Detection of the historical Askja-AD1875 and modern Icelandic cryptotephra in varved lake sediments – results from a first systematic search in northern Poland

Running title: Cryptotephra in northern Poland

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Abstract:

Volcanic ash can disperse thousands of kilometres from the source volcano and provide valuable chronostratigraphic marker for palaeoclimate studies. We present new cryptotephra findings of historical and modern Icelandic eruptions in annually laminated lacustrine sediment records from several sites within a 570-km SW-NE transect across northern Poland. Sediments from the two lakes Wąsoskie and Szurpiły contain glass shards originating from the Plinian Askja-AD1875 eruption and showing bimodal, rhyolitic and dacitic affinities. A further cryptotephra finding in Lake Lubińskie suggest a potential origin from the Hekla-AD1845 eruption. These new findings extend the tephra dispersal map towards the southeast and provide valuable isochrons for the synchronisation of palaeoclimate proxy data at the termination of the Little Ice Age in central-eastern Europe. Very low glass concentrations of modern cryptotephra in Lake Wąsoskie were potentially correlated with the Eyjafjallajökull-AD2010 eruption. Further findings in the uppermost sediments of lakes Szurpiły and Żabińskie in Northeastern Poland tentatively suggest other sources from either Hekla and/or Kamchatkan volcanoes.

Keywords: cryptotephra; Askja-AD1875; Hekla-AD1845; Eyjafjallajökull-AD2010; northern Poland

1. Introduction

The widespread ash dispersal of the recent eruptions from Eyjafjallajökull in April/May 2010 and Grímsvötn in May 2011 in southern Iceland had a considerable impact on air travel across Europe leading to large economic losses and new risk assessments by the aviation sector. Volcanic ash cloud transport and dispersion of the Eyjafjallajökull-AD2010 eruption in particular have been observed by satellites and became subject of detailed computer simulations (e.g., Davies et al., 2010; Gudmundsson et al., 2012). However, despite the wide ash plume extent over the European continent, tephra fallout material of the Eyjafjallajökull-AD2010 eruption has been identified so far only in very few archives (e.g., Lettino et al., 2012; Stevenson et al., 2012, 2013).

The Eyjafjallajökull-AD2010 and Grímsvötn-AD2011 eruptions were both of relative low magnitude with a Volcanic Explosivity Index (VEI) of 4 (Gudmundsson et al., 2012; Hreinsdóttir et al., 2014) compared to previous Icelandic eruptions. During the last two centuries, at least 21 distinct explosive eruptions occurred from volcanic centres in southern and eastern Iceland (Larsen et al., 1999; Thordarson and Larsen, 2007). Some of these eruptions were of comparable or higher magnitude (VEI>4), including the rhyolitic, caldera-forming eruption of Askja on 28-29 March 1875 (VEI=7; Carey et al., 2009). This Plinian event in particular dispersed large amounts of ash over wide parts of Scandinavia and the Baltic region as inferred from eye-witnessing (Mohn, 1878) and many visible tephra findings in geological archives (e.g., Oldfield et al., 1997; Pilcher et al., 2005; Wastegård and Davies, 2009; Plunkett and Pilcher, 2018). Methodological and analytical advances in tephrochronology allowed for the recent identification of also non-visible ash layers (cryptotephra) of the Askja-AD1875 eruption in further distal sites in central and northeastern central Europe (e.g., Wulf et al., 2016; Watson et al., 2017a; Kalliokoski et al., 2019; Vakhrameeva et al., 2020),

significantly extending its previously known dispersal and providing a precise isochron for testing varve chronologies (Tylmann et al., 2016) and synchronising evolving palaeo-proxy data for the time interval at the termination of the Little Ice Age time period (Ott et al., 2018).

The aim of this study is to identify the historical Askja-AD1875 and modern Icelandic cryptotephra from the Eyjafjallajökull-AD2010 and Grímsvötn-AD2011 eruptions in nine annually laminated lake records that are situated in a 570-km SW-NE transect across northern Poland. Comparisons of glass shard concentrations of individual tephra events will be used to densify and extend ash dispersal maps in this region in order to estimate future impact of ash plumes of comparable magnitude.

2. Study sites and methodology

Based on the knowledge of the presence of varved sediments (Tylmann et al., 2013) nine relatively small and deep lakes across northern Poland were selected for sediment and cryptotephra sampling (Fig. 1, Table 1). Short sediment cores of 85.5 cm to 140 cm length containing intact sediment-water interfaces were retrieved in autumn 2016 from the deepest parts of the lakes using a gravity corer with a 90 mm-diameter (Figs. 1, 2; Table 1). Sediments of all sites contain 0.1-29.1 mm-thick biogenic varves, where one varve is generally composed of a pale calcite lamina representing spring/summer season and a dark lamina formed by mixed, organic and clastic, material deposited in autumn/winter. Varve chronologies from Lake Szurpiły and Lake Żabińskie have been already published in Kinder et al. (2013) and Żarczyński et al. (2018) and required a short extension only, while annual lamination counting at the other sites was performed on core photographs to narrow down sampling intervals of interest for detecting the Askja-AD1875 and other modern Icelandic tephra. The

specific sediment sections were subsampled in contiguous 1-cm increments with a volume of 1 cm³. Samples were subsequently treated with a 30% H₂O₂ and a 7-10% HCl solution (1 hour) in order to remove organic matter and carbonates, respectively. A 2M Na₂CO₃ solution was added for 6-7 hours in a 70-80°C water bath to dissolve biogenic silica. Wet sieving was carried out using 20 µm and 100 µm meshes, and liquid density separation with a Sodium Polytungstate solution at 1.95 and 2.55 g cm⁻³ for mineral-rich samples was applied using the method by Blockley et al. (2005). The grain size fraction 20-100 µm was inspected under a polarizing microscope (AXIO Imager A2, Zeiss) at 200× magnification. Identified glass shards were picked in a water medium with a 5-ml gas chromatography syringe and a 110-µm-diameter micromanipulator (Lane et al., 2014), embedded in epoxy resin (Epofix™) in a single-hole aluminium stub, and sectioned and polished for electron probe microanalyses (EPMA). In addition to the cryptotephra samples, polished stubs of tephra material of the Eyjafjallajökull-AD2010 and Grímsvötn-AD2011 eruptions, sampled in September 2012 from proximal sites in Iceland, were prepared for EPMA analysis. The major and minor element compositions of individual glass shards of cryptotephra and proximal tephra were obtained by a JEOL-JXA8230 probe (WDS) at the GFZ Potsdam, Germany using a 15 kV voltage, 10 nA beam current, and 5-10 µm beam diameter. Natural (Lipari obsidian; Kuehn et al., 2011) and artificial glass standards (Max-Planck Institute MPI glasses GOR-132, StHs6/80 and ATHO-G; Jochum et al., 2006) were used for analytical data verification (Appendix 1). EPMA data with analytical totals of <95 wt% for intermediate and <90 wt% for rhyolitic compositions have been rejected, except for tephra with extreme low glass shard concentrations (Appendix 1). Data were normalised to total of 100 wt% on a water- and volatile-free basis prior to presenting in bivariate elemental diagrams (Fig. 3). Cryptotephra were labelled

according to their core number, core section and sample depth, e.g. LUB-16/2_67-68, and counts of detected glass shards were expressed as 'shards cm⁻³ wet sediment'.

3. Tephra identification

Four out of the nine selected lakes (i.e., Lubińskie, Wąsoskie, Żabińskie, and Szurpiły) contain cryptotephra in one or two horizons within the targeted 200-years-time interval which could be geochemically fingerprinted and attributed to the Askja-AD1875, Hekla-AD1845, Eyjafjallajökull-AD2010, and yet undefined modern Icelandic (Hekla) or Kamchatkan eruptions (Figs. 2, 3). The other five sites (Dubie, Gorzyńskie, Salno, Krzywe, Priamy) contain glass shards in certain sections (Fig. 2, Table 1), but those were not geochemically confirmed due to difficulties during glass shard extraction.

3.1 *Askja-AD1875 tephra and Hekla-AD1845(?)*

Glass shards of the Askja-AD1875 cryptotephra were recognized at different depths but within the expected varve age around AD 1875 in the two lakes Wąsoskie (WAS) and Szurpiły (SUR) (Fig. 2, 3A-D, Appendix 1). Due to the previously finding of the Askja-AD1875 tephra in Lake Żabińskie (Tylmann et al., 2016), the respective core section from this lake was not re-investigated.

A larger glass shard concentration of the Askja-AD1875 tephra was found in lake Wąsoskie in sample WAS-16/2_40-41 (40 shards cm⁻³) and in the easternmost lake Szurpiły in two subsequent samples, SUR-16/3_33-34 and SUR-16/3_34-35 (73 shards cm⁻³). Both findings show wide ranges in the silica contents of 66.1-73.8 wt% (WAS) and 65.2-77.4 wt% (SUR), respectively (normalised data; Fig. 3A-D, Appendix 1). This bimodal dacitic-rhyolitic composition of the Askja-AD1875 tephra is unusual for tephra deposits in proximal sites in Iceland, however, it has been reported from

distal archives in Finland, Sweden (Boygles, 2004; Kalliokoski et al., 2019), and possibly northern Italy (Luongo et al., 2017).

In Lake Lubińskie, in the westernmost part of Poland, three out of four detected glass shards in samples LUB-16/2_68-69 (1 shard) and LUB-16/2_67-68 (2 shards) show a similar high silicic, rhyolitic composition with considerable lower FeO (1.1-2.0 wt%), MgO, CaO, and higher K₂O values compared with the identified Askja-AD1875 tephra in lakes Wąsoskie, Żabińskie, and Szurpiły (Fig. 3A-D). They resemble rather the composition of the silicic component of the Hekla-AD1845 tephra (Wastegård, 2002; Watson et al., 2015; Watson et al., 2017b; Gudnason et al., 2018) and the tentatively assigned Askja-AD1875 tephra found at Cole Gnifetti glacier (northern Italy; Luongo et al., 2017) (Fig. 3A-D). We suggest a potential correlation with both tephras, implying that the tentative correlation of the Cole Gnifetti tephra to the Askja-AD1875 eruption may have to be revised.

3.2 Modern tephras from Icelandic and potential Kamchatkan volcanoes

Very low concentrations of glass shards were found in the uppermost sediments of lakes Wąsoskie (WAS), Żabińskie (ZAB), and Szurpiły (SUR) (Figs. 2, 3E-H). However, the single shards identified in these three records do not form a compositionally homogeneous group (Fig. 3E-H, Appendix 1).

One trachydacitic shard in sample WAS-16/2_4-5, varve-dated to AD 2005-2007, is characterized by a SiO₂ value of 68.3 wt% accompanied by concentrations of FeO of 1.9 wt% and CaO of 0.2 wt%. This composition resembles most the composition of the Eyjafjallajökull-AD2010 tephra except for the lower CaO and FeO values (Fig. 3E-H, Appendix 1). Therefore, we propose only a tentative correlation with this eruption.

Two single shards were found in samples ZAB-16/2_2-3 and ZAB-16/2_6-7, varve-dated to AD 2009-2010 and AD 2003-2004, respectively. Both shards have distinct rhyolitic compositions with SiO₂ and CaO values of 76.0 wt% and 0.7 wt% (ZAB-16/2_2-3), and 74.5 wt% and 0.1 wt% (ZAB-16/2_6-7), and are therefore considered to derive from two different eruptions (Fig. 3E-H, Appendix 1). Both compositions show some similarities with glass compositions of tephras from historical Hekla and modern Shiveluch (Kamchatka; 56.653°N, 161.36°E; Fig. 1) eruption; however, an unambiguous correlation to either source is not possible at this stage.

Sample SUR-16/3_3-4 from Lake Szurpiły, varve-dated at AD 2004-2007, revealed one single shard of andesitic composition with concentrations in SiO₂ of 58.8 wt% and CaO of 9.3 wt% (Appendix 1). This composition does not match any known tephra composition (Fig. 3E-H, Appendix 1), and therefore a correlation remains open.

Overall, correlations of cryptotephra layers found in the uppermost sediments of the Polish lake records are only tentative, and reliable assignments will require larger glass chemical datasets of both the distal findings and their considered proximal correlatives.

4. Implications: Tephra dispersal pattern

Visible layers of the Askja-AD1875 tephra have been for long reported in sediment records from Norway (e.g., Pilcher et al., 2005) and Sweden (e.g., Oldfield et al., 1997; Bergman et al., 2004; Wastegård and Davies, 2009; Plunkett and Pilcher, 2018). Recent cryptotephra findings in northern Germany (van den Bogaard and Schmincke, 2002; Wulf et al., 2016), Latvia (Stivrins et al., 2016), Finland (Kalliokoski et al., 2019), and western Russia (Vakhrameeva et al., 2020) extended the dispersal fan further to the east. In Poland, cryptotephra of the Askja-AD1875 eruption has been

detected in only five of the numerous peat bogs and varved lake sediment record available, namely in Linje mire (Watson et al., 2017a) and in lakes Czechowskie (Wulf et al., 2016), Głęboćek and Jelonek in north-central Poland (Ott et al., 2018), as well as in Lake Żabińskie in eastern Poland (Tylmann et al., 2016) (Fig. 1, Table 2). Our new findings in lakes Wąsoskie and Szurpiły densify and slightly extend the previously known dispersal fan of the Askja-AD1875 tephra to the south and southeast (Fig. 4A). Notably, glass shard concentration of the Askja-AD1875 cryptotephra in Polish sites are relatively low with slight variations of 5 to 40 shards cm^{-3} in western and central Poland and 47 to 73 shards cm^{-3} in sites in eastern Poland, and are within the range of glass concentrations observed in archives in north-western Germany (>40 shards cm^{-3} ; Wulf et al., 2016) and Latvia (8-23 shards cm^{-3} ; Stivrins et al., 2016) (Table 2). In comparison, Kalliokoski et al. (2019) report Askja-AD1875 glass shard concentrations in peat bogs and lake sediments ranging between 559 shards cm^{-3} and 14 shards cm^{-3} in western and eastern Finland, respectively, while only a single glass shard was detected in northwestern Russia (Vakhrameeva et al., 2020). This pattern confirms the observed and modelled initial eastward ash trajectory from Iceland across Scandinavia and a subsequent change of the major wind direction over Finland towards the south (Carey et al., 2009; Kalliokoski et al., 2019). The slight variations of tephra concentrations across eastern-central Europe (including Poland) is most likely a result of different meteorological conditions during tephra shard deposition in these ultra-distal (> 2000 km) areas in addition to varying sediment accumulation rates in these sites.

Volcanic ash of the Eyjafjallajökull-AD2010 eruption has been found mainly in rainwater samples in Great Britain (Stevenson et al., 2012, 2013), and fallout in further distal locations is only sparsely documented despite the evidence of volcanic ash

plumes over those areas (Fig. 4B). The most distal depositions of the Eyjafjallajökull-AD2010 tephra were recorded in the Czech Republic (Navrátil et al., 2013), Italy (Lettino et al., 2012; Rossini et al., 2012), Spain (Revuelta et al., 2012), and Hungary (Stevenson et al., 2012). The new potential finding in lake Wąsoskie in north-central Poland extend the existing tephra deposition map towards the east (Fig. 4B). Observed and modelled ash dispersal data at the time of the eruption (Davies et al., 2010) suggests a deposition of this single shard likely from the lower atmospheric ash plume (<20,000 ft) on 19 April 2010 (Fig. 4B).

In summary, glass shard concentrations of the Askja-AD1875 cryptotephra found in Lake Wąsoskie (40 shards cm⁻³) appear large in comparison to the potential single shard finding of the Eyjafjallajökull-AD2010 and the absence of the Grímsvötn-AD2011 tephras in the same archives. This most likely reflects the differences in magnitude of the Askja-AD1875 and the modern eruptions, accompanied by the complex trajectories of the atmospheric transport, implying that ash clouds of future Plinian events from Icelandic volcanoes will have a major impact in northern Poland.

Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.

Appendix 1. Raw EPMA glass data, varve ages and volcanic sources of analysed cryptotephra samples from lake sediments in northern Poland (this study).

Acknowledgments and funding

We would like to thank Wojciech Tylmann, Maurycy Żarczyński, Anna Poraj-Górska, and Filip Duda for their help during the fieldwork, and Esther Guðmundsdóttir for

fruitful discussions. This study was funded by the Polish National Science Centre (grant number 2015/19/D/ST10/02854).

We have no conflicts of interest to disclose.

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Tables

Table 1. List of investigated lacustrine sites located in northern Poland

Lake	Longitude N	Latitude E	Water depth [m]	Core label	Core length [cm]	Sediment accumulation rate [mm/year]*
Lubińskie	52°18'33"	14°54'29"	21.6	LUB-16/2	85.5	4.1
Dubie	53°30'31"	15°40'39"	25.8	DUB-16/2	125	3.3
Wąsoskie	52°56'48"	17°44'23"	25.8	WAS-16/2	131	4.0
Gorzyńskie	52°34'06"	15°53'08"	31.2	GOR-16/1	128.5	3.3
Krzywe	53°22'54"	17°52'34"	20.5	KRY-16/2	126.5	9.0
Salno	53°29'17"	18°57'29"	43.6	SAL-16/1	111	7.0
Priamy	53°32'11"	20°36'55"	20.5	PRI-16/2	140	4.7
Żabińskie	54°07'54"	21°58'59"	44.4	ZAB-16/2	138.5	6.2
Szurpiły	54°13'49"	22°53'53"	46.2	SUR-16/3	137	1.3

* mean for the laminated sections of the investigated cores

Table 2: Summary of Askja-AD1875 tephra findings and shard concentrations in annually laminated lake records and peat bogs from Poland in comparison to previous ultra-distal findings in northern and central Europe.

Site	Sediment depth (cm)	Varve age (AD) incl. uncertainty	Shard count cm ⁻³	Reference
Wąsoskie, central Poland	40.5	older than 1894	40	This study
Czechowskie, N central Poland	48.5	-	10	Wulf et al. 2016
Jelonek, N central Poland	52	-	5	Ott et al. 2018
Głęboćek, N central Poland	23.5	-	25	Ott et al. 2018
Linje Bog, central Poland	59.5	-	29	Watson et al. 2017a
Żabińskie, NE Poland	78.5	1869 – 1880	47	Tylmann et al. 2016
Szurpiły, E Poland	34	1819 – 1869	73	This study
Tiefer See, NE Germany	46.7	-	>40	Wulf et al. 2016
Teiči Bog, E Latvia	61	-	>23	Stivrins et al. 2016
Lake Āraišu, central Latvia	63.5	-	12	Stivrins et al. 2016
Lake Trikātas, N central Latvia	57.5	-	8	Stivrins et al. 2016
Rehtsuo Bog, SW Finland	32	-	559	Kalliokoski et al 2019
Hanhisuo Bog, SE Finland	61	-	14	Kalliokoski et al 2019
Vodoprovodnoe Bog, NW Russia	2.5	-	1	Vakhrameeva et al. 2020

Figure legends

Figure 1. (A) Schematic map showing the positions of volcanic sources and the study area (rectangle); (B) Locations of study sites in northern Poland (red dots) with chemically confirmed (red labels) and unconfirmed (grey labels) cryptotephra occurrences alongside other archives with previously Askja-AD1875 tephra findings (blue squares); (C) Aerial maps of lakes containing chemically confirmed historical and modern cryptotephra horizons (this study), showing coring positions and their respective water depths.

Figure 2. Core photographs, sediment structures and positions of cryptotephra horizons in the investigated cores from northern Poland (this study). Cores labelled in red contain chemically confirmed cryptotephra layers. Numbers in brackets behind tephra sample labels refer to the number of shards identified in 1 cm³ wet sediment. Numbers with question marks refer to the potential glass shards not geochemically confirmed due to difficulties during extraction.

Figure 3. Bivariate elemental plots of glass compositions of cryptotephra horizons identified in northern Polish lakes (this study) compared to other distal and proximal tephra data: (A-D) Askja-AD1875 (Stivrins et al., 2016; Wulf et al., 2016; Tylmann et al., 2016; Luongo et al., 2017; Kalliokoski et al., 2019; Vakhrameeva et al., 2020; Tephabase, 2020) and Hekla-AD1845 (Wastegård, 2002; Watson et al., 2015; Watson et al., 2017b), (E-H) Eyjafjallajökull-AD2010 (Navrátil et al., 2013; Laeger et al., 2017; this study: Appendix 1), Grímsvötn (Óladóttir et al., 2011; this study: Appendix 1), Hekla (historical tephra: Larsen et al., 1999; Höskuldsson et al., 2007; Moune et al., 2007; Tephabase, 2020), and modern Kamchatkan tephra from Shiveluch and Kliuchevskoi volcanoes (Ponomareva et al., 2015; Portnyagin et al., 2020). Data of this study are shown with symbols, while reference data are shown with envelopes.

Figure 4. Schematic ash dispersal maps of historical and modern Icelandic volcanic eruptions based on published (dots) and new tephra findings (stars, this study) in European geological archives. (A) Distribution map of the Askja-AD1875 tephra, modified from Kalliokoski et al. (2019) and Vakhrameeva et al. (2020). (B) Sites of Eyjafjallajökull-AD2010 tephra deposition compared to the lower atmospheric ash dispersal (solid black line) modelled for 19 April 2010 by Davies et al. (2010). Data

for sites are obtained from Colette et al. (2011), Bukowiecki et al. (2011), Pitz et al. (2011), Schleicher et al. (2012), Lettino et al. (2012), Rossini et al. (2012), Revuelta et al. (2012), Stevenson et al. (2012, 2013) and Navrátil et al. (2013).

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