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Dating landslides in the Gorce Mts. (Polish Outer Carpathians) – preliminary results

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Preliminary results of dating landslides in the Gorce Mts. (Polish Outer Carpathians) are given, where ages of landslide activity have been poorly constrained. Four landslide zones with minerogenic mires (fens) were selected in order to determine the age of landslide movements, with depositional sequences of six fens being investigated by boreholes. Conventional radiocarbon dating of wood samples from mineral sediments sealing the landslide depressions was carried out to establish the age of landslide formation or rejuvenation. Loss on ignition analyses were obtained at 2.5 cm intervals along the cores to indicate possible delivery of allochthonous material into the peat bogs. Landslide formation in the Gorce Mts. corresponds to phases of mass movement hitherto identified in the Polish Outer Carpathians. Increased mass movements activity in the Gorce Mts. relate to cold and humid periods of the Holocene which occurred: ~11.1 ka cal BP, 8.6–8.0 cal BP; 6.5–5.9 ka cal BP, 4.8–4.5 cal BP, 3.3–2.5 cal BP and 1.75–1.35 cal BP. Loss on ignition analyses revealed changes in sedimentation in the landslide mires such as formation of mineral and illuvial horizons in peat sequences, and mineral covers overlying fens, associated with humid climatic phases of the Holocene.

Key words: radiocarbon datings, landslide fen, mass movement activity, Holocene, Flysch Carpathians.

INTRODUCTION

Mass movements have strongly influenced the relief of the Outer Western Carpathians (OWC; e.g., Starkel, 1960; Ziętara, 1968; Alexandrowicz and Margielewski, 2010). Landslide depressions filled with water – lakes, subsequently transformed into fens – are common phenomena in landslide areas (Margielewski, 2006, 2018; Buczek, 2016). Deposits sealing the bottoms of these depressions allow dating of the beginning of landslide formation and the minimum age of the landslides. The specific sedimentary environment of these depressions means that the landslide fen deposits are also very sensitive indicators of palaeoenvironmental changes during the Late Glacial and the Holocene (Margielewski, 2006, 2018). Although in the OWC deposits associated with many landslides (with over 80 radiocarbon dates) have been dated so far, the landslides in the Gorce Mts. have remained poorly investigated. The only examples of dated events of mass movement activity involve studies of landslide lakes: Iwankowskie Lake (Bucała et al., 2014) and Pucołowski Stawek Lake (Buczek, 2016), while the beginning of accumulation of ombrogenic peat in the ridge-top trench on Kiczora Mt. has been palynologically referred to the Subatlantic Phase (Koperowa, 1962).

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Over 20 radiocarbon dates on landside deposits have been made in the mountain ranges surrounding the Gorce Mts.: Beskid Wyspowy (Margielewski and Kovalyukh, 2003; Margielewski, 2006), Beskid Sądecki (Alexandrowicz, 1993, 1996; Margielewski, 1997, 2006; Margielewski et al., 2011) and Pieniny (Alexandrowicz, 1996, 2009, 2013).

The paper provides new radiocarbon dates of bottommost landslide deposits in the Gorce Mts. supplementing the database of dated landslides in the OWC, as well as radiocarbon dates of selected mineral horizons within the fens. These dates together with geomorphological mapping of the landslides studied has constrained landslide activity events in the Gorce Mts. and correlated them with principal phases of mass movements in the Polish Outer Carpathians.

MATERIALS AND METHODS

Over a dozen landslide depressions in the Gorce Mts. were investigated by the author using a spiral auger (Fig. 1). The six with the greatest thickness of infilling sediments were selected for further analysis (Fig. 1), including previously described or partly elaborated by the author: the Iwankowskie Lake fen (Bucała et al., 2014) and Pucołowski Stawek Lake (Buczek, 2016). Logs (cores) from all selected fens were sampled using an *INSTORF* peat sampler, 6 cm in diameter. Conventional radiocarbon dating was carried out using wood samples from mineral sediments sealing the basins as well as from several illuvial horizons in the depositional sequences. All dates were obtained in the Laboratory of Absolute Dating in Skała near Kraków in order to establish the date of landslide formation or

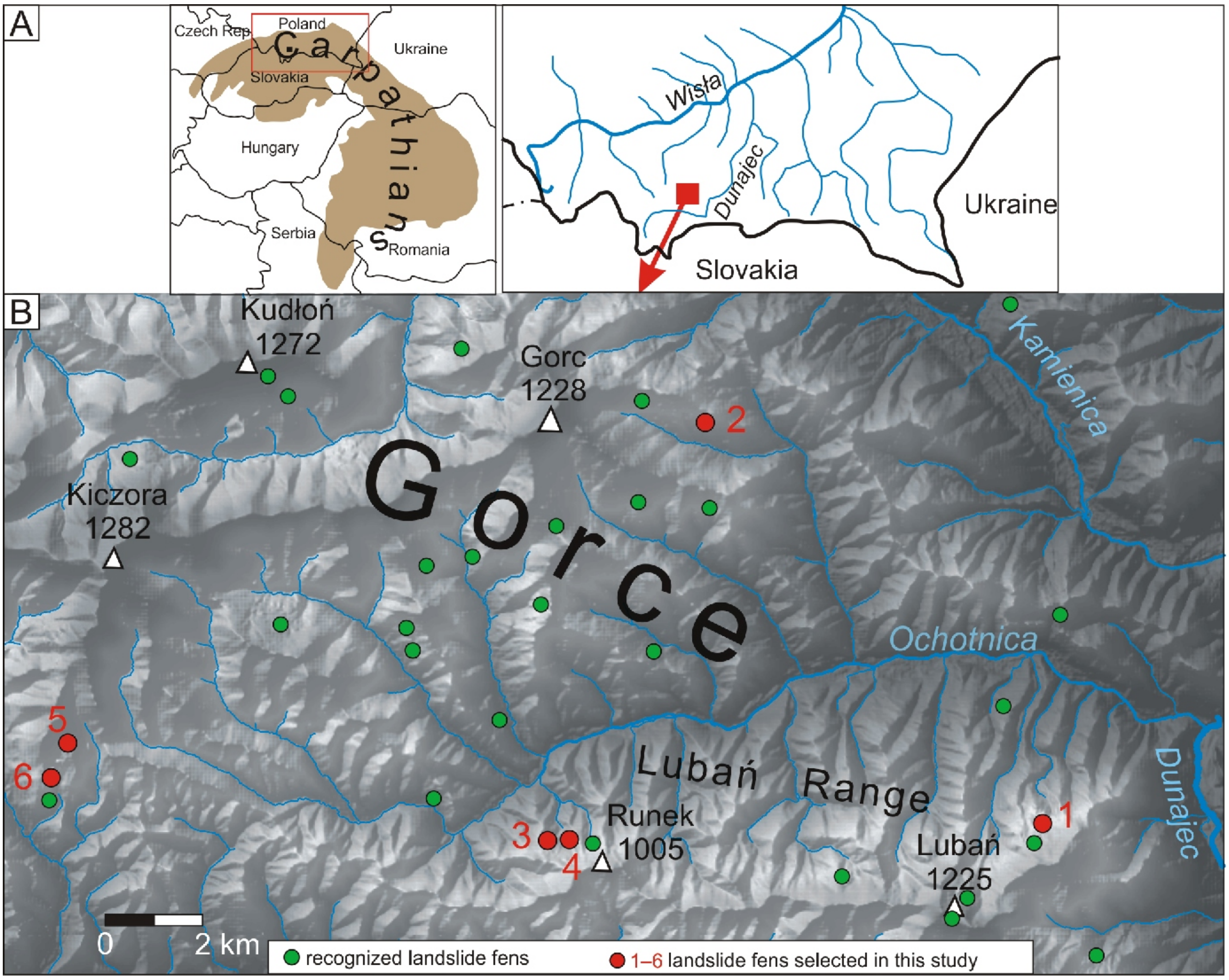

Fig. 1. Location of the study area (A), with the landside fens recognized and examined in this paper (B)

1 – Tokarnia fen; 2 – Lelonek fen; 3 – Zawadowskie Lake; 4 –, Iwankowskie Lake (Bucała et al., 2014); 5 – Pucołowski Stawek Lake; 6 – Srokówki fen

rejuvenation. They were calibrated using the *OxCal 4.2* software (Bronk Ramsey, 2009) with the application of the *IntCal13* calibration curve (Reimer et al., 2013). Loss on ignition (LOI) analyses at a temperature of 550°C (Heiri et al., 2001) were made for each 2.5 cm long section of the main logs in order to indicate possible delivery of allochthonous material to the fens (Margielewski, 2006, 2018). Detailed geomorphological mapping of selected landslide areas was carried out on the basis of LiDAR derived hillshade maps.

STUDY AREA

Study area includes the central and eastern parts of the Gorce Mts., which are located in the Outer Western Carpathians (Poland). In geological terms this part of the Gorce Mts. is built principally of Upper Cretaceous–Eocene flysch rocks of the Krynica Subunit of the Magura Unit (Burtan et al., 1976; Paul, 1978; Kulka et al., 1987). Only a small part of the study area, situated to the north of Mt. Gorc (1228 m a.s.l.) is built of deposits of the Bystrica Subunit of the Magura Unit. The oldest deposits of the Krynica Subunit in the study area belong to the Szczawnica Formation (Kulka et al., 1987). These deposits comprise mostly thin-bedded sandstones and shales and occur mainly along the upper sections of right tributaries of the Ochotnica river (Burtan et al., 1976; Paul, 1978; Kulka et al., 1987). Most of the area of the Gorce Mts., including the highest ridges, are formed by thick-bedded sandstones and conglomerates of the Magura Formation (Poprad and Piwniczna Sandstone members; Kulka et al., 1987). The strata of the Gorce Mts. are strongly folded and dislocated by faults. Faults have mostly NNW–ESE and NNE–WSW directions (Chrustek et al., 2005; Buczek and Górnik, 2019). The Gorce Mts. are intermediate mountains with strongly incised V-shaped valleys, relatively flat ridges and steep slopes (Starkel, 1960). The slopes of the Gorce Mts. are transformed by numerous landslides (Margielewski, 1999; Bucała et al., 2014; Płaczkowska, 2014; Buczek, 2016). Apart from erosion, mass movements are the main factor which has reshaped the relief of the Gorce Mts. Large, deep-seated landslides are responsible for the creation of the specific relief of most slopes with numerous depressions which are commonly filled with water, resulting in the formation of landslide lakes and fens (Margielewski, 1999). Mean annual precipitation in the Gorce Mts. ranges from 800–1200 mm, while mean annual temperature varies from 3 to 6°C (Miczyński, 2015).

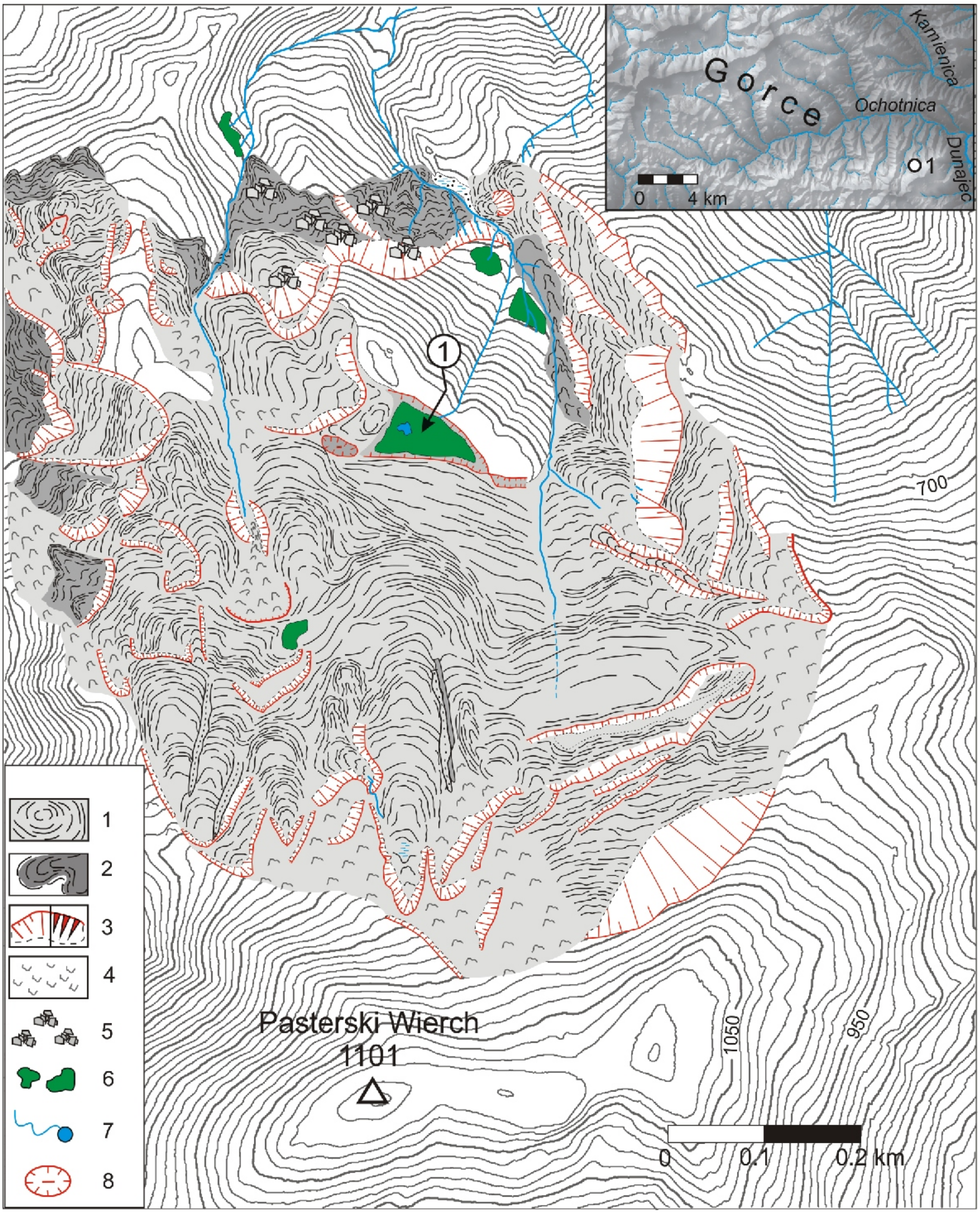

Fig. 2. Geomorphological map of the Tokarnia landslide zone (1)

1 – landslide body; 2 – colluvial tongues; 3 – scarps (a – rocky, b – soil); 4 – creeping zones; 5 – rock blocks and debris; 6 – fens, swamps; 7 – streams, springs; 8 – landslide depressions

SITE DESCRIPTIONS

TOKARNIA LANDSLIDE (LUBAŃ RANGE)

Northern slope of Mt. Pasterski Wierch (1100 m a.s.l.) is covered by a complex range of slope deformation structures (according to Dikau et al., 1996). This landslide zone, the area of which reaches ~0.8 km^2 (1.34 0.98 km), is one of the largest in the Gorce Mts. It lies within an altitudinal range of 740–1042 m a.s.l. and is developed in thick-bedded sandstones, conglomerates, shales and locally thin-bedded flysch of the Piwniczna Sandstone Member (Paul, 1978; Kulka et al., 1987). The landslide was progressively formed by several generations of mass movements caused by headward erosion of the Janczurowski Stream (Fig. 2).

The Tokarnia fen is situated on the lower part of the landslide area, near to its northern margin (Fig. 2). Recent fen deposits fill a large triangular depression within this area reaching 5780 m^2 (Fig. 3A, B). Based on morphology and plant associations the Tokarnia fen is divided into two parts. The western and lower part is overgrown by plant associations characteristic for

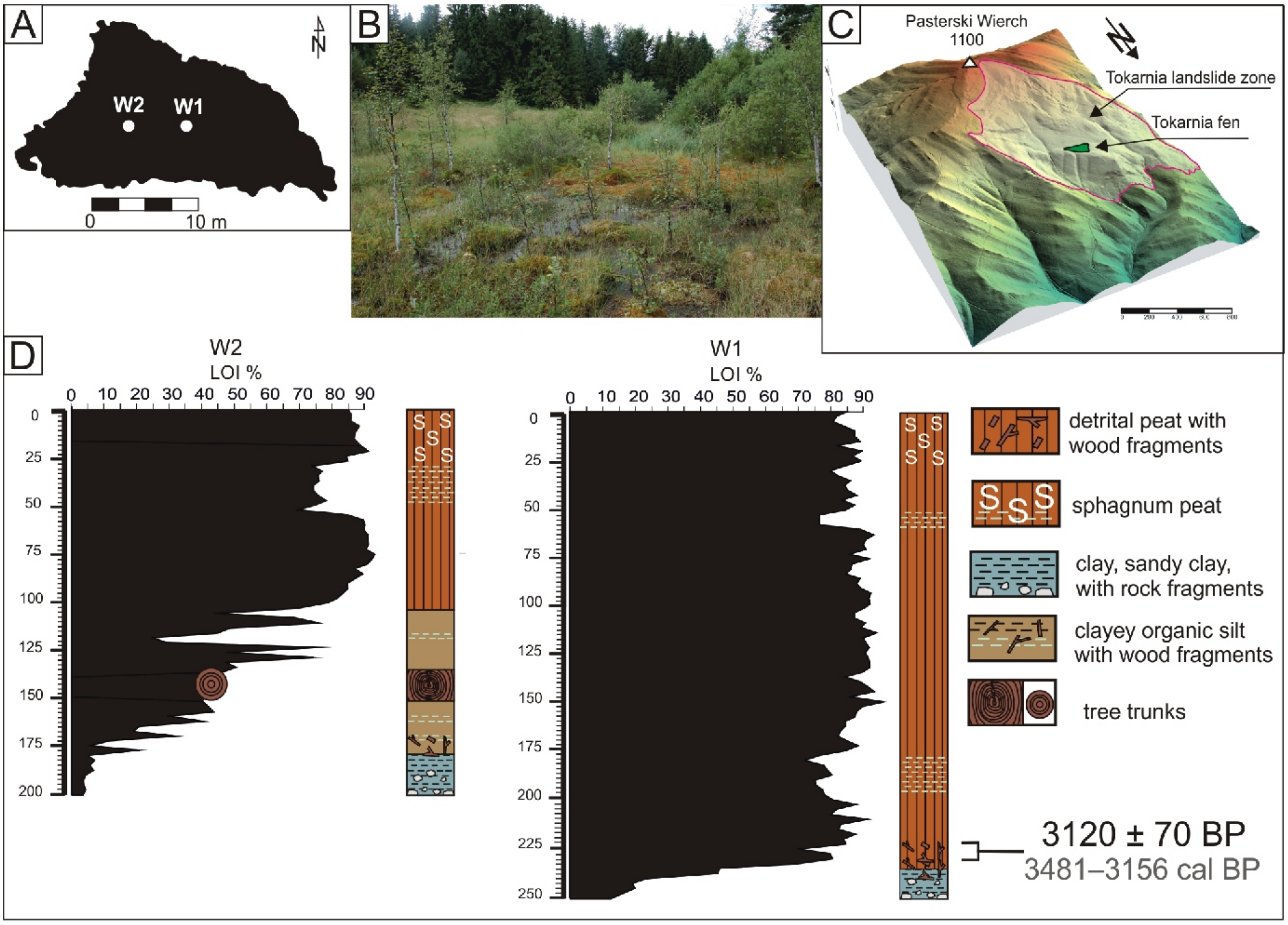

Fig.3. Tokarnia fen with locations of the boreholes (A); view of the Tokarnia fen with a floating mat around the bog pond (B); 2.5 D view of the northern slope of Mt. Pasterski Wierch with the extent of the Tokarnia landslide and location of the fen (C); sequence of deposits of the Tokarnia fen (D)

Valeriano–Caricetum flavae (Lisowski and Kornaś, 1966). The eastern and higher (0.5 m) part of peat bog is overgrown by taxa characteristic for raised bogs, e.g. *Ledum palustre* L., *Betula pubescens* Ehrh., *Drosera rotundifolia* L. (Lisowski and Kornaś, 1966). The depression is drained by a small, seasonal stream. The Tokarnia peat bog was investigated by 2 boreholes located in the central part of the depression (Fig. 3A). The maximum depth of the peat bog (2.5 m) was is seen in log 2.

The bottom of the Tokarnia fen basin (2.5–2.3 m) is sealed with mineral sediment (Fig. 3D, log 1 – W2): sandy clay with small fragments of sandstone. This is overlain by woody peat (2.3–2.0 m) with many fir needles (*Abies alba*). Wood fragments from this unit were dated by the radiocarbon method at 3120 ± 70 BP (3481–3156 cal BP). The slight drop in the loss on ignition curve (~10%) above the woody peat marks an illuvial layer within the peat sequence. A unit of strongly decomposed, detrital peat occurs upon this illuvial horizon (1.75–0.60 m), where the percentage of organic material increases, reaching almost 96% loss on ignition at a depth of 1.5 m. Above this peat unit, a distinct decline in the loss on ignition curve is visible in the interval 0.60–0.52 m, indicating delivery of mineral material to the basin (Margielewski, 2006, 2018). The topmost part of the peat (the top 0.35 m) is formed of pure *Sphagnum* peat.

The second borehole, located 10 m to the west of the first, is characterized by a lesser thickness of sediments (2.0 m) that includes a thinner layer of decomposed, detrital peat (Fig. 3D, log 2 – W1). By contrast with the main log (log 1 – W2), the bottom mineral deposits here (1.7 m) are overlain by clayey organic silt with wood fragments. In the upper part of this section (1.30–1.02 m), a distinct decline in the loss of ignition curve occurs (~60%), which indicates a supply of mineral material to the peat bog (Fig. 3D, log 2 – W1). An interval of pure peat occurs above 1.02 m, as is clearly marked on loss on ignition curve. In the middle part of this unit (0.52–0.3 m) an illuvial layer is marked by a ~10% drop in the loss on ignition curve. As in log 1, the uppermost section of peat is formed of pure *Sphagnum* peat (Fig. 3D, log 2 – W1).

LELONEK LANDSLIDE (MT. GORC RANGE)

This landslide lies on the southern slope of Mt. Lelonek (992 m a.s.l.) in the Mt. Gorc Range. The upper part of the landslide, including head scarps and the main landslide body with fen deposits, was formed in the thick-bedded Magura Sandstones, whereas the lower segment is in thin-bedded flysch of the Szczawnica Formation (Paul, 1978). The movement of the landslide was generally consequent to the strata dip direction and was formed due to the lateral erosion of the Młynne Stream. The area of the Lelonek landslide reaches 0.17 km^2, and lies in the altitude span of 882–704 m a.s.l. The landslide area can be divided into two parts: a main landslide body with fen deposits; and younger, elongated colluvial tongues in the eastern part of landslide area (Fig. 4). One of the landslide toes (25 m high) probably blocked the valley floor of the Młynne Stream, forming a landslide dam lake.

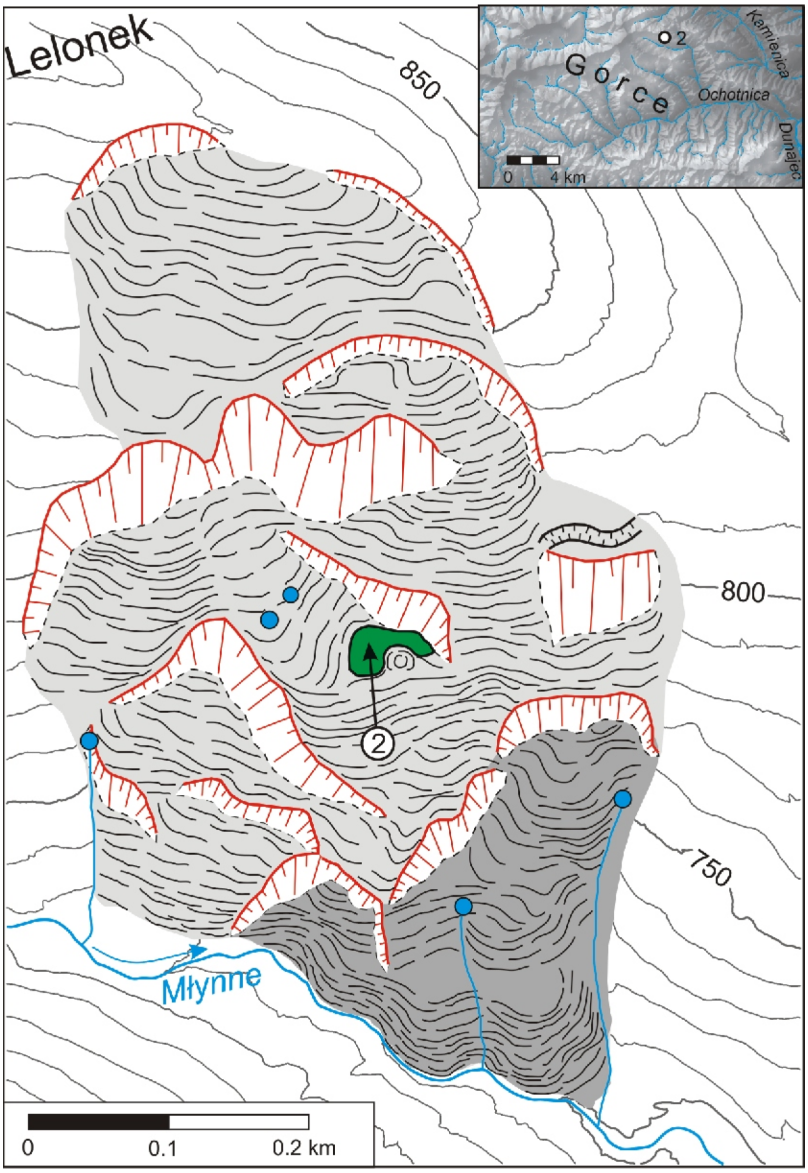

Fig. 4 . Geomorphological map of the Lelonek landslide (2)

Explanations as on Figure 2

The Lelonek fen occupies the central part of the landslide body (788 m a.s.l.), below the steep, 15 m high secondary scarp. Fen deposits fill an irregular depression some 1060 m^2 in area. Presently, there is no evidence of any surface inflow and outflow from the mire.

The maximum depth of the depression (2.0 m) was measured in the western part of the mire. The bottom part of the fen sequence comprises sandy clayey silt. Above this bottom layer, at the depth of 1.65 m, organic silts are reflected in a rise of the loss on ignition curve (Fig. 5A). Wood fragments at the bottom of the sequence were radiocarbon dated at 4010 ± 70 BP (4810–4756 and 4654–4284 cal BP). In log 3, the organic silts include a mineral layer at the depth of 1.45–1.37 m, though this is not recorded in the other logs. All logs include a mineral layer at the depth of ~0.75 cm (Fig.5A), which varies in thickness from 0.2 to 0.5 m. In boreholes from the central part of the peat bog (log 1 and log 2) this layer includes a thin layer of organic silt. Above the mineral layer, decomposed peat (0.25–0.5 m) occurs in all logs, the percentage of organic material reaching 80–85%. The peat layer thins from log 1 to log 5, due to reduced mineral supply from the western to the eastern part of the peat bog.

ZAWADOWSKIE LANDSLIDE ZONE (LUBAŃ RANGE)

Nearly all the northern slope of Mt. Runek (997 m a.s.l.) has been transformed by a large (0.4 km^2 in area) multistage landslide (Fig. 6). This landform developed within thick-bedded sandstones and conglomerates of the Poprad Sandstone Member (Burtan et al., 1976) in the altitude span of 738–943 m a.s.l. The landslide zone was successively formed by several mass movement generations induced by headward erosion of the Zawadowski Creek. The main movement of the landslide was generally consequent to the strata dip direction (30°). Located near to the drainage divide, low (2.0–2.5 m), gently dipping scarps are probably remains of the oldest phase of gravitational movements (Fig. 6). The landslide body below the scarps consists of several levels of flat, landslide blocks. The next generation of landslide movements comprised rota-

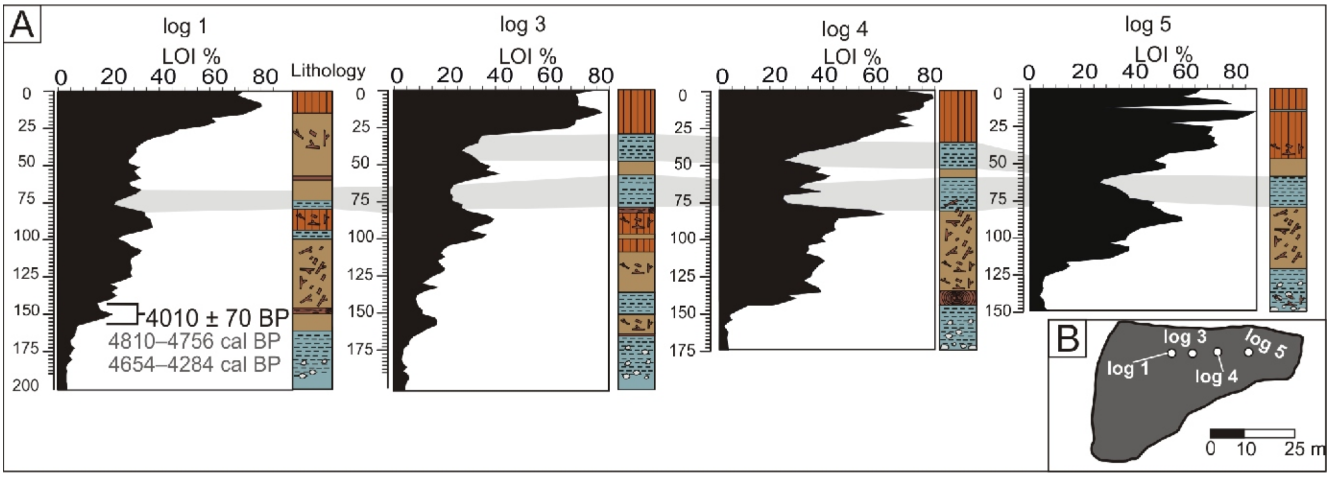

Fig. 5. Lithostratigraphic sequence of the Lelonek fen with loss on ignition curves (A) and map with location of the boreholes (B)

Explanation as on Figure 3

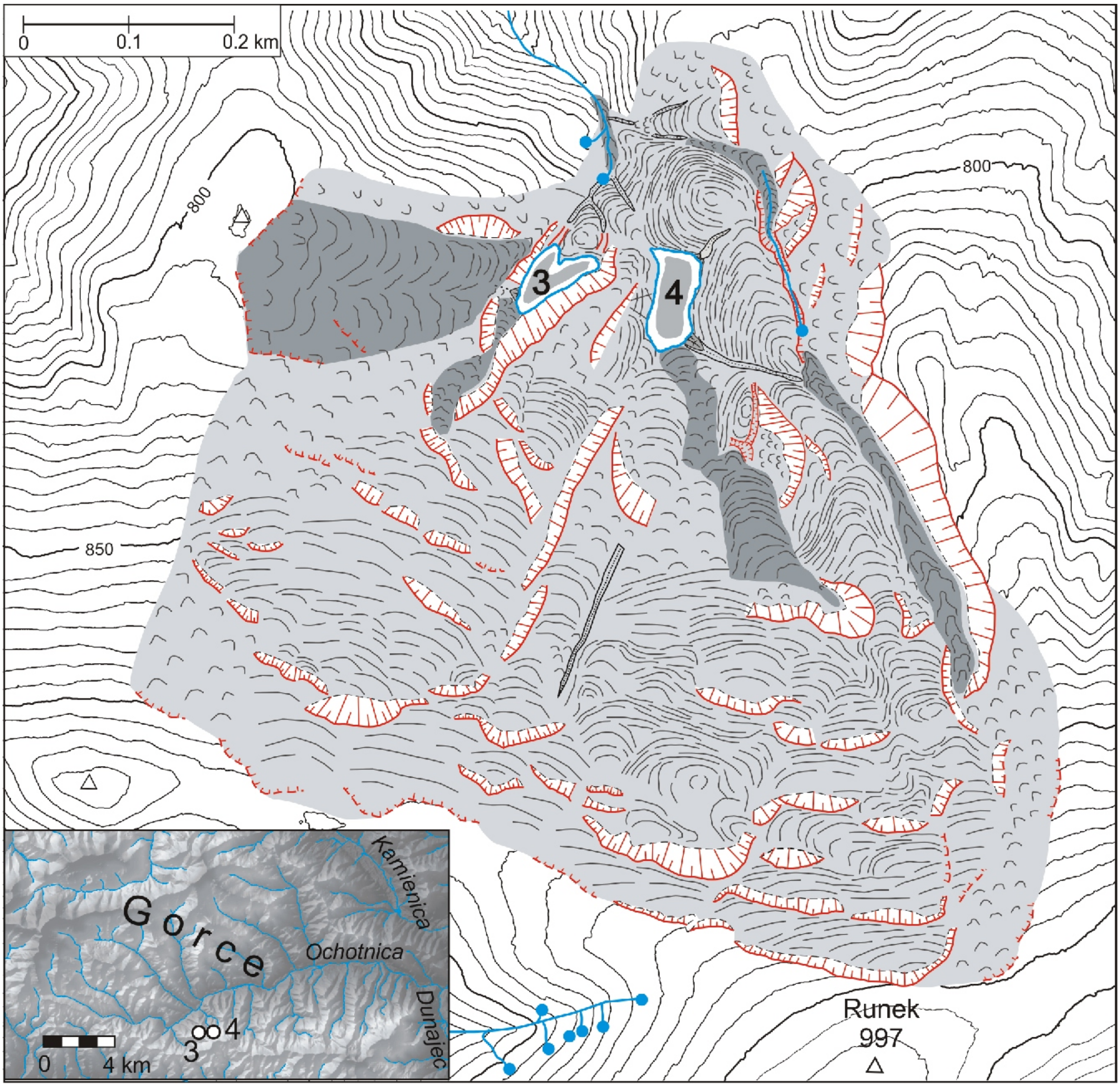

Fig. 6. Geomorphological map of the Zawadowskie landslide zone with the location of Iwankowskie Lake (3) and Zawadowskie Lake (4)

Explanations as on Figure 2

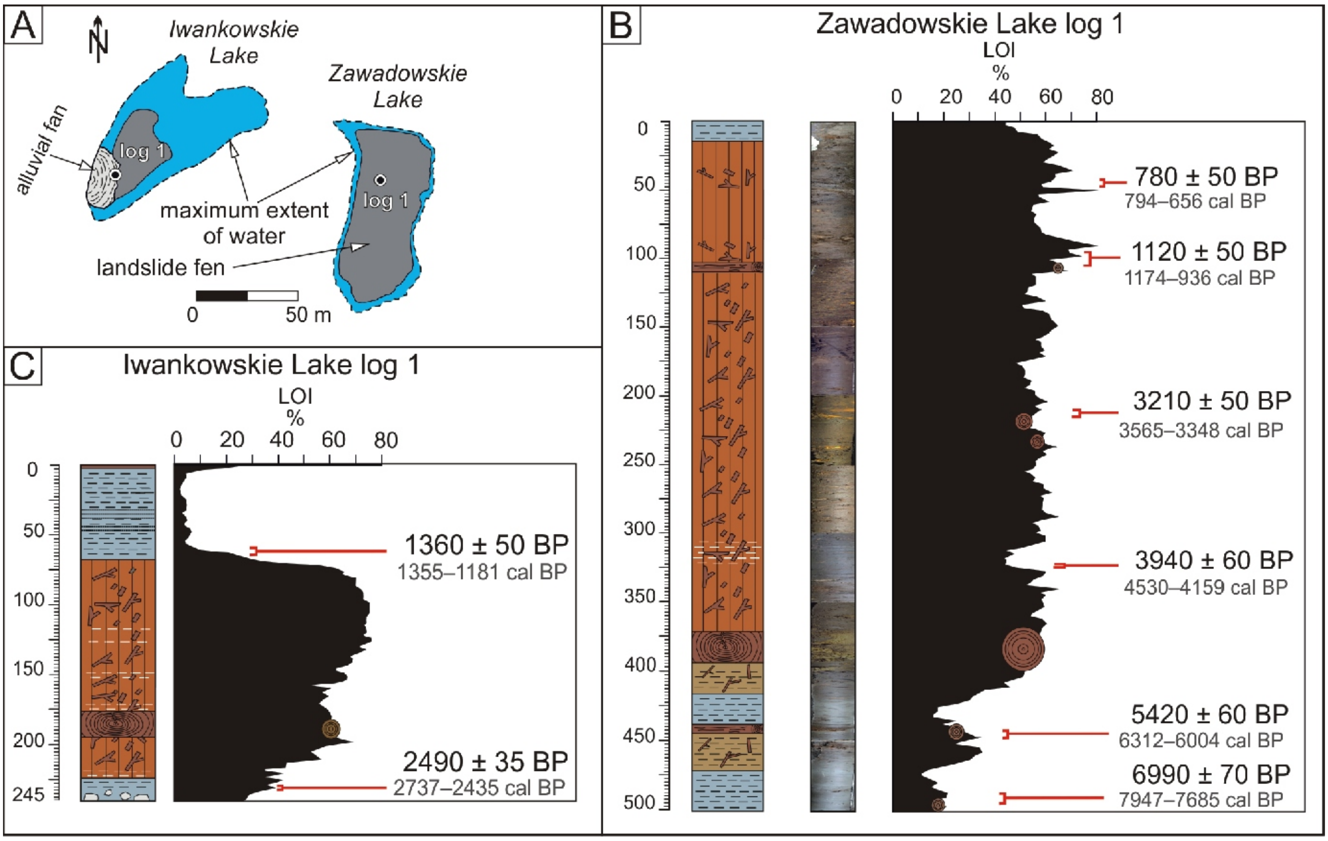

Fig. 7A – Iwankowskie Lake and Zawadowskie Lake with locations of boreholes; B – sequence of deposits in Zawadowskie Lake; C – sequence of deposits in Iwankowskie Lake (after Bucała et al., 2014, simplified)

Explanations as on Figure 3

tion of large, rock packets from the east towards the west, that formed an elongated rampart 0.55 km long. The height of the landslide rampart increases downslope reaching ~25 m in its lower part. This group of landslide blocks is separated from the main scarp by a trench, the valley of a small, seasonal creek. The movement of the largest landslide block caused the formation of vast depression of Zawadowskie Lake, currently filled with organic-minerogenic fen deposits (Fig. 7). The formation of this depression has been radiocarbon dated at 6990 ± 70 BP (7947–7685 cal. BP) During subsequent mass movements in the lowermost part of the landslide zone, rotation of the rock packets formed the depression of the Iwankowskie Lake, framed by a ~5 m high landslide rampart. The rejuvenation of the landslide zone has been dated at 2490 ± 35 BP (2727–2435 cal. BP).

The surfaces of both fens have been periodically inundated, forming some of the largest seasonal lakes in the Polish Flysch Carpathians (Margielewski, 1997; Buczek and Franczak, 2014). During rapid thaw or heavy rainfall, the lake basins are completely water-filled, overflowing the landslide ramparts and forming the Zawadowski Creek.

The deposits filling the Iwankowskie Lake basin have been studied by Bucała et al. (2014). The bottom of the depression being recognized in numerous boreholes. The longest log (2.4 m) was obtained from the southern part of the mire in the marginal zone of the alluvial fan. At the bottom of the fen within the interval 2.40–2.11 m, sandy silty clay occurs. A wood fragment sampled in this layer was dated at 2490 ± 35 BP (2737–2435 cal BP). This mineral layer is overlain by a 1.36 m thick unit of decomposed, woody peat characterized by high loss on ignition values ranging 75–80%. Within this unit, at 1.95–1.75 m, a beech trunk (*Fagus sylvatica*) was penetrated. The uppermost part of this peat unit was dated at 1360 ± 60 BP (1355–1181 cal BP). This peat is covered by 0.72 m of alluvial fan deposits, comprising poorly sorted ($_1$~3) sandy clayey silt with a few thin sand intercalations at 53–56; 32–37 and 11–16 cm (Bucała et al., 2014). Macroscopic charcoal fragments occurring at 0.6 m depth, dated at 183 ± 28 BP (298–... cal BP), indicate a hiatus between the peat unit and the overlying mineral cover deposits (Bucała et al., 2014).

The longest (5.0 m) core was drilled in the central part of the fen (Fig. 7A). In the bottom of the depression, in the interval 5.0–4.75 m, coarse silt (5.8) occurs (Fig. 7B), including a wood fragment dated at 6990 ± 70 BP (7947–7685 cal. BP). Above 4.75 m a distinct rise of loss on ignition (up to 34%) indicates a layer of organic silt (in the interval 4.75–4.45 m) that contains numerous wood fragments. The deposition of organic silts was interrupted at a depth of 4.45 m by minerogenic input dated at 5420 ± 60 BP (6312–6004 cal BP). Above this mineral layer the accumulation of detrital peat started. At 3.9–3.6 m a piece of spruce trunk (*Picea abies* L.) was drilled. Within the 3.6 m thick woody peat layer several illuvial horizons are marked in the loss on ignition curve by gradual decreases in values from ~60 to ~40% (Fig. 7B). More distinct illuvial layers occur at the following depths: 0.85, 1.35, 1.95 and 3.25 m. A spruce cone found in the last of these layers was dated at 3940 ± 60 BP (4530–4159 cal BP). Loss on ignition values gradually decrease in the uppermost part of the log (above 0.2 m) marking increasing minerogenic supply to the fen.

WYSZNIA LANDSLIDE ZONE (MT. TURBACZ MASSIF)

Pucołowski Stawek Lake and Srokówki fen are situated within an extensive landslide zone covering ~0.23 km^2 in the altitude span of 1027–802 m a.s.l.. These landforms developed in thick-bedded sandstones, conglomerates, shales and locally thin-bedded flysch of the Piwniczna Sandstone Member with marl intercalations (Burtan et al., 1976). The landslide represents complex translational-rotational gravitational displacements (according to Dikau et al., 1996) displaced consequently to the strata dip and formed in several stages due to headward erosion by the tributary of the Łopuszna Stream. In the older stage of landslide development a wedge-shaped, relatively gently dipping scarp was formed. Below this scarp a sequence of flat colluvial ramparts developed, which produced the stair-shaped profile of the slope. Currently, this scarp and colluvial ramparts are being dissected by small stream. During the main stage of landslide development the large (2900 m^2), elongated depression of the Srokówki fen formed. This was dated at 9500 ± 90 BP (11 143–10 653 cal BP). Nowadays, the fen is bounded to the north by a small seasonal stream (Fig. 9C). During periods of rapid snow melt or heavy rain the surface of the Srokówki fen is temporarily inundated. Due to rejuvenation of the eastern zone of the landslide area, colluvial material has partially slipped over older landslide deposits down the step of a 10 m high marginal scarp. Below this scarp, at 946 m a.s.l., a small (830 m^2), circular depression formed, where a permanent landslide lake (sag pond) called Pucołowski Stawek is situated (Buczek, 2016). Acceleration of plant overgrowth caused the disappearance of the lake in 2008 (Fig. 8D). In 2011, due to deepening (“renovation”) of the lake by its owners ~1.5 m of peat sediments were removed from it. A wood fragment preserved in the mineral deposits which seal the bottom of the lake was dated at 2050 ± 60 BP (2290–2277 and 2153–1879 cal BP).

Though all the organic sediments were removed from Pucołowski Stawek Lake, the mineral deposits, which seal the bottom of the lake, were preserved. In the central part of Pucołowski Stawek Lake, 6 cores were made in order to sample wood fragments adequate for radiocarbon dating. The depositional sequences, 0.3–0.5 m thick, are composed of minerogenic deposits (sandy sility clay) with fragments of sandstone and nearly no organic matter. Wood fragments were found in only one core at the depth of 0.43 m (Fig. 8D).

The maximum depth of the Srokówki fen (4.5 m) was measured in the central part of the mire (Fig. 8C, E). In the bottom of the depression, at 4.5–4.1 m mineral-organic deposits containing many needles of spruce and wood fragments occur. Within this interval, depths of 4.2 m and 4.14 m, spruce cones were found. A wood fragment occurring in the lowermost part of the core was dated at 9500 ± 70 BP (11 143–10 563 cal BP).

Peat appears above 4.1 (Fig. 8E). The lowermost part of this unit (4.1–3.8 m) is formed by decomposed peat with many needles and wood fragments. At 3.87 m thin (2 cm) illuvial horizons mark accelerated delivery of allochthonous material to the basin. Above this, in the interval of 3.89–3.60 m, pure moss fen peat is present, which includes a substantial increase of wood detritus above the next thin illuvial horizon (3.6–3.0 m). Above a cored tree trunk at 3.0–2.9 m, there is considerably decomposed detrital peat. Within this thick unit (from 2.9 m to the sequence top), intercalations of mineral material occur at 2.8, 2.6, 2.2, 1.4 and 1.1 m.

THE FORMATION OF LANDSLIDES IN THE GORCE MTS. IN RELATION TO CLIMATE CHANGES DURING THE HOLOCENE

The oldest (radiocarbon dated) landslide deposits in the Gorce Mts. (11 143–10 653 cal BP) indicate the formation of landslides due to climate cooling and increased humidity during the later part of the Preboreal Phase. This climatic fluctuation corresponds to the Schlatten Phase of glacier advance in the Alps (Bortenschlager, 1982) and to an increase in mass movement activity in the Swiss Alps (Lateltin et al., 1997). Sudden change to a more humid climate caused lake level to rise in many lakes in west-central Europe (Magny, 2004) as well as in the Netherlands (Bos et al., 2007). In the Polish Carpathians, the formation of a few landsides (Fig. 9), as well as the beginning of depositional gaps in landslide fen deposits, was recorded at the Preboreal–Boreal transition (Margielewski, 2006; Kołaczek et al., 2017).

The next phase of landslide formation recorded in the Gorce Mts. was dated at 7947–7685 cal BP in Zawadowskie Lake. Increased climate humidity and cooling at ~8 ka BP was recorded by the delivery of coarse deposits to lakes in the Tatra Mts. (Baumgart-Kotarba and Kotarba, 1993), a minor rise in Vistula river fluvial activity (Starkel et al., 2013) and the formation of several landslides in the Polish Outer Carpathians (Margielewski, 2006, 2018) as well as in the Czech Outer Carpathians (Panek et. al., 2013).

The next cooling event recorded in the landslide fen deposits of the Gorce Mts. led to mineral influx into the sedimentary sequence of Zawadowskie Lake (Fig. 7B). This period of increased delivery of allochthonous material to the fen basin occurred in between 6312–6004 cal yr BP, and coincides with Bond event 4 (Bond et al., 1997; Wanner et al., 2011). This phase corresponds to a significant increase in Vistula River fluvial activity (Starkel et al., 2013), higher lake levels in the Central European Lowlands (Magny, 2004), and the Rotmoos 1 glacier advance phase in the Alps (Bortenschlager, 1982).

The formation of the Lelonek landslide (4010 ± 70 BP) coincides with a distinct concentration of landslide dates in the Polish Outer Carpathians during ~4.0–4.9 ka cal BP (Fig. 9; Margielewski, 2018). The global climate perturbations that mark the beginning of the Neoglacial phase called the “4.2 ka climatic event” (*sensu* Bond et al., 1997) caused intensification of mass movement activity in mountain areas all around Europe: the Appenines (Bertolini, 2007), Scandinavia (Matthews et al., 2009) and the British Islands (Ibsen and Brunsden, 1997) as well as increased debris flow activity in the Tatra Mts. (Baumgart-Kotarba and Kotarba, 1993; Kłapyta et al., 2016). In the Alps, the “4.2 ka BP hydrological event” is considered as the main deep-seated landslide triggering factor (Zerathe et al., 2014). The increased delivery of allochthonous material to peat bogs as thin illuvial horizons, related to this period, has been observed in many landslide fens of the Polish Carpathians (Margielewski et al., 2010, 2011; Michczyński et al., 2013). In the Gorce Mts. it has been recorded as a thin illuvial horizon in the peat sequence of Zawadowskie Lake, dated at 4530–4159 cal BP.

In the Western Carpathians, the expansion of *Abies alba* and *Fagus sylvatica* taxa, which prefer high moisture availability, corresponds to the global “4.2 ka BP” event (Czerwiński et

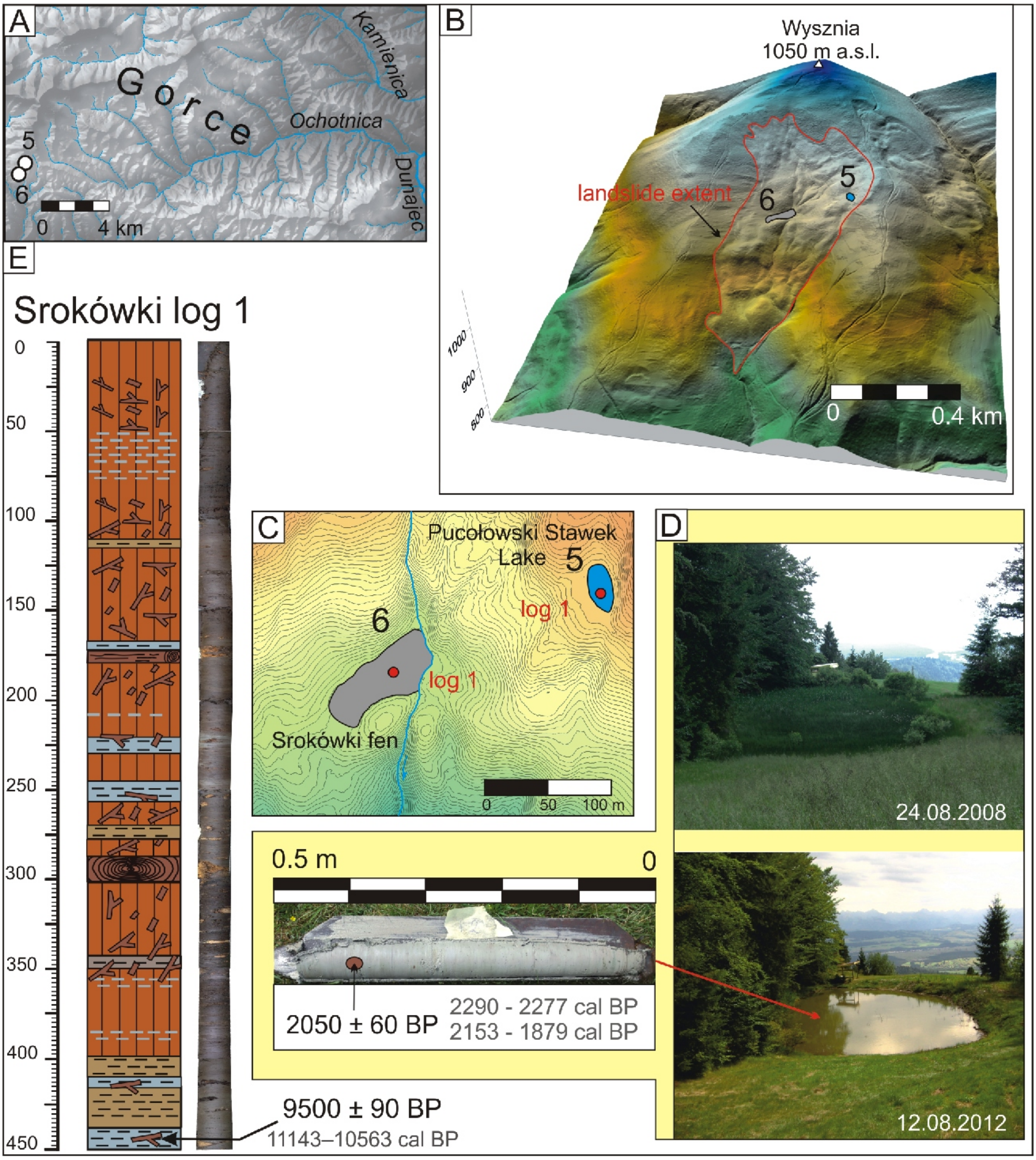

Fig. 8A – location of Pucołowski Stawek Lake (5) and Srokówki fen (6); B – 2.5 D view of southern slope of Mt. Wysznia with the extent of the landslide; C – location of objects studied; D – Pucołowski Stawek Lake overgrown by aquatic plants in 2008, after the deepening of the lake in 2012 and the sediment core from the lake bottom; E – lithostratigraphic sequence of the Srokówki fen (E)

Explanations as on Figure 3

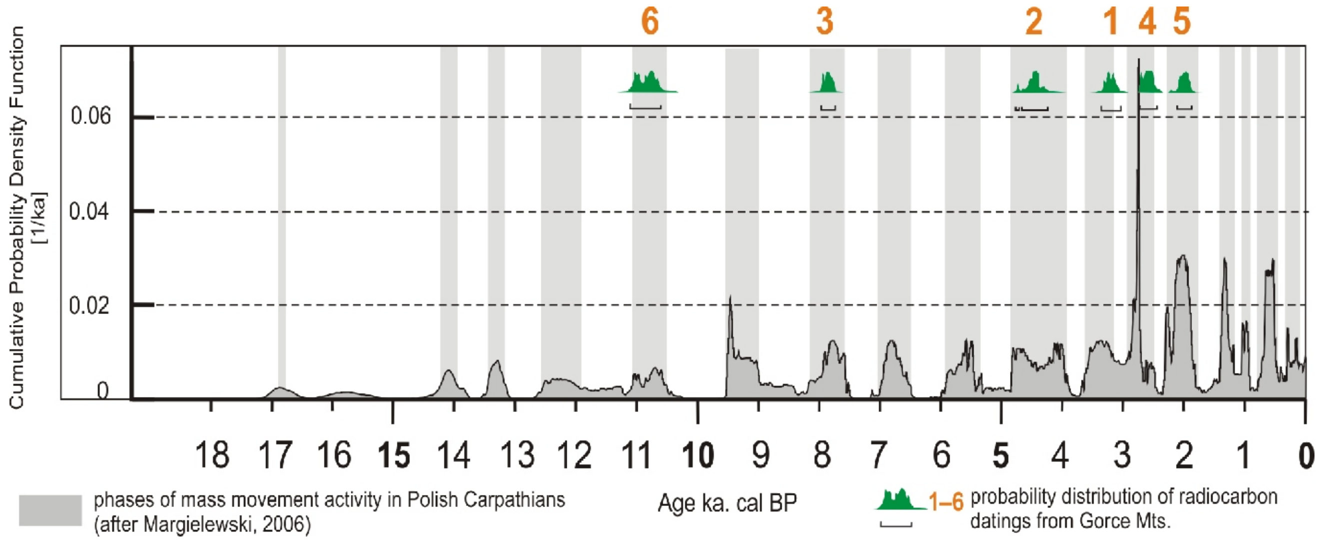

Fig. 9. Distribution of the radiocarbon dates from the Gorce Mts. with respect to the Cumulative Probability Density Function of the dated landslides in the Polish Carpathians (Margielewski, 2006, 2018; Starkel et al., 2013); phases of increased mass movement activity (after Margielewski, 2006) are marked as grey bands

al., 2019). Dying-off phases of pine trees (*Pinus sylvestris* L.) caused by raised water level closely associated with the increase in climate humidity, have been identified in the Puścizna Wielka peat bog in the intervals 4330–4200 and 4130–3990 cal BP (Krąpiec et al., 2016).

Mass movements that caused the formation of the Tokarnia fen are correlated with a less distinct concentration of landslide dates in the Polish Carpathians (Fig. 9). This landslide phase is part of a longer global cool event that occurred in between 3.3 ka and 2.5 ka BP (Wanner et al., 2011) which corresponds to Bond event 2 (Bond et al., 1997).

The formation of Iwankowskie Lake and Pucołowski Stawek Lake at ~2.7–2.4 ka and ~2.3–1.9 ka cal BP was related to the largest concentration of landslide dates in the Polish Carpathians (Fig. 9). This cooling period has been linked with glacier advances in the Alps, of the Geoschner 1 stage (Bortenschlager, 1982). Global cooling at the Subboreal–Subatlanic transition caused an increase in mass movement activity in mountain areas all around Europe: in the Apennines (Bertolini, 2007), the Italian Dolomites (Corsini et al., 2000), acceleration of debris flows in Scandinavia (Matthews et al., 2009), and the British Isles (Ibsen and Brunsden, 1997). Intercalations of high-energy sediments in the lakes of the Tatra Mts. were associated with heavy downpours occurring during this wet period (Baumgart-Kotarba and Kotarba, 1993). Markedly increased climatic humidity caused permanent changes in sedimentary conditions (the mineral cover formation) in many landslide fens in the Beskid Makowski Mts. and the Beskid Wyspowy Mts. (Margielewski, 2006, 2018), as well as the formation of numerous mineral and illuvial horizons in peat (Margielewski, 2006; Margielewski et al., 2010; Czerwiński et al., 2019). Interestingly, the global humid period at ~3300–2500 cal BP (Wanner et al., 2011) which caused the rejuvenation of the Zawadowskie landslide zone is not clearly reflected in the depositional sequence of the nearby Zawadowskie Lake (Fig. 7B). The formation of Pucołowski Stawek Lake coincided with intensification of fluvial activity of the Upper Vistula River at 2.1–1.7 ka BP (Starkel et al., 2006), as well as a period of high water level in the Alpine lakes at 1.8–1.7 cal BP (Magny, 2004) and in the Central Europe lakes (Ralska-Jasiewiczowa, 1989).

The formation of a mineral cover in Iwankowskie Lake (1350–181 cal BP) corresponds with the Dark Ages or the Migration Period Cooling known also as Bond event 1 (Bond et al., 1997). The climate cooling at ~1.4 cal BP caused a significant increase in mass movement activity in the Polish Carpathians (Fig. 9; Margielewski, 2018). Furthermore, a substantial acceleration of mineral delivery to the landslide fens has been recorded in neighbouring mountain ranges: the Beskid Wyspowy Mts. and Beskid Makowski Mts. (Margielewski and Kovalyukh, 2003; Margielewski, 2018).

CONCLUSIONS

Radiocarbon dates of deposits sealing the bottoms of six landslide depressions (lakes and fens) in the Gorce Mts., allow determination of the age of landslide formation and stages of their rejuvenation. These dates were performed in a previously poorly investigated mountain group, and hence substantially supplement the database of dated landslides in the Outer Western Carpathians.

All dated landslide events in the Gorce Mts. correspond to periods of intense mass movement recorded in the mountain areas in Europe. The dated landslide events as well as the formation of mineral horizons in the peat sequences corresponds with global cold and humid periods in the Holocene, termed "Bond events". The events recorded in the Gorce Mts. fall within the following periods: ~11.1 ka cal BP, 8.6–8.0 cal BP; 6.5–5.9 ka cal BP, 4.8–4.5 cal BP, 3.3–2.5 cal BP and 1.75–1.35 cal BP.

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REFERENCES

Alexandrowicz, S.W., 1993. Late Quaternary landslides at eastern periphery of National Park of the Pieniny Mountains, Carpathians, Poland. Studia Geologica Polonica, **102**: 209–225.

Alexandrowicz, S.W., 1996. Stages of increased mass movements in the Carpathians during the Holocene. Kwartalnik AGH, Geologia, **22**: 223–62.

Alexandrowicz, W.P., 2009. Malacofauna and phases of development of landslide in Tylka near Krościenko (Pieniny Mts). Geologia, **35**: 69–75.

Alexandrowicz, W.P., 2013. Molluscan assemblages in the deposits of landslide dammed lakes as indicators of late Holocene mass movements in the polish Carpathians. Geomorphology, **180–181**: 10–23.

Alexandrowicz, Z., Margielewski, W., 2010. Impact of mass movements on geo- and biodiversity in the Polish Outer (Flysch) Carpathians. Geomorphology, **123**: 290–304.

Baumgart-Kotarba, M., Kotarba, A., 1993. Późnoglacjalne i holoceńskie osady z Czarnego Stawu Gąsienicowego w Tatrach (in Polish). Dokumentacja Geograficzna IGiPZ PAN, **4–5**: 9–29.

Bertolini, G., 2007. Radiocarbon dating on landslides in the Northern Apennines (Italy). In: Landslides and Climate Change (eds. R. McInnes, J. Jakeways, H. Fairbank and E. Mathie): 73–80. Taylor & Francis Group, London.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., de Menocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial scale cycle in the North Atlantic Holocene and glacial climates. Science, **294**: 2130–2136.

Bortenschlager, S., 1982. Chronostratigraphic subdivision of the Holocene in the Alps. Striae, **16**: 75–79.

Bos, J.A.A., van Geel, B., van der Plicht, J., Bohncke, S.J.P., 2007. Preboreal climate oscillations in Europe: wiggle-match dating and synthesis of Dutch high-resolution multi-proxy records. Quaternary Science Reviews, **26**: 1927–1950.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon, **51**: 337–360.

Bucała, A., Margielewski, W., Starkel, L., Buczek, K., Zernitskaya, V., 2014. The reflection of human activity in the sediments of Iwankowskie Lake from Subatlantic Phase (Polish Outer Carpathians). Geochronometria, **41**: 377–391.

Buczek, K., 2016. Wpływ działalności człowieka na funkcjonowanie jeziora osuwiskowego, na przykładzie Pucołowskiego Stawku w Gorcach (in Polish). Geographical Studies, **142**: 41–56.

Buczek, K., Franczak, P., 2014. Wpływ warunków geograficznych na powstanie i zróżnicowanie jezior osuwiskowych na Babiej Górze oraz w Gorcach (in Polish). Wierchy, **78**: 169–182.

Buczek, K., Górnik, M., 2019. Aktywność neotektoniczna Pasma Lubania (Gorce) na podstawie analizy parametrów morfometrycznych (in Polish). Przegląd Geologiczny, **67**: 270–278.

Burtan, J., Paul, Z., Watycha, L., 1976. Szczegółowa mapa geologiczna Polski 1:50 000, arkusz Mszana Górna. Państwowy Instytut Geologiczny, Warszawa.

Chrustek, M., Golonka, J., Janeczko, A., Stachyrak, F., 2005. Geological characterization of the Krynica Subunit in the vicinity of Krościenko on the Dunajec River (Magura Nappe, the Outer Flysch Carpathians). Geologia, **31**: 127–144.

Corsini, A., Pasuto, A., Soldati, M., 2000. Landslides and climate change in the Alps since the late glacial: evidence of case studiesin the Dolomites (Italy). In: Landslides in Research, Theory and Practice (eds. E. Bromhead, N. Dixon and M. Ibsen): 229–234. Proceedings of the 8th International Symposium on Landslides held in Cardiff on 26–30 June 2000. Thomas Telford, London.

Czerwiński, S., Margielewski, W., Gałka, M., Kołaczek, P., 2019. Late Holocene transformations of lower montane forest in the Beskid Wyspowy Mountains (Western Carpathians, Central Europe): a case study from Mount Mogielica. Palynology, doi: 10.1080/01916122.2019.1617207

Dikau, R., Brunsden, D., Schrott, L., Ibsen, M.L., eds., 1996. Landslide Recognition. Identification, Movement and Causes. J. Wiley and Sons.

Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology, **25**: 101–110.

Ibsen, M.L., Brunsden, D., 1997. Mass movement and climatic variation on the south coast of Great Britain. Paleoclimate Research, **19**: 171–182.

Kłapyta, P., Zasadni, J., Pociask-Karteczka, J., Gajda, A., Franczak., P., 2016. Late Glacial and Holocene paleoenvironmental records in the Tatra Mountains, East-Central Europe, based on lake, peat bog and colluvial sedimentary data: a summary review. Quaternary International, **415**: 126–144.

Kołaczek, P., Margielewski, W., Gałka, M., Apolinarska, K., Płóciennik, M., Gąsiorowski, M., Buczek, K., Karpińska-Kołaczek, M., 2017. Five centuries of the Early Holocene forest development and its interactions with palaeoecosystem of small lake in the Beskid Makowski Mountains (Western Carpathians, Poland) – high resolution multiproxy study. Review of Palaeobotany and Palynology, **244**: 113–27.

Koperowa, W., 1962. Późnoglacjalna i holoceńska historia roślinności Kotliny Nowotarskiej (in Polish). Acta Paleobotanica, **2**: 3–62.

Krąpiec, M., Margielewski, W., Korzeń, K., Szychowska-Krąpiec, E., Nalepka, D., Łajczak, A., 2016. Late Holocene palaeoclimate variability: the significance of bog pine dendrochronology related to peat stratigraphy. The Puścizna Wielka raised bog case study (Orawa–Nowy Targ Basin, Polish Inner Carpathians). Quaternary Science Reviews, **148**: 192–208.

Kulka, A., Rączkowski, W., Żytko, K., Paul, Z., 1987. Szczegółowa mapa geologiczna Polski 1:50 000, arkusz Krościenko. Państwowy Instytutu Geologiczny, Warszawa.

Lateltin, O., Beer, C., Raetzo, H., Caron C., 1997. Landslides in flysch terranes of Switzerland: causal factors and climate change. Eclogae Geologicae Helvetiae, **90**: 401–406.

Lisowski, S., Kornaś J., 1966. Mchy Gorców (in Polish). Fragmenta Floristica et Geobotanika **12**: 41–111.

Magny, M., 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. Quaternary International, **113**: 65–79.

Margielewski, W., 1997.Ochrona jeziorek osuwiskowych w paśmie Lubania koło Ochotnicy Górnej (in Polish). Chrońmy Przyrodę Ojczystą, **53**: 74–84.

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., 1999. Formy osuwiskowe Gorczańskiego Parku Narodowego i ich rola w kształtowaniu geo- i bioróżnorodności Gorców (in Polish). Chrońmy Przyrodę Ojczystą, **55**: 23–53.

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**: 1–149.

Margielewski, W., 2018. Landslide fens as a sensitive indicator of paleoenvironmental changes since the Late Glacial: a case study of the Polish Western Carpathians. Radiocarbon, **60**: 1–15.

Margielewski, W., Kovalyukh, N., 2003. Neoholocene climatic changes recorded in landslides peat bog on mount Cwilin (Beskid Wyspowy range, outer Carpathians, south Poland). Studia Geomorphologica Carpatho-Balcanica, **37**: 59–76.

Margielewski, W., Michczyński, A., Obidowicz, A., 2010. Records of the Middle and Late Holocene palaeoenvironmental changes in the Pcim-Sucha landslide peat bogs (Beskid Makowski Mts., Polish Outer Carpathians). Geochronometria, **35**:11–23.

Margielewski, W., Kołaczek, P., Michczyński, A., Obidowicz, A., Pazdur, A., 2011. Record of the Meso- and Neoholocene palaeoenvironmental changes in the Jesionowa landslide peat bog (Beskid Sądecki Mts., Polish Outer Carpathians). Geochronometria, **38**: 138–54.

Matthews, J.A., Dahl, S.O., Dresser, Q., Berrisford, M.S., Lie, Ø., Nesje, A., Owen, G., 2009. Radiocarbon chronology of Holocene colluvial (debris-flow) events at Sletthamn, Jotunheimen, southern Norway: a window on the changing frequency of extreme climatic events and their landscape impact. The Holocene, **19**: 1107–1129.

Michczyński, A., Kołaczek, P., Margielewski, W., Michczyńska, D.J., Obidowicz, A., 2013. Radiocarbon age-depth modeling prevents from misinterpretation of vegetation dynamic in the past: case study Wierchomla Mire (Polish Outer Carpathians). Radiocarbon, **55**:1724–34.

Miczyński, J., 2015. Klimat rządzi przyrodą (in Polish). In: Gorczański Park Narodowy – Przyroda i krajobraz pod ochroną (eds. P. Czarnota and M. Stefanik): 35–38. Wydawnictwo GPN, Poręba Wielka, Poland.

Pánek, T., Smolková, V., Hradecký, J., Baroň, I., Šilhán, K., 2013. Holocene reactivations of catastrophic complex flow-like landslides in the Flysch Carpathians (Czech Republic/ /Slovakia). Quaternary Research, **80**: 33–46.

Paul, Z., 1978. Szczegółowa mapa geologiczna Polski 1:50 000, arkusz Łącko. Państwowy Instytut Geologiczny, Warszawa.

Płaczkowska, E., 2014. Geological aspects of headwater catchments development in the Lubań Range (the Outer Carpathians, Poland). Zeitschrift für Geomorphologie, **58**: 525–537.

Ralska-Jasiewiczowa, M., 1989. Environmental changes recorded in lakes and mires of Poland during the last 13000 years. Acta Palaeobotanica, **29**: 1–120.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatte, C., Heaton, T.J., Hoffmann, D.L., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Staff, R.A., Turney, C., van der Plicht, J., 2013. Intcal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon, **55**: 1869–1887.

Starkel, L., 1960. Rozwój rzeźby Karpat fliszowych w holocenie (in Polish). Prace Geograficzne Instytutu Geografii PAN, **22**.

Starkel, L., Michczyńska, D.J., Krąpiec, M., Margielewski, W., Nalepka, D., Pazdur, A., 2013. Holocene chrono-climatostratigraphy of Polish territory. Geochronometria, **40**: 1–21.

Wanner, H., Solomina, O., Grosjean, M., Ritz, SP., Jetel, M., 2011. Structure and origin of Holocene cold events. Quaternary Science Reviews, **30**: 3109–3123.

Zerathe, S., Lebourg, T., Braucher, R., and Bourlès, D., 2014. Mid-Holocene cluster of large-scale landslides revealed in the South-western Alps by ^{36}Cl dating. Insight on an Alpine-scale landslide activity. Quaternary Science Reviews, **90**: 106–127.

Ziętara, T., 1968. Rola gwałtownych ulew i powodzi w modelowaniu rzeźby Beskidów (in Polish). Prace Geograficzne, **60**.