Calibrating ^{210}Pb dating results with varve chronology and independent chronostratigraphic markers: problems and implications

Wojciech Tylmann¹, Alicja Bonk¹, Tomasz Goslar^{2,3}, Sabine Wulf^{4,5}, Martin Grosjean⁶

¹Faculty of Oceanography and Geography, University of Gdańsk, Poland

²Faculty of Physics, Adam Mickiewicz University, Poznań, Poland

³Poznań Radiocarbon Laboratory, Foundation of the Adam Mickiewicz University, Poznań, Poland

⁴Helmholtz Centre Potsdam, German Research Centre for Geosciences GFZ, Section 5.2 Climate dynamics and landscape evolution, Potsdam, Germany

⁵Senckenberg Gesellschaft für Naturforschung, BIK-F, TSP6 Evolution und Klima, Frankfurt a.M., Germany

⁶Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Switzerland

Corresponding author: Wojciech Tylmann, Faculty of Oceanography and Geography, University of Gdańsk, Bażyńskiego 4, PL-80952 Gdańsk, wojciech.tylmann@ug.edu.pl

Key words: varves; tephra; ^{137}Cs ; CFCS model; CRS model; lake sediments; limnogeology

Abstract

Varved lake sediments provide a unique opportunity to validate results of isotope dating methods. This allows testing of different numerical models and constraining procedures to produce reliable and precise chronologies. Here we present results of the model testing and validation by multiple dating approaches for the varved sediment record from Lake Żabińskie (northeastern Poland). Our goal was to assess possible deviations of ^{210}Pb -derived ages from true sediment ages provided by varve chronology and to check how different numerical procedures can improve the consistency of the chronologies. Different methods for age estimation were applied including varve counting, ^{210}Pb , ^{137}Cs , ^{14}C and tephra identification. Microscopic analysis of the varve microfacies revealed that laminations found in Lake Żabińskie were biogenic (calcite) varves. Three independent counts indicated a good preservation quality of laminae in the sediment profile which contained 178^{+4}_{-8} varve years. The calendar-year time scale was verified with two maxima of ^{137}Cs activity concentrations in the sediments (AD 1963 and 1986) and a terrestrial leaf dated to AD 1957-1958 by the ^{14}C method. Additionally, geochemical analysis of the glass shards found in the sediments indicated a clear correlation with the Askja AD 1875 eruption of Iceland which provided an unambiguous verification of the varve chronology. For testing ^{210}Pb dating we used two routinely applied models: Constant Flux Constant Sedimentation (CFCS) and Constant Rate of Supply (CRS). None of the models in their standard forms produced a chronology consistent with varve counts and independent chronostratigraphic markers. Both models yielded ages much younger than the calendar age with a difference of ca. 50 years at the bottom part of the profile. However, a significant improvement was introduced after using the composite CFCS model with sediment accumulation rates calculated for different zones of the sediment profile. This provided highly

consistent values along the time scale with deviations <5 yrs compared with calendar ages. Also constraining the CRS model with ^{137}Cs peaks as well as testing the correction values for incomplete ^{210}Pb inventory provided results that finally deviated from the calendar age only by ≈ 10 yrs for the 120 years old sediments.

Highlights

- We investigate a varved sediment core from Lake Żabińskie in northeastern Poland.
- The age-depth model compares ages from varves, tephra, ^{14}C , ^{137}Cs and ^{210}Pb .
- We test most commonly used models for ^{210}Pb dating: CFCS and CRS.
- Discrepancies might occur when using simple CFCS or unconstrained CRS models.
- Numerical procedures can improve consistency between ^{210}Pb models and varve age.

1. Introduction

Reliably dated lake sediments are most valuable archives of past environmental changes. Obtaining the best possible time control is especially critical for high-resolution studies of the most recent past, when precise comparison of proxy records to historical information allows an identification of direct reasons of changes in the surrounding environment. From a wide selection of dating methods, varve chronologies based on counting of preserved annual sediment increments provide an accurate chronology in calendar years (Zolitschka, 2007). However, well-preserved varved sediment records are relatively rare (Ojala et al., 2012). Therefore, in most cases there is a need to use other methods. For sediments younger than ca. 150 years, methods that employ short-lived radionuclides are most widely used, for instance ^{210}Pb ($T_{1/2} = 22.3$ yr) which may provide continuous chronologies for the last 120-150 years. The radioisotope ^{137}Cs serves commonly as a chronostratigraphic marker that provides at least one validation horizon related to maxima in the ^{137}Cs atmospheric fallout in the year 1963 and in large part of Europe also the second time marker in the form of 1986 peak fallout from the Chernobyl accident (Klaminder et al., 2012). Furthermore, other diagnostic marker layers like volcanic ash (tephra) layers (von Gunten et al., 2009), sediment structures related to earthquakes (Arnaud et al., 2006), flood markers (Lavrieux et al. 2013), profiles of spheroidal carbonaceous particles (Rose, 2001) or peak Hg discharge from mining activity (Baskaran et al. 2014) can provide additional time control.

During the last several decades, ^{210}Pb has become the most common dating tool for recent sediments. The method was proposed for dating glacier ice (Goldberg, 1963) and was first applied to lacustrine sediments by Krishnaswamy et al. (1971). Using different numerical models with their specific assumptions it is possible to calculate sediment ages and sediment accumulation rates from ^{210}Pb activity profiles (Appleby, 2001). Additionally, the vertical profiles of ^{210}Pb in sediment cores are used to evaluate sediment dynamics that include erosion, transport and mixing rates of sediments in lacustrine systems (Woszczyk et al., 2014). This wide interest resulted in significant developments of numerical age modeling (Carroll and Lerche, 2003; Sanchez-Cabeza and Ruiz-Fernández, 2012), but also some constraints were pointed out (MacKenzie et al., 2011; Abril and Brunskil, 2014). Caveats are related to a number of factors that influence the vertical activity profile of ^{210}Pb in a sediment core, e.g. variations in (1) the mass flux of sediment particles, (2) the atmospheric depositional flux of ^{210}Pb , and (3) the additional input of ^{210}Pb other than the depositional flux (Baskaran et al., 2014). Apart from theoretical issues, the most important practical problems for users of the ^{210}Pb lake sediment dating method are the differences in results obtained from different model calculations, over- or under estimation of the sediment age, poor reconstruction of changes in sediment accumulation rates and large uncertainties. For non-varved lake sediments these problems become crucial as the ^{210}Pb chronology combined with ^{137}Cs peaks is often the only possibility. Also for varved sediments precise $^{210}\text{Pb}/^{137}\text{Cs}$ chronologies are needed to test whether laminations observed in the sediments are annual which is a key for all proxy-based reconstructions.

In this study, we use multiple dating approaches to assess the performance of some of the most commonly used ^{210}Pb dating models and to validate the ^{210}Pb model ages with independent

layer counts of a varved sediment profile from Lake Żabińskie (NE Poland). Several reasons make this lake suitable for our study:

- The mechanisms of varve formation and preservation in this lake are well-documented and understood (Bonk et al., 2014);
- The varves in the uppermost sediments are excellently preserved and allow the construction of a reliable calendar chronology with maximally reduced counting uncertainty;
- An unambiguous validation of the varve chronology is provided by a historical cryptotephra preserved in the sediments;
- Varve thickness and mass accumulation rates are high enough enabling the sediment subsampling according to age intervals: each sample for isotope measurements contains comparable number of years;
- Variable sedimentation rates during the last 180 years allow verification how this variability influenced ^{210}Pb activity in the sediments.

Taking advantage offered by this unique sediment record, our goal is to assess possible deviations of ^{210}Pb -derived ages from true sediment ages provided by varve chronology and to check how different numerical procedures can improve consistency of the chronologies. We decided to use two models, i.e. Constant Flux Constant Sedimentation (CFCS) and Constant Rate of Supply (CRS) which are routinely applied for sediment dating (Appleby 2001). Although a range of more sophisticated dating models is available (e.g. Sediment Isotope Tomography; Carrol and Lerche, 2003), they are mathematically complex and hence rarely used. We demonstrate how variable sediment accumulation rates and ^{210}Pb fluxes can affect the dating results and may lead to substantial misinterpretations of the sediment ages. With this paper, we also would like to reinforce the importance of independent validation of ^{210}Pb chronologies with at least one other method.

2. Study site

Lake Żabińskie (54°07'54.5'' N; 21°59'01.1'' E; 120 m a. s. l) is a postglacial lake situated in the Masurian Lake District in northeastern Poland (Fig. 1A). The surrounding catchment area is dominated by glacial and fluvioglacial sediments, i.e. morainic till, sand and gravel. The lake drains westward through a short channel into the much larger Lake Gołdopiwo. The major inflow (I1) enters the lake from the north-eastern part and comes from Lake Purwin. Two smaller creeks (I2 and I3) provide water from cultivated fields and afforested areas south of the lake. Our field observations indicate that especially inflow I3 is important because, after snowmelt in spring and heavy rains in summer, it transports significant amounts of sediment particles and organic remains into the lake.

Lake Żabińskie has a surface area of 41.6 ha and a maximum water depth of 44.4 m. The lake basin is aligned in a W-E direction with a central deepest part surrounded by steep slopes. According to limnological measurements, Lake Żabińskie is a hardwater and eutrophic water body, the water column is stratified during most of the year with a well isolated and anoxic hypolimnion. These conditions form an ideal environment for the formation and preservation of annually laminated sediments. Thus, the lake holds a sediment record with well preserved

biogenic varves and a large potential for high-resolution paleoclimatic studies (Bonk et al., 2014).

3. Methods

3.1. Sediment core collection, primary varve counting and subsampling

Five cores were collected in September 2011 and January 2012 using a 90-mm diameter UWITEC gravity corer. All sediment cores were split lengthwise into two halves (A and B), macroscopically described and stored at 4°C before subsampling. Two overlapping sediment cores (ZAB-11/3 and ZAB-12/1) with perfectly preserved varves and undisturbed sediment-water interface were correlated visually using macroscopic marker horizons and allowed us to construct a composite sediment profile which was used for further analysis.

Core half A was sampled for the analyses necessary for sediment age estimation, i.e. water content, dry density, varve counting, tephra identification and radioisotopes (Fig. 1B). First, primary varve counting was done based on high-resolution digital photographs of fresh sediment surfaces. Next, the sediment profile was subsampled continuously for thin sections preparation. Samples were cut from the fresh sediment using aluminum foil trays (10 cm long x 2 cm wide x 1 cm deep) keeping an overlap of 2 cm. The sediment profile covering the last 180 varve years was then subsampled with 3-yr resolution according to varve boundaries based on primary varve counting.

From each of the 60 sediment samples obtained in this way volumetric samples were collected and measured for wet density (weighted mass of 1cm³ of fresh sediment), water content (percentage loss of mass after drying at 105°C for 24 hours) and dry density (weighted mass of dry sediment from 1cm³ of fresh sediment after drying). From the lower core section we additionally collected 1 cm³ of fresh sediment from each 3-yr sample for cryptotephra analyses. The remaining sediment from each of the 60 samples was freeze dried, homogenized in agate mortar and stored tight in glass vials prior to isotope analysis.

3.2. Microfacies analysis and varve counting

Preparation of thin sections followed the procedure described by Lotter and Lemcke (1999). Sediment blocks collected in aluminum foil trays were shock-frozen in liquid nitrogen, freeze-dried and subsequently impregnated with Araldite©2020 epoxy resin. Then large-sized thin sections were prepared from impregnated sediment blocks (MK Factory, Germany).

The varve microfacies (composition of individual laminae and varve structures) were inspected with a petrographic microscope. Next, thin sections were scanned at 2400 dpi resolution using a flatbed scanner and a polarizing foil. All digital images were correlated using varve-by-varve comparison and sections for varve counting were marked in each image. The number of varves was determined manually by three different counters using the CooRecorder software (<http://www.cybis.se>). Each ambiguous section was individually checked under a microscope and classified as varve or not.

Based on three independent counts, the final varve chronology was established and its uncertainty was estimated according to the following procedure: (1) varves indicated in all three counts were added to the chronology without increasing the uncertainty; (2) varves missed in

one counting were added to the chronology and the uncertainty was also increased by 1 year in minus (toward younger age); (3) varves missed in two counts were not added to the chronology but the uncertainty in plus (toward older age) was increased by 1 year.

3.3. Tephra identification

The identification of tephra used (1) the stepwise targeted sediment sampling from potential tephra bearing intervals based on the varve chronology, (2) the chemical and physical separation of volcanic glass shards and (3) their geochemical fingerprinting. Chemical preparation of sediment samples included a successive treatment with 15% hydrogen peroxide H_2O_2 in order to remove organic matter and 10% hydrochloric acid HCl for decalcification. The remaining sediment was wet sieved. The 20-100 μm grain size fraction was dried with Ethanol in a plastic lid and inspected under a transmitted light microscope at 100x magnification. Detected glass shards were handpicked with a single brush hair into a single-hole stub and embedded in epoxy resin (Araldite©2020). Glass shards were then sectioned and their surface was polished for geochemical analyses. The major element composition of single glass shard was determined using a JEOL JXA-8230 microprobe at the GFZ Potsdam with a 15 kV voltage, 10 nA beam current and 5 μm beam size. Natural mineral standards and a rhyolitic glass standard (Lipari obsidian: Hunt and Hill, 1996; Kuehn et al., 2011) were used for instrumental calibration. Compositional data was re-calculated on a volatile-free basis and plotted against EPMA data of potential tephra correlatives in Harker diagrams.

3.4. ^{14}C dating

Terrestrial plant fragments found in the sediments were treated with 1M HCl (80°C, 20+ min), 0.2M NaOH (room temperature) and then 0.25M HCl (80°C, 1 hour). The residual material was combusted in sealed quartz tubes, together with CuO and Ag wool, in 900°C over 10 hours. The obtained CO_2 was then reduced with hydrogen, using Fe powder as a catalyst. Content of ^{14}C in a sample of carbon was measured using the spectrometer "Compact Carbon AMS" (Goslar et al. 2004), in comparison to that in the modern standard "Oxalic Acid II", and the conventional ^{14}C age was calculated using correction for isotopic fractionation (Stuiver, Polach 1977).

3.5. ^{137}Cs , ^{226}Ra and ^{210}Pb measurements

Freeze-dried and homogenized sediment samples were stored in measurement containers for a minimum of three weeks to obtain secular equilibrium of radon and its short-lived daughter products with ^{226}Ra . The activity of ^{137}Cs and ^{226}Ra was determined directly by gamma-ray spectrometry. Gamma measurements were carried out using a HPGe well-type detector (GCW 2021) with a relative efficiency of 27% and FWHM of 1.9 at the energy of 1333 keV (Canberra). The detector was coupled to a multi-channel analyzer and shielded by a 15 cm thick layer of lead. Counting efficiency was determined using reference materials (CBSS-2 for ^{137}Cs at 661.6 keV and RGU-1 for ^{226}Ra via ^{214}Pb at 352 keV) in the same measurement geometry as for the samples. The counting time for each sediment sample was 72 h.

It was not possible to determine the ^{210}Pb activity directly using gamma spectrometry (46.5 keV), because of a relatively low mass of sediment available and high uncertainty of the results.

Therefore, activity of total ^{210}Pb was determined indirectly by measuring its daughter product ^{210}Po ($\alpha = 5.308$ MeV, $T_{1/2} = 138$ d) using alpha spectrometry. Dry sediment samples of 0.2 g were transferred into Teflon digestion vessels, spiked with ^{208}Po yield tracer ($\alpha = 5.105$ MeV, $T_{1/2} = 2.9$ yr) and digested at a temperature of 120°C using concentrated HNO_3 , HClO_4 and HF . After 24 h the solution was transferred into a Teflon beaker, evaporated with 6M HCl to dryness and then dissolved in 0.5M HCl . Polonium isotopes were spontaneously deposited within 4 h on silver discs (Flynn, 1968). After deposition, discs were washed with methanol and analyzed for ^{210}Po and ^{208}Po . Activities were measured for 24 h using a 7200-04 APEX Alpha Analyst integrated alpha-spectroscopy system (Canberra) equipped with PIPS A450-18AM detectors. A certified mixed alpha source (^{234}U , ^{238}U , ^{239}Pu and ^{241}Am ; SRS 73833-121, Analytics, Atlanta, USA) was used to check the detector counting efficiencies, which varied from 18.6% to 19.4% for the applied geometry. The deposition efficiency estimated by comparing the measured and spiked ^{208}Po activities was $84 \pm 3\%$ ($n=60$). Two blank samples were analyzed with each sample batch to additionally verify the quality of the chemical procedure.

3.6. Data processing

Annual sediment accumulation rates (SAR, $\text{g cm}^{-2} \text{ yr}^{-1}$) were calculated from sediment dry density and the thickness of individual varves. The cumulative mass depth (g cm^{-2}) was calculated by summing up annual accumulation rates.

The Constant Flux Constant Sedimentation model (CFCS; Krishnaswamy et al., 1971) and the Constant Rate of Supply model (CRS; Appleby and Oldfield, 1978) allowed calculations of the sediment ages at different depth intervals. The main distinction between the two models is that CFCS assumes a constant atmospheric flux of ^{210}Pb to the sediment surface and constant sediment accumulation rate, whereas CRS assumes a constant atmospheric flux of ^{210}Pb and variable accumulation rate of sediments. Model calculations and standard uncertainty estimations were carried out following Appleby (2001), Binford (1990), and a recent review presented by Sanchez-Cabeza and Ruiz-Fernández (2012).

4. Results

4.1. Lithology, varve chronology and sediment accumulation rates

The sediment profile had a length of 105.4 cm and exhibited a clear laminated structure. Generally, the laminations could be characterized as a regular succession of pale calcite layers and dark organic-rich layers. The preservation quality of the laminae was very good with clear sedimentary contacts between the laminae. However, distinct changes in the sediment color and the laminae thickness were observed along the profile (Fig. 2). Thin section analyses revealed also differences in the structure of the annual depositions. In the lowermost part (105.4-85.8 cm), olive-colored sediment formed thick laminae couplets (4-11 mm) with a distinct calcite lamina and a dark organic detrital-rich lamina that is covered by a thin clay layer. In the next section (85.8-70 cm), the sediment color became reddish, varve thickness ranged from 3.9 to 7.5 mm and microscopic analysis indicated lower contents of clastic material. At the sediment depth of 70-48.2 cm more variable varves were observed ranging in thickness from 2.8 to 5.9 mm. Some visible disturbances in the sediment structure caused difficulties in delineating varve

boundaries in the lower part of this section. Calcite laminae became less distinct and laminae rich in vivianite and pyrite grains were observed in many varves of this unit. The uppermost part (48.2-0 cm) of the profile consists of excellently preserved varves composed of multiple calcite laminae interbedded with diatom rich layers, chrysophytes, amorphous organic matter and minor contents of minerogenic detritus. A positive trend in varve thickness reaching maximum values of 9.8 mm was observed in the lower part of this section (48.2-20.5 cm) while, in the topmost part (20.5-0 cm), varve thickness decreases consequently to minimum values of 4 mm at the sediment core surface. These changes were accompanied by distinct changes in the sediment color from blackish to brown-reddish.

Microscopic analysis of the varve microfacies and three independent counts indicated excellent preservation quality of varves in the topmost 51.7 cm which contain 83^{+2}_{-0} varve years (Fig. 2). Further downcore (51.7-70.8 cm) the preservation quality was less good and some visible disturbances in the sediment structure caused difficulties in the counts. Still, the counting uncertainty was very low: at 70.1 cm the sediment age was estimated to 125^{+2}_{-5} varve years. Finally, at the lowermost part of the sediment profile (105.4 cm) the sediment age reached 174^{+4}_{-8} , which differed from the primary macroscopic counting (180 yrs) insignificantly.

Sediment accumulation rates (SAR) varied for individual varves in the range between 0.05 and $0.26 \text{ g cm}^{-2} \text{ yr}^{-1}$ with a mean of 0.14 and standard deviation of $0.05 \text{ g cm}^{-2} \text{ yr}^{-1}$. Highest values were recorded in the lowermost part 105.4-87.5 cm (Fig. 2). Then, SAR varied in a range between 0.06 and $0.17 \text{ g cm}^{-2} \text{ yr}^{-1}$ without any long-term trend until 26 cm sediment depth where a significant peak was recorded between 26 and 17 cm with values $>0.2 \text{ g cm}^{-2} \text{ yr}^{-1}$. The topmost part of the sediment profile is characterized by a decrease in SAR to minimum values of $<0.1 \text{ g cm}^{-2} \text{ yr}^{-1}$ at the sediment core surface.

4.2. Tephra

A total of 47 volcanic glass shards/ cm^3 was detected in the sample at 78-79 cm sediment depth. 12 of these shards were geochemically analyzed (ESM – Appendix 1). EPMA measurements revealed a homogenous rhyolitic composition of this cryptotephra that is distinct from other widespread, historical silicic tephtras from Iceland (Fig. 3). The volcanic material was found in the sample dated by varve counting to AD 1872-1874 (AD 1869-1880 including the counting uncertainty). The major element composition in combination with the stratigraphic position of the cryptotephra in the sediments of the Lake Żabińskie sediment record suggests a clear correlation with the Askja AD 1875 eruption of Iceland.

4.3. ^{14}C age

In the sediment section of interest, only one sample of terrestrial plant leaves was found at 33.5 cm depth, varve-dated to AD 1960. It revealed a ^{14}C age of -619 ± 36 BP. The negative ^{14}C age of this sample obviously reflected the period when ^{14}C concentrations in the atmosphere were rising due to the atomic bomb tests. The ^{14}C value of the leaf sample corresponds to carbon assimilated from atmospheric CO_2 in late AD 1957 (Hua et al. 2013). This leaf fragment is not expected to be deposited in the sediment before spring AD 1958, and a 2-years delay between AD 1958 (the earliest possible deposition in the lake) and AD 1960 (the age of sediment determined by varve counting) seems reasonable.

4.4. ^{137}Cs , ^{226}Ra and ^{210}Pb distribution

The activity concentrations of ^{137}Cs in the Lake Żabińskie sediment record show two distinct maxima that are perfectly consistent with the history of atmospheric deposition (Fig. 4). First traces of ^{137}Cs occurred in the section at 36-38 cm sediment depth which was dated by varve counting to AD 1952-1957. A significant increase was recorded at a depth of 34.5-36 cm followed by a maximum at 31-34 cm sediment depth dated by varve counting to AD 1961-1965. Above, the activity decreased continuously up-core until the second peak recorded at 12-14.5 cm sediment depth. This sediment stratum has been dated by varve counting to AD 1984-1989. From that point, the activities decreased to minimum values in the uppermost part of the sediment record.

The sediment profile displays a decrease of total ^{210}Pb activities from the sediment surface until 71 cm depth (Fig. 4). Below this depth activities varied irregularly without a decreasing trend. We estimated the level of $^{210}\text{Pb}_{\text{supported}}$ using the activity of ^{226}Ra which was measured by an independent analytical technique. Overall, no long-term trend along the core has been observed and the ^{226}Ra activity concentration varied in the range of 30-90 Bq kg⁻¹ with a mean of 55 Bq kg⁻¹. Unsupported ^{210}Pb activity values were obtained by subtraction the supported ^{210}Pb activity from the total ^{210}Pb activity on a level-by-level basis. The resulting downcore profile of unsupported ^{210}Pb activities follows closely the exponential decrease with mass depth ($R^2=0.92$).

4.5. ^{210}Pb dating

We applied two alternative dating models (CFCS and CRS) to estimate the age-depth relationships in the sediment core (Fig. 5). For the CFCS model we calculated a mean SAR for the entire profile from the exponential equation and obtained $0.199 \pm 0.009 \text{ g cm}^{-2} \text{ yr}^{-1}$. Although the coefficient of determination for the entire profile is high, it is evident that a simple regression line does not explain the full variability in the profile. Therefore, we used this piecewise linear behavior and divided the profile into three segments. Next, we calculated the mean SAR for each segment of the profile. From the derived SAR values, the ages of sediments at different depths were calculated. Alternative interpretations, i.e. simple model (CFCS-1) and composite model (CFCS-2) provided significantly different sediment ages, especially in the lower part of the profile (Fig. 6).

To use the CRS model we calculated the total $^{210}\text{Pb}_{\text{uns}}$ inventory in the sediments which was equal to $13.9 \pm 0.27 \text{ kBq m}^{-2}$. Next, we corrected this value based on extrapolation of the exponential equation to eliminate a systematic deviation of CRS dates toward erroneously old ages, i.e. the so-called “old-date error” (Binford, 1990). The value of correction amounted to 1.45 kBq m^{-2} . As a result of unconstrained CRS model calculations (CRS-1) we obtained the age-depth relationship which was similar to the CFCS-1 model results, and deviated significantly from the varve chronology (Fig. 6). Constraining the CRS model with the ^{137}Cs peaks (AD 1963 and AD 1986; CRS-2) improved the consistency in the upper part of the profile, but in the older section significant differences still occurred. After decreasing the correction value for the total ^{210}Pb inventory to 0.62 kBq m^{-2} calculated from the exponential equation for the lowermost zone alone, the constrained CRS-3 model produced much better results.

Although the CRS-3 ages are still younger than the varve ages in the deeper parts of the core, the discrepancy in the age–depth relation is smallest and, taking into account the uncertainty of both chronologies, becomes statistically insignificant.

5. Discussion

5.1. Mechanisms of ^{210}Pb deposition

The sediment core from Lake Żabińskie reveals a quite complex picture of sedimentation conditions. On one hand, the lake environment is suitable for using ^{210}Pb as a dating tool: (1) the well-preserved varves confirm the absence of physical and biological mixing in the sediments; (2) post-depositional migration of ^{210}Pb along the sediment column should be limited by distinct boundaries between individual laminae and substantial changes of physical properties between loose organic and cohesive calcite layers, and (3) there is no evidence of any other disturbances of the sedimentation process, e.g. slumps or turbidities. On the other hand, sediment lithology is not uniform throughout the core and varve thickness varies indicating considerable changes in SAR over time. These changes may reflect variable sedimentation directly from the water column caused by different rates of autochthonous production, but they may also be caused by different rates of sediment focusing and catchment inputs into the lake. Therefore, some constraints in using the ^{210}Pb dating models can be expected.

Although the overall exponential decrease of ^{210}Pb with depth is seen, varying SAR cause some irregularities in the ^{210}Pb vertical profile. Apart from that, we also found the supported ^{210}Pb level for the sediments of Lake Żabińskie relatively high and variable. The detected values are comparable to Lake Łazduny (Tylmann et al., 2013a) and much higher compared to studies of shallow lakes in Poland (Gąsiorowski and Hercman, 2005; Pempkowiak et al., 2006; Tylmann et al., 2007). This can be explained by the geological setting and morphology of the Lake Żabińskie basin. In postglacial areas of northeastern Poland such deeply incised lake basins receive groundwater inputs from aquifers related to surrounding outwash plain sands or deeper inter-morainic sediments (Bajkiewicz-Grabowska 2002). It has been shown that lakes with significant groundwater input may be substantially enriched in ^{226}Ra which is particularly important for supported ^{210}Pb levels in the sediments (Brenner et al., 2004). Variable groundwater inputs can also provide additional amounts of ^{222}Rn to the lake which can result in variable amounts of production of unsupported ^{210}Pb (Baskaran et. al., 2014). However, it is impossible to evaluate quantitatively the role of groundwater inputs to the Lake Żabińskie due to the lack of long-term data series regarding the water balance of this lake.

The corrected total inventory of $^{210}\text{Pb}_{\text{uns}}$ determined by integration of dry mass and activity into individual vertical increments of the core amounted to $>15 \text{ kBq m}^{-2}$, which is a very high value. To validate these calculations we applied the reference level method (Appleby, 2001) using the well-defined ^{137}Cs peaks and obtained an inventory that equals 11.7 kBq m^{-2} and 13.7 kBq m^{-2} based on the AD 1986 and AD 1963 ^{137}Cs peaks, respectively. These differences indicate that the ^{210}Pb flux to the sediments was variable in time and in the lower part of the profile (below the cesium peaks) it must have been much higher than expected from the cumulative inventories above the cesium peaks. Although direct measurements of ^{210}Pb atmospheric deposition are not available for this area, based on the relationship with sums of annual precipitation (Appleby,

2001) it can be estimated roughly to 110-130 Bq m⁻² y⁻¹. This range is also consistent with values for continental Europe presented by Preiss and Genthon (1997) in their global database and with global atmospheric depositional fluxes of ²¹⁰Pb presented by Baskaran (2011), who estimated the value for the latitude belt 40-50°N to 155±75 Bq m⁻² y⁻¹. Thus, the mean annual flux obtained for Lake Żabińskie sediments (432±8 Bq m⁻² y⁻¹) is ca. 2-4 times higher. Regardless of statistical uncertainty which goes along with these calculations, it is evident that sources other than atmospheric input play a major role in the ²¹⁰Pb delivery to the coring site. This is also confirmed by the total ¹³⁷Cs inventory in the sediments which is 3.57 kBq m⁻² while the mean value for soils in Poland was equal to 1.54 kBq m⁻² and values for northeastern Poland varied in the range of 1.0-2.0 kBq m⁻² in 2012 (GIOS 2014). Interestingly, the ¹³⁷Cs profile indicates that the peak corresponding to AD 1963 is diffused, suggesting lateral inputs of sedimentary particles. Indeed, the pre-Chernobyl inventory related to fallout from atmospheric nuclear weapons tests shows the value of 3.82 kBq m⁻² (decay corrected to May 1986), which is much higher compared to 1.45 kBq m⁻² and 1.61 kBq m⁻² reported for pre-Chernobyl fallout in Poland by Stach (1996) and Poręba and Bluszcz (2007), respectively. Lower contribution of the post-Chernobyl inventory (2.70 kBq m⁻², decay corrected to May 1986) to the total inventory is not surprising because no rainfall was noted between 26.04 and 08.05.1986 in all meteorological stations around the lake catchment.

The morphology of the Lake Żabińskie basin with steep slopes surrounding the deep and flat central coring area enhances potentially downslope movements of sediments. Therefore, high values of total ²¹⁰Pb and ¹³⁷Cs inventories in Lake Żabińskie may indicate intense sediment focusing, which leads to a higher net accumulation in the deeper parts of the lake basin and involves the resuspension of sediments in shallow zones by waves and water currents, subsequent transport and deposition in the deeper zones (Blais and Kalff, 1995; Crusius and Anderson, 1995). However, this process should be distinguished from more dynamic turbidity currents which can also occur on steep slopes but produce characteristic sedimentary structures (turbidities). Instead, sediment focusing leads to higher sediment accumulation rates without disturbances in the sediment structure. Additional inputs from sediment focusing may have important implications for dating as the degree of sediment focusing is independent from direct sedimentation from the water column and may be variable in time.

The three zones specified in Fig. 5 may show periods of different sedimentation conditions which have their explanation in the catchment history. Before AD 1910 Lake Żabińskie had a wide hydraulic connection with much larger Lake Gołdopiwo, which enabled water exchange between the two lakes and exposed the shallow western part of the Lake Żabińskie basin to erosion caused by wave action during westerly winds. Around AD 1910 a road was built across the connection between the two lakes which isolated Lake Żabińskie from direct influence of the Lake Gołdopiwo waters. This caused a significant change in the hydrological regime and sedimentation dynamics. In the hitherto protected and virtually closed basin, less variable sedimentation conditions occurred with limited possibility of erosion. Such conditions prevailed until ca. AD 1970 when increasing tourism in the region caused considerable enlargement of the recreation center located on the northern shore of the lake. As a consequence of increasing eutrophication (Amann et al. 2014), a sharp increase in SAR was recorded in the 1970's. Despite changes in "vertical inputs" to sediments directly from the water column, the

crucial role in the SAR variability was played by different rate of “horizontal inputs” which include sediments delivered to the sediment-water interface by slow sedimentation of redeposited material, sediment focusing and turbidity currents. It is evident that “horizontal inputs” have contributed largely to the overall sediment accumulation in Lake Żabińskie, which would explain very high sedimentation rates in this lake as well as high total $^{210}\text{Pb}_{\text{uns}}$ and ^{137}Cs inventories.

5.2. Dating implications

To assess the reliability of the ^{210}Pb dating results, a varve-based time scale must first be critically validated. Thus, four independent techniques were employed to confirm the reliability of the varve counts in the Lake Żabińskie sediments: (1) microfacies analysis, (2) peak activities of radiocesium, (3) tephra identification, and (4) radiocarbon dating of plant tissues grown during the ^{14}C bomb-period. Results of the microfacies analysis indicate that laminations found in Lake Żabińskie are biogenic (calcite) varves. This type of varves is characteristic for many lakes in northeastern Poland (Tylmann et al., 2013b) where input of clastic material is minor and sedimentation is governed mainly by seasonal changes in lake productivity, marl formation and water column dynamics. The annual character of the lamination is consistent with process studies carried out by Bonk et al. (2014), which showed limnological conditions and mechanisms leading to varve formation in this lake. Other evidence is provided by the validation of the varve counting by the position of well-defined ^{137}Cs peaks, which correspond to the record of its atmospheric fallout in the Northern Hemisphere resulting from nuclear weapon tests in the 1950s and 1960s, and the nuclear reactor accident in Chernobyl in AD 1986 (Pennington et al., 1973; Ritchie et al., 1973; Klaminder et al., 2012). Not only the two peaks but also the onset of significant levels of ^{137}Cs activity in the sediment profile (AD 1952-1957) is precisely consistent with the varve age at the respective depth interval. The varve chronology is also supported by ^{14}C analysis of a terrestrial leaf grown in AD 1957-1958 in the sediment layer deposited in AD 1960. Additionally, we found in the sediment core volcanic glass shards forming a cryptotephra layer at a sediment depth of 78-79 cm. Geochemical analysis of the glass shards indicated a clear correlation with the Askja AD 1875 eruption of Iceland. This eruption was the largest historical eruption on Iceland (Carey et al., 2010) and distinct from other historical silicic tephtras from the same region (Larsen et al., 1999; Meara, 2012). The Askja tephra has been detected in numerous terrestrial sequences in Norway and Sweden (e.g. Mohn, 1878; Oldfield et al., 1997; Bergman et al., 2004; Pilcher et al., 2005; Davies et al., 2007; Wastegård and Davies, 2009), north-central Germany (van den Bogaard and Schmincke, 2002), and recently in northeastern Germany and north-central Poland (Wulf et al., 2014). Excellent agreement between the position of the Askja AD 1875 tephra in relation to the varve chronology leaves no doubts about the true age of the sediment (Fig. 6).

As shown in Fig. 7, neither the CFCS nor the CRS models in their standard forms produced a chronology that is consistent with varve counts and independent chronostratigraphic markers. Both models yielded ages much younger than the calendar age with a difference of ca. 50 years at the bottommost part of the profile. This example confirms that similarities between chronologies produced by stand-alone CRS and CFCS models cannot be considered for independent validation (Abril and Brunskil, 2014).

For the CFCS model, a significant improvement was introduced after using composite CFCS with different SAR values for the three zones. The model could not reproduce exactly the AD 1963 ^{137}Cs peak, yet provided highly consistent values along the time scale with deviations <5 yrs compared with calendar ages. As suggested by Sanchez-Cabeza and Ruiz-Fernández (2012) this approach can be used when the $^{210}\text{Pb}_{\text{uns}}$ profile is piecewise linear and shows two or more linear segments, which is exactly our case. The underestimation of sediment ages by the CRS model is rather surprising because many authors reported overestimation of sediment age by the CRS model (von Gunten et al., 2009; Tylmann et al., 2013a). This relatively young sediment age obtained for Lake Żabińskie is the result of a large correction of the total $^{210}\text{Pb}_{\text{uns}}$ inventory estimated from the exponential equation and applied for the calculations. Even constraining the CRS model with the ^{137}Cs peaks did not help because, in older sediments, the difference was still unacceptable (ca. 30 years). Nevertheless, much better consistency was obtained after recalculating the correction value based on the exponential equation for the lowermost part of the profile only. In this form, the constrained CRS model provided results that deviated from the calendar age only by ≈ 10 yrs for the 120 years old sediments (Fig. 7).

From the above considerations it is clear that several factors are important for reliable ^{210}Pb dating. Vertical profiles of $^{210}\text{Pb}_{\text{uns}}$ can be affected by: 1) variations in the direct atmospheric ^{210}Pb flux, 2) variations in the sedimentary ^{210}Pb flux from the catchment, and 3) variable contributions from groundwater discharge. All these sources are variable in time and their relative role might change over time. It implies that, in some cases, it is not possible to obtain reliable sediment chronologies from the vertical profile of $^{210}\text{Pb}_{\text{uns}}$ using any of the existing models (Baskaran et al., 2014). This is also true for varved lake sediments which are regarded as an ideal sedimentary environment with very limited physical mixing or bioturbation.

6. Conclusion

The sediment core from Lake Żabińskie documents complex sediment structures and composition as well as variable sediment accumulation rates. Our goal in this study was to take this excellent sediment archive to assess possible deviations of ^{210}Pb -derived ages from real sediment ages as revealed by the tephra-supported varve chronology and to check how different numerical procedures can improve the consistency of the chronologies.

Although the $^{210}\text{Pb}_{\text{uns}}$ activity decreases with mass depth near-exponentially in this core, we found a number of factors that make reliable dating difficult, i.e. high and variable supported ^{210}Pb levels and the total $^{210}\text{Pb}_{\text{uns}}$ inventory that exceeds the expected atmospheric deposition by a factor of 4. We demonstrated that, under these conditions, the two routinely employed models (Constant Flux Constant Sedimentation CFCS and Constant Rate of Supply CRS) may lead to substantial misinterpretations of the sediment ages. However, when the true age of sediments is known from varve counts, we could show how constraining the ^{210}Pb model ages with independent chronostratigraphic markers and correction procedures could improve the consistency of different chronologies.

Our study shows the challenges of routine procedures in the ^{210}Pb dating method and the importance of careful testing and validation of the different numerical and model options. Although it has been used numerously, the method still is not a well-established dating

technique applicable to all situations (Abril, 2015). Still, more detailed studies are required to address the potential problems and pitfalls that affect ^{210}Pb -based sediment age modeling.

Acknowledgments

The research was supported by a grant from Switzerland through the Swiss Contribution to the enlarged European Union, Project CLIMPOL (PSPB-086/2010). Dirk Enters (University of Bremen) is acknowledged for sharing his expert knowledge in sediment impregnation for thin sections. We also thank Oona Appelt for technical support during EPM analyses of volcanic glass shards.

References

- Abril, J.M., 2015. Why would we use the Sediment Isotope Tomography (SIT) model to establish a ^{210}Pb -based chronology in recent-sediment cores? *Journal of Environmental Radioactivity* 143, 40–46.
- Abril, J.M., Brunskil, G.J., 2014. Evidence that excess ^{210}Pb flux varies with sediment accumulation rate and implications for dating recent sediments. *Journal of Paleolimnology* 52, 121–137.
- Amann, B., Lobsinger, S., Fischer, D., Tylmann, W., Bonk, A., Filipiak, J., Grosjean, M., 2014. Spring temperature variability and eutrophication history inferred from sedimentary pigments in the varved sediments of Lake Żabińskie, north-eastern Poland, AD 1907–2008. *Global and Planetary Change* 123, 86–96.
- Appleby, P.G., 2001. Chronostratigraphic techniques in recent sediments. In: Last, W.M., Smol, J.P. (Eds.), *Tracking Environmental Change Using Lake Sediments. Basin Analysis, Coring, and Chronological Techniques*, vol. 1. Kluwer Academic Publishers, Dordrecht, pp. 171–203.
- Appleby, P.G., Oldfield, F., 1978. The calculation of Lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. *Catena* 5, 1–8.
- Arnaud, F., Magand, O., Chapron, E., Bertrand, S., Boës, X., Charlet, F., Mélières, M.-A., 2006. Radionuclide dating (^{210}Pb , ^{137}Cs , ^{241}Am) of recent lake sediments in a highly active geodynamic setting (Lakes Puyehue and Icalma e Chilean Lake District). *Science of the Total Environment* 366, 837–850.
- Bajkiewicz-Grabowska, E., 2002. *Obieg materii w systemach rzeczno-jeziornych*. Uniwersytet Warszawski, Wydział Geografii i Studiów Regionalnych, Warszawa, pp. 1–274.
- Baskaran M., 2011. Po-210 and Pb-210 as atmospheric tracers and global atmospheric Pb-210 fallout: a Review. *Journal of Environmental Radioactivity* 102, 500–513.
- Baskaran, M., Nix, J., Kuyper, C., Karunakara, N., 2014. Problems with the dating of sediment core using excess ^{210}Pb in a freshwater system impacted by large scale watershed changes. *Journal of Environmental Radioactivity* 138, 355–363.
- Bergman, J., Wastegård, S., Hammarlund, D., Wohlfarth, B., Roberts, S.J., 2004. Holocene tephra horizons at Klocka Bog, west-central Sweden: aspects of reproducibility in subarctic peat deposits. *Journal of Quaternary Science* 19 (3), 241–249.
- Binford, M.W., 1990. Calculation and uncertainty analysis of ^{210}Pb dates for PIRLA project lake sediment cores. *Journal of Paleolimnology* 3, 253–267.

- Blais, J.M., Kalff, J., 1995. The influence of lake morphometry on sediment focusing. *Limnology and Oceanography* 40 (3), 582–588.
- Bonk, A., Tylmann, W., Amann, B., Enters, D., Grosjean, M., 2014. Modern limnology and varve-formation processes in Lake Żabińskie, northeastern Poland: comprehensive process studies as a key to understand the sediment record. *Journal of Limnology*, doi:10.4081/jlimnol.2014.1117.
- Boygles, J., 1998. A little goes a long way: discovery of a new mid-Holocene tephra in Sweden. *Boreas* 27, 195–199.
- Brenner, M., Schelske, C.L., Kenney, W.F., 2004. Inputs of dissolved and particulate ^{226}Ra to lakes and implications for ^{210}Pb dating recent sediments. *Journal of Paleolimnology* 32, 53–66.
- Carey, R.J., Houghton, B.F., Thordarson, T., 2010. Tephra dispersal and eruption dynamics of wet and dry phases of the 1875 eruption of Askja Volcano, Iceland. *Bulletin of Volcanology* 72, 259–278.
- Carroll, J.L., Lerche, I., 2003. *Sedimentary Processes: Quantification Using Radionuclides*. Elsevier, Amsterdam.
- Crusius, J., Anderson, R.F., 1995. Sediment focusing in six small lakes inferred from radionuclide profiles. *Journal of Paleolimnology* 13, 143–155.
- Davies, S.M., Elmquist, M., Bergman, J., Wohlfarth, B., Hammarlund, D., 2007. Cryptotephra sedimentation processes within two lacustrine sequences from west central Sweden. *The Holocene* 17, 319–330.
- Flynn, W., 1968. The determination of low levels of polonium-210 in environmental samples. *Analitica Chimica Acta* 43, 221–227.
- Gąsiorowski, M., Hercman, H., 2005. Recent changes of sedimentation rate in three Vistula oxbow lakes determined by ^{210}Pb dating. *Geochronometria* 24, 33–39.
- GIOŚ, 2014. Stan środowiska w Polsce. Raport 2014. Biblioteka Monitoringu Środowiska, Warszawa, 204pp.
- Goldberg, E.D., 1963. Geochronology with Pb-210. In: *Proceedings of a Symposium of Radioactive Dating*. International Atomic Energy Agency, Vienna, pp. 121–131.
- Goslar, T., Czernik, J., Goslar, E., 2004. Low-energy ^{14}C AMS in Poznań radiocarbon Laboratory, Poland. *Nuclear Instruments and Methods in Physics Research B* 223–224, 5–11.
- Hua, Q., Barbetti, M., Rakowski, A.Z., 2013. Atmospheric radiocarbon for the period 1950–2010. *Radiocarbon* 55, 2059–2072.
- Hunt, J.B., Hill, P.G., 1996. An inter-laboratory comparison of the electron probe microanalysis of glass geochemistry. *Quaternary International* 34–36, 229–241.
- Klaminder, J., Appleby, P., Crook, P., Renberg, I., 2012. Post-deposition diffusion of ^{137}Cs in lake sediment: Implications for radiocaesium dating. *Sedimentology* 59, 2259–22667.
- Krishnaswamy, S., Lal, D., Martin, J., Meybeck, M., 1971. Geochronology of lake sediments. *Earth and Planetary Science Letters* 11, 407–414.
- Kuehn, S.C., Froese, D.G., Shane, P.A.R., Intercomparison Participants (INTAV), 2011. The INTAV intercomparison of electron-beam microanalysis of glass by tephrochronology laboratories: results and recommendations. *Quaternary International* 246, 19–47.

- 610 Larsen, G., Dugmore, A., Newton, A., 1999. Geochemistry of historical-age silicic tephra in
611 Iceland. *The Holocene* 9 (4), 463–471.
- 612 Lavrieux, M., Disnar, J.R., Chapron, E., Bréheret, J.G., Jacob, J., Miras, Y., Reyss, J.L.,
613 Andrieu-Ponel, V., Arnaud, F., 2013. 6,700-year sedimentary record of climatic and
614 anthropogenic signals in Lake Aydat (French Massif Central). *The Holocene* 23, 1317–1328.
- 615 Lotter, A.F., Lemcke, G., 1999. Methods for preparing and counting biochemical varves.
616 *Boreas* 28, 243–252.
- 617 MacKenzie, A.B., Hardie, S.M.L., Farmer, J.G., Eades, L.J., Pulford, I.D., 2011. Analytical
618 and sampling constraints in ^{210}Pb dating. *Science of the Total Environment* 409, 1298–1304.
- 619 Meara, R.H., 2012. Geochemical fingerprinting of Icelandic silicic Holocene tephra layers.
620 PhD Thesis, College of Science and Engineering, University of Edinburgh, 361pp.
- 621 Mohn, H., 1878. Askeregnet den 29de-30te Marts 1875. *Forhandlinger i Videnskabselskabet*
622 *i Christiania* 1877 10, 1–13.
- 623 Ojala, A.E.K., Francus, P., Zolitschka, B., Besonen, M., Lamoureux, S.F., 2012.
624 Characteristics of sedimentary varve chronologies – a review. *Quaternary Science Review* 43,
625 45–60.
- 626 Oldfield, F., Thompson, R., Crooks, P.R.J., Gedy, S.J., Hall, V.A., Harkness, D.D., Housley,
627 R.A., McCormac, F.G., Newton, A.J., Pilcher, J.R., Renberg, I., Richardson, N., 1997.
628 Radiocarbon dating of a recent high-latitude peat profile: Stor Åmyrån, northern Sweden. *The*
629 *Holocene* 7 (3), 283–290.
- 630 Pempkowiak, J., Tylmann, W., Staniszewski, A., Gołębiewski, R., 2006. Lignin
631 depolymerization products as biomarkers of the organic matter sedimentary record in ^{210}Pb –
632 ^{137}Cs -dated lake sediments. *Organic Geochemistry* 37, 1452–1464.
- 633 Pennington, W., Cambray, R.S., Fisher, E.M., 1973. Observations on lake sediments using
634 fallout Cs-137 as a tracer. *Nature* 242, 324–326.
- 635 Pilcher, J., Bradley, R.S., Anderson, L., 2005. A Holocene tephra record from the Lofoten
636 Islands, Arctic Norway. *Boreas* 34, 136–156.
- 637 Poręba, G., Bluszcz A., 2007. Determination of the initial ^{137}Cs fallout on the areas
638 contaminated by Chernobyl fallout. *Geochronometria* 26, 35–38.
- 639 Preiss, N., Genthon, C., 1997. Use of a new database of lead 210 for global aerosol model
640 validation. *Journal of Geophysical Research* 102 (D21), 25,347–25,357.
- 641 Ritchie, J.C., McHenry, J.R., Gill, A.C., 1973. Dating recent reservoir sediments. *Limnology*
642 *and Oceanography* 18, 254–263.
- 643 Rose, N.L., 2001. Fly-ash particles. In: Last, W.M., Smol, J.P. (Eds.), *Tracking*
644 *Environmental Change Using Lake Sediments. Physical and Geochemical Methods*, vol. 2.
645 Kluwer Academic Publishers, Dordrecht, pp. 319–349.
- 646 Sanchez-Cabeza, J.A., Ruiz-Fernández, A.C., 2012. ^{210}Pb sediment radiochronology: An
647 integrated formulation and classification of dating models. *Geochimica et Cosmochimica*
648 *Acta* 82, 183–200.
- 649 Stach A., 1996. Możliwości i ograniczenia zastosowania cezu-137 do badań erozji gleb na
650 obszarze Polski. In: *Ochrona agroekosystemów zagrożonych erozją. Ogólnopolskie*
651 *Symposium Naukowe*, Puławy, pp. 203–226.
- 652 Stuiver, M., Polach, H.A., 1977. Discussion: reporting of ^{14}C data. *Radiocarbon* 19, 355–363.

- Tylmann, W., Gołębiewski, R., Woźniak, P.P., Czarnecka, K., 2007. Heavy metals in sediments as evidence for recent pollution and quasi-estuarine processes: an example from Lake Druzno, Poland. *Environmental Geology* 53 (1), 35–46.
- Tylmann, W., Enters, D., Kinder, M., Moska, P., Ohlendorf, Ch, Poręba, G., Zolitschka, B., 2013a. Multiple dating of varved sediments from Lake Łazduny, northern Poland: toward an improved chronology for the last 150 years. *Quaternary Geochronology* 15, 98–107.
- Tylmann, W., Zolitschka, B., Enters, D., Ohlendorf, C., 2013b. Laminated lake sediments in northeast Poland: distribution preconditions for formation and potential for paleoenvironmental investigation. *Journal of Paleolimnology* 50, 487–503.
- van den Bogaard, C., Schmincke, H.-U., 2002. Linking the North Atlantic to central Europe: a high-resolution Holocene tephrochronological record from northern Germany. *Journal of Quaternary Science* 17, 3–20.
- von Gunten, L., Grosjean, M., Beer, J., Grob, P., Morales, A., Urrutia, R., 2009. Age modelling of young non-varved sediments: methods and limits. Examples from two lakes in Central Chile. *Journal of Paleolimnology* 42, 401–412.
- Wastegård, S., Davies, S.M., 2009. An overview of distal tephrochronology in northern Europe during the last 1000 years. *Journal of Quaternary Science* 24(5), 500–512.
- Woszczyk, M., Tylmann, W., Jędrasik, J., Szarafin, T., Stach, A., Skrzypczak, J., Lutyńska, M., 2014. Recent sedimentation dynamics in a shallow coastal lake (Lake Sarbsko, northern Poland): driving factors, processes and effects. *Marine and Freshwater Research* 65, 1102–1115.
- Wulf, S., Dräger, N., Ott, F., Serb, J., Brauer, A., 2014. Findings of historical Icelandic (Askja AD 1875) tephras in varved lake records from Lake Tiefer See and Lake Czechowskie: a new potential for synchronizing the recent environmental history in NE Germany and N central Poland. *EGU Geophysical Research Abstracts* 16, EGU2014–9947.
- Zolitschka, B., 2007. Varved lake sediments. In: Elias, S.A. (Ed.), *Encyclopedia of Quaternary Science*. Elsevier, Amsterdam, pp. 3105–3114.

Figures

Fig. 1. Location of Lake Żabińskie and work strategy. A: Bathymetric contour map of Lake Żabińskie with the coring location. B: Subsampling scheme for different analyses.

Fig. 2. Lithology, typical varve structures and results of varve counting for the sediment core.

Fig. 3. Chemical bi-plots of historical silicic volcanic glass from Iceland and volcanic glass from Lake Žabińskie. EPMA data for comparison are obtained from Oldfield et al. (1997), Boyle (1998), Larsen et al. (1999), Bergman et al. (2004), Pilcher et al. (2005) and Meara (2012).

Fig. 4. Downcore distributions of total ^{226}Ra , ^{210}Pb , and ^{137}Cs activities in the sediment core.

Fig 5. Application of the CFCS model in two versions: simple (CFCS-1) and composite (CFCS-2).

Fig. 6. Comparison of different ^{210}Pb models applied to surface sediments of Lake Żabińskie.

Fig. 7. Differences between ^{210}Pb -based chronologies and real ages of sediments based on varve chronology validated by independent chronostratigraphic markers.

Electronic Supplementary Material – Appendix 1.

Major element compositions of single glass shards from sample CLIMPOL ZAB138-140 and the Lipari obsidian glass standard obtained by electron probe microanalyses (EPMA). All results are given in %, values lower than detection limit indicated as n.d.

Sample	SiO₂	TiO₂	Al₂O₃	FeO	MnO	MgO	CaO	Na₂O	K₂O	P₂O₅	Cl	F	Total
glass #1	74.1	0.83	12.6	3.65	0.08	0.68	2.37	3.42	2.37	0.09	0.04	0.00	100.2
glass #2	73.5	0.90	12.6	3.67	0.08	0.67	2.31	3.63	2.35	0.11	0.04	0.00	99.9
glass #3	72.2	0.89	12.7	4.12	0.10	0.86	2.78	3.46	2.23	0.22	0.05	0.06	99.6
glass #4	72.5	0.87	12.7	3.87	0.07	0.77	2.58	3.48	2.36	0.16	0.03	0.00	99.4
glass #5	72.9	0.85	13.0	4.08	0.13	0.76	2.36	3.55	2.35	0.17	0.04	0.00	100.2
glass #6	73.7	0.79	12.8	3.51	0.12	0.64	2.31	3.37	2.46	0.20	0.03	0.00	99.9
glass #7	74.1	0.79	12.6	3.45	0.09	0.64	2.25	3.36	2.48	0.12	0.05	0.09	100.0
glass #8	74.3	0.82	12.5	3.36	0.10	0.63	2.29	3.27	2.47	0.18	0.06	0.05	100.1
glass #9	73.4	0.76	12.6	3.24	0.12	0.63	2.19	3.38	2.40	0.16	0.04	0.00	98.9
glass #10	72.8	0.87	12.8	3.96	0.13	0.80	2.35	3.51	2.42	0.16	0.06	0.00	99.9
glass #11	71.6	0.91	12.9	4.21	0.12	0.86	2.79	3.56	2.35	0.18	0.05	0.00	99.4
glass #12	72.3	0.87	12.9	3.87	0.10	0.76	2.61	3.37	2.31	0.15	0.04	0.00	99.2
Glass standard													
(Lipari obsidian)	SiO₂	TiO₂	Al₂O₃	FeO	MnO	MgO	CaO	Na₂O	K₂O	P₂O₅	Cl	F	Total
20 µm beam	73.6	0.06	13.2	1.60	0.09	0.04	0.73	3.88	5.11	0.00	0.35	0.01	98.7
15 µm beam	73.7	0.06	13.1	1.66	0.02	0.01	0.71	3.82	5.37	0.00	0.35	0.00	98.8
10 µm beam	74.9	0.08	13.2	1.53	0.07	0.05	0.72	3.90	5.11	0.00	0.36	0.05	99.9
Hunt and Hill													
(1996), 12 µm beam	74.4	n.d.	12.9	1.51	0.07	0.05	0.74	3.93	5.11	n.d.	n.d.	0.35	99.0

Electronic Supplementary Material - Appendix 2

Analytical data and results of model calculations

Sample ID	Depth (cm)	Mass depth (g cm-2)	SAR (g cm-2 yr-1)	Varve age	"+"	"-"	Cs-137	±	210Pb _{uns}	±
ZAB_1-3	0.65	0.23	0.08	3	0	0	11.4	2.3	314.9	17.9
ZAB_4-6	1.89	0.46	0.08	6	0	0	13.0	1.6	270.1	16.3
ZAB_7-9	3.18	0.68	0.07	9	0	0	12.1	1.8	284.2	15.7
ZAB_10-12	5.13	0.99	0.10	12	0	0	22.4	2.0	222.2	13.9
ZAB_13-15	6.65	1.28	0.10	15	0	0	23.2	1.9	181.1	12.8
ZAB_16-18	8.09	1.54	0.13	17	0	0	19.2	1.8	202.6	13.3
ZAB_19-21	10.17	1.92	0.09	21	0	0	34.1	2.0	200.8	13.0
ZAB_22-24	12.23	2.35	0.14	24	0	0	116.3	3.0	170.2	12.1
ZAB_25-27	14.32	2.78	0.14	27	0	0	132.3	3.5	160.7	12.1
ZAB_28-30	16.97	3.43	0.22	30	0	0	34.1	2.0	132.6	11.2
ZAB_31-33	19.47	4.01	0.19	33	0	0	23.5	1.5	108.9	9.8
ZAB_34-36	20.52	4.26	0.25	34	0	0	30.4	1.7	90.7	8.8
ZAB_37-39	23.57	4.89	0.21	37	0	0	33.6	1.5	89.3	8.4
ZAB_40-42	26.02	5.44	0.18	40	0	0	47.1	1.3	112.0	9.9
ZAB_43-45	27.65	5.78	0.11	43	0	0	40.7	1.8	109.4	9.6
ZAB_46-48	28.65	5.98	0.10	45	0	0	54.4	2.4	121.3	10.0
ZAB_49-51	31.04	6.39	0.13	48	1	0	68.7	2.2	92.1	9.3
ZAB_52-54	32.77	6.71	0.16	50	2	0	75.3	2.4	109.9	9.9
ZAB_55-57	34.53	7.12	0.14	53	2	0	65.9	2.5	99.3	10.4
ZAB_58-60	36.08	7.41	0.10	56	2	0	31.8	2.0	105.4	10.3
ZAB_61-63	37.98	7.75	0.11	59	2	0	8.6	1.4	80.5	9.0
ZAB_64-66	39.82	8.11	0.12	62	2	0	6.1	1.6	85.6	9.9
ZAB_67-69	41.52	8.42	0.10	65	2	0			59.3	8.9
ZAB_70-72	43.98	8.87	0.15	68	2	0			73.4	8.6
ZAB_73-75	45.59	9.20	0.11	71	2	0			57.5	8.0
ZAB_76-78	47.51	9.66	0.15	74	2	0			41.0	8.4
ZAB_79-81	48.93	10.00	0.09	78	2	0			46.3	9.0
ZAB_82-84	50.44	10.33	0.11	81	2	0			52.1	9.2
ZAB_85-87	51.69	10.65	0.16	83	2	0			33.2	8.5
ZAB_88-90	53.60	11.09	0.11	87	2	1			37.0	9.7
ZAB_91-93	54.54	11.27	0.09	89	2	2			40.2	7.7
ZAB_94-96	55.79	11.55	0.09	92	2	2			28.2	7.3
ZAB_97-99	57.51	11.94	0.13	95	2	2			26.4	8.2
ZAB_100-102	59.21	12.32	0.10	99	2	2			47.6	7.6
ZAB_103-105	60.49	12.63	0.08	103	2	3			44.5	8.8
ZAB_106-108	62.27	12.97	0.09	107	2	3			48.2	8.0
ZAB_109-111	63.54	13.24	0.09	110	2	4			26.2	7.9
ZAB_112-114	64.68	13.48	0.08	113	2	5			43.0	8.2
ZAB_115-117	65.64	13.70	0.07	116	2	5			34.3	8.1
ZAB_118-120	67.03	13.98	0.14	118	2	5			27.9	7.9
ZAB_121-123	67.83	14.14	0.05	121	2	5			23.2	7.7
ZAB_124-126	69.00	14.51	0.12	124	2	5			20.4	7.5
ZAB_127-129	70.83	14.63	0.12	125	2	5			34.2	7.5
ZAB_130-132	71.39	14.91	0.14	127	2	5			17.5	7.7
ZAB_133-135	73.06	15.28	0.12	130	2	5				
ZAB_136-138	75.08	15.73	0.15	133	3	5				
ZAB_139-141	76.52	16.06	0.17	135	3	5				
ZAB_142-144	79.34	16.63	0.10	141	3	6				
ZAB_145-147	81.51	17.13	0.16	144	3	6				
ZAB_148-150	83.78	17.65	0.17	147	3	6				
ZAB_151-153	85.84	18.17	0.17	150	3	6				
ZAB_154-156	87.51	18.83	0.16	154	3	6				
ZAB_157-159	89.92	19.21	0.19	156	3	6				
ZAB_160-162	92.32	19.70	0.24	158	3	6				
ZAB_163-165	94.85	20.43	0.24	161	3	6				
ZAB_166-168	96.50	20.85	0.21	163	4	7				
ZAB_169-171	97.88	21.32	0.24	165	4	7				
ZAB_172-174	100.05	21.96	0.21	168	4	8				
ZAB_175-177	102.70	22.73	0.26	171	4	8				
ZAB_178-180	105.36	23.44	0.24	174	4	8				