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LANDFORM EVOLUTION IN MOUNTAIN AREAS

GRZEGORZ HACZEWSKI, JÓZEF KUKULAK (KRAKÓW)

EARLY HOLOCENE LANDSLIDE-DAMMED LAKE IN THE BIESZCZADY MOUNTAINS (POLISH EAST CARPATHIANS) AND ITS EVOLUTION

Abstract. A huge landslide dammed the Muczny stream ca 8,200 years BP. The lake so created was 40 m deep and 2 km long and existed for several hundred years. It was partly filled with sediments: a basal layer of organic-rich mud overlain by gravel delta and silty sand laid down in the deepest part of the lake. The landslide dam is now partly dissected by a stream flowing through a 350 m long gap cut in colluvium.

Key words: landslide, natural dam, lacustrine sediments, Holocene

INTRODUCTION

Landslides often result in damming of water courses. In the Carpathians, the reservoirs thus formed are usually small and short-lived. Large, long-lasting lakes are quite rare. Vestiges of an extensive, deep and long-lasting landslide-dammed lake have been found by the authors in the course of geological mapping in the south-east corner of the Polish Carpathians. Neither the huge landslide nor the lake sediments have been earlier known. This paper presents the description of the landslide dam and the sediments interpreted as laid down in the dam lake, together with an attempt at reconstruction of the lake history.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The studied lake sediments were found in the middle course of the Muczny stream, the right tributary of the San river in its upper reach (Fig. 1). The landslide blocked the Muczny valley 2.5 km upstream from the junction with the San, at the downstream end of a 5 km long, subsequent, SE–NW-trending section of the val-

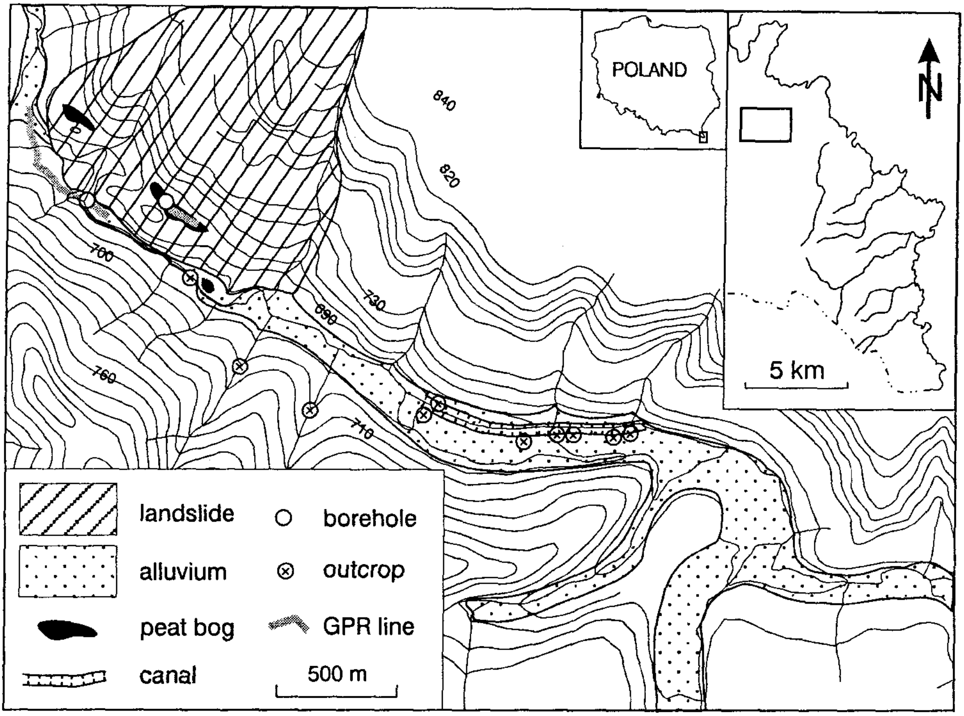

Fig. 1. Location of the studied area

ley. The valley bottom near the landslide is flat and 50–200 m wide. The north-east slope of the valley, up to 180 m high, is dissected only by a few small valleys. The south-west slope of the valley is dissected by tributary valleys descending from a more distant (2–2.5 km) and higher (540–800 m above the valley bottom) ridge. The largest tributary has built an extensive alluvial fan where it descends to the Muczny valley. The drainage basin upstream of the landslide has area of ca 12 km^2.

The area is built of the Oligocene flysch (Haczewski et al. 2000). The flysch series consists of alternating packages of thick-bedded sandstones and thin- and medium-bedded sandstones and shales. The packages are several tens of metres thick. The thick-bedded sandstones are relatively resistant to weathering and erosion. The strata on the north-east slope of the valley dip at an angle of 11° and less, equal or slightly gentler than the slope inclination. The south-west slope of the valley is built of strata with a general steep NE dip and is free of major landslides.

The relief of flysch bedrock at the valley bottom is difficult to decipher because of the thick cover of Quaternary sediments (Fig. 1). The nearest downstream exposure of bedrock in the stream channel lies 300 m downstream of the lower end of the landslide, at altitude of 660 m a.s.l. The next bedrock exposure upstream is distant 2,800 metres along the valley axis and lies at 705 m

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L A N D F O R M E V O L U T I O N I N M O U N T A I N A R E A S

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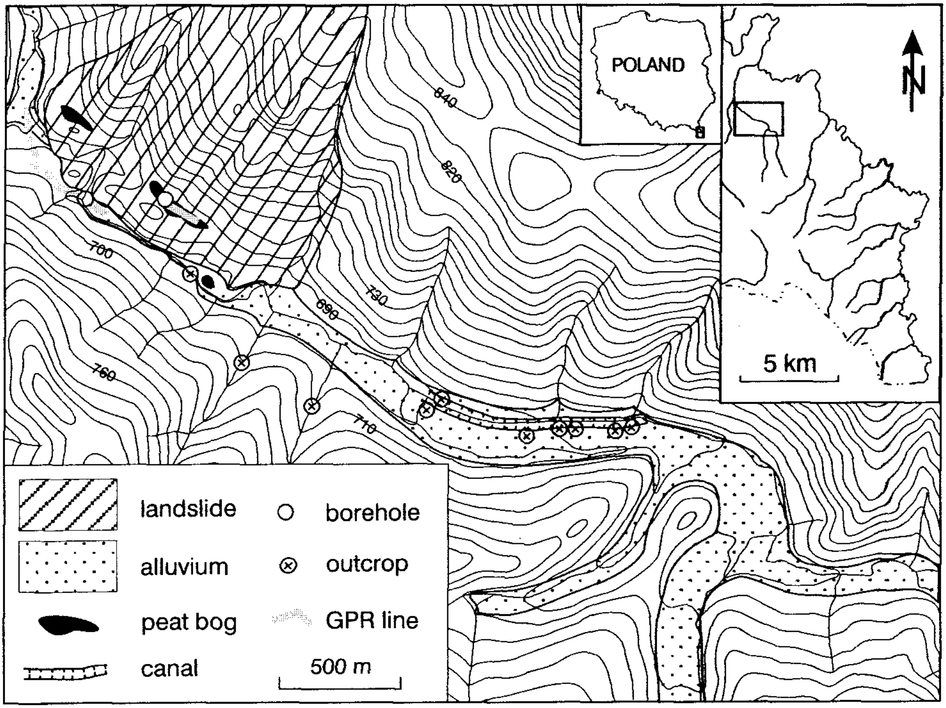

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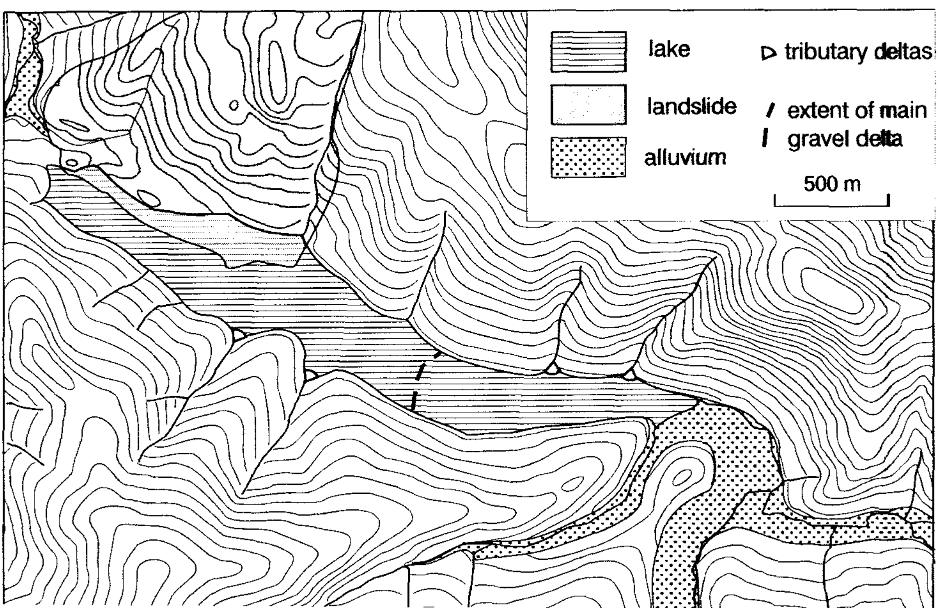

a.s.l., at the feet of the right slope of the valley. At the same altitude bedrock is also exposed in the left bank of a left affluent, about 170 m downstream along the valley axis. However, both exposures are cut in the valley slopes, so the bedrock surface between them may lie several metres deeper. The valley slopes are covered with a thin regolith mantle.

Good exposures of the Quaternary sediments on the valley bottom are present in the walls of an artificial canal, 850 m long (Fig. 1) and up to 5 m deep, excavated in 1970 to keep the Muczny stream away of the road. Near the upstream end of the canal the valley bottom has been then artificially levelled. The former natural channel of the Muczny, along the left side of the valley bottom, is now used by a left tributary that after 850 m crosses the valley bottom and joins the present course of the Muczny at the base of the right slope (Fig. 1).

Downstream from the junction the Muczny flows for 500 m over the flat bottom of the valley in a meandering channel cut in sandy silt, until it encounters the toe of the landslide. The colluvial mass leaves a narrowing strip of the flat alluvial bottom beneath the left slope of the valley. The stream follows there a straight course for 650 m along the narrowing bottom to the place where the valley bottom is blocked by the landslide over its whole width. The stream enters there into a gap cut through the landslide dam. This gap entrance is used below as a reference point for determining locations along the former lake basin.

METHODS

The field part of the study consisted in the description of the landslide and in the detailed description and sampling of the lake sediments. Exposures of the lake sediments were studied in the walls of the canal, in isolated outcrops downstream of it and in two left tributaries. Hand drilling (up to 7 m deep) was used to study the thickness and lithology of the lake sediments near the gap entrance and of peat on the landslide (Fig. 1). Additionally, ground-penetrating radar (GPR) profiles were made in an attempt to determine the thickness of these sediments (Fig. 1). Two samples of organic material were radiocarbon-dated. Field data and map measurements were used to calculate basic parameters of the landslide, the lake and the lake fill. Altitudes of sediment occurrences were determined using the topographic map 1 : 10,000 with contour intervals of 2.5 m.

DESCRIPTION OF THE LANDSLIDE

The landslide fell from the NE slope of the valley, immediately upstream of the sharp turn to the north and of the mouth of a large left tributary. The landslide occupies nearly the whole length of the slope (1,000–1,100 m) and ex-

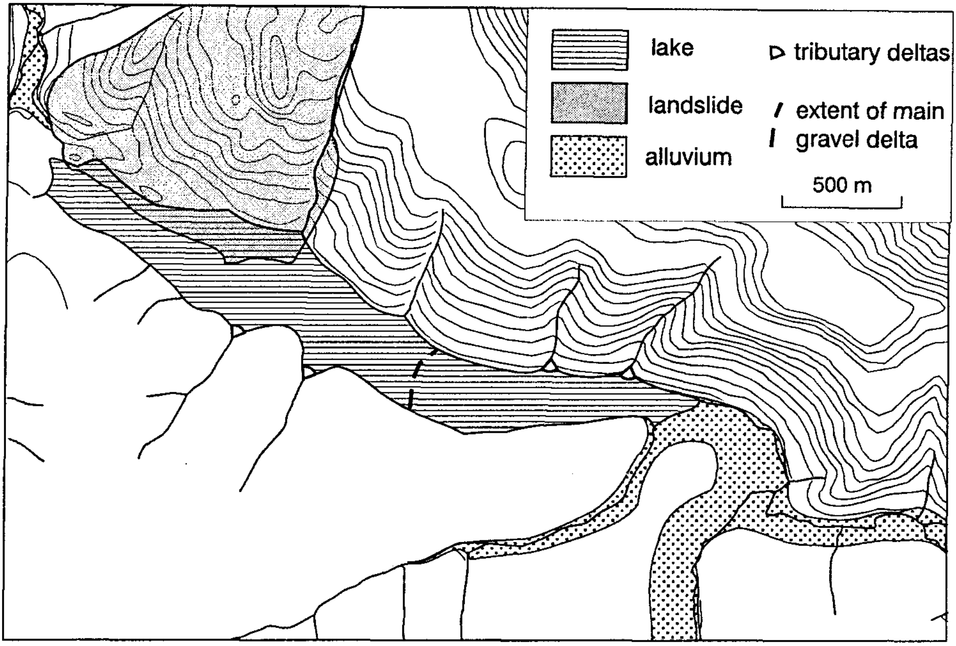

Fig. 2. Restored extent of the dam lake and gravel delta

tends along the valley for 950 m (Fig. 2). The upper end of the landslide lies 165 m above the alluvial bottom of the valley. The landslide involved the thick-bedded sandstones and thin-bedded flysch. The upper margin of the landslide is marked by a series of trenches, 2–3 m deep, roughly parallel to the contours. The major part of the landslide consists of elongated blocks 30–100 m wide, up to 350 m long and up to 30 metres high. The blocks are separated by depressions of similar size and various orientation. Many depressions have flat bottoms, some are closed. The two largest depressions lie near the base of the slope at the rear side of the largest landslide blocks, aligned subparallel to the valley axis. These depressions have wide flat bottoms occupied by peat-bogs. The peat has been penetrated by hand drilling in only one place where it is 6 m deep. A peat sample collected from the bottom of the peat has been dated by radiocarbon at 5,260 (+ 50, –270) BP (KR-183).

The toe of the landslide lies on alluvial deposits of the valley bottom. The landslide mass is conspicuous by its hummocky relief and it is dissected by a narrow gap, 15 m deep, cut by the Muczny stream. The stream bed is armoured with boulders of various size. Outcrops along the stream channel reveal thick-bedded sandstones and, less commonly, packages of thin-bedded flysch. No sediments or clearly colluvial nature are now exposed in the gap banks. The only indication of the landslide nature of these outcrops is provided by the abrupt changes in attitude of beds in adjacent outcrops.

The surface of the landslide shows its old age and stabilised nature. The trees on the slope, more than a hundred years old, do not display any growth disturbances attributable to mass movements. The ground surface is completely overgrown, rocky surfaces are covered with grass, moss or lichens. Only in the lowest part of the landslide, near its downstream end, fresh clefts 2–3 m deep dissect the colluvium above the erosional escarpment in right bank of the Muczny stream.

DAM-LAKE SEDIMENTS

The sediments laid down in the landslide-dammed lake include dark, organic-rich mud, silt, sand, gravel and calcareous tufa.

A layer of dark mud and sand, 30–50 cm thick, is visible in many good exposures along the canal walls. Typically, the dark-mud-and-sand layer has sharp lower and upper boundaries marked by the presence of the dark mud (Photo 1). The mud passes gradually to sand with dispersed organic matter towards the centre of the layer. In the sections located downstream of the junctions with two right tributaries the mud layer is split by lenses of gravel and cross-beded sand, up to 50 cm thick (Fig. 3).The mud is dark blue, almost black. Mesoscopically it is dense, homogenous, with loosely dispersed frag-

Photo 1. Typical outcrop in the left bank of the Muczny stream with older alluvial gravel at the bottom, followed by lake-bottom sediments (hammer) and gravel-delta sediments. Hammer is 30 cm long

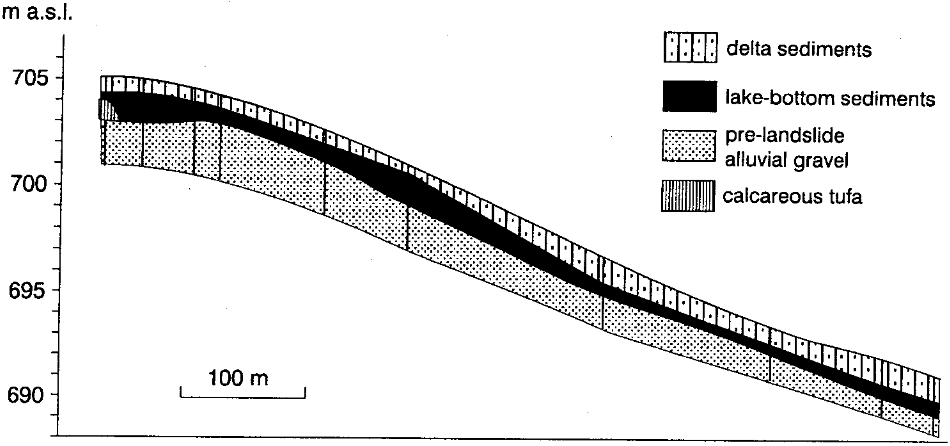

Fig. 3. Cross-section of the lake sediments and underlying alluvium along the canal. Vertical bars represent logged outcrops

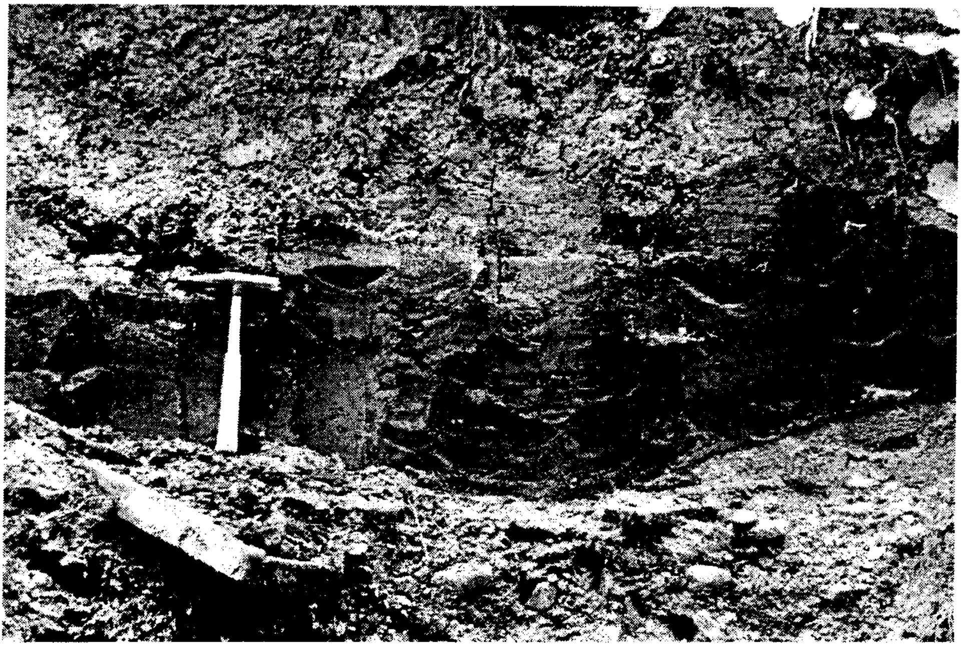

Photo 2. Base of the lake-bottom sediments with laminated organic-rich mud. Hammer is 30 cm long

ments of wood, cones, beech seeds, small shoots and rootlets. Black laminae of millimetric thickness are locally present in the mud (Photo 2). As seen under the microscope, the mud displays matrix composed of very fine-grained, dark organic matter. Embedded in it are abundant silt-size grains of quartz and subordinate grains of other minerals (mica, calcite). Numerous are fragments of wood less than 1 mm in size. Upon drying the mud shrinks, cracks and hardens. The sand in this layer is fine- and medium-grained, usually devoid of discernible depositional structures.

The dark-mud-and-sand layer was found in most exposures along the canal. This layer is underlain by gravel and overlain by clastics of various grain-size. No traces of lake sediments can be identified in the former natural channel of the Muczny, lying at the base of the left slope and used now by a small left tributary. The dark mud was also found in the channels of two left tributaries that join the Muczny 750 and 900 m upstream of the gap entrance (Fig. 1). In both streams the mud layer is about 10 cm thick and overlain with gravel. No exposures of the dark mud have been found downstream from the lower end of the canal. We interpret the dark-mud-and-sand layer as the bottom deposit of the lake that formed by damming the Muczny valley, and the lenses of gravel and sand within this layer as underwater extensions of deltas formed by tributaries descending from steep right slope of the valley.

The dark-mud-and-sand layer in the canal exposures is everywhere underlain by coarse gravel, typical alluvium of the Muczny stream. At the farthest upstream exposure the bottom of the dark-mud-and-sand layer lies about 2,5 m below the ground surface, at altitude of 702.5 m. In the two left tributaries (see above) the mud layer lies at altitude of 702–703 m. Consequently we accept the maximum level of the lake at ca 703–704 m a.s.l., about one metre above the highest occurrences of the lake-bottom mud. Small wood fragments, mainly cones, collected from the base of the dark mud in the farthest upstream exposure have been dated by radiocarbon at 8,170 ± 200 BP (KR-176).

The layer of the lake-bottom sediments is overlain with clastic sediments, mostly muddy gravel and gravely mud up to 1.5 m thick. These sediments differ from the older alluvial gravel by the high content of finer sediment. They were apparently laid down in a gravel delta prograding from the headwater part of the basin. The downstream extent of the gravel delta (see Fig. 2) can be recognised by disappearance of gravels overlying the lake-bottom sediments. This extent is distinguishable in present landscape as a gentle step on the valley bottom. The gravel accumulations over the dark mud in the two left tributaries rise slightly above the bottoms of their valleys and may be interpreted as small fan-deltas, less that 1 metre thick, that prograded into the lake over the organic sediments. The ancient gravel delta on the valley bottom and the small ones in the tributaries have been since dissected by stream erosion (and by the canal in the main valley).

The valley bottom at the downstream end of the former lake is covered with fine-grained sediment, mainly sandy silt, for about 500 metres upstream from the gap entrance. Hand drilling on the right bank 20 m upstream of the gap entrance did not penetrate the sandy silt to 6.5 m below the stream level and no change in lithology was detected. The results of GPR sounding seem to indicate that the sandy silt is there about 10 m deep.

Clastic calcareous tufa is present in one exposure, in the right bank of the canal in the farthest upstream exposure of the lake sediments, at the mouth of a small right tributary. The lake sediments are there ca 1 m thick and they overlie alluvial gravel with a sharp boundary. The lower part, 30–35 cm thick, consists of white calcareous mud with gastropod shells, overlain with light-brown, dense clay 5–8 cm thick and then another layer, whose main component are grains of calcareous tufa 1–2 mm in size. Fine sandstone debris and sand occur as thin intercalations in this calcareous layer, which is covered with 1 m-thick deluvial clay rich in sadstone fragments. The debris carried nowadays by this stream does not include tufa, but 370 m upstream from the stream mouth there is a small spring secreting calcareous tufa in the form of millimetric coating on rock debris. This is the only known location of calcareous tufa formation within the drainage basin of the Muczny stream.

RECONSTRUCTION OF THE LAKE HISTORY

The huge landslide that fell from the right slope of the valley covered the valley bottom with a thick mass of colluvium over the length of 950 m (Fig. 4b). Of this, for 300 m the valley has been blocked over its whole width. The dammed stream inundated the valley to the altitude of 703–704 m a.s.l. (Fig. 4c). The presence of what we interpret as small gravel fans directly on the highest situated occurrences of the dark mud in the two left tributaries suggests that this level represents also the maximum acceptable altitude of the lake level. Reconstruction of headwater part of the lake is impossible because the valley bottom has been heavily transformed by the stream diversion, construction of the road, buildings and excavation of a fish pond.

It is noteworthy that the top of the landslide dam lies today about 10 m lower than the inferred lake level. Top of the highest hummock reaches 702 m a.s.l. Without finding of the lake mud, any estimate based on the landslide dam itself would significantly underestimate the lake depth and size.

The radiocarbon age of the fine wood debris from the base of the lake-bottom sediments in the headwater part of the lake is accepted as the age of the complete filling of the lake. The wood debris fragments selected for the analysis were ones of low resistance to decay, so as to reduce the possibility of dating material older by more than a few years than the embedding dark mud. The minimum time necessary for complete filling of the basin is calculated by dividing the lake volume by the discharge of the streams that fed it. For the present values of the stream discharge this results in a period of a couple of weeks. Filling of the lake probably lasted much longer time because the colluvial dam consisting of huge blocks of massive rock with relatively smaller amounts of fine-grained material had to be permeable, thus delaying the process of the lake filling by unknown time. Accumulation of fine sediment from suspension and compaction of the col-

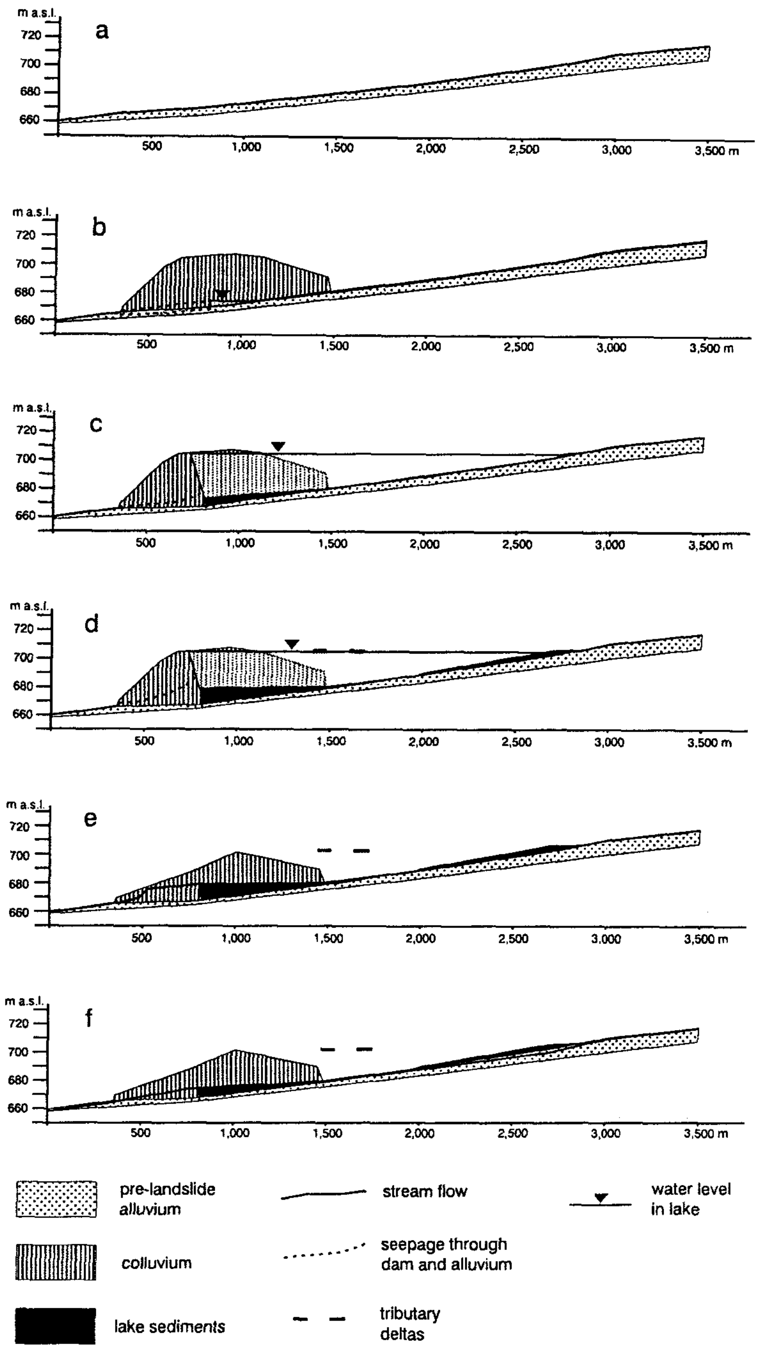

Fig. 4. Stages of the Muczne valley evolution in the area of the ancient dam lake. a — before landslide, b — immediately after the landslide, c — after filling with water to the maximum lavel, d — after partial filling with sediments and immediately before breaching of the dam, e — after breaching the dam to the level of the sediment fill, f — at present

luvium would reduce the dam permeability with time, improving its effectiveness. The sharp lower boundary of the dark mud suggests, however, that the complete filling of the basin was relatively rapid, so we may accept that the lake filling was delayed with respect to the landslide by no more than a dozen years. The landslide thus occurred at ca 8,170 BP, during the early phase of the Atlantic stage. The radiocarbon date from the base of peat in the landslide depression — 5,260 (+ 50, -270) BP — suggests that the beginning of peat deposition in the landslide depression was delayed by nearly 3,000 years with respect to the landslide formation.

The age of the landscape coincides with many other landslides in the Carpathians (Margielewski 2002) dated at 8,500–8,000 BP. This is interpreted by L. Starkel et al. (2002) as a phase of climatic wettening, manifest also in increased dynamics of fluvial processes.

The approximate volume of the lake was calculated as $3 \cdot 10^6$ m^3. The extent of the lake is shown in Fig. 2. The deepest part of the bottom lied probably near the present gap entrance. The present stream channel altitude at this point is marked on the map as 674.8 m The base of the lake fill is inferred at the depth of about 10 m beneath the 0.5 m high floodplain level, so the lake bottom lied at approximately 664 m a.s.l., giving the maximum depth of the lake as 40 m (Fig. 4c).

The dark mud accumulated from suspension on those parts of the lake bottom which were protected from bottom currents and clastic supply. Its largest thickness in the farthest upstream exposures along the canal suggests that the right side of the valley received less clastic sediment for most time of the lake existence. Gravel supplied to the lake by the Muczny stream accumulated in a delta prograding into the lake over the lake-bottom sediments, apparently along the left side of the valley leaving an embayment at the feet of the right slope of the valley. With progradation of the delta the embayment grew in length, and received progressively less clastic sediment, resulting in the gradual transition to dark mud at the top of the dark-mud-and-sand layer. The calcareous tufa laid down at the mouth of tributary entering the lake at farthest upstream end of this embayment could be laid down in part by precipitation of calcium carbonate in the zone of mixing of the hard stream water with the stagnant water of the embayment. The upper surface of the gravel slopes gently downstream, in a manner typical of coarse-clastic deltas in artificial reservoirs (cf. Harrison 1953). The gravel delta prograded about 1000 m into the lake as is shown by the extent of gravels overlying the dark mud.

The accumulation of silty sand, up to 10 m thick, in the downstream part of the lake is due to suspension flows transporting silt and fine sand to the deepest part of the lake during high water stages. The total thickness of the clastic sediments accumulated at the downstream end of the lake is now reduced by erosion after partial breaching of the dam. GPR data from the slope of the dam close to the gap entrance suggest that the silty sand extended to the level of 4–5 m above the present level of the floodplain at the stream's entrance to the gap. The total volume of sediment accumulated in the lake during its existence was estimated at $9 \cdot 10^5$ m^3. The gravel delta prograded into the lake over the lake-bottom sediments gradually reducing the area of their deposition (Fig. 4d).

The duration of the lake existence at its maximum level is difficult to estimate. Such estimate may be based on, in the order of increasing accuracy and precision: 1) analogy to other landslide dams described in literature, calculation of time necessary for the accumulation 2) of the dark mud and 3) of the coarser clastic fill and 4) radiocarbon dating of the earliest and the youngest sediments laid down in the lake during its maximum extent.

The literature data on landslide dams (Costa and Schuster 1988) show that most such dams collapse within days of their formation, when water overflows the dam and dissects it by erosion. The process of the dam dissection usually slows down due to armouring of the stream bed with residual boulders left in place after the removal of the finer colluvium. The large volume of sediments accumulated in our lake indicates its prolonged existence. The mean rate of gravel supply to a much smaller landslide-dammed Szmaragdowe Jeziorko (Emerald Pond) that formed in 1980 in the valley of the Wetlinka stream in the Bieszczady Mountains was calculated by R. Malarz (1993) at 487 m^3 per year. Because of the small size of the Emerald Pond only gravel was stored within it, while finer clastics by-passed it in suspension. Literature data on the proportion of suspended load to bed load in the Carpathian rivers vary (Brański 1975; Froehlich 1982, 1986), but a value of 20% of gravel (= bed) load has been accepted for the purpose of this estimate. If so, the total rate of sediment supply to the Emerald Pond would be about 2,500 m^3 per year. The accumulation of the clastic sediments laid down in the studied lake at similar rate would take 360 years. This seems also reasonable time for the accumulation of the dark organic mud 30–40 cm thick after compaction. Additional radiocarbon dating of the top part of the dark-mud layers may in future provide a check for this estimates.

We may thus conclude that the lake in the Muczny valley existed for a few hundred years at its maximum level. Draining of the lake was probably rapid, as we do not find any traces of gradual fall of the lake level. However, details of the fluvial forms of relief that could reflect the falling lake level in the downstream part of the basin are now obscured by the results of diverting of the Muczny stream to the canal and by later partial erosion of this layer. One of the authors (Grzegorz Haczewski) observed in 1971, soon after the stream diversion, the valley floor upstream of the gap entrance with riparian trees buried up to the height of about one metre in fresh silt.

The long existence of the lake is not typical of large landslide-dammed lakes (see above). The longevity of the lake may suggest the lack of overflow if the inflow to the lake was approximately balanced by the seepage through the dam, so that the level of the lake could oscillate near maximum with minimal overflow, insufficient for initiation of effective erosion (fig. 4d). The present course of the stream gap across the dam is conspicuous by its deepest and steepest initial section transverse to the valley bottom. The farther downstream course of the gap goes around the larger blocks of resistant rock and may be inherited after the small stream flowing from the landslide (Fig. 2) and cutting slowly into the dam until it captured the lake water. The capture could occur by increasing seepage from the lake to the deepening stream channel (see Pederson 2001). After capture, the lake probably drained rapidly to the level of its bottom sediments (Fig. 4e). Later, headward erosion of the dam resulted in partial removal of the uppermost part of these sediments (Fig. 4f). The stream bottom at the gap entrance is now formed by a huge block of vertically dipping flysch strata extending across the channel. This resistant block seems to act as a threshold that hampers the progress of downcutting.

CONCLUSIONS

The huge landslide that dammed the valley of the Muczny stream during the early Atlantic stage of the Holocene, caused inundation of the valley by a lake up to 2 km long and 40 m deep, that persisted for a few centuries and was partly filled with sediments, including gravel that built a 2 m-high terrace over the distance of 1 km along the valley. Afterwards, the lake was drained, possibly in a rapid event. The landslide dam is not yet dissected to its base and the 350 m long stream gap eroded in colluvium is an uncommon landform in the Carpathians.

Three comments based on the results of this study may be applicable in the studies on the relief evolution of mountain stream valleys and landslides:

- the height of preserved ancient landslide dams alone may be the base of underestimation of ancient landslide-dammed lake levels;
- caution is needed when anomalies in the heights of alluvial terraces along the valleys are interpreted solely as a result of young tectonic movements without considering the possible presence of lacustrine gravel deltas;
- peat accumulation in landslide depressions may be delayed by thousands of years with respect to the landscape formation and the use of such peat deposits for landslide dating should be supported by other data.

ACKNOWLEDGEMENTS

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STRESZCZENIE

G. Haczewski, J. Kukulak

WCZESNOHOLOCEŃSKIE ZAPOROWE JEZIORO OSUWISKOWE W BIESZCZADACH (POLSKIE KARPATY WSCHODNIE) I JEGO EWOLUCJA

W dolinie potoku Mucznego w Bieszczadach znaleziono osady jeziora powstałego wskutek jej przegrodzenia osuwiskiem. Koluwia pokrywają dno doliny na długości 950 m, i są rozcięte przełomem nie sięgającym ich podstawy. Osady jeziora odsłaniają się w sztucznym przekopie długim na 850 m i głębokim do 5 m, którym obecnie płynie potok Muczny.

Osady jeziora składają się z ciemnego mułku organicznego, mułku piaszczystego, piasku, żwiru i martwicy wapiennej. Warstwa ciemnego mułku ma 30–50 cm grubości, a jego najdalsze w górę doliny stanowiska znajdują się na wysokości 702–703 m n.p.m. Na tej samej wysokości mułek ten występuje w dwu lewych dopływach uchodzących do Mucznego powyżej jęzora osuwiskowego. W obu tych potokach na mułku leżą lokalne nasypy żwirowe o grubości ok. 1 m — delty stożkowe osadzone przy ujściach potoków do jeziora, którego poziom znajdował się na wysokości ok. 703–704 m n.p.m. W przekopie na warstwie mułku leży żwir o grubości do 1,5 m — osad delty potoku Mucznego. Poza czołem delty i w wąskiej zatoce pozostawionej pod prawym zboczem osadziły się z zawiesiny mułki piaszczyste, najgrubsze w najgłębszej części zbiornika, u podstawy zapory osuwiskowej, gdzie ich miąższość wynosi 8–10 m.

Powstanie jeziora określa data radiowęglowa ze spągu czarnego mułku (8170 ± 200 BP — wczesny atlantyk). Jezioro początkowo miało 40 m głębokości i około 2 km długości. Czas jego istnienia oceniono na kilkaset lat na podstawie miąższości ciemnego mułku i objętości żwirów deltowych. Częściowe zdrenowanie jeziora nastąpiło po rozcięciu górnej części zapory przy udziale dopływu spływającego z osuwiska. Następnie osady dna zbiornika zostały częściowo usunięte przez potok Muczny wcinający się głębiej w przegrodę koluwialną. Stopniowe uzbrajanie dna koryta rezydualnymi głazami zatrzymało wcinanie na obecnym poziomie. Zwraca uwagę fakt, że obecna wysokość zapory jest niższa od dawnego poziomu jeziora, zapewne wskutek osiadania, co może również dotyczyć innych dawnych zapór osuwiskowych.