**Sustained volcanic impact and ecosystem disturbance over continental Europe during the
Early Holocene**

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Abstract

Estimating the environmental and societal impact of recent volcanic eruptions is a task aided by direct measurements and historical sources. Beyond the reach of first-hand accounts, our understanding of pre-historic volcanism is often hindered by the dating uncertainties inherent to stratigraphic archives. Here, we minimise this source of error by analysing the annually laminated sequences of two European lakes. We focus on environmental transformations that occurred in the decades preceding and following the deposition of the Icelandic Saksunarvatn tephra, dated between ca. 10,300 and 10,200 cal. BP. Evidence for continuous eruptive activity pre-dates the tephra deposition by nearly two decades, revealing a period of sustained volcanism and its effects on aquatic and terrestrial ecosystems. These results provide a new insight into the spatial and temporal effects of clustered volcanic eruptions. As such, they might prove useful to refine the simulation of volcanic forcing on continental ecosystems and to evaluate the resilience of prehistoric societies against sudden environmental downturns.

Introduction

Volcanism can severely affect the survival of human communities. Volcanic pollution and shorter growing seasons can decimate livestock and cause harvest failures, potentially escalating to social unrest, epidemics and migration fluxes¹. The impact of past and present eruptions on continental ecosystems is generally addressed at local-to-proximal scales. Studies with a wider spatial reach require precisely synchronised chronologies (e.g. ref. ²), which limit their application to the last few millennia. Especially for pre-historic eruptions, distal and ultra-distal effects on terrestrial and lacustrine biota, as well as on human societies, remain poorly investigated. In an attempt to address this gap, we focus on volcanic events and ecosystem responses surrounding the deposition of the ‘Saksunarvatn ash’, which originated from the Grímsvötn volcanic system (Iceland) around 10,300-10,200 cal. BP.

This basaltic tephra derives its name from Lake Saksunarvatn on the Faroe Islands³. Ash layers with comparable geochemistry have been identified between northern Greenland and northwestern Europe

(Fig. 1), prompting an early adoption of this tephra as an important North Atlantic stratigraphic marker⁴⁻⁶. Later investigations revealed multiple Saksunarvatn-like layers within individual cores: at least seven between Iceland and Greenland, spanning a period of ca. 120-500 years⁷⁻⁹, and at least four on the Faroe Islands within ca. 200 years¹⁰. These multiple events have not been detected so far in more distal archives. A single ash layer is dated to 10,210±35 cal. BP¹¹ or 10,176±49 cal. BP¹² at Kråkenes Lake (Norway), and to ca. 10,297±45 cal. BP in the NGRIP record¹³. In addition to these rather diverse estimates, trace element evidence points to distinct volcanic plumes directed towards Greenland and towards the continent^{14,15}.

Nevertheless, chronological offsets between the different eruptive episodes also depend on dating uncertainties. The NEEM sulfate record shows peak values concentrated between 10,320 and 10,300 cal. BP (Fig. 2a). In the GISP2 sequence, a sulfate peak dated to 10,275 cal. BP (Meese/Sowers scale) occurs in connection with a Saksunarvatn-like layer (Fig. 2b). Notably, a proposed correction to the GICC05 chronology¹⁶ would date the volcanic forcing associated with this peak to ca. 10,230 cal. BP (Fig. 2c-d), reducing the gap between the Greenland and Kråkenes age estimates. The absence of prominent acidity peaks between ca. 10,275 and 10,000 cal. BP appears to suggest that a younger sequence of eruptions – supposedly responsible for the tephra deposits to the east of Iceland – has left only minor or no traces at all.

The environmental impact of the Saksunarvatn events has been loosely addressed so far. Both the NEEM and GISP2 curves show a ca. 30-year-long phase of nearly uninterrupted sulfate accumulation preceding the Saksunarvatn tephra (Fig. 2a-b). It is unclear whether all of these continuous emissions can be attributed to Saksunarvatn-like eruptions; nonetheless, climate modeling suggests that this highly active period had a marked decadal impact on northern hemisphere temperatures (Fig. 2c-d). These results are corroborated by a reduction in the amplitude of $\delta^{18}\text{O}$ fluctuations in stratigraphic connection with the Saksunarvatn tephra, which might point to changes in atmospheric patterns as a response to sustained volcanic activity (Fig. 2d-e).

Here, we investigate this period of long-lasting volcanism through the analysis of two lacustrine archives from Woseriner See and Poggensee, Northern Germany (Fig. 1, Supplementary Fig. S1). Ecosystem reactions are investigated across a ca. 70 varve-year-long window centred on a single Saksunarvatn ash layer. Near-synchronous disturbance events detected at both sites allow us to suggest a precise correspondence between continental dynamics and Greenland acidity records. Furthermore, we provide two new age estimates for the tephra itself, with the aim to improve its reliability as a chronostratigraphic marker.

Fig. 1 | Origin of the Saksunarvatn tephra (red triangle) and location of sites where its presence has been variously reported. Named points refer to sites mentioned in this paper (all coordinates provided in Supplementary Tab. S1; possibly incomplete list).

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79 **Fig. 2 | Age estimates for different Saksunarvatn ash layers contextualised against ice core proxies and**
80 **modeled volcanic forcing between 10,500 and 10,000 cal. BP. a, Sulfate content of the NEEM ice**
81 **core⁴⁹. b, Volcanic sulfate within the GISP2 core^{17,18}. c, Volcanic forcing inferred from the GISP2**
82 **volcanic sulfate record¹⁶ and d, Modeled northern hemisphere climate anomaly¹⁶. e, NGRIP oxygen**

isotopes (5 cm resolution record and one-year linear resampling)^{13,50}. *f*, Rolling standard deviation of *e* (interpolated curve); see methods section. The presence of Saksunarvatn layers in the NEEM, GISP2 and NGRIP cores is marked by vertical dashed lines and follows refs. ⁵¹ and ¹⁸. Saksunarvatn age estimates and relative standard deviations follow refs. ^{11,12,51} and ¹⁸.

The Woseriner See (WOS) and Poggensee (POG) sequences

The Saksunarvatn tephra was initially identified as a dark band in both WOS and POG cores. Age-depth modelling and microprobe elemental data confirmed the attribution of these ash layers to Saksunarvatn, while thin-section analysis revealed that the tephra fallout occurred between the end of summer and spring (Supplementary Figs. S3-5). The Early Holocene chronology of both sequences is based on multiple radiocarbon dates constrained by varve counts. The Saksunarvatn layer is dated to ca. 10,282±45 cal. BP in WOS and to ca. 10,264±24 cal. BP in POG, both ±1σ (Fig. 2). No other tephra peaks were detected between ca. 10,400 and 10,000 cal. BP (Supplementary Fig. S6).

The annually laminated nature of both WOS and POG cores enables for a fine synchronisation of these two archives around the Saksunarvatn ash layer. Environmental reconstructions are based on the combined interpretation of pollen, geochemistry, varve microfacies analysis and lake-water pH reconstructions. These analyses were conducted at sub-decadal or annual resolution across core sections spanning ca. 70 varve-years and centred on the tephra layers. See the methods sections for all relevant details concerning dating, elemental composition, sample analysis and pH reconstruction procedure.

Tracers of volcanic activity

Evidence for volcanic activity in the WOS and POG cores is not limited to the visible tephra layer. The WOS sequence shows a distinct enrichment in sulfur after ca. -18 varve-years ‘From Tephra Deposition’

(FTD) (Fig. 3). This phenomenon ends with the deposition of the tephra. POG also shows a minor increase in sulfur after ca. -16 varve-years FTD, with a major peak visible within the ash-bearing sample. In POG, the pre-tephra accumulation of sulfur is rapidly followed by a lake-water pH decline of 0.3 units (after ca. -15 varve-years FTD). As with the increased sulfur input in WOS, the acidification trend in POG ends with the deposition of the tephra. The sandy young moraine landscape in which both WOS and POG are located does not provide a geological explanation for this burst in acidity, or for the quasi-contemporaneous pre-tephra rise in sulfur (e.g. erosion of gypsum, anhydrite or pyrite). Lacking any apparent local driver, we explicitly attribute these events to an external atmospheric source, namely volcanic eruptions. Building upon this interpretation, the combined evidence of sulfur increase and water acidification point to a continuous input of volcanic pollution that preceded tephra deposition by approximately 18 years. This long-lasing volcanic activity was then apparently followed by the tephra-bearing eruption, which marked the end of the sustained pollution influx and a return to pre-disturbance pH values.

The $\delta^{34}\text{S}$ signature of sulfur was analysed in order to further recognize a potential volcanogenic source. Lakes in the study area suffer from a shortage of the essential bioelement sulfur. As a consequence, its isotopic discrimination by activity of sulfate reducing bacteria preferring the lighter ^{32}S isotope is hampered. The addition of atmospheric sulfur would increase the sulfur pool available for bacterial sulfate reduction (BSR), and isotope discrimination would yield lighter $\delta^{34}\text{S}$ values. This is not observed, although POG in general shows lighter $\delta^{34}\text{S}$ values than WOS due to more intensive BSR in a better stratified kettle lake environment (Supplementary Fig. S10).

Notably, the WOS sequence lacks both a distinct pre-tephra marked acidification signal and a prominent sulfur peak in connection with the ash layer. The ratio between lake surface area and lake volume is smaller in WOS (0.11) compared to POG (0.33), suggesting that any effect from airborne compounds should manifest itself more severely in the latter. The diminished response of WOS is then considered to be a result of sulfuric acid buffering in the catchment and a larger lake volume, allowing for a higher

dilution of acid rain input and a higher in-lake neutralisation capacity. Environmental perturbations like acid rain are better recorded within smaller and more sensitive lake systems, as is the case of POG.

Given its dispersal capabilities, we can assume that the volcanic episode beyond the POG and WOS ash layers should have left traces of itself in the Greenland acidity records too. Between ca. 10,305 and 10,275 cal. BP (Meese/Sowers scale¹⁷), the GISP2 core registers a rather continuous occurrence of high SO_4^{2-} values (Fig. 3). Two prominent peaks within this time interval can be ascribed to major eruptions. The younger peak (ca. 10,275 cal. BP) is linked to a visible Saksunarvatn-like ash layer¹⁸. The older peak (ca. 10,284 cal. BP) is not associated with any detectable tephra. Trace element data exclude a direct correlation between continental and Greenland Saksunarvatn layers, and thus between the POG/WOS tephra and the 10,275 cal. BP GISP2 peak. Consequently, we propose a correspondence between the POG/WOS Saksunarvatn event and the 10,284 cal. BP sulfate peak. Despite representing a novel interpretation, this connection is generally supported by our dates for the continental Saksunarvatn ash layer, which place it considerably close to any Greenland age estimate (Fig. 2). Furthermore, the GISP2 sequence records a ca. 21 years-long continuous sulfate input before the 10,284 cal. BP peak (Fig. 3). A comparable distance (ca. 18-16 varve-years) separates the onset of sulfur enrichment in WOS and POG from the tephra layer, further suggesting a direct equivalence between these events and the GISP2 record. The apparent offset between lake reactions and Greenland acidity records might depend on combinations of soil buffering, dilution in the water column and biological assimilation, which masked the actual onset of sulfuric pollution in both lakes.

Semi-synchronous environmental response

Both WOS and POG show marked ecological changes within our study window. Disturbance evidence is first recorded across multiple proxies approximately two decades before tephra deposition (Fig. 4). The green algae *Phacotus lenticularis* displays an initial positive trajectory in both sequences, peaking

between -18 and -17 varve-years FTD. The POG diatom abundance curve shows a similar behavior, with an overall positive trend lasting until -18 varve-years FTD. In contrast, the WOS diatom curve displays a rapid growth only after -19 varve-years FTD, peaking at -17 varve-years FTD. These rising values are then followed by a generalised decline across all curves. The diatom flora composition is affected as well. The occurrence of *Fragilaria* sp. declines markedly in the POG sequence between -18 and -2 varve-years FTD. In the WOS record, the same taxon is partly replaced by a more regular occurrence of *Epithemia* sp. from -14 varve-years FTD onwards. Major changes in the diatom flora occur once again shortly after tephra deposition. In POG, *Stephanodiscus minutulus* becomes a common occurrence and *Asterionella* sp. is recorded for the first time, while in WOS the presence of *Aulacoseira* sp. becomes more stable. Marked eutrophication pulses in the post-tephra layers are visible in the erratic behavior of *P. lenticularis* (POG) and diatom curves (both records). Similar blooms do not occur in the WOS *P. lenticularis* record.

Shared behaviors are visible across pollen and algal influx records too, with prominent maxima occurring between -15 and -13 varve-years FTD (Fig. 5). The lowest influx values across all sequences are then invariably reached after these short-lived peaks, although with various timings. The WOS woody vegetation reaches its influx minimum shortly before tephra deposition, transitioning directly afterwards into a steady positive trend. In contrast, the woody vegetation at POG shows a long-lasting negative trend until +12 varve-years FTD. Herbaceous vegetation behaves similarly across both sites, with largely stagnating influx values persisting until ca. +28 varve-years FTD. Between ca. -13 and -4 varve-years FTD, while the influx of woody species shows a general decline, *Corylus* percentages at both sites react positively. This event occurs at the expense of *Betula* in POG and *Pinus* in WOS. This situation is then subverted after tephra deposition, when *Pinus* recovers in WOS, and POG exhibits a succession of *Betula* and *Pinus*.

The main features emerging from these comparisons are the generalised pre-tephra negative trends affecting lake productivity and pollen influx alike. Their occurrence within both sites appears to exclude strictly local phenomena, pointing instead to the presence of a region-wide forcing. Different proxies

show different reaction times, likely reflecting the complex reactions of different biota and lake systems to external stimuli, as well as possible varve count uncertainties.

Fig. 3 / Comparison between the GISP2 volcanic sulfate record (a) and geochemical data from Woseriner See (b) and Poggensee (c). The horizontal dashed lines highlights the chronological relationship between volcanic tracers in WOS and POG (onset of sulfur enrichment and acidification trend; tephra deposition) and possible corresponding events in the GISP2 sulfate curve (approximate onset of sulfate accumulation; 10,284 cal. BP peak). The black arrows in (a) mark the position of the Saksunarvatn-like ash layers in the GISP2 sequence. The grey shading in (b) and (c) highlight the period between -18 and -13 varve-years FTD, which marks the onset of environmental disturbance across multiple proxies (see Figs. 4-5). It was not possible to separate the tephra from the surrounding sediment during sampling. Therefore, sample no. 11 in both sequences includes the ash layer itself at its base.

Fig. 4 | Varve microfacies data from Woseriner See (WOS) and Poggensee (POG). The grey shading highlights the period between -18 and -13 varve-years FTD, which marks the onset of environmental disturbance across multiple proxies.

Fig. 5 / Palynological data from Woseriner See (a) and Poggensee (b). The black arrows highlight episodes of *Corylus* rise and decline common to both sequences. The grey shading highlights the period between -18 and -13 varve-years FTD, which marks the onset of environmental disturbance across multiple proxies.

Volcanism as a driver of change

In the years 1783-1784 CE, the Icelandic Laki eruption emitted 95 megatons SO_2 in the upper troposphere/lower stratosphere over the course of 8 months¹⁹. The resulting volcanic haze caused visible vegetation damage between Iceland and Western/Northern Europe, and affected temperatures across the

northern hemisphere for a few years. We propose that a comparable episode, although with a much longer duration, is responsible for at least part of the environmental dynamics recorded at WOS and POG. A sustained stream of volcanic pollution, lasting approximately two decades, might be responsible for the general decline in lake productivity recorded after -18 varve-years FTD, as suggested by the contemporaneous sulfur enrichment and acidification trend. This behavior is nonetheless preceded by growth episodes across most algal curves in Fig. 4, starting after ca. -20 varve-years FTD. It is unclear whether these positive trajectories can be interpreted as very early reactions to volcanic disturbance. Arguably, the initial exposition to acid compounds might have caused both sulfur fertilisation and nutrient mobilisation^{20,21}, thus promoting plant growth before causing the opposite effect through soil/water acidification. Volcanic emissions might have also triggered tropospheric warming (see ref. ²², but also ref. ²³), causing brief bursts across all proxies. The prominent influx peaks measured after ca. -17 varve-years FTD (Fig. 5) might equally be explained with a fertilisation/warming response, with any chronological offset between different proxies possibly depending on dating uncertainties. Yet, the absence of a prominent influx spike in the WOS *Corylus* curve (Supplementary Fig. S8) might exclude warming as the driver behind all -15/-13 varve-years FTD influx peaks. Being a thermophilous taxon, *Corylus* can be regarded as a diagnostic species to track temperature patterns (e.g. ref. ²⁴). For this reason, the rising percentages of this taxon after ca. -15 varve-years FTD (Fig. 5) might still suggest that *Corylus* was benefiting from relatively favorable growing conditions (e.g. longer/warmer growing seasons), while all species were generally affected by sulfuric pollution (i.e. broadly decreasing influx values). Using *Corylus* percentages to isolate volcanic-triggered warming is nonetheless a task complicated by the general post-glacial recovery trend characteristic for this taxon²⁵. For this reason, the declining *Corylus* percentages immediately after tephra deposition – paired with a consistent increase in more cold-tolerant taxa – represent more convincing evidence for a climatic downturn. The tephra bearing eruption can be considered directly responsible for this cooling phase, likely through a stratospheric injection of volcanic aerosol. Given our proposed connection with the GISP2 sulfate record, stratospheric cooling was possibly

initiated by the 10,284 cal. BP eruption and reinforced shortly afterwards by the 10,275 cal. BP volcanic emissions (Fig. 3), not unlike the sequence of events behind the 536-550 CE cold anomalies². The long-term effects of these combined eruptions are possibly responsible for the post-tephra shift in diatom flora composition, where the occurrence of *Stephanodiscus minutulus* and *Aulacoseira* sp. points to decadal changes in lake circulation²⁶.

In summary, the WOS and POG records suggest the presence of a bipartite episode of environmental disturbance. Approximately two decades of sulfur emissions caused widespread acid deposition and arguably triggered more continental climatic conditions. This situation ended with the tephra-bearing volcanic event, which marks the onset of a cooler climate. It remains difficult to pinpoint the end of this disturbance episode. *Corylus* percentages exhibit a positive trend at both sites after ca. +15 varve-years FTD, and all pollen influx values show positive trajectories by +30 or +35 varve-years FTD at the latest, suggesting that any major effect on terrestrial vegetation was limited to a few decades. Nonetheless, not all algal proxies return to pre-disturbance conditions within our study window (most notably diatom flora composition and *P. lenticularis* in WOS).

The multi-decadal extent of this event and its wide spatial reach might have had consequences not just on the vegetation but also on game and human communities, making it suitable to explore the resilience of Early Holocene societies to abrupt environmental downturns. Performing comparable studies in other high-resolution archives might contribute to an enhanced simulation of volcanic forcing in land-atmosphere models, and lead to a deeper understanding of (future) sustained volcanic episodes. Furthermore, confirming a connection between ice core acidity records and continental archives could further delimit the age of the most prominent Saksunarvatn ash layers in Greenland and on the continent, ultimately supporting their reliability as North Atlantic chronostratigraphic markers.

Methods

Site descriptions and sampling. Sediment cores were recovered from two Northern German lakes, Woseriner See (WOS) and Poggensee (POG) (Supplementary Fig. S1). Both lakes are located within the young moraine belt in Northeastern Germany, and arguably originated from melting dead-ice blocks following the retreat of the Late Weichselian (MIS 2) ice front^{27–29}. Woseriner See has a total water surface of ca. 2.17 km², a maximum depth of ca. 37.5 m and an above-ground catchment area of 75.8 km²³⁰. The much smaller Poggensee covers an area of ca. 0.088 km², has a maximum water depth of ca. 6.4 m and an above-ground catchment area of ca. 2.04 km²³¹. Sediment cores were retrieved from the deepest area of each lake through an Usinger piston corer³².

Master-sequence age-depth modeling. Age-depth modeling is based on radiocarbon dates and varve counts. It was carried out using a V_Sequence model in OxCal 4.3.2^{33,34} with the IntCal13 calibration curve³⁵.

For radiocarbon measurements, only short-lived macroremains from terrestrial plants were chosen. The careful examination of the freshly cut core surfaces enabled the identification of leaf fragments which could be attributed to a single varve year. For WOS and POG, 17 and 12 radiocarbon samples, respectively, have been measured (Supplementary Tab. S2).

For both sites, the individual core segments of three parallel core sequences have been linked to a master scale sequence using stratigraphical marker horizons, i.e. distinct layers identifiable in all parallel cores (master scale length of varved sequence WOS: 851.1 cm with 84 marker layers; POG: 471.8 cm with 132 marker layers). Varve counting has been carried out on high-resolution scans of the freshly cut core surface using the software C-DENDRO (<http://www.cybis.se/forfun/dendro/>). For each site, a varve count record was established using a similar approach as Dörfler et al.³⁶. This involved multiple counting of varve years between marker layers from different analysts in order to establish a maximum and minimum varve count record (*maxVCR* and *minVCR*, for more details see Dörfler et al.³⁶). For the OxCal model, the

maxVCR values were used to define the gap between two events, i.e. the marker layers. The difference between the *maxVCR* and *minVCR* values has been used as associated error estimates in the OxCal *gap()* function. Furthermore, the relative difference between the *maxVCR* and *minVCR* is used to evaluate the varve quality with respect to countability of the particular sections (*varve quality index* = $(\text{maxVCR} - \text{minVCR}) / \text{maxVCR} * 100$, cf. Supplementary Fig. S2, right side). The higher this index, the more difficult it was to achieve reliable varve counts. For sections with very high varve quality index values from POG (master scale 30,251 to 31,064 mm), more time-consuming varve counts on thin sections have been carried out and have been subsequently used in the OxCal V_Sequence model. In the case of WOS, ten homogeneous layers of unlaminated greyish sediment up to 1.3 cm thick (average 0.7 cm) are present in the lower core section (red bars in the varve quality index column in Supplementary Fig. S2a). These short uncountable sections are regarded to represent potential slump events. Therefore, a single year has been attributed to these sections as a prior gap value. As an associated error, we used the number of interpolated years – using the average sedimentation rate of the upper and lower ten varves – in the V_Sequence.

The *maxVCR* and *minVCR* consisted of 6,515 and 6,211 varve years for WOS, and 4,616 and 4,366 for POG, respectively. The latter excludes the difficult-to-count lower section (see above). For this part, the thin-section varve counts resulted in additional 1,946 varve years.

The result of the age-depth modeling is presented in Supplementary Fig. S2 and suggests a modeled range of 6,558 years (spanning from 4,051 to 10,609 cal. BP with an average sedimentation rate of 7.7 years cm^{-1}) for WOS and 6,369 years (spanning from 5,314 to 11,683 cal. BP with an average sedimentation rate of 13.2 years cm^{-1}) for POG, respectively.

Microprobe analysis. A visible tephra layer was detected in POG at a depth of ca. 30.4 m (master scale depth: 30,419.5 mm) and in WOS at a depth of ca. 55 m (master scale depth: 54,950 mm). Glass shards from these layers appear brown to greenish in colour, with blocky morphologies (Supplementary Fig. S3) and an average size of 60 μm . Shards from both layers were prepared in polished thin sections and

analysed via a JEOL JXA 8200 electron microprobe at GEOMAR (Kiel, Germany). Major and minor element geochemistry was determined using its five wavelength dispersive spectrometers. The analytical conditions were 15 kV accelerating voltage, 6 nA current and 5 μ m electron beam size. A set of natural reference materials from the Smithsonian collection was used for calibration and monitoring of routine measurements. Two to three analyses of standard glasses were performed at the beginning and at the end of an analytical session, and after every 50-60 analyses. The quality of the calibration and the performance of the probe were tracked by running the Lipari obsidian standard as a secondary glass standard. The laboratory contributed to INTAV (International Quaternary Association's focus group on tephrochronology) comparison of tephrochronology laboratories, which confirmed the high quality of the major-element data produced by the instruments set up³⁷. The secondary standard data measurements enabled the direct comparison of data sets published in the literature and analysed in other labs. All data presented here and those compared to literature are normalised to 100% volatile free totals.

The geochemical analyses of the glass shards from the layers in the two lakes are identical. The glass shards reveal a basaltic composition, with 49.2–50.3 wt.-% SiO₂, 2.5–3.3 wt.-% TiO₂, 13.2–15.1 wt.-% FeO, and 9.7–11.1 wt.-% CaO (Fig. S5). Average values are reported in Supplementary Tab. S3.

The chemical composition suggests that they are the result of the same volcanic fallout event and is consistent with the composition of the Saksunarvatn ash identified in terrestrial and marine sites in NW Europe. The tephra layer in both Woseriner See and Pogensee cannot be distinguished from the tephra described from sites in NW Europe based on their major and minor element composition (Supplementary Fig. S5). Shards with low MgO content, as found as precursors of Saksunarvatn tephra on the Faroer Islands (Havn-3 and Havn-4 in Wastegård et al.¹⁰), were not seen in the investigated cores. We did not analyse the trace element composition of the shards.

Cryptotephra identification. Core sections around the POG tephra layer were sampled at a resolution of 0.5-2 cm (Supplementary Fig. S6) and analysed in order to detect possible cryptotephra layers. Sediment samples were treated with HCl to dissolve carbonates, NaOH (10%) to eliminate diatom silicates, and

concentrated H₂SO₄ and HNO₃ to remove organic matter. Heavy mineral particles above 2.7 g/cm³ were separated from lighter particles, including tephra grains with gas inclusions, using Sodium polytungstate. The lighter fraction was mounted in glycerol-gelatin and subsequently analysed using a light microscope under bright field at ×250 magnification. With the exception of minor amounts of possibly reworked shards, these analyses show no evidence of additional tephra layers apart from the visible one.

High-resolution sampling and age-depth modeling for pollen and geochemical analysis. Sediment samples from WOS and POG were collected around the Saksunarvatn tephra layer using equally spaced razor blades. The distance between each blade was set to ca. 3.75 mm for Woseriner See and to ca. 2 mm for Pogensee, allowing for differences in the sedimentation rates of the two lakes in order to achieve a comparable temporal subsampling resolution. Sampling took place on parallel core sections, not on the master core sequence (see for instance Supplementary Fig. S6). A total of 20 samples was collected from each core (Supplementary Fig. S7). The computation of the age-depth models for these core sub-sections is independent from their respective master-sequence models. To allow a coherent comparison of these two sets of samples, their chronologies are based exclusively on varve counts and are synchronised using the tephra layer as a shared time-marker. In order to compute error estimates, multiple varve counts were performed by different analysts across each sub-section. Nine count estimates are available for POG. Five estimates were deemed sufficient for WOS due to its thicker and easier to count layers. The models were produced by iteratively adding all estimates for one sample to all estimates of the preceding one, then calculating median, mean and standard deviation across all the resulting combinations. These computations were performed separately for samples below and above the tephra layers.

Pollen analysis. WOS samples were treated with HCl 10% and KOH 5% in order to remove carbonates and humic acids. Pollen grain staining and cellulose removal were carried out via acetolysis³⁸. Mineral and organic particles below and above pollen grain size were removed through filtration with 6µm and 200µm sieves, respectively. *Lycopodium* markers were added before the chemical treatment in order to allow the calculation of pollen and palynomorph concentrations³⁹. The POG samples were processed

following a similar protocol yet, given the smaller amount of sediment available, the sieving step was not performed in order to minimise the number of steps and sediment loss. Pollen identification is based on dichotomic identification keys^{40,41} and on the reference collection of the palynological laboratory of Kiel University. A minimum of 700 grains of arboreal taxa were counted for each sample. Pollen influx and percentage data of selected groups and taxa are presented in fig. 5. Pollen influx (PI) is defined as the number of pollen grains deposited annually in a unit area of sediment ($grains \cdot cm^{-2} \cdot year^{-1}$). Influx values are calculated with the following formula⁴²:

$$PI = PC \cdot SR$$

where:

$$PC = \text{Pollen Concentration} = \frac{\text{total Lycopodium markers added to sample}}{\text{Lycopodium markers counted}} \cdot \frac{\text{grains}}{cm^3}$$

$$SR = \text{Sedimentation Rate} = \frac{cm}{year}$$

Sample-specific mean influx values and error estimates (as presented in Fig.5) were obtained by calculating influx values across every combination of base parameters (volume, thickness, number of years) available for each sample. Due to their regular shapes and easily measurable dimensions, volume estimates for WOS samples was carried out with the simple formula:

$$\text{Volume} = (\text{Height} \cdot \text{Length} \cdot \text{Width})$$

applied to every sampled sediment slice. A more careful approach was applied to POG samples due to their smaller thickness and occasional irregular shapes. Area calculations for each sediment slice (10 estimates) were carried out with the software ImageJ⁴³ (Supplementary Fig. 8). Volumes were then calculated by multiplying each area estimate by three different sample thickness values (0.19 cm, 0.20 cm, 0.21 cm), thus introducing an arbitrary 5% error margin to the established thickness parameter (0.2 cm). This error margin was applied equally to all 20 POG samples and, as such, it does not influence

mean volume calculations across the sequence. Given the thickness of the POG samples, the flexibility of the razor blades used for sampling might have had an impact on sample volume. While this effect cannot be quantified, the introduction of this arbitrary 5% error serves – at the very least – to acknowledge its existence and produce more realistic influx error estimates.

We focus our analysis on two main ecological assemblages: woody vegetation and terrestrial herbaceous vegetation. The woody and herbaceous assemblages are composed by the sum of multiple taxa (list in Supplementary Tab. S4). The main components of these curves (*Betula*, *Corylus*, *Pinus* for the woody vegetation curve; Poaceae for the herbaceous one) are presented separately in Supplementary Fig. S9. The influx curve of the algae *Botryococcus* is also presented in Fig. 5 due to its broad similarities with the pollen influx curves. Different other algal taxa were detected in pollen slides. In the POG sequence, *Pediastrum* and *Tetraedron* show behaviors comparable to *Botryococcus*. In contrast, the WOS communities appear to follow independent trajectories. Algal taxa fairly frequent in the POG record (e.g. *Gloeotrichia*, *Scenedesmus*) are absent or rare in the WOS sequence, and therefore were not included in Supplementary Fig. S9. The calculation of pollen percentages is based on the Total Terrestrial Pollen Sum (TTPS). Only the curves of *Pinus*, *Betula* and *Corylus* are shown in Fig. 5, since they represent the major components of the pollen flora at both sites.

Thin-section analysis. The algal proxies presented in Fig. 4 are recorded at annual resolution. Their time-scale is based on varve microfacies analysis on thin sections and centred on the tephra layer. Varve years were defined as a sequence of sub-layers associated with known limnological processes. The succession of a planktic diatom layer (spring mixing), a calcite precipitation layer (summer), and re-deposition detritus layer (fall) together were interpreted as the deposition of one year. The shells of *Phacotus lenticularis* and the amount of diatom shells (on species/genus level) were recorded semi-quantitatively in arbitrary units for each layer. A repeated cross-check of estimations of the years was carried out to guarantee the quality of the estimation. The semi-quantitative values were then multiplied by the thickness of the respective sub-layer to calculate the presence of a component in a year.

NGRIP rolling standard deviation. Fig. 2f is meant to highlight a reduction in the amplitude of $\delta^{18}\text{O}$ fluctuations visible in the NGRIP record. The one-year interpolated record from fig. 2e was linearly detrended with R package ‘pracma’ v2.2.5⁴⁴. Standard deviation values were then calculated using a rolling 30-year window applied to the detrended curve. This procedure does indeed reveal a pronounced negative peak in connection with the Saksunarvatn tephra layer. To determine the statistical significance of this signal, the same procedure was applied to 999 sequences with the same structure (mean and standard deviation) of the original data. The percentile boundaries are based on the pools of maximum and minimum values recorded across all 999 simulations. The choice of a 30-year window is based on the approximate length of the continuous sulfate input detected in the GISP2 sequence between 10,305 and 10,275 cal. BP (Fig 2).

Chemical characterisation of the sediment. The following measurements (sulfur content, sulfur isotope analysis, GDGT analysis) were carried out for both cores at the same depths sampled for pollen analysis.

Sulfur content. The total sulfur (TS) content of the sediments was determined with an Elementar Vario EL-III CNS analyser following standard procedures. Sulfanic acid (S= 18.5 weight %) was used for instrument calibration and an analytical error of $\pm 0.01\%$ was determined. The resulting values, reported in Fig. 3, were log-transformed specifically to highlight pre-tephra patterns in the POG sequence, which are dampened by the prominent sulfur peak within the tephra-bearing sample.

Sulfur isotope analysis. Sulfur isotope analysis was performed using a Thermo Finnigan Delta V irMS coupled to a Flash EA via a ConFlo III interface. The Flash EA is equipped with an NCS Sulfinert® separation column (2m $\times$ 0.210 mm, Restek, USA) which was kept at a constant temperature of 100° C. The combustion reactor (left oven) of the Flash EA was a quartz reactor tube filled with electrolytic copper, quartz wool and tungsten oxide. The right oven was equipped with an empty quartz reactor tube. Reactors were operated at 1,020 °C and 400 °C, respectively. Standards used for calibration and subsequent correction of measured samples were silver sulfide reference materials IAEA-S-1, IAEA-S-2, and IAEA-S-3 (International Atomic Energy Agency, Austria).

Isotope ratios are expressed in conventional delta notation: $\delta_{\text{sample}} (\text{‰}) = [(\text{R}_{\text{sample}} - \text{R}_{\text{standard}}) / (\text{R}_{\text{standard}} - 1)] \times 1000$, where R is the ratio of $^{34}\text{S}/^{32}\text{S}$ of the sample and the standard VCDT (Vienna-Canyon Diablo Troilite) for sulfur. The results are presented in Supplementary Fig. S10.

GDGT analysis. Sulfuric acid rain persisting over years will have affected the palaeoecosystem by acidification of lake water and catchment soils. Microbial consortia thriving in catchment soil or in lake water and sediment would need to adjust their cellular plasma membrane composition to the decrease in pH values. This is recorded in sedimentary archives in the molecular composition of glyceroldialkylglyceroltetraethers (GDGT). As a response to decreasing pH, bacteria will increase the number of cyclopentyl-rings in the GDGT molecule^{45–47}, expressed as the cyclisation of branched tetraether index (CBT). The analysis of GDGT and determination of the palaeo-pH value based on CBT values employ a calibration set for lake sediments from Ajioka et al.⁴⁵.

Lipids were extracted using pressurised liquid Extraction (DIONEX ASE150) using a solvent mixture of hexane/dichloromethane (9/1; v/v) and separated into non-polar and polar compound classes by automated SPE (LC-Tech Freestyle) on 2g of activated silica. Non-polar compounds were eluted with hexane/dichloromethane (9/1; v/v) and polar compounds with methanol/dichloromethane (1/1; v/v). The polar fractions were dried under a gentle stream of nitrogen, dissolved in n-hexane:2-propanol (99:1, v/v) to a concentration of 1mg/ml and passed through a 0.45µm polytetrafluoroethylene (PTFE) filter (Macherey-Nagel, Germany) prior to analysis. GDGTs were analysed using a Waters Alliance 2695 HPLC system following the analytical protocol described by Hopmans et al.⁴⁸, enabling separation of 5- and 6-methyl branched GDGT isomers. The HPLC system was equipped with two Waters BEH HILIC silica columns (2.1 × 150 mm; 1.7µm particle size) and a guard column maintained at 30 °C. GDGTs were eluted at a flow rate of 0.2ml/min starting isocratically with 82% eluent A (n-hexane) and 18% eluent B (n-hexane:2-propanol (9:1, v/v)) for 25 min. A linear gradient was set to 65% eluent A and 35% eluent B in 25 min, followed by a linear gradient to 0% eluent A and 100% eluent B in 30 min. Detection

of isoprenoid and branched GDGTs was achieved using a Micromass ZQ single quadrupole mass spectrometer equipped with an APCI interface operated in positive ion mode.

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Author contributions

MZ and WD designed the research. IF took care of pollen analysis along the Woseriner See sequence, as well as producing the master-scale age-depth models for both Woseriner See and Poggensee. SD took care of varve microfacies analysis for both sequences. LS conducted sulfur analysis and pH reconstructions for both sequences. CvdB performed microprobe analyses on tephra shards from both sequences. MZ is responsible for pollen analysis on Poggensee samples, plus data elaboration and high-resolution age-depth modeling for both sequences. The manuscript was written by MZ with contributions from WD, IF, SD, LS and CvdB.

Competing Interests

The authors declare no competing interests.

Figure Legends

Fig. 1 | Origin of the Saksunarvatn tephra (red triangle) and location of sites where its presence has been variously reported. Named points refer to sites mentioned in this paper (all coordinates provided in Supplementary Tab. S1; possibly incomplete list).

Fig. 2 | Age estimates for different Saksunarvatn ash layers contextualised against ice core proxies and modeled volcanic forcing between 10,500 and 10,000 cal. BP. a, Sulfate content of the NEEM ice core⁴⁹. **b,** Volcanic sulfate within the GISP2 core^{17,18}. **c,** Volcanic forcing inferred from the GISP2 volcanic sulfate record¹⁶ and **d,** Modeled northern hemisphere climate anomaly¹⁶. **e,** NGRIP oxygen

isotopes (5 cm resolution record and one-year linear resampling)^{13,50}. **f**, Rolling standard deviation of **e** (interpolated curve); see methods section. The presence of Saksunarvatn layers in the NEEM, GISP2 and NGRIP cores is marked by vertical dashed lines and follows refs. ⁵¹ and ¹⁸. Saksunarvatn age estimates and relative standard deviations follow refs. ^{11,12,51} and ¹⁸.

Fig. 3 | Comparison between the GISP2 volcanic sulfate record (a) and geochemical data from Woseriner See (b) and Poggensee (c). The horizontal dashed lines highlights the chronological relationship between volcanic tracers in WOS and POG (onset of sulfur enrichment and acidification trend; tephra deposition) and possible corresponding events in the GISP2 sulfate curve (approximate onset of sulfate accumulation; 10,284 cal. BP peak). The black arrows in **(a)** mark the position of the Saksunarvatn-like ash layers in the GISP2 sequence. The grey shading in **(b)** and **(c)** highlight the period between -18 and -13 varve-years FTD, which marks the onset of environmental disturbance across multiple proxies (see Figs. 4-5). It was not possible to separate the tephra from the surrounding sediment during sampling. Therefore, sample no. 11 in both sequences includes the ash layer itself at its base.

Fig. 4 | Varve microfacies data from Woseriner See (WOS) and Poggensee (POG). The grey shading highlights the period between -18 and -13 varve-years FTD, which marks the onset of environmental disturbance across multiple proxies.

Fig. 5 | Palynological data from Woseriner See (a) and Poggensee (b). The black arrows highlight episodes of *Corylus* rise and decline common to both sequences. The grey shading highlights the period between -18 and -13 varve-years FTD, which marks the onset of environmental disturbance across multiple proxies.

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634 **Fig. S1 | Geographic contextualisation of Woseriner See and Poggensee. a,** location of the
635 study sites within Northern Germany. **b,** basin outline of Woseriner See. **c,** basin outline of
636 Poggensee.

Fig. S2 | Age-depth models for the Woseriner See and Poggensee master sequences. Age-depth models (left) and varve quality index (right) for Lake Woserin (**a**) and Lake Poggensee (**b**). Calibrated median and 2 sigma ranges are indicated for the radiocarbon dates (dots; outliers marked in red). The modeled median age and the 2 sigma ranges of the age-depth models are shown as black lines and grey ranges, respectively. Red bars in the varve quality index of Lake Woserin indicated un laminated/disturbed layers (potential slump). The red bar in the varve quality index of Poggensee indicates the section for which varve counts from thin sections have been used.

Fig. S3 | Saksunarvatn tephra from Poggensee. Shards visible in the sediment sample prepared from pollen analysis (sample no. 11 in fig. 3, POG core).

Fig. S4 | Varve layers from Poggensee. Photos of thin sections under transmitted-light microscope. **a**, un-polarised light. **b**, crossed nicols plus red filter. The arrows highlight the position of few tephra shards.

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655 **Fig. S5 | Selected bi-plots showing tephra glass shard major element compositions.** All
 656 major and minor data are plotted as volatile free normalised values. **a**, The data sets from the
 657 analysed tephra layers in Poggensee and Woseriner See plotted using the Total Alkali Silica
 658 (TAS) classification of Le Bas et al.¹. **b–c**, Geochemical composition of the basaltic shards from
 659 Poggensee and Woseriner See tephra compared to the composition of the Saksunarvatn tephra
 660 close to the source (Iceland) and tephra layers in distal sites correlated to Saksunarvatn Ash.
 661 References: Greenland²; North Atlantic²; Iceland³; Faroer – Sandoy⁴; Faroer – Fosen⁵; Faroer –
 662 Havn T.0-4⁶; Scotland⁷; Hämelsee⁸; Tiefer See⁹; Potremser Moor¹⁰.

665 **Fig. S6 | Position of the Saksunarvatn tephra layer in two parallel Poggensee core sections.**
666 **a**, Master core section with position of samples analysed for tephra presence (black bars) and
667 related shard counts; sediment ages are based on the age-depth model from Supplementary Fig.
668 S2. **b**, Parallel core section used for all environmental analysis addressed in the paper. Black
669 squares indicate the depth of the 20 samples used for pollen and geochemistry (see also
670 supplementary Fig. S7).

Fig. S7 | Samples selected for pollen and geochemical analysis. a, Woseriner See sequence. **b,** Poggensee sequence (see also Supplementary Fig. S3). Black squares indicate the position and thickness of samples collected for pollen and geochemical analysis. Sample ages are relative to the tephra layer. Tephra influx values are based on shards counted in pollen slides.

Fig. S8 | Estimating the area of a POG sediment sample with the software package ImageJ.

The sediment sample is contained in a plastic bag to minimise direct handling and avoid contaminations. Ten area estimates were carried out for each sample. After each measurement, the software was re-calibrated on different parts of the photographed ruler (only parts adjacent to the sample) as an attempt to counter any image distortion introduced by the camera.

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Fig. S9 | Influx values of selected pollen and algal taxa from Woseriner See and Poggensee.

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Fig. S10 | Total sulfur (TS) vs. $\delta^{34}\text{S}$ ‰ for Woseriner See and Poggensee. Sample numbers for each site match those reported in fig. 3. The relationship between sulfur abundance and $\delta^{34}\text{S}$ signature for Woseriner See shows a deviation during the phase of pre-ash volcanogenic sulfur deposition, with heavier $\delta^{34}\text{S}$ values recorded. Volcanogenic $\delta^{34}\text{S}$ signatures vary between -5 to +20‰, with dependence mainly on the magma type¹¹, with most values centered around +3 to +8‰. Average atmospheric sulfate $\delta^{34}\text{S}$ values for the study area were reported to be about +2‰¹². These values are affected by anthropogenic sulfur emissions and contrast $\delta^{34}\text{S}$ values of sedimentary sulfur averaging -6‰ for Lake Steisslingen in SW Germany¹³, arguing for a comparable atmospheric background $\delta^{34}\text{S}$ signal. Holocene lake sediment $\delta^{34}\text{S}$ composition for these three German lakes are compatible with predominantly sulfate aerosol sulfur sources derived from sea spray. Deviation to heavier $\delta^{34}\text{S}$ values in comparison to sulfur abundance could then indicate a volcanogenic sulfur aerosol source. Given an average atmospheric $\delta^{34}\text{S}$ signature of -6‰ for the POG sulfur rich sample, sediment sulfur would be expected to yield a $\delta^{34}\text{S}$ value around -20‰ as observed for sulfur rich-Pleistocene sediments from Lake Steisslinger¹³. The $\delta^{34}\text{S}$ value of -9.3‰ observed for the sulfur-rich POG ash layer can be attributed to an isotopically heavier volcanogenic sulfur source. In addition, only a part of the sulfur in the ash layer may have been accessible to BSR due to its isolation in glass and thus a mixed signal of ash-sulfur and BSR-sulfur is isotopically recorded. For both studied lakes, a volcanogenic sulfur component is manifested in the $\delta^{34}\text{S}$ record.

710 **Tab. S1 | Location of sites with reported presence of Saksunarvatn-like tephra.**

Site	Longitude	Latitude	Location	notes	Reference paper
NEEM	-51.07	77.45	Greenland		14
NGRIP	-42.05	75.016667	Greenland	coordinates taken from NGRIP website http://www.gfz.ku.dk/~www-glac/ngrip/index_eng.htm	15
GISP2	-38.5	72.6	Greenland	coordinates taken from www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/ice-core	16
GRIP	-37.64	72.58	Greenland	Correlation with Saksunarvatn reported as uncertain. Coordinates taken from ref. ¹⁷ .	18
JM-96-1214/2-GC	-30.966667	67.3	Kangerlussuaq Trough (East Greenland shelf)		19
JM-96-1215/2-GC	-30.86	67.046667	Kangerlussuaq Trough (East Greenland shelf)		19
JM-96-1216/2-GC	-30.633333	65.962833	Kangerlussuaq Trough (East Greenland shelf)		19
B997-315	-24.3355	66.732667	Djúpáll (off Iceland coast)		20
MD99-2265	-24.257833	66.277167	Ísafjar-árdjúp (off Iceland coast)	These coordinates might refer to core 2266. Disagreement between figure and table in ref. paper.	20
MD99-2265	-24.257833	66.277167	Ísafjar-árdjúp (off Iceland coast)		20
MD99-2264	-24.196	66.679	Djúpáll (off Iceland coast)		20
MD99-2264	-24.196	66.679	Djúpáll (off Iceland coast)		20
B997-335	-24.161667	66.686833	Djúpáll (off Iceland coast)	Coordinates in ref. paper appear to be incorrect. They seem to refer to core 334 instead. Coordinates of core 336 used here, as it appears to be located close to core 335.	20
B997-336	-24.161667	66.686833	Djúpáll (off Iceland coast)		20
B997-336	-24.161667	66.686833	Djúpáll (off Iceland coast)		20
B997-337	-24.127167	66.669333	Djúpáll (off Iceland coast)		20
B997-339	-22.800633	66.018433	Ísafjar-árdjúp (off Iceland coast)		20
B997-339	-22.800633	66.018433	Ísafjar-árdjúp (off Iceland coast)		20
Efstadalsvatn	-22.665	65.943833	Iceland		20
Efstadalsvatn	-22.665	65.943833	Iceland		20
Efstadalsvatn	-22.665	65.943833	Iceland	Coordinates reported in paper are off by one degree. More accurate coordinates taken from ref. ²⁰ .	21
Seltjörn	-22.022844	64.157986	Iceland		22
Reykjarfjörður	-21.65265	65.974667	Iceland		20
Nordurfjörður	-21.58	66.056333	Iceland		20
B997-332	-21.418	66.1365	Húnaflói/Húnaflóadjúp (off Iceland coast)		20
B997-329	-21.2985	65.966667	Húnaflói/Húnaflóadjúp (off Iceland coast)		20
B997-325	-20.999833	66.567167	Húnaflói/Húnaflóadjúp (off Iceland coast)		20
MD99-2269	-20.852667	66.6255	Húnaflói/Húnaflóadjúp (off Iceland coast)		20
Torfadalsvatn	-20.382977	66.059931	Iceland		23
HM107-04	-19.05	67.227222	off Iceland coast		24

B997-317	-18.864167	66.587833	Eyjafjararáll (off Iceland coast)	Unclear identification	20
B997-319GGC	-18.837333	66.447	Eyjafjararáll (off Iceland coast)	Unclear identification	20
HM107-05	-17.905278	66.902222	off Iceland coast		24
P57-7	-13.872667	68.429	southern Norwegian Sea		25
Saksunarvatn	-7.156332	62.240405	Faroe Islands		26
Mjáuvøtn	-7.001616	62.127663	Faroe Islands	Coordinates in ref. paper a bit imprecise. Point placed in Mjáuvøtn lake.	27
Høvdarhagi	-6.916667	61.9	Faroe Islands		4
Havnardalsmyren	-6.851389	62.016667	Faroe Islands	Approximate coordinates from ref. ²⁸	6
LINK14	-5.948917	61.729084	East Faroe Shelf Trough	Approximate position. Coordinates not reported in ref paper.	29,30
HM57-14	-5.2	65.983333	Norwegian Sea		31
Quoyioo Meadow	-3.309714	59.066634	Orkney		32
Crudale Meadow	-3.306061	59.016375	Orkney		32
Loch of Benston	-1.162242	60.263858	Shetland		33
Dallican Water	-1.098413	60.387472	Shetland		34
HM79-6.2	2.7	62.966667	Norwegian sea		35
Kråkenes Lake	5.003807	62.025904	Norway		36
Eversener See	9.308427	53.042063	Germany		37
Hämlensee	9.310562	52.759457	Germany		37
Muggesfelder See	10.3312	54.025603	Germany		37
Poggensee	10.385179	53.826739	Germany		this paper
Plußsee	10.444036	54.182187	Germany		37
Grønli fen	10.48	63.784444	Norway	Coordinates in ref. paper might be a bit off.	5
Woseriner See	12.03528	53.665991	Germany		this paper
Potremser Moor	12.275659	53.991213	Germany		10
Tiefer See	12.53	53.591667	Germany		9
Lusvatnet	15.566667	69.066667	Norway		38

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714 **Tab. S2 | Radiocarbon dates used in the construction of the age-depth models for the**
715 **Woseriner See and Poggensee master sequences.**

716	Lab. no.	Master scale (mm)	^{14}C age (BP) $\pm 1 \sigma$	delta ^{13}C (‰ PDB)
717	<i>Lake Woserin</i>			
718	KIA-49175	46,765	3,699 ± 46	-26.89
719	KIA-49176	47,195	3,888 ± 28	-27.38
720	KIA-49174	47,341	4,222 ± 49	-29.47
721	KIA-49173	47,511	4,019 ± 29	-30.76
722	Poz-63881	47,560	4,035 ± 35	-25
723	KIA-49171	47,955	4,201 ± 35	-28.17
724	Poz-63880	48,012	4,140 ± 35	-25.4
725	KIA-49172	48,055	4,333 ± 28	-28.11
726	KIA-49055	48,427	4,620 ± 70	-28.53
727	Poz-63882	49,598	5,310 ± 40	-30
728	KIA-49053	49,984	5,480 ± 35	-27.01
729	KIA-49052	50,277	5,708 ± 23	-25.89
730	KIA-53220	51,847	6,985 ± 35	-27.57
731	KIA-53221	52,532	7,525 ± 40	-30.9
732	KIA-53222	53,703	8,145 ± 40	-24.67
733	KIA-53424	54,544	8,840 ± 35	-28.2
734	KIA-53223	55,133	9,390 ± 35	-26.68
735	<i>Lake Poggensee</i>			
736	KIA-40936	26,365	4,525 ± 30	-27.92
737	KIA-42091	27,193	5,190 ± 35	-26.76
738	KIA-42092	27,983	5,885 ± 25	-28.5
739	KIA-52322	28,829	6,729 ± 23	-26.75
740	KIA-40937	28,865	6,835 ± 30	-30.13
741	KIA-52323	29,059	7,067 ± 24	-30.75
742	KIA-52324	29,547.5	7,846 ± 25	-31.35
743	KIA-52325	29,827	8,283 ± 26	-31.5
744	KIA-53423	29,900	8,344 ± 37	-27.5
745	KIA-52326	30,681	9,428 ± 28	-28.05
746	KIA-52327	30,827.5	9,580 ± 50	-31.3
747	KIA-52328	30,885	9,735 ± 40	-28.6
748				

749 **Tab. S3 | Geochemical composition of the tephra in Woseriner See and Poggensee.** Mean
750 values and one standard deviation.

Site	Poggensee (POG)			Woseriner See (WOS)		
Master scale depth (mm)	30,419.5			54,950		
no. of analyses	40			63		
SiO ₂	49.68	±	0.20	49.82	±	0.26
TiO ₂	3.15	±	0.12	3.12	±	0.10
Al ₂ O ₃	12.97	±	0.12	13.03	±	0.15
FeO	14.59	±	0.31	14.50	±	0.37
MnO	0.25	±	0.04	0.24	±	0.04
MgO	5.63	±	0.19	5.64	±	0.27
CaO	10.01	±	0.22	10.05	±	0.23
Na ₂ O	2.88	±	0.15	2.81	±	0.24
K ₂ O	0.46	±	0.03	0.46	±	0.03
P ₂ O ₅	0.33	±	0.03	0.31	±	0.04
F	0.04	±	0.05	0.04	±	0.05
SO ₃	0.24	±	0.05	0.23	±	0.05
Cl	0.02	±	0.01	0.03	±	0.01
Total	99.11	±	0.43	99.01	±	0.55

752 **Tab. S4 | Woody and terrestrial herbaceous pollen taxa used in influx calculations.**

Woody taxa			
<i>Abies</i>	Ericaceae	<i>Picea</i>	<i>Sambucus ebulus</i>
<i>Alnus</i>	<i>Frangula</i>	<i>Pinus</i>	<i>Sambucus nigra</i>
<i>Betula</i>	<i>Fraxinus</i>	<i>Populus</i>	<i>Sorbus</i>
<i>Calluna</i>	Genista-type	<i>Prunus</i>	<i>Tilia</i>
<i>Cornus sanguinea</i>	<i>Hedera</i>	<i>Quercus</i>	<i>Ulmus</i>
<i>Corylus</i>	<i>Hippophaë</i>	Rosaceae	<i>Vaccinium</i>
<i>Empetrum</i>	<i>Juniperus</i>	<i>Salix</i>	<i>Viburnum opulus</i> -type
Terrestrial herbaceous taxa			
<i>Adoxa</i>	<i>Cerastium</i> -type	<i>Melampyrum</i>	<i>Sanguisorba officinalis</i>
Amaranthaceae	cf. <i>Pulsatilla vulgaris</i>	<i>Mentha</i> -type	<i>Saxifraga</i> undiff.
<i>Anthemis</i> -type	<i>Cirsium</i> -type	<i>Persicaria amphibia</i>	Scrophulariaceae
Apiaceae	Fabaceae	Plantaginaceae undiff.	<i>Scrophularia</i> -type
<i>Artemisia</i>	<i>Filipendula</i>	<i>Plantago major</i> / <i>P. media</i>	<i>Sinapis</i> -type
Cichorioideae	<i>Galium</i> -type	Poaceae	Spergularia
Asteraceae undiff.	<i>Geranium</i>	Cerealia-type	<i>Thalictrum</i>
<i>Aster</i> -type	<i>Geum</i>	<i>Polygonum aviculare</i>	<i>Triticum</i> -type
<i>Astragalus</i> -type	<i>Helianthemum</i>	Primulaceae	<i>Urtica</i>
<i>Bidens</i> -type	<i>Heracleum sphondylium</i>	Ranunculaceae	
Brassicaceae	<i>Hordeum</i> -type	<i>Ranunculus acris</i> -type	
<i>Caltha</i>	<i>Humulus/Cannabis</i>	<i>Rhinanthus</i> -type	
Campanulaceae	<i>Hypericum</i>	<i>Rumex acetosa</i> -type	
Caryophyllaceae	<i>Jasione</i>	<i>Sanguisorba minor</i> -type	

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