S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
Vol. XLIV, 2010: 35–47 PL ISSSN 0081-6434
L A N D F O R M E V O L U T I O N I N M O U N T A I N A R E A S

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ALPINE CLIFF EVOLUTION AND DEBRIS FLOW ACTIVITY IN THE HIGH TATRA MOUNTAINS

Abstract. Glacial valleys in the High Tatra running more or less east-west had evolved in the postglacial era under different climate conditions. Thus, north- and south-facing rockwall/rocky slopes consist two clearly different shapes. The local climate and the geomorphic activity of rapid mass movements; the combined action of debris flows and snow avalanches was an important mechanism for routing paraglacial/periglacial sediments from ridge crests to valley floors. Northern-facing slopes experienced less regelation and fewer changes in relief due to the more severe local climate. Southern-facing slopes evolved faster, thus their profiles are characterized by smoother and smaller gradients.

Key words: valley-confined debris flow, rockwall fragmentation, Holocene, High Tatra Mountains

INTRODUCTION

Debris flows are fast-moving mass movements typical of high mountain areas in all climate zones. Geomorphologists have been interested in such processes since the second half of the 19th century. The first descriptions of the effects of debris flows came from the Alps (B o n n e y 1902, I n n e s 1983) as well as the Himalayas and the Karakorum (C o n w a y 1893, fide I n n e s 1983), although travelers exploring other mountain ranges had mentioned them much earlier. One Polish traveler was S. S t a s z i c (1815) who mentions debris flows in his observations about the Tatra Mountains. The research literature in this field has substantially evolved since. This is especially true of debris flow descriptions from the Alps, the Rockies, the Caucasus, and the Himalayas-Karakorum.

Contemporary interest in debris flows stems, in part, from the fact that they cause catastrophic damage in inhabited areas. This includes both damage to the infrastructure as well as the threat to the lives of local residents and tourists (A u l i t z k y 1970; T r o p e a n o, T u r o n i 2005). Corps of engineers work with residents in mountain areas to help them build homes and other types of infrastructure designed to mitigate the threat of debris flows. The vast majority of papers published by geomorphologists on the subject of debris flows concern movement mechanisms of loose weathered material, physical parameters, and theoretical models that need to be tested based on field observations and measurements. A number of field techniques for measuring debris flow dynamics in a variety of mountain environments have evolved in recent decades (Pierson 1985).

Debris flow research took a new turn when D. Brunsden (1979) developed a classification system where he used the scale and nature of source areas as criteria designed to differentiate debris flows. Brunsden identified three types of debris flows: catastrophic flows, hillslope flows, and valley-confined flows. Lahars or debris flows taking place on the slopes of volcanic mountains were later added to the classification system (Innes 1983). The introduction of the concept of valley-confined debris flows made it possible to look at these processes in broader terms that include passive characteristics of the natural environment such as lithological properties of parent rocks as well as slope relief. The purpose of the paper is to describe the role of valley-confined debris flows in the Holocene evolution of high mountain slopes in the High Tatra Mountains.

POSTGLACIAL EVOLUTION OF SLOPES IN THE HIGH TATRAS AND THE GEOMORPHOLOGICAL REQUIREMENT FOR DEBRIS FLOW

The postglacial development of slopes in glacial valleys in the crystalline part of the High Tatras took place gradually as valley-type and cirque-type glaciers melted over time. Contemporary observations in glaciated mountain areas indicate that slope processes are very intensive under paraglacial conditions but then their intensity diminishes. Slope processes continue to occur today under periglacial conditions. The latest stage of slope development in the High Tatras has been observed in glacier cirques in the form of recession moraines and has been classified as Alpine Venediger stage (8,400–8,700 ka BP) (Kotarba, Baumgart-Kotarba 1999).

According to M. Lukniš (1973), the process of rock wall and rocky slope retreat as well as the lowering of ridgelines (5 meters) took place over the course of 10,000 years. The evolution of slopes began in the lower portions of glacial valleys before taking place in their upper portions. The Rybi Potok glacial valley began to undergo deglaciation processes starting at approximately 14 ka BP. On the other hand, cirque glaciers in the Morskie Oko Lake area still existed during the Daun — 12 ka BP (Kotarba, Baumgart-Kotarba 1999).

Loose weathering material began to form on slopes as a result of gelifraction. The material made its way was transported to valley floors in the form of mass gravitational movements, which included a very large number of debris flows. Debris flows activating and transporting rain-saturated weathering material tended to take place in rock gullies filled with debris. One indication of this is the presence of alluvial talus cones at the toe of each given rock gully. The largest cones form the base of rocky slopes in valleys where glaciers had receded the earliest. The longer period of postglacial relief development allowed for more changes in the shape of rocky slopes, with the vast majority of the changes being caused by alluviation processes. Initial rock formations usually develop on slopes in the cryonival zone, above the edge formed by glacial erosion, and extend on rocky slopes and alpine cliffs. Slope instability initiated under rocky ridge crests continues down as far as the steep slope extends. When a flow enters a channel within a gully, it becomes a valley-confined debris flow. The deposition of debris below the gully creates debris aprons at the toe of steep slopes in the form of single or coalescing debris fans. Single debris fans form at the toe of slopes fragmented by gullies far away from one another. When the degree of slope fragmentation is substantial, that is when gullies are found close to one another, debris fans coalesce to form larger fans. A typical valley-confined debris flow in an alpine environment consists of three parts (Fig. 2):

– initial niche, i.e. slope catchment, which constitutes debris source area (A),
– branch gully, i.e. debris flow channel in bedrock (B),
– deposition area, i.e. debris fan at the toe (C).

The natural processes acting in this type of landform and the distribution of relevant geomorphic processes were analyzed by T. Glade (2005). This model of slope evolution is also at work in the Tatra Mountains.

Contemporary high mountain slope relief is the product of glacial erosion during the Last Ice Age and postglacial modelling. The factors that have helped shape high mountain slopes include paraglacial processes as well as periglacial processes intensified by rapid mass movements during the Holocene. Only 32% of the Tatra Mountains experienced glaciation (Klimaszewski 1988). Mountain ridges rising above valley glaciers were not covered with ice. Mountain areas found above the trimline of Würm glaciers were shaped by processes in a morphoclimatic zone called "supra-périglaciaire", which existed at the time (Chardon 1984). The main stage of periglacial morphogenesis began towards the end of the ice age.

On very steep sides of slopes above the trimline, morphogenetic processes were assisted by the action of powerful snow avalanches. As glaciers receded, the travel distances of avalanches increased and deeply incised gullies began to form. The immense erosive power as well as transportation capability of snow avalanches has been documented for many mountains (i.e. Rapp 1960, Luckman 1977).

M. Klimaszewski (1988) developed a model that explained the gully fragmentation of rocky slopes undercut by glaciers. According to the model, rock walls gradually became rocky slopes as a result of postglacial weathering, rock falls, and fragmentation by gullies. As gullies became deeper and wider, in part thanks to the effects of snow avalanches, the rocky ridges between them became smaller. Longitudinal gully profiles gradually became smoother and eventually reached a gradient of 30–35°. The convex rocky ridge marking the trimline of valley glaciers became fragmented and slowly began to disappear. In spite of this, fragments of such ridges remain till this day and have been used to help reconstruct the thickness of Tatra glaciers. This was how forms consisting of an initial niche in the uppermost part of the slope and gullies dissecting rocky slopes created fragmented slopes. These landform complexes became debris source areas and path branches for alpine valley-confined debris flows.

STUDY AREA AND METHODOLOGY

B. Halicki (1932) studied the High Tatras and noticed the existence of an asymmetry in the shape of slopes in glacial valleys running more or less east-west. This was especially true in the Hlinska and Nefcerka valleys (Kriváň group). The valleys are straight and not directly connected with other valleys. Hence, the relief of their slopes was not affected by lateral erosion caused by Pleistocene valley glaciers. Halicki stated that “the asymmetry of gullies is most likely the effect of variable regelation processes acting during ice ages and in-between ice ages on shaded and unshaded rock walls” (pg. 311). At the same time, Halicki did not find any proof of the existence of tectonic or petrographic tendencies that could have caused the cross sectional asymmetry of these types of gullies with respect to the east-west direction.

Research in a number of high mountain areas in the northern hemisphere has shown that asymmetries do exist on opposite-facing slopes that result from differences in the annual range of temperature and solar radiation, the freeze-thaw cycle, and especially precipitation. Moreover, geo-ecological zones differ in terms of height and contemporary morphogenetic processes vary in intensity (Plesnik 1973). P. Höllermann (1973) used the example of the Eastern Alps to show that “the influence of slope exposure is rather distinct in the actual landscape pattern” (pg. 157).

The statements above prompted more advanced studies of debris flows shaped by glacier valley relief in Hlinska Valley (Fig. 1). The valley had evolved in the postglacial era under different climate conditions on northern- and southern-facing slopes. The slopes are not different in terms of lithology and tectonics (Nemčok, ed. 1994), therefore, any differences in relief must be the product of climate conditions. Hlinska Valley is located in the western part of the High Tatras and is formed entirely of biotite granodiorite. It is a deeply incised glacial valley, four kilometers long. Hlinska Valley hangs above Koprova Valley with elevations ranging from approximately 1,450 m to more than 2,400 m (Fig. 1). Present-day climate characteristics are shown in Table 1.

To determine the overall condition of relief of Hlinska Valley, the geomorphic situation of chosen elements was mapped. The analysis was based on Ikonos high resolution satellite image, which was obtained from the authorities of the Tatra National Park. The photo was taken in 2004 and showed three passes:

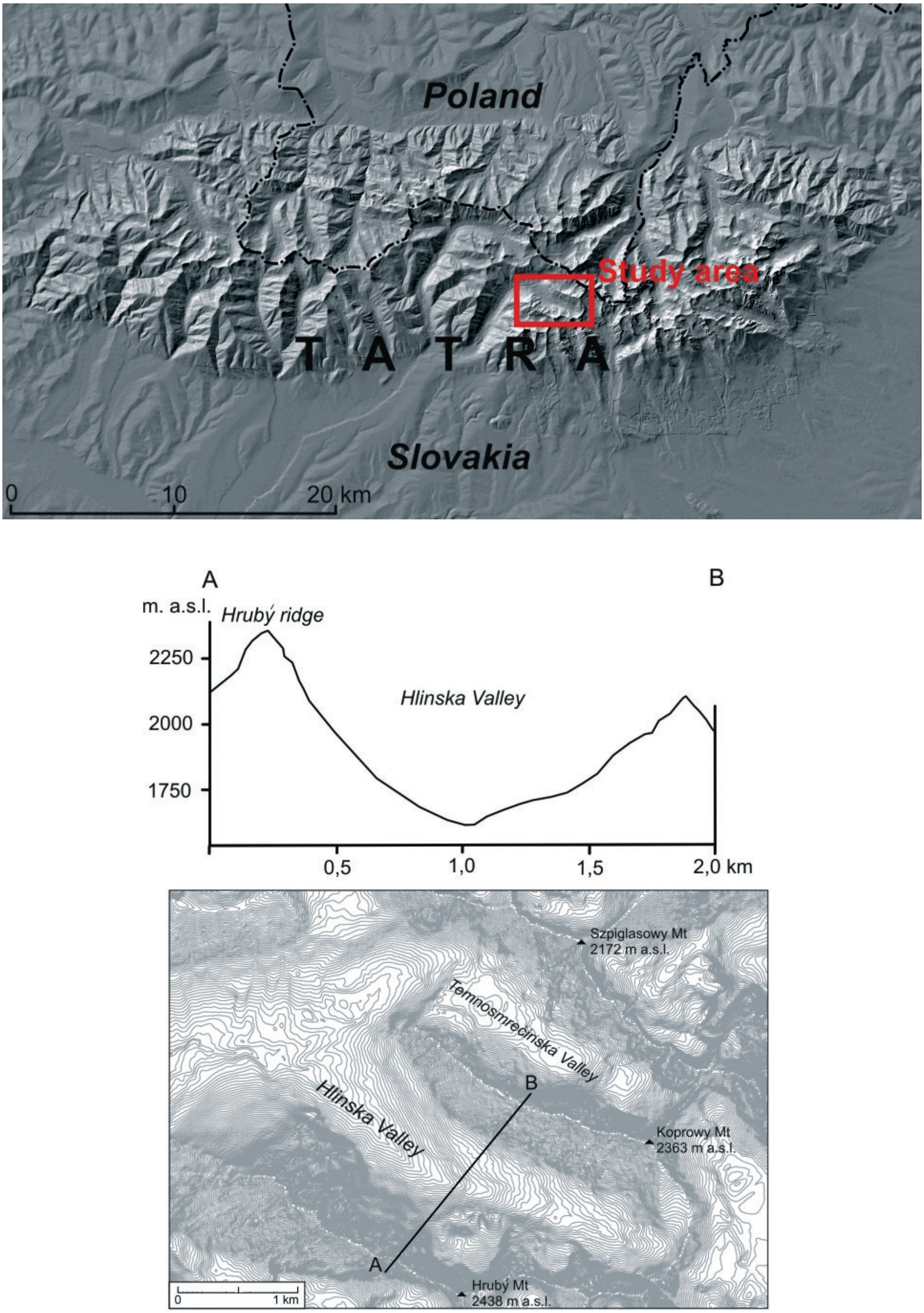

Fig. 1. Shaded relief map of the Tatra Mountains showing location of the study area and topography of the Hlinska Valley

Table 1

Recent principal climate elements on Tatra slopes, at elevation ca. 1700 m (after H e s s 1974)

Rocky slope/rockwall	North-facing	South-facing
Mean annual temperature [°C]	0.8	1.8
Number of days; temp. min <–10°C	51	45
Number of days; temp. max <10°C	124	95
Number of days; temp. min.<0°C	89	103
Number of freeze-thaw days	99	112
Number of days with snow cover	217	189
Annual precipitation [mm]	1610	1250

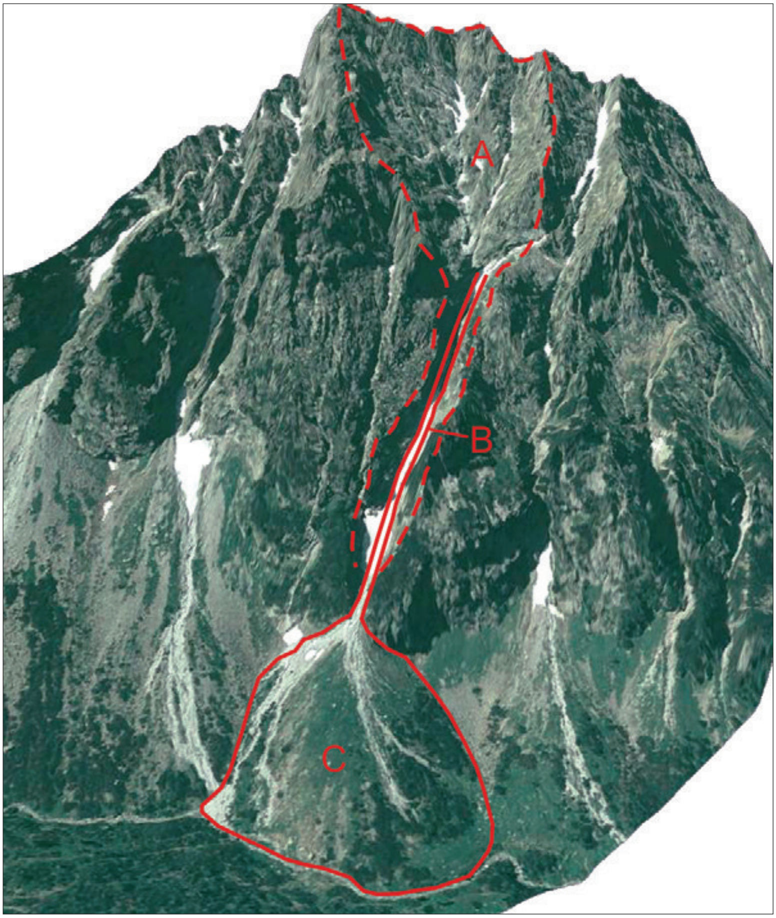

Fig. 2. Elements of valley-confined debris flow system (A, B, C) in the study area – North-facing slope of Hrubý ridge. Explanation in the text

11 km wide pass and 56 km long pass. Ikonos imagery is similar in scope to average quality aerial photography. The process of orthorectification was carried out in cooperation with the specialists from the Polish and Slovakian Tatra National Parks, Institute of Geography and Spatial Management Jagiellonian University, and Satellite Center of Regional Operation (G u z i k et al. 2006).

The obtained map depicts debris flow source areas, including potential catchments size for rainfall events, debris flow travel paths and the deposition areas. Topographic parameters such as water catchment areas, length of debris-flow tracks and height differences between the source and the deposition of debris flow systems have been delineated from a digital terrain model. The model was generated on the basis of data owned by both National Parks and had resolution 10 × 10 m. In addition, a cross-profile of Hlinska Valley have been recorded (Fig. 1). All of the maps and analysis, were made using the Integrated Land and Water Information Systems ILWIS 3, 6.

RESULTS

Research on slope relief in Hlinska Valley has shown that while its slopes are quite homogeneous in terms of geology, the postglacial evolution of southern-facing slopes has been more intensive than its northern-facing counterpart. It may be assumed that the erosive power of the valley glacier during the Pleistocene was the same on both slopes, as the valley is straight and does not possess tributary valleys. Today, both slopes bear evidence of glacial undercuts, which marked the trimline of the Würm glacier. Only in the Holocene did the rate of slope evolution change, with the two opposite-facing slopes in question evolving at different rates (Fig. 3). Northern-facing slopes consist of two clearly different units — alpine cliffs and debris accumulations at the toe. Southern-facing slopes are rocky in nature, less steep, and more smooth (Fig. 4). Northern-facing slopes are well-shaded, with a minimum of present-day freeze-thaw activity and snowpack instability. On the other hand, southern-facing slopes experience numerous freeze-thaw cycles (Tab. 1). Thus, it is believed that after Würmian glaciation slope climatic asymmetry produces differentiated fragmentation of slopes, more conducive to snow avalanching and debris-flow activity on southern-facing slopes. The local climate and the geomorphic activity of rapid mass movements manifest themselves in yet another way: The different path of evolution of opposite-facing slopes can be expressed in terms of measured parameters of debris flow (Tabs. 2 and 3). Northern-facing slopes possess fewer valley-confined debris flow tracks. However, their debris source areas are larger and their debris flow tracks are longer. Southern-facing slopes are more fragmented by debris flows with smaller source areas and shorter flow tracks.

Geomorphological research in the Alps has shown that erosion forms created by valley glaciers are remnants of the Last Glacial Maximum (LGM) (K e l l y

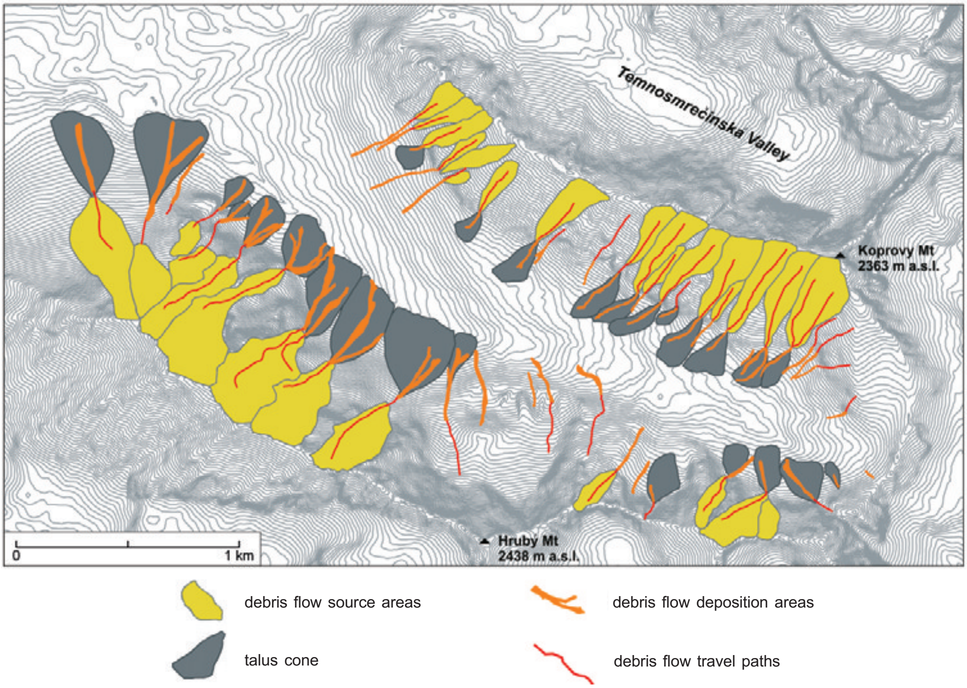

Fig. 3. Study area with valley-confined debris flows. Source areas and deposition areas have been determined. North is at top of map

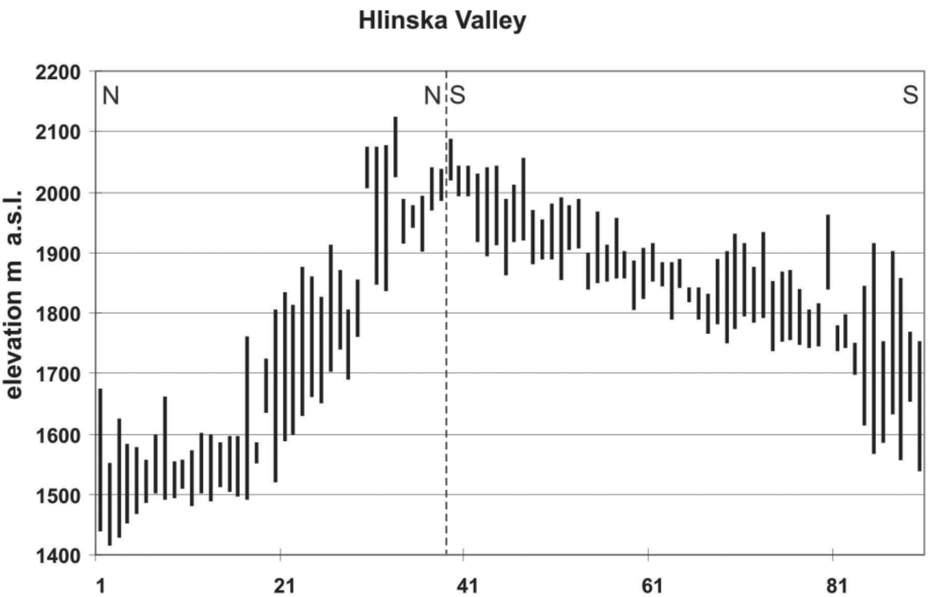

Fig. 4. Elevational extent of 92 debris flow paths on N-facing and S-facing slopes of the Hlinska Valley

Table 2

Measured parameters of debris flows on N, NE and NW facing slopes of Hlinska valley

No.	Top elevation [m]	Botton elevation [m]	Relief [m]	Lenght [m]	Slope Aspect
1	1674	1439	235	484,8	W
2	1552	1415	137	298,3	N,E
3	1626	1429	197	411,3	N
4	1584	1452	132	260,9	E
5	1577	1467	110	184,4	N,E
6	1556	1486	70	133,8	N
7	1598	1503	95	161,8	N
8	1662	1492	170	266,3	N,E
9	1555	1494	61	135,5	N,E
10	1558	1511	47	88,9	N,E
11	1572	1482	90	187,1	N,E
12	1601	1502	99	180,6	N
13	1598	1488	110	222,1	N
14	1585	1513	72	152,1	N
15	1597	1505	92	202,1	N
16	1597	1497	100	244,4	N
17	1760	1492	268	484,8	N
18	1585	1552	33	75,6	N,W
19	1724	1635	89	141,5	N,E
20	1804	1521	283	483,5	N,E
21	1833	1587	246	446,8	N,W
22	1814	1600	214	352,4	N
23	1877	1629	248	393,9	N
24	1860	1662	198	315,0	N
25	1826	1650	176	284,1	N,W
26	1913	1703	210	335,0	N
27	1870	1740	130	210,1	N
28	1805	1691	114	225,0	N
29	1855	1762	93	200,8	N,W
30	2074	2007	67	121,2	N
31	2074	1847	227	256,3	N
34	2078	1836	242	251,9	N,W
35	2123	2025	98	158,1	N,W
36	1987	1914	73	153,5	N,W
37	1978	1940	38	64,6	N
38	1994	1903	91	186,7	N
39	2041	1971	70	128,7	N
40	2037	1985	52	102,1	N
Mean	1774	1640	134	236,0	

Table 3

Measured parameters of debris flows on S and SW-facing slopes of the Hlinska Valley

No.	Top elevation [m]	Botton elevation [m]	Relief [m]	Lenght [m]	Slope Aspect
41	2088	2020	68	114,5	S,W
42	2043	1993	50	77,3	W
43	2043	1993	50	88,9	S,W
44	2031	1918	113	215,1	S,W
45	2041	1895	146	305,2	S
46	2043	1912	131	264,7	S
47	1989	1863	126	345,8	S
48	2012	1917	95	216,9	S
49	2056	1920	136	257,8	S,W
50	1969	1881	88	202,2	S,W
51	1953	1889	64	136,0	S
52	1981	1888	93	197,3	S
53	1992	1855	137	308,1	S,W
54	1977	1905	72	125,7	S
55	1988	1908	80	118,1	S
56	1900	1839	61	159,2	S,W
57	1968	1850	118	247,0	S,W
58	1912	1853	59	143,7	S
59	1957	1857	100	164,8	S
60	1902	1858	44	72,6	S,W
61	1887	1806	81	185,6	S
62	1906	1823	83	149,2	S,W
63	1914	1851	63	92,6	S,W
64	1884	1844	40	78,7	S
65	1884	1790	94	192,5	S,W
66	1890	1843	47	81,4	S
67	1843	1818	25	54,7	S
68	1843	1789	54	108,8	S
69	1831	1767	64	135,1	S,W
70	1890	1783	107	210,3	S,W
71	1903	1751	152	334,5	S,W
72	1930	1773	157	289,3	S,W
73	1914	1796	118	195,6	S,W
74	1875	1785	90	164,8	S,W
75	1933	1791	142	242,8	S,W
76	1853	1736	117	213,8	S,W
77	1868	1752	116	198,4	S,W
78	1871	1755	116	188,0	S,W

Table 3 cont.

No.	Top elevation [m]	Botton elevation [m]	Relief [m]	Lenght [m]	Slope Aspect
79	1838	1747	91	176,3	S,W
80	1805	1742	63	122,4	S,W
81	1815	1744	71	125,1	S,W
82	1963	1840	123	200,2	S,W
83	1779	1736	43	83,3	S,W
84	1797	1743	54	96,0	S,W
85	1750	1697	53	99,7	S,W
86	1845	1615	230	421,3	S,W
87	1916	1568	348	645,8	S,W
88	1753	1586	167	382,4	W
89	1902	1633	269	491,2	S,W
90	1857	1556	301	597,4	S,W
91	1769	1654	115	222,1	S,W
92	1754	1538	216	368,0	S,W
Mean	1910	1801	108	210,0	

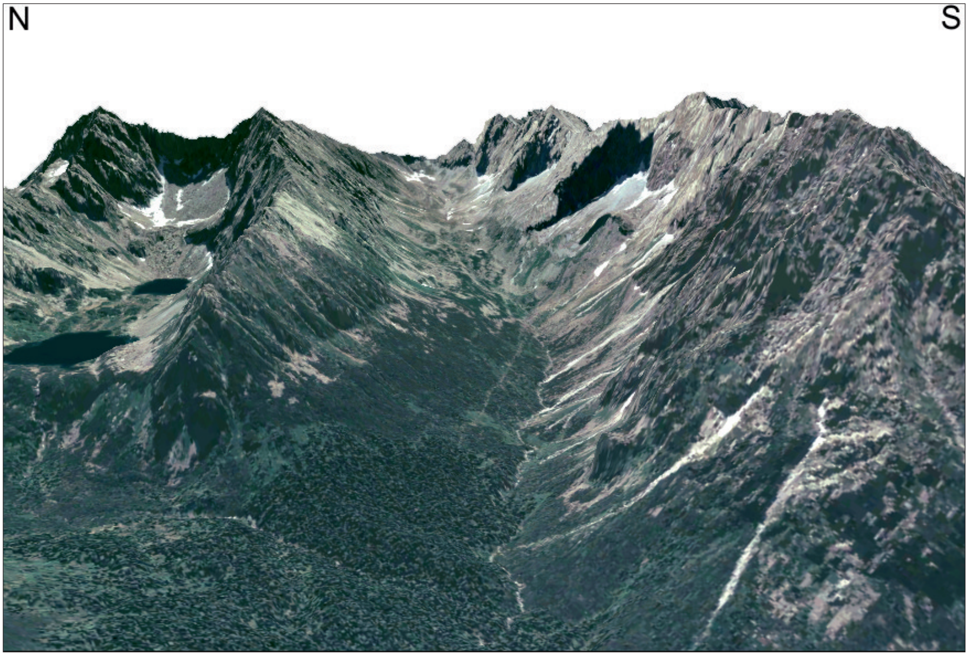

Fig. 5. 3D model of the Hlinska Valley. Well visible trimline extent of Würmian valley glacier, ortophotomap, 2004

et al. 2004). If this is accepted as true, then the glacial trimline on the slopes of Hlinska Valley must have also formed during this time period. It may be further stated that postglacial erosion, of which valley-confined debris flows were an important part, did not lead to their degradation. Yet, the trimline on northern-facing slopes is much more distinct than its counterpart on southern-facing slopes.

The slope asymmetry identified in Hlinska Valley may be interpreted as the result of local climate differences during the entire postglacial period and not lithological or tectonic conditions. Slope asymmetry in periglacial high mountain areas can be found in a number of places in the northern hemisphere. A similar situation was identified in Glacier National Park in the United States in glacial valleys found at elevations of approximately 1,000 m to 3,000 m (Butler et al. 1992).

Conclusion of H.M. French (1996) with respect to the importance of various types of avalanches and debris flows in periglacial areas and high mountain relief, argues that "during Quaternary cold stage, warm south- and west-facing slopes experienced more rapid frost weathering due to more frequent and deeper periods of thawing". Thus, the presence of asymmetrical high mountain valleys in the High Tatra Mountains seems to be a reliable indicator of past periglacial conditions.

CONCLUSIONS

The Holocene evolution of High Tatra relief was merely a retouching of glacial relief, yet it produced an array of different landforms on the slopes of glacial valleys. Slopes with identical geology (lithology and tectonics) but affected by very different climate conditions — facing north or south — experienced certain climate-induced changes. Northern-facing slopes experienced less regelation and fewer changes in relief due to the more severe nature of their local climate. The end result was less generation of large-grained weathering material and less slope fragmentation via snow avalanching and debris flow activity.

Southern-facing slopes, on the other hand, evolved faster. A dense network of valley-confined debris flow tracks evolved on southern-facing slopes. This gradually led to smoother slopes and smaller gradients (under 32°).

Both northern-facing and southern-facing slopes still possess erosion undercuts caused by Würm era valley glaciers. Trimlines still exist, although they have experienced more severe weathering processes on southern-facing slopes. The combined action of Holocene snow avalanches and debris flows was an important mechanism for routing cold climate sediments from initial niches via steep rocky gullies to valley floors.

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