Calendar time scale for Lake Wigry sediments on the basis of radiocarbon dating

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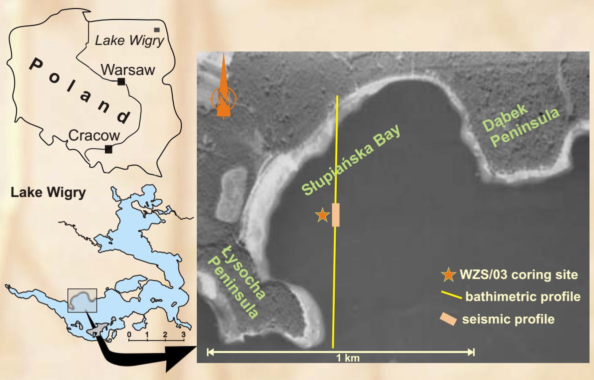
INTRODUCTION

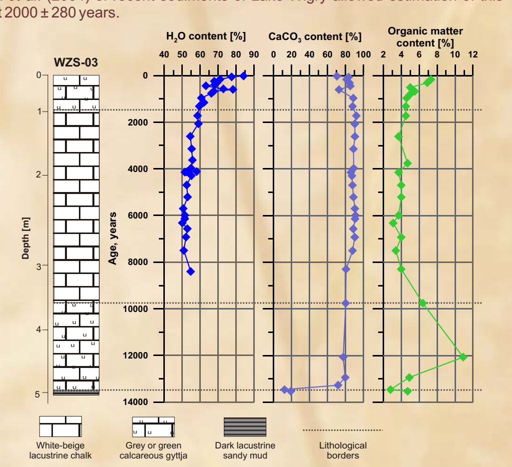
Lake Wigry, one of the largest (21.2 km^2) and deepest (mean depth 15.8 m) lakes in Poland, is located in North Eastern Poland, on the area of Suwalki Lakeland (54.09N; 23.03E). The area of Wigry National Park includes also 41 lakes in the neighbourhood. Lake Wigry has complex origin, being partially tunnel-valley and also kettle lake to some extent. Lake bathymetry, as well as the coastline, are relatively tortuous and (are) divided into several main basins by underwater shallows. The surrounding area was shaped during Baltic Glaciation, which peaked between 24,000 and 18,500 calBP. During this time the northern part of the present area of the Wigry National Park was covered by ice, while the southern part was the area, where accumulation of glacial material coming from the front of the ice occurred. All of the Wigry National Park lakes were formed by retreated glacier.

The lake is mainly supplied with water from two rivers (Czarna Hańcza and Wiatrołuża), which have their inflows in the northern part of the lake, and some minor watercourses from nearby lakes. The underground inflow mostly in the southern part of the lake might also contribute considerably to the water budget. The only outlet of the lake is through the Czarna Hańcza river, though the main loss of the water is due to evaporation. The water supplying the lake is rich in dissolved calcium carbonate, as a result from the presence of numerous calcareous pebbles in the surrounding postglacial bedrock. Therefore, the lake water is characterised by high concentration of calcium carbonate, ranging from 150 up to 266 mgCaCO$_3$/dm^3. As a consequence, Lake Wigry sediments are mostly carbonate-organic formations (carbonate gyttjas), characteristic for profundal areas, and almost pure carbonate (lake chalk) occurring in littoral zone. In the vicinity of coast some clastic sediments also can be found. The geological research in Lake Wigry sediments is described by Rutkowski *et al.* (2002 and 2003), who classified the facies on the basis of seismoacoustic investigations. The trophy of lake water varies from eutrophic in the northern part to mesotrophic southern basins, including also Słupiańska Bay.

The sediments of Słupiańska Bay constitute mainly carbonate gyttja with calcium carbonate content reaching up to 90%, the remaining fraction is organic matter. The 5.3 m long WZS/03 core was collected in July 2003 by drilling in the profundal of 18.2 m water depth. Lithological investigations of the core revealed several units characteristic of post-glacial Polish lakes. In the uppermost section the sediments are classified as dark-grey carbonate gyttja and from 0.86 m gradually turning to brighter lake chalk, followed by dark-grey gyttja in the depth range of 4.2 5.0 m. The bottom part of core (5.0 - 5.3 m) contains dark, vaguely sandy lake muds with low CaCO$_3$ content, comprising also plant macrofossils and admixture of sand and gravel.

The sediments of Słupiańska Bay provide very interesting material from the point of view of radiocarbon investigations. Carbonate as well as organic fration is an ideal source of carbon for ^{14}C measurements aimed at construction of chronology, although the carbonates are affected by reservoir effect. Preliminary isotopic studies by Pawlyta *et al.* (2004) of recent sediments of Lake Wigry allowed estimation of this effect at 2000 ± 280 years.





METHODS

Radiocarbon dating is commonly used to construct time scales of various Late Pleistocene and Holocene climatic record. Dating of lake sediments, which often provide excellent evidence of climatic changes, requires preliminary recognition of material present in particular sediment, which determine the strategy for sampling, measurements and age-depth model construction. The age of a sediment sample should reflect the time of its deposition, and the most important issue is to identify this fraction of sediment, which would lead to reliable results and is present in sufficient quantity.

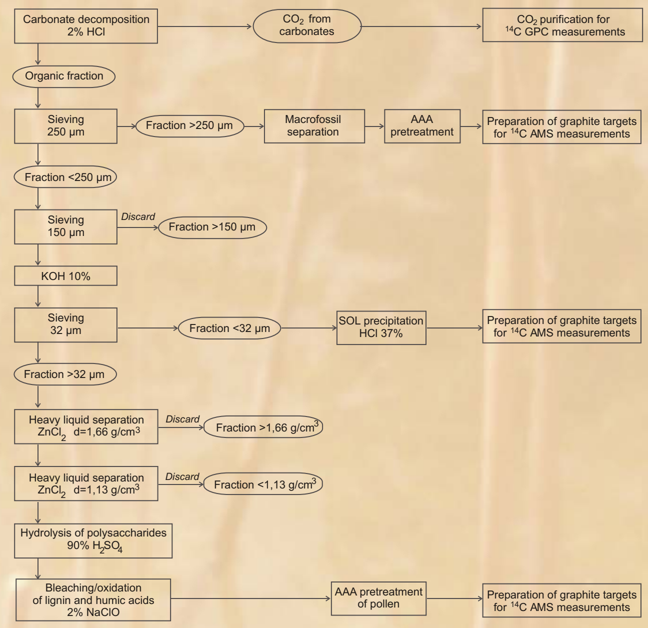
In the frame of present study, the ^{14}C concentration in 22 organic and 16 carbonate samples have been measured. Immediately after recovery of the 8-cm in diameter core was subdivided into 5-cm thick samples. During the sampling several larger organic remains, like wood or reed pieces, moss, have been picked out and collected for AMS ^{14}C dating. For most of organic samples the dating was possible only with use of accelerator mass spectrometry technique because of small mass of samples, while all carbonates were dated using the gas proportional counting technique.

From the bottom of the core the material of high organic content was collected, comprising peat, small wood fragments, roots and other unidentified plant remains. Total organic carbon content of this sample allowed for ^{14}C measurements by means of GPC technique, however, in later studies the dating was also performed on small wood pieces picked out from this mixture.

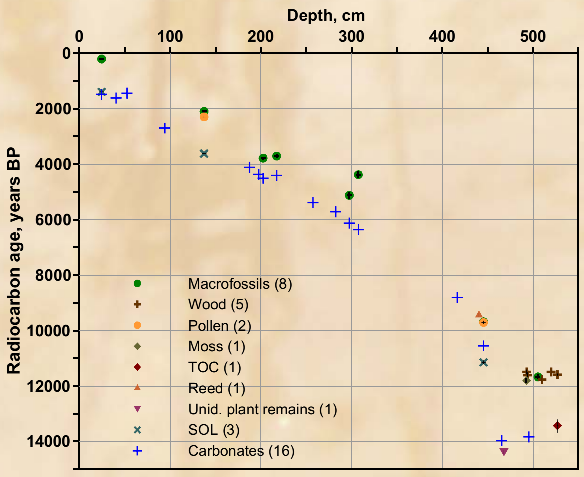
Separation and preparation of nearly all macrofossil, pollen and alkali-soluble (SOL) samples, as well as AMS measurements have been carried out in ^{14}C lab at the Swiss Federal Institute of Technology (ETH), Zurich, Switzerland. Successively, all the samples were combusted and graphitised according to standard procedure applied in ETH laboratory (Hajdas *et al.*, 2004). Measurements of radiocarbon concentration were carried out by means of 6MV AMS system (Bonani *et al.* 1987; Synal *et al.* 1997). Pretreatment and graphitisation of two samples was made in AMS Gliwice Radiocarbon Laboratory (Goslar and Czernik, 2000) with subsequent AMS measurements in Poznań Radiocarbon Laboratory (Goslar *et al.*, 2004).

All organic samples were carefully decalcified. After 250 μm sieving the coarse fraction was examined under the binocular microscope and the terrestrial macrofossil fragments have been picked out. The method followed procedure described by Hajdas (1993). Obtained samples included fossils typical for sediments of our climatic zone, like birch nut and scale, fragments of willow leaves, pine needle and periderm. Standard acid-alkali-acid treatment was subsequently applied.

Pollen was extracted with use of sieving, heavy liquid separation, and then the polysaccharides as well as lignin and humic acids were removed. In case of pollen separation procedure and evaluation of sample purity was followed the preparation of pollen from Lake Baikal sediments (Piotrowska *et al.*, 2004). The effect of each step of the treatment was controlled under the binocular microscope. Obtained samples were composed mostly of pine pollen, with some spruce grains and infinitesimal number of other organic particles.



RESULTS OF RADIOCARBON DATING



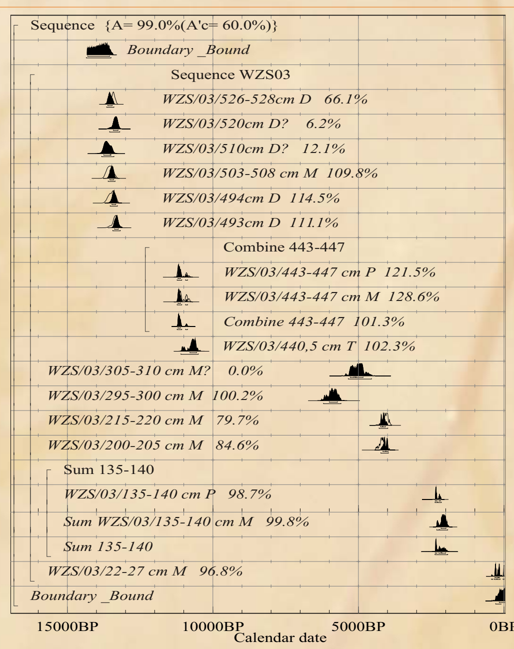
All results of measurements are presented versus depth on the figure. As expected, radiocarbon ages of carbonates have proved to be affected by high apparent age, ranging from few hundred up to 1500 years. Similar alteration observed for alkali-soluble fraction (SOL) may suggest, that this fraction comprises decomposed organic material, which had incorporated carbon dissolved in lake water. Furthermore, the ages of total organic carbon from the bottom of core and of unidentified plant material from the depth 468 cm are significantly older, which could be explained by reservoir effect or redeposition process. For TOC sample the first explanation seems fairly probable, especially when the TOC age is compared with the date obtained for wood pieces separated from this sample, which is in quite good agreement with the remaining data. Similar, although not so distinct effect is observed for moss sample from the depth 493 cm. However, the plant material, discovered as a several millimetres thick layer is even older that carbonate sample from the same depth, also seeming to be an outlier. It could be interpreted as an occurrence of a short disturbance event, but the measured $\delta^{13}C$ of -44.3‰ for this plant material is anomalously low, suggesting some perturbations in graphite target preparation or measurement. For the reasons described above the ages obtained for these three samples were not taken into consideration while age-depth model was built.

Age reversals shown around 200 and 300 cm and for the bottom samples imply, that more outliers should be removed, but the choice of outliers is not a straightforward procedure at this stage, and this problem was solved by bayesian analysis incorporated into calibration of sequence of dates (Buck *et al.* 1991) with use of OxCal 3.10 software (Bronk Ramsey, 2001) and Intcal04 calibration curve (Reimer *et al.* 2004).

SEQUENCE CALIBRATION

Samples from the depths 137.5 and 445.5 cm were double-dated on macrofossil and pollen samples. Both materials represent terrestrial organic fractions and the results obtained for macrofossils and pollen from the depth 445.5 cm are in perfect agreement (confirmed by *t*-test for independent samples), what permits combination or weighted average of the dates. Conversely, the dates from 137.5 cm are not consistent in terms of statistical test, although they are quite close. Averaging of such incoherent dates could lead to confusing conclusions and illusionary precision, and it was not possible to exclude unambiguously one of them. For these samples the probabilities of calendar ages were summed, resulting in wider calibrated age range (and furthermore larger uncertainty of age-depth model), but this range seems much more reliable.

In OxCal 3.10 programme so-called agreement index allows to evaluate results of MCMC modelling. An agreement between assumed chronological order and data is obtained when the agreement index *A* approaches 60% or more. The first results of calculations obtained for WZS/03 sequence were characterised by extremely poor overall *A* (14.2%) as well as low *A* for several dates, as it was expected, while age reversals have occurred. For two samples around 300 cm the younger date (4385 ± 130) was suspected to be an outlier, because of extremely small sample mass (only 0.23mgC) and absence of age reversal for carbonate samples from the same depths, and accepting such an young age would increase the reservoir effect to ca. 1800 years. Similar considerations for samples around 200 cm, and quite high *A* values for these samples (both ca. 80%) lead to the conclusion, that none of them is an outlier. More complicated situation is present regarding four dates on wood from the bottom part of the core, and several trials to question only one of them have not given satisfactory results, so in the final analysis the oldest and the youngest have been questioned. The conclusive results of calibration as described above are presented on the right. The overall agreement index reached 99% and *A* for all samples exceeds 60%.

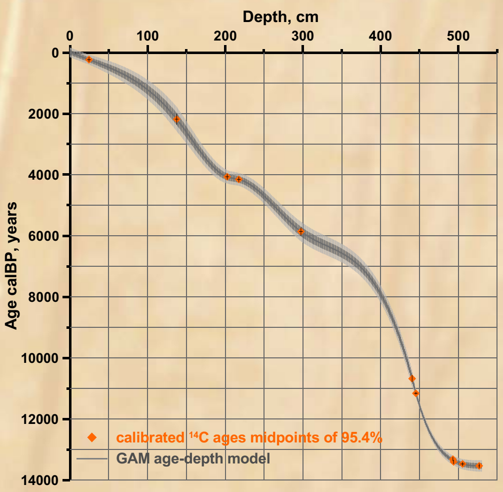


GAM MODELLING

The calibrated radiocarbon ages (midpoints of 95.4%) of samples plotted versus depth do not show linear dependence, which makes the assumption about constant sedimentation rate not justified, at least for the whole sequence. For purposes of age model construction the non-linear regression method, called generalised additive models (GAMs) have been used. GAMs, first introduced by Hastie and Tibshirani (1990 and 1995), are a statistical tool used for non-linear fits to experimental data and predicting the system response for specified conditions, with use of smoothing techniques, most often spline functions.

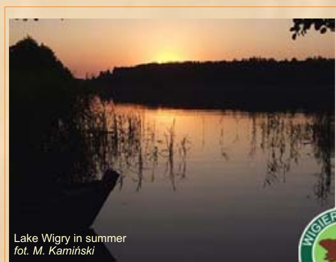
In the presented work the GAMs were used for the depth as independent variable and age as system response, taking advantage of its most important feature - lack of assumptions about age-depth relationship. Use of GAMs for age-depth modelling was first proposed by Birks and Heegaard (2003) and developed by Heegaard (2005). The aforementioned functions allow also calculations of the uncertainty of age-depth relation, taking into account not only the uncertainty of age determination, but also thickness of sample and uncertainty of the model itself (Heegaard 2005). Therefore, the application requires depth and age intervals as incoming data.

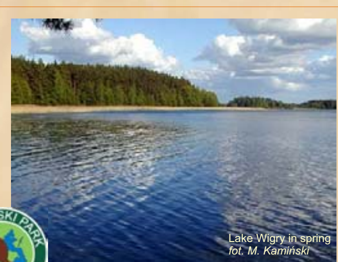
The results of modelling are presented on the graph together with the data used for calculations, plotted as midpoints of 95.4% range used as a point estimator and half of the range as an uncertainty estimator.



DISCUSSION AND CONCLUSIONS

Radiocarbon dating of Lake Wigry sediments has provided results, which enabled age-depth model construction. Application of generalised additive models is based on the assumption of high reliability of data used for modelling procedure. Therefore, it requires especially critical selection of data on which the age model is strongly dependent, what may be considered somewhat insecure. Other important feature of GAM implementation is consistent calculation of standard deviation, which includes all main sources of uncertainty in case of dating of sediment core. The model uncertainty clearly increases in the ranges, where less dates are available or the dates are less certain, and decreases in ranges of higher-resolution data. Hence, combining careful selection of sample material and dates, sequence calibration and GAM computation seems to be advisable approach to age-depth modelling. The main weakness of GAM method is assumption about gaussian distribution of calibrated age and consequent use of midpoints of age range, which is obviously incorrect. Bearing in mind the low resolution of the data for WZS/03 core, as well as uncertainties of the model and the data, this approximation may be justified and the use of other point estimator would not introduce considerable alteration of the model in this case.


Lake Wigry in summer
fot. M. Kamiński


Lake Wigry in spring
fot. M. Kamiński

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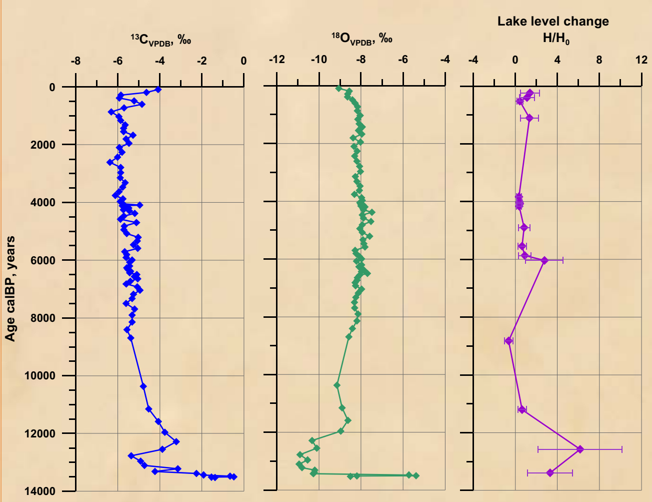
ISOTOPE INVESTIGATIONS



The study of carbon and oxygen isotope in contemporary environment of Lake Wigry and its surroundings has been carried out by Sensuła *et al*. (2005) and Pawlyta *et al*. (2004).
Other isotope investigations include modelling of lake level change on the basis of radiocarbon measurements, as well as stable carbon and oxygen isotope composition of carbonates from WZS/03 core.

Basically, the reservoir age of carbonate depends on several factors, and one of them is lake level. The lower the level is, the surface exchange of CO_2 is faster, resulting in dissolved carbonates less ^{14}C-depleted. A model of carbon and radiocarbon cycle in lake basin (after Broecker and Walton, 1959; Benson, 1978; Peng *et al*., 1978) has been used by Pazdur et al. (1995) for Lake Gościąż study.

Similar calculations were carried out for Lake Wigry sediments on the basis of following parameters of the model:

	Parameter	Value	unc.	
Modern atmospheric ^{14}C concentration	C_A	111,52	0,8	pMC
^{14}C concentration in DIC from water supply	C_R	66,8	4	pMC
^{14}C concentration in DIC from lake water	C_L	97,8	1,1	pMC
Average dilution factor for the sediments	q_L	0,893	0,087	
Concentration of total carbon in water entering the lake	k_R	2,2	0,5	mol/m^3
Rate at which the CO_2 enters lake surface	R	6	1	mol/m^{2}year
Linear evaporation rate from lake surface	l_E	0,575	0,06	m/year

Radiocarbon measurements in carbonate and organic fractions allow calculation of the dilution factor q_L (and/or reservoir age T_R):

$$q_L \quad \frac{A_{carb}}{A_{atm}} \exp \frac{T_R}{8033}$$

Basing on the q_L values and carbon model, the relative changes of mean lake depth can be estimated as H/H_0 (H_0 being the present-day level).

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