Constraining the time span between the early Holocene Hässeldalen and Askja-S Tephras through varve counting in the Lake Czechowskie sediment record, Poland

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Abstract

We report the first findings of co-existing early Holocene Hässeldalen and Askja-S cryptotephras in a varved sediment record in Lake Czechowskie (Poland). A time span of 152 +11/-8 varve years between both tephras has been revealed by differential dating through varve counting. This is in agreement within the uncertainties with calculations from radiocarbon-based age models from the non- varved Hässeldala port record in southern Sweden, but shorter than assumed from the non-varved lake record on the Faroe Islands. We discuss possible reasons for the observed differences in duration between both tephras and provide a revised absolute age for the Askja-S tephra of 11,228 ± 226 cal a BP based on anchoring our floating varve chronology to the absolute timescale by using the Hässeldalen Tephra as dated in the Hässeldala port sediments (11,380 ± 216 cal a BP). This age is in agreement with radiocarbon age models with larger uncertainty ranges, but is slightly older than radiocarbon-based age models with narrow uncertainty bands and even 200-300 years older than the age reported from the Faroe Islands record. In addition to these chronological issues we discuss the possible response of the Czechowskie sediment record to the Preboreal climate oscillation.

Keywords: Early Holocene, Askja-S, Hässeldalen, varved lake sediments, differential dating

Introduction

Tephra layers (volcanic fallout deposits) are ideal stratigraphic isochrones that allow precise synchronisation of palaeoclimate and palaeoenvironmental records and thus the determination of potential temporal and spatial offsets of proxy signals. The recent methodological advance in cryptotephra (non-visible tephra layers) identification enabled the first synchronisation even of proxy records in great distances (Lane *et al*., 2012a, 2013; Wulf *et al*., 2013; Davies, 2015). Annually laminated (varved) sediment records are of particular value for tephra dating because of their potential for differential dating, i.e. precise determination of the time between volcanic ash layers (Wohlfarth *et al*., 2006; Blockley *et al*., 2014; Lane *et al*., 2015).

The Hässeldalen and the Askja-S tephras areconsidered as key isochrones for synchronising early Holocene sediment records in western and northern Europe (Davies *et al*., 2003; Wohlfarth *et al*., 2006; Lane *et al*., 2012a, 2012b). The chronostratigraphic importance of these tephras is due to their occurrence immediately before (Hässeldalen) and after (Askja-S) the Preboreal Oscillation (PBO) as inferred from pollen data and lower organic carbon contents in the Hässeldalen record (Wohlfarth *et al*., 2006) The PBO is a brief cold oscillation during the early Holocene that likely has been triggered by a slow-down of the North Atlantic thermohaline circulation (Lowe *et al*., 1994; Björck *et al*., 1996, 1997; Fisher *et al*., 2002; van der Plicht *et al*., 2004; Rasmussen *et al*., 2007; Bos *et al*., 2007). Early Holocene cold periods have also been named as ‘Friesland Oscillation’ in Denmark (Iversen, 1973), ‘Youngest Dryas’ in Germany (Behre, 1978), ‘Rammelbeek Phase’ in the Netherlands (Bos *et al*., 2007) and ‘Piottino Oscillation’ in Switzerland (Zoller, 1960).

The exact timing and duration of the PBO particularly in lake records remain uncertain because of dating uncertainties due to two early Holocene radiocarbon plateaus and unclear proxy evidence. In the NGRIP ice core record a distinct decline in stable oxygen isotope data is dated in the GICC05 chronology at 11,650 - 11,270 ice layer yrs BP with the coldest part between 11,470 and 11,350 ice layer yrs BP labelled as ‘11.4 ka event’ (Rasmussen *et al*., 2014). This is slightly older than ages based on the GRIP chronology (11,300-11,150 yrs BP (Björck *et al*., 1997). The so- called ‘ice core PBO’ has been related to the ‘Rammelbeek Phase’, a cold and dry period that caused an interruption of the early Holocene forest succession, dated at 11,430 - 11,350 cal a BP (Bos *et al*., 2007) or 11,450 - 11,250 cal a BP (van der Plicht *et al*., 2004). In the Netherlands, the ‘Rammelbeek Phase’ further has been distinguished from a subsequent shift towards more humid conditions commencing at ca 11,250 cal a BP and labelled as ‘terrestrial PBO’ (van der Plicht *et al*., 2004; Bos *et al*., 2007). Other reports dated the ’terrestrial PBO‘ older (11,387-11,298 cal a BP) than the ’Rammelbeek Phase’ (11,127-10,830 cal a BP) (Bohncke and Hoek, 2007), while Merkt and Müller (1999) did not distinguish between an ’ice core’ and a ‘terrestrial’ PBO in the Hämelsee record from central Germany. Also in the Hässeldalen port record from southern Sweden only one fluctuation in pollen data and organic carbon contents labelled as PBO has been reported.

The Hässeldalen Tephra originates from the Snæfellsjökull volcano (W Iceland) and has first been discovered in the Hässeldala Port palaeolake sequence in SE Sweden and dated by Bayesian probability methods to 11,380 ± 216 cal a BP (11,596-11,164 cal a BP; model C, 95.4% range, IntCal04) (Davies *et al*., 2003; Wohlfarth *et al*., 2006). The Askja-S tephra originating from the Dyngjufjöll volcanic center (Askja system, NE Iceland) also occurs in the Hässeldala port record (Davies *et al*., 2003) and has been dated by Bayesian modeling at 11,050-10,570 cal a BP (model B, 95.4%, IntCal04) (Wohlfarth *et al*., 2006). The Askja-S has further been found even as far south as Switzerland in Lake Soppensee and there dated at 10,991-10,702 cal a BP (95.4% range, IntCal09) (Lane *et al*., 2011). More recent age models based on refined Bayesian statistics revealed about the same age for the Askja-S but with slightly reduced uncertainty estimates (10,956-10,726 cal a BP; 95.4%; IntCal13) (Bronk Ramsey *et al*., 2015). A significantly younger age of 10,500-10,350 cal a BP for the Askja-S has been reported from a lake record on the Faroe Islands (Lind and Wastegård, 2011). The age for the Hässeldalen Tephra of 11,360-11,300 cal a BP in this record resembles that form Hässeldala port, thereby suggesting a much longer time span between the two ash falls. A summary of the published data is given in Table 1. Other co-existing occurrences of both tephras are reported from SW Sweden (Lilja *et al*., 2013) and NE Germany (Lane *et al*., 2012b; Wulf *et al*., 2016), however, without providing independent age constraints of either one of these tephras. In summary, the individual age uncertainties reported for both tephra layers lead to a quite large possible range for the time interval between both volcanic eruptions. Since all previous reports of co-occurring Hässeldalen and Askja-S tephras are from non-laminated sediment records, our finding of both tephras in varved sediments for the first time allows to independently determine the time span between both eruptions through differential dating applying annual layer counting.

This study aims (i) to present the floating varve chronology which includes both tephra deposits, (ii) to determine the time interval between both tephras based on varve counting, (iii) to discuss published absolute ages for both tephras including aspects of the new differential dating and (iv) to discuss a possible PBO signature in the varved sediments based on micro-facies and geochemical data.

Site, sediments and methods

Lake Czechowskie (Jezioro Czechowskie: JC; 53°52'N, 18°14'E) is located 60 km southeast of Gdańsk, Poland (Fig. 1) in a subglacial channel formed during the Weichselian Glaciation. Its recent catchment is characterized by pine forest growing on glacial outwash plain deposits (Błaszkiewicz, 2005; Błaszkiewicz et al., 2015). The lake has a surface area of 73 ha and a maximum water depth of 32 m. In 2009 and 2012 four parallel core sequences were obtained from the deepest part of the lake (Fig.1) and used to establish a master composite profile (JC-M2015) covering 1346 cm (Ott *et al*., 2014; Czymzik *et al*., 2015) (Fig. 2).

The sediment record is predominantly composed of annual laminations (calcite varves) except one organic-rich and one clastic-rich sediment section in the lower part of the profile. Intercalated between these two non-varved sections is another varved segment from 1172 to 1073 cm depth. A systematic search for cryptotephra was carried out in this varved interval in order to find an isochronous anchor point for a link to the absolute time scale. Therefore, we applied chemical-physical separation techniques on samples taken at 0.5 or 1 cm intervals (Wulf et al., 2016). Microscopically detected glass shards were handpicked and embedded into single- hole stubs and geochemically analysed using a JEOL JXA-8230 microprobe at the German Research Centre for Geosciences Potsdam. Instrumental setups used a 15 kV voltage, a 10 nA beam current and beam sizes of 5 µm (sample JC12_D6_112- 113_T) and 8 µm (sample JC12_D6_95-95.5_T). Exposure time for each analysis was 20 seconds for the elements Fe, Cl, Mn, Ti, Mg and P and 10 seconds for F, Si, Al, K, Ca and Na. Instrument calibration is based on natural mineral and the Lipari obsidian glass standards (Hunt and Hill, 1996; Kuehn *et al*., 2011). Averaged major- element glass data are listed in Table 2. Single raw sample and glass reference data are provided in Wulf *et al*. (2016).

Varve counting including thickness measurements down to sub-layer resolution has been performed for this floating varved interval on a continuous series of large thin sections (100x20 mm) using a petrographic microscope with 25x to 200x magnifications. Error estimates are obtained from double counting by the same investigator.

Geochemical composition has been measured using the ITRAX µ-XRF spectrometer (Croudace et al., 2006) equipped with a chromium X-Ray source. Measurements were performed every 200 µm (30 kV, 30 mA, 10 s) directly at the smoothed and cleaned split core surface (archive halve). The initial element intensities have been centre log-ratio (clr) transformed to minimize the effects of changes in sediment properties due to varying water and organic contents (Tjallingii *et al*., 2007; Weltje and Tjallingii, 2008).

Pollen analysis has been carried out at 1 cm resolution between 1143 and 1184 cm depth in order to biostratigraphically define the Younger Dryas/Holocene transition.

Results

Composition and origin of tephras

Two cryptotephra horizons were identified in samples JC12_D6_112-113_T in 1158-1159 cm and JC12_D6_95-95.5_T in 1141-1141.5 cm composite depth, respectively (Fig. 2). No further glass shards have been detected in the over- and underlying sediments indicating a primary deposition of both cryptotephras (Fig. 2).

Geochemical glass data of both tephras revealed distinct rhyolitic compositions suggesting an Icelandic provenance (Fig. 3). The glass composition of the older tephra JC12_D6_112-113_T (3 shards/cm^3) is more evolved with high SiO_2 and K_2O values (~78.3 wt% and ~4.2 wt%, respectively; normalized volatile-free data) and relatively low FeO (~1.1 wt%) and CaO (~0.5 wt%) concentrations that match well the

Glass composition of the early Holocene Hässeldalen tephra (Snæfellsjökull, W Iceland)(Fig. 3). The younger tephra JC12_D6_95-95.5_T (20 shards/cm^3) reveals lower SiO_2 and K_2O values of ~76.5 wt% and ~2.5 wt%, respectively, while concentrations in FeO (~2.5 wt%) and CaO (~1.6 wt%) are higher compared to the Hässeldalen tephra. The composition of the younger tephra is typical for the Askja-S

tephra, that originated from a caldera forming eruption of the Dyngjufjöll volcanic centre in NE Iceland (Fig. 1,3).

Varve counting and Geochemistry

The finely laminated sediments between 1073-1172 cm depth are well-preserved and composed of light calcite and dark organic sub-layers and are interpreted as calcite varves (Fig. 2) (Kelts and Hsü, 1978; Lotter et al., 1997; Brauer et al., 2008). Detrital components are rare and hardly detectable by micro-facies analyses. In total, 967 ± 14 varve years (3% uncertainty) have been counted in the floating varved interval. Total varve thickness ranges between 0.2 and 6.3 mm with a mean of 1.02 mm (Fig. 2), while sub-layer thickness varies between 0.08 and 1.08 mm (calcite layer) and between 0.08 and 6 mm (organic layer). Within the 967-year floating varve chronology the Askja-S tephra has been dated at 730±3 varve years (counting from top to base), while the Hässeldalen tephra is dated at 881±6 varve years (Fig. 2). Varve ages for the tephra horizons are given as the midpoint of the sample interval in which the glass shards were found. For the Hässeldalen tephra it is the 1 cm interval from 1158-1159 cm depth and for the Askja-S tephra it is the 0.5 cm interval from 1141 – 1141.5 cm depth. The number of varves within the sample interval has been added to the overall age uncertainty resulting in 152+11/-8 (144-163) varve years between the Hässeldalen and Askja-S tephra layers.

Due to the scarcity of visible detrital components we used titanium (Ti) determined by µ-XRF scanning as proxy for changes in detrital matter. The Ti record shows elevated values which started to decrease at ca. 1180 cm depth until the onset of varve formation at 1172 cm depth. Between 1172 and 1050 cm the Ti record exhibits only low variability except the interval from 1162 to 1140 cm depth with lowered Ti values. The calcium record reflects biochemical calcite precipitation in the lake and shows an interval of increased values between 1162 and 1140 cm depth corresponding to lower Ti values (Fig. 2).

The Younger Dryas/Holocene boundary has been defined by means of pollen stratigraphy applying the same criteria as in the Lake Gościąż record (Ralska-Jasiewiczona *et al*., 1992). The abrupt decline of *Juniperus* and non-arboreal pollen (*Artemisia*) and parallel increase of pine at 1176-1177 cm depth in the JC sediments (data not shown) closely resembles the pollen data from Lake Gościąż, allowing to transfer the age of 11,515±35 cal a BP (Litt *et al*., 2001) to the JC age model.

Estimating the absolute age of the floating varve interval

An independent absolute varve age for the tephra layers cannot be obtained because the varved interval is floating. The closest AMS ^{14}C date of 9919±239 cal a BP (sample Poz-52862) from the overlying non-varved section confirms an early Holocene age for the floating varve chronology and thus for both tephras (Fig. 2). Further support of an early Holocene age is given by the biostratigraphic determination of the Younger Dryas/Holocene boundary as defined by Ralska-Jasiewiczowa et al. (1992) in the Gościąż record 18 cm below the older tephra at 1176-1177 cm composite depth in our record (Fig. 2). We adopt the age of 11,515±35 cal a BP from the Lake Gościąż record for this transition (Ralska- Jasiewiczowa *et al*., 1992; Litt *et al*., 2001) for the JC chronology.

Discussion

Records with co-existing Hässeldalen and Askja-S tephras are rare and include besides the original site of Hässeldala port, the Høvdarhagi Bog record from the Faroe Islands (Lind and Wastegård, 2011), sites in SW Sweden (Davies *et al*., 2003; Lilja *et al*., 2013), the Endinger Bruch (Lane *et al*., 2012b) and Lake Tiefer See record (Wulf *et al*., 2016) in NE Germany. JC is the southeastern most sediment record where both tephras co-exist, thereby extending the distribution fans of these ash falls. Glass shards are only found in one 0.5 and one 1-cm sample, respectively, and not distributed along a wider core interval proving absence of post-depositional sediment mixing (Fig. 2) (e.g. slumping, bioturbation). The low number of glass shards found can be explained with the very distal position of JC with respect to the eruption center.

It is interesting to note that the amount of Askja-S glass shards found in the southern Swedish sites (5-20 shards/cm^{-3} in SW Sweden; Lilja *et al*., 2013) and 9 shards/cm^{-3} in Hässeldala Port (Davies *et al*., 2003) commonly is lower than the number of glass shards originating from the Hässeldalen tephra (ca. 100 shards/cm^{-3}; Lilja *et al*., 2013) and 75 shards/cm^{-3} (Davies *et al*., 2003). In the JC sediments we found more Askja-S than Hässeldalen shards (20 versus 3 shards/cm^{-3}), which is in agreement with reports from other southern Baltic findings like the Endinger Bruch (77 shards g^{-1} from Askja-S versus 59 shards g^{-1} from Hässeldalen, Lane *et al*., 2012b). It remains unclear, if this regional pattern of glass shard concentrations is only by coincidence or if it reflects a real difference in tephra distribution.

The first occurrence of co-existing Hässeldalen and Askja-S tephras in the JC varved sediment record enabled differential varve dating even if the early Holocene part of the JC varve chronology is floating. The resulting time span between both tephra layers of 152+11/-8 varve years is a few decades shorter than the difference calculated from published radiocarbon-based age models. Accepting the age of 11,380±216 cal a BP (11,596-11,164cal a BP) for the Hässeldalen tephra (Wohlfarth *et al*., 2006) and the modelled age estimate of 10,956-10,716 cal a BP for the Askja-S (Bronk Ramsey *et al*., 2015) results in a possible minimum difference of ca 210 years between both tephras, which is five to six decades longer than revealed from our varve counts. Possible explanations of this discrepancy are uncertainties in either the varve counting and/or the radiocarbon age modelling. We consider an underestimation of varve counts in the range of several decades as unlikely because of the very good varve preservation (Fig. 2) enabling unambiguous identification of varve boundaries. This is supported by the agreement of the JC varve counts with radiocarbon models obtained for the Hässeldala port record by Wohlfarth et al. (2006), which would allow even for minimum differences between both tephras of 94 (model A) to 114 years (model B).

Absolute ages for the Askja-S and Hässeldalen tephras

Previously published absolute ages for the Hässeldalen and Askja-S tephra layers are all based on radiocarbon based age modeling either from the Hässeldala port record alone or a combination with age constraints obtained from other records like Lake Soppensee (Fig. 4). Since an independent absolute varve dating for the tephra layers in the JC record is not possible due to the lack of a continuous varve formation to present times, the assignment of absolute ages relies on anchoring the floating varve interval based on published radiocarbon dates. Accepting the Hässeldalen age of 11,380 ± 216 cal a BP tephra (Wohlfarth *et al*., 2006) as anchor point and adding the differential varve counts reveals an age for the Askja-S tephra of 11,454-11,002 cal a BP (Fig. 4), which is older than the modelled ages of 10,956-10,726 cal a BP (95.4% range) (Bronk Ramsey *et al*., 2015) and 10,991-10,702 cal a BP (Lane *et al*., 2011). However, our age is in agreement within the uncertainties of the Wohlfarth et al. (2006) age model for the Askja-S tephra (11,050-10,570 cal a BP). Thus the agreement or disagreement of our age with different radiocarbon age models mainly depends on the uncertainty ranges given in these models. The reduction of uncertainties in radiocarbon-based models is partly related to the incorporation of age constraints from the Askja-S in the Soppensee record (Lane *et al*., 2011b; Bronk Ramsey *et al*., 2015)). Therefore, one possible explanation for the discrepancy with the JC varve count might be in the age modelling of the Lake Soppensee record. Despite dense radiocarbon dating (Hajdas *et al*., 1993) rather large uncertainties of up to 330 years in the early Holocene interval (Lane *et al*., 2011) might reflect either overlooked sedimentation rate changes or imprecise radiocarbon ages (Lane *et al*., 2011). Since six out of eight ^{14}C samples in this interval (509 - 536 cm sediment composite depth in Soppensee) show low C contents ≤ 1mg (Hajdas *et al*., 1993), why slightly too young ages cannot be excluded (Wohlfarth *et al*., 1998). Incorporating too young ages into the model might have shifted the modelled ages to slighty too young ages. Considering only one single ^{14}C date, which is closest to the Askja-S horizon in the Soppensee record (sample ETH-7700 at 518.5-520.5 cm (9530±95 ^{14}C a BP, Hajdas *et al*., 1993) instead of the age model would increase the possible age range (11,163-10,587 cal a BP; 95.4%, IntCal13) compared to the modelled ages (10,991-10,702 cal a BP, Lane *et al*., 2011; 10,956-10,726 cal a BP, Bronk Ramsey *et al*., 2015). This in turn would reconcile radiocarbon age models and our age for the Askja-S age (11,454-11,002 cal a BP) within the (larger) uncertainties. Accepting this suggestion would further indicate that the 'true' age of the Askja-S tephra falls into the older range of the uncertainty band rather than in its midpoint.

Although the absolute Askja-S ages obtained from JC and the Soppensee record could be reconciled in this way, the discrepancy to the much younger age obtained from the Faroe Islands (Fig. 4) (10,500 - 10,530 cal a yr BP; Lind and Wastegård, 2011) remains suspicious. A possible explanation for the longer time span between both tephras found in the Faroe Island record might be that changes in sedimentation rate have not been considered in the age model. Although details on the sediment characteristics are not given in Lind and Wastegård (2011), it is noticeable that in this record the sediment section between the Hässeldalen and Askja-S tephras is >1m and thus much thicker than in all other records where both tephras co-exist (9-12.5 cm in Hässeldala port (Davies *et al*., 2003; Wohlfarth *et al*., 2006); 52 cm in Endinger Bruch (Lane *et al*., 2012b); 7 cm in Lake Tiefer See (Wulf *et al*., 2016) and 17.5 cm in our JC record). The rather late deglaciation on the Faroe Islands during the time of the ash falls between 11,400 – 11,150 cal a BP (Jessen *et al*., 2008; Lind and Wastegård, 2011), might have caused a dynamic environment including sediment reworking in this region. However, without detailed sedimentological analyses this remains a speculation that needs to be further tested.

In contrast to the robust differential varve dating of the time interval between the Hässeldalen and Askja-S tephras in the JC record, a precise estimate of the time span from the onset of the Holocene to the Hässeldalen tephra is more difficult to determine. The Hässeldalen tephra in the JC record locates ca 18 cm above the YD/Holocene boundary of which only the upper 14 cm are varved (onset of varve formation at 1172 cm), not allowing continuous varve counting down to the onset of the Holocene (Fig. 2). Therefore, the best estimate of ca 120 years for the time span between the biostratigraphically defined onset of the Holocene and the Hässeldalen tephra in the JC record has been determined by varve counting (87±1 varves) and extrapolation of the basal 5 cm of non-varved Holocene sediments.

The Preboreal Oscillation (PBO)

Since Wohlfarth *et al*. (2006) reported the occurrence of the Hässedalen and Askja-S tephras shortly before and after the PBO we are able to discuss the impact of this short climatic fluctuation on the sediment characteristics in the JC record. However, further discussion of the absolute dating for comparison with other PBO reports where these tephras as time constraints are lacking does not appear meaningful because of the rather large uncertainties of most individual chronologies. Thin section analyses of the JC sediments reveal no significant change in varve micro-facies (Figs. 2 and 5) and total organic carbon also does not exhibit any clear fluctuation (data not shown). The only visible signal bracketed by the two cryptotephras is an interval of decreased Ti and increased Ca values (Figs. 2 and 5). The Ti minima might indicate a decrease in the input of detrital matter which would be in agreement with the assumed drier climate during this period (van der Plicht *et al*., 2004; Bos *et al*., 2007). The length of this period with possibly drier conditions in JC is determined by varve counting to 178±3 varve years (Figs. 2 and 5) and thus roughly agrees with the duration calculated for the PBO or Rammelbeek Phase in Hässeldala port (Wohlfarth *et al*., 2006) and the Borchert records (van der Plicht *et al*., 2004; Bos *et al*., 2007), respectively. However, without prior knowledge about the PBO bracketed by the two ash falls, we most likely would not have interpreted this fluctuation in terms of a distinct climatic oscillation. This confirms earlier reports that the PBO can be difficult to detect in lake sediments (Björck *et al.,* 1997).

Conclusions

First differential varve counting of co-existing Hässeldalen and Askja-S tephras in a floating varve interval of the JC sediment record in northern Poland revealed a time span between both eruptions of 152 +11/-8 years. This is in agreement with radiocarbon-based age models with larger uncertainties, but not with the latest age model with reduced uncertainties. This implies that a reduction of uncertainties through advanced model approaches might have been misleading in this case, even if there is common agreement that it is important to further reduce age uncertainties.

Despite the improvement of determining the relative positions of the early Holocene Hässeldalen and Askja-S tephra layers, there is still a need to improve absolute dating of these important isochrones. Although our data does not allow for more precise absolute ages because of the floating nature of the varved interval in JC that comprises both tephras, differential varve dating suggests that the currently considered best estimate for modelled ^{14}C age of the Askja-S tephra (10,830 ± 57 cal a BP) might be 200-300 years too young. Consequently, this age should be critically discussed if used for anchoring non-varved sediment records to an absolute time scale.

In addition to the perhaps too optimistic uncertainty reduction, our data raise the well-known problem of generally using the midpoint of ^{14}C age ranges as anchor point. In case of the Askja-S tephra there is some indication that the ‘true’ age is rather in the older part of the given age range than at the midpoint. In general, it should be also discussed if including as many as possible dates in an age model is the best approach, or if a pre-selection of well-constrained dates can provide more reliable results.

The co-existence of the Hässeldalen and Askja-S tephras in the JC record and prior knowledge that the Preboreal Oscillation (PBO) occurred between both tephras allowed us to interpret a minor fluctuation in the Ti curve indicating reduced detrital influx due to drier climate as the local lake response to the PBO. A lack of visible changes in varve micro-facies during this interval indicates that the climatic response of the lake's depositional system was rather weak supporting the idea that the PBO can be difficult to determine in lake records. In general, these results demonstrate the high potential of tephrochronology to address questions of lake and environmental responses to climatic fluctuations.

This study further demonstrates the value of differential dating for constraining tephra ages. However, there is still need to improve the dating of early Holocene tephra isochrones by both, additional differential dating of continuously varved records and improved radiocarbon dating.

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