A tephra-based correlation between the Faroe Islands and the Norwegian Sea raises questions about chronological relationships during the last interglacial

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ABSTRACT

Marine ash zones from the last interglacial period have been described from cores from the North Atlantic and an ash zone from the middle part of the interglacial has been observed in connection with a major cooling event. Here we present evidence for a coeval ash zone in a terrestrial site on the Faroe Islands. The investigated sediments are correlated with the upper part of oxygen isotope stage 5e and the beginning of stage 5d. The Eemian climatic optimum is represented in the lower part of the sequence close to the first occurrence of the ash zone. A tephra-based correlation suggests that the climatic optimum was synchronous with the marine record from the Norwegian Sea, but several thousand years later than in Eemian sections of west central Europe. However, many questions on the chronological relationship between the Eemian and oxygen isotope stage 5e still remain to be answered.

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Introduction

The Last Interglacial, or the Eemian [oxygen isotope stage (OIS) 5e], has usually been regarded as generally warmer and more stable than the present interglacial, the Holocene. This view was challenged when data from the GRIP ice-core suggested several high-amplitude climatic fluctuations within the Eemian interglacial (Dansgaard et al., 1993; Johnsen et al., 1995). Some North Atlantic marine sediment records also show considerable variation during the Eemian (Cortijo et al., 1994; Fronval and Jansen, 1996; Fronval et al., 1998). Most European terrestrial records, however, suggest a more stable climate (Cleveringa et al., 2000; Rialu et al., 2001). Other records show partly unstable conditions; one example is the Hollerup site in Denmark where distinct hydrological changes have been identified and tentatively correlated with cold events in the North Atlantic (Fig. 1; Björck et al., 2000). The timing and duration of the Eemian is now under discussion, and several authors suggest that the duration of interglacial conditions in the North Atlantic region lasted well into OIS 5d (Kukla et al., 1997, 2002; Björck et al., 2000). A total length of nearly 20 000 years has been suggested for warm interglacial conditions in the North Atlantic (e.g. McManus et al., 2002). Furthermore, Kukla et al. (2002) and Shackleton et al. (2003) concluded that the warming event associated with the Eemian in northwestern Europe started at c. 126 ka, up to 5–6 ka after the OIS 6–5 transition. It has also been suggested that the increase in ocean surface temperatures at the OIS 6–5e transition was not synchronous in the North Atlantic (Rasmussen et al., 2003).

In this paper we present the first tephra-based correlation of marine and terrestrial records from OIS 5 within the North Atlantic. Ash zones are frequently recorded in North Atlantic marine sediments. The most prominent are the so-called North Atlantic Ash Zones (e.g. Ruddiman and Glover, 1972; Lacasse et al., 1996), dated to c. 11 ka (Ash Zone I), 54 ka (Ash Zone II) and 340 ka (Ash Zone III). The ash zones were primarily transported southward from Iceland by ice-rafterong as far south as 45°N and consist of a mixture of basaltic and rhyolitic tephra ejected from major volcanic eruptions on Iceland, although originally defined as intervals of increased concentration of rhyolitic shards. The geochemistry and distribution of the North Atlantic Ash Zones has been described by, among others, Kvennma et al. (1989), Lacasse et al. (1996) and Haflidason et al. (2000). Ash Zones I and II are important because they provide points of fixation between ice-core records from Greenland and marine cores from the North Atlantic (Bond et al., 1993; Haflidason et al., 1995; Austin et al., 2004). No such land–sea correlations based on tephra have been attempted for OIS 5. An ash zone deposited during the early part of OIS 5 has been described from the Iceland Plateau, southern Norwegian Sea (Sjøholm et al., 1991; Fig. 1). This zone is characterized as two peaks with a lower peak dominated by light rhyolitic grains and the upper peak dominated by dark basaltic grains. This pattern was confirmed in cores from the Norwegian and Greenland seas (Fronval et al., 1998) where one ash zone of OIS 5d age and two ash zones of OIS 5e age were found. Two of these zones, the early stage 5e ash zone and the 5d ash zone, were dominated by basaltic tephra, while the mid-stage 5e ash zone consisted of...
a mixture of silicic and basaltic–intermediate tephra particles. A rhyolitic tephra, 5e-Midt/RHY, dominates the silicic component. This tephra has also been found in several marine cores from the North Atlantic (Lacasse and Garbe-Schönberg, 2001; Wastegård and Rasmussen, 2001; Wallrabe-Adams and Lackschewitz, 2003). It has an age of about 124 ka based on a correlation to the SPECMAP time-scale (Fronval et al., 1998).

In the present paper, we show that this widespread tephra has a terrestrial equivalent on the Faroe Islands. The purpose is to correlate marine and terrestrial data using this tephra as a time-synchronous marker and to compare spatial and temporal variation of the Eemian climate in the North Atlantic region.

**Eemian lacustrine unit on the Faroe Islands**

An organic unit sandwiched between diamict units was described in the late 19th century from Klaksvík on the Faroe Islands (Fig. 1) (Geikie, 1880). Radiocarbon datings on tree trunks of *Picea* and/or *Larix* (Rasmussen, 1972) yielded infinite radiocarbon ages and led to the conclusion that the unit was of interglacial or interstadial age. A re-investigation of the Klaksvík section, situated a few metres above sea-level, was recently performed (Greve, 2001). A 106-cm-long section covering the complete organic unit was analysed for pollen, macrofossils, microtephra, $\delta^{13}$C and total organic carbon (TOC) (Fig. 2). These data confirm that the organic unit at Klaksvík is of interglacial age. Although correlation of the pollen stratigraphy with the European pollen zonation of the Eemian (Zagwijn, 1996) provides only an indication of age, the occurrence of the 5e-Midt/RHY/Klaksvík tephra shows that the unit was indeed deposited during the last Interglacial, the Eemian.

Rhyolitic microtephra (25–80 μm) was separated from the organic unit with a flotation technique described by Turney (1998). This technique relies upon the difference between the specific gravity of the tephra shards and the host sediment matrix and sodium polytungstate prepared to a density of 2.3–2.5 g cm$^{-3}$ concentrates rhyolitic particles. The concentration of tephra particles was calculated with the aid of *Lycopodium* spores (Stockmarr, 1971), and ranges between $\approx$ 3000 and 130 000 per gram of dry sediment, although no tephra horizon was visible to the naked eye. Microprobe analyses of individual tephra shards from six levels show that the composition is rhyolitic and that low- to medium-K glass predominates (Table 1). The spread in the data is small as are

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**Fig. 1** Map of the Faroe Islands area showing sites mentioned in the text.

**Fig. 2** Diagram showing selected physical and biological parameters for the Klaksvík sequence. Black boxes in the column for tephra concentration column show samples selected for microprobe analyses.
standard deviations, indicating a common volcanic source for all analysed samples. The extremely low K\textsubscript{2}O/\text{SiO}_2 ratios (0.023–0.027) point towards a source in the main rift zones of Iceland (Lacasse and Garbe-Scho¨ nberg, 2001). The Klaksvík tephra can be geochemically correlated with the 5e-Midt/RHY tephra found in several north Atlantic cores in mid-stage 5e sediments (Figs 3 and 4; Fronval et al., 1998; Wastega ˚rd and Rasmussen, 2001). A few analyses of tephra with a dacitic composition occur in one sample (42–44 cm; Table 1, Fig. 3). This is referred to here as the Klaksvík dacite.

The abundance of tephra particles of the same geochemical composition in all analysed samples can have two explanations. It could imply deposition of tephra from one major volcanic eruption, or recurrent eruptions from the same volcanic system. In the first case, a prominent first peak in tephra concentration would be expected, instead of the observed consistently fairly high concentrations. However, the entire organic unit could have been deposited after the ash-fall. In that case, the tephra was deposited near the basin before sediments began to accumulate and tephra was gradually washed or blown into the lake basin from the catchment area.

### Table 1
Mean oxide data of five out of six analysed samples of volcanic glass from Klaksvík (8–10 and 65–68.5 cm not shown) compared with other analyses of the mid-stage 5e rhyolitic tephra from the North Atlantic (MD95-2009, Wastegård and Rasmussen, 2001; 907A, Sjøholm et al., 1991; HM71-19; Fronval et al., 1998). Mean and 1\sigma standard deviations are shown. Usually analyses above 95% are considered a minimum. This was difficult to achieve with the Klaksvík tephra, however, probably due to a high water content.

<table>
<thead>
<tr>
<th>Core/site</th>
<th>Klaksvík</th>
<th>Klaksvík</th>
<th>Klaksvík</th>
<th>Klaksvík</th>
<th>Klaksvík</th>
<th>MD95-2009</th>
<th>907A</th>
<th>HM71-19</th>
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<td>Faroe Islands</td>
<td>Norwegian Sea</td>
<td>Iceland Plateau</td>
<td>Iceland Sea</td>
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<tr>
<td>Depth</td>
<td>2–4 cm</td>
<td>42–44 cm</td>
<td>42–44 cm</td>
<td>50–52 cm</td>
<td>74–76 cm</td>
<td>1830.5 cm</td>
<td>?</td>
<td>129–130 cm</td>
</tr>
<tr>
<td>Classification</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
<td>Dacite</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
</tr>
<tr>
<td>Name</td>
<td>Klaksvík tephra</td>
<td>Klaksvík tephra</td>
<td>Klaksvík dacite</td>
<td>Klaksvík tephra</td>
<td>Klaksvík tephra</td>
<td>Se-Midt/RHY</td>
<td>St. 5e ash</td>
<td>Pop. Se-hylol</td>
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<td>Analyses</td>
<td>11</td>
<td>4</td>
<td>4</td>
<td>13</td>
<td>14</td>
<td>7</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>SiO\textsubscript{2}</td>
<td>73.46 ± 0.93</td>
<td>73.86 ± 0.43</td>
<td>67.00 ± 0.58</td>
<td>73.75 ± 0.59</td>
<td>73.79 ± 0.50</td>
<td>73.81 ± 0.41</td>
<td>73.79 ± 1.66</td>
<td>73.40 ± 0.70</td>
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<td>TiO\textsubscript{2}</td>
<td>0.15 ± 0.02</td>
<td>0.10 ± 0.04</td>
<td>0.37 ± 0.04</td>
<td>0.20 ± 0.03</td>
<td>0.19 ± 0.03</td>
<td>0.15 ± 0.02</td>
<td>0.23 ± 0.11</td>
<td>0.21 ± 0.02</td>
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<tr>
<td>Al\textsubscript{2}O\textsubscript{3}</td>
<td>10.80 ± 0.18</td>
<td>11.14 ± 0.27</td>
<td>14.69 ± 0.09</td>
<td>11.01 ± 0.16</td>
<td>10.98 ± 0.13</td>
<td>10.96 ± 0.13</td>
<td>11.04 ± 0.39</td>
<td>11.25 ± 0.18</td>
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<td>FeO\textsubscript{tot}</td>
<td>2.88 ± 0.22</td>
<td>2.79 ± 0.09</td>
<td>5.58 ± 0.30</td>
<td>2.90 ± 0.16</td>
<td>2.79 ± 0.08</td>
<td>2.77 ± 0.11</td>
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<td>MnO</td>
<td>0.09 ± 0.02</td>
<td>0.10 ± 0.02</td>
<td>0.18 ± 0.02</td>
<td>0.11 ± 0.04</td>
<td>0.11 ± 0.04</td>
<td>0.14 ± 0.05</td>
<td>0.06 ± 0.06</td>
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<td>MgO</td>
<td>0.06 ± 0.01</td>
<td>0.06 ± 0.01</td>
<td>0.53 ± 0.05</td>
<td>0.05 ± 0.02</td>
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<td>CaO</td>
<td>1.51 ± 0.04</td>
<td>1.65 ± 0.27</td>
<td>3.30 ± 0.23</td>
<td>1.56 ± 0.09</td>
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<tr>
<td>Na\textsubscript{2}O</td>
<td>3.39 ± 0.21</td>
<td>3.49 ± 0.39</td>
<td>3.91 ± 0.10</td>
<td>3.56 ± 0.18</td>
<td>3.47 ± 0.21</td>
<td>3.51 ± 0.25</td>
<td>4.83 ± 0.32</td>
<td>2.88 ± 0.51</td>
</tr>
<tr>
<td>K\textsubscript{2}O</td>
<td>1.80 ± 0.01</td>
<td>1.73 ± 0.16</td>
<td>2.05 ± 0.04</td>
<td>1.83 ± 0.08</td>
<td>1.85 ± 0.12</td>
<td>1.68 ± 0.08</td>
<td>1.84 ± 0.11</td>
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<tr>
<td>Total</td>
<td>94.14</td>
<td>94.92</td>
<td>97.61</td>
<td>94.72</td>
<td>94.64</td>
<td>94.10</td>
<td>94.08</td>
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</tbody>
</table>

Fig. 3 A tentative correlation between the Klaksvík record and a marine core from the Norwegian Sea, MD95-2009 (Rasmussen et al., 1999, 2003; Wastegård and Rasmussen, 2001). The correlation is based on the first distinct occurrence of the 5e-Midt/RHY tephra in both records, at c. 75 cm in the Klaksvík sequence and at c. 1830 cm in MD95-2009. The possibility that the entire organic unit at Klaksvík was deposited after the volcanic event cannot be excluded, however. A correlation of the marine core with the European pollen zonation of the Eemian (Zagwijn, 1996) is shown to the right (see also Rasmussen et al., 2003).
The second possibility is that the Klaksvík tephra is a result of eruptions from the same volcanic system; peaks in tephra concentration at c. 10 and 45–50 cm (Fig. 2) may represent two primary tephra depositions, while interjacent samples denote a kind of background noise of reworked in-washed tephra particles from the catchment. The occurrence of dacitic shards in at least one sample (42–44 cm; Table 1) suggests that at least one other volcano was active on Iceland during the deposition of the Klaksvík tephra. The virtual absence of basaltic particles is surprising. This can partly be explained by the tephra concentration technique, which concentrates rhyolitic rather than basaltic microtephra (Turney, 1998). Usually, however, some basaltic particles always survive the preparation if present in the original sample (cf. Wastegård et al., 2001). Irrespective of which interpretation is preferred, our conclusion is that the main part of the lacustrine unit in Klaksvík post-dates the mid-OIS 5e volcanic event(s) at c. 124 ka, and thus the lower part of the Eemian is missing at Klaksvík, or alternatively that the onset of the Eemian is registered in the Klaksvík sediments. Organic silty sediments dominate the next two zones (K2 and K3) with intercalated sand layers at 56–60 and 65–68.5 cm. These are interpreted as washed-in storm layers from the adjacent ocean, which is also supported by the presence of supposed driftwood of *Picea* and/or *Larix* in connection with these. This suggests they represent the regional sea-level highstand of the Last Interglacial. The lower part of zone K2 represents the local climate optimum with a high diversity in terrestrial and lacustrine plants. Fruits of *Ajuga* indicate a higher temperature than during the Holocene climate optimum (Greve, 2001) and occurrences of statoblasts of *Cristatella mucedo* up to the 18-cm level also indicate slightly higher temperatures than during most parts of the Holocene (Bennike et al., 1998). From the middle of zone K2, TOC starts to decrease, indicating a small reduction in organic productivity. Increasing numbers of Ericaceae in K3 and K4 indicate that vegetation became more...
Marine-terrestrial correlations: implications for the Eemian palaeoclimatic development

With the 5e-Midt/RHY/Klaksvík tephra a marine–terrestrial correlation within the North Atlantic region is possible. Our 5- to 8-kyr-long Klaksvík record begins at or after the Carpinus expansion, and therefore post-dates the Eemian climatic optimum in north-western Europe (Zagwijn, 1996; Björck et al., 2000). The Eemian climate optimum predates the increase in Picea and Carpinus in west European pollen records (Zagwijn, 1996; Björck et al., 2000). The presence of these species from the bottom of the organic unit in Klaksvík indicates that the entire unit was deposited after the climatic optimum in Europe.

A tentative correlation between the Klaksvík record and a marine core from the Norwegian Sea, MD95-2009 (Rasmussen et al., 1999, 2003; Wastegård and Rasmussen, 2001), is presented in Fig. 3. The correlation is based on the first distinct occurrence of the 5e-Midt/RHY tephra in both records, at c. 75 cm in the Klaksvík sequence and at c. 1830 cm in MD95-2009. The first occurrence of this tephra in marine cores is c. 3000 years into the OIS 5e sediments (Fronval et al., 1998; Wastegård and Rasmussen, 2001), which agrees with the suggested age of the lower part of the Klaksvík sequence correlated to the Carpinus pollen zone (zone E5; Zagwijn, 1996). The ash seems to be present in both records throughout the rest of the interglacial. In addition, the marine record indicates the possibility of several rhyolitic eruptions during the middle to late OIS 5e, but an exact correlation based on tephra concentration between the two records is not possible at present. The local climate optimum is found in the lower part of the Klaksvík sequence (zone K2) and at c. 1820–1840 cm in MD95-2009, indicated by, for example, the high abundance of N. pachyderma (d) (Fig. 3). This is much later than in Eemian sections of Western Europe where the temperature rise after the Saalian glaciation was extremely rapid and the thermal optimum occurred very early in the interglacial (pollen zones E1–E4; e.g. Zagwijn, 1996; Aalbersberg and Litt, 1998). Thus, our tephra-based correlation between a terrestrial record on the Faroe Islands and MD95-2009 suggests that the climatic optimum was reached several thousand years later on the Faroe Islands and in the Norwegian Sea than in continental Europe. Our results also concur with the correlation of marine cores across the Iceland–Scotland ridge (Rasmussen et al., 2003), which shows a steep temperature gradient with a temperature difference of at least 8 °C at the initial phase of the Eemian/OIS 5e.

A delayed climatic optimum at more northern latitudes along the European west coast may have important implications for the palaeoclimatic scenario of the Last Interglacial. It implies that the vigour of the North Atlantic Current may have reached its maximum rather late into the Last Interglacial, indicating a fairly southern position for deepwater formation during the initial stage of the interglacial. This could, for example, be explained by a high influence of freshwater from a delayed deglaciation along the Scandinavian west coast, postponing the warming further north. Such an implication is, however, contradicted by Shackleton et al.’s (2003) conclusion that the Eemian in north-west Europe began at least 4 kyr after the onset of OIS 5e and the final melting of the Saalian ice sheet. By contrast, our tephra correlation between core MD95-2009 and the Klaksvík pollen signals raises doubts about such a time lag between the Eemian and OIS 5e, unless the early finds of Carpinus pollen in Klaksvík are old reworked grains. In fact, the uncertainty about the temporal relationship between the onset of the Eemian and OIS 5e also creates problems with direct correlations between Klaksvík and the Iceland–Scotland ridge sites.

It is also possible that the closure of the Baltic–White Sea connection, a few millennia into the interglacial (Funder et al., 2002), resulted in a more vigorous North Atlantic Current along the Norwegian coast and could thus spread the warming into more northern Atlantic latitudes. Such an oceanographic reconfiguration, triggered by palaeogeographical changes, would have resulted in a delayed climatic optimum in the Norwegian Sea–Faroe Island region.

With the aid of our sea–land tephra correlations we can conclude that the climatic optimum of the Last Interglacial may not have been simultaneous in the North Atlantic–European region, and that many questions on the chronological relationship between the Eemian and OIS 5e still remain to be answered.

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References


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Greve, C., 2001. En litto-, bio-, og kronostratigrafisk undersøgelse af et interglacial, lakustrin sediment ved Klaksvik, 


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