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COMPARING VARVE COUNTING AND ^{14}C-AMS CHRONOLOGIES IN THE SEDIMENTS OF LAKE ŻABIŃSKIE, NORTHEASTERN POLAND: IMPLICATIONS FOR ACCURATE ^{14}C DATING OF LAKE SEDIMENTS

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Abstract: Varved lake sediments from Lake Żabińskie (northeastern Poland) provide a high-resolution calendar-year chronology which allows validation of ^{14}C dating results. 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 348 cm long sediment profile which contained $1000^{+12}/_{-24}$ varves. The varve chronology was validated with the ^{137}Cs activity peaks, the tephra horizon from the Askja eruption at AD 1875 and with the timing of major land-use changes of known age inferred from pollen analysis. 32 AMS ^{14}C dates of terrestrial macrofossils distributed along the profile were compared with the varve chronology. After identification of outliers, the free-shape model performed with 21 ^{14}C dates provided the best possible fit with the varve chronology. We observed almost ideal consistency between both chronologies from the present until AD 1250 while in the lower part (AD 1000–1250) the difference increases to *ca.* 25 years. We demonstrate that this offset can be explained by too old radiocarbon ages of plant remains transported to the lake by the inflowing creek. Results of this study highlight that careful interpretation of radiocarbon age-depth models is necessary, especially in lakes where no annual laminations are observed and no independent method are used for cross-validation.

Keywords: lake sediments, varve chronology, AMS ^{14}C dating, radionuclides, age-depth model.

1. INTRODUCTION

Varves were recognized and described for the first time by Swedish geologist Gerard De Geer who introduced the term “varve” for clastic silt-clay sediments found in proglacial environments (Zolitschka, 2007). Further studies have shown that different processes may lead to seasonal changes in sediment composition and accumulation of distinguishable sediment layers due to e.g. variations in biological activity, chemical processes and influx of terrestrial material (Zolitschka *et al.*, 2015). Annually laminated (varved) sediments are preserved in lakes under different climate conditions and environmental settings. At present, varved lake sediments are regarded as one of the best archives to chronicle climatic and

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environmental changes (Ojala, 2001; Snowball *et al*., 2002). They are also important recorders of hydrological and limnological processes within lakes (Larsen *et al*., 1998; Ojala *et al*., 2000; Zillén *et al*., 2003; Bonk *et al*., 2015).

One of the major advantages of varved sediments is their potential for developing accurate and high-resolution chronologies in calendar-year time scales for relatively long periods of time (Kitagawa and van der Plicht, 1998; Ralska-Jasiewiczowa *et al*., 1998; Brauer *et al*., 2001; Lücke *et al*., 2003; Stanton *et al*., 2010). Typically, for well-preserved varved sequences it is possible to obtain varve counting uncertainties as low as 1–2% (Kinder *et al*., 2013). Ideally, varve counting should be supported by experimental verification of the annual nature of the observed laminations by sediment trap studies as well as microscopic analysis of varve structures and compositions of individual laminae. Moreover, validation of the varve chronology with additional independent age-controls is necessary. This is usually made with chronostratigraphic markers of known ages or application of radiometric dating methods such as ^{137}Cs, ^{210}Pb and ^{14}C (Brauer *et al*., 2000; Ojala and Tiljander, 2003; Enters *et al*., 2006; Stanton *et al*., 2010; Kinder *et al*., 2013; Tylmann *et al*., 2013). If available, volcanic ash (tephra) horizons are excellent chronostratigraphic markers that indicate precisely the age of the deposited layers (Brauer *et al*., 1999; Lowe, 2001; Wulf *et al*., 2013). Also biological proxies may provide robust and independent validation of the sediment ages (biostratigraphy). For example, pollen data in combination with historical information about human activities in the lake surroundings enable the reconstruction of environmental events and thus may help validate the varve chronology in certain time windows (Seppä, 2007).

Comparison between varve-based chronologies and independent dating methods is not always straightforward and, in some cases, it is difficult to obtain consistent results. Differences or offsets between varve chronologies and calibrated radiocarbon ages are often reported in the literature (Stanton *et al*., 2010; Mellström *et al*., 2013). The problem is particularly pronounced when the time-scale of interest is relatively short, e.g. the last millennium, very high chronological accuracy is required and even small differences between both chronologies become crucial for accurate interpretation of proxy records, e.g. as for detection/attribution studies that allow recognition of forced and unforced climate variability (Hegerl *et al*., 2011). High-resolution dating of such records remains a challenging task that requires multiple methods and advanced algorithms for age-depth modeling. Excellent preservation of varves allowing for highly accurate calendar-year chronologies provide a unique opportunity to assess potential depositional lags or re-depositional effects of individual samples (^{14}C outliers) or to assess chronologies with ^{14}C age-depths models (e.g., Blaauw, 2010; Blaauw and Christen, 2011; Goslar *et al*., 2009).

This paper describes the establishment and validation of a 1000-yr long chronology for the varved sediment record from Lake Żabińskie, northeastern Poland. The exceptional scientific value of this site is due to a very good preservation of varves in the sediments and high sedimentation rates which allow high-resolution (annual) analysis of different proxies. The lake already showed its high potential for quantitative paleoenvironmental reconstructions (Amann *et al*., 2014; Hernández-Almeida *et al*., 2015; Larocque-Tobler *et al*., 2015). Therefore, the best possible accuracy of the chronology is crucial for the reliability of the millennial-long climate reconstructions derived from the sediments of this lake. To obtain this, we employed two dating methods, *i.e.* continuous varve counting and ^{14}C AMS dating of terrestrial macrofossils. Additionally, the uppermost part of the profile was validated with the ^{137}Cs activity peaks and the Askja AD 1875 tephra horizon (Tylmann *et al*., submitted). In the lower part, where no other chronostratigraphic markers were available, we used pollen data and historical information to check the reliability of the varve- and radiocarbon-based chronologies against major land-use changes of known ages in the catchment. In this respect, we will (1) provide a varve-based chronology for the sediment record of Lake Żabińskie, (2) present results of radiocarbon dating of terrestrial macrofossils found in the sediments, (3) show that analysis of ^{14}C ages and indication of outliers can help in developing a robust chronology, and (4) explain and discuss potential reasons of discrepancies between varve- and radiocarbon-based chronologies.

2. STUDY SITE

Lake Żabińskie is located in the Masurian Lake District in northeastern Poland (**Fig. 1**). The landscape in this area was formed during the Pomeranian Phase of the Vistulian (Weichselian) glaciation (Szumański, 2000). Hence, the catchment area is dominated by glacial sediments with fluvial and biogenic sediments in river valleys and waterlogged areas, respectively. The northwestern and southwestern parts of the direct catchment are dominated by forests that consist of pine, spruce and birch trees. Cultivated areas and wetlands dominate in the eastern part.

Lake Żabińskie is a small (41.6 ha) and deep lake (44.4 m). The lake basin is slightly elongated in W-E direction and two parts can be distinguished: a shallow basin in the western part and the deep central basin in the middle of the lake. The lake has three inflows and one outflow (O1) that discharges water westward to the much larger Lake Gołdopiwo. The major inflow is from Lake Purwin (I1) in the north; two minor creeks feed Lake Żabińskie from the south (I2 and I3). The mouth of the I3 creek, which forms a small delta, is situated close to the deepest part of the lake. The creek supplies water from cultivated fields and woodlands, therefore provides sig-

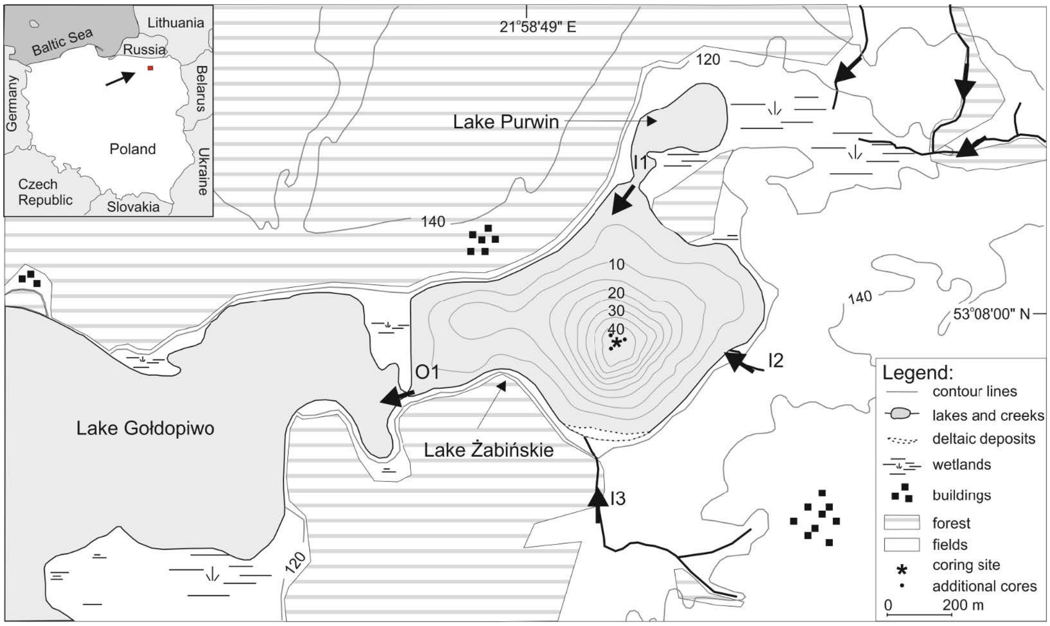

Fig. 1. *Location of Lake Żabińskie with the basin bathymetry and coring sites.*

nificant amounts of sediment and organic material from the catchment.

Presently, Lake Żabińskie is highly productive and has a calcium-rich epilimnion and a seasonally anoxic hypolimnion (Bonk *et al*., 2015). These conditions form almost an ideal environment for the formation and preservation of biogenic varves.

3. MATERIALS AND METHODS

Coring and composite profile correlation

Overlapping sediment cores were collected from the deepest part of Lake Żabińskie (54°07'54.5"N; 21°59'01.1"E) during two field surveys in 2011 and 2012. The short core ZAB-12/1 (48 cm) with an undisturbed sediment-water interface was recovered using a UWITEC gravity corer (Ø 90 mm); cores ZAB-11/3 (214 cm), ZAB-12/3-2 (200 cm) and ZAB-12/4-2 (198 cm) were recovered using a UWITEC piston corer (Ø 90 mm). Immediately after collection the cores were tightly capped, labeled and stored in cold conditions prior to analysis. In the laboratory the cores were split lengthwise into two halves, macroscopically described and photographed.

The composite sediment profile was obtained by stratigraphic correlation based on macro- and microscopic comparison of well-preserved laminations and diagnostic horizons (**Fig. 2A**). The section of slightly disturbed laminae at a composite depth of 50–100 cm was additionally correlated with three cores recovered from different locations in the deepest part of the lake bottom (**Fig. 2B**). This correlation showed a comparable number of varves between the diagnostic horizons in each core which confirms that the composite profile has no sedimentary gaps in this disturbed section.

Varve counting and error estimation

The entire profile was subsampled continuously for thin sections. Fresh sediment blocks were collected using aluminum foil trays, frozen in liquid nitrogen, freeze-dried and impregnated with Araldite©2020 epoxy resin following the procedure described by Lotter and Lemcke (1999). Cutting and slab-polishing to the thickness of 25–30 μm was done by MK Factory (Germany). Then, thin sections were scanned with 2400 dpi resolution between two polarizing foils on a flatbed scanner equipped with a transparency unit.

First, typical varve structures were established for the entire composite profile. Thin sections were microscopically analyzed at 20× to 500× magnification and different varve microfacies were recognized and described. Using these microfacies types, the number of varves was counted by three persons on high-resolution digital images of thin sections using the CooRecorder software (http://www.cybis.se). In case of identification discrepancies, each ambiguous layer was checked in the thin section under a microscope. Based on three independent countings the final chronology and its uncertainty was estimated according to the following procedure: (1) varves identified in all three countings 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 one year in the minus direction; (3) varves missed in two countings were not added to the chronology but the uncertainty (in the plus direction) was increased by one year. This method

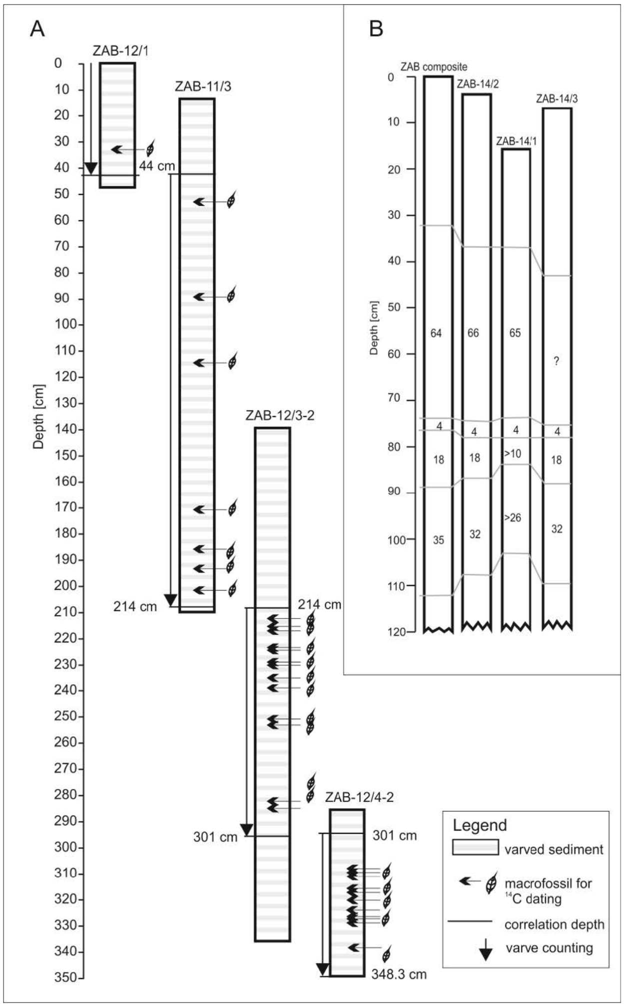

Fig. 2. *Composite sediment profile from Lake Żabińskie: A — scheme of core correlation with the position of macrofossils dated, B — correlation of the composite profile with additional cores showing the comparable number of varves in the section of slightly disturbed varves.*

contrasts with commonly used methods where, if the boundary is not clear, half a year is counted and the second half year is counted as uncertainty (Rasmussen *et al.*, 2006; Vinther *et al.*, 2006; Stanton *et al.*, 2010).

The varve thickness was measured along three parallel lines (middle, left- and right-side of the thin section) to account for horizontal variability within one varve. A mean from three different measurements was calculated and defined as a varve thickness. To evaluate the quality of varve preservation we determined the Varve Quality Index (VQI) as suggested by Zolitschka (1990), Lotter and Lemcke (1999) and Brauer and Casanova (2001) with slight modifications. Each varve was assigned to one of the three classes:

- VQI 1: low quality, boundaries interrupted, counting difficult;
- VQI 2: high quality, regular varves, boundaries slightly interrupted, counting reliable;
- VQI 3: perfect quality, regular varves, boundaries ideally horizontal, counting reliable.

Radiocarbon dating

Plant remains preserved in the sediments were collected during subsampling of both core halves for different multi-proxy analyses. The macro-remains were picked during the year-by-year subsampling from well-identified varves. After botanical identification at the Department of Plant Ecology (University of Gdańsk), only well-preserved terrestrial plant fragments were selected for radiocarbon dating. Additionally, we collected plant remains of different kinds (leafs, needles, pieces of bark) from living and dead trees at the lake shore and macrofossils transported to the lake by the southern creek (I3; **Fig. 1**). The macrofossils 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, at 900°C for 10 hours. The obtained CO_2 was then reduced with hydrogen, using Fe powder as a catalyst. The 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 a correction for isotopic fractionation (Stuiver and Polach, 1977). The radiocarbon ages were calibrated using the INTCAL13 (Reimer *et al.*, 2013) and the BombNH1 (Hua *et al.*, 2013) calibration curves.

Pollen analysis

Samples for pollen analysis of 1 or 0.5 cm^3 in volume were collected at regular intervals of 3 varve years. Every second sample was prepared for studies with the modified Erdtman’s acetolysis method (Berglund and Ralska-Jasiewiczowa, 1986; Faegri and Iversen, 1989). In order to estimate pollen and spores concentration (and pollen influx) *Lycopodium* tablets with a known number of spores were added (Stockmarr, 1971). Counting of pollen was continued until a minimum of 800 tree and shrub pollen grains was reached in each sample. For pollen identification, keys (Reille, 1995 and 1998; Beug, 2004) and the reference collection of modern sporomorphs at the Department of Palaeobotany of the W. Szafer Institute of Botany, Polish Academy of Sciences in Kraków were used. Percentage values of taxa were calculated from the total sum of tree and shrub (AP) and herbaceous terrestrial plant (NAP) pollen grains.

4. RESULTS

Lithology and varve microfacies

Macroscopic correlation of the cores allowed constructing the composite profile with a total length of 348.3 cm. The whole profile was annually laminated but differences in sediment lithology and the character of laminations were noticeable. At first sight the sediment color changed from brownish in the upper part of the core through reddish and olive in the middle section and, finally, to brownish in the basal part of the record. The macroscopic investigation shows also significant changes in varve thickness that varies between 0.4 and 15.5 mm. These observations and microscopic investigations of thin sections allowed determining three major types of varve microfacies (**Fig. 3**).

Varve microfacies type I (0–48.2 cm) represents the most complex structure in the entire sediment profile. Spring starts with the deposition of large amounts of calcite grains (the most distinct bright lamina), followed by diatoms in early summer. Intense calcite precipitation may form multiple calcite laminae deposited also in summer and fall. During fall, pyrite and vivianite crystals occur, while during winter the deposition consisted mainly of amorphous organic matter. The varve thickness in this section varies in the range between 1.68 and 12.78 mm with a mean of 6.41 ± 2.32 mm. The varve boundaries are very clear and the preservation can be described as excellent.

Varve microfacies type II (48.2–156.6 cm) is structurally less complex but the preservation is not ideal. The annual cycle starts with the deposition of large amounts of centric diatoms and a thick calcite layer (spring and early summer). During summer, pennate and centric diatoms and different algae, mainly *Oscillatoria rubensces* and *Phacotus*, start to occur. In fall vivianite and pyrite grains dominate with small amounts of calcite crystals and pennate diatoms. Chrysophyte cysts occur more often in the second part of the annual cycle. The last structural element which occurs at the end of the year is a thin clay layer deposited during winter. Although it is very characteristic, it does not occur in every individual varve in this section. Varve microfacies type II can be divided into two subtypes according to the varve thickness: subtype IIa (48.2–85.8 cm) with a mean thickness of 5.09 ± 2.04 mm and subtype IIb (85.8–156.6 cm) with a mean thickness of 7.22 ± 2.73 mm. In this part of the sediment profile, varve boundaries are often deformed by gas expansion which occurred after the core retrieval.

Varve microfacies type III (156.6–348.3 cm) represents well-preserved and relatively simple laminated structures. The spring-summer deposition consists of large amounts of diatoms and a thick calcite lamina. In the summer layer, vivianite grains and chrysophyte cysts appear. At the end of the annual cycle minerogenic and organic detritus with only few calcite grains or diatoms occur. In some varves of this type distinct double calcite laminae are present within the same one-year deposition. Minor admixtures of minerogenic material are also visible in some varves. The laminations in this part of the sediment profile are fine (mean varve thickness 2.51 ± 1.05 mm); boundaries are very clear and horizontal.

Varve chronology

The varve chronology for Lake Żabińskie (**Fig. 4**) covers the last millennium (from AD 1000 to AD 2011). Counting uncertainty at AD 1000 amounts to $^{+12}/_{-24}$ varve years. The most pronounced increase in uncertainty occurred between 52.4 cm (AD 1926$^{+2}/_{-1}$) and 210.1 cm (AD 1630$^{+7}/_{-18}$) which corresponds to the section with slight disturbances in the sediment structure and generally lower quality of varve preservation. The reliability of the varve counting is consistent with the analysis of the Varve Quality Index (VQI) (**Fig. 4**). Varves classified as VQI 2 and VQI 3 constitute 92% of the total number of varves counted (VQI 2 – 53.8%, VQI 3 – 38.2%). Therefore, only 8% of the varves were difficult to interpret.

Radiocarbon dating results

In total, 32 samples preserved in the core sediments were dated using AMS ^{14}C technique (**Table 1**). The samples are well distributed along the composite profile with only short sections devoid of macrofossils, e.g. between 115 cm and 170 cm sediment depth. In general, the pattern of ^{14}C ages (^{14}C BP) plotted against the varve ages (Year AD) follows the shape of the ^{14}C calibration curve (**Fig. 5A**). Also a series of dates around *ca.* 920 ^{14}C BP in the lowest section of the profile is in accordance with the quasi plateau of the calibration curve between *ca.*

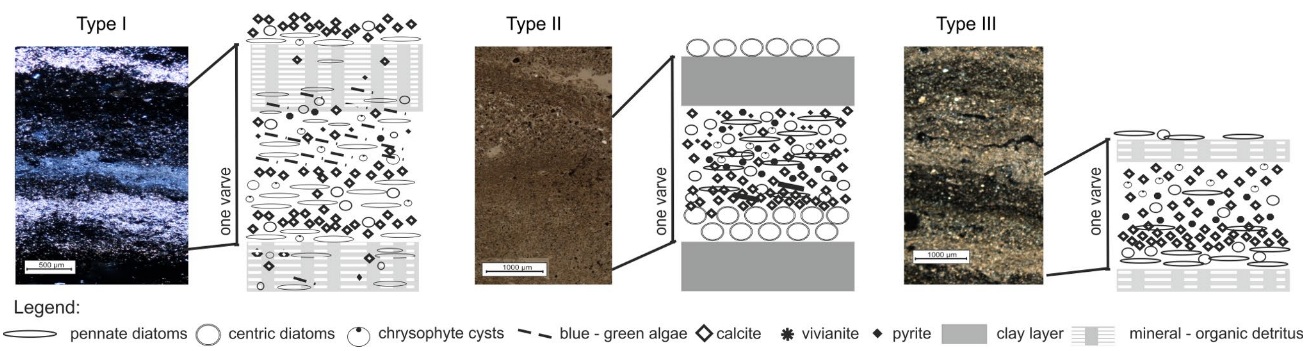

Fig. 3. *Major varve microfacies identified in the sediments of Lake Żabińskie.*

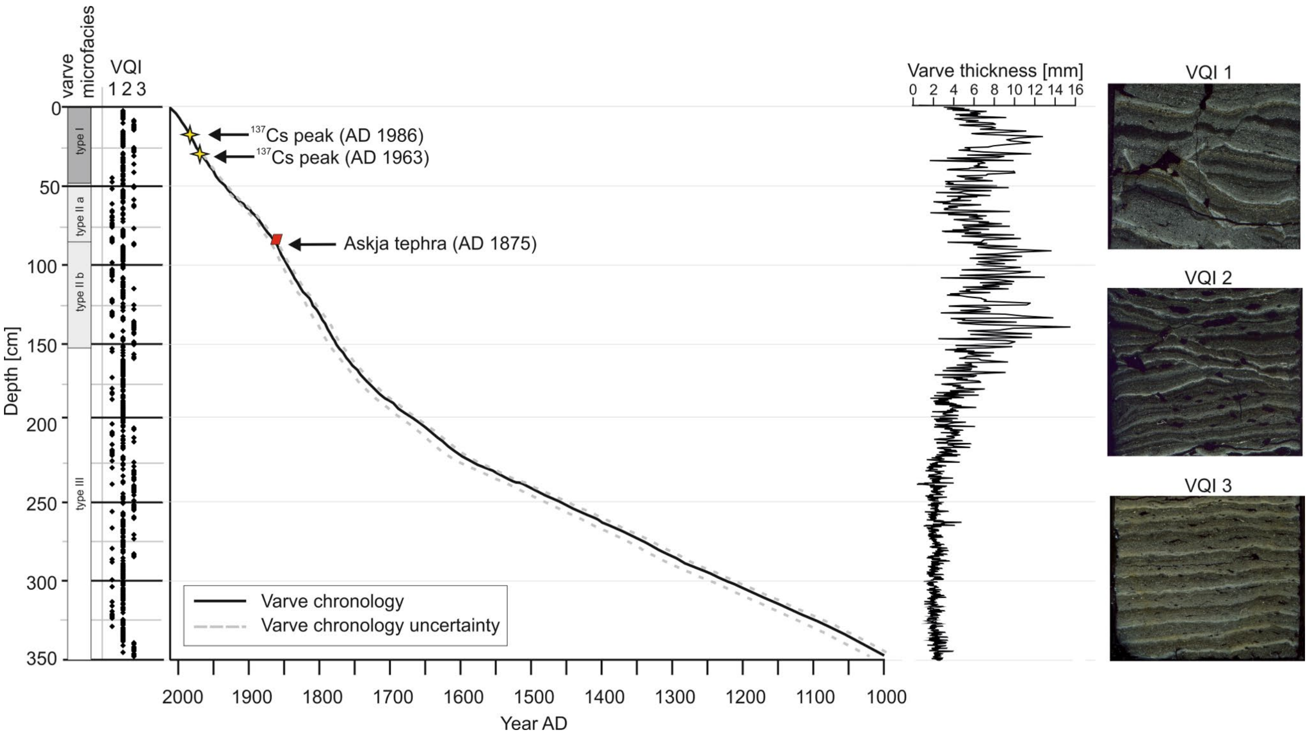

Fig. 4. *Varve characteristics and chronology. Validation data (^{137}Cs and tephra horizon) according to Tylmann* et al. *(submitted).*

AD 1050–1200. The inversion of the ^{14}C ages between *ca.* 300 and 400 ^{14}C BP follows the wiggle of the ^{14}C calibration curve between *ca.* AD 1500–1600, and a series of ^{14}C ages around 150 ^{14}C BP roughly follows the quasi plateau of the ^{14}C calibration curve between AD 1680 and 1950. However, in the set of 32 ^{14}C dates, as many as 17 dates deviate from the calibration curve by more than it is statistically justified by the uncertainty of ^{14}C dating, and the deviating ages are too old.

To obtain a continuous radiocarbon-based age model, we used the free-shape algorithm (Goslar *et al*., 2009). This algorithm allows for balancing two basic concepts: (i) maximizing the likelihood of calendar ages of the ^{14}C-dated samples, and (ii) maximizing the smoothness of the age-depth relation, the balance between them to be set by so-called weight of curvature (of age-depth line). In the case of Lake Żabińskie, where the varve chronology has already been built and we expected that a potential error in the varve chronology would change with age rather gradually, we replaced in the modeling the domain of depth with that of the varve age. Therefore, the model could be rather called as "age-varve_age" model. In the model calculations, the weight of curvature (of age-varve_age line) was set quite small, allowing its slope to change by *ca.* 50% within a century. This setting was quite conservative, because at any level of the profile, so large errors in varve counting were unlikely. **Fig. 5B** shows the ^{14}C ages (^{14}C BP) plotted against the free-shape ^{14}C age model (Years AD) and the ^{14}C calibration curve (black line). Still, some samples (^{14}C ages) are significantly outside the calibration curve (white circles): these are the dates older than 1000 ^{14}C BP occurring among the series of dates that cluster around the quasi plateau at 920 ^{14}C BP, three dates at the local minimum of the calibration curve around AD 1600, and two dates in the section where the calibration curve oscillates between 100 and 200 ^{14}C BP. All these ^{14}C dates have been rejected for the further free-shape age modeling. After multiple runs of the model performed with a different number of remaining ^{14}C dates to obtain the best possible consistency with the varve chronology using as many ^{14}C dates as possible, we also rejected the two ^{14}C ages at 900 ^{14}C BP of the samples varve-dated at *ca.* AD 1300 (**Fig. 5B**, marked in grey). The reason for the rejection was that the time span encompassed by all the samples dated around 900 ^{14}C BP, exceeded the length of the quasi plateau at 920 ^{14}C BP of the calibration curve.

The final ^{14}C free-shape model compared to the varve chronology is shown in **Fig. 6**. Almost ideal consistency can be observed between both chronologies from the present until AD 1250. For this section the radiocarbon age-depth model provides results which differ only by a few years from the varve chronology which is within the range of uncertainty of both chronologies. In the lower part (AD 1000–1250), the difference increases to *ca.* 25 years and exceeds the uncertainty of the chronologies.

Table 1. *Description of terrestrial macrofossils dated with the AMS radiocarbon method. The calibrated dates were calculated with the OxCal v4.2 software (Bronk Ramsey, 2009). The modeled dates were obtained using free-shape algorithm (Goslar* et al.*, 2009). Samples indicated in grey were rejected from final age model.*

Lab No. Poz-	Sample name	Varve date AD	Material	Age ^{14}C BP	Calibrated date AD (95.4%)	Modeled date AD (95.4%)
50996	Zab 33.5 cm	1960	Piece of a terrestrial plant	–619 ± 36	1957–1957; 2001–2005	1956–1958
50999	Zab 51.7 cm	1929	Pine needle and bark	70 ± 50	1680–1939	1910–1933
50987	Zab 88.5 cm	1858	Piece of a terrestial plant, 1 Carex nigra nut	145 ± 35	1667–1950	1806–1877
50988	Zab 115.3 cm	1825	1 spruce needle	400 ± 40	1432–1633	1768–1840
55842	Zab 173.3-178.9 cm	1727	Anthropogenic detritus, common corn cockle seed	235 ± 30	1528–1955	1693–1736
55786	Zab 185.2 cm	1704	1 upright sedge nut, piece of shoot	150 ± 40	1666–1955	1677–1712
50989	Zab 193.3 cm	1680	Piece of a leaf of a terrestrial plant	205 ± 35	1642–1955	1659–1685
55843	Zab 202.4-203.4 cm	1650	1 common juniper needle	410 ± 40	1427–1632	1638–1655
55844	Zab 213.1-213.9 cm	1621	Pine bud scale	520 ± 60	1296–1456	1618–1627
50990	Zab 215.1 cm	1617	Piece of a terrestrial plant	385 ± 35	1441–1634	1614–1623
50992	Zab 217.1 cm	1611	1 common juniper needle	435 ± 35	1415–1618	1608–1618
50993	Zab 223.0 cm	1589	1 Juniperus communis needle	470 ± 50	1320–1619	1584–1598
55787	Zab 223.6-224.5 m	1586	Piece of brich leaf	405 ± 35	1432–1630	1581–1595
50994	Zab 229.4 cm	1560	2 common juniper needle	315 ± 30	1484–1648	1552–1571
55788	Zab 230.3-231.1 cm	1554	Pine bark	270 ± 30	1514–1799	1544–1564
55845	Zab 235.3-235.7 cm	1533	1 common juniper needle and shoot	285 ± 30	1493–1791	1518–1542
50995	Zab 239.9 cm	1509	Piece of a fructification of lime	355 ± 30	1453–1635	1489–1517
55846	Zab 251.6-252.3 cm	1451	1 fruit of lime	465 ± 30	1410–1465	1423–1448
55847	Zab 253.4-253.8 cm	1444	Piece of birch leaf	540 ± 30	1316–1437	1413–1440
55849	Zab 282.0-284.2 cm]	1305	Piece of birch leaf	890 ± 40	1034–1220	1254–1319
55850	Zab 289.7-290.7 cm	1277	2 pines bud scales and bark	910 ± 50	1024–1218	1226–1282
50997	Zab 308.5 cm	1185	2 pieces of pine needle	930 ± 30	1025–1165	1155–1168
55851	Zab 309.7-309.9 cm	1178	Pine bud scale and bark	915 ± 30	1030–1189	1150–1157
50998	Zab 310.4 cm	1175	Piece of bark	920 ± 30	1028–1184	1147–1155
55852	Zab 314.2-314.6 cm	1154	Piece of birch leaf	990 ± 30	989–1153	1122–1135
55853	Zab 315.1 cm	1151	Pine bud scale	890 ± 40	1034–1220	1119–1132
55911	Zab 318.9 cm	1132	Pine bark	960 ± 30	1020–1155	1100–1114
55855	Zab 323.1 cm	1111	Piece of birch leaf	1005 ± 30	978–1151	1080–1092
55857	Zab 326.9-327.4 cm	1092	Pine bark	1040 ± 35	895–1040	1061–1070
55856	Zab 326.9 cm	1091	Birch bark	965 ± 30	1018–1155	1060–1069
55859	Zab 327.6-328.2 cm	1087	Pine bark	920 ± 30	1028–1184	1056–1065
55860	Zab 339.9 cm	1035	Shoots of grass	1175 ± 30	770–963	——

To check possible depositional lags or other reasons for small discrepancies between ^{14}C ages and varve ages, we measured ^{14}C activities in several samples of modern plant remains from the catchment of Lake Żabińskie (**Table 2**) and from the collection of modern samples from western Poland (Goslar, unpublished data). ^{14}C ages of leaves and green needles collected from birch and pine, and of leaves collected from the southern creek I3 appeared to correspond to the atmospheric ^{14}C level in AD 2013–2014 (sampling in January 2015). This result was obtained by calibration of the ^{14}C activities of the modern samples against extrapolated atmospheric post-bomb data (Hua *et al.*, 2013) beyond AD 2010. Yellow aged needles still attached to the pine tree appeared *ca.* 6 years old, while pieces of bark collected from the southern creek I3 (*i.e.* the major path of transportation of terrestrial plant remains to the lake) had an age of *ca.* 25 years. Also test measurements of ^{14}C concentrations in the outer layer of bark periderms collected from living pine tree in western Poland in January 2015 revealed a ^{14}C age of –473 ± 26 ^{14}C BP, which corresponds to an apparent age of 8 years (Goslar, unpublished data). The modern ^{14}C samples suggest that depositional lags between a few years up to 25 years are, in fact, expected and help explaining the differences between ^{14}C ages (time when the macrofossils were biosynthesized) and varve ages (time of deposition in the lake).

Pollen analysis

According to the palynological results presented along with the varve-based time scale (**Fig. 7**), the area of Lake Żabińskie was strongly forested until the turn from the 16th to the 17th century. Co-domination of pine forests with spruce and deciduous forests of *Tilio-Carpinetum*

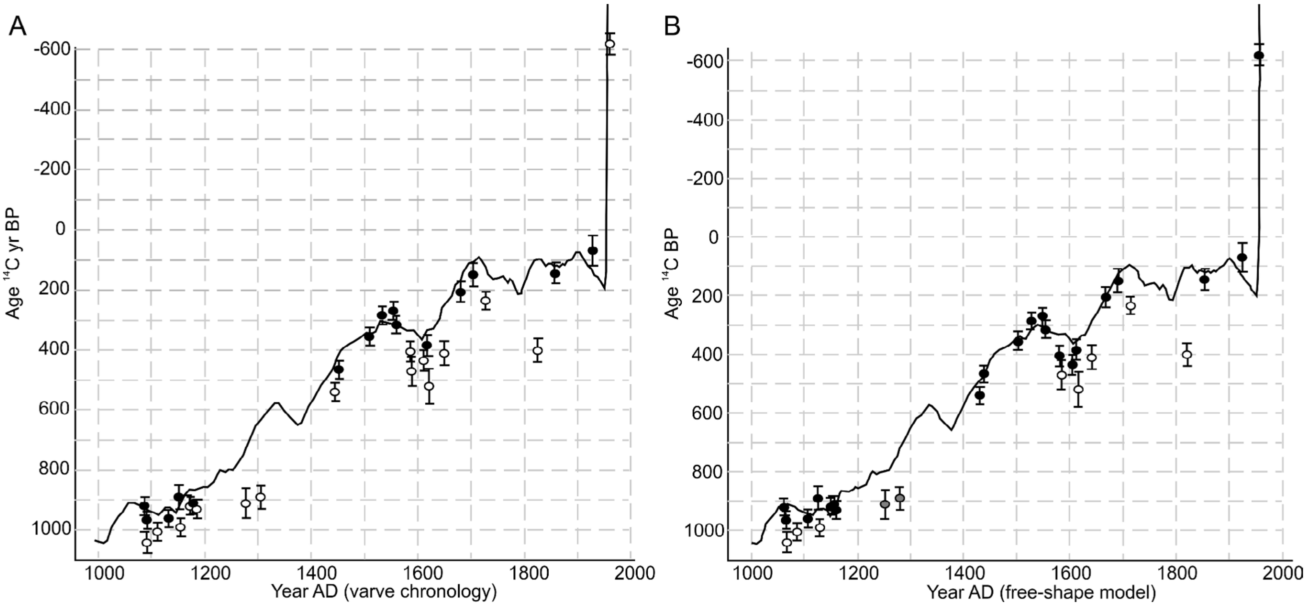

Fig. 5. *Comparison of ^{14}C ages of samples with the calibration curve INTCAL13. A — the calendar time scale (horizontal axis) is derived from varve counting; dates consistent with the calibration curve are marked in black; outliers marked in white. B — the calendar time scale (horizontal axis) is derived from radiocarbon-based free-shape age model; 21 dates used in the final age model are marked in black; two dates rejected from the final model are marked in grey; outliers marked in white.*

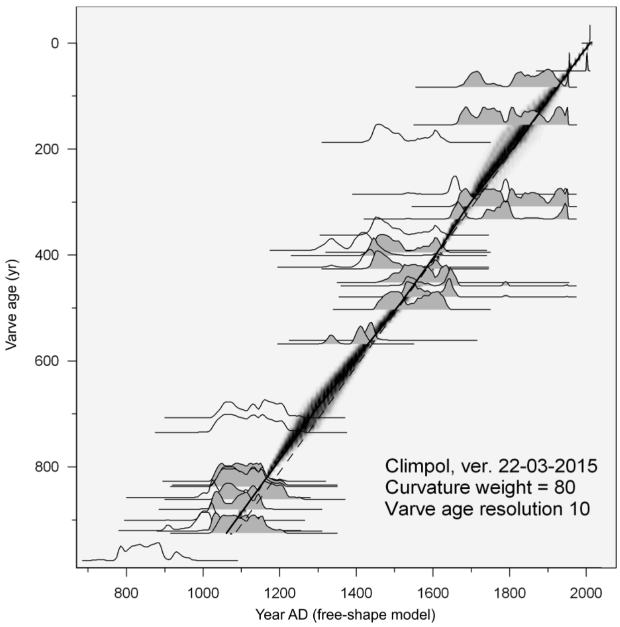

Fig. 6. *Comparison of radiocarbon-based age model and varve chronology. The ^{14}C-based free-shape model is represented by the grey-shaded band passing through the probability distributions of the calibrated dates while the varve chronology is represented by the dashed line.*

Table 2. *^{14}C dates of plant remains collected from the catchment of Lake Żabińskie in January 2015. Calibrated dates were calculated by comparison with the atmospheric ^{14}C data compiled by Hua* et al. *(2013). * — calibration approximate, dates younger than 2010 extrapolated from Hua* et al. *(2013).*

Lab No. Poz-	Sample name	Material	Age ^{14}C BP	Calibrated date AD
69544	ZAB needle 1	Green pine needles collected from a living tree	–246 ± 26	2013*
70130	ZAB needle 2	Yellow pine needles collected from a fallen tree	–396 ± 25	2008
69545	ZAB leaf	Birch leaves collected from a fallen tree	–226 ± 25	2014*
70131	ZAB bark	Bark collected from a fallen tree	–2210 ± 23	1978
69645	ZAB inflow 1	Leaves transported by the southern creek (I3)	–244 ± 25	2013*
69646	ZAB inflow 3	Bark transported by the southern creek (I3)	–1244 ± 25	1989

type, as well as the presence of birch and alder woods overgrowing wet surfaces were observed in the lower part of the profile. First increases in local agriculture was recorded after AD 1450 and starting from AD 1610 the habitats previously occupied by hornbeam-oak woods were cleared and used for cereals, buckwheat, hemp and/or hop, flax cultivation. The most intensive anthropogenic impact on the environment began from AD 1806 and lasted at least until AD 1939. Since the 1960s pollen data suggest a decrease in agricultural activity and an increase of woodland communities with birch and alder (**Fig. 7**). The varve-based timing of the recorded chang-

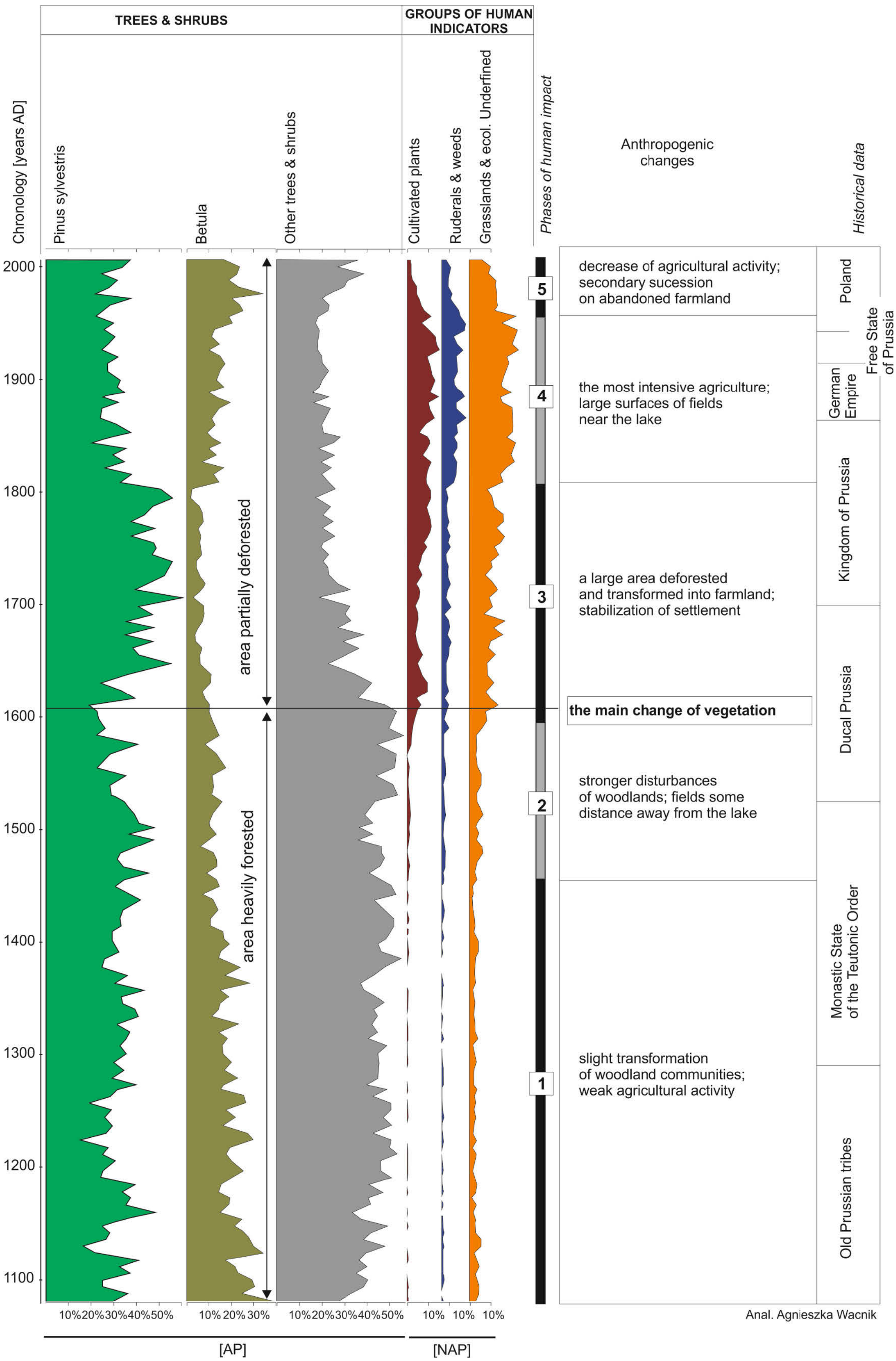

Fig. 7. *Percentage pollen diagram from Lake Żabińskie sediments with indications of major environmental changes.*

es, especially the major shift in land-use change around AD 1600, is in agreement with the settlement history in this region documented in historical sources (Białuński, 1996).

5. DISCUSSION

All chronologies contain different uncertainties that cannot be avoided. For varve chronologies, systematic uncertainties can be attributed to different sources (Zolitschka, 2007, Brauer *et al*., 2014): (i) technical problems with core collection and correlation; (ii) depositional events that cause erosional gaps in the record, (iii) complex structures of individual varves, which makes it difficult to distinguish annual layers, and (iv) poor preservation of laminations. These are possible reasons why replicate counts provide different results. Regardless of the limited uncertainty of varve chronologies, it is important to validate varve chronologies with other independent dating methods (O'Sullivan, 1983; Lamoureux, 2001; Zolitschka, 2007).

The varve chronology for the Lake Żabińskie sediments was validated in the uppermost part with the ^{137}Cs activity peaks and the tephra horizon from the Askja eruption at AD 1875 (Tylmann *et al*., submitted). Both methods provided independent controls of the sediment ages and are in perfect agreement with the varve chronology (**Fig. 4**). Also age modeling based on radiocarbon dates provided results that are in very good agreement with the varve chronology for the last 800 years. From the present back until AD 1250, only insignificant differences (<10 yr) are observed between both chronologies. However, these differences increase to 25 years in the lowermost part of the sediment profile and are statistically significant taking into account the small uncertainties of the varve- and the radiocarbon-based chronologies in this part ($^{+12}/_{-24}$ and ±10, respectively). Radiocarbon ages that deviate significantly from varve-based chronologies have been observed in many studies (Brauer *et al*., 2000; Brauer and Casanova, 2001; Hajdas *et al*., 1998; Zillén *et al*., 2003). In most cases radiocarbon dates indicate older ages than expected from varve chronology which can be explained by many reasons, e.g. depositional lags and redeposition of sediment (for terrestrial macrofossils) or hard-water effect on samples that were synthesized from dissolved inorganic carbon in the lake (Geyh *et al*., 1999).

For Lake Żabińskie, none of the available chronostratigraphic markers or other information can help in such a precise determination which chronology is more accurate. The only method available to check the reliability of both chronologies is pollen analysis combined with historical information. Most of the villages in this region were founded in the 16th century including two villages located close to Lake Żabińskie (Brożówka and Jeziorowskie) which were established in AD 1562 and AD 1570, respectively (Wakar and Wilamowski, 1968). Stabilization of local settlements was associated with permanent deforestation of large surfaces and placement of fields and meadows in the lake catchment. Therefore, these years should mark major transformations of plant cover as pollen analysis is an excellent tool for the reconstruction of natural and man-made changes in vegetation (Allen *et al*., 1999; Barnekow, 2000; Ralska-Jasiewiczowa, *et al*., 2003; Pędziszewska, *et al*., 2015). Indeed, the major change in the pollen diagram is recorded around AD 1600 (according to the varve chronology) and manifested by reduction of arboreal pollen (AP) and simultaneous increase in non-arboreal pollen (NAP) (**Fig. 7**). Interestingly, it is just about AD 1570 when continuous and increasing appearance of pollen from cultivated plants commenced, which could reflect early stages of the development of the two villages mentioned above. At this time interval the varve- and radiocarbon-based chronologies are perfectly consistent (**Fig. 6**). Therefore, the timing of land-use changes in the lake catchment registered by pollen analysis generally confirms that both chronologies are accurate.

Some offsets between ^{14}C-based and varve chronologies can be explained with a delay between the growth of a plant (or a part of the plant) and its transport and burial in the varved sediment (depositional lags). In the almost ideal example, a tree leaf grown in one year, stays on a tree until late fall, and is then wind-transported directly to the lake center. However, other plant tissues (such as bark, needles or twigs) may stay on a plant for years before they are mobilized and transported. This can be the case for tree needles that fall from the tree several years after their growth, or pine bark that forms layers of peridermis with the outermost one (and the oldest!) being the most susceptible for tearing off. The measurements of ^{14}C in plant remains collected in January 2015 show different ages: especially the plant material transported by the southern creek I3 might be dozens of years older than the moment of its deposition in the sediments (**Table 2**). All these data indicate that several years of difference between the ^{14}C- and the varve-based chronologies must be considered. Also the increase of discrepancies between the chronologies in the lowermost section of the profile (before AD 1250) can be explained, as that part of the ^{14}C-based model relies almost exclusively on dates of pine bark fragments (**Table 1**).

6. CONCLUSIONS

We investigated a varved sediment record of Lake Żabińskie in northeastern Poland to establish a reliable chronology for the last millennium. The varve-based chronology was validated with several independent methods, *i.e.* ^{137}Cs activity peaks, a tephra horizon, palynological data and historical information about land-use change in the catchment. Radiocarbon dating of some terrestrial macrofossils revealed significant discrepancies with the varve chronology. Despite careful selection of plant material used for ^{14}C dating, 35–50% of the samples dated appeared to be reworked and thus were rejected for age modeling. Reworked macrofossils were probably delivered to the lake by the southern creek supplying the lake with waters from cultivated fields and woodlands.

After elimination of the ^{14}C outliers, the ^{14}C chronology established with the free-shape algorithm deviated only by 10–25 years from the varve chronology. Between AD 1250 and today, the deviation did not exceed 10 years and was insignificant taking into account uncertainties of the ^{14}C- and varve-based chronologies. Statistically significant (up to 25 yr) deviations in the earlier section (AD 1000–1250) could be attributed to specific types of macrofossils as this part of the model relied on dates of plant fragments, that might have been transported to the lake with considerable deposition lags.

All these data seem consistent and highlight the reliability of the chronology with the accuracy of decade. They also demonstrate that, when an accuracy of a decade is required, age-depth models of lake sediments based solely on ^{14}C dates of terrestrial macrofossils may reveal too old ages, and that the amount of the deviation may depend on the type of terrestrial macrofossils dated.

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