Detection of Lateglacial distal tephra layers in the Netherlands

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Three distal tephra layers or cryptotephras have been detected within a sedimentary sequence from the Netherlands that spans the last glacial–interglacial transition. Geochemical analyses identify one as the Vedde Ash, which represents the southernmost discovery of this mid-Younger Dryas tephra so far. This tephra was found as a distinct horizon in three different cores sampled within the basin. The remaining two tephras have not been geochemically 'fingerprinted', partly due to low concentrations and uneven distributions of shards within the sequences sampled. Nevertheless, there is the potential for tracing these tephra layers throughout the Netherlands and into other parts of continental Europe. Accordingly, the possibilities for precise correlation of Dutch palaeoenvironmental records with other continental, marine and ice-core records from the North Atlantic region are highlighted.

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Attention has been drawn in recent years to the important contributions that tephrochronology can make to late Quaternary palaeoclimatic research (Westgate & Gorton 1981; Turney & Lowe 2001). Tephra layers constitute time-parallel markers between diverse stratigraphical records, and hence offer great potential for effecting more reliable correlations between sequences (Lowe 2001; Davies *et al*. 2002; Turney *et al*. 2004), for independent testing of sedimentary age-depth models constructed using radiocarbon dating (Sandiford *et al*. 2003; Lowe *et al*. 2004), and to provide a basis for estimating the magnitude of reservoir errors that have affected radiocarbon dates obtained from different sectors of the oceans (Bard *et al*. 1994; Austin *et al*. 1995; Siani *et al*. 2001). Some widely dispersed ash layers may also provide the basis for high-resolution correlations between marine, terrestrial and ice-core records (Kvamme *et al*. 1989; Sejrup *et al*. 1989; Grönvold *et al*. 1995; Stein *et al*. 1996; Lackschewitz & Wallrabe-Adams 1997), thereby offering the potential for testing hypotheses of synchronous climatic change, independent of radiocarbon age estimates, which can be problematic.

The scope of tephrochronology has changed significantly within the last decade or so, with the discovery that distal tephras, deposited hundreds and even thousands of kilometres from volcanic sources, can be detected in sedimentary sequences, even though the constituent glass shards may be present in very small quantities. Controlled density separation using a heavy liquid medium enables tiny fragments of volcanic glass (termed cryptotephra (Lowe & Hunt 2001; Turney *et al*. 2004), though frequently referred to in the literature as 'microtephra' (e.g. Turney *et al*. 1997; Wastegård *et al*. 2000b)) to be extracted even from mineral-rich sediments, and their concentrations to be estimated (Lowe & Turney 1997; Turney 1998). This development has led to the known distribution of some tephras of Icelandic origin being extended into the British mainland, southern Sweden and even NW Russia (Turney *et al*. 1997; Wastegård *et al*. 1998, 2000b; Turney *et al*. 2001; Davies *et al*. 2003), while some Campanian tephras can now be traced much further north than hitherto, into the northern Apennines, and the southern Alps of Italy and Austria (Schmidt *et al*. 2002; N. Branch, pers. comm. 2002).

Here we report on the discovery, for the first time, of cryptotephra horizons of Lateglacial age in a sediment sequence from the Netherlands. We discuss the origin and stratigraphic significance of these records, and conclude that there is a high likelihood that distal tephras of Lateglacial age can be traced throughout the Netherlands, significantly enhancing the potential for robust correlation between Dutch Lateglacial palaeoenvironmental records and those from other parts of the North Atlantic region.

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Site description and methods

Kostverloren Veen, located on the Drente Plateau, NE Netherlands (53°06′33″N; 06°32′52″E) is one of the most northeasterly pingo remnants mapped in the Netherlands (Fig. 1). A series of three remnants occur in this area, on the east-facing slope of the Eelder Diep valley, formerly a part of the Drentsche Aa drainage system (De Gans 1982). The depressions are 100–150 m in diameter and are formed within fluvial valley deposits (sorted sands and gravels) of the Middle Weichselian Aa Deposits (De Gans & Cleveringa 1981). The majority of pingos in the Netherlands were formed during the Upper Pleniglacial, when discontinuous permafrost conditions prevailed. Since the degradation of these pingos began during the temperature rise at the onset of the Bølling warm interval and was completed during this period, hundreds of small, isolated lake basins were formed in the northern Netherlands at this time. Therefore, most of the remnants contain a suite of Lateglacial sediments (Bohncke 1993; Hoek & Bohncke 2002). This is also the case for the Kostverloren Veen basin, which contains a thick infill of gyttja and peat (*c.* 6 m in depth) that extends into the Younger Dryas. As Younger Dryas coversand deposits decrease in thickness from the southwest towards the east and northeastern parts of the Drente Plateau (Bosch 1990; Hoek 2000), thick layers of coversand are absent and do not complicate the stratigraphy at Kostverloren Veen. Accordingly, this sequence was considered ideal for the detection of Lateglacial cryptotephras. In addition, a number of detailed pollen diagrams from pingo remnants in this region are available (Bohncke 1993; Hoek 1997, 2000) and therefore biostratigraphy can be used as a relative dating tool.

Eight cores of 6 cm diameter were recovered from the Kostverloren Veen basin in November 2000, using a Livingstone corer. Cores 1 to 5 were obtained from boreholes set out along transect AA in Fig. 1, while cores 6 to 8 were obtained from a SW–NE transect (*c.* 25 m NW of transect AA) through the central and deepest part of the basin. Cores 6–8 are used to support extensive palynological and tephrochronology investigations of the sequence and a summary pollen diagram is presented here for biostratigraphic correlation. The aim of this article, however, is to report on the work of relevance to detecting and analysing the cryptotephra layers.

Loss-on-ignition (LOI) measurements (2 h at 550°C) were performed at 1–2 cm intervals for core 6 and on 5 cm contiguous samples from cores 7 and 8. Contiguous sub-samples of 5 cm length were then extracted and analysed for tephra following the laboratory protocol outlined in Fig. 2. For each 5 cm block in which glass shards were detected, contiguous 1 cm^3 samples were analysed in order to determine more precisely the stratigraphical position of any peak in shard concentration. The material from between 345 and 340 cm in core 6 (within which shards of the rhyolitic component of the Vedde Ash had been detected – see below) was also subjected to a magnetic separation procedure (Fig. 2). As the Vedde Ash is

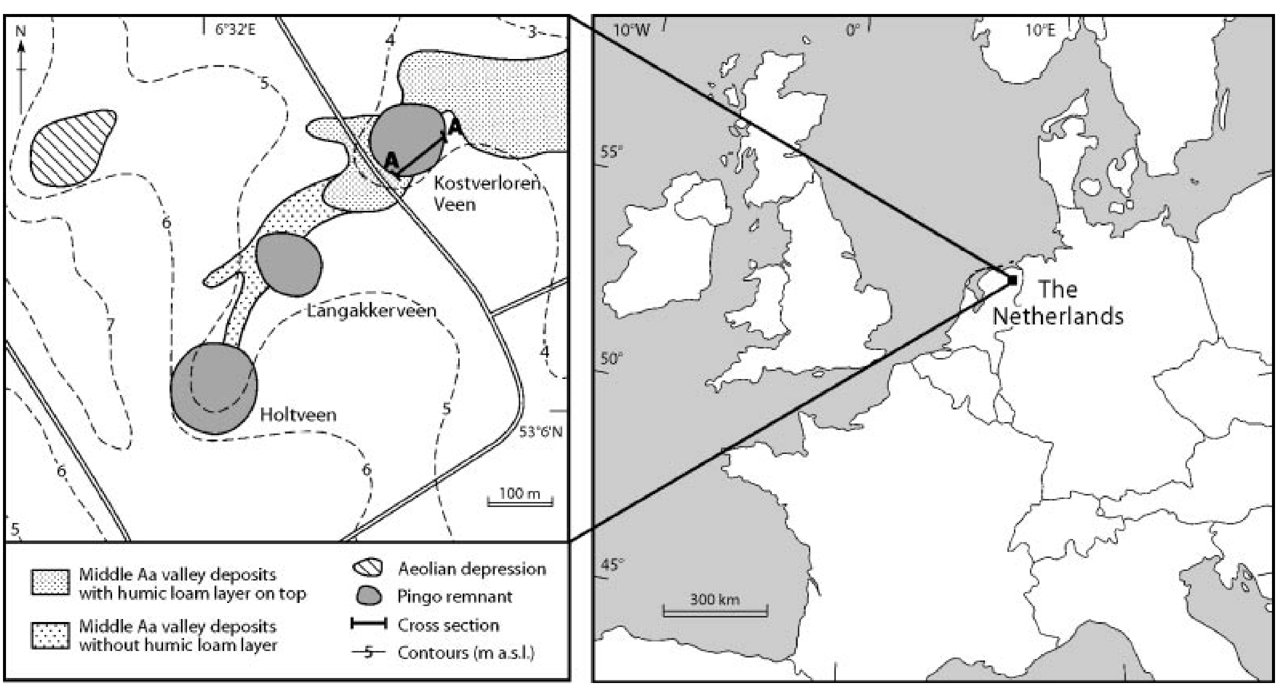

Fig. 1. Location of Kostverloren Veen within the Drentsche Aa area of the northeastern Netherlands (modified after De Gans 1982).

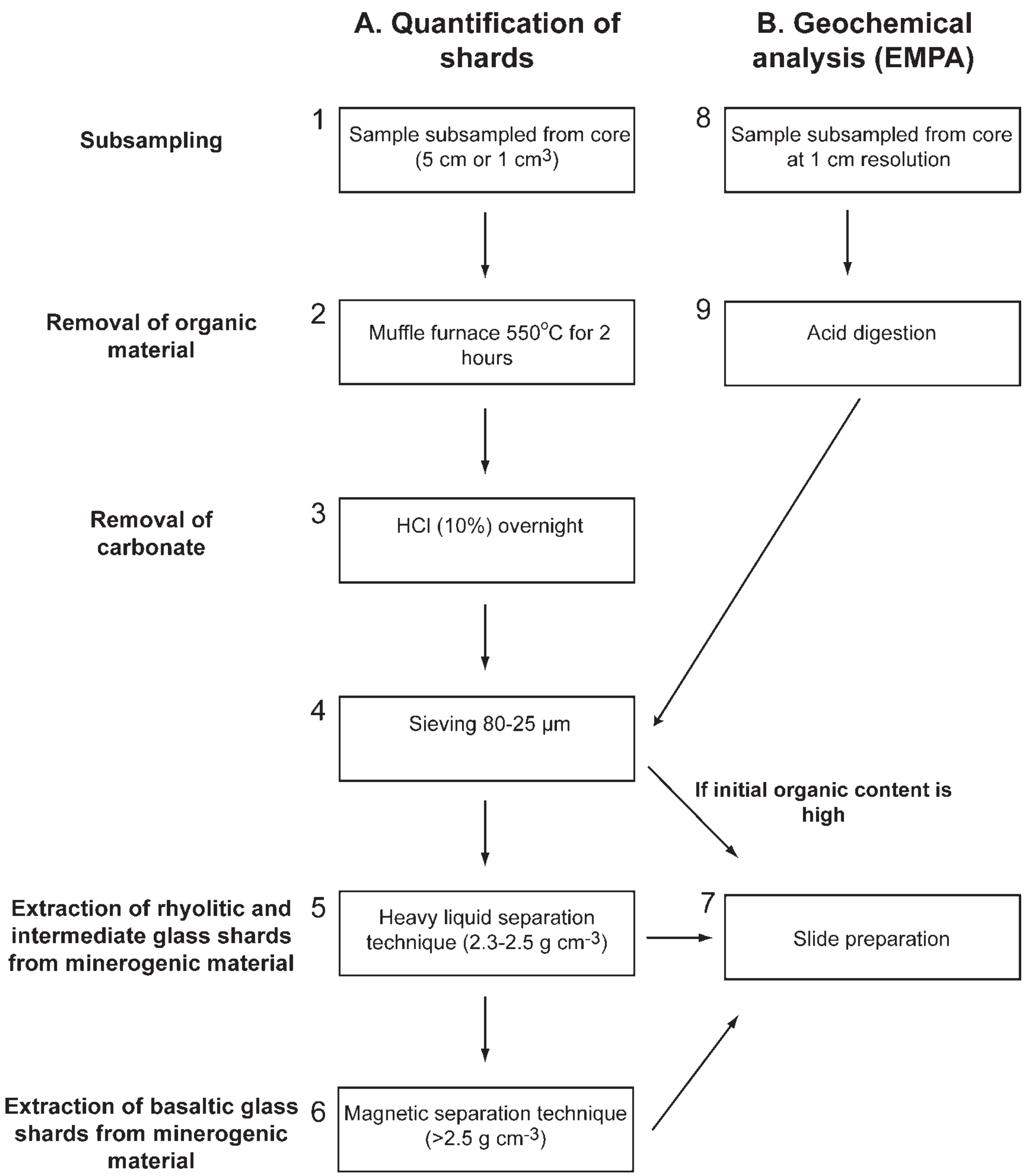

Fig. 2. Summary of laboratory procedures followed for the extraction of cryptotephras from sedimentary material, following the ashing method (for organic sediments) of Pilcher & Hall (1992), the density separation technique (for minerogenic sediments) developed by Turney (1998) and the magnetic separation procedure (15 amp current, forward tilt of 15° and a sideward tilt of 10°) outlined in Mackie *et al*. (2002). Samples for geochemical analysis by electron microprobe (EPMA) were prepared using the acid digestion technique of Dugmore *et al*. (1995).

known to contain a basaltic component (e.g. Mangerud *et al*. 1984; Björck *et al*. 1992; Birks *et al*. 1996; Davies *et al*. 2001), this technique was used here to establish whether any basaltic shards of Vedde Ash age were also present in the record from Kostverloren Veen. The latter has been used successfully to extract basaltic cryptotephra shards from mineral-rich Lateglacial sequences in Scotland (Mackie *et al*. 2002).

Tephra material recovered using these methods was subsequently analysed using the Cambridge Instruments Microscan V electron microprobe at the NERC Tephrochronology Unit, Department of Geology, University of Edinburgh. Wavelength dispersive

Table 1. Major oxide concentrations of glass shards extracted from Kostverloren Veen. *n* = number of shards analysed. Mean and 1 standard deviations are shown. All oxides are expressed as weight %. Total iron is expressed as FeO. Electron microprobe operating conditions: wavelength dispersive spectrometry with an accelerating voltage of 20 kV, 15 nA beam current and a beam diameter of 1 μm. Sodium was measured in the first and last counting period to monitor the degree of mobilization. Calibration was undertaken by analysing standards of pure metals, synthetic oxides and silicates and an andradite was analysed at regular intervals to monitor any drift in the readings. Atomic number, absorption and fluorescence effects were corrected for by a ZAF adjustment (Sweatman & Long 1969) and corrections for the counter dead time were also applied. The data are not normalized following European convention (Hunt & Hill 1993).

n	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total
Kostverloren Veen 345–346 cm (Vedde Ash rhyolitic)										
1	71.17	0.24	13.38	3.83	0.17	0.22	1.34	4.55	3.43	98.34
2	70.73	0.25	13.17	3.82	0.13	0.22	1.31	4.95	3.40	97.96
3	71.08	0.21	13.11	3.82	0.17	0.19	1.29	4.55	3.45	97.88
4	70.66	0.28	12.98	3.85	0.12	0.25	1.34	4.65	3.46	97.58
5	70.41	0.30	13.12	3.78	0.13	0.23	1.31	4.71	3.46	97.44
6	70.42	0.29	13.17	3.86	0.20	0.18	1.28	4.40	3.46	97.26
7	70.04	0.21	13.22	3.82	0.12	0.24	1.29	4.85	3.38	97.26
8	70.30	0.29	13.18	3.60	0.15	0.18	1.30	4.64	3.36	97.00
9	69.31	0.21	13.16	3.80	0.16	0.24	1.20	4.80	3.47	96.34
10	69.74	0.24	13.18	3.62	0.14	0.23	1.07	4.76	3.35	96.32
11	69.81	0.29	13.15	3.74	0.11	0.21	1.34	4.39	3.26	96.30
12	69.39	0.31	13.05	3.71	0.14	0.22	1.29	4.66	3.50	96.29
13	69.54	0.25	12.95	3.64	0.16	0.21	1.22	4.60	3.35	95.94
14	69.25	0.37	12.89	3.67	0.13	0.19	1.27	4.46	3.38	95.61
15	69.09	0.26	12.93	3.65	0.12	0.19	1.33	4.46	3.35	95.55
Mean	70.19	0.27	13.10	3.75	0.15	0.21	1.29	4.63	3.40	97.01
1 SD	0.68	0.04	0.13	0.09	0.02	0.02	0.07	0.17	0.07	0.88

spectrometry (WDS) was employed to determine the concentrations of nine major elements expressed as oxides. The operating procedures for the electron microprobe are outlined in Table 1.

Stratigraphic context

The LOI data obtained from cores 6, 7 and 8 reflect the typical Lateglacial sediment succession for the Netherlands (Fig. 3), which is described here using the terminology of the regional event stratigraphy defined by van Geel *et al*. (1989) and Hoek (1997). The LOI curves and lithostratigraphic sequences from all three cores show essentially the same trends, even though core 7 was obtained from a much shallower part of the basin than 6 and 8, and the lowermost basal sands were only recovered from core 6. This suggests that sediment recruitment responded to environmental factors that affected the whole basin. The sediment succession is described here for core 6, the core selected for detailed palynological investigations and other stratigraphical studies.

The lowermost deposits in core 6 consist of horizontally laminated coarse-grained sands (527–488.5 cm) and humic-stained sands (488.5–481 cm) that were deposited after the ice in the pingo melted during the Bølling interval (approximately equivalent to Greenland Interstadial GI-1e; Walker *et al*. 1999). Evidence in support of this is provided by the palynological data (Fig. 4) from the overlying sandy gyttja unit (481–455 cm). Typically low values of arboreal pollen and relatively high *Juniperus* percentages indicate that accumulation of this overlying unit commenced during the Older Dryas (GI-1d) (Hoek 1997; Hoek & Bohncke 2002). The transition from sandy gyttja to the overlying black, fine-grained silty gyttja (455–447 cm) is very sharp, as reflected in the LOI curve by an abrupt increase to values in excess of 80%. This unit is assigned to the first part of the Allerød interval (approximately GI-1c to GI-1a) based on the lithostratigraphy and the high *Betula* and *Pinus* values, typical of the first part of the Allerød biozone (2a) in the Netherlands (Hoek 1997; Hoek & Bohncke 2002). The overlying peat bed (447–410 cm), which is characterized by continuously high LOI values, is assigned to the second part of the Allerød interval. Relatively high values of *Pinus* between 447 and 417 cm are indicative of the second phase of the Allerød biozone (2b) (Hoek 1997). This unit is overlain by a silty, fibrous gyttja unit (410–380 cm) that grades into a sandy gyttja (380–344 cm) which, in turn, is overlain by a light brown humic-stained sand unit (344–328 cm). Progressively declining LOI values starting from 415 cm characterize these units, which are interpreted as heralding the onset of cold conditions during the Younger Dryas interval (approximately GS-1). The end of the Allerød biozone is marked by the reduction in *Pinus* pollen percentages, while indicators of a more open vegetation like Rubiaceae and Saxifragaceae reappear and *Empetrum* values begin to increase during the Younger Dryas interval. High

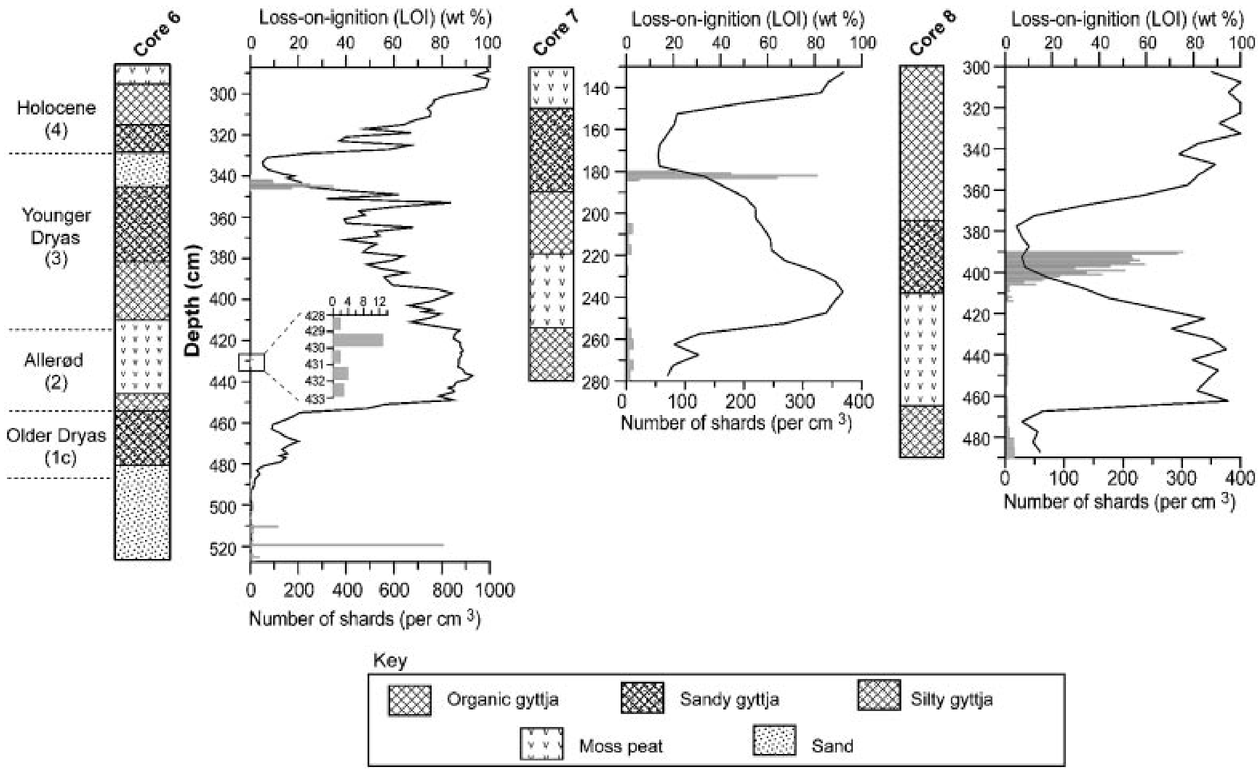

Fig. 3. Generalized lithostratigraphy, loss-on-ignition (percentage weight loss) and tephra counts for core 6–8 from Kostverloren Veen. Depth is reported in centimetres below the ground surface at the coring location. Numbers in parentheses refer to the pollen assemblage zones defined by Hoek (1997). The shard concentration for samples below 200 cm and 415 cm for cores 7 and 8, respectively, represent 5 cm samples (approximately 5 cm^3).

Empetrum values, particularly in the upper part, and slightly lower arboreal pollen values also characterize this biozone (Hoek 1997). The transition into the Holocene is marked by a sharp increase in LOI values (between 328 and 325 cm), though the high LOI values are short-lived, because significant fluctuations in LOI values characterize the sediments between 329 and 316 cm. A strong increase in arboreal pollen between 330 and 327.5 cm (Fig. 4), typical of the onset of the Holocene in the Netherlands (Hoek 1997), supports this interpretation of the LOI values. A fine-detrital organic gyttja (316–295 cm) that grades into a dark brown peat (295–252 cm) marks the final establishment of stable environmental conditions during the early Holocene.

Tephrostratigraphy

A prominent peak of glass shards was detected in the Younger Dryas interval in all three cores, with the shard concentration from each core being remarkably similar (>300 shards cm^{-3}). In core 8, the maximal tephra concentration occurs well within the lowest LOI values, whereas in cores 6 and 7 they appear to occur slightly lower in the sequence, where LOI values are still declining. The shards in these Younger Dryas sandy gyttjas are typically colourless to pale pink and have a platy and fluted morphology (Fig. 5). No basaltic shards were detected in this part of the sediment sequence from core 6 using the magnetic separation method.

WDS measurements were obtained for 15 shards from the peak shard level (345 cm) in core 6 (Table 1). Although there are some outliers, the resulting data cluster within the rhyolitic envelope of the Katla system (Fig. 6) and within the envelope for the rhyolitic component of the Vedde Ash obtained from Norwegian samples (Birks *et al*. 1996). It is concluded, therefore, that the ash layer within the Younger Dryas sediments at Kostverloren Veen can be confidently assigned to the Vedde Ash, a conclusion supported by a similarity coefficient value of 0.97 for statistical comparison between the Kostverloren data and geochemical results from other occurrences in the North Atlantic region (Birks *et al*. 1996; Lackschewitz & Wallrabe-Adams 1997; Turney *et al*. 1997) (Table 2).

Glass shard concentrations in the lower sediments in each profile, with the exception of three horizons near the base of core 6, are exceedingly low – generally <10 shards cm^{-3}. In core 6 a small isolated peak (maximum 13 shards cm^{-3}) occurs at around 429 cm, consisting of

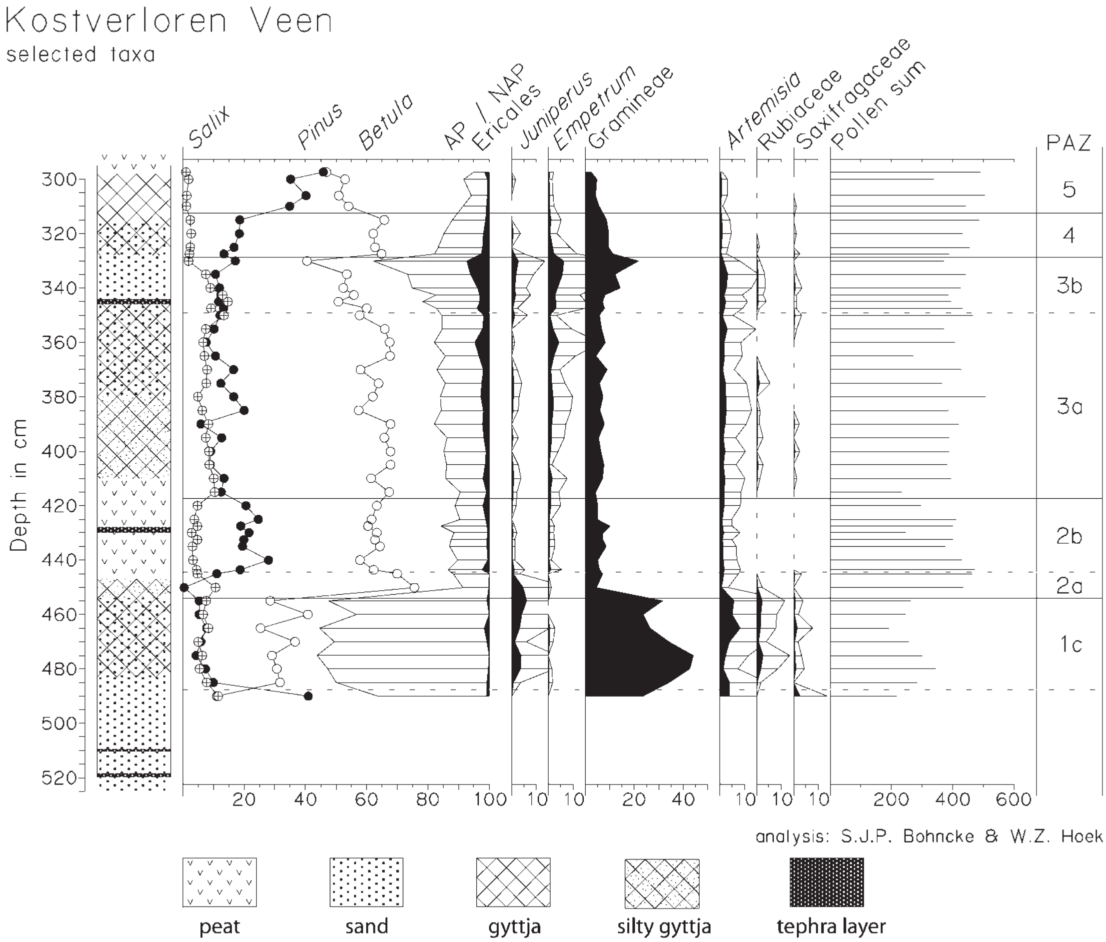

Fig. 4. Summary percentage pollen diagram for Kostverloren Veen. The unshaded area represents ×5 exaggeration. Pollen samples were treated according to standard procedures (Faegri & Iversen 1989).

platy pale to dark brown, vesicle-poor shards (Fig. 5). It was not possible to recover a sufficient quantity of shards from this level to carry out geochemical analysis. Low shard counts (maximum 6 shards) were also detected in 5 cm samples from cores 7 and 8 (230–250 cm and 430–450 cm, respectively) at levels considered to be approximately equivalent to level 429 cm in core 6, but in each case a distinct peak is not evident. These shards were typically fluted with a few vesicular shards, very different to the platy shards in core 6.

Tephra shards were also recovered from the basal sediments of core 6. Three distinct peaks were determined at 510, 519 and 525 cm and glass shards at these levels are typically colourless and platy with some fluted and vesicular shards and fine-grained sediment was observed adhering to the shard surfaces (Fig. 5). One level in core 6 (519 cm) yielded a count of >800 shards cm^{-3} during an initial investigation of the sequence which involved ashing of the samples. Since that procedure leads to alteration of shard geochemistry (Dugmore *et al*. 1992), a second extraction was undertaken, without ashing, to recover material for microprobe analysis. Surprisingly, this failed to yield any shards. Several further attempts were made to recover shards from the base of core 6, but all attempts failed. The reasons for this are difficult to understand, since subsamples were employed that came from the same core that yielded the original counts. This observation may indicate that reworking has taken place in the basal sediments and that the tephra may not be present as a discrete horizon. It is possible that, after the collapse of the pingo at the end of the Pleniglacial cold stage, coarse sands were inwashed in pulsed events from which the tephra shards may have been removed or reworked during flow or settling. Alternatively, resampling or chemical treatment at these depths may have precluded shard extraction and recovery. The low level of shards at the base of cores 7 and 8 are not considered to be equivalent of those in core 6 due to the difference in stratigraphic position.

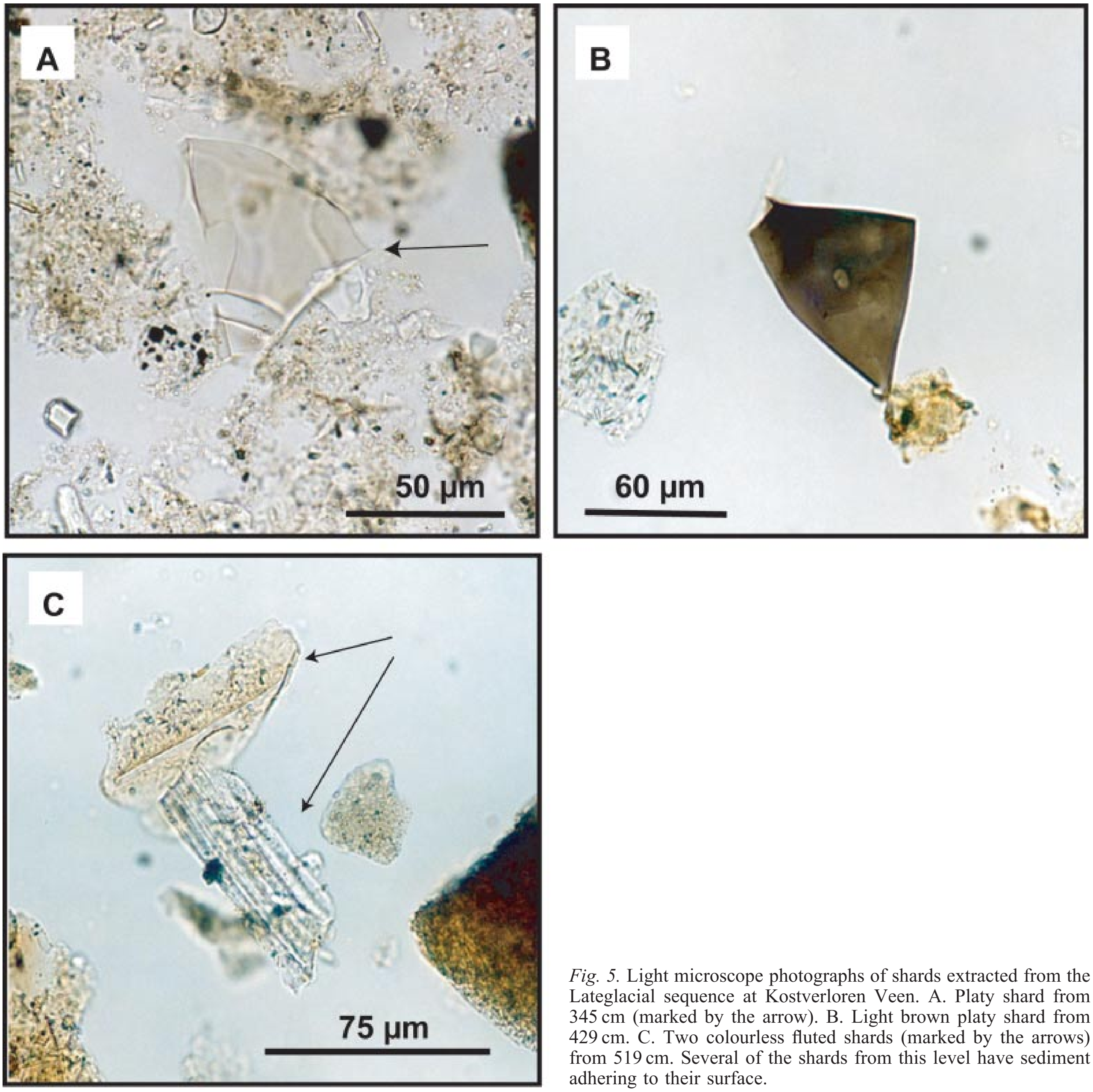

Fig. 5. Light microscope photographs of shards extracted from the Lateglacial sequence at Kostverloren Veen. A. Platy shard from 345 cm (marked by the arrow). B. Light brown platy shard from 429 cm. C. Two colourless fluted shards (marked by the arrows) from 519 cm. Several of the shards from this level have sediment adhering to their surface.

Implications of the results

The Vedde Ash

Terrestrial occurrences of the rhyolitic Vedde Ash suggest two main plumes of dispersal, one extending north over northern Iceland and the Greenland Ice Sheet, and the other spreading in an easterly/south-easterly direction over northern Britain, southern Scandinavia and western Russia (Fig. 7). The discovery of the rhyolitic component of the Vedde Ash in the Netherlands extends the known limits of the latter plume much further south. Kostverloren Veen lies some 500 km south of Lake Kullatorpssjön in southern Sweden, which hitherto marked the most southerly reported limit of the Vedde Ash (Wastegård *et al.* 2000a). The new results indicate there is a high probability that rhyolitic Vedde Ash shards may have been deposited in Lateglacial sequences in southern Britain,

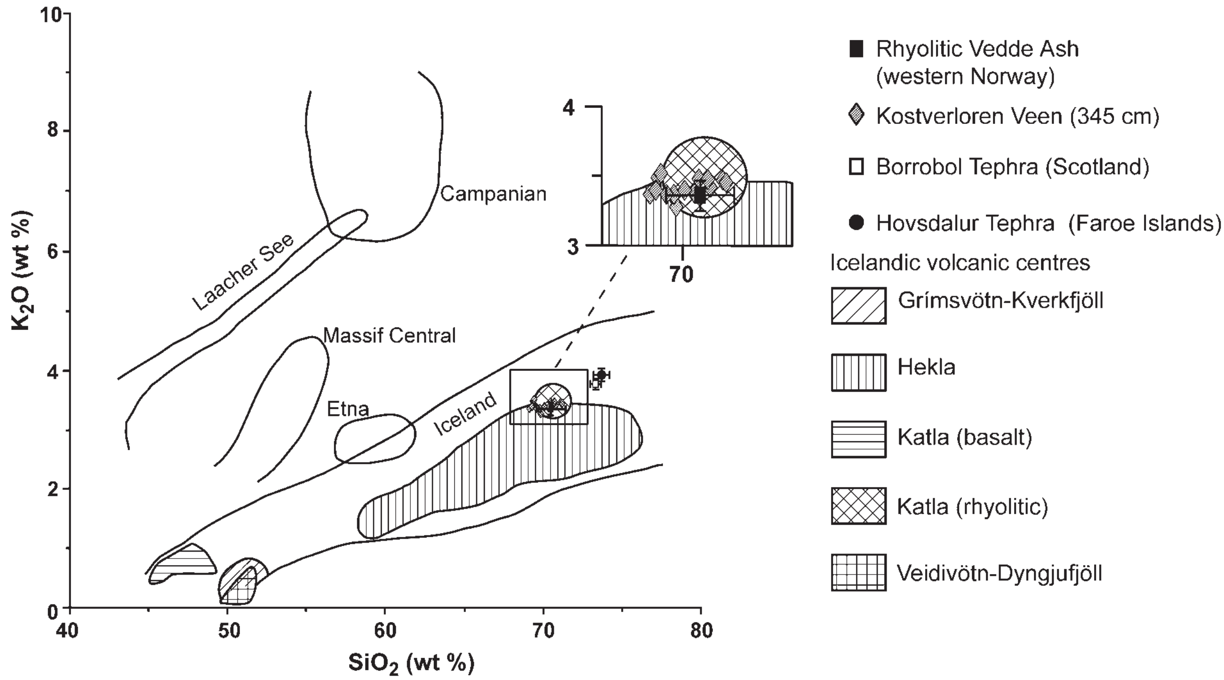

Fig. 6. Biplot of SiO_2 and K_2O for glass shards extracted from Kostverloren Veen (345 cm). Geochemical envelopes for the European volcanic centres, modified after Mangerud *et al*. (1984), Dugmore (1989) and Davies *et al*. (2002), are shown for comparison along with the mean and 1 standard deviation for the Vedde Ash horizon found in western Norway (Birks *et al*. 1996). Mean and 1 standard deviation for the Borrobol Tephra (Turney *et al*. 1997) and the Hovsdalur Tephra (Wastegård 2002) are also shown for comparison. All oxides are expressed as weight %.

and further afield in areas of northern, central and possibly eastern Europe (Fig. 7). The potential to detect the Vedde Ash in Germany and Poland is significant, since some of the Lateglacial sequences reported from those regions are varved, and hence offer the opportunity for developing very precise chronologies (Brauer *et al*. 1999; Litt & Stebich 1999; Merkt & Müller 1999; Leroy *et al*. 2000). Examination of these sequences using a thin section technique (Merkt *et al*. 1993; Schmidt *et al*. 2002), however, has failed to detect the Vedde Ash (T. Litt, pers. comm. 2002). A search for cryptotephra in these sites, using the methods employed to recover shards from the Kostverloren Veen sequence, may prove more practical and rewarding.

The southeasterly plume of the rhyolitic Vedde Ash was dispersed by westerly winds at the time of eruption. Model predictions of the Vedde event reported by Lacasse (2001) suggest an eruption column between 20 and 30 km in height that was dispersed by intensified stratospheric westerlies during the winter and/or autumn. Shard concentration data obtained from

Table 2. Similarity coefficient values for the glass shards extracted from Kostverloren Veen (K 345 cm). The data from this horizon are compared with the rhyolitic component of the Vedde Ash from western Norway (Birks *et al*. 1996), the British Isles (Borrobol, Tynaspirit West, Whitrig Bog) (Turney *et al*. 1997), North Atlantic marine records (Lackschewitz & Wallrabe-Adams 1997). The similarity coefficient equation follows that outlined by Borchardt *et al*. (1972) and Hunt *et al*. (1995). Similarity coefficients are obtained on mean analyses, which are not normalized (Hunt & Hill 1993). Only oxides with concentrations >1.0% are used for these comparisons (Hunt *et al*. 1995). Similarity coefficients are expressed between 0.6 and 1, with 1 indicating an exact match and 0.6 representing dissimilar tephras. Numerical values in excess of 0.95 are usually taken as a representation of a positive correlation (Begét *et al*. 1992).

	K 345 cm	W. Norway	Borrobol	Tynaspirit West	Whitrig Bog	N. Atlantic
K 345 cm	1.00					
W. Norway	0.98	1.00				
Borrobol	0.99	0.97	1.00			
Tynaspirit West	0.97	0.95	0.98	1.00		
Whitrig Bog	0.98	0.96	0.98	0.99	1.00	
N. Atlantic	0.97	0.97	0.98	0.96	0.97	1.00

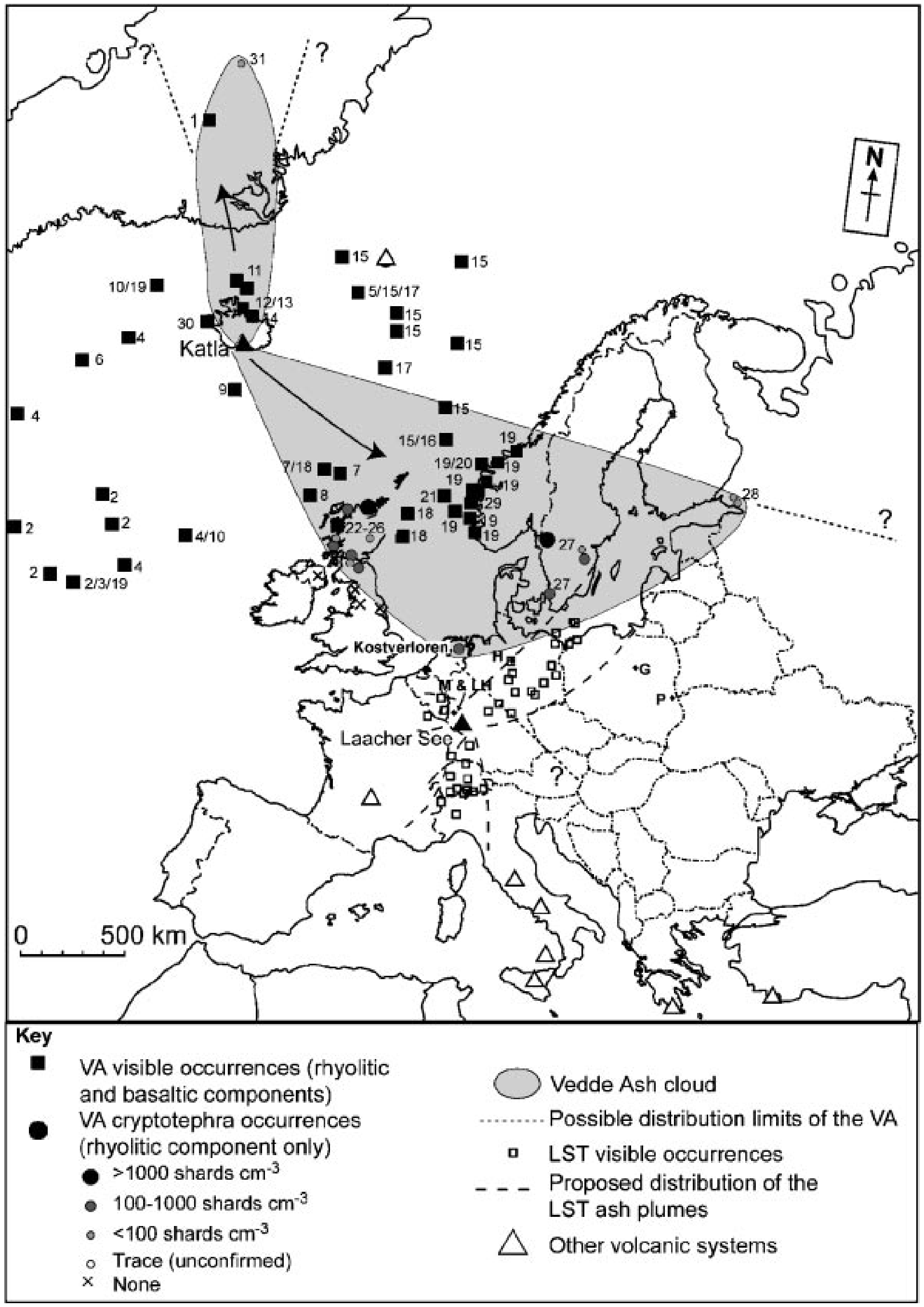

Fig. 7. Distribution of the Vedde Ash (VA) and Laacher See Tephra (LST). Shard concentrations (per cm^3 of wet sediment) for the rhyolitic component of each Vedde Ash cryptotephra horizon and the two proposed main axes of tephra fall-out are shown. The Vedde Ash horizons in the marine records are not considered to have been deposited from atmospheric fall-out. The distribution of the LST is based on work by van den Bogaard & Schmincke (1985) and results from the site investigated in this study are shown in comparison to these limits. The locations of five varved sequences discussed in the text from continental Europe are also indicated: H, Hämelsee; M, Meerfelder Maar; LH, Lake Holzmaar; G, Gosciaz; P, Perespilno (Litt *et al*. 2001). References for the VA occurrences – 1: Grönvold *et al*. (1995); 2: Ruddiman & Glover (1972, 1975); 3: Sigurdsson (1982); 4: Kvamme *et al*. (1989); 5: Sejrup *et al*. (1989); 6: Lackschewitz & Wallrabe-Adams (1997); 7: Stoker *et al*. (1989); 8: Austin *et al*. (1995) and Hunt *et al*. (1995); 9: Lacasse *et al*. (1995); 10: Bard *et al*. (1994); 11: Eiríksson *et al*. (2000); 12: Björck *et al*. (1992); 13: Ingólfsson *et al*. (1997); 14: Norddahl & Haflidason (1992); 15: Koç *et al*. (1993); 16: Koç & Jansen (1992); 17: Sjøholm *et al*. (1991); 18: Long & Morton (1987); 19: Mangerud *et al*. (1984); 20: Birks *et al*. (1996); 21: Haflidason *et al*. (1995); 22: Lowe & Turney (1997); 23: Turney *et al*. (1997); 24: Turney *et al*. (2001); 25: Roberts (1997); 26: Davies *et al*. (2001); 27: Wastegård *et al*. (2000a); 28: Wastegård *et al*. (2000b); 29: Bondevik *et al*. (2001); 30: Jennings *et al*. (2000); 31: Mortensen *et al*. (in press). The Vedde Ash forms part of the North Atlantic Ash Zone 1 identified in over 30 cores from the North Atlantic by Ruddiman & Glover (1972, 1975); however, not all have been identified geochemically and thus are not shown in this figure.

cryptotephra layers of the rhyolitic Vedde Ash do not show an exponential or linear decrease in quantitative counts with distance from the source (Fig. 7). For instance, the relatively high concentration of Vedde shards at the site of Kostverloren Veen is similar to other cryptotephra records of the Vedde Ash obtained from sites in Sweden and Britain, indicating little geographical variation in shard deposition. Other factors, such as the prevailing meteorological conditions, local taphonomic processes and site-specific characteristics must also be influential in determining the distribution and concentration of distal tephra shards (Davies *et al*. 2001; Pyne O'Donnell 2004). The latter is highlighted at Kostverloren Veen, as the Vedde Ash shard distribution in cores 6 and 7 shows a sharp lower boundary to Vedde Ash concentrations, whereas the shard distributions in core 8 are somewhat diffuse, exhibiting a strong tailing downwards below the maximum shard concentration. Since core 8 is located close to the margin of the depression and former lake, this lower tail most probably reflects downward relocation of shards by plant roots penetrating the layer containing the ash. The most prominent tail in cores 6 and 7 is above the peak value, suggesting a degree of secondary deposition of tephra after the volcanic event. As the area around the basin is exceedingly flat, and catchment transportation can therefore be considered to be negligible, the upward tailing is likely to reflect aeolian transportation.

Failure to detect the basaltic component of the Vedde Ash in the northeastern Netherlands supports other data which suggest that this component is considerably more restricted in distribution in Europe than the rhyolitic component (Davies *et al*. 2001). So far, visible layers of basaltic Vedde Ash have been reported from sites in Norway and only one site in the Scottish Hebrides, though it has also been detected as a cryptotephra layer at one other site in Scotland, using the magnetic separation method (Mackie *et al*. 2002). It was considered possible that the lack of detection of basaltic Vedde Ash shards might reflect the influence of the laboratory procedures employed, since the density separation method does not isolate basaltic shards from other mineral components. This cannot be the case at Kostverloren Veen, however, where the magnetic separation method was also employed. Uneven distribution across a basin is another possibility, however, as basaltic tephra deposits have been shown to be patchy at some sites (Davies *et al*. 2001) and the magnetic separation technique was only used on material from core 6.

Minor shard concentrations at Kostverloren Veen

The small shard peak at 429 cm in core 6 of the Kostverloren Veen sequence could not be analysed geochemically due to the low shard concentration. The stratigraphic position of these shards, however, raises the possibility that they may be attributable to the Laacher See Tephra (LST), a tephra originating from the Eifel District in Germany, which is dated to *c*. 11.0 ^{14}C ka BP and 12.88 varve ka BP (van den Bogaard & Schmincke 1985; Brauer *et al*. 1999). The distribution pattern of the LST is well known, with three main dispersal plumes to the northeast, southwest and south of the volcano. It would, therefore, be unexpected to find evidence of the LST north of the source. This tephra horizon occurs in the middle of the second phase of the Allerød biozone (2b), generally dated between 11 250 and 10 950 ^{14}C BP (Hoek 1997), just before the transition between the Allerød and Younger Dryas, according to the pollen-stratigraphic data (Hoek 1997). In the absence of detailed geochemical data, such an attribution is highly speculative, but invites further research.

In a similar vein, we can only speculate about the origin of the tephra material recovered from the basal sediment of core 6 (i.e. within the Bølling unit). Again, attempts to fingerprint these glass shards by geochemical tests failed because we were unable to replicate the high counts of tephra initially recovered from the basal levels of core 6 (discussed above). Although this may indicate that the tephra horizon is not present as a discrete horizon, pollen-stratigraphic correlation suggests that the basal sands in core 6 can be assigned to the very end of the Bølling period, shortly before the beginning of the Older Dryas biozone (Hoek 1997). It is possible that this may correspond to the Borrobol Tephra traced in early Lateglacial sediments in Scotland, Sweden and the Icelandic plateau (Turney *et al*. 1997; Lowe *et al*. 1999; Eiríksson *et al*. 2000; Davies *et al*. 2004) – but again, further research is necessary to test this assumption.

Even if these two events are not related to the LST and Borrobol Tephra, the data nevertheless indicate the potential presence of two tephras at Kostverloren Veen that may not yet be included in the database of European Lateglacial tephras (Haflidason *et al*. 2000; Davies *et al*. 2002), and which might be better represented in other sequences from the Netherlands.

Conclusions

The geographical distribution of the Vedde Ash is extended to the Netherlands, and represents the southernmost discovery of this tephra so far. This discovery outlines the potential of using this tephra as a time-parallel marker horizon for the precise correlation of terrestrial records in the Netherlands, continental Europe and marine and ice-core records within the North Atlantic region.

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