Small shards and long distances — three cryptotephra layers from the Nahe palaeolake including the first discovery of Laacher See Tephra in Schleswig-Holstein (Germany)

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ABSTRACT: Investigations of Lateglacial to Early Holocene lake sediments from the Nahe palaeolake (northern Germany) provided a high-resolution palynological record. To increase the temporal resolution of the record a targeted search for cryptotephra was carried out on the basis of pollen stratigraphy. Three cryptotephra horizons were detected and geochemically identified as G10ka series tephra (a Saksunarvatn Ash), Vedde Ash and Laacher See Tephra. Here we present the first geochemically confirmed finding of the ash from the Laacher See Eruption in Schleswig-Holstein—extending the so far detected fallout fan of the eruption further to the north-west. These finds enable direct stratigraphical correlations and underline the potential of the site for further investigations.

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KEYWORDS: cryptotephra; Laacher See Tephra; Saksunarvatn Ash; Vedde Ash

Introduction

Schleswig-Holstein, the northernmost German federal state, holds a key position in palaeo-environmental as well as archaeological research of the Lateglacial and Early Holocene. This is due to the fact that the region provided a north-facing corridor after the retreat of the glaciers. Despite numerous palaeo-environmental investigations (Krüger et al. 2020 and literature cited therein), a correlation of the individual records is difficult because age modelling is mainly missing, or because of hiatuses (Usinger 1981). The analyses of sediment cores from the Nahe palaeolake (NAH; Dreibrödt et al. 2020; Krüger et al. 2020) fill a gap in Lateglacial/Early Holocene palaeo-environmental research in Schleswig-Holstein. For the first time a complete Lateglacial to Early Holocene sequence is described without being affected by the Allerød-Younger Dryas hiatus that had been documented for numerous lake sediments in northern Germany and Denmark (Krüger and Damrath 2019; Bennike et al. 2004; Usinger 1981). Furthermore, a sequence of the sediment is annually laminated, allowing for a high resolution of the temporal scale (Dreibrödt et al. 2020). Therefore, an attempt was made to identify tephra layers as additional chronological horizons to supplement radiocarbon dating of macrofossils, as volcanic ash layers mainly represent single events. This would, moreover, provide the opportunity to directly correlate the record with important European key sites of Lateglacial–Early Holocene research. However, while recording and describing the NAH sediment sequence, no visible ash horizons could be detected.

The advancements in search techniques for non-visible volcanic ash beds, or cryptotephra, have widened the possibilities of searching for additional chronological markers in sediment archives (Blockley et al. 2005; Lowe and Hunt 2001; Turney 1998; Turney et al. 2004). In this way the detection of non-visible tephra horizons has been extended to further distal sites throughout Europe (Blockley et al. 2007; Bramham-Law et al. 2013; Hallidayson et al. 2018; Lane et al. 2012b; Larsson and Wastegård 2018; Wastegård and Boygle 2012; Wastegård et al. 2000; Wulf et al. 2013). Palaeo-environmental studies provide the possibility of combining specific tephra horizons with pollen stratigraphy. Conversely, this implies that pollen stratigraphy can be used to locate the position of non-visible ash beds in sediment sequences. To successively increase the temporal resolution of the NAH sediment record a targeted search for well-dated cryptotephra horizons was performed based on their expected position in pollen stratigraphy. We aimed at searching for cryptotephra of the Vedde Ash (VA) and Laacher See Tephra (LST). Apparently, the Saksunarvatn Ash (SA) is the product of a series of eruptions in the Grimsvötn system and hence, does not represent one fixed event date (Davies et al. 2012; Harning et al. 2018; Óladóttir et al. 2020). However, this study also attempts to identify the SAG10ka series tephra at least as an event interval (Óladóttir et al. 2020).

The SA was erupted in the Grimsvötn volcanic system in the Eastern Volcanic Zone on Iceland. The ash has been described from numerous sites in Northern Europe from Iceland, the British Isles, Norway, the Faroe Islands, Greenland and the North Atlantic (Birks et al. 1996; Björck et al. 1992; Grönvold et al. 1995; Harning et al. 2018; Mangerud et al. 1984; Timms et al. 2017). In Germany, the ash has been recorded at Pottermoor Moor in Mecklenburg Western Pomerania (Bramham-Law et al. 2013) and in Schleswig-Holstein at two locations 30 and 50 km north-east of the Nahe palaeolake, Lake Plüßsee and Lake Muggesfeld (Merkt et al. 1993). Furthermore, the visual evaluation of thin sections from Lake Belau revealed brownish cryptotephra shards that have been assigned to the G10ka series tephra on the basis of their morphology (pers. com. W. Dörfler). Most recently, Saksunarvatn

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tephra has also been discovered in a sediment sequence from Lake Poggensee (Zanon et al. 2019; Fig. 1).

The only known location at which the VA has been detected in Schleswig-Holstein is the site of Ahrensbüttel. Here, the cryptotephra has been found in two sediment profiles embedded in an archaeological context (Housley et al. 2012). Nevertheless, the tephra has not been found in the chronologically well-secured context of a lake sediment sequence. As the Nahe palaeolake is situated within the known fallout zone of the VA, as suggested by Bramham-Law et al. (2013), Davies et al. (2012) and Wulf et al. (2016), this ash was suspected to be preserved in sediments from there.

The most prominent Lateglacial volcanic eruption in central Europe was the eruption of the Laacher See Volcano in western Germany. Dated to 12 880 ± 40 varve w (Brauer et al. 1999), ash was distributed over wide areas of central Europe. Laacher See Tephra has been documented at more than 400 sites, extending from the Alps and central France to Bornholm and Poland (Bronk Ramsey et al. 2015; Riede 2016; Riede et al. 2011; Turney et al. 2006; van den Bogaard and Schmincke 1984). The LST, however, has so far not been identified in Schleswig-Holstein, which is outside the known and documented visible fallout lobes.

The aims of this study were:

1. to detect cryptotephra horizons in NAH sediment cores based on their expected occurrence in pollen stratigraphy;
2. to geochemically fingerprint the tephra layers;
3. to gain additional chronological tie-points for the age–depth model of the NAH record;
4. to underline the potential of future research into NAH sediments regarding cryptotephra layer identification.

Study site

The NAH is located in Schleswig-Holstein about 30 km north of Hamburg (Germany). The basin of the former lake was part of a larger glacial lake system and is separated from further elongated incised lakes by two narrow sand ridges to the north-west and south-east (Smed 1998; Woldstedt 1935, 1954). To the south-east, Lake Itzstedt is the water-bearing remnant of the lake system.

The size of the palaeolake surface was about 16 ha during the Lateglacial (Fig. 1). The terrestrialisation process was completed in the course of the late Holocene. Today, the river Rönne flows in the centre of the still existing depression and thereby follows the course of the former lake in a north-westerly direction before turning southwards and draining off into the river Alster. The area is today used as pasture and partly forested by alder, birch and willow. The coring location is situated in the formerly deepest part of the incised lake (53° 48.711’ N, 10° 8.082’ E).

At the coring location approximately 1.6 m of fen peat overlie a sequence of 12.2 m of predominantly detrital gyttja. The shift from the Lateglacial to Holocene is reflected in a gradual shift from clayish to calcareous and finally detrital gyttja. Lateglacial mainly organic depositions of 1.6 m thickness contain a 50 cm sequence of very fine annual lamination (Dreibrodt et al. 2020; Krüger et al. 2020). The sediment cores reached glacial sand at 15.8 m. The chronology is based on AMS radiocarbon dates, pollen events, varve counting and additionally on the identified tephra layers (Dreibrodt et al. 2020).

Methods

Field methods and sampling

The coring campaign in the dry centre of the Nahe palaeolake took place in October 2017. A modified Livingston piston corer (Mingram et al. 2007)—the so called Usinger corer—was used to extract the sediment cores. Two overlapping sediment sequences with a diameter of 80 mm and 16 m in length have been reached by coring. Each 1 m segment was cut longitudinally and stored as well as processed at the Institute for Pre- and Protohistoric Archaeology in Kiel, Germany. In order to connect the core sequences, a series of distinct layers and stratigraphic marker horizons have been defined in the parallel cores. In this way, a composite core was constructed, providing a continuous record avoiding gaps (Dörfler et al. 2012).

The interdisciplinary approach of the study requires that the results of different methods must be easily correlated across depths. Therefore, a grid of 5 mm step size was created spanning the lower 5 m of the sequence. Each sample was
labelled according to consecutive numbers (953 potential samples in total, 11.10–15.86 m below the surface).

Pollen analysis

Samples for pollen preparation were mostly taken every centimetre but at least every fourth centimetre. Sample preparation was carried out according to standard techniques (Erdtman 1960; Fægri and Iversen 1989). Lycopodium spore tablets were added to enable the calculation of pollen concentrations (Stockmarr 1971). Pollen counting was performed at a total magnification of ×400 for routine counting and ×1000 for critical objects. A pollen sum of at least 550 TTP (total terrestrial pollen) per sample was achieved. Pollen identification followed mainly Beug (2004) as well as Moore et al. (1991). The reference collection at the Institute of Pre- and Protohistoric Archaeology in Kiel was further consulted. The results were visualised using the CountPol software (I. Feeser, Kiel University) as well as Inkscape (ver. 0.92.4). The general results of the pollen analysis of the complete section are presented by Krüger et al. (2020).

Tephra analysis and identification

On the basis of the preceding pollen analysis and a preliminary comparison of these results with investigations in northern central Europe (Krüger et al., 2020), certain sequences were selected for a search for cryptotephra (Fig. 2). The selected depths were sampled in 2 cm steps (Lateglacial sequence) and 1 cm steps (Holocene sequence) resulting in sample weights between 5 and 11 g. The chemical preparation included treatment with HCl to dissolve carbonates, concentrated H2SO4 and HNO3 to remove the organic material from the samples and KOH (10%) to eliminate diatom silicates. Moreover, a density separation using sodium polytungstate was applied to separate heavy mineral particles of more than 2.7 g/cm³ from the lighter particles (Turney 1998). The lighter fraction was mounted in glycerol-gelatine and subsequently analysed using a light microscope under bright field, ×250 magnification. Cross-polarisation was additionally used to check critical particles. The identified cryptotephra horizons were labelled according to sample numbers. As one cryptotehrn sample spans 2 cm (equalling four samples on the composite core) the bottom sample numbers according to the composite core were utilised for the tephra samples.

To gain material for electron-microprobe analyses (EMPA) the mounted material was re-dissolved and embedded in synthetic resin. Subsequently polished thin sections were prepared from these slides.

Electron-microprobe analyses

The major- and minor-element geochemistry of the glass shards was determined with the JEOL JXA 8200 electron microprobe equipped with five wavelength dispersive spectrometers at GEOMAR (Kiel, Germany). The analytical conditions were 15 kV accelerating voltage, 6 nA current and 5 μm electron beam size. For calibration, a set of natural reference materials from the Smithsonian collection was used, the quality of the calibration was tracked by running the Lipari
Identification, characterisation and correlation of tephra layers

NAH-466

The Saksunarvatn eruption(s) can be assigned to the phase of rapidly increasing Corylus (Hazel) pollen values during the Boreal period in northern central Europe (Bramham et al. 2013; Merkt et al. 1993). As this increase is strikingly and unequivocally reflected in the NAH record (Krüger et al. 2020), a rough determination of the position of the ash could easily be made.

Here, the targeted search for cryptotephras revealed a two-part maximum of shards (Fig. 2) in samples NAH-460 (13,390–13,400 m) as well as NAH-466 (13,420–13,430 m). Both peaks (NAH-460 and 466) correlate to the rapid increase and first Corylus pollen maximum of the (biostratigraphical) Boreal period.

Table 1. Geochemical data on glass shards from NAH-466 determined by electron-microprobe analysis.

| Analysed total | Comment | Analysed total | Comment | Analysed total | Comment |
|----------------|---------|----------------|---------|----------------|---------|
| Volatile-free normalised values | SiO₂⁺ | TiO₂⁺ | Al₂O₃⁺ | FeOtot⁺ | MnO⁺ | MgO⁺ | CaO⁺ | Na₂O⁺ | K₂O⁺ | P₂O₅⁺ | F | SO₃⁻ | Cl | 
| NAH-466 | >97% | 49.66 | 3.17 | 13.06 | 14.57 | 0.19 | 5.65 | 10.21 | 2.66 | 0.48 | 0.35 | 0.11 | 0.23 | 0.03 | 97.47 | Saksunarvatn |
| | | 49.29 | 3.12 | 13.18 | 14.94 | 0.25 | 5.65 | 9.94 | 2.78 | 0.47 | 0.37 | 0.00 | 0.26 | 0.04 | 97.67 | Saksunarvatn |
| | | 48.97 | 2.69 | 13.52 | 14.27 | 0.22 | 6.25 | 10.71 | 2.66 | 0.39 | 0.32 | 0.10 | 0.15 | 0.04 | 97.66 | Saksunarvatn |
| | | 49.88 | 2.89 | 13.10 | 14.30 | 0.26 | 5.81 | 10.26 | 2.78 | 0.41 | 0.32 | 0.00 | 0.26 | 0.04 | 98.42 | Saksunarvatn |
| | | 49.80 | 3.15 | 13.08 | 14.82 | 0.23 | 5.38 | 9.99 | 2.78 | 0.46 | 0.30 | 0.03 | 0.15 | 0.03 | 99.40 | Saksunarvatn |
| | | 49.44 | 3.11 | 13.10 | 14.80 | 0.25 | 5.50 | 10.16 | 2.88 | 0.46 | 0.29 | 0.09 | 0.18 | 0.03 | 98.23 | Saksunarvatn |
| | | 49.45 | 3.00 | 13.10 | 14.12 | 0.23 | 5.93 | 10.12 | 2.95 | 0.46 | 0.35 | 0.00 | 0.25 | 0.06 | 97.63 | Saksunarvatn |
| | | 49.75 | 3.11 | 12.97 | 14.68 | 0.24 | 5.65 | 10.02 | 2.78 | 0.45 | 0.35 | 0.00 | 0.31 | 0.04 | 99.61 | Saksunarvatn |
| | | 50.01 | 3.20 | 13.10 | 14.28 | 0.25 | 5.54 | 10.14 | 2.70 | 0.49 | 0.30 | 0.00 | 0.19 | 0.03 | 97.40 | Saksunarvatn |
| | | 49.84 | 3.14 | 13.23 | 14.68 | 0.23 | 5.30 | 9.87 | 2.93 | 0.46 | 0.31 | 0.14 | 0.20 | 0.04 | 99.29 | Saksunarvatn |
| | | 49.71 | 3.14 | 13.13 | 14.60 | 0.27 | 5.56 | 10.07 | 2.76 | 0.46 | 0.30 | 0.05 | 0.23 | 0.04 | 98.80 | Saksunarvatn |
| | | 49.86 | 3.23 | 12.97 | 14.37 | 0.28 | 5.50 | 10.01 | 2.96 | 0.48 | 0.34 | 0.03 | 0.21 | 0.04 | 97.90 | Saksunarvatn |
| | | 49.40 | 2.90 | 13.54 | 14.24 | 0.22 | 5.89 | 10.30 | 2.78 | 0.44 | 0.27 | 0.05 | 0.24 | 0.05 | 97.29 | Saksunarvatn |
| | | 49.65 | 3.24 | 13.21 | 14.28 | 0.29 | 5.41 | 10.24 | 2.88 | 0.47 | 0.33 | 0.00 | 0.22 | 0.04 | 97.62 | Saksunarvatn |
| | | 49.76 | 3.16 | 13.06 | 14.70 | 0.18 | 5.49 | 9.98 | 2.91 | 0.49 | 0.27 | 0.06 | 0.23 | 0.04 | 97.68 | Saksunarvatn |
| | | 49.79 | 3.20 | 12.93 | 14.67 | 0.22 | 5.64 | 10.02 | 2.76 | 0.47 | 0.31 | 0.06 | 0.23 | 0.04 | 97.35 | Saksunarvatn |
| | | 49.29 | 3.17 | 13.04 | 14.86 | 0.21 | 5.60 | 9.95 | 3.07 | 0.47 | 0.34 | 0.00 | 0.21 | 0.04 | 98.01 | Saksunarvatn |
| | | 50.09 | 2.92 | 13.20 | 13.84 | 0.22 | 6.02 | 10.49 | 2.53 | 0.40 | 0.29 | 0.08 | 0.17 | 0.04 | 97.98 | Saksunarvatn |

avg. | 49.65 | 3.09 | 13.14 | 14.52 | 0.24 | 5.65 | 10.14 | 2.81 | 0.46 | 0.32 | 0.02 | 0.22 | 0.04 | 97.94 |
| ±1σ | 0.29 | 0.15 | 0.17 | 0.29 | 0.03 | 0.24 | 0.21 | 0.13 | 0.03 | 0.03 | 0.04 | 0.04 | 0.01 | 0.75 |

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Table 2. Geochemical data on glass shards from NAH-633 determined by electron-microprobe analysis.

| Analysed total | Comment |
|----------------|---------|
| ±1s            |         |

increasing values of Corylus pollen in the NAH record. A 9 cm sediment sequence was sampled in 1 cm steps, equivalent to a rather narrow scope of investigation. As large-scale turbations have been excluded for the whole NAH sequence this result either reflects: (i) potentially two very closely spaced eruptions; or (ii) small-scale rearrangement, bioturbation or secondary inwash of shards.

(i) At Potremser Moor—an in-filled lake about 230 km east of NAH—Bramham-Law et al. (2013) recorded two close and significant peaks in tephra shard concentration that correlate to

Table 3. Geochemical data on glass shards from NAH-711 determined by electron-microprobe analysis.

| Analysed total | Comment |
|----------------|---------|
| ±1s            |         |

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the main expansion of Corylus. Here, shard morphology has been utilised to distinguish between the two peaks. The lower peak contained brown platy and curvilinear shards, whereas the upper mainly comprised colourless shards with occasionally closed vesicles but mainly irregular morphologies. The lower and more distinct has been geochemically identified as a SA (Bramham et al. 2013).

However, the double peak observed in the NAH record does not contain separate peaks of morphologically different shards. The geochemical composition of the lower and more pronounced peak clearly reflects a known SA fingerprint. Here, one explanation could be two temporally close successive eruptions of the same volcanic system or two separate basaltic volcanic systems.

There is more than one known eruption from the Grímsvötn volcanic system that is linked to SA (Bramham-Law et al. 2013; Davies et al. 2012; Jóhannesdóttir et al. 2006; Wastegård et al. 2018; Wulf et al. 2016). Recent studies by Harning et al. (2018) and Wastegård et al. (2018) as well as the review by Öldödottir et al. (2020) demonstrated that there were at least three, potentially even seven, eruptions from the Grímsvötn volcanic system.

One ash plume was distributed towards the north-west of the system and was recorded in the Greenland ice cores (Rasmussen et al. 2006). At least one other dispersal envelope was directed towards the south-east, and has been identified at a variety of sites in continental Europe (Bramham-Law et al. 2013; Jones et al. 2018; Lohne et al. 2013; Merkt et al. 1993; Wulf et al. 2016). The SA recorded in the NAH is most likely related to this south-east dispersal fan.

In this respect, only single cryptotephra horizons associated with the SA have been recorded in annually laminated sequences in northern Germany (Dörfler et al. 2012; Jones et al. 2018; Merkt et al. 1993). One of those sequences derives even from Lake Poggensee (Zanon et al. 2019)–a lake less than 30 km east of the Nahe palaeolake.

(ii) The palaeo-environmental record of NAH revealed the presence of increasing amounts of undefined shells and shell fragments in the depth that corresponds to the SA. They can potentially be associated with small-scale lake-level fluctuations within the Nahe palaeolake. This assumption is in line with indicators of small-scale rearrangement. Therefore, it is probable that the two separate peaks can be explained by the redeposition of material or a secondary inwash of shards, respectively. Consequently, redeposition could be considered as a determining factor for the observed distribution pattern of cryptotephra in the sediment sequence (NAH-460 and NAH-466).

The SA is intended to provide an additional time span to the age–depth model of the NAH sequence. Therefore, the depth needs to be clarified to which the tephra is to be assigned. In this respect, the NAH record could be correlated to the pollen sequence from close by Lake Poggensee (POG; M. Zanon pers. com.). Here, the SA is embedded as a single visible layer in annually laminated sediments.

The results of the palynological analysis revealed that the curves of Corylus pollen ratios of NAH and POG match closely (pers. com. M. Zanon). This is not surprising as the distance is less than 30 km and the size as well as the catchment of the two lakes would be approximately equal. Palynologically, the SA was detected in the sediments of Lake Poggensee, exactly where the lower SA peak was detected in the NAH record. Considering this, the event horizon is assigned to the depth of the lower shard peak (NAH-466).

NAH-633

The pollen stratigraphic location of the VA is challenging. The fallout date of the VA has been placed in the
mid-Younger Dryas period and was determined to represent a distinct marker horizon that separates the early and the later phase of the Younger Dryas period (Bakke et al. 2009; Halldíason et al. 2018; Lane et al. 2012a, 2013; Mangerud et al. 1984). The VA has been associated with pollen stratigraphy from Scotland (Lowe and Turney 1997), Sweden (Björck and Wastegård 1999) and Russia (Wastegård et al. 2000). For a pollen stratigraphic comparison with the present study, however, these are too remote to be used for comparison with the NAH record in northern Germany.

In north and north-western Germany, the second half of the (biostratigraphical) Dryas 3 period (terminology following Krüger et al. 2020) is linked to the spread of Empetrum sp. (cf. E. nigrum) in different degrees, reflecting climatic alterations towards increased oceanity (Krüger et al. 2020; Merkt and Müller 1999; Overbeck 1975). As an increase in Empetrum-type pollen has also been seen during the Dryas 3 period in the NAH record, a search for VA cryptotephra has been carried out in corresponding depths.

Here, the targeted search revealed one clear maximum concentration of shards in sample NAH-633 (14.245–14.265 m). The depth of the sample position corresponds pollen-stratigraphically directly to a rapid increase in Empetrum-type pollen values as observed midway through the Dryas 3 period (Fig. 2; Krüger et al., 2020).

Shard counts yielded about 395 shards/g. The shards are exclusively colourless (Fig. 3c–d). Morphologically, they appear platy to highly vesicular, and a few have tubular properties. The size spectrum ranges from 20 to 50 μm.

The tephra has a homogeneous geochemical composition. In the total-alkali-silica (TAS) classification diagram it falls into the field of rhyolite composition with 71.3 ± 0.3 wt% SiO₂, 5.2 ± 0.2 Na₂O and 3.6 ± 0.1 K₂O (Fig. 4). The full geochemical analyses are given in Table 2.

The general characteristics of geochemical composition (Fig. 6), age and morphology of shards are in line with the description of shards of the rhyolitic phase found at sites across Northern Europe (among others: Davies et al. 2005; Mangerud et al. 1984; Timms et al., 2017, Jones et al. 2018).

NAH-711

The Laacher See Eruption occurred after the palynologically defined termination of the Gerzensee Oscillation and around 200 years before the Dryas 3 period became fully established (Litt et al. 2003; Litt and Stebich 1999; Merkt and Müller 1999; von Grafenstein et al. 1994). In a number of pollen diagrams from north-eastern Germany a significant decrease of Pinus pollen values in the last third of the Allerød period is seen around the LST horizon (Jahns 2000; Theuerkauf 2003). This trend, albeit not strikingly pronounced, is observable in the pollen concentration values of the NAH record.

Here, the targeted search revealed one clear maximum concentration of glass shards at the 14.635–14.655 m core depth (NAH-711).

With respect to pollen stratigraphy, the sample depth corresponds to the last third of the Allerød period (Fig. 2). The high resolution of the pollen record allowed a clear distinction between the termination of the (palynologically defined) Gerzensee Oscillation and the timing of cryptotephra deposition (Dreibrodt et al. 2020; Krüger et al. 2020). It correlates to decreasing Pinus pollen values as well as increasing concentration values of pollen from grasses and herbaceous plants towards the end of the Allerød period.

Glass shard counts yielded about 160 shards/g. The tephra horizon consists of colourless vesicle-rich pumiceous shards with spherical vesicles, and pipe-like elongated bubbles (Fig. 3e–f). The external shape of these shards is determined by densely packed, open (burst) vesicle cavities. Single brownish shards occur. The size spectrum ranges from 20 to 75 μm.

Geochemical analysis was done on 31 shards (analyses that resulted in major-element weight percentage totals <96 wt% were discarded). The tephra has a phonolitic composition with 60.2 ± 0.8 wt% SiO₂, a range of 7.8 to 4.3 wt% Na₂O, a range of 8.4 to 6.6 wt% K₂O and 2.6–1.5 wt% CaO. The full geochemical analyses are given in Table 3.

The geochemical fingerprinting of the NAH-711 glass shards confirms an identification with tephra from the Laacher See Eruption (Fig. 4). The glass shards of NAH-711 show the geochemical and morphological characteristics of the glass...
shards described from the proximal Plinian eruption phases (Fig. 3e–f), following the comparison with data from LST from the proximal type sites (van den Bogaard and Schmincke 1985; C. van den Bogaard, unpublished data).

The published data from distal sites in the north-western fallout (Housley et al. 2012; Jones et al. 2018; Lane et al. 2015; Larsson and Wastegård 2018; Pröcházka et al. 2018; Riede et al. 2011; Turney et al. 2006; van den Bogaard and Schmincke 1984, 1985; Wulf et al. 2013) are in line with this interpretation. The chemistry suggests a fallout from the

Figure 6. Geochemical composition of Tephra NAH-633 compared with the composition of the rhyolitic Vedde Ash at Hämelsee (Jones et al. 2018) and from Quoyloo Meadow, Orkney (Timms et al. 2017) in (a) SiO₂ versus alkali, (b) SiO₂ versus CaO and (c) TiO₂ versus FeO. [Color figure can be viewed at wileyonlinelibrary.com]

Figure 7. Tephra NAH-711 compared with glass shard composition of proximal Laacher See Tephra (LST) from the different eruption phases: LLST, MLST A, B, C1, C2 and ULST (after van den Bogaard and Schmincke, 1984; unpublished data). (a) silica versus alkalai, glass shard composition from Plötzensee Berlin (unpublished data) represent the LLST fallout, (b) bi-plot Na₂O versus K₂O (c) and CaO versus TiO₂. [Color figure can be viewed at wileyonlinelibrary.com]
eruption phases MLST C1 (Fig. 7). This is also supported by the morphology of NAH-711 glass shards: the glass shards are highly vesicular and colourless. This is indicative of shards described from the LST eruptive phase that resulted from Plinian eruptions. Vesicle-rich pumiceous clasts with pipe-like elongated vesicles, are typical for LLST, MLST B and MLST C1 deposits, pumiceous clasts with spherical bubbles are described throughout the eruption sequence, but especially from LLST to the base of ULST. Glass shards from the phreatomagmatic phases of the eruption MLST A, MLST C2 and ULST are mostly angular and blocky with few vesicles (Jones et al. 2018; van den Bogaard and Schmincke 1985).

**Targeted cryptotephra search based on palynology**

It has been shown before that palynological records can be useful tools when intending to find cryptotephra layers (Dörrlér et al. 2012). Preceding pollen analyses inherit the strength to narrow down the extent of the sediment sequence to be subsampled for tephra analysis.

In the present study, three cryptotephra layers out of three suspected were detected. The scope of the respective search sequence was in each case comparatively narrow (7–16 cm) due to the high resolution of the pollen record. Regarding all cryptotephra layers, the targeted search has been directly successful. Consequently, it must be questioned whether the detection of tephra in narrow sequences of very homogeneous sediments (here in the case of sediments deposited during the Dryas 3 and Boreal periods) means that cryptotephra is generally present throughout the sediment due to different depositional processes or turbations.

Nevertheless, with regard to the representation of shards per sample and depth of the VA and LST, large-scale rearrangement becomes very unlikely. In both cases a clear maximum of shards below the main peak can be explained by minor bioturbation (Anderson et al. 1984). As suggested by Davies et al. (2012), the concentration of shards per depth can decrease above the concentration peak, indicating the mobilisation of shards in the catchment. In this respect, the NAH cryptotephra record mainly contains expectable minor redepositions of shards resulting in a common tail-off pattern.

In order to exclude the possibility that shards are not generally present in every sample, specific sequences of transitional sediments were analysed. In addition, sequences were also considered in which no tephra layer would be expectable—this again on the basis of pollen stratigraphy and the current state of knowledge of tephra-producing events. Therefore, a sequence of 24 cm was selected spanning a transition from laminated to gradually more homogeneous sediments. According to pollen stratigraphy, this sequence was deposited during the last third of the Allerød period as well as during the transition from the Allerød to the Dryas 3 period. In the samples from the bottom of this sequence, the LST shows a clear peak. All samples above this maximum contained at most two shards, but predominantly no cryptotephra shards at all (cf. grey shaded areas shown in Fig. 2).

Consequently, two conclusions can be drawn. Firstly, only minor and expectable rearrangements of shards can be observed. This is in line with previous results from other approaches (Dreibrodt et al. 2020; Krüger et al. 2020). Therefore, large-scale rearrangements can be excluded.

Secondly, it becomes apparent that pollen stratigraphy is a very valuable instrument as a basis for a targeted search for cryptotephra horizons. However, this of course requires a high resolution of the palynological record as well as a profound knowledge of pollen stratigraphic positioning of the cryptotephra layers in compared regional diagrams.

**Tephrochronological discussion**

The detected cryptotephra layers could successfully be correlated by comparing their geochemical compositions with known volcanic eruptions of the Lateglacial and Early Holocene. NAH-466 correlates to a SA/G10ka series tephra, NAH-633 to the VA and NAH-711 to the LST. Hence, we here present the first geochemically confirmed find of LST in Schleswig-Holstein—placed outside the known dispersal envelope of visible LST (Fig. 8) (Riede et al. 2011; van den Bogaard and Schmincke 1984).

These results provide three independent age estimates for the age–depth model of the NAH record. As only a segmental sequence of the sediment is laminated, we here refrain from estimating our own age model of the eruptions. Therefore, it is crucial to discuss which available chronological tie-points should be used for the individual events (Table 4).

For the LST, reference is made to Bronk Ramsey et al. (2015) who compiled and improved age estimates for Late Quaternary European tephra horizons. The age estimate for the LST is based on tree-ring data from Friedrich et al. (1999), as well age estimates from Holzmaar, Soppensee and Rotee. The resulting age estimate 12 937 ± 23 (μ ± σ; IntCal13), is in good agreement with estimates by Brauer et al. (1999) and dating by van den Bogaard (1995).

The record from Lake Holzmaar (HØ; Zolitschka 1998; Zolitschka et al. 1995) provides lamination until recent times, inheriting the opportunity to easily correlate further sequences. One of these sequences is the Meerfelder Maar (MFM) sequence that is correlated to the HZM record by using the Ulmener Maar tephra as chronological anchor (Brauer et al. 1999). The MFM record in turn provided varves throughout the Younger Dryas and the mid-Allerød period resulting in a very accurate estimate of 12 880 ± 40 varve years BP for the LST.

Based on 118 AMS 14C dates from a sequence of Lake Kräkenes, Lohne et al. (2013) – IntCal09; 2014 – IntCal13) provided the most accurate dating of the VA to date. The age estimate of 12 066 ± 42 cal yr BP is in line with further estimates from lake sediments in Europe (Birks et al., 1996; Wastegård et al., 2012).

![Figure 8. Estimated fallout of the Laacher See Tephra (LST) by van den Bogaard and Schmincke (1985) and modified by Housley et al. (2013), with the locations of the Nahe palaeolake (NAH), Kürstättamossen (KLM; Lanson/Wastegård 2018), Lake Hamelsee (HAM; Jones et al. 2018), the Allerød-type locality (AL; Hartz/ Milthers 1901) and the Belling-type locality (BO; Iversen 1942). [Color figure can be viewed at wileyonlinelibrary.com]](image-url)
Table 4. Overview of recent dating of the respective cryptotephra horizons found in the Nahe palaeolake record.

| Sample          | Correlation                        | Age estimate            | Reference          |
|-----------------|------------------------------------|-------------------------|--------------------|
| NAH-466         | Saksunarvatn Ash                   | 10 210 ± 35 cal. a BP   | (Lohne et al. 2013)|
| NAH-633         | Veddé Ash                          | 12 064 ± 48 cal. a BP   | (Bronk Ramsey et al. 2015)|
| NAH-711         | Laacher See Tephra                 | 12 023 ± 43 cal. a BP   | (Lane et al. 2015)  |
|                 |                                    | 12 140 ± 43 varve a BP   |                    |
|                 |                                    | 12 937 ± 23 cal. a BP   | (Bronk Ramsey et al. 2015)|
|                 |                                    | 12880 ± 40 varve a BP   | (Brauer et al. 1999)|

et al., 1998; Matthews et al., 2011) but provides a considerably smaller uncertainty.

The combined age model by Bronk Ramsey et al. (2015) to estimate the age of the VA is based on data from Lake Krákenes, Abernethy, Soppensee, Rotsee and Bled. The resulting estimate of 12 023 ± 43 (μ ± σ; IntCal09) is in good agreement with the GICC05 date by Rasmussen et al. (2006).

In their analysis on the synchronicity of high-precision 14C ages and the Greenland Ice Core Chronology, Lohne et al. (2013) further provided an age estimate for the SA of 10 210 ± 35 (μ ± σ; IntCal09). Based on the review by Öladóttir et al. (2020) it cannot be clarified with certainty to which of the GI0ka series tephra the shards of the NAH record would correlate. Nevertheless, it has been shown that the pollen stratigraphical position of the lower shard peak from the NAH record correlates to the position of the SA layer in the pollen stratigraphy from Lake Poggenense (Zanon et al. 2019). At the near Lake Poggenense as well as Lake Woserin (Zanon et al. 2019; I. Feeser, pers. com.) only one ash layer has been identified in a laminated sequence. Both have been assigned to a SA (Zanon et al. 2019). As their individual dating falls well within the given age estimate by Lohne et al. (2013) this age has been utilised for the NAH age–depth model.

Resulting tephrostratigraphical framework, regional implications and future work

The identification of the volcanic eruptions allow for a direct correlation between the NAH sediment sequence and European key sites for palaeo-environmental research such as Meerfelder Maar (Brauer et al. 1999; Litt and Stebich 1999), Lake Hämelsee (Jones et al. 2018; Merkt and Müller 1999), Endinger Bruch (De Klerk 2002; Lane et al. 2012b), Lake Krákenes (Lohne et al. 2013; Mangerud et al. 1984), Lake Tiefer See (Wulli et al. 2016) and Lake Soppensee (Lane et al. 2011; Lotter 2001). This highlights the relevance of the NAH location in correlating important key sites in northern and central Europe.

In combination with finds of LST at Lake Hämelsee (Jones et al. 2018) as well as Körsättamossen fen (Larsson and Wastegård 2018) the results of the present study demonstrate that the dispersal envelope of the Laacher See Eruption can be reached further to the north-west.

In this respect it might even be possible to detect non-visible ash beds of the LST in Denmark (apart from Bornholm where it had already been identified—Turney et al. 2006) which would imply that biozonal-type localities such as Bölling (Krüger and Damrath 2019; Iversen 1942) or especially Allerød (Hartz and Wastegård 2018) the results of the present study demonstrate the considerable potential of future investigations.

Conclusion

Three cryptotephra layers have been discovered and geochemically confirmed as GI0ka series tephra (SA), VA and LST in sediments from the NAH. Consequently, we here present the first finding of LST in Schleswig-Holstein—located outside the ash plume that was reconstructed on the basis of visible ash layers. The combination of published LST findings from Lake Hämelsee (Jones et al. 2018) as well as Körsättamossen fen (Larsson and Wastegård 2018) reveals that the dispersal fan reached further to the north-west than previously assumed (Litt et al. 2003; Riede et al. 2011; Schmincke et al. 1999; Theeuwkauf 2003; van den Bogaard and Schmincke 1985).

Hence, the detection of LST in Jutland or the Danish Islands (adding to the finds on Bornholm) comes within reach, inheriting the potential to correlate important Lateglacial-type localities with recent palaeo-environmental investigations.

Furthermore, these results add three independent ages to the age–depth model for the NAH sequence (Dreibrodt et al. 2020), thereby emphasising the considerable potential for further investigations into both the site itself and general further tephrochronological studies in Northern Europe.

Data availability statement

All data generated or analysed during this study are included in this published article. Palynological data are available from the corresponding author on reasonable request.

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