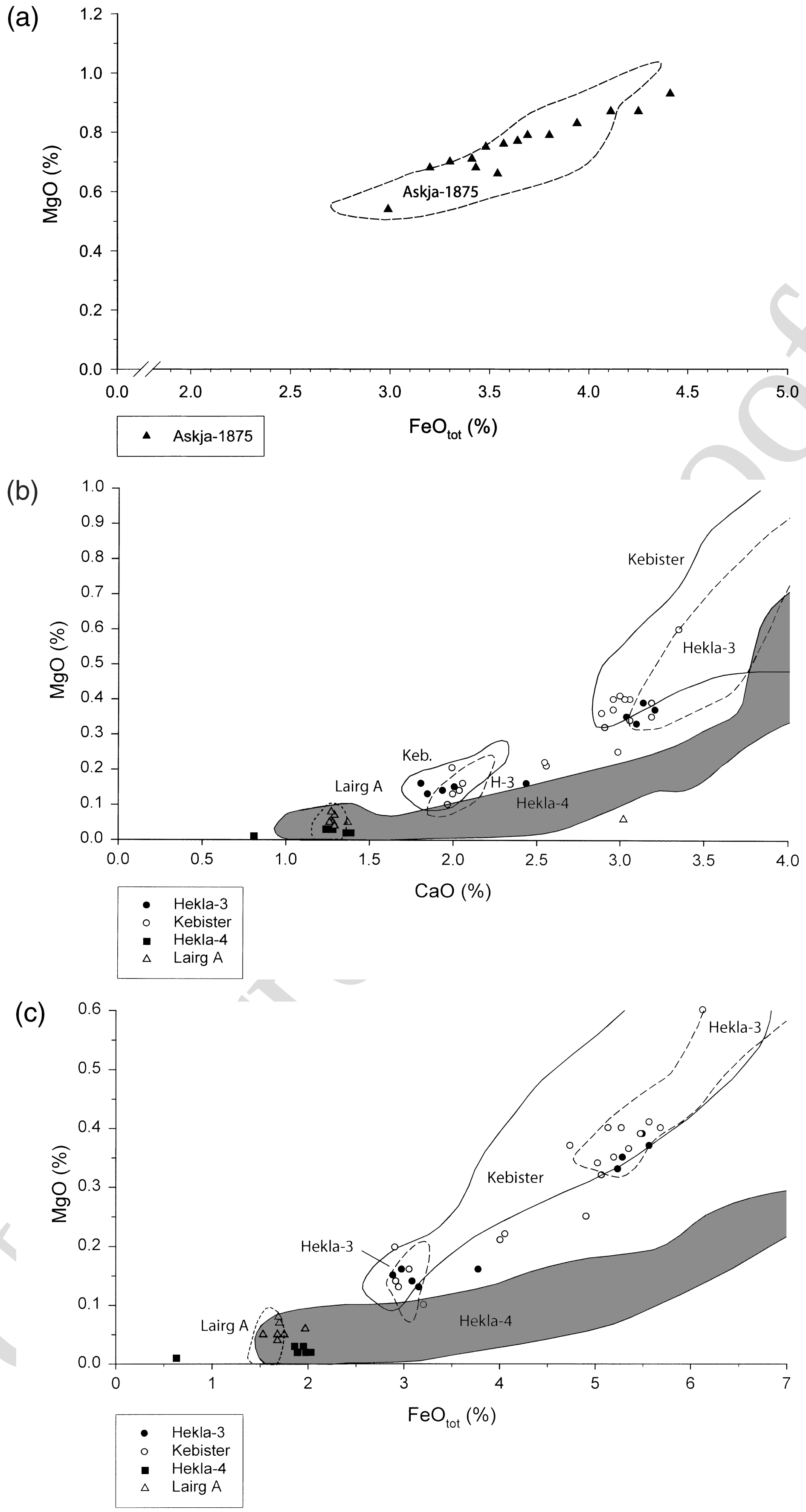

Figure 3 Major oxide data of glass shards from Klocka Bog expressed as wt%. (a) Binary plot of FeO$_{tot}$ versus MgO for the Askja-1875 tephra. The field marked with dashed lines shows the main geochemical distribution of the Askja-1875 tephra in Iceland and Sweden (Oldfield *et al.*, 1997; Larsen *et al.*, 1999; Wastegård, in press). Binary plots of CaO versus MgO (b) and FeO$_{tot}$ versus MgO (c) for the Hekla-3, Kebister, Hekla-4 and Lairg A tephras compared with the main geochemical distribution of these tephras in Iceland, the Faroe Islands, Sweden and the British Isles (data from Boygle, 1994, 1998; Dugmore and Newton, 1992, 1998; Dugmore *et al.*, 1992, [Q3]1995a; Pilcher *et al.*, 1995, 1996, Pilcher and Hall, 1996; Wastegård *et al.*, 2001; Hall and Pilcher, 2002; Wastegård, in press[Q1])

Q3

Q1

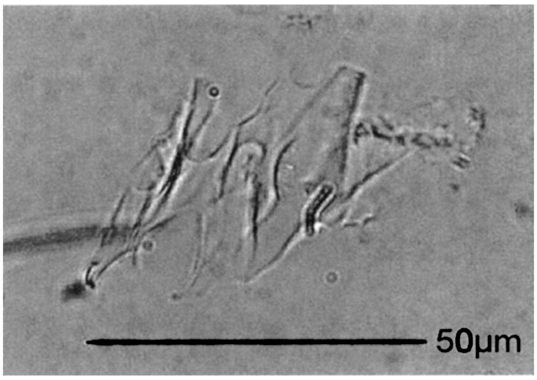

Figure 4 Glass shard from the tephra horizon at 172–173 cm in profile 1, correlated to the Lairg A tephra

In order to further assess the impact of meteorological conditions and associated processes on deposition and reproducibility of distal microtephra horizons, additional detailed studies of peat sequences are needed. Transects of multiple cores and comparative studies of adjacent sites with, for example, fen peat (pool peat) and raised bog peat are required. Also, further tephra investigations of geological archives with annual- or seasonal resolution, such as laminated lake sediments and the Greenland ice-cores, will be highly beneficial in advancing the findings of this study.

Conclusions

1. Five tephra horizons were identified geochemically at Klocka Bog, west-central Sweden. The tephras were correlated to the Icelandic eruptions of Askja 1875, Hekla-3, Kebister, Hekla-4 and Lairg A.
2. Tephra ages determined by radiocarbon dating were found to be in agreement with previously published ages. The two dates of Lairg A yielded ages of 7035 ± 235 cal. yr BP and 6925 ± 275 cal. yr BP.
3. The discontinuous nature of tephra horizons at the study site suggests that post-depositional processes associated with fallout on snow cover, such as redeposition by wind and meltwater, may have resulted in patchy distributions of the tephras across the bog surface.

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