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^{210}Pb DATING OF YOUNG HOLOCENE SEDIMENTS IN HIGH-MOUNTAINS LAKES OF THE TATRA MOUNTAINS

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Abstract: Topmost sediments in two oligotrophic lakes of the High Tatra Mountains were studied in terms of sedimentological characteristics and ^{210}Pb dating. An alpine lake sediments are important source of information on geomorphic process activity in glacial catchments. Two different sediment transfer models are represented. In Morskie Oko lake basin majority of extreme, short lasting geomorphic events triggered on the surrounding slopes are registred in lake sediments (minerogenic laminae), while in Zelene Pleso lake only an effect of prolonged flooding periods are to be seen. The sedimentation rates in both lakes are similar.

1. INTRODUCTION

Contemporary geomorphological evolution of mountain landscape could be studied by use direct measurement of the effects of geomorphic processes on slopes and in valley floors. Such studies are conducted by field experiments, in which some fragments of landforms are taken into monitoring of morphological changes after certain periods. In this way one can collect quantitative data on the rate and mode of transformation both by erosion and accumulation processes. However, such data are valuable for relatively small fragments of a given landscape, and cannot be used for evaluation of geomorphological changes within larger units, e.g. they are not sufficient for estimates of sediment budget in alpine catchments. Therefore, lacustrine sediment budgets are commonly used as a measure of the operation of contemporary and paleogeomorphological processes in mountain catchments (Wolman and Miller, 1960; Larsen and Magnerud, 1981; Owens and Slaymaker, 1993). In such studies, duration of the erosion period and the volume of eroded bedrock, deposited in lake, is used as a measure of erosion in glacial cirques since the ice withdrawal. It is evidences by many authors that mountain cirque lakes may trap a high portion of allochtonous minerogenic material inflowing from the surrounding slopes. The sediments remain in the lake, and give records of environmental changes in the catchment, but not all material detached from hillslopes reaches the lake basin. Thus, erosion rates calculated according to sedimentation rates and total sediment volume may underestimate the true values.

This paper attempts to calculate sedimentation rate for two alpine catchments of the granodiorite High Tatra Mountains, which differ in size and geomorphological units responsible for transfer of surficial material (**Fig. 1**).

Fig.1. *Location map for the Tatra Mountains.*

2. METHODOLOGICAL BACKGROUND AND STUDY AREA

An alpine sediment transfer model developed by N. Caine (1974) consists seven possible internal transfers. Complete set of slope and valley units contain all possible geomorphological units within which transfer of surficial material is going on. These fundamental units are used in the examination of geomorphic process activity in a sequence of sediment transfers from interfluve to lake basin. The final products of sediment transfers are stored and registered in lake, and sedimentation rate in lake is quantitative measure of alpine geomorphic activity. Precise dating of sediment units (members) provides an important tool in these studies. Thus, ^{210}Pb dating seems to be a useful method in studies of youngest Holocene sediments.

This study assesses dynamics and mode of two glacial cirques in the High Tatra Mountains (Southern Poland and Slovakia) during the last *ca* 150 years on the basis of ^{210}Pb dating of lacustrine sediments; in the Morskie Oko Lake of Poland (MO) and the Zelene Pleso Lake of Slovakia (ZP). These two oligotrophic lakes which a straddle upper timberline-alpine ecotone are located on the northern side of the mountains (**Fig. 2**). Two different models are presented in the catchments taken into consideration. The Morskie Oko model contains only three internal transfers: free-face/rocky slope – talus – lake basin. Zelene Pleso model contains five internal transfers: free-face/rocky slope – talus – talus foot – valley floor – lake basin. In hanging valley called "Medena Dolina" the greatest Tatra glacierette exists. Hydraulic connection exists periodically between glacierette and Zelene Pleso. Morskie Oko Lake is located at 1395 m a.s.l., with a surface area of 34.5 ha, and maximum depth of 51 m. The basin is glacially scoured, with infill sediment thickness 5–6 m (Baumgart-Kotarba *et al.,* 1993). The core was extracted from the southern side of the basin at the depth of 37 m. Zelene Pleso Lake located at 1542 m a.s.l., is relativelly small (surface area of 1.77 ha) and shallow (4 m). The core was extracted from a flat bed 4 m below the water table.

Lake sediments were sampled with a 0.65 m Axelsson corer. Cores were immediately stored vertically and transported to the Laboratory at the Department of Geomorphology and Hydrology, Polish Academy of Sciences in Cracow together with the water rich uppermost unit. Coring tubes filled with the sediment were X-rayed. On extrusion the cores were sliced into subsamples, and taken for absolute dating and grain-size distribution analyses. The main reference for ^{210}Pb dating of the Morskie Oko sediments is Baumgart-Kotarba *et al.* (1993). The Zelene Pleso core was extracted in 2000.

The Zelene Pleso core was sectioned at 2-3 mm increments. The dry mass of sediment samples was 1-3 g. ^{210}Pb activities were determined via its granddaughter ^{210}Po. It was assumed that both isotopes were in radioactive equilibrium. Polonium separation procedure followed the method of Flynn (1968). The samples were treated with a hot nitric acid and then H_2O_2 was added to them in order to oxygenate organic matter. After mineralisation the solution was evaporated to dryness. The dry residue was dissolved in HCl and evaporated again. Nitric acid was completely replaced with hydrochloric acid after dissolution and evaporation cycle was repeated three times.

Polonium was deposited on silver disc from the 0.5 M solution of HCl at 93^{0}C. 0.4 g of hydrazine dichloride was added in order to remove ions disturbing polonium deposition. After 3 hours of deposition, the silver disc surface was covered with white coating. Alpha activity was measured by Canberra Alpha Analyst spectrometer with Si PIPS detector. Before the samples were treated with the nitric acid ^{208}Po was added to control efficiency of polonium deposition and alpha detection. Counting time of single sample was approximately 2 – 3 days. Errors of total ^{210}Pb specific activities depended on counting times and sample ^{210}Pb activities and varied in the range 0.002 – 0.016 Bq/g (1.6 – 8.8%).

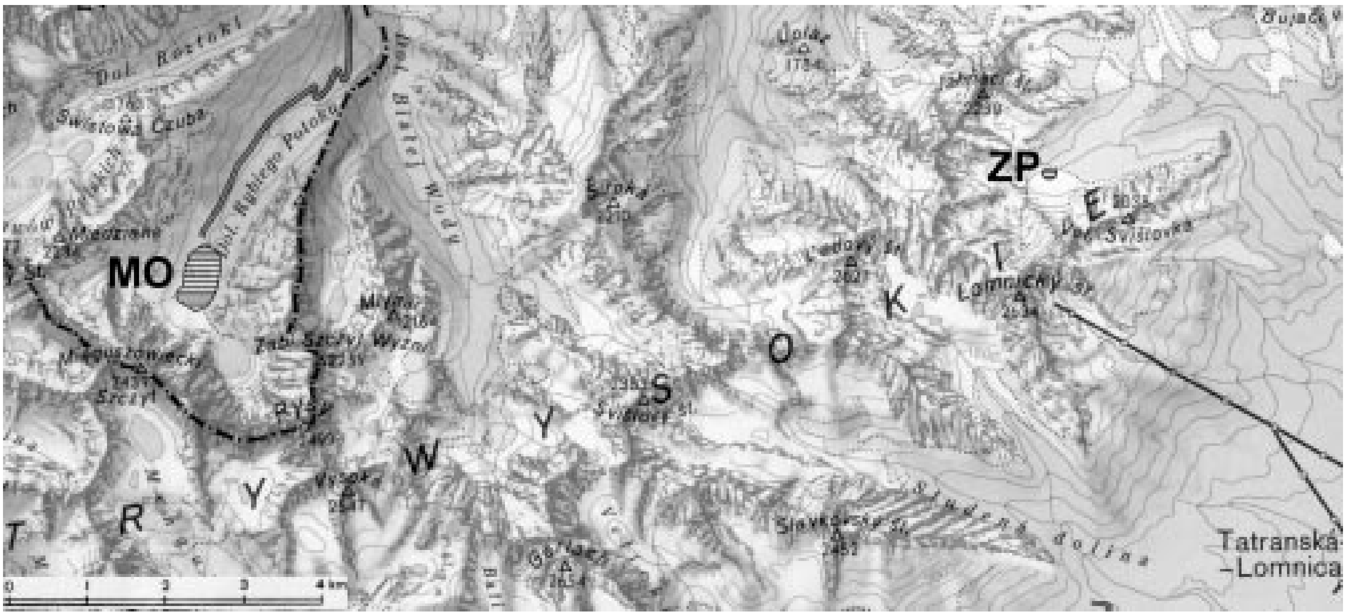

Fig.2. *Location map for Morskie Oko (MO) and Zelene Pleso Lake (ZP).*

3. RESULTS AND DISCUSSION

Morskie Oko

Two distinct sediment types: gyttja and inorganic clastic sediments dominates in the core. Inorganic individual laminae or layers (silty and clayey material, with < 3% of sand) are sharp and horizontally interbedded within gyttja (**Fig. 3**; Kotarba, 1995).

Fig. 4 summarises results of ^{210}Pb dating obtained for the Morskie Oko sediments (Baumgart-Kotarba *et al.*, 1993). Ages of 2-3 mm thick layers shown in the figure were calculated assuming the constant sedimentation rate (0.37 mm/year) for the whole core. This sedimentation rate was derived from the mean slope of ^{210}Pb specific activity plotted on a logarithmic scale (Robbins, 1978). Ages of specific layers were determined by dividing their depths by the sedimentation rate.

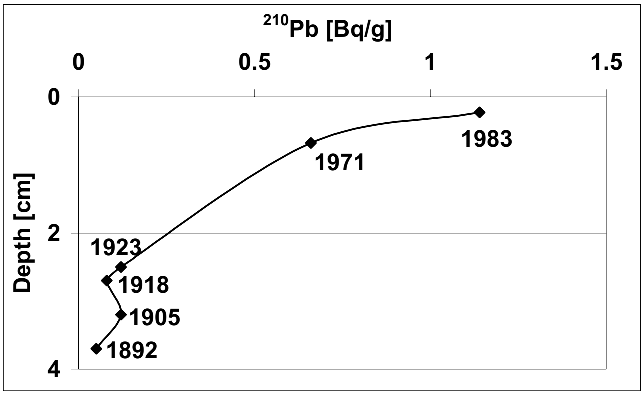

Fig.4. *Profile of specific activity of unsupported ^{210}Pb and ages 2-3 mm thick layers of the Morskie Oko sediments (Baumgart-Kotarba et al., 1993).*

Zelene Pleso

Sediments of the Zelene Pleso Lake are different in terms of lithological properties and sedimentation rate values. Homogeneous, inorganic material is very fine-grained, clayey-silty, grain size between 0.5 - 200 µm, and median values (M_{50}) between 20-50 µm. Organic matter content is very low (2.15-6.23%) as well as organic carbon content (1.25-3.61%).

Fig. 5 shows total ^{210}Pb activities in sediment core from Zelene Pleso. It was assumed that ^{210}Pb activities at depths 6.15 cm (0.064 Bq/g) and 7.05 cm (0.060 Bq/g) represent supported ^{210}Pb levels. Mass weighted average activity of these two sediment layers (0.061 Bq/g) was subtracted

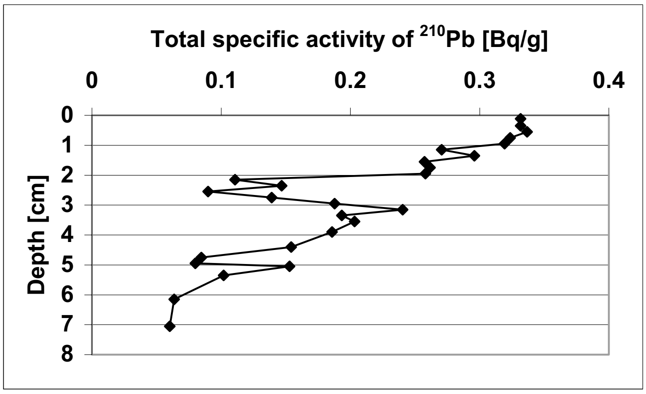

Fig.5. *Profile of total specific activity of ^{210}Pb in sediments of Zelene Pleso Lake.*

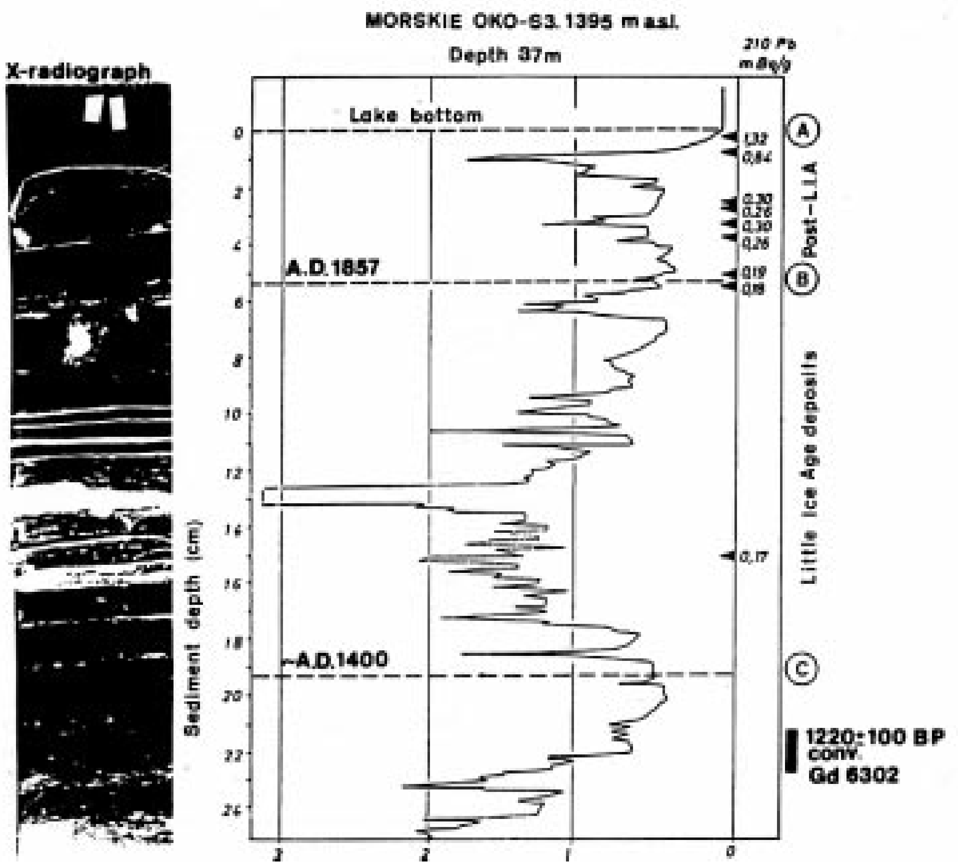

Fig.3. *X-radiograph, densitometric curve and dating of sediment core S3 from Morskie Oko Lake (according to Kotarba, 1995).*

from total ^{210}Pb activities in order to obtain unsupported ^{210}Pb levels. Unsupported ^{210}Pb activity varied in the range 0.019 (4.95 cm) to 0.276 Bq/g (0.55 cm). The decline in unsupported ^{210}Pb activity with depth is nonmonotonous with two distinct minima corresponding to depth ranges 2.0–3.0 cm and 4.8–5.0 cm (lowest activities in these ranges are 0.090 and 0.080 Bq/g, respectively). Due to pronounced non-monotonic change of the unsupported ^{210}Pb activity profile the CRS (constant rate of supply; Goldberg, 1963) model seems to be an appropriate mathematical framework to evaluate ages and sedimentation rates for the Zelene Pleso Lake sediments. The following formula was used to determine ages of sediment layers:

$$t=(1/\lambda)^{*} \ln (A_c(0)/A_c(x)), \tag{3.1}$$

where $A_c(0)$ is cumulated specific activity of unsupported ^{210}Pb integrated over the whole profile, and $A_c(x)$ represents cumulated activity integrated for the part of profile below the depth x. **Fig. 6** shows absolute ages calculated for all sediment layers. Uncertainties (1σ) of age determination were lower than 4 years.

Ages of sediment layers were used to calculate apparent sedimentation rates for each layer. It was assumed that the calculated age corresponds to the centre of the layer. Sedimentation rates presented in **Fig. 7** were calculated according to the following formula:

$$r_n = (h_n - h_{n-1})/(t_n - t_{n-1}), \tag{3.2}$$

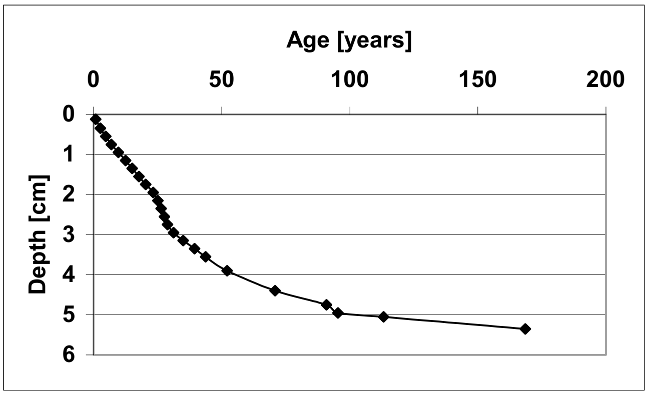

Fig.6. *Profile of ages of 2 mm thick layers of the Zelene Pleso sediments.*

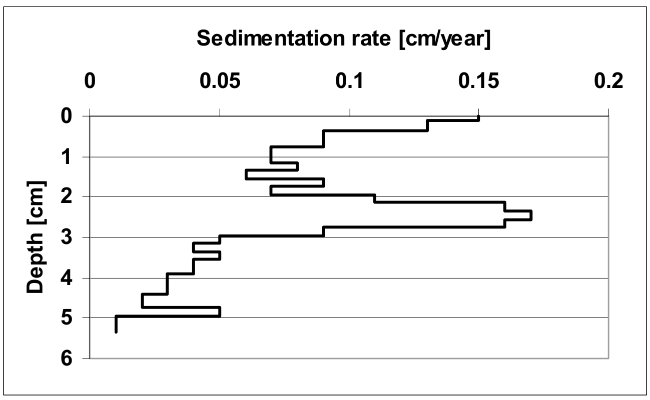

Fig.7. *Profile of sedimentation rates for Zelene Pleso Lake.*

where r_n is sedimentation rate for the interval between centres of the n-1 and n-th layer, h_n and t_n are depth and age of the n-th layer, $h_0 = 0$, $t_0 = 0$. General decrease of the sedimentation rate down the profile reflects compaction and/or diagenesis of the sediments. Superimposed on this general trend are peaks of increased sedimentation rates at depth ranges 4.8–5 cm and 2–3 cm. These ranges correspond to periods 1905–1910 AD and 1970–1975 AD, respectively. Average sedimentation rate calculated for the whole profile is 0.044 cm/year.

Fig. 8 shows dry surface mass accumulation rates calculated according to the CRS model:

$$r(x) = \lambda^{*}A_c(x)/C(x), \tag{3.3}$$

where r(x) is mass accumulation rate at depth x and C(x) is unsupported ^{210}Pb activity at depth x. Distinct maxima of mass accumulation rate correspond to minima in ^{210}Pb specific activity (**Fig. 5**). According to the CRS model such patterns reflect periods of accelerated sedimentation when unsupported ^{210}Pb bearing sediments were diluted by material with lower ^{210}Pb content.

The inventory of ^{210}Pb in the sediment profile ($A_c(0)$) equalled 0.632 Bq/cm². Provided that there is a steady state between atmospheric supply and radioactive decay, the flux of ^{210}Pb from the atmosphere (Bq/cm²*year) was obtained as:

$$^{210}Pb \text{ flux} = \lambda^{*}A_c(0), \tag{3.4}$$

and equalled 0.020 Bq/cm²*year. This flux is less than twice as much as atmospheric fluxes estimated for this part of Europe (Preiss *et al.*, 1996) what advocates (Oldfield and Appleby, 1984) use of the CRS model in this case.

4. CONCLUSIONS

Lake sediments in two glacial cirques of the High Tatras differ in terms of sedimentological properties. This is conditioned by various transfer of surficial material to lake basins by contemporaneous geomorphic processes. In the case of three internal transfers model of Morskie Oko lake, lacustrine sediment contains relatively precise record of all major geomorphic events which occurred on the slopes, first of all rapid mass wasting (debris flow).

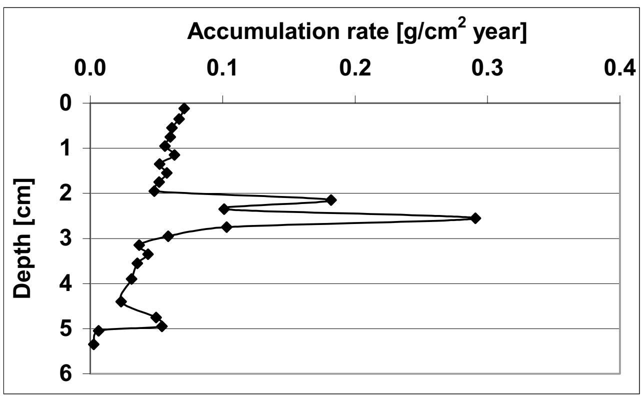

Fig.8. *Profile of mass accumulation rates for Zelene Pleso Lake.*

^{210}Pb dating of minerogenic laminae allow to distinguish exact time of their trigger.

On contrary, within Zelene Pleso lake, where five internal transfers model is appropriate, the main source of terrestrial sediment supply to lake basin is fluvial ("glacifluvial"). The surrounding gullies and braided channels are seasonally active mainly during snowmelt periods. Thus, the sediments reaching the lake are fine grained and monotonous. Distinct boundaries within these sediments mark only seasons of catchment flooding caused by snowmelt waters supplemented with continuous summer rains. Signals of debris flow activity do not exist. Increased sedimentation rate at depth range 4.8–5.0 cm and 2-3 cm, which corresponds to period 1905–1910 AD and 1970–1975 AD could be interpreted as an effect of specific weather conditions. Initial analysis made for Zelene Pleso sediments showed that there exists significant relation between precipitation regime and sedimentation rate. Rainfalls of long duration (several days of continuous rains) followed by intensive downpours, produced the great melt and high discharges in the High Tatra Mountains and on the northern foreland. Substantial summer floods were recorded at that time span. Probably, glacierette-generated runoff in hanging valley (the Medena Dolina valley within catchment basin) was intensified by summer rainfalls of 102.5 mm/day (Skalnate Pleso station) and 300 mm/day (Hala Gąsienicowa station) in 30 June 1973, and respectively 328–596.4mm in June 1973. These circumstances explain maximum accumulation rate at the depth of 2-3 cm. An important period of slope alluviation, mainly by debris flows, identified by the use of lichenometry at the beginning of 20th century, was also distinguished at Hala Gąsienicowa area (Kotarba, 1997).

In spite of similar rate of sedimentation in both lakes (MO–0.044 cm/year, ZP–0.037 cm/year), these indices are not valuable as a measure of geomorphic process activity on the surrounding slopes of alpine lake, because sediment delivery to the lakes is a function of catchment size, topography and first of all - surficial water circulation.

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