First discovery of cryptotephra in Holocene peat deposits of Estonia, eastern Baltic

TIIT HANG, STEFAN WASTEGÅRD, SIIM VESKI AND ATKO HEINSALU

This article reports the first discovery of middle Holocene cryptotephra from a peat sequence in Estonia, eastern Baltic. Two sequences, Mustjärve and Parika (located 110 km apart), were chosen for a pilot study aimed at finding traces of tephra fallout during the middle Holocene. Peat accumulation at both sites started in the early Holocene (c. 9500–9000 \(^{14}C\) yr BP; c. 11000–10000 cal. yr BP) and continued throughout the whole Holocene. The radiocarbon-dated intervals between c. 2000 and 5000 \(^{14}C\) yr BP (c. 2000–5500 cal. yr BP) were chosen from both sites for the study. Colourless tephra shards were identified at 312–316 cm below the peat surface in the Mustjärve peat sequence, while no tephra was found in peat of the same age at Parika. Electron microprobe analyses suggest a correlation with the initial phase of the Hekla-4 eruption (c. 4260 cal. yr BP), although the age-depth model indicated an age around 4900 cal. yr BP. Small concentrations of colourless to light brown tephra shards at 266–270 cm in the Mustjärve sequence indicate that the Kebister tephra (c. 3750 cal. yr BP) might also be present, but geochemical analyses were not possible. The low concentration and small size of the tephra particles indicate that Estonian bogs are probably on the verge of where tephrochronology is possible in northwestern Europe. Further studies of full Holocene sequences are required in order to discover traces of other ash plumes reaching as far east as the eastern Baltic area.

Methods and material

Two sequences, one from the Mustjärve bog and one from the Parika bog (Fig. 1), were collected from the Holocene peat record. The manually operated Russian type peat-corer (length 1 m, diameter 7 cm) was used. Tephra was detected using the method described by Pilcher & Hall (1992). Continuous 10-cm samples were initially combusted at 550°C for 4 h and treated in HCl in order to dissolve the carbonates. For those samples from which tephra shards were detected as a result of this initial application, the equivalent sediment interval was resampled using 2-cm slices in order to determine the tephra distribution more precisely. Geochemical analyses were performed on a WDS (Wavelength
Dispersive Spectrometer) Cameca SX100 electron microprobe at the Department of Geology and Geophysics, University of Edinburgh (Table 2).

Only samples dated to the time interval between 2200 and 5000 $^{14}$C yr BP (c. 2000–5500 cal. yr BP) were chosen for analyses within the current study. Several widespread tephra horizons from this time interval (Hekla-3, Microlite, Kebister, Hekla-4) have been found in Sweden and northern Germany (Boygle 1998, 2004; van den Bogaard & Schmincke 2002; Zillén et al. 2002; Bergman et al. 2004; Wastegård 2005). The source of these, with the exception of the Microlite tephra, is the Hekla volcano in southwest Iceland; it is reasonable to speculate that ash clouds from these explosive eruptions could also have reached the eastern Baltic area.

Table 1. Lithology of investigated cores from the Mustjärve and Parika bogs. For location of the sites, see Fig. 1. For exact location of the boreholes, see Veski (1998) and Niinemets et al. (2002).

<table>
<thead>
<tr>
<th>Mustjärve bog</th>
<th>Parika bog</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Depth, cm</strong></td>
<td><strong>Description</strong></td>
</tr>
<tr>
<td>0–20</td>
<td>Sphagnum peat, low humification, light green</td>
</tr>
<tr>
<td>20–100</td>
<td>Sphagnum peat with some Eriophorum</td>
</tr>
<tr>
<td>100–200</td>
<td>Sphagnum–Eriophorum peat, low humification, brown</td>
</tr>
<tr>
<td>200–510</td>
<td>Sphagnum–Eriophorum peat, with changing humification level</td>
</tr>
<tr>
<td>510–660</td>
<td>Woody Carex–Phragmites peat, medium to low humification, brown</td>
</tr>
<tr>
<td>600–660</td>
<td>Woody Carex–Phragmites peat</td>
</tr>
<tr>
<td>660–685</td>
<td>Coarse detritus gyttja + woody Carex–Phragmites peat</td>
</tr>
<tr>
<td>685–734</td>
<td>Coarse detritus gyttja, greyish</td>
</tr>
<tr>
<td>734–743</td>
<td>Fine to medium sand</td>
</tr>
<tr>
<td>743–760</td>
<td>Silty clay with black FeS bands</td>
</tr>
<tr>
<td>760–770</td>
<td>Gravel</td>
</tr>
</tbody>
</table>

Fig. 1. Location of the study area and investigated sites at the Mustjärve and Parika bogs.
The coring site at Mustjärvve bog (N59°04'41", E24°06'31") is situated in northwest Estonia, on the coastal plain of the Baltic Sea at an altitude of 39 m a.s.l. (Fig. 1). The ombrotrophic bog is 2 km in diameter and the thickness of organic deposits in the central and deepest part reaches 7.5 m (Veski 1998). The basin was a shallow coastal lake after deglaciation and was finally isolated during the Ancylus Lake stage of the Baltic Sea and later infilled by peat. At the coring site, the beginning of organic sedimentation was dated to 9590 ± 120 ¹⁴C yr BP (Veski 1998), c. 10 900 cal. yr BP.

The age–depth model from the Mustjärvve sequence is based on eight radiocarbon dates of bulk peat and gyttja (Fig. 2). These were calibrated using the OxCal program, version 3.9 (Bronk Ramsey 2001) and the IntCal98 calibration curve (Stuiver et al. 1998). The peat accumulation is relatively uniform throughout the Holocene (0.7 to 2.26 mm/yr; Fig. 2).

The coring site at Parika bog (N58°28'48", E25°46'11") is located in the Lake Võrtsjärv depression, central Estonia (Fig. 1). The total area of the ombrotrophic Parika bog is 34 km² and the altitude of the peat surface varies between 45 and 50 m a.s.l. (Niinemets et al. 2002). The thickness of organic deposits is 8.80 m in the deepest parts and the onset of organic sedimentation has been dated to 9000 ± 75 ¹⁴C yr BP (Niinemets et al. 2002) or 10 200 cal. yr BP.

The age–depth model from the Parika sequence is based on uncalibrated radiocarbon dates of bulk peat (Fig. 2) calibrated using the same method as the dates from Mustjärvve. Also, in Parika bog the peat accumulation has been relatively uniform throughout the Holocene (0.40 to 1.60 mm/yr) (Niinemets et al. 2002).

Results

Colourless and light brownish glass particles were observed in two 10-cm samples from the Mustjärvve sequence. Subsequent analyses of 2-cm samples showed that tephra occurred at 266–270 cm and 312–316 cm. No calculation of the concentration of tephra particles was attempted, but the extremely low number of shards identified on the microscope slides suggests a very low concentration, probably below 25 shards/cm³. Electron microprobe analysis was attempted on samples from these two levels from Mustjärvve; however, only a few shards from 312–316 cm survived the preparation. This is not uncommon when dealing with small concentrations of tephra from peat. The results of the analyses (Table 2; Fig. 3) show a correlation with the Hekla volcanic system on southwest Iceland (e.g. Larsen & Thorarinsson 1977; Dugmore et al. 1995). The CaO/MgO and FeO tot/TiO₂ ratios show that tephra from the initial, most evolved Plinian phase of the Hekla-4 eruption is present (e.g. Larsen & Thorarinsson 1977; Boygle 1999; Kirkbride & Dugmore 2001; van den Bogaard & Schmincke 2002). This distribution is similar to most analyses of the Hekla-4 tephra from bogs in Sweden, Norway and northern Germany (van den Bogaard & Schmincke 2002; Bergman et al. 2004; Boyle 2004; Pilcher et al. 2005; Wastegård 2005). This also excludes the possibility that the tephra identified in Mustjärvve is the Hekla-3 or the Kebister tephra (Fig. 3). However, the Lairg A tephra (c. 7000 cal. yr BP; Hall & Pilcher 2002; Bergman et al. 2004) has a similar geochemistry, but this can be excluded owing to its much higher age. No tephra was found in the samples from the Parika bog.

The crude age–depth model for Mustjärvve bog (Fig. 2) indicates an age of c. 4800–5000 cal. yr BP for the tephra at 312–316 cm. This is several hundred years older than the generally accepted age for the Hekla-4 (c. 4260 cal. yr BP; Pilcher et al. 1995), but since the age–depth relationship in this part of the core is based on only a few radiocarbon dates, an exact age of the tephra cannot be anticipated. The fact that bulk peat was used for dating may also be a source of dates...
that are too old. The unidentified tephra at 266–
270 cm has an age around 4000 cal. yr BP according
to the age–depth model (Fig. 2). This age matches the
Kebister tephra (c. 3750 cal. yr BP; Gunnarson
et al. 2003), rather than the much younger Hekla-3 tephra
(c. 3000 cal. yr BP; van den Bogaard et al. 2002),
especially since the age–depth model suggests a slightly
higher than expected age for the Hekla-4 tephra. The
Kebister tephra is widespread in Sweden (e.g. Boygle
1998; Zillén et al. 2002; Bergman et al. 2004; Wastega˚rd
2005). Some of the particles at 266–270 cm had a light
yellowish to brownish colour. This has also
been observed in occurrences of the Kebister tephra in
Sweden, but only occasionally in the Hekla-3 and
Hekla-4 tephras.

Discussion and conclusions
The first discovery of the middle Holocene Hekla-4
tephra of Icelandic origin in Estonia is reported. In one
(out of two) studied peat sequence, namely Mustjärve,
at the depth interval 3.12–3.16 m, a low concentration
of tephra shards was detected. The microprobe analysis
demonstrated that tephra from the explosive initial
phase of the Hekla-4 eruption reached as far east as
northwest Estonia. An unidentified tephra at 266–
270 cm in the same site is tentatively correlated with
the Kebister tephra. Thus, the finding of the Hekla-4
tephra in Mustjärve confirms that this tephra is
probably the most widespread known Holocene tephra
layer in the North Atlantic region, so far detected in
Scotland, England, Ireland, northern Germany, Faroe
Islands, Norway and Sweden (e.g. Persson 1971;
Dugmore 1989; Pilcher & Hall 1992, 1996; Wastegård
2005). Some of the particles at 266–270 cm had a light
yellowish to brownish colour. This has also been
observed in occurrences of the Kebister tephra in
Sweden, but only occasionally in the Hekla-3 and
Hekla-4 tephras.

Table 2. Geochemical composition of analysed volcanic glass from Mustjärve 312–316 cm analysed on a Cameca SX100 electron microprobe
equipped with five vertical WD spectrometers. Ten major elements were measured with a counting time of 10 s. All elements are expressed as
weight%. An accelerating voltage of 20 kV and a beam strength of 10 nA determined by a Faraday cup were used, with a rastered beam over an
area of 10 × 10 μm to reduce instability of the glass and subsequent sodium loss. An empirical correction was applied to reduce to the P2O5
figure due to overlap with CaO counts (P. Hill, pers. comm. 2004). Calibration was undertaken using a combination of standards of pure
metals, simple silicate minerals and synthetic oxides, including andradite. These were used regularly between analyses to correct for any drift in
the readings. A PAP correction was applied for the effects of X-ray absorption (Pouchou & Pichoir 1991). All analyses with totals above 91%
were accepted due to the small number and low concentration of shards.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Mean</th>
<th>1σ</th>
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<tr>
<td>SiO2</td>
<td>71.576</td>
<td>73.501</td>
<td>73.155</td>
<td>70.099</td>
<td>68.895</td>
<td>71.442</td>
<td>1.967</td>
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<tr>
<td>TiO2</td>
<td>0.098</td>
<td>0.058</td>
<td>0.072</td>
<td>0.071</td>
<td>0.097</td>
<td>0.079</td>
<td>0.015</td>
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<tr>
<td>Al2O3</td>
<td>13.005</td>
<td>12.948</td>
<td>13.406</td>
<td>12.479</td>
<td>12.117</td>
<td>12.791</td>
<td>0.500</td>
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<tr>
<td>FeOtot</td>
<td>1.985</td>
<td>1.984</td>
<td>1.935</td>
<td>2.084</td>
<td>2.006</td>
<td>1.999</td>
<td>0.054</td>
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<td>MnO</td>
<td>0.108</td>
<td>0.087</td>
<td>0.124</td>
<td>0.124</td>
<td>0.090</td>
<td>0.107</td>
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<tr>
<td>MgO</td>
<td>0.045</td>
<td>0.031</td>
<td>0.018</td>
<td>0.000</td>
<td>0.052</td>
<td>0.029</td>
<td>0.021</td>
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<td>CaO</td>
<td>1.301</td>
<td>1.314</td>
<td>1.291</td>
<td>1.283</td>
<td>1.345</td>
<td>1.307</td>
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<td>Na2O</td>
<td>3.937</td>
<td>3.756</td>
<td>3.859</td>
<td>4.774</td>
<td>4.278</td>
<td>4.121</td>
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<td>K2O</td>
<td>2.600</td>
<td>2.827</td>
<td>2.641</td>
<td>2.614</td>
<td>2.755</td>
<td>2.687</td>
<td>0.099</td>
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<tr>
<td>P2O5</td>
<td>0.000</td>
<td>0.022</td>
<td>0.000</td>
<td>0.009</td>
<td>0.000</td>
<td>0.006</td>
<td>0.010</td>
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<tr>
<td>Total</td>
<td>94.655</td>
<td>96.528</td>
<td>96.501</td>
<td>93.537</td>
<td>91.645</td>
<td>94.571</td>
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</table>

Fig. 3. Geochemical characterization of the Hekla-4 tephra from
Mustjärve bog (diamonds) compared with the main geochemical
distribution of the Hekla-3 (dotted line), Kebister (solid line) and
Hekla-4 (shaded area) tephras in Iceland, the Faroe Islands,
the British Isles and Sweden (data from TephraBase; http://www.
tephrabase.org), presented as CaO wt% vs. MgO wt% and FeOtot
wt% vs. TiO2 wt%.

Fig. 3. Geochemical characterization of the Hekla-4 tephra from
Mustjärve bog (312–316 cm) compared with the main geochemical
distribution of the Hekla-3 (dotted line), Kebister (solid line) and
Hekla-4 (shaded area) tephras in Iceland, the Faroe Islands,
the British Isles and Sweden (data from TephraBase; http://www.
tephrabase.org), presented as CaO wt% vs. MgO wt% and FeOtot
wt% vs. TiO2 wt%.
recorded in peat bogs in an area extending from Iceland to the British Isles and Scandinavia and now into the eastern Baltic area. For example, expansion of peatlands and/or a shift to wetter conditions has been observed in many bogs in northwest Europe at around 4200 cal. yr BP, i.e. close in time to the Hekla-4 eruption (e.g. Nilssen & Vorren 1991; Körhola 1995; Hughes et al. 2000; Langdon & Barber 2004; Borgmark 2005). Whether this is coincidental or is related to the eruption remains to be proven (cf. Blackford et al. 1992; Edwards et al. 1996), but the presence of the Hekla-4 tephra in northwest European bogs and lake sediments opens up the possibility to test if this climate deterioration was synchronous or asynchronous throughout northwest Europe.

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