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Discovery of tephra in a Late-glacial and early Holocene organic sediment sequence in Schünsmoor (Niedersachsen, Germany)

Entdeckung von Tephra in einer späteiszeitlichen und frühholozänen organischen Sedimentfolge in Schünsmoor

Rupert A. Housley[a#], Felix Riede[b], Klaus Gerken[c], Holger Niemann[d], Cassian W.F. Bramham-Law[e], Christine S. Lane[e], Victoria L. Cullen[e], and Clive S. Gamble[f]

Schlüsselwörter: *Mikrotephra, Tephrenstratigraphie, Katla, Oldendorf*

Keywords: *Tephrostratigraphy, cryptotephra, Katla, Oldendorf*

Zusammenfassung: *Explosive Vulkanausbrüche produzieren in den meisten Fällen feinkörnigen Auswurf (Tephra) in oft großen Mengen. Je intensiver der Ausbruch, desto höher der Fragmentierungsgrad und damit auch die Feinkörnigkeit des Förderprodukts. Insbesondere die kleinsten Teilchen (< ca. 200µm) können durch atmosphärische Vektoren (Höhenwinde) eine sehr weite Verbreitung erfahren. Aus dem Spätglazial und Holozän sind europaweit unzählige Tephren bekannt, deren Herkunft auf verschiedene Zonen eruptiver Aktivität (z. B. Eifel, Mittelmeer, Massif Central, Jan Mayen und Island) zurückgeführt werden kann. Im östlichen Teil Norddeutschlands dominiert die Vulkanasche des Laacher See Ereignisses (12.920 cal BP) mit einer Verbreitung über Hessen, Südost-Niedersachsen, Brandenburg und Mecklenburg-Vorpommern. In den westlichen Teilen Norddeutschlands sind vor allem isländische Tephren anzutreffen.*

Da der Ausfall feinkörniger vulkanischer Teilchen oft schon während- oder unmittelbar nach dem Ausbruch stattfindet, aus geologischer- und archäologischer Sicht also augenblicklich, bilden sich unter positiven Erhaltungsbedingungen meist ungestörte Marker-Horizonte, so genannte Isochrone aus. Die Isochrone können dann entweder zur relativen- oder absoluten Datierung von Schichtfolgen verwendet werden, je nachdem ob der in Frage kommende Ausbruch selbst absolut datiert ist oder nicht. Das Auffinden identischer Tephrenschichten

a Department of Geography, Royal Holloway, University of London, Egham Hill, Egham, TW20 0EX, UK
b Laboratory for Past Disaster Science, Department of Archaeology - Campus Moesgård, Aarhus University, Moesgård Allé 20, DK-8270 Højbjerg, Denmark
c Gerken-Archäologie, Hohes Ufer 10, 31535 Neustadt, Germany
d Hohenlohestr. 8, 28209 Breman, Germany
e Research Laboratory for Archaeology and History of Art, University of Oxford, Dyson Perrins Building, South Parks Road, Oxford OX1 3QY, UK
f Faculty of Humanities (Archaeology), Building 65A, Avenue Campus, University of Southampton, Southampton SO17 1BF, UK
Corresponding author (Rupert.Housley@rhul.ac.uk)

in mehreren Fundstellen, sowie in unterschiedlichen Archiven (z. B. terrestrische- oder marine Seeablagerungen oder Eisbohrkerne) erlaubt dann eine regionale oder sogar überregionale Korrelation. Dies ermöglicht es dann wiederum die zeitliche und räumliche Dynamik (der so genannte lead-and-lag effect) landschaftlicher- und kultureller Veränderungen in ihrer Gleich- oder Gegenläufigkeit zu untersuchen. Durch die methodischen Weiterentwicklungen der letzten Jahre können nun auch die mit bloßen Auge nicht sichtbaren Crypto- oder Mikrotephrenschichten im Labor identifiziert werden. Archäologen, Palynologen und Geologen nutzen sichtbare Aschelagen schon seit langer Zeit als chronostratigraphische Marker. Die Einbeziehung von Mikrotephren hat diese Methode in ihrer Wirkung stark erweitert. Eine zweifelsfreie Identifizierung einzelner Tephrenvorkommen ist dabei unumgänglich, manchmal aber nur begrenzt möglich. Verschiedene analytische Methoden können zur Bestimmung des geochemischen „Fingerabdrucks" der aufgefundenen Tephrenlagen herangezogen werden, wobei sich die Element- und Spurenelementanalyse mit Hilfe der wellen- längendispersiven Elektronenstrahlmikrosonde derzeit als die zuverlässigste Methode präsentiert.

Im Rahmen der archäologischen Ausgrabungen der spätglazialen und spätmesolithischen Fundstellen Oldendorf FStNr. 52 und 69 wurden im Jahre 2008 Grabungsprofile und im unweit davon gelegenen Schünsmoor Proben für Pollen- und Makrofossilanalysen, sowie für tephrenchronologische Untersuchungen entnommen (Abb. 1 und 2). Die tephrenchronologischen Untersuchungen fanden im Rahmen der fünfjährigen Drittmittelförderung des britischen Natural Environment Research Council (NERC) für das RESET Konsortium (http://c14.arch.ox.ac.uk/reset/) statt.

Obgleich sich die sandigen Sedimente der Fundstelle als tephrenfrei erwiesen haben, gelang es in den Moorsedimenten Glasfetzen zu identifizieren und zu extrahieren (Tabelle 1). Diese mit bloßen Auge nicht zu erkennenden Tephrenvorkommen verteilen sich stratigraphisch multimodal und mehr oder weniger diffus im Übergangsbereich zwischen der Jüngeren Dryas und dem frühen Holozän (Abb. 3). Eine geochemische Zuordnung der Tephrenpartikel mit Hilfe von Elektronenmikrosondeanalyse weist auf einen oder mehrere Ausbrüche des isländischen Katla-Systems hin, wobei die größte geochemische Ähnlichkeit mit der spätglazialen Vedde Ash (ca.12.1 ka cal BP) besteht (siehe Abb. 5 und 6, Tabellen 2a und 2b). Eine solche Ansprache widerspricht allerdings der pollenstratigraphischen Position der Glasfetzen, die eher auf ein Ausfallen vulkanischer Aschen in der ausgehenden Jüngeren Dryas bzw. im frühen Holozän hinweist. Eine solche zeitliche Zuordnung wird zudem durch eine Reihe von AMS-14C Daten unterstützt (Abb. 4 und Tabelle 3). Für die Grenze Pleistozän-Holozän würden sich somit zwei bisher in Norddeutschland noch nicht identifizierte Tephren, mit fast identischer geochemischer Signatur anbieten: Die Abernethy Forest AF555 Tephra (11.79 - 11.20 ka cal BP), die bisher nur in Schottland aufgefunden wurde und die Suðuroy Tephra (ca. 8.0 ka cal BP), die bisher nur auf den Färöer Inseln und aus Nord-Norwegen bekannt ist (Abb. 7 und Tabelle 4). Mit ihrer begrenzten Verbreitung deutet die bisher bekannte Verteilung dieser Aschelagen auf kleinere Ausbrüche hin, deren Auswurffahnen sich eher nach Osten bzw. Nordosten zogen. Im Gegensatz zu anderen tephren- chronologischen Untersuchungen aus Nordwestdeutschland gelang es interessanterweise nicht die frühborealzeitliche Saksunarvatn Tephra (ca. 10.25 ka cal BP) im Schünsmoor zu identifizieren, obwohl Sedimente aus diesem Zeitabschnitt erhalten sind.

Der Ausfall vulkanischer Teilchen ist, wie hochauflösende Analysen im Zuge der Eruption des Eyjafjallajökull aus dem Jahre 2010 gezeigt haben, nicht geographisch einheitlich. Außerdem können kleinräumige taphonomische Faktoren die Erhaltung von Tephra auch innerhalb einzelner Seen oder Moore stark beeinflussen. Das Fehlen bestimmter Tephren im Schünsmoor kann also durchaus durch solche Faktoren erklärt werden. Eine nachhaltige und widerspruchsfreie Interpretation der stratigraphischen Situation des Tephrenbefundes im

Schünsmoor lässt sich derzeit noch nicht geben. Sollten weitere Nachforschungen bestätigen, dass die Abernethy Forest AF555 und/oder die Suðuroy Tephra im Schünsmoor ausfielen, würde dies die Verbreitung dieser Auswurffahnen großräumig erweitern. Zukünftige Untersuchungen im Landkreis Rotenburg (Wümme) oder angrenzenden Gebieten werden dazu beitragen, den Befund von Schünsmoor besser zu verstehen. Obwohl die Untersuchung dieses Moores keine Ascheschichten erbrachte, die sich direkt mit dem archäologischen Befund am Rande des Moores verknüpfen lassen, verspricht die angewendete Methode, besonders im moor- und seereichen Norddeutschland, in Zukunft nachhaltig zu unserem Verständnis der Landschaftsentwicklung und dem Einfluss des vorzeitlichen Menschen auf das Ökosystem beizutragen.

Abstract: *Investigation of an in-filled lake basin in Schünsmoor, Ldkr. Rotenburg (Wümme), northern Germany, reveals the discovery of 'cryptotephra' (non-visible volcanic ash) in biogenic sediments dating to the Late-glacial and early Holocene periods (c.15.4 - 7.5 ka cal BP). Major element geochemistry of glass shards shows the tephra originates in Iceland from the Katla volcanic system. However, uncertainties in the bio-stratigraphic position and dating of the tephra in Schünsmoor mean it is not clear if more than a single tephra is present nor is it possible to correlate confidently to previously documented eruptions. Three potentially relevant correlates are identified: the Vedde Ash (c.12.1 ka cal BP), an eruption documented from many regions of Europe that dates from the Younger Dryas sub-stage; the Abernethy Forest AF555 tephra, previously identified in Scotland with a age of 11.79 - 11.20 ka cal BP; and the c. 8.0 ka cal BP Suðuroy Tephra, first observed in the Faroe Isles. Future tephrostratigraphic investigations may ultimately resolve the ambiguities identified in Schünsmoor, thereby allowing the tephra record to be placed in a wider European context.*

Introduction

'Tephrostratigraphy' is the study of sequences of tephra and associated deposits: their distribution and stratigraphic relationships (superpositions) and their relative and numerical ages (Lowe 2011, Davies 2015). It involves defining, describing, and characterizing ('fingerprinting') tephra layers using their physical, mineralogical, or geochemical properties from field and laboratory-based observations or analyses.

Tephrochronology provide time-parallel markers ('isochrons') that permit environmental records to be synchronised and dated across a range of climate archives. The main methodological assumptions underlying this form of dating are that: (i) tephra horizons are distributed over the landscape instantaneously at least in terms of geological/archaeological time; (ii) tephra horizons can be geochemically characterised and have a distinctive compositional label; (iii) the marker horizons maintain a degree of integrity in the stratigraphy following the depositional event and are not moved substantively up or down the profile (Langdon and Barber 2004).

Although broadly correct, there are instances where the chemical composition is insufficiently distinctive to allow a fully-unique chemical signature to be obtained. In such cases researchers are forced to use other criteria to differentiate eruptive units (e.g. Davies et al. 2004, Matthews et al. 2011). In terms of the tephrochronology of NW Europe, the fact that many tephra originate from Iceland and draw repeatedly on the same magmatic chamber in the same volcanic centre means there is a high chance of non-unique geochemical fingerprints taking place. We report just such an example in this paper, and discuss how such complex tephra occurrences can nonetheless provide novel insights relevant to associated archaeological sites.

The last 30 years have seen several tephrochronological studies in north Germany. In the late Quaternary the region was impacted by tephra originating from sources in Iceland and the Eifel. Studies of the Late-glacial Laacher See eruption (BOGAARD and SCHMINCKE 1984; 1985; BOGAARD 1995; RIEDE et al. 2011), of Holocene Icelandic volcanic marker horizons in raised peat bogs, e.g. Jardelunder Moor, Dosenmoor and Grambower Moor (BOGAARD and SCHMINCKE 2002; BOGAARD et al. 2002); and of tephra in lake basins, e.g. Hämelsee (MERKT et al. 1993) and Endinger Bruch HBG (LANE et al. 2012b), have shown how past atmospheric transport/circulation pathways have carried tephras to northern Germany. Recent work on tephra in archaeological sites in Schleswig-Holstein (HOUSLEY et al. 2012) and Lüchow-Dannenberg (TOLKSDORF et al. 2013; HOUSLEY et al. 2013) indicate the potential to link to past human settlement.

Research Objectives

This study extends the previous research of MERKT et al. (1993) and MERKT and MÜLLER (1999) by making a tephrostratigraphical investigation of a Late-glacial and early Holocene peat and gyttja sequence in Niedersachsen. The aim is to tie an organic sediment sequence into the network of Northern European tephras (DAVIES et al. 2002; TURNEY et al. 2006). The research was undertaken within the context of RESET (http://c14.arch.ox.ac.uk/reset/), a 5-year Consortium research project funded by the UK's Natural Environment Research Council (NERC).

Microscopic tephra concentrations are detected in the laboratory from a pollen-analysed organic sediment sequence and characterised chemically on major elements on single glass shards. The peaks in tephra are traced by chemical composition to an individual volcano. Probable correlates to known eruptions are discussed and compositional similarities noted between temporally discrete events. Although the tephra can be dated broadly to Termination 1 and the Early Holocene (c.13-7.5 ^{14}C ka BP) it is not possible to correlate to a specific eruption within this period.

Study Area and Field Sampling

Study of the organic sequence at Schünsmoor (53° 15' 29" N, 9° 14' 19" E, ~24 m a.s.l.) was undertaken as part of archaeological investigation of Late-glacial and early Holocene lithics scatters in the area around Oldendorf (Gde. Stadt Zeven, Ldkr. Rotenburg/Wümme, northwest Germany; *Figure 1a*). Investigations previously had shown the presence of stone tool assemblages from the Palaeolithic (Federmessergruppen - arch-backed point groups) and late Mesolithic periods (GERKEN 2001a; 2001b; 2009). The archaeological sites in Oldendorf are located on slightly elevated sand ridges, which rise above the surrounding low-lying land. The peat and gyttja sediments at Schünsmoor are situated in the low-lying area located c.350 m west of the archaeological site of Oldendorf FStNr 52/69 (*Figure 1b*). Field sampling in August 2008 gave access to onsite minerogenic and offsite organic sediments. One of the offsite profiles was studied for pollen and micro-charcoal content – the results of which are reported elsewhere (NIEMANN et al. 2010).

Three profiles were sampled, one from Oldendorf FStNr. 52/69 and two from Schünsmoor:

(i) Forty-nine bag samples were taken from the archaeological layers of Oldendorf FStNr. 52 (grid square 51 72 south profile, 0.83-1.46 m depth below site datum) for cryptotephra analysis;

(ii) Three overlapping 30 cm long monolith tins were removed for cryptotephra analysis from a test pit located on the margins of the peat-filled depression in Schünsmoor (0.22-0.97 m depth below ground surface);

Fig. 1a
Map showing the general location of this study and the two localities Schünsmoor and Ahrenshöft.

Abb. 1a
Übersichtskarte des Untersuchungsgebietes mit den im Text diskutierten Lokalitäten Ahrenshöft und Schünsmoor.

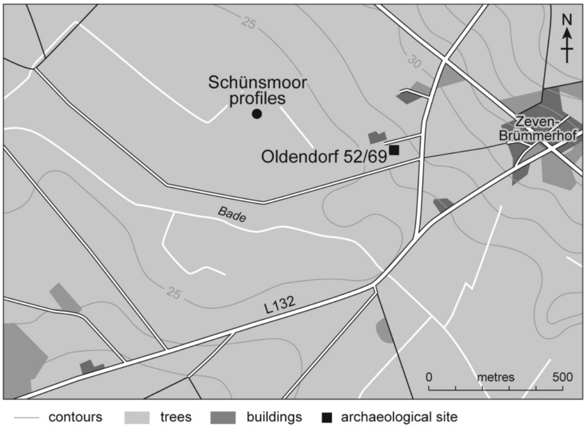

Fig. 1b
Local map showing the relationship of sampling profiles in Schünsmoor to Zeven-Brümmerhof and the archaeological site of Oldendorf FStNr 52/69.

Abb. 1b
Detailkarte mit der räumlichen Zuordnung der Profile Schünsmoor und den Fundstellen Oldendorf 52/69.

(iii) Four overlapping 30 cm monolith tins (R profile) were removed from a second test pit in the centre of the peat-filled depression (total recovery 0.92 m, excluding 0.68 m of surface sedimentation). A further three overlapping 50 cm tins (L profile) were taken by Prof. Hermann Behling of the University of Göttingen from the same test pit (*Figure 2*, total recovery 1.4 m, excluding ~0.4 m of surface sediments). The 50 cm tins were analysed for pollen and micro-charcoal in Göttingen. Subsequently, cryptotephra and ^{14}C analyses were made in the University of Oxford.

Methods

The bag samples from Oldendorf FStNr. 52 were sub-sampled and the monolith tins from Schünsmoor were divided into 10 cm contiguous range-finding sections prior to processing for cryptotephra. Each sub-sample or section was sieved to recover all particles between 80-25 µm. The resulting fraction was extracted using the non-destructive heavy-liquid proce-

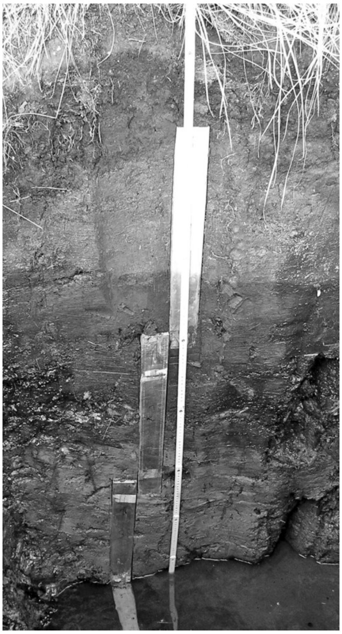

Fig. 2
Cryptotephra sample tins in profile L of the lake centre test pit at Schünsmoor (tin A: 0-50 cm, tin B: 44-94 cm, tin C: 90-140 cm). Note that ~40 cm of upper peat was not sampled. The top 30 cm of peat in tin A was not included in Niemann and colleagues' (2010) study but was analysed for cryptotephra.

Abb. 2
Profilschienen zur Entnahme der Cryptotephrenproben am Profil L im Zentrum des ehemaligen Sees (Schiene A: 0-50 cm, Schiene B: 44-94 cm; Schiene C: 90-140 cm). Die obersten ca. 40 cm des Torfes wurden nicht beprobt. Die obersten 30 cm der Schiene A wurden in der Untersuchung von Niemann und Kollegen (2010) nicht berücksichtigt.

dures of Blockley et al. (2005). Tephra glass shards from the supernatant of the extraction float were identified and counted under high-powered polarizing light microscopy. Where significant numbers of glass shards were recorded in the monolith tins, a second contiguous series of 1 cm-long sub-samples were prepared to precisely define the tephra shard distribution. Identified tephra horizons were re-extracted and prepared for major element geochemical analysis.

The lake centre sediments underwent additional analyses for pollen, micro-charcoal, loss-on-ignition (LOI) and ^{14}C dating. The ^{14}C ages were analysed in the accelerator mass spectrometry (AMS) facility of the Research Laboratory for Archaeology and History of Art, University of Oxford. For details of the chemical pre-treatment, target preparation and AMS measurement see Bronk Ramsey et al. (2002; 2004).

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, however 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). The ATHO-G, StHs6/80-G and KL2-Basalt fused volcanic glass secondary standards from the MPI-DING collection (Jochum et al. 2006) were analysed between and within analytical runs to check for precision and accuracy.

Results

Cryptotephra

Of the three analysed profiles two yielded negligible quantities of tephra: (i) the lake margin test pit at Schünsmoor recorded no tephra; (ii) the archaeological deposits at Oldendorf FStNr. 52 had a single tephra shard from 0.94-105.5 m depth. Such negligible levels mean no further processing is possible from these profiles.

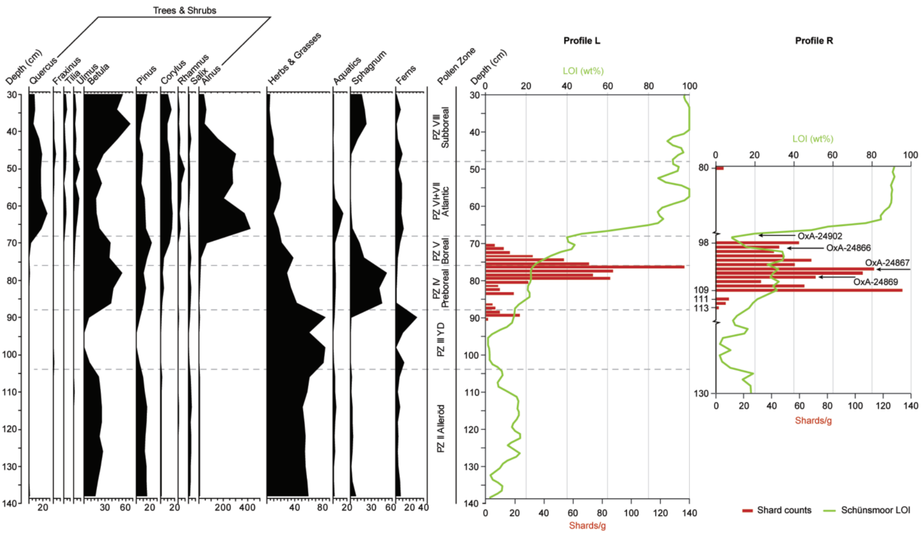

Fig. 3
Glass shard concentrations (per g dry weight) against depth for profiles L and R in the lake centre test pit at Schünsmoor. Displayed are the percentage loss-on-ignition (LOI) curves, selected pollen taxa results and local pollen assemblage zones.

Abb. 3
Glasfetzen-Konzentrationen (Gramm Trockengewicht) der Profile L und R aus dem Zentrum des Schünsmoores, im Vergleich mit den Pollenanalytischen Ergebnissen (nur ausgewählte Arten) und der Glühverlustkurve (LOI, in %).

In contrast the L and R profiles in the lake centre pit at Schünsmoor gave higher counts of cryptotephra. The percentage carbon LOI and shard concentration data (per g dry weight) are presented in *Figure 3*, the recorded lithology is presented in *Table 1*. In profile L the local pollen assemblage zones (LPAZ) as defined by Niemann et al. (2010) marks the chronostratigraphic positioning of the tephra. Lacking pollen data no such positioning is possible in profile R. Nevertheless, the LOI curves permit tentative correlation to be made between the two profiles. The highest concentration of cryptotephra (136 shards g^{-1}, OxT4751) is observed at 76-77 cm depth, coinciding with the Pz IV/V (Preboreal/Boreal) pollen zone boundary. A smaller peak (23 shards g^{-1}, OxT4764) is noted from a stratigraphically lower position, 89-90 cm, located just prior to the end of pollen zone Pz II (Younger Dryas). The morphology of the shards in the two peaks is identical comprising of predominantly colourless fluted to platy forms.

Depth (cm)	Description
0-31	Disturbed peat, wood fragments (13-18 cm)
31-71	Black-brown compressed peat with many rootlets, wood (46-47 cm) and charred wood fragments (66-69 cm)
71-77.5	Dark brown mud gyttja (clayey-silt), with many rootlets
77.5-95	Brown mud gyttja (clayey-silt), with many rootlets throughout and wood fragments (79-86 cm)
95-136	Reddish-brown mud gyttja (clayey-silt), with sand and rootlets (105-113 cm)
136-145	Fine sand (disturbed by groundwater)

Table 1
Lithology of lake centre test pit at Schünsmoor (~40 cm of disturbed peat above datum is not included in the sampling). The pollen and micro-charcoal study focused on the sequence from 31 to 139 cm in profile L.

Tab. 1
Lithologie des Profils im Zentrum des Schünsmoores. Die obersten ca. 40 cm Torf sind vermutlich rezent gestört und daher nicht beprobt worden. Die palynologischen Untersuchungen und Mikroholzkohlestudien beschränkten sich auf den Bereich zwischen 31 und 139 cm im Profil L.

Analysis stub	SiO_2	TiO_2	Al_2O_3	FeOt	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cl	Total	Std batch
OxT4764_1	71.538	0.307	13.640	3.692	0.173	0.198	1.289	4.961	3.453	0.034	0.185	99.470	(a)
OxT4764_2	66.720	0.346	13.219	3.770	0.174	0.264	1.387	4.485	3.176	0.072	0.272	93.884	(a)
OxT4764_6	69.216	0.275	13.345	3.602	0.201	0.154	1.242	5.014	3.346	0.056	0.185	96.634	(a)
OxT4764_7	68.531	0.276	13.324	3.622	0.088	0.193	1.334	4.870	3.281	0.039	0.223	95.781	(a)
OxT4764_8	65.138	0.227	12.568	3.520	0.125	0.165	1.224	5.052	3.241	0.035	0.309	91.603	(a)
OxT4751_1	69.328	0.310	13.109	3.817	0.153	0.175	1.306	5.215	3.379	0.019	n.a.	96.809	(b)
OxT4751_3	67.304	0.173	12.296	3.432	0.168	0.042	0.989	5.183	3.330	0.004	n.a.	92.918	(b)
OxT4751_6	69.076	0.288	13.388	3.509	0.262	0.192	1.279	5.213	3.247	0.033	n.a.	96.487	(b)
4751_1A_1	69.956	0.295	13.277	3.666	0.179	0.208	1.257	5.096	3.328	0.056	n.a.	97.316	(c)
4751_2A_1	71.047	0.252	13.530	4.005	0.096	0.187	1.321	5.282	3.466	0.061	n.a.	99.245	(c)
4751_2A_2	70.964	0.280	13.552	3.879	0.126	0.192	1.333	5.201	3.468	0.065	n.a.	99.060	(c)
4751_5A_1	71.225	0.270	13.669	3.906	0.100	0.171	1.307	5.495	3.311	0.031	n.a.	99.485	(c)

Table 2a
Major and minor element data, from WDS-EPMA, for cryptotephra samples: OxT4751 (76-77 cm) and OxT4764 (89-90 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.
For secondary glass analyses listed in the "Std batch" column, see *table 2b*.

Tab. 2a
Element- und Spurenelementdaten der wellenlängendispersiven Elektronenstrahlmikroanalyse für die Proben OxT4751 (76-77 cm) und OxT4764 (89-90 cm). Die Daten sind als nicht normalisierte Gewichtsprozente (Gew.-%) angegeben (n.a.= nicht analysiert). Die Genauigkeit der Analyse wurde laufend gegen gängige Standards getestet und liegt bei <1 bis <10 % (2σ) für die Elementanalyse, sowie bei 10-40 % (2σ) für die Spurenelementanalyse.
Die Ergebnisse der Standardanalysen sind in *Tabelle 2b* wiedergegeben.

Batch	Standard		SiO_2	TiO_2	Al_2O_3	FeOt	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cl	Total
(a)	ATHO-G	(n=10)	74.78	0.25	12.20	3.28	0.10	0.10	1.66	4.18	2.70	0.03	0.03	99.30
(a)		2σ	0.60	0.07	0.18	0.21	0.06	0.02	0.07	0.22	0.12	0.03	0.03	
(a)	StHs6/80-G	(n=9)	63.44	0.70	17.61	4.35	0.08	1.98	5.30	4.33	1.29	0.15	0.01	99.24
(a)		2σ	0.50	0.05	0.33	0.31	0.08	0.10	0.12	1.07	0.07	0.03	0.03	
(b)	ATHO-G	(n=9)	74.82	0.23	12.14	3.29	0.12	0.10	1.74	4.02	2.68	0.03	n.a.	99.16
(b)		2σ	1.10	0.05	0.22	0.32	0.09	0.02	0.07	0.18	0.10	0.04	n.a.	
(b)	StHs6/80-G	(n=10)	63.35	0.70	17.64	4.42	0.06	1.95	5.25	4.44	1.30	0.18	n.a.	99.28
(b)		2σ	0.58	0.09	0.17	0.26	0.08	0.07	0.14	0.33	0.07	0.03	n.a.	
(c)	ATHO-G	(n=4)	75.48	0.23	12.33	3.26	0.10	0.09	1.75	4.00	2.69	0.02	0.05	99.91
(c)		2σ	0.30	0.05	0.24	0.14	0.11	0.03	0.07	0.29	0.03	0.02	0.02	
(c)	KL2-BASALT	(n=2)	50.37	2.63	13.62	10.63	0.23	7.52	11.01	2.08	0.47	0.27	0.02	98.52
(c)		2σ	0.21	0.17	0.11	0.61	0.08	0.07	0.07	0.47	0.01	0.06	0.01	
(c)	StHs6/80-G	(n=4)	63.60	0.74	17.82	4.38	0.08	2.05	5.34	4.55	1.30	0.15	0.02	99.85
(c)		2σ	0.71	0.08	0.22	0.18	0.04	0.05	0.08	0.38	0.09	0.03	0.03	

Preferred Values

Standard		SiO_2	TiO_2	Al_2O_3	FeOt	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
ATHO-G		**75.6**	**0.255**	**12.2**	**3.27**	**0.106**	**0.103**	**1.7**	**3.75**	**2.64**	**0.025**
	95% cl	0.7	0.016	0.2	0.1	0.005	0.01	0.03	0.31	0.09	0.004
KL2-BASALT		**50.3**	**2.56**	**13.3**	**10.7**	**0.165**	**7.34**	**10.9**	**2.35**	**0.48**	**n.a.**
	95% cl	0.6	0.18	0.4	0.2	0.018	0.18	0.4	0.16	0.02	n.a.
StHs6/80-G		**63.70**	**0.703**	**17.8**	**4.37**	**0.076**	**1.97**	**5.28**	**4.44**	**1.29**	**0.164**
	95% cl	0.50	0.021	0.2	0.07	0.004	0.04	0.09	0.14	0.02	0.018

Table 2b

Associated secondary standard glass analyses for the batches listed in the "Std batch" column of table 2a. Quoted preferred values for the standards are from Jochum et al. (2006).

Tab. 2b

Daten der parallel zur Cryptotephrenanalyse durchgeführten Glasstandardanalysen.

Glass shards from both peaks in profile L (76-77 and 89-90 cm) were selected for major element analysis. A total of 7 (OxT4751) and 5 (OxT4764) analysis points were obtained (*Table 2a*). These show that both peaks have indistinguishable major element chemistry of rhyolite composition. The analyses point to an origin in a volcanic centre of Iceland.

The LOI curves allow a comparison of the tephra distributions in profiles L and R. Although some similarities are evident (both have smaller lower and larger upper peaks of tephra) differences in relative concentration are observable. Given observations made elsewhere (Riede and Thastrup 2013) we believe small stratigraphic or taphonomic variations over no more than metres may be responsible for the observed differences in the field. Whilst the general pattern is identifiable, a cautious approach to inter-profile correlation has been adopted on account of such discrepant patterning.

Radiocarbon dating

Radiocarbon samples were taken from both lake centre profiles (*Table 3*). Five samples (Betula plant macrofossils) from profile L give AMS ^{14}C ages that disagree significantly with the expected chronostratigraphy based on the pollen analyses. The mid Holocene ages (c. 6500 and 5750 yr cal BP) are much younger than the pollen assemblages would imply. The δ13C values, carbon yields and age-depth profile were examined but none reveal obvious analytical problems. To account for this discrepancy some form of contamination is needed, although a precise explanation for this anomaly remains unclear.

Four paired radiocarbon samples (8 measurements on humin and humic fractions) were measured from profile R. The two age pairs from the upper sequence (depths: 97-98 and 99-100 cm) give overlapping age ranges when the different dating fractions are compared;

					Unmodelled Ages		Modelled Ages
Lab code (OxA-)	**Profile**	**Material / depth / fraction (cm)**	**Pollen zone horizon**	**$\delta^{13}C$ (‰)**	**^{14}C age (yr BP) ± 1σ**	**Cal BP (2σ)**	**Cal BP (2σ)**
23606	L	*Betula* plant remains, tin B, 67-68.5 cm	PZ V/VI+VII boundary	-28.16	5074 ± 30	5910-5745 ∫	-
23607	L	*Betula* plant remains, tin B, 76-77 cm; peak in tephra shards	PZ IV/V boundary	-27.93	5525 ± 32	6400-6280 ∫	-
23608	L	*Betula* plant remains, tin B, 87-89 cm	PZ III/IV boundary	-28.84	5596 ± 32	6440-6305 ∫	-
23609	L	*Betula* plant remains, tin C, 103-105 cm	PZ II/III boundary	-28.63	5594 ± 32	6440-6305 ∫	-
23582	L	*Betula* plant remains, tin C, 137-139 cm	Base of zone PZ II	-28.26	5623 ± 37	6480-6310 ∫	-
24903	R	Bulk peat, tin 2, 97-98 cm, humin	-	-27.46	6840 ± 45	7785-7590	-
24902	R	Bulk peat, tin 2, 97-98 cm, humic	-	-27.82	6750 ± 40	7675-7520	7675-7520
24904	R	Bulk peat, tin 2, 99-100 cm, humin	-	-27.11	9005 ± 45	10,245-9935	-
24866	R	Bulk peat, tin 2, 99-100 cm, humic	-	-27.00	8970 ± 40	10,230-9920	10,230-9920
24868	R	Bulk peat, tin 2, 104-105 cm, humin	-	-27.34	10,885 ± 45	12,910-12,625 ∫	-
24867	R	Bulk peat, tin 2, 104-105 cm, humic	-	-27.55	10,175 ± 40	12,040-11,705	11,950-11,620
24870	R	Bulk peat, tin 2, 106-107 cm, humin	-	-23.71	11,415 ± 45	13,400-13,155 ∫	-
24869	R	Bulk peat, tin 2, 106-107 cm, humic	-	-26.68	10,110 ± 40	11,975-11,405	12,015-11,705

Table 3
AMS ^{14}C age determinations on plant material from the lake centre test pit at Schünsmoor. 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 with the measured δ13C values. The quoted δ13C values are measured independently on a stable isotope mass spectrometer (to ±0.3 per mil relative to VPDB). Calibration is by IntCal09 (Reimer et al. 2009) and OxCal v.4.2.2 calibration program (Bronk Ramsey 2009). ∫= anomalous age determinations, see text.

Tab. 3
AMS-^{14}C Datierungen von Pflanzenresten aus der Mitte des Schünsmoor. Die Datierungen sind unkalibriert (BP vor 1950), kalibriert (mit OxCal v.4.2.2.2 und IntCal09) und modelliert (mit OxCal v.4.2.2.2.) angegeben. Das nicht kalibrierte Alter wurde mit einer Halbwertzeit von 5568 Jahren errechnet. δ13C wurde unabhängig mit einem Massenspektrometer gemessen.

however the two age pairs from lower in the profile (104-105 and 106-107 cm) yield discordant age ranges. Lacking control from pollen it is not easy to resolve the alternate fractions. Related studies (Shore et al, 1995/ Brock et al. 2011) have demonstrated the difficulty in resolving if the age of one peat fraction is more reliable than another. This is further discussed below.

Discussion

The major elemental data from Schünsmoor indicate the presence of at least one rhyolite tephra from Iceland. The most likely centre of origin is the volcano of Katla thereby ruling out a series of late Late Glacial/early Holocene tephras derived from other volcanic centres in Iceland (cf. Lind et al. 2013). However the chemical composition is not sufficiently unique to correlate to a single eruption; at least seven previously identified Katla-sourced ash units are compatible with these analyses (*Table 4*). The correlate list may be reduced if the dating evidence from Schünsmoor profile R is factored in. An age model based on the humic acid fraction is presented in *Figure 4*. In this example the humic acid fraction is clearly more reliable since the pollen data show the tephra cannot be older than Pz III (Younger Dryas sub-stage). From this the two earlier humin ^{14}C determinations (OxA-24868 and 24870) can be dismissed as anomalously old suggesting that the deposition date of the tephra in Schünsmoor is c.7.5-12.0 ka cal BP. In addition, since there is no evidence that the NGRIP 1508.26 m rhyolite was dispersed south-east from Iceland, it may be excluded. Only three potential correlates remain: the rhyolitic portion of the Vedde Ash, the Abernethy Forest AF555 and the Suðuroy tephra.

Tephra Layer	Zone or sub-stage	Age (ka cal BP)	Dating reference	Chemical composition reference(s)
Suðuroy	Early Holocene	~8.0	Wastegård, 2002	Wastegård, 2002; Pilcher *et al*., 2005
Abernethy Forest AF555	Late GS-1	~11.79-11.20	Matthews *et al*., 2011	Matthews *et al*., 2011
Vedde Ash (rhyolite)	Mid GS-1	~12.07	Rasmussen *et al*., 2006	Blockley *et al*., 2007; Davies *et al*., 2001; 2005; Mangerud *et al*., 1984; Wastegård *et al*., 2000; Lane et al., 2012a & b
NGRIP 1508.26 m	Early-Mid GS-1	>12.1	Mortensen *et al*., 2005	Mortensen *et al*., 2005
IA2	GI-1	~12.8-14.7	Bond *et al*., 2001	Bond *et al*., 2001
R1	GS-2	>15.1	Thornalley *et al*., 2011	Thornalley *et al*., 2011
Dimna Ash	GS-2	>15.1	Koren *et al*. 2008	Koren *et al*. 2008

Table 4
Previously documented tephra layers with similar major and minor elemental chemistry to the tephra discovered in Schünsmoor. On the basis of the dating evidence in this study only the younger three tephras are relevant potential correlates.

Tab. 4
Bisher dokumentierte Eruptionsereignisse bzw. Aschelagen die den Proben aus dem Schünsmoor geochemisch ähnlich sind. Auf Grund der stratigraphischen Lage des dortigen Tephrenvorkommens bieten sich prinzipiell nur die drei jüngeren Tephren zur Korrelation an.

Closer examination of the geochemistry would favour correlation of the Schünsmoor crytotephra to the Vedde Ash (*Figures 5 and 6*). However the biostratigraphic context of the peaks could argue an opposing point of view. OxT4751 lies on the boundary between the Preboreal and Boreal whilst OxT4764 is situated close to the end of the Younger Dryas Stadial. Based on this positioning OxT4751 correlates best to the Suðuroy tephra, dated by Wastegård (2002) to 7.88-8.16 cal ka BP. The smaller lower peak, OxT4764, would correlate with the Abernethy Forest tephra AF555 for which Matthews et al. (2011) dated to 11.20-11.79 cal ka BP. Tephra can move considerable vertical distances within a given stratigraphy and even form secondary concentrations that mimic true layers (Beierle/Bond 2002). Our dating is insufficiently precise to resolve these opposing positions: biostratigraphic context and geochemical composition appears to be divergent and so we favour leaving the interpretation open. Tephra from one, or two, of these eruptions of Katla is most likely present in Schünsmoor, but precisely which cannot currently be resolved.

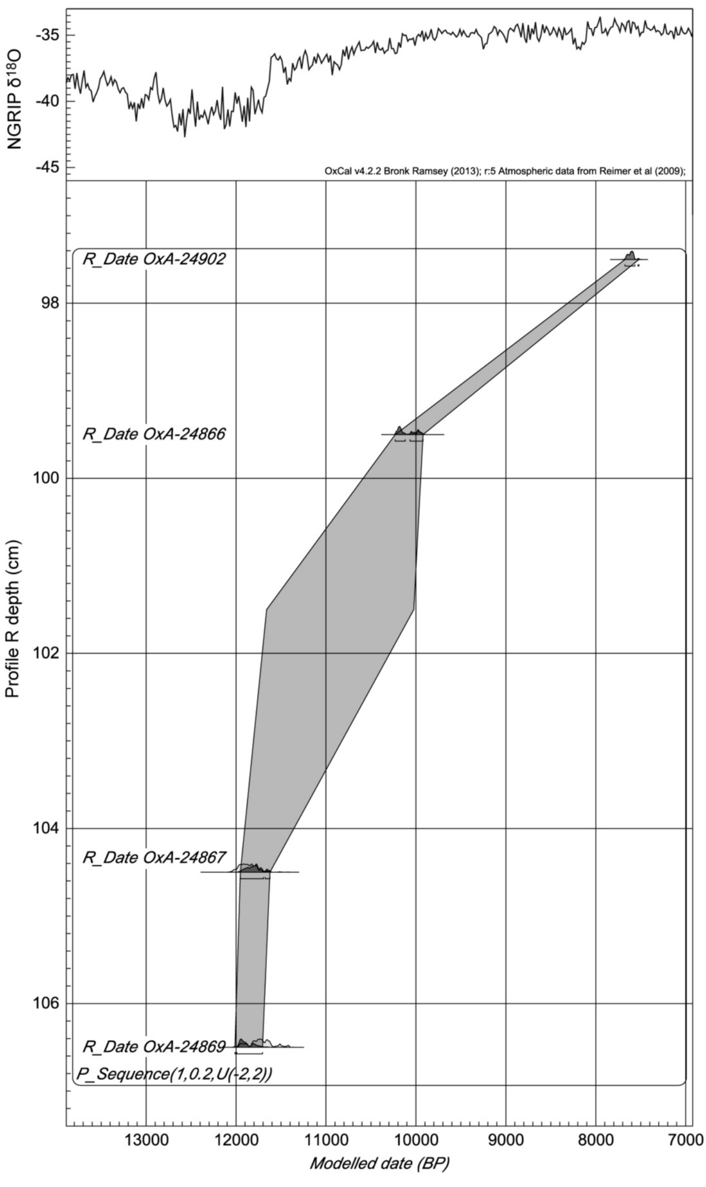

Fig. 4
Age model for Schünsmoor lake centre profile R based on the humic acid fraction determinations. The age model was generated using the 'P_Sequence' function (Bronk Ramsey 2008) in OxCal v.4.2.2 (Bronk Ramsey 2009) and the IntCal09 calibration curve (Reimer et al. 2009).

Abb. 4
Alters-Tiefen Model des Profils R Schünsmoor, erstellt mit dem Programmen OxCal v.4.2.2.2 und der InCal09 Kalibrierungskurve.

Conclusions

Tephrochronological research at Schünsmoor has identified three candidate eruptions that deposited their airfall tephra at this site in northern Germany. Of these the Vedde Ash has been reported in many areas of Europe (Blockley et al. 2007; Davies et al. 2001; 2005; Mangerud et al. 1984; Wastegård et al. 2000; Lane et al. 2012a & b and references therein). The presence of this tephra at Schünsmoor would not significantly alter our existing understanding of the geographical patterning of this eruption, although each additional data-point does improve our understanding of past transport dynamics and eruption volume. The detailed tracking of tephra clouds and deposition of the 2010 Eyjafjallajökull eruption has provided key insights into the complex ways in which such clouds move (Davies et al. 2010). The reporting of even well-known past tephras is therefore not trivial as each additional data-point allows a more fine-grained and thus more realistic picture of past airfall distributions. Such mapping exercises in turn provide important information on eruption volume and dynamics, and function as useful research tools for designing future tephrochronological projects. Likewise, it is also important to note the absence of other important and widespread early Holocene tephras at Schünsmoor. A number of localities in north-western Germany, at least one of which (Eversner See) not far from the Schünsmoor have, for instance, yielded clear evidence of the Saksunarvatn tephra (Merkt et al. 1993). As accurate mapping is an important part of tephrochronological studies, the reporting of both presence and absence of particular tephras is arguably an important part of studies such as the present (see also Riede et al. 2011, Riede/Thastrup 2013).

In contrast to the Vedde Ash, neither the Abernethy Forest AF555 nor the Suðuroy tephra have been reported outside lands bordering the NE Atlantic Ocean and so subsequent identification of one of these tephras would be of more significance, extending the known ash-fall footprints to mainland Europe (*Figure 7*). Future study will, however, be needed to resolve this picture. The tephrochronological investigations at Schünsmoor have, unfortunately, not yielded dating results relevant to the nearby archaeology. Housley et al. (2012) reported a very similar outcome to a crypotephra study of Ahrenshöft LA58 D, an open-air Havelte archaeological site in Schleswig Holstein. Again the tephra originated from Katla and the three contenders were the same eruptions proposed here. Other sites in north Germany are likely to have a similar record and a better preserved locality should permit resolution of which eruption (or eruptions) are represented. Once the regional picture is clarified, further tephrostratigraphic studies have the potential to link to an important regional marker horizon. Yet, the fact that an increasing number of especially quite shallow peat/open-air sites on the North European Plain have yielded Younger Dryas/early Holocene tephras in stratigraphically reworked positions may in itself provide clues to the depositional histories of these sites. Seen through the lens of geomorphology, such non-discrete layers nonetheless speak about the instability of landscapes and lakes at this time of major climatic and environmental transition. This instability may, in turn, have has an impact on the way that people used these landscapes at this time. As Dugmore/Newton (2012, 50) have recently noted "geomorphological, palaeoenvironmental and archaeological applications…require engagement with poorly developed tephra sequences, complex stratigraphies, isochrons, time transgressive horizons and the consideration of a wide range of deposits. When this is done, it can illustrate the power of tephrochronology, even in less than ideal settings". The Schünsmoor study represents just such a less than ideal setting and, although immediately disappointing, brings us closer to a better overarching understanding of the depositional contexts and significance of tephra within and across disciplines.

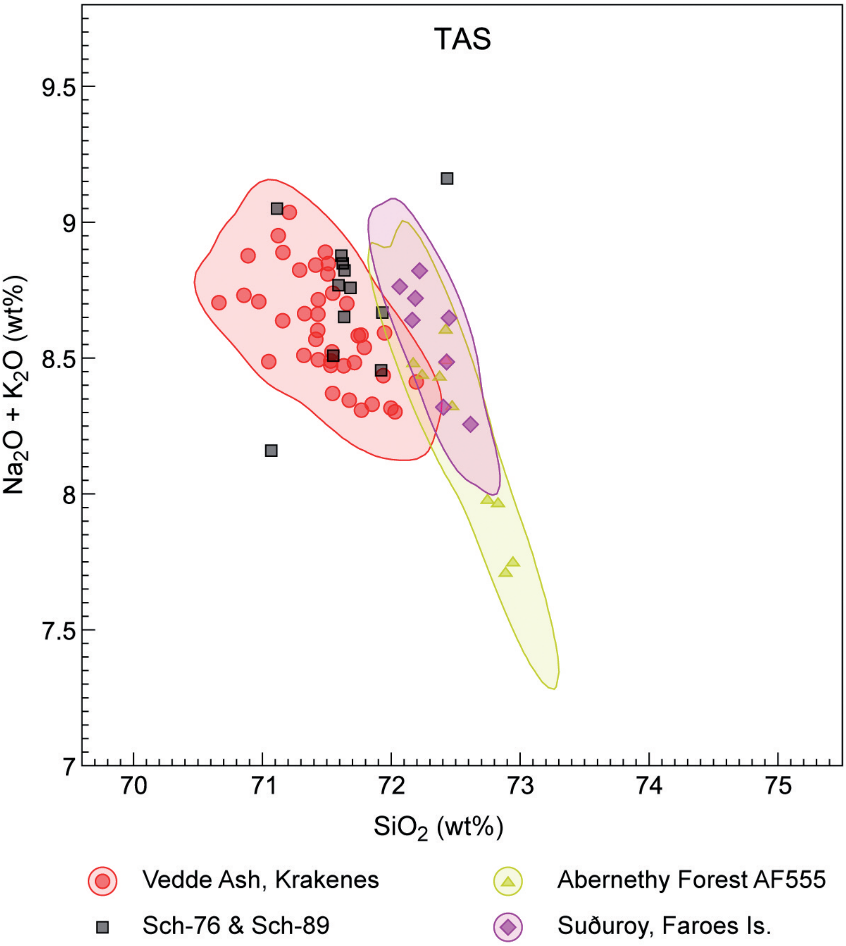

Fig. 5
WDS-EPMA major and minor element TAS plot (Total Alkali-Silica: LE BAS et al. 1986; normalised wt% oxide water-free totals). Included are data for Sch-76 (OxT4751) and Sch-89 (OxT4764) together with comparative data for the rhyolitic component of the Vedde Ash (KRÅKENES, Western Norway; LANE et al. 2012a), the Abernethy Forest AF555 tephra (Scotland, UK; MATTHEWS et al. 2011) and the Suðuroy tephra (Faroe Islands; WASTEGÅRD et al. 2002).

Abb. 5
Element- und Spurenelementdaten der wellenlängendispersiven Elektronenstrahlmikroanalyse. Dargestellt in einem TAS-Diagramm (Total Alkali vs. Silica), welches zur Klassifikation von Ergussgesteinen genutzt wird. Abgebildet sind die Ergebnisse für Sch-76 (OxT4751) und Sch-89 (OxT4764) zusammen mit den Vergleichswerten der felsischen Anteile der Vedde Ash (KRÅKENES, West-Norwegen), der Abernethy Forest AF555 Tephra (Schottland) und der Suðuroy Tephra (Färöer Inseln).

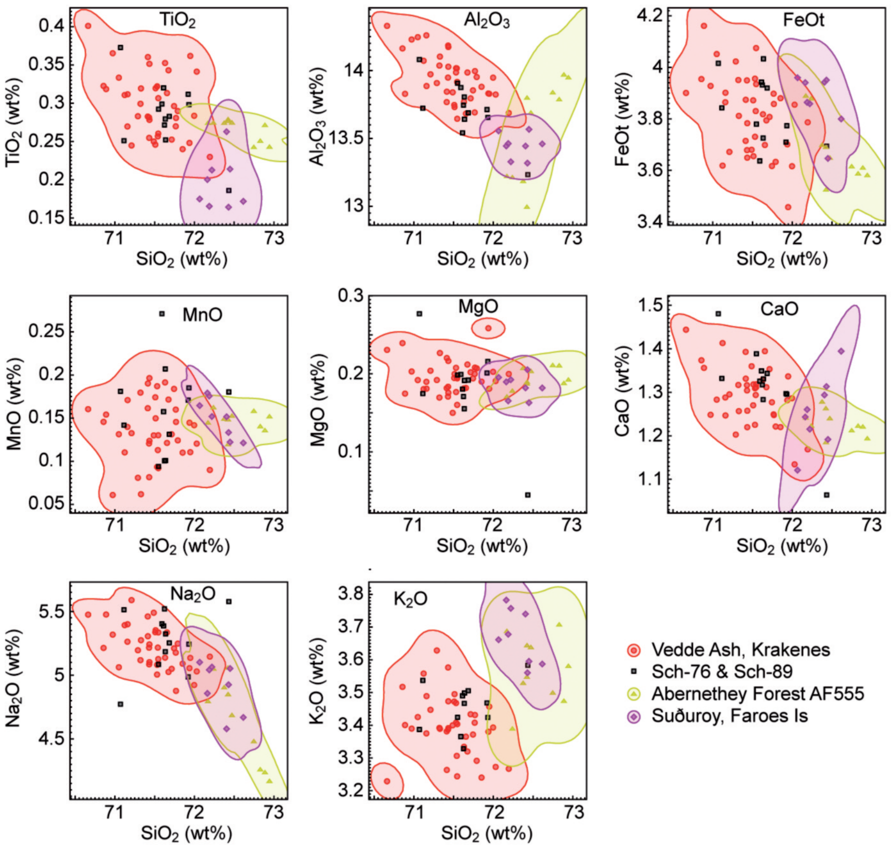

Fig. 6
WDS-EPMA major and minor element bi-plots for Schünsmoor (normalised wt% oxide water-free totals). The figure presents TiO2, Al2O3, FeOt, MnO, MgO, CaO, Na2O and K2O against SiO2. The bi-plots use the same data as Figure 5.

Abb. 6
Multiple Element- und Spurenelementkombinationen der Proben aus dem Schünsmoor: TiO2, Al2O3, FeOt, MnO, MgO, CaO, Na2O und K2O im Vergleich mit SiO2.

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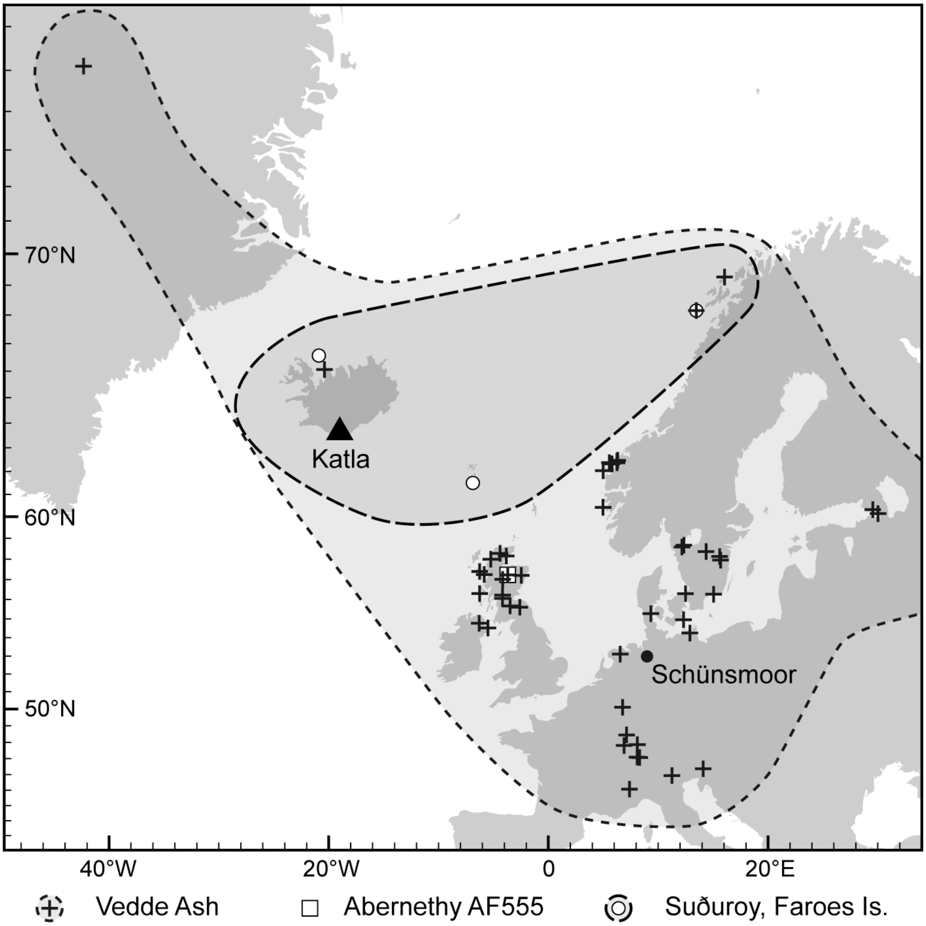

Figure 7
Map of ash footprints for the possible eruptions represented by the tephra layer in Schünsmoor (Vedde Ash: LANE et al. 2012a and references therein; Suðuroy: KRISTJANSDOTTIR et al. 2007, PILCHER et al. 2005, WASTEGÅRD et al. 2002; Abernethy Forest AF555: MATTHEWS et al. 2011).

Abb. 7
Karte der momentan bekannten Ablagerungsrelikte, die den drei möglichen im Schünsmoor identifizierten Eruptionen zugeordnet werden können.

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