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LANDFORM EVOLUTION IN MOUNTAIN AREAS

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GEOMORPHIC PROCESSES AND VEGETATION PATTERN CHANGES CASE STUDY IN THE ZELENÉ PLESO VALLEY, HIGH TATRA, SLOVAKIA

Abstract. The subject of this study is the age of landforms generated by extreme geomorphic events. Debris-flow activity on the alluvial cone in the High Tatra Mountains is documented and dated with the use of historical sources, terrophotogrammetric picture and lichenometry. Three episodes of debris-flow activity since ca. 1850 have been distinguished according to lichen cover generations.

Key words: extreme geomorphic processes, alluvial cone, High Tatra Mountains

STUDY AREA

The Zelené pleso glacial cirque is situated in the easternmost part of the High Tatra Mountains and belongs to the Tatra National Park (TANAP) (Fig. 1). It represents a classic alpine landscape comprising a system of hanging valleys and trough valleys that were formed by the Pleistocene valley glaciers. The discussed area was investigated by M. Lukniš (1973), and depicted on the geomorphological map of the Tatras in the scale of 1:50,000. The map shows the distribution of landforms and their age. It is a unique area on the scale of the entire Tatras. Rockwalls, with the highest one — the 700 m high north-facing rockwall of Malý Kežmarský Mt., rise above the mean water level of Zelené pleso lake, located at 1,545 m a.s.l. Talus slopes, partly remodelled by debris flows, are formed at the base of this rockwall. Hanging glacial cirques rise above the lake basin from the west and northwest. The largest of these, the Medená kotlina, extending from below Lomnický Mt. (2,633.9 m a.s.l), is nowadays filled with a glacierette (Firnovisko v Medenej kotlinie), featuring some glacier ice properties (Jania 1993). This valley has a hydrological connection with the Zelené pleso basin through a rocky gorge (Medený vodopad). Proglacial waters outflowing from the glacierette, as well as rainwater, have given

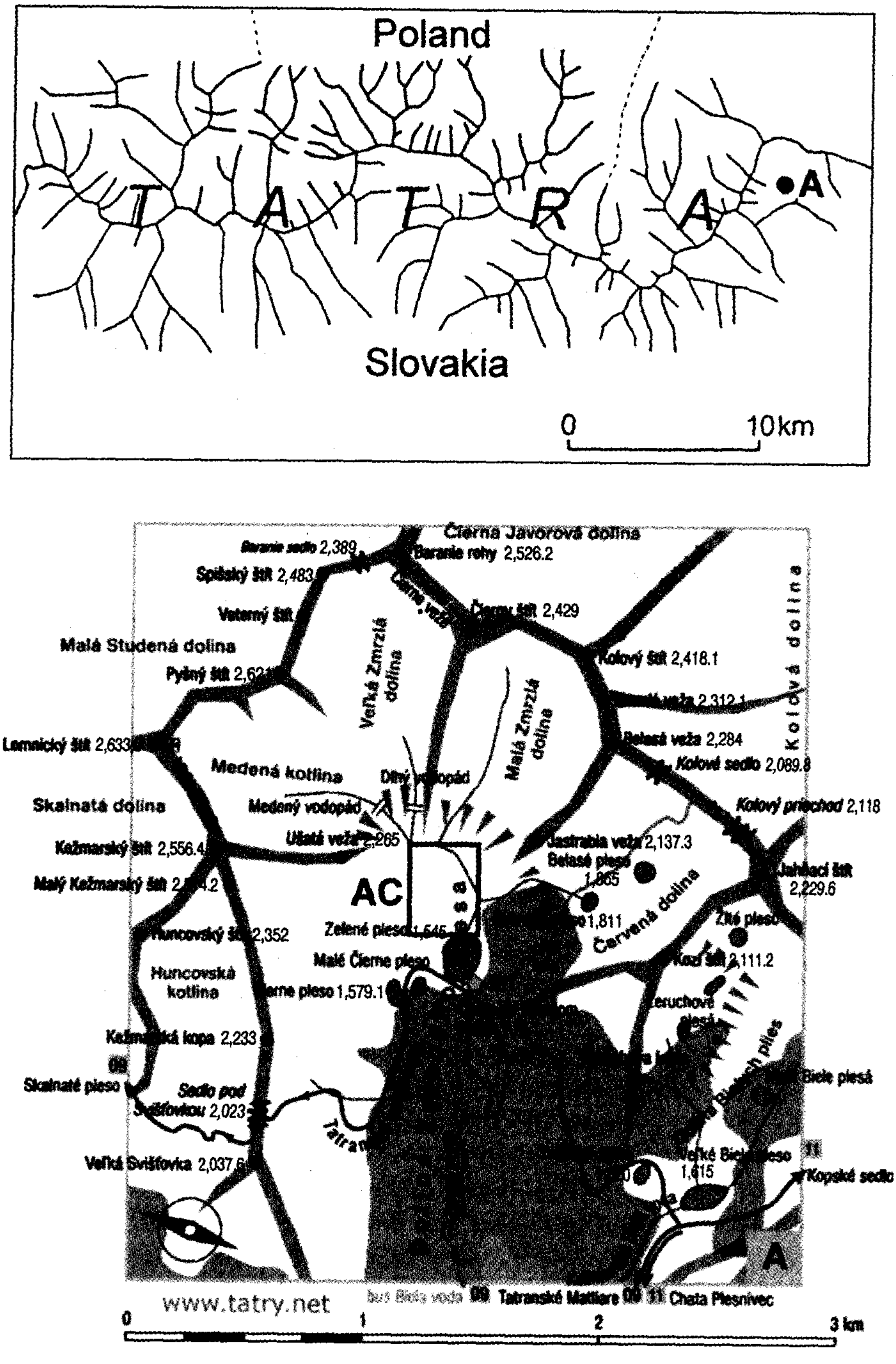

Fig. 1. Sketch map of the Tatra Mountains showing the location of the Zelené pleso valley. AC — location of alluvial cone

Fig. 2. Geomorphology and topography of the study site. Slope and valley landforms dated by lichenometry. I–IV geomorphological transects. 1 — fresh, lichen-free debris deposit, 2 — debris stabilised by dwarf pine, 3 — debris stabilised by alpine meadow, 4 — talus sheet, 5 — individual boulder, 6 — limit of valley bottom, 7 — lower limit of talus slope, 8 — rockfall talus slope, 9 — alluvial talus slope, 10 — debris-mantled slope, 11 — active gully formed in 2002, 12 — limit of debris-flow deposits formed in 2002, 13 — fine grain delta deposits in the Zelené pleso lake, 14 — lichenometric age of surficial deposits, 15 — moraine

rise to a vast alluvial cone. This cone was formed during the Late Glacial and Holocene by fluvial processes and debris flows (Fig. 2).

METHODS AND INTERPRETATION

A map in the scale of 1 : 2,000 has been elaborated for the slopes surrounding Zelené pleso lake. The fundamental material, in the form of terro-photogrammetric pictures, used for devising the map, was collected in 2001. The map sheet was set in the scale of 1 : 2,000, with a kilometre grid, and Universal Transverse Mercator — WGS 84 cartographic projection. This map was the reference for the detailed geomorphological mapping of the surroundings of Zelené pleso lake, as well as for devising geomorphological transects on the alluvial cone. The extent of the distinguished morphological forms and their shapes have been depicted on the transects, and detailed lichenometric measurements have been performed there. The aggregated lichen species *Rhizocarpon*, one of the more commonly used groups in lichenometry, was employed. The measured thali diameters *Rhizocarpon* agg. were converted to their age in AD — *Anno Domini*. The dating of the alluvial cone surface was based on the lichen growth curve constructed for the northern slope of the Tatras by A. Kotarba (1988). Figure 2 presents the fragment of the original map which shows only the closest vicinity of Zelené pleso lake. As a rule, the topographical elements on the map did not need to be covered with the elements of the valley floor relief. Therefore, the "openwork" hachure was used. Such cartographic solutions allow for simultaneously reading from the map information regarding topographic and geomorphological features, as well as the percentage of dwarf pine, alpine meadow and bare debris cover.

The purpose of this paper is to reconstruct the phases of alluvial cone formation based on the analysis of forms and sediments, as well as on lichenometry dating.

Four geomorphologic transects on the alluvial cone comprise the following parts: proximal (I and II), middle (III) and distal (IV). For each transect, the lichenometric age expressed in AD has been calculated. This approach was used to investigate, map and date individual levees, tongues and troughs of debris flows, which became the basis for reconstructing hydrometeorological events during the last 200 years (Fig. 3). Elements of cone relief prior to AD 1800 have not been found, although small fragments of the older relief are found on the talus slope in the nearest vicinity of the cone. Older deposits building the cone are buried under sediments deposited in the 19th and 20th centuries. Phases of intensified alluvial processes and debris flow activity are distinctively marked on the transects. Geomorphological processes continue to remodel this surface today. A small fragment of the cone side, dated 1788-1850, has been preserved on transect I, however, these dates are not certain due to the presence of dwarf pine patches there.

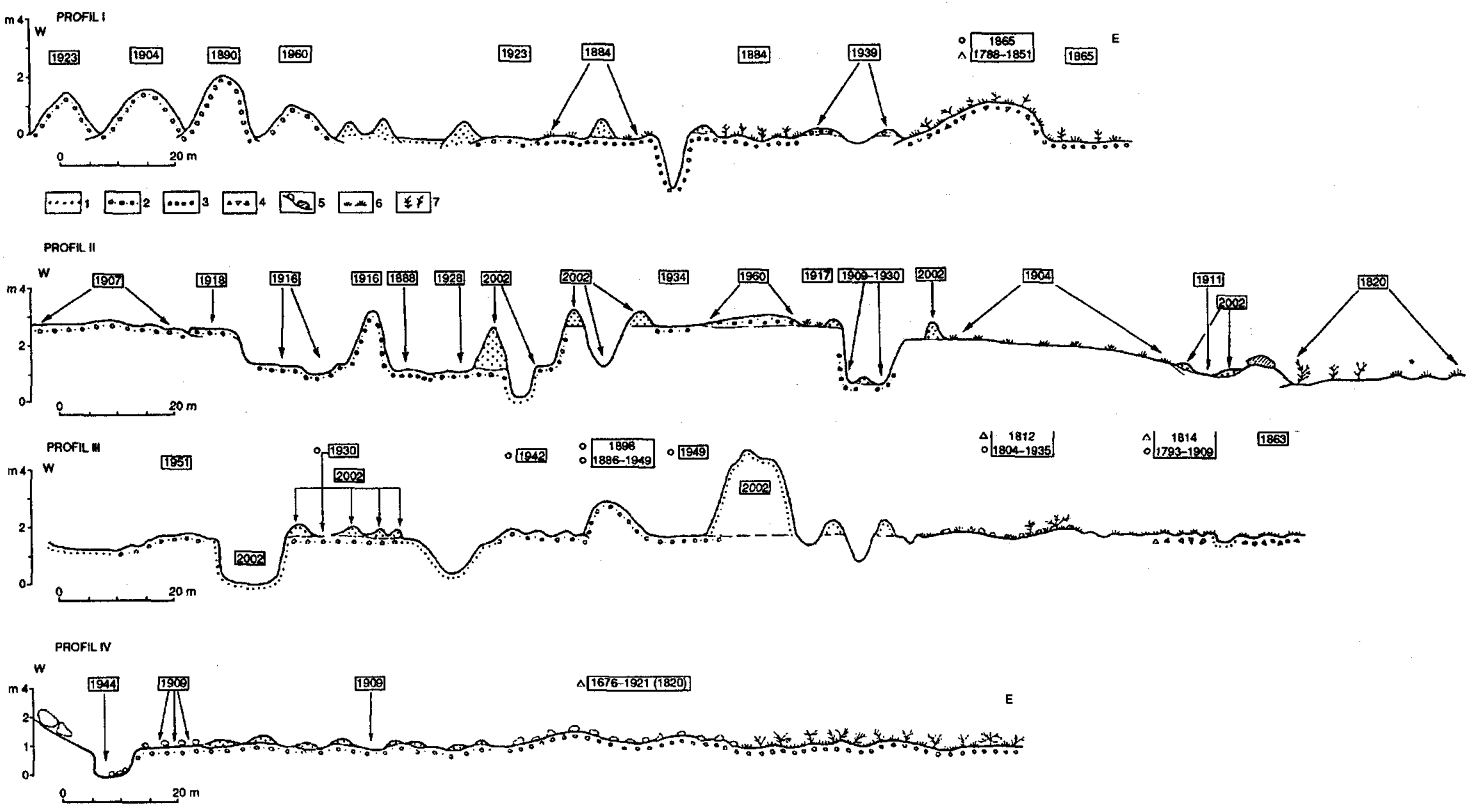

Fig. 3. Geomorphological transects on alluvial cone. 1 — recent debris flow deposit, lichen-free, 2 — relict debris flow deposit (XX century), 3 — oldest dated debris flow deposit (19th century), 4 — boulder cover from rockfall and avalanching, 5 — individual boulder, 6 — alpine meadow, 7 — dwarf pine

HUMAN IMPACT ON THE NATURAL ENVIRONMENT OF THE CONE AND EFFECTIVENESS OF GEOMORPHIC PROCESSES

Although Man entered the Tatras relatively late, he did not find conditions allowing him to settle there permanently, yet his impact on the environment was significant especially during the Little Ice Age. The degrading influence on the biotic and abiotic environment had various forms. The most substantial effects were related to mining, metallurgy, and sheep husbandry. In the first half of the 12th century treasure hunters visited the Tatras. Since the 15th century, precious ores were sought, and the main period of mining work took place at the turn of the 17th and 18th centuries (Paryscy 1995; Szaflarski 1972). Mining ceased in the middle of the 19th century and, at the same time, the last metallurgy works were closed. The main period of mining exploitation coincided with the climate deterioration — Little Ice Age. Due to climate degradation, cereal yields were low, plants were afflicted with diseases, which led to food crises. The boundaries of vegetation belts and vertical zones respond to even a slight deviation from normal climatic indices. Inhabitants of the Sub-Tatras sought a recovery either in forest down cutting in the lower zones of the Tatras with the aim of enlarging their farmland, or in trying to find precious ores in the mountain interior. People imposed impact on the Tatra environment especially in easily accessible valleys and those where the ores had been found. In the 17th and 18th centuries sheep husbandry entered the Tatras and, with variable intensity, lasted until the end of World War II.

Zelené pleso valley and the neighbouring valleys were subjected to particular anthropopression. Copper ores were exploited in a primitive way in the Medená kotlina valley, and even on the slopes of Malý Kežmarský Mt. and Lomnicky Mt. Some ores were exploited in the 18th century or earlier. Mining work ended in the middle of the 19th century.

In the Dolina Bielych plies valley a refinery and distillery of dwarf pine oil, known under the name of *balsamum hungaricum* or *balsamum poluchrestum*, was opened. In 1897 production almost reached an industrial scale. Although the concession for producing volatile oils had ceased quite quickly, limited production continued still in 1904 (Gaspar 2002), and did not cease completely before 1914. Broad areas became devoid of dwarf pine. This also referred to the alluvial cone above Zelené pleso lake.

The watercolours created by Austrian painter Thomas Ender in the Zelené pleso area around 1850 (316 × 495 mm, MTAK, Ms 4409/152), and deposited with the Department of Manuscripts and Rare Books of the Library of the Hungarian Academy of Sciences (http://ender.mtak.hu) show a totally destroyed dwarf pine cover on the cone (Photo 1). Poor alpine meadow partially stabilised the cone surface at the side of Malý Kežmarský Mt. Permanent streams are visible on the picture both on the left and right sides of the cone, and the entire surface was affected by debris flow activity. On the earliest photos of the cone taken by W. Eliasz (23.08.1891) one can see the first small patches of dwarf pine in the centre of the cone.

A photo taken 110 years later by L. Kolondra (Photo 2) points to a subsequent, though slow re-succession of dwarf pine. This is not a one-way course of action, as the geomorphic processes — mainly debris flows — act against the complete stabilisation of the alluvial cone above Zelené pleso lake. The stabilising function of the dwarf pine is very important, as it provides protection for the slopes and valley floors against slope wash and slow debris creep, and mitigates the eroding effect of snow avalanches on the ground. Thus, W. Eliasz (1874) called the dwarf pine a "life protector". Extreme geomorphic processes are able to damage vegetation cover, as demonstrated in Photos 3 and 4, but threshold values needed to mobilise debris material by torrential, high energy rainstorms, must be much higher. The analysis of the old tracks of debris flows formed in the second half of the 19th century, that is during the climax phase of the Little Ice Age, showed that those tracks were much larger than contemporary ones. Moreover, the coarser size of boulders in the old debris flow tracks suggests that the competence of surface waters on bare debris covers was much higher than in recent hill slope debris flows (Midriak 1985; Kotarba 1992).

PLANT COVER AND GEOMORPHIC PROCESSES ON THE ALLUVIAL CONE BETWEEN CA. 1850 AND 2002

In 1850 the cone was completely bare of dwarf pine and was actively remodelled by proglacial and storm rainwater, both at the right and left sides of the cone. The entire surface of the cone was transformed by the tracks of the debris flows commonly present on the watercolour. Only small fragments at the base of the alluvial cone at Zelené pleso lake were stabilised by alpine meadow. When compared to the period before 1850, the alluvial cone had been significantly stabilised by the vegetation of the dwarf pine belt. In the middle of the 19th century both sides of the cone (right and left), were drained by the active surface water network, which were also the routes of water outflowing from the melting glacierette in Medena kotlina (Photo 1). At present, the right side of the cone at Malý Kežmarský Mt. is permanently covered with dwarf pine and water does not flow out during the spring melting nor during summer downpours. On the other hand, the left side of the cone, at the slopes of Jastrabia veža, continues to be active and is not stabilised with vegetation (Photo 2, Fig. 2 and 3). Taking into consideration that 150 years ago this area was totally free of dwarf pine, one can observes that nowadays is gradually being restored on the right side half of the cone 38.3% of this area is re-colonised by dwarf pine. In contrary to that, left side half of the cone is only fragmentary covered by dwarf pine (3.3%), and still modelled by running water and debris flow activity. Geomorphological transects II and II (Fig. 3) show that the activity of water flowing on the right side lasted until the beginning of the 20th century (lichenometry dates: 1904–1909–1911). Then, water erosion did not occur in this part of the cone, and a subsequent succession of dwarf pine began.

Photo 1. Alluvial cone above Zelené pleso lake. The watercolour created by Austrian painter Thomas Ender ca. 1850 (source: Department of Manuscripts and Rare Books of the Library of the Hungarian Academy of Sciences (http://ender.mtak.hu). Surface of the cone devoid of dwarf pine by human impact

Photo 2. Alluvial cone above Zelené pleso lake. Re-succession of dwarf pine and alpine meadow (Photo L. Kolondra, 22 August 2001)

Photo 3. Alluvial cone above Zelené pleso lake (Photo L. Kolondra 22 August 2001)

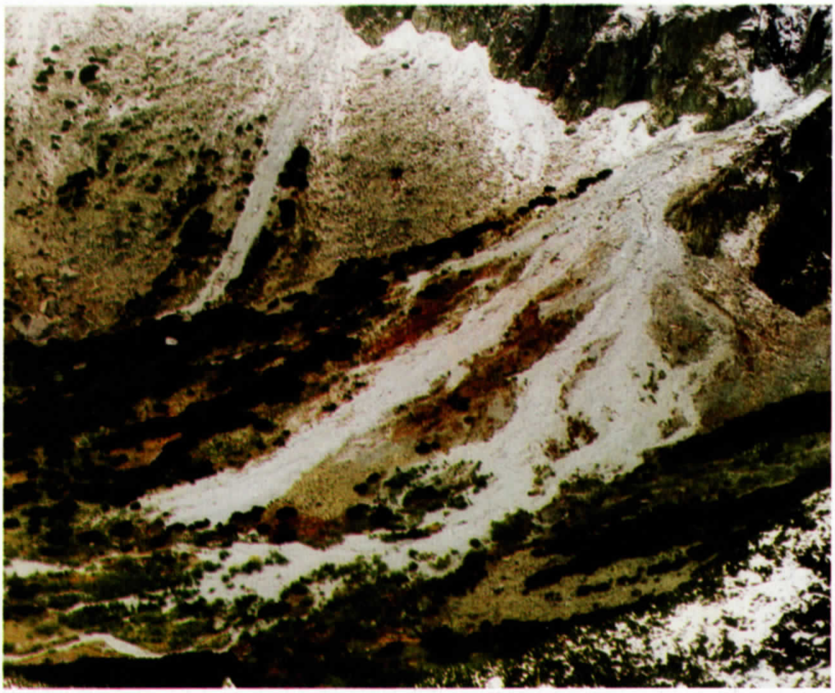

Photo 4. Alluvial cone above Zelené pleso lake after a summer storm in 2002 (Photo S. Kędzia, 20 September 2002). New generation of debris flow triggered on 15 July 2002 as an effect of daily rainfall totalling 54 mm)

On the other hand, on the left side of the cone, which is still functioning today, there are erosional gullies, levees and debris flow tongues generated in the apex zone that are not stabilised by vegetation. They are still remodelled during extreme hydrometeorological events. The central part of the alluvial cone is also evolving. On transects I–IV, three phases of intense water erosion processes are noticeably marked: 1801–1825, 1901–1925, 1976–2002 (Fig. 4). The cone surface modelled during the first phase is to be related to the flood of 1813 described i.a. by G. Wahlenberg (*vide* Szaflarski 1972). The best preserved surfaces, corresponding to this catastrophe in time, are in the central part of the cone. The flood of 1813 was associated with a global climate event. That was the largest catastrophic flood on a historical scale and affected broad areas of Europe and the Carpathians.

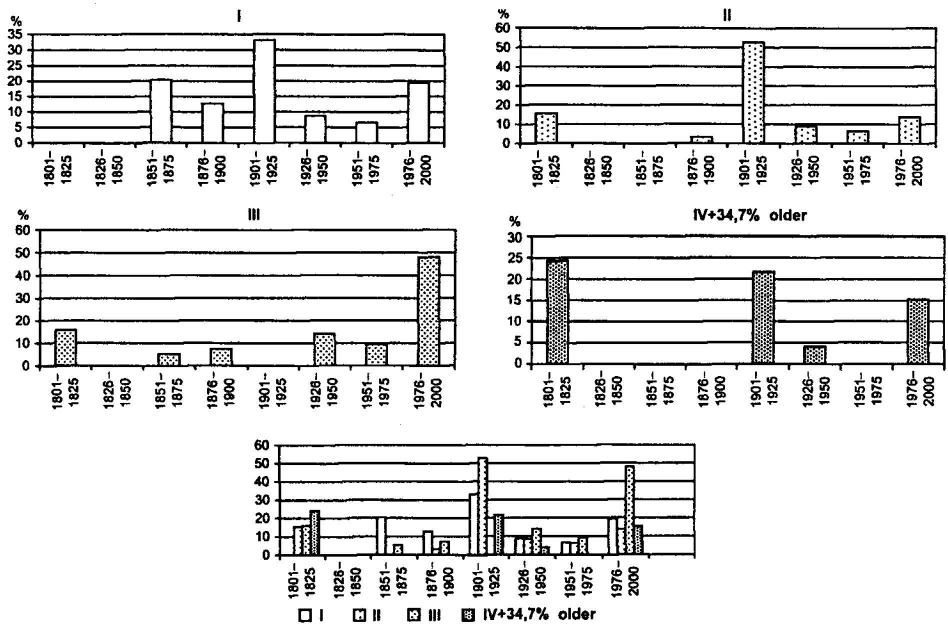

Fig. 4. Age of debris flow deposits on alluvial cone. Three episodes of more intense debris flow activity are documented on geomorphological transects

The second phase, which took place in the first 25 years of the 1900s, clearly marked on the analysed cone (Fig. 4), is well documented in other Tatra valleys, especially in the Morskie Oko valley. This picturesque valley was frequently visited and photographed. In 1900–1912, both in the mountain interior and at their foreland, catastrophic floods and precipitation occurred in 1900, 1902, 1903, 1910, 1912 (Kotarba 2004).

Contemporarily, the cone relief is still transforming under the influence of short-lasting and intense convectional precipitation. Luckily photos were taken in 2001 and 2002 (Photos 1 and 2), and it was then possible to compile the results of the processes which occurred on 15 July 2002 onto a detailed geomorphological map (Fig. 2) and the transects (Fig. 3). The precipitation gauging post at the summit of Lomnicky štit, located ca. 1.5 km from the studied cone, recorded 36 mm of rainfall during six night hours (a daily total of 54 mm). The intensity as well as the duration of this event significantly exceeded the threshold values of slope instability as established by N. Caine (1980). This rainfall gave rise to a new system of two-metre-deep erosional gullies, and up to three-metre-high levees and tongues (Photo 4, Fig. 3). The rainfall total-duration relationship, reported as debris-flow triggering activity (Innes 1983), shows that even 20 mm of rainfall over six hours is enough to mobilise debris transport on scree slopes. Short-lasting, high intensity rainfall events (40 mm/hour) have been occurring relatively more frequently over the last 25 years in the High Tatra Mountains (Kotarba 2004).

CONCLUSIONS

Deposits in the form of levees and/or lobes located on the alluvial cone have been providing a record of debris flow activity since ca. 1850. This study has shown that the general trend of vegetation re-succession on debris flow deposits is closely related to high energy geomorphic events.

Three episodes of debris flow deposits have been distinguished according to lichen cover generations. They have clearly originated during high intensity rainfalls rather than in connection with recurring snowmelt.

There are no grounds to state a cyclicity of debris flows expressed in three episodes as presented in Figure 4. The first episode registered in the middle and lower part of the alluvial cone shows that the extreme geomorphic processes triggered in August 1813 affected a significant part of the cone, and subsequent processes were not able to remodel the cone relief and mask the traces of the event. This singular, spectacular event caused the 25-year-long period (1801–1825) to be outstanding during the last 150 years. The second episode (1901–1925) is evidenced by lichenometry documented deposits formed by rapid mass movements in numerous Tatra valleys. According to T. Niedźwiedź (2004) climate cooling occurred in 1906-1926, and the summer of 1913, with a mean temperature of 7.6°C, must be assumed as the coldest summer in the Tatras since the middle of the 16th century. The reason for this cool summer is believed to be the eruption of the Katmai volcano in Alaska in 1912. Summer season precipitation in the Tatras shows irregular fluctuations. In the second half of the 20th century wet phases were registered in 1958–1980. Since 1995 summer season precipitation has shown a characteristic increase. This explains the third period of intense activity of debris flows in the last 25 years of the 1900s.

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REFERENCES

Caine N., 1980. *The rainfall intensity — duration control of shallow landslides and debris flows.* Geografiska Annaler 62A, 1–2, 23–27.

Eliasz W., 1874. *Szkice z podróży w Tatry.* Poznań–Kraków.

Gaspar J., 2002. *Tatry, staré pohl'adnice rozpravája, świadectwo dawnych widokówek.* Poprad.

Innes J. L., 1983. *Lichenometric dating of debris-flow deposits in the Scottish Highlands.* Earth Surface Processes and Landforms 8, 579–588.

Kotarba A., 1988. *Lichenometria i jej zastosowanie w badaniach geomorfologicznych w Tatrach.* Wszechświat 89, 13–15.

Kotarba A., 1992. *Denudacja mechaniczna Tatr Wysokich pod wpływem opadów ulewnych.* Prace Geograficzne IG i PZ PAN 155, 191–208.

Kotarba A., 2004. *Zdarzenia geomorfologiczne w Tatrach Wysokich podczas małej epoki lodowej.* Prace Geograficzne IG i PZ PAN 179, 9–55.

Midriak R., 1985. *Debris flows and their occurrence in the Czechoslovak high-mountain West Carpathians,* [in:] *Proceedings International Symposium on Erosion, Debris Flow and Disaster Prevention*, September 3–5, 1985, Tsukuba, Japan, 175–180.

Niedźwiedź T., 2004. *Rekonstrukcja warunków termicznych lata w Tatrach od 1550 roku.* Prace Geograficzne IG i PZ PAN 179, 57–88.

Paryscy Z. and W., 1995. *Wielka encyklopedia tatrzańska.* Wydawnictwo Górskie, Poronin.

Szaflarski J., 1972. *Poznanie Tatr, szkice z rozwoju wiedzy o Tatrach do połowy XIX wieku.* Wydawnictwo Sport i Turystyka, Warszawa.

STRESZCZENIE

A. Kotarba

PROCESY GEOMORFOLOGICZNE I ZMIANY POKRYWY ROŚLINNEJ W DOLINIE ZIELONEGO STAWU KIEŻMARSKIEGO W SŁOWACKICH TATRACH WYSOKICH

Badaniami objęto rozległy stożek napływowy położony pod progiem skalnym zawieszonych dolin Zmarzłej i Miedzianej Kotliny. Jest to najbliższe otoczenie Zielonego Stawu Kieżmarskiego uformowane przez procesy glacifluwialne, fluwialne i spływy gruzowe. Celem pracy jest odtworzenie głównych faz formowania stożka w oparciu o analizę form i osadów oraz ich datowanie przy pomocy

dokumentów historycznych i lichenometrii. W roku 1850 stożek był całkowicie pozbawiony kosodrzewiny i był aktywnie modelowany przez wody opadów burzowych i „proglacjalnych" pochodzacych z topienia lodowczyka w Miedzianej Kotlinie. Obraz otoczenia Zielonego Stawu został udokumentowany na akwareli wykonanej przez austriackiego malarza Thomasa Endera w połowie XIX wieku. Stan obecny pokazano na mapie, transektach geomorfologicznych i na fotografii. Stwierdzono, że w okresie ostatnich 150 lat nastąpiła ponowna sukcesja kosodrzewiny i muraw alpejskich. Ponownie utrwalenie przez kosodrzewinę wystąpiło na obszarze 27918 m^2, co stanowi 17.9% całkowitej powierzchni stożka. Jest więc to proces powolny Na transektach geomorfologicznych pokazano, że wystąpiły trzy wyraźne fazy wzmożonych procesów erozji wodnej w latach 1801–1825, 1901–1925 i 1976–2002. Najlepiej zachowane powierzchnie odpowiadają czasowo katastrofalnej powodzi w roku 1813 związanej z globalnym zdarzeniem klimatycznym zarejestrowanym w wielu obszarach Europy i Karpat. W czasach współczesnych nadal zachodzi ewolucja rzeźby stożka pod wpływem krótkotrwałych i intensywnych opadów konwekcyjnych.