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Icelandic volcanic ash from the Late-glacial open-air archaeological site of Ahrenshöft LA 58 D, North Germany

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ABSTRACT

Cryptotephra of Icelandic origin from the open-air archaeological site of Ahrenshöft LA 58 D (Kr. Nordfriesland, Schleswig-Holstein), northern Germany overlies a Late-glacial Havelte lithic assemblage, hitherto dated by ^{14}C and biostratigraphy to the earliest part of the Late-glacial interstadial (GI-1e to GI-1c$_3$). Peaks in ash shards are observed in two profiles. Major and minor element geochemistry indicates volcanic ash originating in the Katla system. Precise correlation to previously described tephra is uncertain due to overlapping chemical characteristics. The Ahrenshöft ^{14}C determinations, litho- and bio-stratigraphy encompass a broad age-span for the cryptotephra bearing sediments, from the end of the Allerød to the Preboreal. The most plausible volcanic eruption correlates are the Vedde Ash (~Younger Dryas), already known from the European mainland, tephra AF555 (late Younger Dryas) and the Suduroy tephra (~Preboreal/Boreal), hitherto recorded only in the North Atlantic region. These three ash horizons have been dated to, respectively, 12,171 ± 57 yr b2k in the NGRIP ice-core, c.11,500 cal BP, in Scotland and c.8000 cal BP, by radiocarbon from the Faroe Isles. Ongoing research on deposits from the type sites for the tephra layers may in the future differentiate these markers leading to better discrimination of the chemistries and a resolution of this question.

1. Introduction

The synchronisation and alignment of palaeoenvironmental archives, whether from lacustrine, peat bog or marine contexts, is of increasing importance to modern climate studies. The value of microscopic non-visible 'crypto' volcanic ash horizons ('tephra isochrons') as a means of furthering this aim is being increasingly recognised (Lane et al., 2011; Langdon and Barber, 2004; Litt et al., 2001; Lowe et al., 2008; Lowe, 2011; Plunkett, 2006). The application of improved extraction and detection methods for such cryptotephra (Blockley et al., 2005) has produced larger geographical 'ash footprints' permitting different sedimentary settings to be precisely correlated, and where linked to historical or known-age events, dated. In Europe, overlapping 'footprints' from separate volcanic centres (Eifel region, Massif Central, Iceland, Italy) are leading to a continent-wide tephra 'lattice'. A Late-glacial example is the Vedde Ash (Mangerud et al., 1984), an Icelandic eruptive unit which has been recorded as far south as lakes in southern Germany, Switzerland, eastern France and northern Italy (Blockley et al., 2007; Lane et al., 2011; Lane et al., in press[a]; Walter-Simonnet et al., 2008), where it overlies the Laacher See, a *c.*12.9 ± 0.1 ka eruption from the east Eifel, and is itself overlain by several eruptive units from the Massif Central and Iceland. The Vedde Ash has also been found in the Greenland ice-core records (Mortensen et al., 2005) and extends over many parts of Scandinavia as far east as northwestern Russia and thus has the potential to be a major marker (Wastegård et al., 2000; Wastegård, 2005).

Tephrostratigraphical research has shown that lakes (Pyne-O'Donnell, 2007, Wulf et al., 2004), peat bogs (Pilcher et al., 1995; Wastegård et al., 2003) and deep marine sediments (Bourne et al. 2010; Lowe et al. 2007) are good settings for the survival and study of visible and cryptotephra. What is less certain is the capacity of archaeological sites to preserve volcanic ash horizons. Whilst visible tephra layers have long been known from cave sites – e.g., Temnata, Bulgaria; Franchthi, Greece (Kozłowski et al., 1992; Farrand, 1977) – and open-air archaeological sites – e.g., Andernach-Martinsberg, Germany; Dmanisi, Georgia and Kostenki, Russia (Baales et al., 2002; de Lumley et al., 2008; Hoffecker et al., 2008, Pyle et al., 2006) – the ability of

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cryptotephra to survive in archaeological contexts is not well documented (see, however, Balascio et al., 2011). This study therefore focuses on the question: do cryptotephra horizons survive in Late-glacial, north European archaeological sites and if they do can useful chronostratigraphic knowledge be obtained? Our research is thus experimental, for it aims to test whether the methodology developed for palaeoenvironmental contexts is appropriate for aerobic terrestrial sediments on archaeological sites. The need for better chronological control on such archaeological sites on the north European Plain is evident both in reviews of this period (e.g. Schild, 1996; Terberger, 2006) and in site specific studies (e.g. Kaiser and Clausen, 2005) where shallow stratigraphy, poor faunal preservation and post-depositional disturbance frequently mean that typological arguments take precedence.

Previous tephrochronology studies in northern Germany have demonstrated that the footprints of some Icelandic and Eifel Late-glacial to early Holocene tephra have regularly criss-crossed the north German plain. Investigations of the Late-glacial Laacher See Eruption (Bogaard and Schmincke, 1984, 1985; Bogaard, 1995); Holocene Icelandic volcanic marker horizons within raised peat bog sedimentation, e.g. Jardelunder Moor, Dosenmoor and Grambower Moor (Bogaard and Schmincke, 2002; Bogaard et al., 2002); and tephra from lacustrine repositories, e.g., Hämelsee (Merkt et al., 1993) have shown that successive volcanic ash footprints do exist in north Germany. Past work in Schleswig-Holstein (Bogaard et al., 1994) highlighted the presence of Icelandic-derived tephra in palaeoecological settings in very close proximity to known archaeological sites (Bokelmann, 1973) in our study area, but so far no non-visible ash horizons have been reported from archaeological sites.

In this paper we present the results of a tephrostratigraphical study of three profiles encompassing Late-glacial and early Holocene deposits on an archaeological site in northwest Schleswig-Holstein. Concentrations of microscopic volcanic ash are detected in the laboratory and characterised by the chemical composition of glass shards. The peaks in tephra shard concentrations are correlated between profiles and have been traced to an Icelandic volcanic source. Probable correlates to known eruptive events are discussed, although compositional similarities between temporally discrete eruptions preclude definitive correlation to specific eruption events. Observations are made concerning the taphonomic preservation of discrete volcanic ash horizons in archaeological settings such as represented by Ahrenshöft LA 58 D. The study contributes to the linkage of anthropogenic events to a wider palynology-based palaeoecological framework for the area and neighbouring regions (De Klerk, 2004, 2008; De Klerk et al., 2008; Lane et al., in press[b]; Usinger, 2004).

2. Study site and methods

2.1. Sampling

Ahrenshöft LA 58 D is an open-air archaeological site in Kr. Nordfriesland of northern Germany (54° 33′ 57″ N, 9° 6′ 29″ E, ∼4 m above sea-level; Fig. 1). Situated in a region known from the

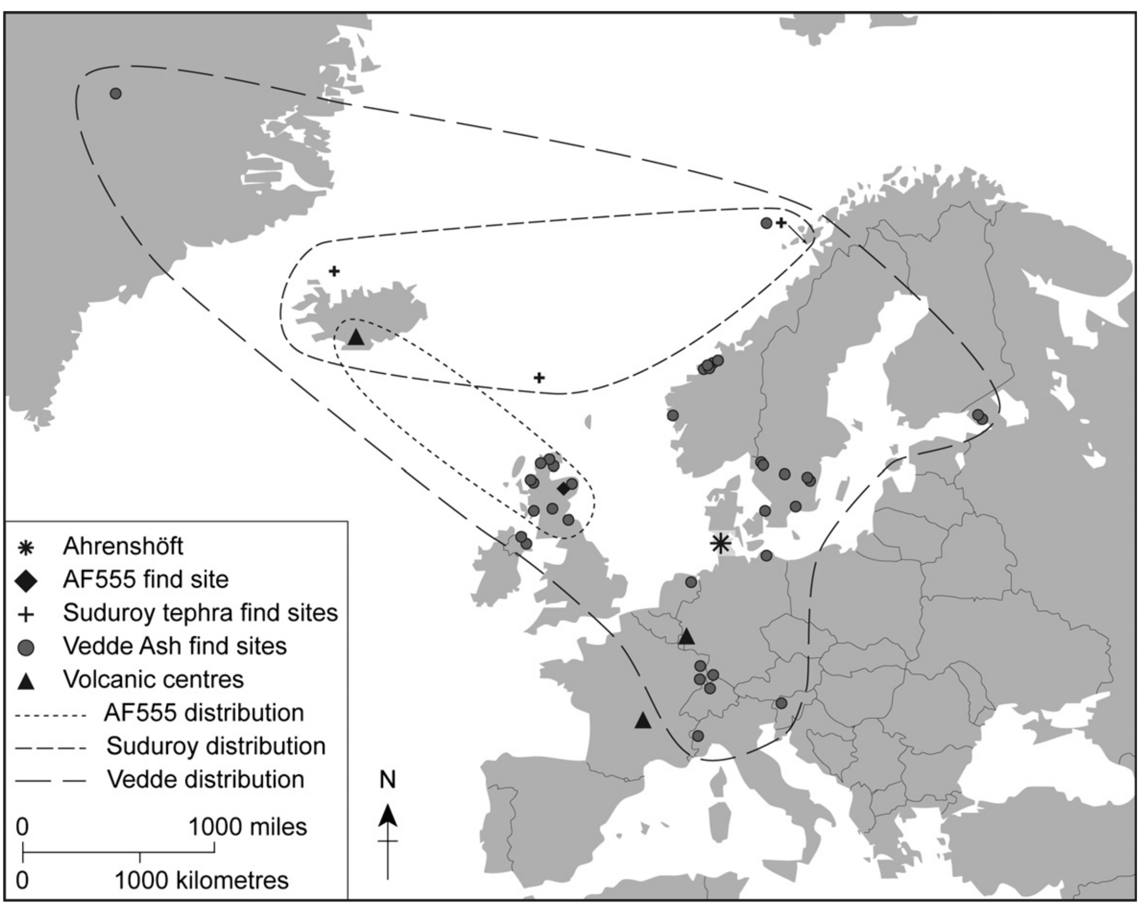

Fig. 1. Map showing location of Ahrenshöft LA 58D, volcanic centres and the known ash fall footprints of the Vedde Ash, tephra AF555 and the Suduroy tephra based on selected published and in press records (see Lane et al. in press[c] for site references).

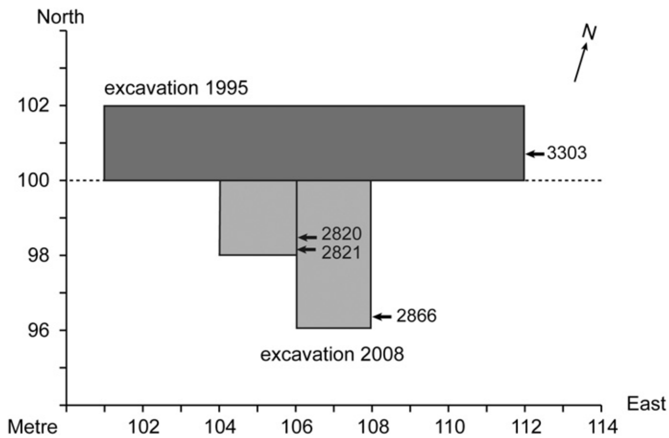

Fig. 2. The position of microtephra samples in relation to excavation trenches. Modified after Weber et al. (2010: 9, Fig. 2).

early 1950s to be rich in Late-glacial archaeology, notably the Hamburgian, the site is characterised by its Havelte Group lithics assemblage. Existing ^{14}C dating suggests the classic Hamburgian and Havelte lithics industries were produced in the period from the end of GS-2a through to GI-1c3 (Grimm and Weber, 2008). Ahrenshöft LA 58 D was first excavated in 1995 by Ingo Clausen (1998). In 2008 Mara-Julia Weber undertook new investigations of the site leading into a project at the Centre for Baltic and Scandinavian Archaeology (Weber et al., 2010). This reinvestigation provided access to deposits suitable for cryptotephra sampling. The research reported here was undertaken within the context of the RESET research initiative, a 5-year Consortium funded by the UK's Natural Environment Research Council (NERC) that brings together archaeologists, volcanologists, tephrochronologists and stratigraphers to investigate the chronology of major phases of human dispersal and development in Europe during the past 100,000 years, and to examine the degree to which these were influenced by abrupt environmental transitions (http://c14.arch.ox.ac.uk/reset/).

Two open profiles were sampled in July 2008 using three 30 cm long monolith tins: two overlapping tins (#2820, #2821) sampled 50 cm of contiguous sediment from square Y6, southeast quadrant (profile 106E); tin #2866 sampled 30 cm of deposit in square W8, southeast quadrant (profile 108E) (for the position of profiles, see Figs. 2 and 3; for a section drawing of profile 108E, see Weber et al. 2010: 17, Fig. 11).

In June 2009 a further 30 cm monolith tin (#3303) sampled profile 112E at the eastern end of the 1995 trench, investigated originally by Clausen (1998). Square Y6 yielded a greater density of lithics compared to square W8 or profile 112E, reflecting a closer proximity to archaeological activity concentrations. In conjunction with the cryptotephra research, both pollen and soil micromorphology samples were taken by H. Usinger and C. E. Miller – the results of these analyses are reported in Weber et al. (2010).

2.2. Laboratory methods

Cryptotephra investigation followed the non-destructive, physical separation technique of Blockley et al. (2005). The initial process involved examination of contiguous 5–10 cm samples from the full length of the sampled sedimentary profiles to determine presence/absence of cryptotephra. Vitreous tephra shards were identified and counted using high-powered optical microscopy. Where tephra shards were found, a further series of contiguous 'high resolution' (1 cm thick) samples were prepared to precisely

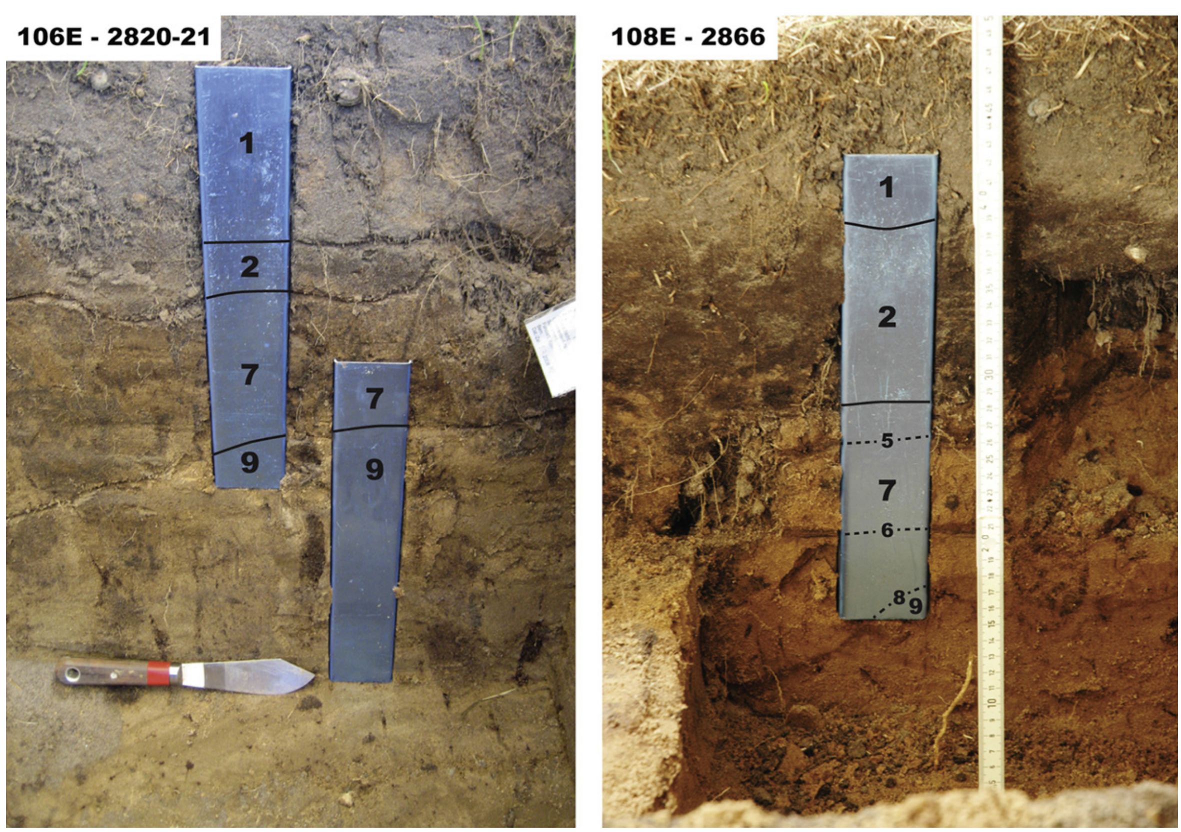

Fig. 3. Cryptotephra sample tins (#2820, #2821 and #2866) in profiles 106E and 108E.

define the tephra shard distributions in the sediment column. Identified ash horizons were then re-extracted and prepared for geochemical analysis.

Volcanic glass was analysed using micro-analytical techniques. Major element compositions were measured using a Jeol JXA8600 wavelength-dispersive electron microprobe (WDS-EPMA) at the Research Laboratory for Archaeology and the History of Art, University of Oxford. The instrument was calibrated using a suite of mineral and oxide standards, and analyses were performed using an accelerating voltage of 15 kV, 6 nA beam current, and a 10 μm beam. Count times for the most elements were 30 s on peak, Na was only analysed for 10 s to minimise the effect of alkali loss, and longer count times were used for low abundance elements (e.g., 60 s for P).

Trace element analysis of the same grains was carried out using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), using an Agilent 7500 ICP-MS coupled to a 193 nm Resonetics ArF eximer laser ablation system, with a two-volume ablation cell (Müller et al., 2009), in the Department of Earth Sciences, Royal Holloway University of London. A 25 μm (μm) laser spot size was used for analysis. The repetition rate was 5 Hz and both sample and gas blank count times were 40 s. Quantification used NIST612 with ^{29}Si as internal standard and corrected using ^{43}Ca. See Tomlinson et al. (2010) for full details of analytical and data reduction methods.

The ATHO-G and StHs6/80-G fused volcanic glass secondary standards from the MPI-DING collection (Jochum et al., 2006) were analysed between and within WDS-EPMA and LA-ICP-MS analytical runs to check precision and accuracy. Summary results are presented in the Supplementary information.

AMS ^{14}C dating of organic matter from a single profile (112E) at Ahrenshöft was carried out with the aim of providing an independent age estimate for horizon 2 that contains cryptotephra glass shards. Unfortunately, absence of identifiable plant macrofossils required the use of bulk organic matrix as the dating material, which is not ideal for reasons outlined in Goslar et al. (2005) and Shore et al. (1995). Despite efforts to physically remove small rhizomes and rootlets from the samples ahead of chemical pretreatment, the dated fractions could not be totally cleaned of these contaminants. To assess the potential bias of this intrusive matter, each sample was divided into 3 size categories (>250 μm, 250–125 μm and 125–63 μm) and the ^{14}C age analysed on the humin fraction. The ^{14}C concentration was measured in the accelerator mass spectrometry facility of the Research Laboratory for Archaeology and History of Art, University of Oxford. For greater discussion of the ^{14}C analyses from Ahrenshöft, see Brock et al. (2011).

3. Results

3.1. Cryptotephra

Profile 106E has yielded very low amounts of tephra (1–5 shard absolute counts, per 5 cm depth), with no clear peak in concentration. Thus no further processing was undertaken on samples from this profile. In contrast, profiles 108E and 112E produced higher tephra shard counts. Table 1 presents the stratigraphy of profiles 108E and 112E. The shard concentrations (per g dry weight of sediment) vs. depth data are shown in Fig. 4. The morphology of the shards in profile 112E is platy to curvilinear, with close affinity to the ‘butterfly shapes’ of the Vedde Ash as described by Mangerud et al. (1984). Shards range from 60 to 80 μm in size across the largest axis. In profile 108E the tephra shards are platy, with some open vesicles and some butterfly shapes ranging from 40 to 100 μm.

In profile 108E tephra glass shards appear in all but one 1 cm samples between 55 and 69 cm depth. However, two small peaks in tephra shard concentrations are suggested, at depths of 55–56 and 65–66 cm (respectively OxT2463 & OxT2473) below x, the 2008 site datum. The 55–56 cm peak in shard concentration is located in Horizon 1; the 65–66 cm peak is in Horizon 2 (Weber et al. 2010). Glass shards from these depths were selected for analysis by WDS-EPMA, while the small shard sizes precluded analysis by LA-ICP-MS. A total of 14 (OxT2473) and 4 (OxT2463) WDS-EPMA analyses were achieved (Table 2a, Fig. 5a). The major element composition of OxT2473 (65–66 cm) and OxT2463 (55–56 cm) indicate an Icelandic eruptive source, with a close compositional affinity to the mid Younger Dryas Vedde Ash eruption from the Katla volcano.

A further tephra peak (OxT4156, ~506 shards/g) is observed in profile 112E, at a depth of 159–160 cm below x_1, the 1995 site datum, within Horizon 2, the decomposed peat layer of Weber et al. (2010) (Table 1). X_1 is 87 cm below x and thus the elevation of this peak relative to the tephra shard concentration peaks in profile 108E is ~72–73 cm depth. The shard morphology is platy, with

Table 1
Profiles 108E and 112E – sediment descriptions. Altitudinal data based on x and x_1, respectively the 1995 and 2008 excavation reference markers. X_1 is 87 cm below x. Layer numbering is different between excavations but the table shows approximate stratigraphical relationships. For detailed descriptions, see Weber et al. (2010: 18).

Depth (m)	N–S profile at 96,00–98,00 m N/108,00 m E; z_{top}: x_1 – 0.55 m; tin #2866	Depth (m)	Profile at 100,90–100,95 m N/112,00 m E; z_{top}: x – 1.59 m; tin #3303
0.55–0.585	Horizon 1: Fine sand, grey, heavily rooted, with some light sand lenses		
0.585–0.69	Horizon 2: Fine sand/black-humus, heavily rooted, mixed with light brown sand lenses by bioturbation (with charcoal)	1.59–1.65	Horizon 2: black-brown amorphous peat. Heavily impregnated by rootlets. Badly decomposed
		1.65–1.71	Horizon 3: yellow-brown humic fine sand. Believed Allerød in age based on palynology
		1.71–1.74	Horizon 4: dark humic silt/fine sand gyttja. Believed Allerød in age based on palynology
		1.74–1.89	Horizon 5: grey-brown silt and fine sand. Believed to be cryoturbated
0.69–0.835	Horizon 7: Reddish brown (ferric oxide-stained) fine to medium sand with rootlets. Basal part clearly laminated. Horizons 5 & 6 are found within this layer		
Respectively 0.705–0.72 & 0.77–0.79	Horizons 5 & 6: dark brown humic silts, 1.5–2.0 cm thick: Horizon 5 subdivided into upper, dark brown layer and lower, light brown layer; Horizon 6 subdivided into upper, light brown layer and lower, dark brown layer. Horizon 5 = cultural layer Havelte		
0.835–0.845	Horizon 8: Fine sand, dark brown in colour (from ferric oxide content or humus)		
0.845–0.85	Horizon 9: Alternating silts, fine and medium-grained sands, yellowish brown. Clearly laminated and cryoturbated, with rootlets.		

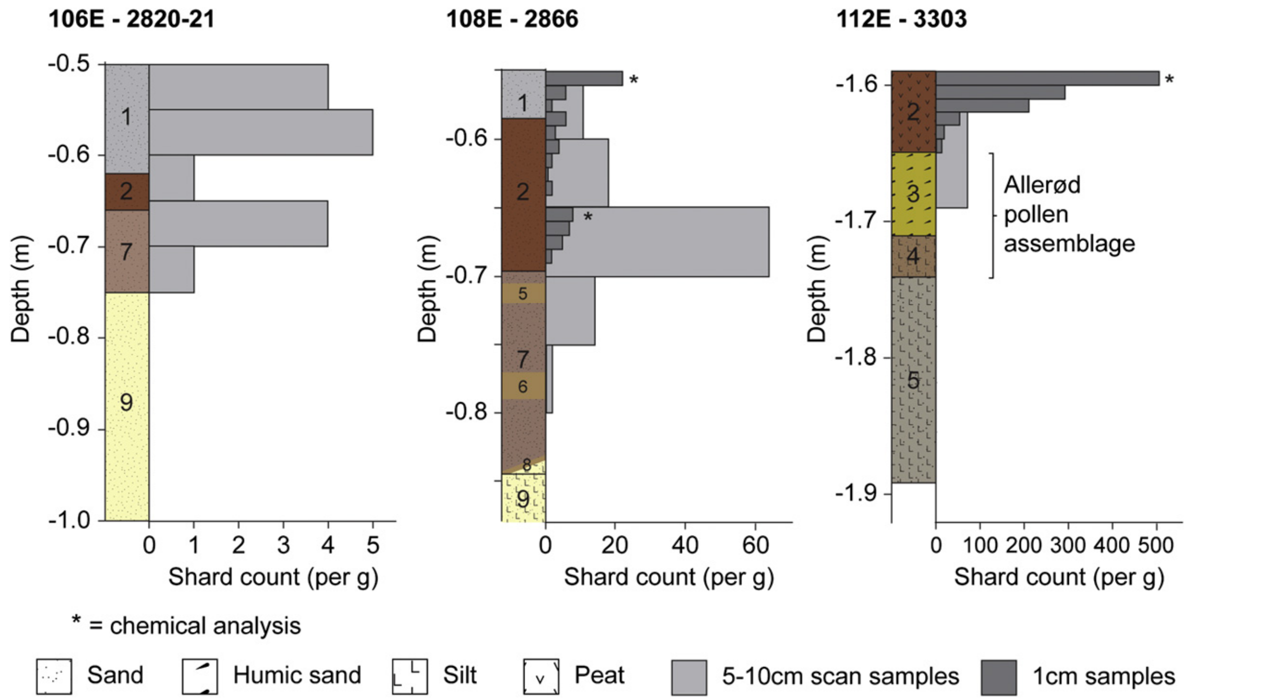

Fig. 4. Results of 5 cm and 10 cm (light grey) and 1 cm (dark grey) shard counts (5 cm and 10 cm are absolute shard counts, 1 cm are shard counts per g dry weight) against depth and stylised stratigraphy, for the 3 analysed profiles at Ahrenshöft. Depth elevations in profiles 106E and 108E relate to the 2008 datum, those in profile 112E are relative to the 1995 datum.

some butterfly shapes and shard sizes ranging from 50 to 80 μm, similar to those in profile 108E. The higher concentrations of tephra shards permitted the use of both WDS-EPMA and LA-ICP-MS. A total of 22 major and 6 trace element analytical hits were obtained (Table 2b and Fig. 5a and b). OxT4156 is a homogeneous rhyolite fully consistent with that of OxT2463 and OxT2473, suggesting that the peaks are possibly from the same eruption deposit. The trace element results from OxT4156 (Fig. 5b) are the first to be produced on an Icelandic cryptotephra within an archaeological sequence from the European mainland and are shown in Fig. 5b to be a good match to rhyolitic phase of the Vedde Ash, as measured from the type site in Kråkenes, Western Norway (Mangerud et al., 1984; Lane et al., in press[c]). However, Lane et al. (in press[c]) have shown that multiple eruptions from Katla have produced the same major, minor and trace element glass compositions as the rhyolitic phase of the Vedde Ash, therefore the correlation of OxT4156 remains uncertain.

3.2. Radiocarbon dating

Two samples from profile 112E yielded 6 AMS ^{14}C determinations (Table 3), each sample being divided into 3 size fractions. The two horizons selected for dating were 159–160 cm, the level that coincides with the largest peak in tephra shards (OxT4156) and 164–165 cm, which is at the contact marking the initiation of peat growth (note: the next cm below proved too low in carbon content). The ^{14}C data show that the >250 μm size fraction gives the oldest age estimates, the medium and fine sieve fractions yield progressively younger results. All results fall in the early to mid Holocene.

4. Discussion

4.1. The taphonomy of the tephra layers

Three tephra peaks are observed from Ahrenshöft LA 58 D, sited in two profiles: 108E and 112E. Two of the peaks are in Horizon 2, described alternatively as a black-humus fine sand, heavily rooted, mixed with light brown sand lenses by bioturbation (profile 108E, tin #2866), and a black-brown amorphous badly decomposed peat, heavily impregnated by rootlets (112E, tin #3303). The third tephra peak is within Horizon 1 (profile 108E, tin #2866), a grey fine sand heavily rooted, with inter-collated light sand lenses. For profile 108E the question is, was tephra deposited in Horizon 2 and reworked upwards into Horizon 1 (hypothesis A), or deposited in Horizon 1 and moved by bioturbation down into Horizon 2 (hypothesis B)?

Soil micromorphology analysis of sample #2846, adjacent to monolith #2866 in profile 108E (Weber et al. 2010: 17, Fig. 11), led the analyst (C. E. Miller) to conclude that Horizon 2 comprised small fragments of peat mixed within sand in a loose structure with no bedding. Due to several post-depositional alterations Horizon 2 was interpreted as a mixture of sand and peat brought together by bioturbation, probably after the area was quarried for peat. Parallel pollen analysis (by H. Usinger) revealed thermophilous trees and modern cultigens in an otherwise birch-dominated assemblage with high amounts of non-arboreal pollen. Together both lines of evidence suggest a degree of contamination from overlying late-Holocene deposits; in profile 108E hypothesis B is certainly plausible however hypothesis A cannot be dismissed. The shard depth distribution plots (Fig. 4) would allow for either hypothesis.

By all accounts profile 112E is less disturbed than 106E or 108E. This is reflected in the higher shard counts in #3303 (159–161 cm), an absence of thermophilous trees and modern cultivars in the 1995 pollen samples and better peat preservation. The morphology of the tephra shard peak (OxT4156) in 112E argues for primary tephra deposition in Horizon 2 and on the basis of this we would favour hypothesis A as the prevailing taphonomic process in the more disturbed areas of the site.

Success in recovering and identifying cryptotephra from Ahrenshöft LA 58 D is probably due to localised topographical and stratigraphic factors. The position of samples #2866 and #3303 coincided with slightly lower ground elevations, resulting in better

Table 2a
Major and minor element data, from WDS-EPMA, for cryptotephra samples: OxT2473 (108E, 65–66 cm), OxT4156 (112E, 159–160 cm) and OxT2463 (108E, 55–56 cm). Data are presented as un-normalised weight percent oxide (wt %) values. n.a. = not analysed. Precision, based upon reproduction of secondary standard glass analyses ranges from <1 to <10% (at 2σ) for major elements and 10–40% (at 2σ) for minor elements. Associated secondary standard glass analyses (listed as batches a–e in "Std batch" column) are reported in Supplementary information Table 1.

	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	Std batch
OxT2473	72.81	0.32	13.79	4.11	0.09	0.21	1.55	5.39	3.21	n.a.	101.48	a
	71.98	0.27	13.19	3.65	0.14	0.23	1.43	4.77	3.22	n.a.	98.89	a
	72.17	0.33	13.74	4.15	0.19	0.24	1.43	4.95	3.28	n.a.	100.47	a
	71.99	0.24	12.96	3.70	0.13	0.19	1.33	5.23	3.24	n.a.	99.01	a
	69.99	0.29	12.80	3.61	0.11	0.19	1.34	4.43	3.20	n.a.	95.95	a
	69.60	0.29	12.79	3.79	0.18	0.18	1.39	4.82	3.18	n.a.	96.22	a
	72.75	0.29	13.41	3.58	0.20	0.20	1.28	4.92	3.46	n.a.	100.09	b
	71.13	0.28	13.17	3.74	0.22	0.18	1.27	4.98	3.28	n.a.	98.25	b
	73.11	0.31	13.47	3.57	0.11	0.21	1.27	5.13	3.44	n.a.	100.63	b
	71.06	0.34	13.64	3.99	0.21	0.15	1.34	4.60	3.43	n.a.	98.78	b
	71.29	0.27	13.59	3.82	0.06	0.20	1.29	5.02	3.50	n.a.	99.03	b
	71.31	0.33	13.61	3.82	0.10	0.24	1.37	5.28	3.36	n.a.	99.43	b
	71.49	0.44	13.79	3.91	0.12	0.27	1.44	5.50	3.17	n.a.	100.13	b
	72.06	0.33	13.58	4.01	0.13	0.24	1.34	5.42	3.49	n.a.	100.61	b
OxT4156	68.54	0.28	12.87	3.77	0.19	0.17	1.21	5.06	3.29	0.07	95.63	c
	71.09	0.31	13.30	3.95	0.15	0.19	1.25	5.35	3.46	0.06	99.28	c
	71.34	0.27	13.58	3.58	0.13	0.21	1.30	4.88	3.45	0.06	99.00	c
	69.88	0.27	13.32	3.72	0.14	0.20	1.06	5.07	3.45	0.07	97.35	c
	70.11	0.29	13.17	3.62	0.11	0.19	1.12	4.84	3.45	0.05	97.12	c
	70.97	0.27	13.44	3.46	0.17	0.16	1.37	5.00	3.45	0.04	98.48	c
	70.28	0.34	13.43	3.65	0.12	0.22	1.26	5.19	3.40	0.03	98.08	c
	71.25	0.29	13.52	3.75	0.15	0.20	1.19	5.13	3.48	0.01	99.16	c
	70.36	0.34	13.21	3.81	0.14	0.19	1.24	5.22	3.52	0.03	98.26	c
	68.59	0.27	12.95	3.52	0.10	0.19	1.28	4.81	3.37	0.06	95.33	c
	68.06	0.27	12.91	3.52	0.17	0.18	1.26	4.84	3.37	0.05	94.80	c
	70.42	0.26	13.60	3.50	0.15	0.22	1.78	5.11	3.17	0.00	98.39	c
	70.80	0.27	13.50	3.72	0.07	0.20	1.24	5.18	3.50	0.06	98.71	c
	70.87	0.33	13.47	3.79	0.13	0.20	1.31	5.19	3.47	0.05	99.00	c
	70.20	0.33	13.41	3.39	0.12	0.19	1.24	5.07	3.54	0.01	97.65	c
	70.39	0.28	13.73	3.74	0.12	0.21	1.29	5.26	3.37	0.04	98.64	c
	68.25	0.31	12.72	3.91	0.22	0.18	1.28	5.34	3.32	0.05	95.58	d
	69.86	0.25	13.00	3.49	0.27	0.19	1.34	5.07	3.48	0.02	96.98	d
	69.78	0.27	13.06	3.58	0.22	0.23	1.23	5.34	3.50	0.00	97.20	d
	70.63	0.32	13.27	3.80	0.14	0.18	1.27	5.20	3.49	0.05	98.33	d
	70.81	0.27	13.26	3.65	0.15	0.21	1.32	5.51	3.33	0.00	98.50	d
	71.05	0.28	13.27	4.06	0.14	0.23	1.29	5.18	3.48	0.06	99.04	d
OxT2463	68.60	0.28	13.05	3.83	0.11	0.20	1.23	5.58	3.37	0.04	96.45	e
	67.95	0.27	13.13	3.67	0.18	0.22	1.33	5.32	3.48	0.03	95.78	e
	69.20	0.33	13.28	3.78	0.19	0.22	1.21	5.49	3.49	0.07	97.46	e
	68.12	0.16	12.85	3.28	0.19	0.07	0.90	5.06	3.43	0.02	94.26	e

peat preservation, and a greater distance from anthropogenic activity focus areas. In contrast, samples #2820 and #2821, from an area with higher lithic density and greater archaeological activity, have absolute counts of $\leq$5 shards, barely above background.

4.2. Identification of the tephra

The major and trace elemental data from the cryptotephra samples in Ahrenshöft all point to an Icelandic rhyolitic source, most likely from the Katla volcanic system. This, unfortunately, is not sufficient as the chemical compositional data are not unique. The eruptive event(s) observed here correlate with at least 3 previously identified Katla-sourced ash units. Previous studies (Mangerud et al., 1984; Wastegård et al., 2000; Wastegård, 2002; Davies et al., 2001, 2005; Blockley et al., 2007; Koren et al., 2008; Matthews et al., 2011; Lane et al. in press[c]) indicate the Dimna Ash ($\sim$late Weichselian in age), the rhyolitic portion of the Vedde Ash ($\sim$Younger Dryas), tephra AF555 (late Younger Dryas) and the Suduroy tephra ($\sim$Preboreal/Boreal) all have major element compositions (and in some cases trace element compositions) that are indistinguishable from one another and from the cryptotephra analysed at Ahrenshöft (Fig. 5a).

The Dimna Ash may be excluded as a potential correlate. Horizon 2 at Ahrenshöft LA 58D is not compatible with the lithostratigraphy typically associated with the late Weichselian; furthermore, the stratigraphic position of the cryptotephra deposits

Table 2b
Trace element compositions of cryptotephra sample OxT4156 (112E, 159–160 cm) from single grain LA-ICP-MS. Data are presented as parts per million (ppm). Analytical precision (at 2σ) averages <10% for Rb to Ce and 10–20% for Pr–U. "<LOD" indicates signals below 6σ of the background. Associated secondary standard analyses are reported in Supplementary information Table 2.

	Rb	Sr	Y	Zr	Nb	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Dy	Er	Yb	Lu	Ta	Pb	Th	U
OxT4156	79	154	79	888	121	466	83	180	21	85	20	3	14	15	8	8	1	6	5	11	3
	81	102	70	781	108	583	71	158	18	77	15	<LOD	14	11	7	6	<LOD	5	<LOD	8	2
	85	127	84	947	125	736	91	194	23	90	18	4	17	17	9	8	1	7	7	12	4
	83	126	88	966	129	732	94	206	23	94	20	4	18	18	10	8	1	8	8	12	4
	85	114	76	854	121	655	81	175	21	80	17	4	14	14	7	8	1	6	<LOD	10	4
	86	120	87	952	133	712	90	199	24	90	19	4	16	17	9	9	1	8	7	12	4

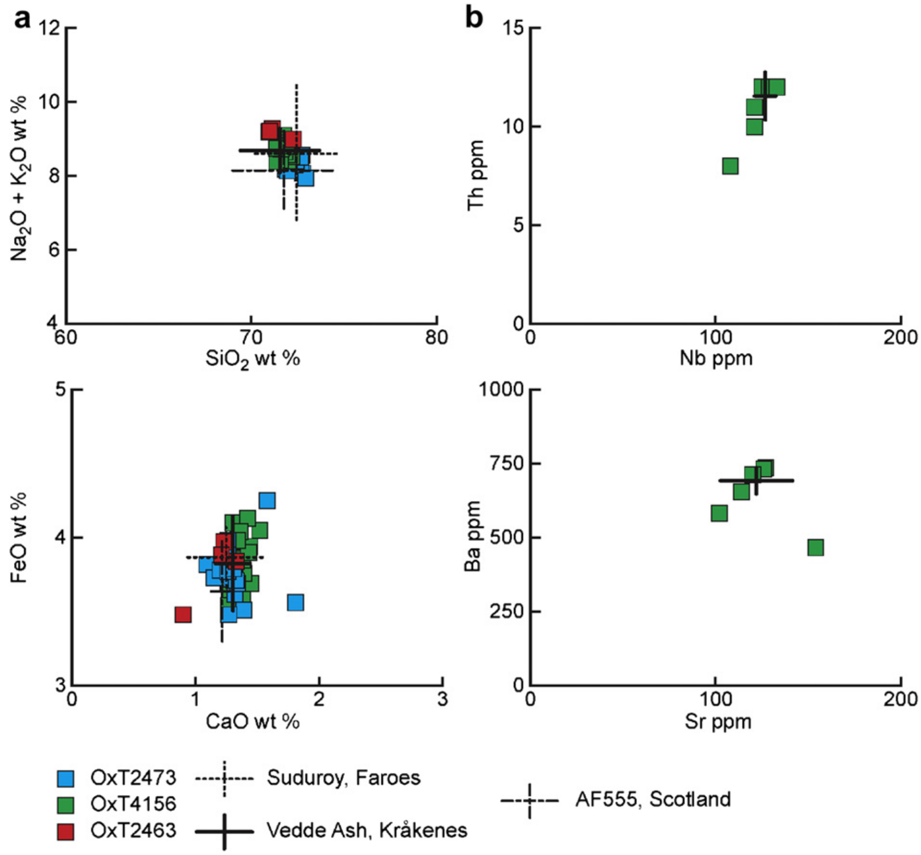

Fig. 5. (a) Major and minor element bi-plots of cryptotephra samples OxT2463, OxT2473 and OxT4156. Also shown are the 2σ compositional ranges for the Suduroy tephra (Wastegård, 2002), tephra AF555 (Matthews et al., 2011) and the rhyolitic fraction of the Vedde Ash from the type site at Kråkenes, Western Norway (Mangerud et al., 1984; Lane et al., in press[c]). All data have been normalised to 100% water-free totals prior to plotting. (b) Selected trace element bi-plots for cryptotephra sample OxT4156, plotted alongside 2σ compositional ranges for the rhyolitic fraction of the Vedde Ash from the type site at Kråkenes, Western Norway (Mangerud et al., 1984; Lane et al., in press[c]).

overlies the Allerød age Horizons 3 and 4 (pollen work of Usinger) precluding ash deposition prior to the Younger Dryas. This leaves the Vedde Ash (12,171 $\pm$ 57 yr b2k, Rasmussen et al., 2006), tephra AF555 (11,200–11,790 cal BP by ^{14}C, Matthews et al., 2011) and the Suduroy tephra (*c*.8160–7880 cal BP by ^{14}C, Wastegård, 2002) as the best candidates.

This study provides the first example of chemical trace element analysis of an Icelandic cryptotephra in an archaeological context. The composition of the cryptotephra at Ahrenshöft matches that of the widespread Vedde Ash (Lane et al., in press[c]). However, with a lack of comparable data on AF555 and the Suduroy tephra, we cannot, at present, use these data to resolve the alternates, nor can we exclude a hitherto unrecognised Katla eruption. Further work on the geochemical composition of these less widely dispersed tephra layers from their type sites may one day hold out the prospect of successful discrimination. In the context of the work at Ahrenshöft such an outcome would be welcomed.

4.3. Radiocarbon age of the tephra in Horizon 2

We believe the degree of contamination of the Ahrenshöft ^{14}C samples is proportional to the number of rootlets/rhizomes penetrating from the soil surface. In the larger sized fraction (>250 μm) we were able to physically remove the intrusive rootlets (albeit not totally) and therefore we contend that this fraction provides the most accurate age estimates (OxA-22716 and OxA-22796). Once calibrated these results give 2σ age ranges of *c*. 7660–7515 and *c*.8400–8200 cal BP for depths 159–160 cm and 164–165 cm, respectively. We therefore interpret 7660–7515 cal years BP (OxA-22716) as a minimum age for the deposition of the cryptotephra within Horizon 2 of

Table 3
AMS ^{14}C ages from Ahrenshöft LA 58D associated with this study. Measurements are on the bulk peat (humin) fraction from monolith #3303, profile 112E. The dates are uncalibrated in radiocarbon years BP (Before Present – AD 1950) using the half life of 5568 years. Isotopic fractionation has been corrected for using the measured δ^{13}C values measured on the AMS. The quoted δ^{13}C values are measured independently on a stable isotope mass spectrometer (to $\pm$0.3 per mil relative to VPDB). Calibration is by IntCal09 (Reimer et al. 2009) and OxCal v4.1 calibration program (Bronk Ramsey, 2009).

Lab code (OxA-)	Layer/depth (cm)	Fraction (μm)	δ^{13}C (‰)	^{14}C age (yr BP) $\pm$ 1σ	Cal BP (2σ)
22714	Horizon 2 with tephra, 159–160	63–125	−28.99	5861 $\pm$ 31	6775–6567
22715	Horizon 2 with tephra, 159–160	125–250	−28.99	6265 $\pm$ 31	7269–7030
22716	Horizon 2 with tephra, 159–160	>250	−27.84	6725 $\pm$ 32	7659–7515
22717	Peat onset, 164–165	63–125	−28.75	6872 $\pm$ 34	7789–7622
22718	Peat onset, 164–165	125–250	−29.11	7060 $\pm$ 35	7963–7828
22796	Peat onset, 164–165	>250	−30.52	7510 $\pm$ 40	8400–8203

Ahrenshöft, which does not resolve which eruption(s) are present at the site. The Vedde Ash, the AF555 tephra and the Suduroy tephra could have been deposited between the end of the Allerød (*c.*12,700 cal BP – laminated sediments in north Germany, Litt et al., 2001) and *c.*7660–7515 cal BP.

5. Conclusions

In this study we show that cryptotephra are present on shallow open-air archaeological sites. Even under adverse conditions as encountered here, low concentration shard peaks may be observed, quantified and chemically analysed. But it is clear that archaeological sites are, in this instance not as good as lakes and peat bogs where tephra layers are commonly well preserved and more abundant. Site taphonomy almost certainly has an important role to play in accounting for these differences, with conditions prevailing at the time of deposition and subsequent to accumulation influencing the degree of intactness.

It is clear from our study that successful tephrochronology sometimes requires good chronological control since chemical compositional data are not always sufficient to resolve temporally-different eruptive events. Complications in the ^{14}C data from Ahrenshöft mean only a very broad age-span (*c.*12.7–7.5 ka cal BP) can be ascribed to Horizon 2 which contained tephra. A clear link to the Icelandic centre of Katla is demonstrated. However, despite trace element analysis and major element chemistry, similarities in elemental composition mean it is not possible to correlate the tephra to one (or possibly more) unique eruption events. The Vedde Ash, AF555 and the Suduroy tephra remain potential correlates, leaving open whether the ash overlying the Havelte phase lithics industry at Ahrenshöft LA 58 D was deposited in the Younger Dryas or the early Holocene.

The study does give general lessons of value to future work on archaeological sites. Site taphonomy is clearly crucial, with local depositional conditions and subsequent processes playing a decisive role in the preservation of useful volcanic event marker horizons. In some instances success will depend on the analysis of multiple profiles. We suggest that the chances of recovering cryptotephra marker horizons should improve on archaeological sites where sampling conditions are more akin to those encountered in palaeoecological research (continuous low energy sedimentation). Where cultural find concentrations are high, sedimentary deposition is intermittent, bioturbation and mixing is likely, the probability of meaningful tephrostratigraphical data diminishes. This has implications for future archaeological sampling in that, with the exception of visible tephra deposits, tephrostratigraphic research may best be concentrated in lower energy sediments marginal to primary archaeological activity areas. In some circumstances neighbouring off-site contexts will be preferable to on-site sampling points, provided good stratigraphic correlation can be established to permit integration with archaeological interpretations.

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Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.jas.2011.11.003.

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