STUDIA GEOMORPHOLOGICA CARPATHO-BALCANICA
ISBN 83-88549-56-1 VOL. XLI, 2007: 77–96 PL ISSN 0081-6434
LANDFORM EVOLUTION IN MOUNTAIN AREAS

TOMÁŠ PÁNEK[1], VERONIKA SMOLKOVÁ[1], JAN HRADECKÝ[1] (OSTRAVA),
KAREL KIRCHNER[2] (BRNO)

LANDSLIDE DAMS IN THE NORTHERN PART OF CZECH FLYSCH CARPATHIANS: GEOMORPHIC EVIDENCE AND IMPRINTS

Abstract. Little attention has so far been given to landslide dams of the flysch Western Carpathians. The article is a pilot study in the investigation of geomorphologic and palaeoenvironmental aspects of landslide dams. 17 (largely fossil) cases of landslide damming have been identified in the northern part of the Czech Flysch Carpathians. Yet, the real number of the cases is estimated to a few tens. Landslide dams have a significant influence on the morphometry of longitudinal profiles of valleys. The geomorphologic regime of affected parts of the valleys has thus been influenced on the order of a few ka. The development and preservation of characteristic sediments of backwater type depends on the grain size of the material of landslide dams. In areas with prevailing sandstones water is not generally retained in the form of lakes or swamps for a long time and sedimentation space is only filled with clastic fluvial, proluvial or debris flow deposits. Preliminary dating results show a great scatter of individual events over the course of the Holocene with a higher concentration of landslides in the Subatlantic. The character of backwater sediments can be an important indicator of geomorphologic and palaeohydrologic events in the Holocene (so far virtually unused in the Carpathians).

Key words: landslide dams, geomorphometry, radiocarbon dating, dam typology, flysch Carpathians, Czech Republic

INTRODUCTION

Landslide dams constitute potential geomorphologic hazards for up- and downstream areas. Except a practical view of landslide dams as the sources of natural hazards, these forms are important indicators of the dynamics of relief development and palaeoenvironmental changes in mountain areas.

Over the last years there has been an increased interest in the problematics of landslide dams in terms of (1) geomorphologic attributes (Korup 2004a), (2) influence on the geomorphologic regime of valleys (Hewitt 2006; Korup 2005, 2006; Korup et al. 2006) and (3) hazards connected with upstream impoundments and catastrophic flooding after dam failures (Ermini and Casagli 2003;

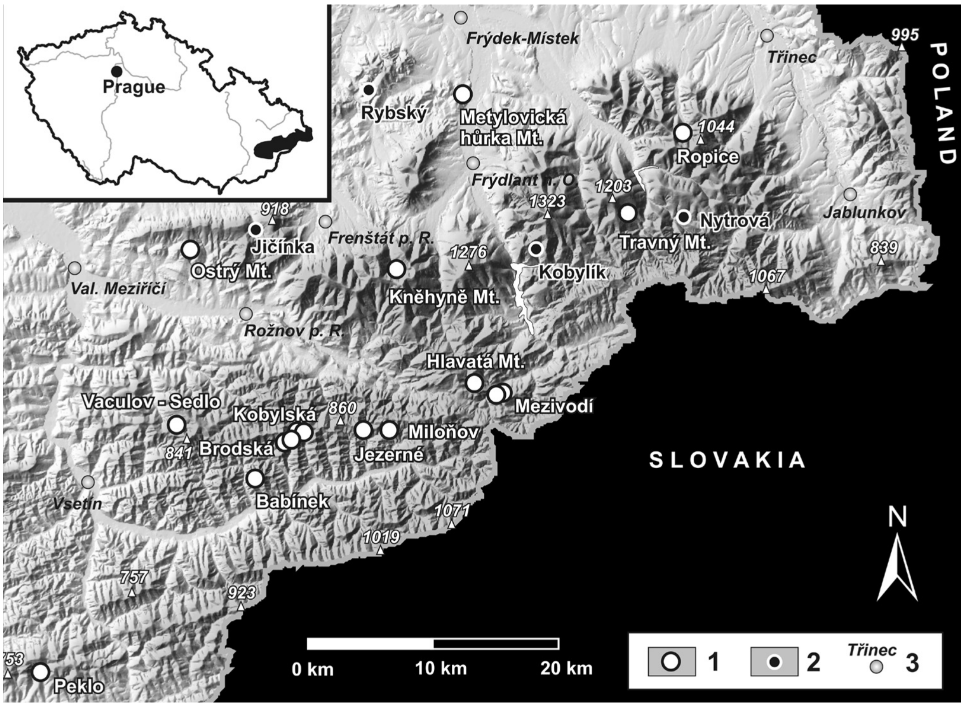

Fig. 1. Landslide dams in the northern part of the Czech Carpathians. 1 — landslide dams studied in this paper, 2 — other landslide dams in the studied area, 3 — towns

Korup 2004c). Most of the existing studies deal with cases of extremely large valley damming in tectonically active alpine areas all over the Earth (e. g. Korup et al. 2006). The aim of this study is to point out relatively frequent (largely fossil) displays of landslide-dammed valleys also in less dynamic mid-mountain conditions of the flysch Carpathians. The area of interest is mainly northern part of flysch Carpathians on the territory of the Czech Republic (Vizovická vrchovina Highland, Vsetínské vrchy Hills, Moravskoslezské Beskydy Mts and Podbeskydská pahorkatina Hillyland) (Fig. 1). The purpose of the article is to serve as a pilot study in the research of geomorphic imprint and palaeoenvironmental significance of landslide dams in the Czech Flysch Carpathians.

LANDSLIDE DAMS

Worldwide research in landslide dams showed that these forms are diverse in their formation, characteristics and longevity and they form in a wide range of physiographic settings (Costa and Schuster 1988; Korup 2004b). Optimal locations for the emergence of temporary or permanent landslide dams comprise the steep terrain of mountain areas where even relatively small volumes of material can cause valley blockages. The most common types of slope deformations that cause a valley blockage are rock avalanches, slumps, slides and flows, whereas the main triggering factors include rainfall, snowmelt and earthquakes (Korup 2004b). The stability of landslide dams consists in factors such as volume, size, shape, sorting of blockage material, rates of seepage through the dam and rates of sediment and water flow into the impoundment. The longevity of the landslide dams can range from a few minutes to a few thousands of years. J. E. Costa and R. L. Schuster (1988) state that 27% of landslide dam failures occur within 1 day of formation and 85% within 1 year of formation. Typical failure mechanisms are overtopping of the dam crest (by gradual lake-level rise or a wave induced by material sliding downslope), breaching, piping, gravity collapse of the dam face and others (Korup 2004b).

Up to now, research has mainly concentrated on large-scale landslide dams all over the world which originated in the historic period and are well documentable. However, remnants of much older, presently non-existing blockages of a small scale can often be well identified and bring information on palaeogeographic conditions and long-term landscape evolution.

There are a few classifications of landslide dam types (and interactions of slope deformations and river systems generally) in literature dealing with landslide dams. O. Korup (2005) created a nominal classification of 5 possible types of geomorphic coupling interface between slope movements and valleys out of which 3 types relate to landslide dams. *Area type (A)* dams include large-area (> 10 km^2) mass movements which can cause a complete change in the pattern of a river network (e.g. collapse of a mountain range or deep-seated gravitational slope deformations). *Linear (L) type* emerges when more than 50% of the landslide deposits move downvalley from the failure and fill a longer reach of the valley. *Point (P) type* represents emplacement of landslide toe at a normal platform angle to the valley (the other two types not causing the blockage are *Indirect (I)* and *Nil (N) types*). This classification is followed by a generalized typology of landslide impact on a river channel (Korup 2005) where out of the total 5 types of interaction the following two relate to landslide dams: *type IV* (blockage — occurrence of a landslide-dammed lake) and *type V* (obliteration — occurrence of landslide-dammed lakes or landslide ponds, complete burial of the valley floor, stream piracy, reversal drainage).

J. E. Costa and R. L. Schuster (1988) created a typology of natural dams classifying landslide dams into six categories based on their morphologic relation to the valley floor. *Type I dams* are small in contrast with the valley width and they do not reach the opposite valley slope. This type was identified by J. E. Costa and R. L. Schuster (1988) in 11% of 184 classified landslide dams of around the world. *Type II dams* (44% of dams) affect the entire valley floor width, in some cases depositing material high on the opposite valley slopes. *Type III dams* (41% of dams) fill the entire valley width and move variously far upvalley and downvalley from the failure. This type of dams is generally characterized by the greatest volume of landslide sediments. *Type IV dams* (< 1% of dams) are formed by material movement from both sides of a valley occurring at the same time. *Type V dams* (< 1% of dams) occur in case a single landslide has multiple debris lobes extending across the valley floor and thus forming two or more landslide dams in the same river reach. *Type VI dams* (3% of dams) are formed by landslides involving one or more failure surfaces that extend under the valley floor and emerge on the opposite valley side.

METHODS

Research of landslide dams in the Czech Flysch Carpathians was carried out on the basis of multidisciplinary approach. The first step comprised terrain survey and geomorphologic mapping of the localities. Furthermore, a digital elevation model (original scale of 1: 10,000) was analyzed in order to acquire further data on landslide dams, slope deformations and longitudinal profiles of streams. This phase of the research was particularly important as the impact of fossil landslide dams on the morphometry of valley profiles was determined. For each affected valley the steepness index was calculated at a 20-m interval from the relation $S = k_S A^{-\theta}$ (Flint 1974), where S is local channel slope [$m \cdot m^{-1}$], A is upstream drainage basin area, k_S is the steepness index [$m^{2\theta}$] and θ is the concavity index (dimensionless) of the longitudinal profile.

A sedimentary sequence of landslide impoundments was studied in outcrops in places of erosional cuttings of streams and test pits and also on samples obtained by augerings (Eijeklkamp equipment). Sediments related to landslide damming were studied by means of conventional sedimentologic methods (e.g. particle-size analysis). In selected localities the age of landslide dams and subsequent sedimentation in the space above the dam were determined through ^{14}C dating of organic content in the deposits of the landslide-dammed lakes. ^{14}C dating of the samples was performed in the Kyiv's radiocarbon laboratory (Kyiv, Ukraine) and the results were calibrated by OxCal 3.9 software.

Geophysical methods of ERT (electrical resistivity tomography) and GPR (georadar) were applied in selected localities in order to study the inner structure of the landslides and dams.

TYPES OF LANDSLIDE DAMS IN THE CZECH FLYSCH CARPATHIANS

So far 17 localities of landslide damming of streams (Fig. 1, Table 1) have been identified and investigated in the Czech Flysch Carpathians. Most of the localities are failed dams whose upvalley impoundments are completely filled such as Peklo (Vlára River damming) in Vizovická vrchovina Highland, Babínek Mt. (Babínek Brook damming), Brodská (damming of two sources of Brodská Brook), Kobylská

Table 1

Geomorphometric and other relevant parameters of studied landslide dams

Dammed streams	Location	H_D [m]	W_D [m]	L_D [m]	R_D [m]	Mean K_S [$m^{0.6}$]	Erosional incision of the stream into impoundment sediments	A_C [km^2]	ASD [km^2]	V_{SD} [x10^6 m^3] estimated	**Slope deformation type**
Babínek Brook	Babínek Mt.	10	115	100	20	8.98	Partly incised	0.340	0.024	0.36	Rotational landslide
Tributary of Brodská Brook	Brodská A	10	230	50	38	8.29	Not incised	0.350	0.035	0.39	Flow-like landslide
Tributary of Brodská Brook	Brodská B	5	75	30	10	5.15	Not incised	0.350	0.035	0.39	Flow-like landslide
Tributary of Miloňovský potok Brook	Miloňov	10	90	55	15	10.13	Incised into former alluvial gravels	0.898	0.038	0.69	Rotational landslide
Jezerní potok Brook	Jezerné	25	200	120	30	11.99	Not incised	2.460	0.038	0.71	Rockslide/rock avalanche
Tributary of Salajský potok Brook	Mezivodí A	25	320	100	70	5.89	Partly incised	0.034	0.052	0.76	Flow-like landslide
Salajský potok Brook	Mezivodí B	10	120	80	16	7.00	Partly incised	0.897	0.052	0.76	Flow-like landslide
Lučovec Brook	Hlavatá Mt.	7	120	80	10	6.1	Incised into bedrock	3.730	0.075	0.98	Flow-like landslide
Vlára River	Peklo	16	350	230	30	7.28	Not incised	1.400	0.112	1.95	Flow-like landslide
Previous headwater of Hodoňovický náhon	Metylovická hůrka Mt.	11 $^{1)}$	415 $^{1)}$	490 $^{1)}$	20 $^{1)}$	3.34 $^{2)}$	Stream piracy	0.093	0.204	2.23	Rotational landslide
Čertoryjský potok Brook	Ostrý vrch Mt.	9	150	80	20	7.17	Incised into former alluvial gravels	0.970	0.304	3.87	Front reactivation of the rotational landslide
Travný potok Brook	Travný Mt.	20	100	80	20	10.49	Not incised	1.130	1.391	11.49	Translational rockslide
Bystřička Brook	Vaculov-Sedlo	12	230	88	25	8.53	Not incised	1.520	0.293	14.00	Front reactivation of the rotational landslide
Bystrá Brook	Kněhyně Mt.	– $^{3)}$	90	–	17	10.23	Not incised	0.860	0.856	14.21	Translational rockslide
Kobylská Brook	Kobylská A	20	295	140	45	10.35	Not incised	0.920	0.268	16.00	Front reactivation of the rotational landslide
Kobylská Brook	Kobylská B	15	130	118	20	9.21	Not incised	0.780	0.268	16.00	Front reactivation of the rotational landslide
Ropičanka Brook	Ropice Mt.	16	400	100	50	8.09	Not incised	0.980	0.200	16.00	Rock avalanche/debris flow

H_D — dam height (maximum crest height of the landslide dam above valley bottom — derived from valley long profiles or geophysical measurement, W_D — dam width (maximum length along the valley), L_D — dam length (maximum length across the valley), R_D — dam range (difference between maximum and minimum elevation of the dam surface), Mean K_S — mean value of the steepness index along the lanslide dam, A_C — contributing catchment area (upstream of the point of blockage), A_{SD} — slope deformation area, V_{SD} — estimated volume of a complex slope deformation at a given area (calculated from missing material of the landslide scarp or moved material from DEM — may be undervalued); $^{1)}$ value of a burried river reach, $^{2)}$ value of a captured river reach, $^{3)}$ value could not be acquired (damming of two sources of Kobylská Brook), Vaculov-Sedlo (Bystřička Brook damming), Miloňov (damming of a tributary of Miloňovský potok Brook) in Vsetínské vrchy Hills, Ostrý vrch Mt. (Čertoryjský potok Brook) in Hodslavický Javorník, Ropice Mt. (Ropičanka Brook), Travný Mt. (Travný potok Brook), Hlavatá Mt. (Lučovec Brook), Mezivodí (damming of Salajský potok Brook and its tributary) and Kněhyně Mt. (Bystrá Brook) in Moravskoslezské Beskydy Mts. Localities where currently water surface remains present above the damming include Brodská B and Jezerné (Jezerní potok Brook) in Vsetínské vrchy Hills. Having failed in the past the dam in the locality of Jezerné was stabilized by man and an artificial reservoir was constructed above it. Interesting localities of damming comprise Metylovická hůrka Mt. (tributary of Ostravice River) in Podbeskydská pahorkatina Hillyland where the landslide body completely destroyed the original river reach. Sediment deposition above the damming did not occur as the stream head of the original valley was captured by backward erosion of another stream.

Landslide dams in the Czech Carpathians were divided into 3 main groups (Fig. 2) pursuant to a modified classification of the geomorphic coupling interface between slope movements and valleys and the landslide impact on the valley floor (Korup 2005). The localities were further evaluated on the base of the landslide morphologic relation to the valley floor (Costa and Schuster 1988) and the rate of stream incision into the upvalley impoundment sediments (Fig. 3). ***A simple type*** of landslide damming corresponds with point type blockages according to the classification by O. Korup (2005). This type of landslide dams is formed by various types of landslides, most commonly rotational landslides, and it is the most frequent type of landslide dams in the studied area (65% of described localities), especially of the *type II* according to J. E. Costa and R. L. Schuster (1988). The localities are Babínek Mt., Vaculov-Sedlo, Kobylská A and B and Travný Mt. with erosionally unsegmented or just partially cut upvalley impoundment sediments and localities of Miloňov, Hlavatá Mt. and Ostrý Mt. where the streams are erosionally incised through impoundment sedimentary fill into former alluvial gravels or as deep as underlying stratum. *Type III* according to J. E. Costa and R. L. Schuster (1988) can be applied to the localities of Peklo and Jezerné. Impoundment fill of both dams is not erosionally disturbed. *Type IV* according to J. E. Costa and R. L. Schuster (1988) can be applied to the damming of Bystrá Brook where a translational rockslide on the western slopes of Kněhyně Mt. caused blockage by valley uplift (Fig. 4).

A "flow-like" type corresponds to linear type blockage according to O. Korup (2005) when landslide deposits move downvalley from the failure and fill a longer valley segment (also *type III* according to Costa and Schuster 1988), however, the condition that the valley is filled with 50% of the landslide deposits, is not satisfied. This type is represented by the localities of Ropice, Mezivodí and Brodská where blockages were formed by flow-like landslides. Upvalley impoundments are either partially erosionally segmented or entirely unsegmented.

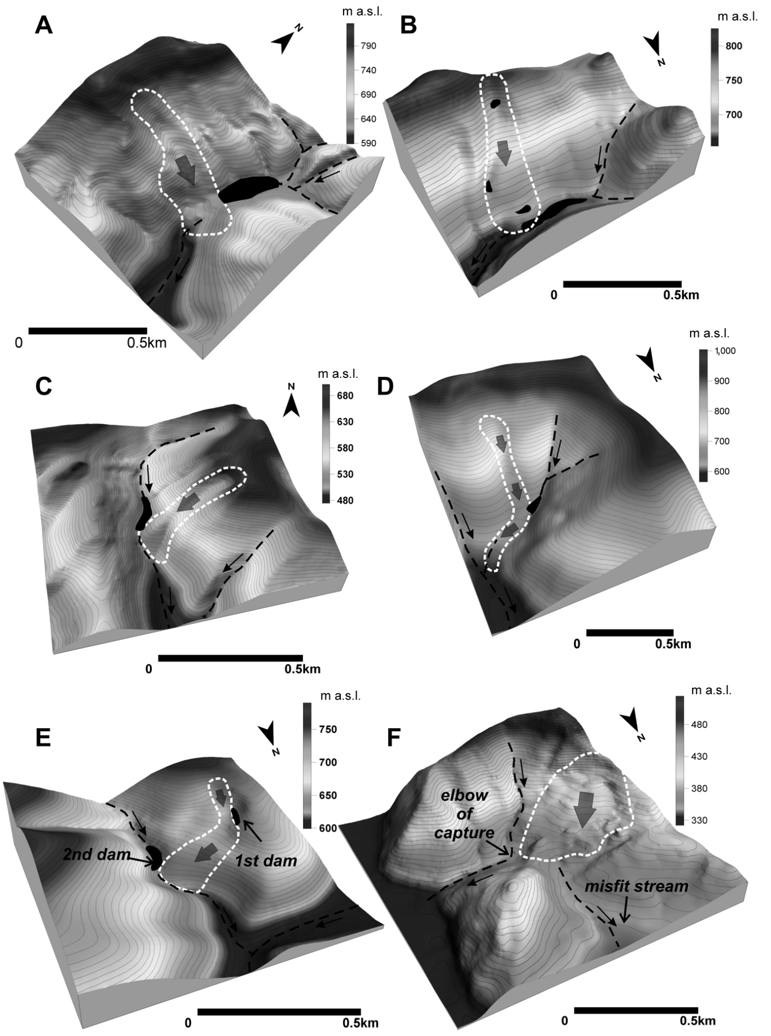

Fig. 2. Types of landslide dams in the Czech Carpathians (white dashed line delimitates landslide bodies, black colour areas represent the extent of original landslide-dammed lakes or depressions on the landslide surface). A — a simple type of valley blockage with a partly breached dam, the river channel is incised under the level of backwater deposits due to backward erosion (an artificial lake is now situated in the original backwater ponding (the Jezerné locality — Vsetínské vrchy Hills), B — a simple type of valley blockage with a completely breached dam, the river channel is incised into the bedrock under backwater deposits due to backward erosion (the Lučovec locality — Moravskoslezské Beskydy Mts), C — a simple type of valley blockage with a partly breached dam, lake sediments are not incised by backwater erosion (the Peklo locality — Vsetínské vrchy Hills), D — a flow-like type of landslide valley blockage with a non-breached landslide dam, backwater deposits are not incised by backwater erosion but at least one incision of the stream in the past is supposed (the Ropice locality — Moravskoslezské Beskydy Mts), E — a double valley blockage by a flow-like landslide (the Mezivodí locality — Moravskoslezské Beskydy Mts), F — a valley reach completely filled with a landslide — triggering factor of river piracy development (the Metylovická hůrka locality — Podbeskydská pahorkatina Hillyland)

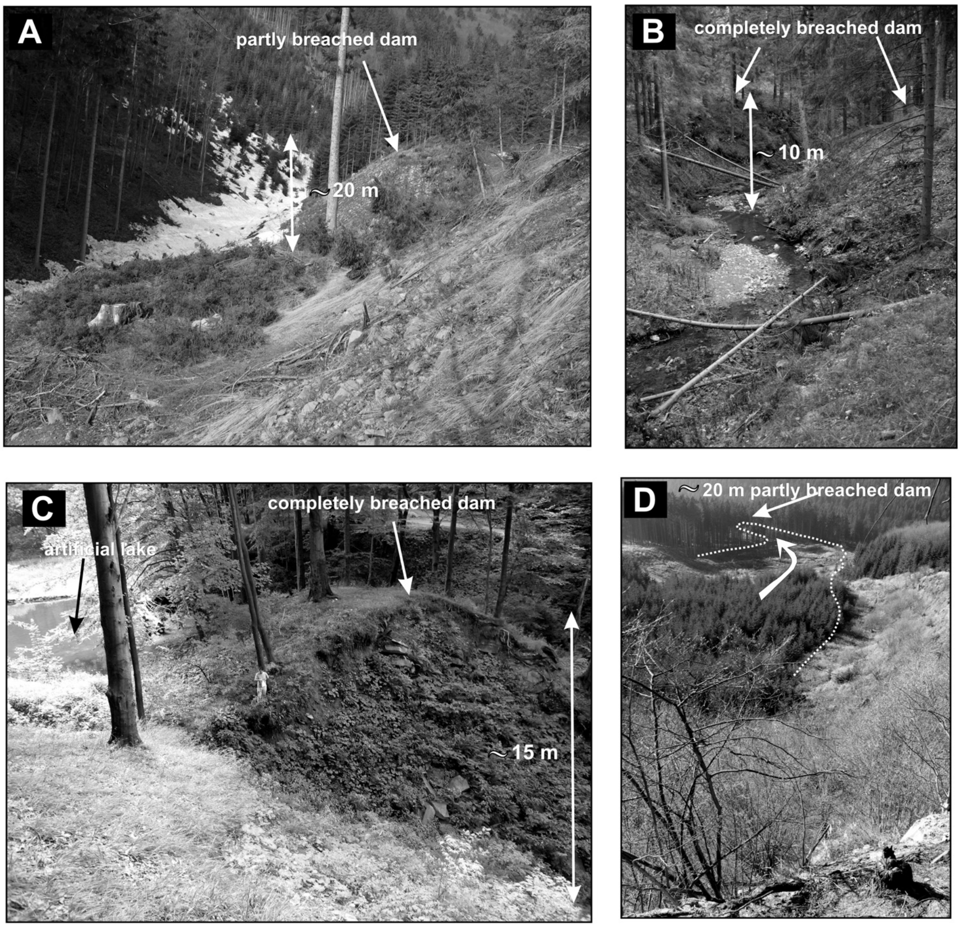

Fig. 3. Examples of landslide dams in the studied area. A — a translational rockslide blocked the upper reach of Travný Brook valley (Moravskoslezské Beskydy Mts), B — a completely breached landslide dam in Lučovec Brook valley (Moravskoslezské Beskydy Mts), C — a dam breached by stream incision in Jičínka River valley (Moravskoslezské Beskydy Mts), D — blockage by a large flow-like landslide in the upper reach of Vlára River (Vizovická vrchovina Highland)

A complex type is represented by a single locality — a blockage formed by a rotational landslide in the area of Metylovická hůrka Mt. It is an area of obliteration type according to O. Korup (2005), however, the condition of >10 km^2 landslide extent is not satisfied. The landslide completely buried a segment of a former valley through which Hodoňovický water race currently passes. Its head was subsequently captured by a left tributary of Ostravice River which incised along the boundary of sliding material and an unaffected slope by backward erosion. Under the blockage a no longer run-through river bed has been preserved in a misfit valley.

Interestingly, typical upvalley impoundment sediments can only be found in blockages formed by clay-rich rocks (almost all the dams mentioned above,

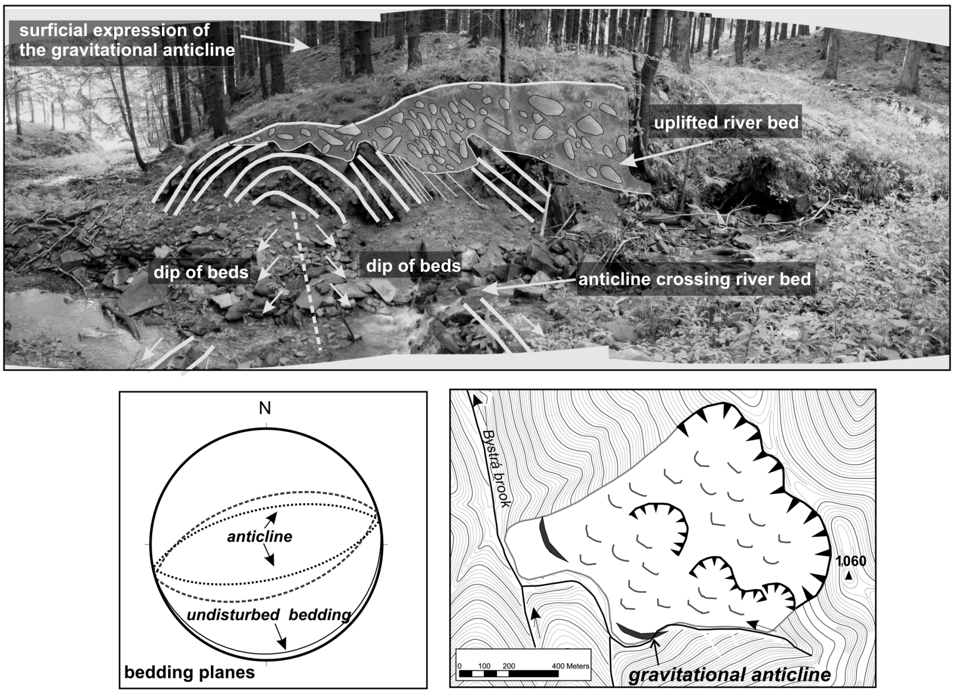

Fig. 4. A special type of a landslide dam in Bystrá Brook valley (Moravskoslezské Beskydy Mts) caused by the valley floor uplift as a result of advance of gravitational anticline in the frontal part of translational rockslide

Fig. 5). In cases of a stream blockage in areas with prevailing sandstones (e.g. all landslide dams in the Godula Nappe), upvalley sediments are either absolutely absent (e.g. Nytrová River) or the upvalley impoundment was filled with untypical sediments coming from one-time supply of a large volume of coarse material (Travný potok Brook). This indicates that the lithological composition of landslide dams (the higher clay content in the landslide dam body, the longer the period of water retention above the dam) can also have an impact on the type of sediments deposited in upvalley impoundments.

GEOMORPHOMETRIC PARAMETERS AND IMPLICATIONS OF LANDSLIDE DAMS

Data on the studied landslide dams acquired by means of DEM analysis and additional methods were incorporated into a GIS-based inventory of geomorphometric and related parameters. The database contains 3 main groups of characteristics describing 1) landslide dams, 2) landslide-dammed lakes and 3) basins above blockage (Korup 2004a; Costa and Schuster 1988). The list of localities and values of some of the parameters are given in Table 1.

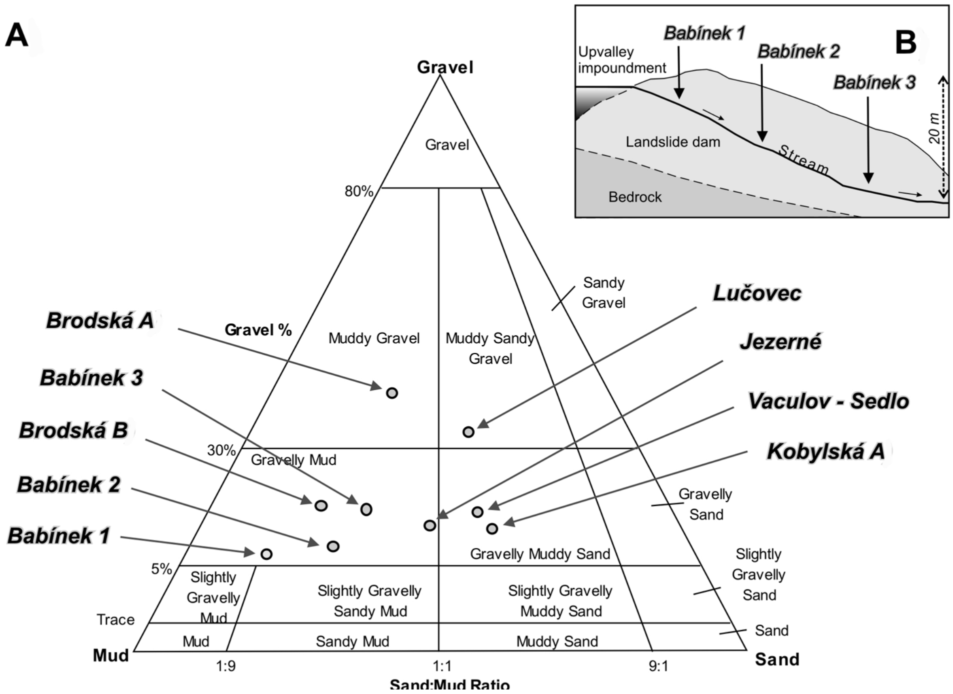

Fig. 5. Results of particle size analysis of matrix of landslide dams (A) and the scheme of cross-section profile of Babínek landslide dam with the identification of sampling sites Babínek 1, 2 and 3 (B)

Basic characteristics of landslide dams include height, width, length and volume of the dam. Heights of landslide dams H_D (maximum crest height of the landslide dam above the valley bottom — derived from valley longitudinal profiles or geophysical measurements) vary between 5 and 25 m. Generally, the highest dams (15–25 m) are dams of simple and flow-like types which affected longer river reaches (Jezerné, Mezivodí A, Ropice, Peklo — all of them represent *type III* according to Costa and Schuster 1988) and are formed by large-volume landslides (Ropice, Travný, Kobylská A). Flow-like type landslide dams that blocked 2 valleys are always higher in the landslide proximal parts than those in the distal parts of slope material accumulation (Mezivodí A–B, Brodská A–B). Lower H_D values are measured with landslide dams of a flow-like type in distal parts of the landslide and dams of a simple type created by small-volume landslides.

Dam widths W_D (maximum length along the valley downstream from the damming) range from 75 to 415 m. Dam lengths L_D (maximum length across the valley) reach the values of 30–490 m. Both planform dimensions are the largest in the locality of Metylovická hůrka Mt. (landslide dam of a complex type) where the slope deformation is of areal character and a relatively large volume. The dam width and length are evidently influenced by the geometry of the slope deformation and dammed valley. Besides those of a complex type, flow-like landslide dams are the widest of all the studied localities.

Dam volumes V_D (approximate volume of landslide dam deposits), as well as the characteristics of landslide-dammed lakes, can be merely estimated in the present state of the research, therefore, the values may show a great error. Hence, the values are not mentioned and instead a parameter of landslide dam range R_D (difference between maximum and minimum elevation of the dam surface) is newly used. Its value is between 10 and 70 meters and it changes depending on a dam width W_D. The most frequent R_D value of the studied group is 20 m. Dams approximating this value (17–25 m) belong to the group of *a simple type* of damming (*type II* and *VI* according to Costa and Schuster 1988) and there is a single case of *a complex type* dam. *Type III* dams (according to Costa and Schuster 1988) of the localities of Peklo and Jezerné are 30 m high. The highest or, on the contrary, lowest values belong to damming of a flow-like type. It is related to the position of a dammed valley towards the dam, the inclination of a longitudinal profile and the landslide dam length (Mezivodí A in the proximal position 70 m, Mezivodí B in the distal position 16 m).

Values of contributing catchment area A_C (upstream of the point of blockage) vary between 0.034 and 3.73 km^2 in the northern part of the Czech Carpathians. Although A_C value does not directly affect geomorphometric parameters of a dam, it exerts a fundamental influence on the dam stability along with the landslide dam height, dam volume, landslide-dammed lake volume and local relief (Korup 2004a). This is supported by the fact that the highest A_C values (3.73 km^2) have been measured in a locality with one of the lowest dam height values H_D (7 m) where heavy erosional destruction can be observed (Hlavatá Mt. — damming of Lučovec Brook). The data show that it is particularly type of slope deformation, landslide volume and the dammed valley geometry that have an effect on landslide dam geomorphometry.

We have investigated geomorphic imprint of landslide dams on the morphometry of longitudinal profiles of valleys. Segments of longitudinal profiles influenced by damming can be well identified in most of the cases (Fig. 6a–n). In longitudinal profiles landslide dams show themselves as more or less distinctive convex shapes whose reaches of sudden lowering of the valley floor gradient correspond with the area of backwater aggradation and related sedimentation. The reaches are separated from incised parts (with a sudden increase of the longitudinal profile gradient) by knickpoints (Korup 2006). Hardly identifiable are landslide dams in longitudinal profiles of valleys dammed by translational landslides (Fig. 6e, 6m).

The impact of landslide dams can be observed in longitudinal profile of valleys also in relation to the steepness of individual segments which is determined on the basis of k_S steepness index (Korup 2006). In order to calculate k_S value fixed concavity index 0.3 (significant value for short steep drainages, Whipple 2004) was used in all longitudinal profiles. Values of k_S steepness index thereby re-

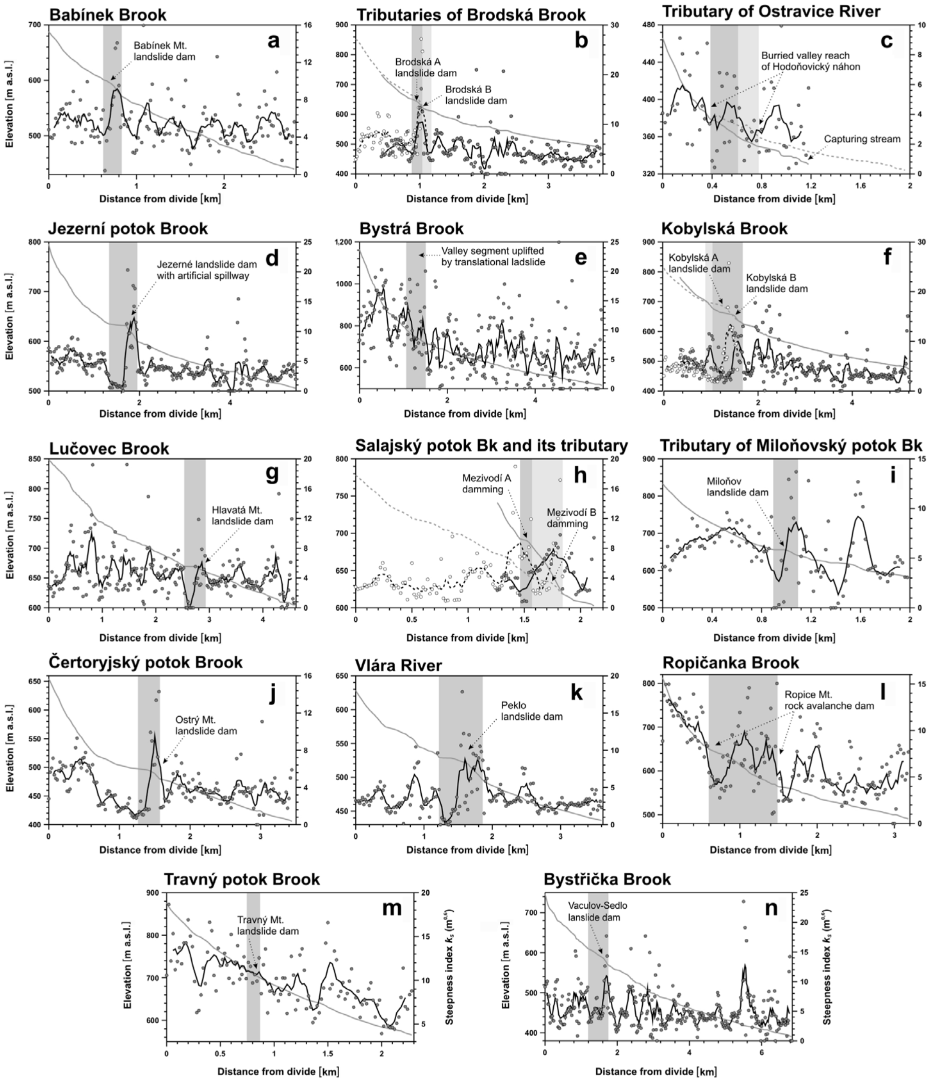

Fig. 6. Longitudinal profiles (gray lines) of dammed valleys with corresponding steepness index k_S (gray dots) and its 7-point running mean (black lines) for fixed concavity index $\theta = 0.3$. Valley reach under direct impact of landslide dam is marked by a dark grey stripe (in case two valleys were dammed, parameters of a longer valley are marked by dashed lines, white dots and light grey stripe up to the confluence)

flect the shape of a longitudinal profile: low values occurring along low-gradient (aggradation) reaches and high values along steep (incised) reaches. K_S values reveal all knickpoints in a longitudinal profile related both to landslide dams and other factors (e.g. structural and lithological boundaries, tectonic controls or non-blocking hillslope failures).

The greatest impact of landslide dams is observed in k_S values of longitudinal profiles of a tributary to Brodská Brook (Fig. 6b), Jezerní potok Brook (Fig. 6d), Kobylská Brook (Fig. 6f), tributary to Miloňovský potok Brook (Fig. 6i), Čertoryjský potok Brook (Fig. 6j), Vlára River (Fig. 6k) and Ropičanka Brook (Fig. 6l). With these dams k_S values reach the highest amplitude in the affected valley reach. The affected reach then shows the highest k_S values even in the whole longitudinal profile of the studied stream. Significant k_S values can also be observed with other studied landslide dams where local decrease and increase of k_S values can be unequivocally related to the displays of damming. They are longitudinal profiles of Babínek Brook (Fig. 6a), tributary of Ostravice River (Fig. 6c), Lučovec Brook (Fig. 6g), Salajský potok Brook and its tributary (Fig. 6h) and Bystřička Brook (Fig. 6n). Small peaking of values ceasing in the whole fluctuation of k_S values can even be traced in the case of dams with indistinctive display in the longitudinal profile (Bystrá Brook — Fig. 6e and Travný potok Brook — Fig. 6m).

Local peakings of the steepness index spatially well coincide with places of landslide damming of streams in all the studied profiles. In most cases, besides the damming of Jezerní potok Brook (Fig. 6d), Čertoryjský potok Brook (Fig. 6j) and Vlára Brook (Fig. 6k), k_S values of valley reaches affected by blocking slope failure do not significantly exceed k_S values of the knickpoints caused by other factors. They are always comparable with them. It can be said that geomorphologic impact of these mostly fossil landslide dams on the morphometry of longitudinal profiles of valleys is as important (if not more) as the impact of other controlling factors (tectonic and lithologic controls or non-blocking hillslope failures).

CHARACTER OF DEPOSITS INFILLING AGGRADATIONAL AREAS

As a consequence of valley profile blockages specific geomorphologic conditions arise mostly connected with the occurrence of abnormally thick sediments in a given valley. Sedimentation conditions above landslide dams are given by the reduction of energy of streams and the presence of small lakes or swamp areas. The thickness of sedimentation in these areas varies between 1 m (e.g. the locality of Čertoryjský potok Brook) and more than 6 m (e.g. the localities of Peklo and Babínek). Sedimentation has generally regular characteristics (Fig. 7). A variously thick layer of fine-grained lacustrine or swampy deposits (e.g. gyttja) lies on alluvial sediments of the original valley floor. These organic-rich sediments indicate the existence of uneventful water sedimentation space. Towards the overlying layers fine-grained deposits verge into fluvial facies (largely overbank deposits) whose presence is connected to the landslide dam failure or spillover and restoration of fluvial sedimentation (Fig. 7A). This type of sedimentation is the simplest model of backwater aggradation. Lake sedimentation does not generally occur in case a landslide dam is built by permeable colluvia (e.g. prevailing sandstones) or rocks; sedimentation space is more likely filled with an increased

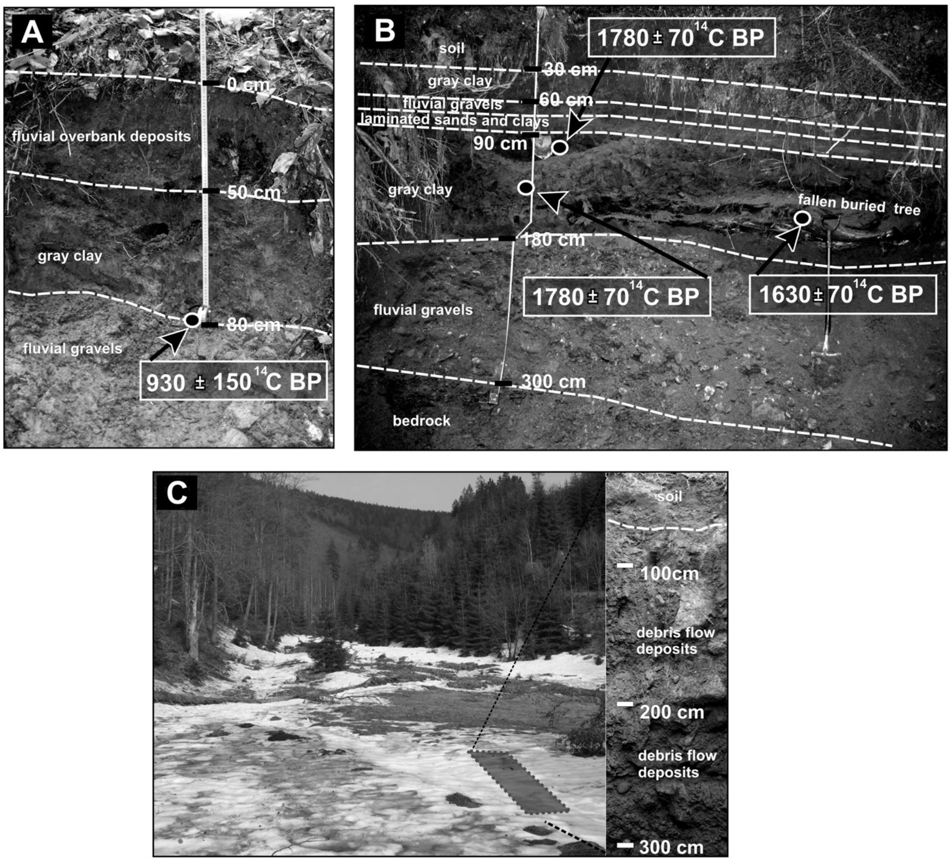

Fig. 7. Examples of backwater deposits. A — a simple type sedimentation with backwater deposits verging upward into fluvial sedimentation (Miloňov locality), B — a complex type sedimentation with both backwater and fluvial deposits (Lučovec locality), C — simple backwater sedimentation consisting of debris flow deposits (Travný locality)

thickness of fluvial or prolluvial sediments. For example, ca a 15–20-m-thick layer of debris flow deposits accumulated behind a barrier caused by a translational rock landslide was studied in a steep valley reach of Travný potok Brook in the topmost part of the Moravskoslezské Beskydy Mts (Fig. 7C).

In most studied cases profiles in impoundment sediment are of a complex character and numerous intercalations of fine-coarse grained fluvial and colluvial deposits between fine-grained lacustrine or swampy facies can be observed (Fig. 7B). This sedimentation reflects the alternation of drier (calmer) periods with the phases of clastic material supply as a result of flood events. In the locality of Babínek a 6-m-deep profile revealed 8 expressive locations of clastic material (sporadically fluvially modified) formed by variously thick (up to about 1 m) layers of largely clayey, organic-rich material. There is very complicated sedimentation in localities where in the past repeated valley blockage appeared in the same place

(Fig. 8). In these cases originally accumulated sediments were often eroded, resedimented and overlaid by the second generation of fine-grained backwater deposits as a consequence of a new valley blockage (e.g. the locality of Ropice).

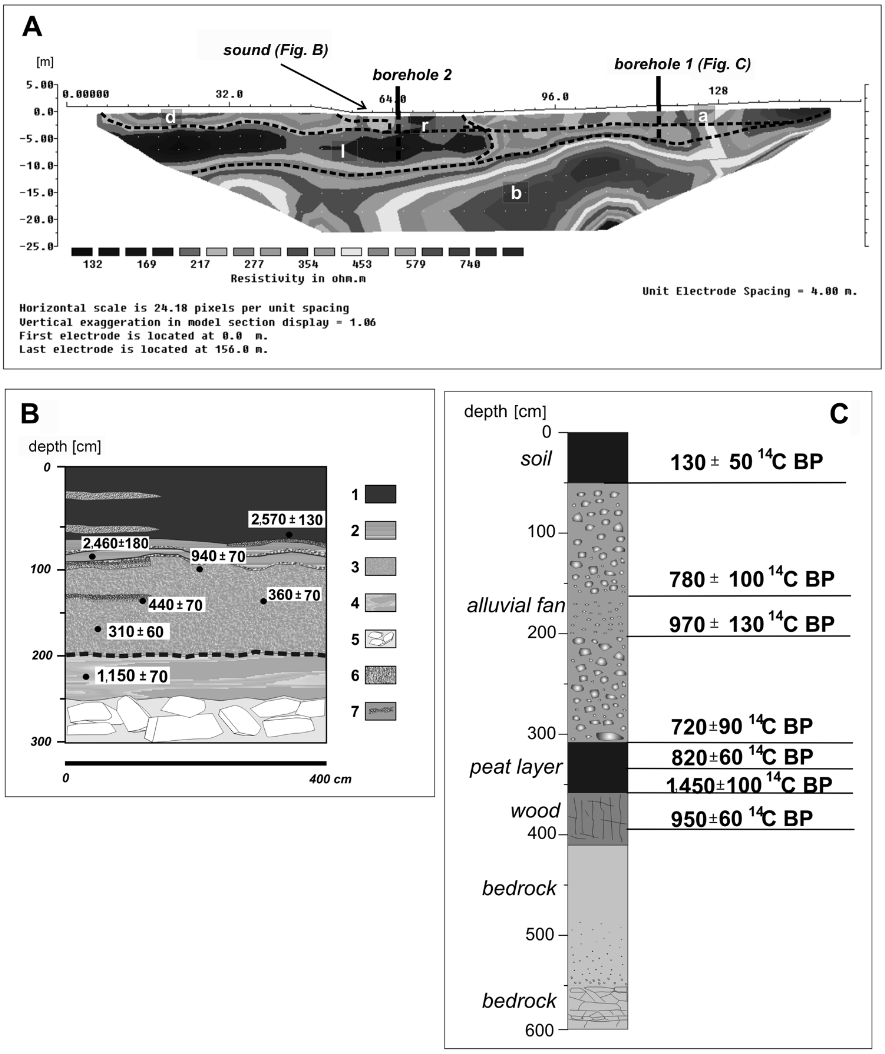

Fig. 8. Complex type sediments in impoundment caused by rock avalanche/debris flow on the northern slope of Ropice Mt. (Moravskoslezské Beskydy Mts). A — the inner structure of a dammed lake interpreted from augerings and electrical resistivity tomography: d — landslide dam, l — matrix supported accumulation of rock avalanche/debris flow, a — alluvial fan, r — redeposited sediments, b — bedrock, B — a test pit with results of radiocarbon dating of resedimented deposits: 1 — dark organic-rich soil, 2 — grey clays with red oxidized stripes, 3 — sandy-loam, 4 — in-situ gray clay, 5 — rock avalanche/debris flow accumulation, 6 — sandy intercalations, 7 — gravels, C — sedimentation structure in delta formation in a dammed area (borehole 1, in borehole 2 rock avalanche/debris flow deposits were located in the depth of 3 m)

AGE OF LANDSLIDE DAMMING EVENTS

Dating of the base level of backwater deposits accumulated as a result of valley blockage approximates the formation of a given landslide. Similarly as in the dating of the base level of peat bogs in landslide's near-scarp depressions we obtain information on the minimum age of the landslide. However, ages obtained by the dating of the base level of landslide-dammed lakes rather approximate the real age of a landslide event as the reaction of the fluvial system on the valley damming is faster than sedimentation in internal drainage depressions on slopes (Haczewski and Kukulak 2004).

At present, radiocarbon dating of just a few localities (Table 2) is available. Some data have already been published by I. Baroň (2004). So far obtained ^{14}C age of landslides that dammed valleys in the Czech Carpathians ranges between 6,810 ± 250 and 930 ± 250 yr BP (Table 2). The correlation of data with palaeoclimatic reconstructions in other central European ranges cannot be carried out yet due to a small amount of acquired data. Despite this fact, the accumulation of the dated events in the period of Subatlantic (mainly its older periods) is obvious, which is in compliance with a large amount of landslides and minerogene sediments inside peat bogs dated to this period in the Polish Carpathians (Margielewski 2006).

In some cases backwater sedimentary fill is of a very complicated age structure caused by the resedimentation of older sediments after multiple erosional cuttings

Table 2

Results of radiocarbon dating of selected landslide dams

Location	Conventional age (BP)	Calendar age 2σ (cal yr BC/AD)	Context of dating	Source
Mezivodí	6,810 ± 250	6,250–5,250 BC	formation of the 1st landslide dam	this study
Peklo	4,540 ± 70	3,550–2,900 BC	minimum age of peat bog caused by landslide dam	this study
Ostrý vrch	3,140 ± 70	1,530–1,210 BC	base of backwater deposits caused by landslide dam	this study
Lučovec	1,780 ± 70	80–420 AD	base of backwater deposits caused by landslide dam	this study
Ropice	Main event: ~1,150 ± 70 to 1,450 ± 100 ^{14}C	~ 380–780 AD to 945–395 BC	reconstructed time interval of the main damming event	this study
Vaculov-Sedlo	1,550 ± 150	—	base of backwater deposits caused by landslide dam	I. Baroň (2004)
Kobylská B	1,065 ± 140	—	base of one of the backwater deposits caused by landslide dam	I. Baroň (2004)
Kobylská A	704 ± 120	—	base of one of the backwater deposits caused by landslide dam	I. Baroň (2004)
Miloňov	930 ± 150	750–1400 AD	base of backwater deposits caused by landslide dam	this study

through the existing backwater deposits. Such case of a very dynamic sedimentation was studied in Ropice Mt. locality in the Moravskoslezské Beskydy Mts (Fig. 8). Radiocarbon dating results are not unequivocal, however, they point out two phases of the valley damming by huge rock avalanche/debris flow deposits. Our interpretation is that the first event occurred roughly in the period between 1,150 ± 70 and 1,450 ± 100 BP and the other (smaller as for the volume) probably in a period younger than 310 ± 60 BP. Between the two phases accumulated swamp and lacustrine deposits were cut through by erosion after breaching of the dam and resedimented in an inversion sequence in the lower part of the dammed space. Another accumulation and follow-up impoundment area filling took place after a new (smaller) landslide event that blocked water outflow from the sediments.

DISCUSSION

Relief development in the territory of the Czech Republic has often been studied in discretely conceived relief categories. Perhaps thanks to this form of research the importance of slope deformations within the Quaternary erosion-denudation development has long been underestimated. The importance of slope deformations in connection with the development of valley floors brings a more complex view of Quaternary phases of the relief development. Geomorphologic research is thus enriched by new locations of stratigraphically and palaeoenvironmentally important sedimentary complexes which were not used in the creation of development schemes of the studied area. Nevertheless, as contemporary research shows, they are not unusual phenomena in the relief and in connection with other palaeoenvironmentally significant sedimentary locations in landslide areas (Margielewski 1998; Hradecký et al. 2007) they represent potential for geomorphologic research of a new quality.

The emergence of landslide dams is often related to tectonically active and still strongly seismic mountain regions (e.g. Korup et al. 2006). However, they also occur in tectonically less active ranges, which Czech Carpathians are. Here landslide activity causing valley floor damming is directly connected to structural-lithological predisposition since a landslide body attacking a valley floor is often a product of a long-term instability of slopes caused by deeply incised disintegration of flysch morphostructures.

Lithological situation of concrete localities has also impact on the persistence of dams and functioning of backwater sedimentation. Generally, it can be said that areas with a more expressive presence of claystone formations are more favourable for the development of active backwater accumulations than landslides of massive sandstones. So far unsolved problem in landslide-dammed valleys is sediment flux in which backwater aggradation and landslide bodies and dams act as sources of sediments. The effect of sudden dam destruction and emergence of outburst floods are also related to this problem as having a potential considerable geomorphic imprint in lower-lying valley reaches (Korup 2005).

The very destruction of a dam can be induced by the increase in pore water pressure in the dam body as a result of the increase in the lake volume whereas a catastrophic flood can even be caused by a secondary landslide into the reservoir (Korup 2005). From this point of view landslides of larger volumes or fast-moving debris flows or hyperconcentrated flows can be of a great impact. As a consequence of a long-term utilization of valley floors by man detecting a flood facie of this type is relatively complicated and it has not been found in the studied area yet. Except the influence of man the absence of evident flood sediments could be caused by lower intensity of such a flood or sediment removal during subsequent long-term fluvial processes.

Despite so far incomplete dating of the origin of landslide dams we can state that the dated dams mostly correlate with landslide activity registered on the basis of sediment dating in landslide bodies in a broader area of the Czech Carpathians. Fundamental seems to be a phase related to the period of Older Subatlantik (Table 2), however, even much older blockage events have been identified. We can assume that similarly as in the case of other slope deformations an important role in landslide-damming of valleys in the study area was played by more humid phases of the Holocene. Unfortunately, more complex local data on parameters of climate during the Holocene are still missing for a detailed analysis of this triggering mechanism. The same extends to the phase bound to the Subatlantic (SA_2).

The emergence and subsequent destruction of landslide dams represent hazard processes in the Czech Carpathians whose potential influence on human activities in the future is evident. Therefore, not only analysis of triggering mechanisms but also frequency-magnitude analysis is pivotal.

CONCLUSION

Landslide dams represent relatively numerous forms of the relief in the Czech Flysch Carpathians. At present, the existence of about 20 cases is documented (17 of which are analyzed in detail in this study). However, preliminary analyses of maps and reconnaissance research show that there are up to a few tens of fossil landslide dams with characteristic sequences of backwater deposits in the territory. The amount of landslide dams without sedimentary record is probably severalfold higher, yet it is very complicated to prove their existence and carry out time classification.

All the documented landslide dams significantly affect longitudinal inclination of valleys even after a few-thousand-year-old existence. In sporadic cases erosional cutting occurred of both the sediments of the respective landslide dam and the body of backwater deposits upstream.

The emergence and preservation of landslide dams is closely associated with lithological characteristics of the underlying stratum. A large number of cases were documented in areas formed by thinly bedded flysch (the Magura

Nappe and Upper Cretaceous — Palaeogenne Flysch of the Silesian Unit). In the topmost parts of the Moravskoslezské and Slezské Beskydy Mts formed by thickly bedded flysch of the Godula Nappe with prevailing sandstones landslide dams are rare and they generally developed solely in connection with valley blockage by large landslides (minimal volumes on the order of million m^3).

Most of the landslide dams originated as a consequence of fast flow-like landslides or due to the reactivization of frontal parts of larger (often rotational) landslide areas. Preliminary dating results show that valley damming processes took place during the whole Holocene. At an early date dating of a larger amount of cases will be finished, on the base of which a more detailed chronology will be created. The investigation shows that beside peat bogs situated on the surface of the landslides backwater accumulations represent the only settings with datable Holocene sedimentary record in mountain areas of flysch Carpathians. A detailed analysis of these sediments connected with radiocarbon dating and pollen analysis are currently being researched.

ACKNOWLEDGEMENTS

The research was supported by a grant project of the Academy of Sciences of the Czech Republic, no. KJB 301870501: “Quaternary geochronology of slope deformations of the culmination part of the Western Beskydy Mts: absolute and relative dating of landforms”.

[1]*Department of Physical Geography and Geoecology*
Faculty of Science, University of Ostrava
Chittussiho 10, 710 00 Ostrava, Czech Republic
tomas.panek@osu.cz, v.smolkova@email.cz, jan.hradecky@osu.cz

[2]*Institute of Geonics, Academy of Sciences of the Czech Republic, v.v.i. Branch Brno*
Drobného 28, 602 00 Brno
Czech Republi,
kirchner@geonika.cz

REFERENCES

Baroň I., 2004. *Structure, dynamics and history of deep-seated slope failures in the Rača Unit, Magura Nappes, Outer Western Carpathians (Czech Republic)*. PhD. Thesis, Faculty of Science, Masaryk Univerzity Brno, 98 pp.

Costa J. E., Schuster R. L., 1988. *The formation and failure of natural dams.* Geological Society of America Bulletin 100, 1054–1068.

Ermini L., Casagli N., 2003. *Prediction of the behaviour of landslide dams using a geomorphological dimensionless index.* Earth Surface Processes and Landforms 28, 31–47.

Flint I. I., 1974. *Stream gradient as a function of order, magnitude, and discharge*. Water Resources Research 10, 969–973.

Haczewski G., Kukulak J., 2004. *Early Holocene landslide-dammed lake in the Biesczady Mountains (Polish East Carpathians) and its evolution.* Studia Geomorphologica Carpatho-Balcanica 38, 83–96.

Hewitt K., 2006. *Disturbance regime landscapes: mountain drainage systems interrupted by large rockslides.* Progress in Physical Geography 30, 365–393.

Hradecký J., Pánek T., Klimová R., 2007. *Landslide complex in the northern part of the Silesian Beskydy Mountains (Czech Republic).* Landslides 4, 53–62.

Korup O., 2004a. *Geomorphometric characteristics of New Zealand landslide dams.* Engineering Geology 73, 13–15.

Korup O., 2004b. *Landslide dam*, [in:] *Encyclopedia of geomorphology*, ed. A. S. Goudie, London, Routlege, 696–698.

Korup O., 2004c. *Geomorphic hazard assessment of landslide dams in South Westland, New Zealand: fundamental problems and approaches.* Geomorphology 66, 167–188.

Korup O., 2005. *Geomorphic imprint of landslides on alpine river systems, southwest New Zealand*. Earth Surface Processes and Landforms 30, 783–800.

Korup O., 2006. *Rock slope failure and the river long profile*. Geology 34, 45–48.

Korup O., Strom A. L., Weidinger J. T., 2006. *Fluvial response to large rock-slope failures: Examples from the Himalayas, the Tien Shan, and the Southern Alps, New Zealand*. Geomorphology 78, 3–21.

Margielewski W., 1998. *Landslide Phases in the Polish Outer Carpathians and their Relation to Climatic Changes in the Late Glacial and the Holocene.* Quaternary Studies in Poland 15, 37–53.

Margielewski W., 2006. *Records of the Late Glacial–Holocene palaeoenvironmental changes in landslide forms and deposits of the Beskid Makowski and Beskid Wyspowy Mts. area (Polish Outer Carpathians).* Folia Quaternaria 76, 149 pp.

Whipple K. X., 2004. *Bedrock rivers and the geomorphology of active orogens.* Annual Rev. Earth Planet. Sci. 32, 151–185.

STRESZCZENIE

Tomáš Pánek, Veronika Smolková, Jan Hradecký
Karel Kirchner

ZAPORY OSUWISKOWE W PÓŁNOCNEJ CZĘŚCI CZESKICH KARPAT FLISZOWYCH: DOWODY GEOMORFOLOGICZNE I ICH ZNACZENIE

Artykuł przedstawia wyniki badań geomorfologicznych nad zaporami osuwiskowymi i omawia paleośrodowiskowe aspekty wynikające z ich powstania. Opracowano 17, głównie fosylnych zapór, chociaż można zidentyfikować co najmniej kilkadziesiąt takich form i osadów na badanym terenie. Formy te mają istotny wpływ na morfometrię profilów podłużnych dolin w Karpatach fliszowych, a wpływ procesów geomorfologicznych uwarunkowanych istnieniem osuwisk przegradzających doliny obejmuje znaczne obszary.

Złożenie i przetrwanie osadów powstałych wskutek przegrodzenia dolin osuwiskami zależy od frakcji materiału budującego zapory osuwiskowe. Na obszarach gdzie przeważają piaskowce woda na ogół nie jest retencjonowana w postaci jezior lub podmokłości trwających przez dłuższe okresy, a osady składane powyżej przegrody składają się z klastycznych utworów rzecznych, proluwiów lub materiału przemieszczonego przez spływy gruzowe. Wstępne wyniki badań pokazują, że zdarzenia osuwiskowe prowadzące do barykadowania den dolin miały miejsce w całym holocenie, chociaż ich większa częstotliwość wystąpiła w subatlantyku. Charakter tych osadów jest ważnym wskaźnikiem zdarzeń geomorfologicznych i paleohydrologicznych w holocenie.