A Lateglacial–early Holocene tephrochronology for SW Sweden

CARL LILJA, EWA M. LIND, BJÖRN MORÉN AND STEFAN WASTEGÅRD

Four cores from southwestern Sweden are presented together with their tephra geochemistry. Two cryptotephra horizons were confirmed geochemically in the cores, the Vedde Ash and the Hässeldalen Tephra. The Lateglacial Hässeldalen Tephra (11 360–11 300 cal. a BP) offers great potential as a regional isochrone to add a new degree of certainty to the deglaciation chronology of southern Sweden, including the extent of glacial Lake Bolmen. In addition, the geographical distribution of the Hässeldalen Tephra has recently been extended outside of Sweden, making it an important time-marker horizon in northern Europe. There are potential difficulties, however. Proper identification of the actual isochrone is complicated by the vertical pattern of shard distribution, which could be the result of several eruptive events, as well as by the fact that shards from the 10-ka Askja horizon (10 500–10 350 cal. a BP) were found in close stratigraphical proximity. The geochemical data presented are the result of improved EPMA methodology, which significantly reduces sodium mobilization. The results therefore have slightly altered values, which has consequences for classifying new finds when they are compared with previous data for geochemically similar tephras. Finally, potential indications of the Borrobol/Penifiler horizon are presented, although the existence of the horizon could not be confirmed geochemically. This highlights the need to retrieve cores from different locations within a basin based on an analysis of basin morphology if horizons are to be located.

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The rapid fluctuations in climate during the Last Glacial–Interglacial Transition (LGIT, c. 15–9 ka BP) make this time period an important focus of study, not least in the field of climate change (Turney et al. 2004). While the broad history of the period is fairly well known, the rapid nature of the changes, together with a need to provide more detail regarding the geographical distribution of the leads and lags in the climate system, requires more specific dating (Lowe et al. 1999). There are several problems involved in the exact dating of events by radiocarbon, one of the most significant for the LGIT/early Holocene being radiocarbon plateaux (Björck et al. 1998; Turney et al. 2004). As volcanic ash should in principle be deposited simultaneously over the whole of its geographic extent, tephra horizons potentially offer an excellent tool for correlating and dating sediment records (Lowe 2001), especially for areas and periods of the LGIT for which dating may be more uncertain owing to, for example, radiocarbon plateaux.

The introduction of new methods to detect cryptotephras, volcanic layers invisible to the naked eye, has greatly increased their geographic extent, as well as the number of glass shard marker horizons possible (Lowe 2011). For example, Lateglacial and early Holocene ash layers of Icelandic origin have been found in the British Isles (e.g. Turney et al. 1997; Pyne-O’Donnell 2007; Matthews et al. 2011) as well as in Scandinavia (Birks et al. 1996; Wastegård et al. 1998; Davies et al. 2003), Estonia (Hang et al. 2006) and as far as Karelia, western Russia (Wastegård et al. 2000b), Germany (Merkt et al. 1993; Lane et al. 2012) and Italy and the Alps in the south (Lane et al. 2011a). A recent study by Lane et al. (2012) demonstrated the potential of tephrochronology by establishing an improved age–depth model for a site in Vorpommern, Germany, solely through the use of the tephra horizons found at the site. The relatively wide dispersal range of distal tephras also offers the potential for rigorous between-site comparisons. There are, however, some concerns related to the use of tephrochronology as a method, such as the identification of the isochrones, the geochemical fingerprinting of a particular tephra, and the details of how a horizon is deposited across a basin (Davies et al. 2007, 2012; Pyne-O’Donnell 2011).

The present study extends the use of tephrochronology in the south of Sweden. It points to the potential offered by the Hässeldalen Tephra, previously identified in other parts of Sweden (Davies et al. 2003) and recently in northern Germany (Lane et al. 2012), as an aid to decrypting the deglaciation of the area, especially the response to the climate warming at the Younger Dryas–Preboreal boundary. Possible risks with the identification of the isochrone, such as confusing it with the 10-ka Askja event (Sigvaldason 2002), are also identified.

Research background and the study sites

This study presents cores from three small lakes in southern Sweden (Fig. 1). The South-Swedish Upland,
where the three lakes are located, was situated above the highest sea levels occurring during the LGIT (Fredén 1994: 126–127). Thus, sites there potentially preserve a continuous sediment record since deglaciation, which is thought to have occurred during the Bølling/GI-1e interstadial, c. 14.5–14.0 ka BP (Lundqvist & Wohlfarth 2001; Fig. 1). Recent cosmogenic nuclide dates of moraines in SW Sweden, however, indicate a slightly older age for the deglaciation (Larsen et al. 2012). It is possible that the sites were at times after deglaciation covered by an ice-dammed lake, which was a precursor to Glacial Lake Bolmen. The shape and size of the

![Fig. 1. Map showing tephra sites investigated in southern Sweden as well as west-coast ice-marginal lines (after Lundqvist & Wohlfarth 2001). Dotted lines represent hypothetical extensions of the ice-margin lines. The investigated sites are HD = Hässeldala port; SH = Skallahult; LKS = Lake Kullatorpssjön; SK = Stora Kräckebosjön; LK = Lilla Kräckebosjön; MKG = Mulakullegöl. The latter three are presented in this study.](image)
various glacial stages of Glacial Lake Bolmen have been a matter of some discussion (Ising 2001), with earlier studies (Nilsson 1953, 1968) envisaging a greater extent, but this later being disputed (e.g. Daniel 1986). However, no glacial varved clay was observed in any of the lakes, and thus a possible higher level of the Lake Bolmen ice-lake remains inconclusive.

A review of the tephrochronology of Sweden was presented by Wastegård (2005). The five LGIT tephra horizons found in Sweden, together with the most recent dates obtained for them, are presented in Table 1. The tephrochronology of southern Sweden remains largely unknown, with only three terrestrial sites having previously been investigated (Fig. 1). The first was Lake Kullatorpssjön in the SW, where Vedde Ash has been found (Wastegård et al. 2000a). A further two sites with infilled lakes are in the SE, namely Hässeldala port, where the eponymous Hässeldalen Tephra as well as the 10-ka Askja Tephra and a Borrobol/Penifiler Tephra were identified (Davies et al. 2003, 2004), and Skällahult, where Hässeldalen and Borrobol/Penifiler were found. The exact nature of the Borrobol/Penifiler Tephra remains a matter of contention. The major element geochemistry of the horizon found in Sweden is indistinguishable from that of the Borrobol Tephra first identified by Turney et al. (1997) and found in several other sites in Scotland (e.g. Ranner et al. 2005; Pyne-O’Donnell 2007; Pyne-O’Donnell et al. 2008; Matthews et al. 2011). The dating of the horizon found in Sweden, however, is somewhat younger than that presented for the Borrobol Tephra in previous Scottish studies (Davies et al. 2004). Pyne-O’Donnell et al. (2008) concluded that the Swedish find must be a slightly younger horizon identified in several Scottish sites, which they labelled the Penifiler Tephra. The nature of the Swedish horizon remains uncertain, as the major element geochemistry of the Borrobol and the Penifiler tephras are identical. There has also been one reported occurrence of the central European Laacher See Tephra in Swedish Baltic Sea sediments (Påhlsson & Bergh Alm 1985). The same horizon was also found in Hässeldala port, although the results were inconclusive (Davies et al. 2003). In addition, the southern parts of the Scandina-

### Table 1. LGIT tephrochronology of Sweden (tephra horizons/dates). Dates are from Lind & Wastegård (2011; 10-ka Askja and Hässeldalen Tephra), Svensson et al. (2008; Vedde Ash), Brauer et al. (1999; Laacher See) and Matthews et al. (2011; Borrobol and Penifiler). The age of the 10-ka Askja Tephra (Lind & Wastegård 2011) is slightly younger than other estimates: c. 10 570–11 050 BP from Hässeldala port (Wohlfarth et al. 2006) and 10 702–10 991 BP from Soppensee (Lane et al. 2011b).

<table>
<thead>
<tr>
<th>Tephra</th>
<th>Age (c.)</th>
<th>Composition</th>
<th>Biozone</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 ka Askja/Askja-S</td>
<td>10 350–10 500 cal. a BP</td>
<td>Rhyolitic</td>
<td>Preboreal</td>
</tr>
<tr>
<td>Hässeldalen</td>
<td>11 300–11 360 cal. a BP</td>
<td>Rhyolitic</td>
<td>Preboreal</td>
</tr>
<tr>
<td>Vedde</td>
<td>12 007–12 235 cal. a BP</td>
<td>Rhyolitic¹</td>
<td>Younger Dryas</td>
</tr>
<tr>
<td>Laacher See (uncertain)²</td>
<td>12 880 cal. a BP</td>
<td>Phonolitic</td>
<td>Allerød</td>
</tr>
<tr>
<td>Borrobol/Penifiler</td>
<td>13 650–14 140 cal. a BP</td>
<td>Rhyolitic</td>
<td>Older Dryas</td>
</tr>
</tbody>
</table>

¹Only the rhyolitic component has been found in Sweden.
²Geochemical identification inconclusive.
170 and 175 m a.s.l. The present-day lake is ~230 by 170 m across, with a mean depth of ~5 m. Lilla Kräckebo-
sjön (57°20′51″N, 12°59′02″E) and Stora Kräcke-
sjön (57°20′48″N, 12°58′50″) lie between 200 and 210 m a.s.l., ~25 km NW of Mulakullegöl. Stora Kräckebo-
sjön is ~250 by 130 m across, while Lilla Kräckebo-
sjön is 50 by 20 m across. Linked by mires, they seem to be remnants of what could have been a larger lake basin. All three sites are situated between the Göteborg and Berghem ice-marginal lines, implying a deglaciation age between the Göteborg and Berghem ice-marginal lines, implying larger lake basin. All three sites are situated between the Göteborg and Berghem ice-marginal lines, implying a deglaciation age between the Göteborg and Berghem ice-marginal lines, implying larger lake basin. 

Methods
Mulakullegöl (MKG) was preliminarily examined in the winter of 2009. One of the cores was studied by Morén (2009, unpublished) and some of those results are presented here. All sites were cored using Russian corers with diameters of 5 and 7.5 cm, and 1-m and 70-cm chambers, respectively. Coring was initially done in the peat surrounding the lake basins, but the sequences obtained were of insufficient depth for an LGIT study around the MKG basin. Coring was then repeated for this site in February 2010, when ice had formed on the lake, and fourteen 7.5-cm cores were retrieved. As the primary objective was to obtain sufficient material for radiocarbon dating, the cores were taken within a ~5-m radius of one another to make subsequent correlation easier. The cores from Stora (SK) and Lilla Kräckebo-
sjön (LK) were retrieved using 5- and 7.5-cm Russian corers from the deepest part of SK and from the mire surrounding LK. All cores were immediately wrapped in plastic film and placed in PVC tubes. They were stored in cold-room facilities until removed for investigation.

Loss on Ignition (LOI) analysis was performed on all cores at 1-cm contiguous intervals. Samples were dried overnight at 105°C before being ground, and the organic carbon content was calculated in an Eltra CS 500 Carbon Sulfur Determinator, a quicker means than traditional methods. Organic contents over 40% were not calculated for some of the cores as the results obtained were uncertain. The methods used for rhyolitic glass shard extraction follow those first described by Turney (1998) and further developed by Blockley et al. (2005). Cores were initially sampled at 5-cm intervals to obtain rangefinder samples. Levels where shards were identified were further subsampled at 1-cm levels for shard counting of tephra. Samples were dried overnight in crucibles at 105°C to remove water before ashing at 550°C for 4 h. These were placed in test tubes with a 10% solution of HCl for 30 min before sieving to remove carbonates. Samples were sieved to obtain particles between 25 and 80 μm. Material >80 μm was retained, and in two randomly chosen cases mounted and investigated. No shards were found >80 μm limit. As the shard concentra-
tions expected were quite low, the metallic sieves were placed in an ultrasonic bath for 5 min between sievings to avoid the possibility of contamination between stratigraphic levels. The samples were then centrifuged in sodium polytungstate (SPT) to float rhy-
olitic shards from the background mineral matrix. Values of 2.3–2.5 g cm⁻³ have usually been used in studies from Sweden, as this has been found optimal for the extraction of rhyolitic shards (e.g. Zillen et al. 2002). These values were used for two of the cores presented here, MKG1 and SK. For the other two cores in this study, MKG2 and LK, shards were extracted using concentrations between 2.0 and 2.5 g cm⁻³. Suitable SPT concentrations for extracting rhyolitic shards can vary depending on glass shard density and volcanic source composition. Because these values are those commonly used for successfully extracting rhyolitic horizons such as the Borrobol/ Peniftler in Scotland (S. Blockley, pers. comm. 2009), the chances of identifying these in Sweden should increase if the same values are used.

Shard concentrations were identified optically under a polarizing light microscope. Shard concentrations are expressed per cm² of wet sediment. It should be noted when making comparisons that some shard concentrat-
tions are expressed per gram dried weight in other studies (e.g. Lane et al. 2012).

Geochemical data were obtained using the Cameca SX100 EPMA (Electron Microprobe) at the University of Edinburgh. For each analysis, a section of the core between 1 and 5 cm around the point of interest was removed. Before analysis, sediment was treated with the acid digestion method of Dugmore et al. (1992). Most geochemical tephra shard analysis has been performed on the EPMA. A major problem in the analysis of small, often highly vesicular cryptotephra shards is sodium mobilization, which often leads to lower reported values for Na and K and increased values for the other major elements, especially Si and Al (Morgan & London 1996). The values reported in this study reflect recent modifications of analytical con-
ditions in Edinburgh (Hayward 2012), which have minimized this problem and allow for more accurate and robust geochemical shard analysis.

Results
Shard counts
The tephrostratigraphies from the three sites are shown in Fig. 2. Two cores are presented for the MKG site, with one core studied by Morén (2009). Tephra corre-
lations based on stratigraphy are indicated in the diagram, with dotted lines showing the assumed links between the cores.
The patterns of shard distribution are roughly similar in the four cores. The pattern is perhaps clearest in the MKG1 core, with three clear, separable horizons and a possible, although indistinct, fourth uppermost horizon. With the exception of the lowest horizon, indications of all the other three can be identified in the other three cores. Organic carbon counts are not given for the entire cores, as readings became uncertain over 40%.

The lowest horizon, located near the base, is present only in the MKG1 core. The stratigraphic position with very low LOI implies that the horizon occurs close to the end of GI-d (e.g. Lowe et al. 2008), indicating that the layer was deposited shortly after the deglaciation of the area. This stratigraphic position corresponds to the Borrobol/Penifiler layer found in southeastern Sweden (Davies et al. 2003, 2004). Shard counts are quite low, reaching a maximum of 25 shards cm⁻³, although the horizon is spread over a 5-cm-wide area.

In three of the cores, MKG1 at 726–728 cm, MKG2 at 712–719 cm and LK at 542–547 cm, another tephra horizon is found higher in the stratigraphy. The stratigraphic position is associated with lower organic carbon values of 3–5%, characteristic of the cooling of the Younger Dryas/GS-1 period, indicating the Vedde Ash. Shard counts are very low for the MKG cores (under 20 shards cm⁻³), while slightly higher in the LK core (60 shards cm⁻³). While there is no distinct horizon present at the appropriate position in the SK core there are shards, although with low concentration. These could be downworked shards from the layer above or could include shards from the Vedde horizon. The pattern of shard distribution is similar in the upper regions of the cores. There is an upper horizon with organic carbon values of roughly 20%, typically indicative of an early Holocene age (e.g. Björck & Wastegård 1999; Davies et al. 2004). Maximum shard counts for this horizon in three of the cores are fairly low, with peaks at about 100 shards cm⁻³, while the SK core has much higher counts of over 1000 shards cm⁻³. There is a clear maximum to the shard counts in this upper horizon, although there is also a distinctly double pattern to this horizon. The highest shard counts are found in the lower peak, which gradually tapers off. A second peak, with lower shard counts, significantly lower in the case of SK, appears 5–20 cm above the lower peak. In three of the cores, the upper peak is separated from the lower by a break in shard counts, while MKG1 has a continuous, although low, shard count linking the upper and lower peaks.

In all four cores, shards are also found directly below the levels of maximum shard count even if concentrations are quite low. The LK core has in addition another comparatively low concentration of shards 10 cm above this double peak at 530 cm.

The double nature of the horizon is of particular interest, as two tephra horizons associated with the earliest part of the Holocene have been found in Sweden, the Hässeldalen and the 10-ka Askja Tephra (Davies et al. 2003). In the Faroe Islands, Lind & Wastegård (2011) found the horizons separated by over a metre of sediment, with between 800 and 1000 years between eruptions. In Germany, Lane et al. (2012) found the same two horizons with only 50 cm separating them, although no new dates were provided. Age–depth modelling of the radiocarbon chronology from the Hässeldala port sequence indicates a smaller age difference of only 500–600 years (Wohlfarth et al. 2006), with only 10 cm separating the two horizons. The modelled age of the 10-ka Askja Tephra in the latter study is based on few dates, however, and has large error margins. It is likely that varying sedimentation rates at the different sites account for the differences in the stratigraphic distance between the two horizons. The Swedish sites report only a few shards for the 10-ka Askja, so the smaller stratigraphic distance could also partially be the result of downward shard mobility. The differing ages highlight the importance of accurately pinpointing the isochrone.
**Geochemical data**

The geochemical data were obtained in the autumn of 2009 and 2010 from the electron microprobe at the Tephrochronological Analytical Unit at the University of Edinburgh, with the improved probe conditions reported above (Hayward 2012). The geochemical data as seen in Table 2 on the whole confirm the classifications arrived at from stratigraphy. The initial assumption that the uppermost horizon contained the Hässeldalen Tephra was confirmed by geochemical analysis of 48 shards from the three sites. In spite of the large number of shards in the SK core, few geochemical results were obtained from this core. SiO$_2$ values are primarily between 73 and 75 wt% with low TiO$_2$ (0.09%), while FeO$_{tot}$ values often hover around 1%.

The double peak of the upper horizon is not clearly represented in the geochemical data. The geochemical data from the MKG2 (680–685 cm) and LK (525–530 cm) cores were specifically taken from this upper peak to see if there was any geochemical basis for the split. Most of the shards are indisputably from the Hässeldalen Tephra, although five of them from this horizon show anomalous values. Among others, the FeO$_{tot}$ values (~2.5–3.8 wt%) are far too high for the Hässeldalen Tephra. The values for two of the shards from MKG for SiO$_2$, TiO$_2$, and FeO$_{tot}$ do correspond to those published for the 10-ka Askja/Askja-S Tephra (Sigvaldason 2002; Davies et al. 2003; Lind & Wastegård 2011; Lane et al. 2011b), with SiO$_2$ values around 72–73% and FeO$_{tot}$ around 2.5 wt%. Although it is difficult to draw any firm conclusions solely on the basis of the two shards found here, the 10-ka Askja horizon has previously been identified in southeastern Sweden (Davies et al. 2003) as well as recently in Switzerland (Lane et al. 2011b). The remaining three shards, one from MKG2 and two from LK, seem to represent a different tephra altogether. The chemistry is similar to the Vedde Ash, and SiO$_2$ values are much lower, namely 66–70 wt%, than those of either the Hässeldal or the 10-ka Askja, while FeO$_{tot}$ values are significantly higher, over 3.5 wt%. The three shards would seem to indicate the presence of a third tephra in the horizon, corresponding with the values found for tephra from the GS-1 position. Interestingly, Matthews et al. (2011) recently reported a new tephra with Vedde-like geochemistry associated with the warming trend at the end of the Younger Dryas. Reworking of shards from the widespread Vedde Ash cannot be excluded, but, if this tephra can be located at other sites, it might provide an additional marker to the growing tephrochronology networks of NW Europe.

The data from the lower peak from MKG2 corresponding to the presumed GS-1 position show SiO$_2$ values of between 68 and 71%, with relatively high FeO$_{tot}$ concentrations of between 3 and 4%. The values conform to those of the rhyolitic phase of the Vedde Ash (e.g. Björck & Wastegård 1999). The Na$_2$O content is somewhat higher than in earlier reported data, probably, as mentioned, reflecting improved analytical EPMA methodologies. The values are similar to those for three of the anomalous shards found in the upper horizon.

The geochemical data are plotted in Fig. 3, together with data for the 10-ka Askja, the Hässeldalen and the Vedde Tephra from other Swedish sites (Wastegård et al. 1998; Björck & Wastegård 1999; Schoning et al. 2001; Davies et al. 2003) as well as with recent data from Switzerland and northern Germany (Lane et al. 2011b, 2012). The TAS (Total Alkali Silica) diagram, Fig. 3A, shows that the values for the geochemical results from the present study are easily discernible as three separate horizons, with the shards tightly organized in three distinct pockets for each of the horizons, the 10-ka Askja, Hässeldalen and the Vedde, geochemically identified in the cores. These three horizons are also closely related to data for the same horizons from other sites. Although geochemically similar, the data from this study, as well as those from Lane et al. (2011b, 2012), show slightly higher Na$_2$O, as well as slightly lower SiO$_2$, values than most data from earlier studies. The same data are also plotted on four biplots, Fig. 3B, of selected major elements. Only one of the biplots, that of FeO$_{tot}$ against Na$_2$O, repeats the pattern with significant differences between earlier data and the data from the present study. This reflects the new Na$_2$O results, usually over 4%, being slightly higher than those reported earlier (Davies et al. 2003). The other three biplots against FeO$_{tot}$ and SiO$_2$ show perfect alignment between the present data and those from previous studies. Although horizons can still be separated as before, caution should be taken when comparing newer data with those from previous studies.

**Discussion**

The upper horizons in the cores from the region present a mixed picture. There is a clear, marked presence of a tephra, which geochemical analysis confirms indisputably as being the Hässeldalen Tephra. The results are statistically robust, with low standard deviations. The horizon has now been found at several sites in the south of Sweden, indicating its potential as a marker horizon in the area. Furthermore, it has been found both in the Faroe Islands (Lind & Wastegård 2011) and in northern Germany (Lane et al. 2012), pointing to an even greater geographical role. In these studies the Hässeldalen horizon itself is relatively clear-cut and unproblematic. In the Faroe study, however, shards are somewhat more spread out, as well as being associated with two much larger basaltic components (Sandoy A and B) on either side, indicating that the Hässeldalen Tephra could be part of a more complex eruptive history.
Table 2. Geochemistry for analysed shards from Mulakullegöl, Stora Kräckebosjön and Lilla Kräckebosjön. Analyses of the Hässeldalen Tephra are shown first, followed by other analyses (Vedde Ash, 10-ka Askja and Katla). All oxides are expressed as wt%. Total iron is expressed as FeOtot. Analyses were obtained on a CAMECA SX100 scanning electron microprobe by wavelength-dispersive spectrometry with an accelerating voltage of 15 kV, a 2-nA beam current, and a beam diameter of 5 μm. Sodium was measured in the first and last counting periods to monitor the degree of mobilization. Calibration was undertaken using standard calibration blocks. Two secondary glass standards, BHVO2 and Lipari obsidian (Hunt & Hill 1996), were analysed at regular intervals to control instrumental drift and the precision and accuracy of the glass analysis. The data are not normalized, following European convention (Hunt & Hill 1993), and analyses with an analytical total above 93% are included.

<table>
<thead>
<tr>
<th></th>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>FeOtot</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>P2O5</th>
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<tr>
<td>Mulakullegöl MKG1 690–695 cm</td>
<td>72.48</td>
<td>0.09</td>
<td>11.53</td>
<td>1.11</td>
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Fig. 3. Total Alkali Silica (TAS) diagram (A) and selected biplots (B) for the tephra horizons reported in this study compared with similar horizons from other study sites. Data are from Björck & Wastegård (1999), Schoning et al. (2001), Wastegård et al. (1998), Lane et al. (2011b, 2012) and Davies et al. (2003). Data in (A) are normalized.
Shard distribution in this horizon is not unequivocal. Ideally, shards should be concentrated in a single peak marking the point of initial deposition as well as the isochrone. While there is a prominent peak for the Hässeldalen horizon, shards are also spread out above this point, increasing again to a second peak. In some cases, there is a more bimodal appearance. This pattern could reflect later conditions in the drainage basin: some major climate event washing down more shards, melting of snow beds with tephra, or even increased erosion during the Preboreal Oscillation. It could also be that the pattern truly is bimodal, with the upper peak representing a new eruptive event, possibly of Katla origin (cf. Matthews et al. 2011). The 10-ka Askja eruption has been identified in sites nearby (Davies et al. 2003), and it would appear that only a few hundred years separate the two events (Lind & Wastegård 2011). Geochemical analysis showed that the majority of shards were of Hässeldalen geochemistry, indicating later basin processes. The two shards with 10-ka Askja geochemistry could indicate a new horizon at the upper peak, but could also be the result of downward shard mobilization with the actual horizon in a position above the retrieved core.

The somewhat diffuse picture of shard distribution highlights the problem of identifying the isochrone marker. In many cases, such as this study, this is more problematic than simply ascertaining the point of highest shard concentration. Not only is there a double-peak, possibly bimodal, pattern to the shard distribution, but there are also shards found below the peak concentration. Payne and co-workers have in a series of experiments demonstrated that even the smaller shards of cryptotephras can migrate a significant distance downwards in peat from their point of initial deposition (Payne & Blackford 2005; Payne et al. 2005; Payne & Gehrels 2010). Davies et al. (2007) also discussed some of the issues surrounding the vertical distribution of shards in cores in central Sweden relating to the AD 1875 Askja event. Their study indicated that, although there was some possibility that reworking or other basin processes could explain the downward migration of shards below the maximum concentration, the isochrone in some cases was more likely to be indicated by the first appearance of shards rather than by the point of maximum concentration. Davies et al. (2012), in discussing shard distribution patterns within individual cores, found in some cases in which shards are spread out vertically that it can be difficult to determine the exact location of the isochrones. This can impact the accuracy of the dates provided. Because of the possibly diffuse upper horizon(s) of the cores presented in the study as well as the (possibly) confused geochemical nature of the horizons, more studies need to be carried out to fully realize the potential of the Hässeldalen Tephra as a marker horizon in the region. The Hässeldalen and Askja Tephra are widely separated in the Faroes and in Germany (Lind & Wastegård 2011; Lane et al. 2012), although in the previously investigated site in Sweden there is only 10 cm between the horizons (Davies et al. 2003). This is probably the result of different sedimentation rates in different basins, with seemingly lower rates occurring in southern Sweden. This could increase the risk of mixing of the two horizons, making their use as regional isochrones more complicated.

The source volcano for the Hässeldalen Tephra was first considered most likely to be Snæfellssjökull (Davies et al. 2003). Lind & Wastegård (2011) point out that, while alkali element concentrations and Na$_2$O and K$_2$O ratios may indicate this, a TAS plot using the new EPMA settings shows that other volcanic systems are also possible as sources. Interestingly, they found that the Hovsdalur Tephra previously found on the Faroe Islands (Wastegård 2002) shared the same general geochemical envelope as the Hässeldalen Tephra. The Hovsdalur was dated to c. 10 500 cal. a BP, although the dating model and the stratigraphic position were somewhat crude. This could indicate either that the two horizons are one, reflecting the same event, or that there were two rhyolitic eruptive vents of similar geochemistry within the same time frame.

The Vedde Ash, while not as prominent as the Hässeldalen Tephra in the present study, is a more easily missed (owing to low shard concentration), but still potentially useful, horizon. According to Lane et al. (2012), the Vedde Ash seems to provide surprisingly clear geochemical analyses in spite of low shard concentrations, possibly reflecting a less vesicular shard morphology.

The inability to confirm the existence of a Borrobol/Penifiler horizon could be the result of several factors. It could reflect operator error or arise from subsequent cores being taken from a different part of the basin. Shards are often concentrated to particular locations within a basin, reflecting basin processes and morphology at the time of deposition and/or re-deposition by wind, meltwater, etc. (Boyle 1999; Bergman et al. 2004; Davies et al. 2007). A horizon can be found in one part of a basin but be entirely missing in a core drilled only a few metres away (Davies et al. 2001). Further studies should utilize our knowledge of basin morphology and tephra deposition (Pyne-O’Donnell 2008; Pyne-O’Donnell 2011) to increase chances of horizon identification.

Conclusions

The Hässeldalen Tephra has now been found at several sites in southern Sweden, which indicates widespread local dispersion and makes it a very useful marker for the area. This is especially so because of the unclear dating of the deglaciation in the region, for
which tephrochronology could provide some solutions. The horizon has also been found in Germany and on the Faroe Islands, indicating an even greater potential for it as a regional isochrone linking records from basins over a wide area.

There are some possible difficulties. The Hässelfalen horizon presented in this study has a diffuse, double-peak appearance, which complicates identification and could reflect two distinct eruptive events. The 10-ka Askja horizon has previously been found in south Sweden, and there is evidence of it at one site in this study. While dating provided in the Faroe Islands (Lind & Wastegärd 2011) indicates that 1000 years separate the Hässelfalen and Askja, low sedimentation rates at sites in southern Sweden make it easy to confuse them. Care must be taken, especially with diffuse horizons, in identifying the isochrone marker, which may or may not be the peak shard concentration.

The Borrobol/Penifiler horizon continues to be problematic. Only a single horizon has so far been identified at Hässelfalen port and Skallahult in SE Sweden (Davies et al. 2003), while studies in Scotland indicate two separate horizons (Pyne-O’Donnell 2007; Matthews et al. 2011). The failure to confirm initial indications of a new site in this study underlines the importance of taking cores from different spots within a basin based on a study of basin morphology at the time of deposition (Pyne-O’Donnell 2011).

New EPMA settings, which reduce the problem of sodium mobilization, provide more robust geochemistries. However, these altered results should be borne in mind when comparing newer results with those previously published.

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