ARE THERE GEOMORPHIC INDICATORS OF PERMAFROST IN THE TATRA MOUNTAINS?

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Abstract: This paper concerns itself with the issue of relief and permafrost in mountains in which the latter phenomenon is only present in the form of isolated patches, as is the case in the Tatra Mountains. Thus the slope morphology and morphodynamics at three permafrost sites in the Tatra Mts. are discussed in the context of the presence of periglacial landforms, especially indicative forms of permafrost. No distinct morphological evidence as to the presence of permafrost was in fact noted.

Key words: permafrost, high-mountains at mid latitudes, debris slope, periglacial landforms

INTRODUCTION

Permafrost is an important feature of periglacial environments as its presence modifies significantly the conditions under which periglacial relief develops. Permafrost is defined as soil or rock that has remained continuously at a temperature below 0°C for more than two years (Harris *et al.* 1988).

Recently, there have been a number of reports of the presence of permafrost in the highest belts of many unglaciated mountains at mid latitudes (Urdea 1992; King and Ackerman 1993; Kędzia *et al.* 1998; Ishikawa *et al.* 2003,; Dobiński 1997, 1998, 2005; Kern *et al.* 2004; Gude *et al.* 2003; Julián and Chueca 2007; Zacharda *et al.* 2007). The Tatra Mts. belong to this group (Dobiński 1997, 1998, 2004; Kędzia *et al.* 1998; Mościcki, Kędzia 2001; Gądek, Kotyrba 2003; Gądek, Żogała 2005). J. Warburton (2007) after J. Brown *et al.* (1997) includes the Tatras, as along with the Făgăraš and Retezat Massifs in the Southern Carpathians (of Romania) within the category of high European mountains featuring isolated patches of permafrost (accounting for less than 10% of their area).

The Tatra Mountains form one of the highest ranges in the Carpathian arc (peaking at Gerlach, 2666 m a.s.l.). Their relief is of alpine character and the climate is severe enough (Table 1) for the middle periglacial belt to be present above the upper timberline, i.e. 1550 m a.s.l. (Jahn 1975). On the basis of climatological analysis and indices of freezing and thawing, W. Dobiński (1997, 2004) asserts that there are potential conditions for permafrost to be present in this belt. Patches of permafrost are expected above 1930 m a.s.l. on north-facing slopes, and above 2300 m on south-facing ones

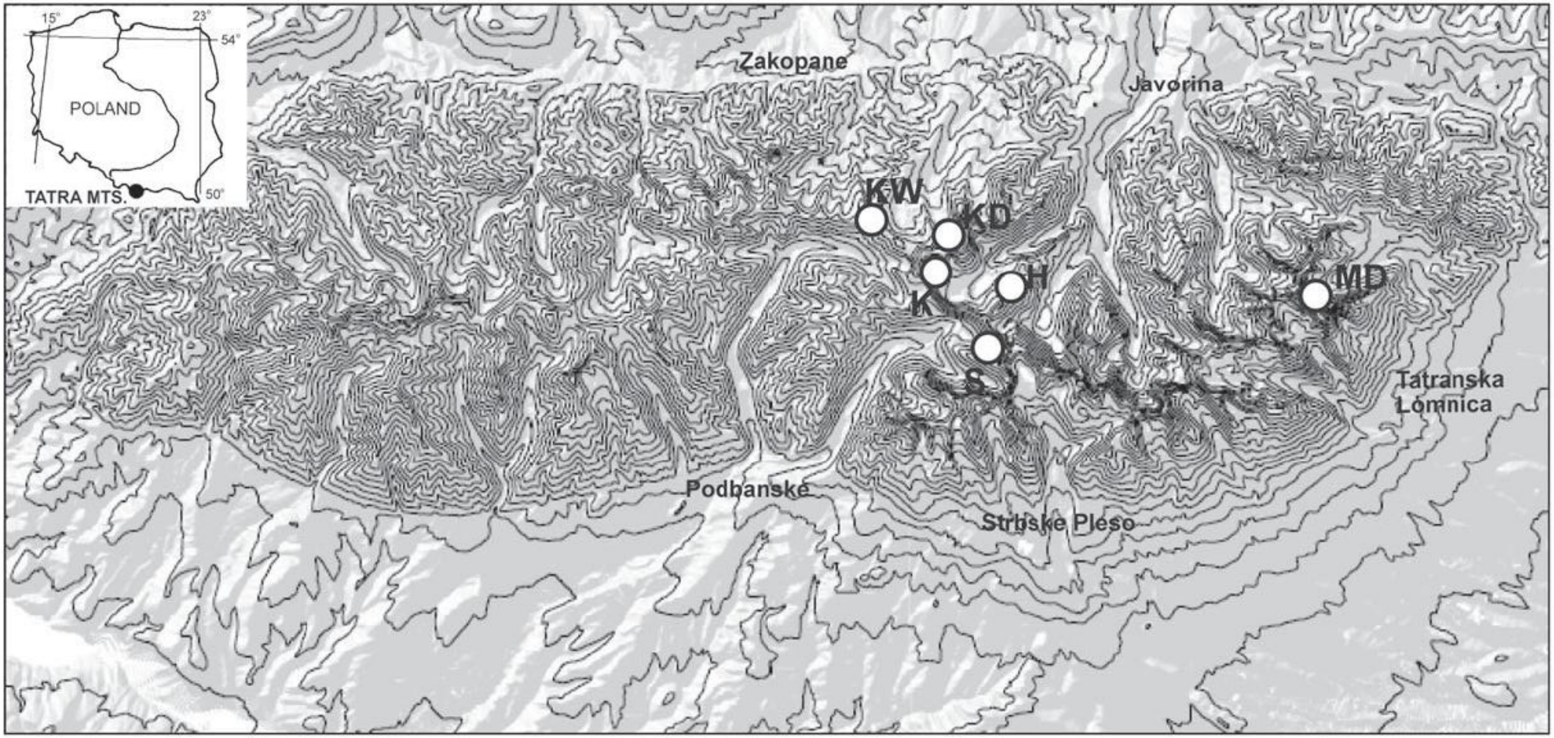

Figure 1. Occurrence of permafrost in the Tatra Mts., as documented by geophysical and georadar examination and direct observations. KW—Kasprowy Wierch (1990 m a.s.l.), K—Dolinka pod Kołem (2100 m a.s.l.), H—Hruby Piarg (1800 m a.s.l.) S—Śnieżny Kocioł (1900 m a.s.l.) (Dobiński 1997, 1998, 2004), KD—Kozia Dolinka (1950–2000 m a.s.l.) (Mościcki, Kędzia 2001; Kędzia 2004); MD—Medena Kotlinka (2000 m a.s.l.) (Gądek, Żogała 2005)—all as shown in Fig. 2.

(Dobiński 1997, 2004). Additionally, the lower climatic limit of permafrost patches corresponds with the altitude at which perennial and longlasting snow patches exist in shadowy fragments of talus slopes, usually in north-facing glacial cirques.

Table 1. Climate characteristics for the Tatra Mts.

Meteorological station		Łomnica	Kasprowy Wierch	Skalnate Pleso	Dolina Pięciu Stawów Polskich	Hala Gąsienicowa	Strbske Pleso	Hala Ornak
Altitude (m a.s.l.)		2635	1991	1786	1670	1520	1330	1109
Mean annual air temp. (°C)		-3.8	-0.8	1.6	1.1	2.3	3.4	3.2
No. of days with temp. min <0°C and max >0°C		88	78	111	94	93	118	126
No. of days without frost		4	48	93	82	102	120	120
Precipitation (mm)	January		142		71	70		74
	July		215		260	247		206
	Mean annual	1645	1889	1323	1692	1664		1490

after T. Niedźwiedź (1992) and M. Konček, ed. (1974)

The 1990s saw studies of permafrost in the Tatra Mts. carried out on the basis of such methods as BTS measurement, electroresistivity sounding, georadar, seismic sounding, infrared imaging, etc. The results of these studies pointed to the possible existence of permafrost in isolated patches within the Tatra Mts., and specifically at: Kasprowy Wierch (1990 m a.s.l.), Dolinka pod Kołem (2100 m a.s.l.), Hruby Piarg (1800 m a.s.l.), Śnieżny Kocioł (1900 m a.s.l.) (Dobiński 1997, 1998, 2004), Kozia Dolinka (1950–2000 m a.s.l.) (Mościcki and Kędzia 2001; Kędzia 2004) and Medena Kotlinka (2000 m a.s.l.) (Gądek and Kotyrba 2003; Gądek and Żogała 2005) as is shown in Fig. 1. In the Medena Kotlinka Valley, the author even observed an outcrop of massive ice on a slope of a nival niche (Fig. 2) during the extremely hot summer of 2003. The results of the above mentioned studies indicate that patches of permafrost are usually located in the bottoms and on the slopes of high-elevation glacial cirques. At sites in which permafrost was found, coarse debris of different sizes, including even boulders, predominated in slope covers. Grain-size composition of slope covers probably facilitates cooling of the ground (via the so-called chimney effect), as has been noted in the Alps (Delaloye *et al.* 2003; Gude *et al.* 2003).

B. Etzelmüller *et al.* (2001) declared that morphological indications of the presence of permafrost in the mountains relate to:

- the creep of coarse debris, which is ice-saturated, and leads to the formation of rock glaciers and push moraines;
- ice bodies buried by debris thicker than the maximum active-layer thickness, as revealed in the formation of thermokarst, ice-cored moraine and palsas.

Periglacial forms, such as patterned ground and solifluction lobes, can be treated as morphological indicators of permafrost, but they are not unambiguous because these forms also develop in areas without permafrost.

Fig. 3 presents the location of periglacial forms in the Tatra Mts. on the basis of earlier geomorphological examination (Rączkowska 2007). The area was found to support periglacial forms of different types and sizes, including solifluction lobes, patterned ground and rock glaciers. Yet the rock glaciers occurring there are relict forms (Kotarba 1991–1992), and so cannot be treated as evidencing permafrost, even

Figure 2. Outcrop of massive ice body (4 m high) in Medena Kotlinka Valley (Slovak part of the High Tatras) in August 2003 (indicated by arrow).

if ground temperature is very low inside glacier tongues, as was the case in the relict rock glacier near the tarn called Hińczowy Staw (Kędzia *et al.* 2004). Moreover, solifuction lobes and patterned ground are not attributed to the presence of permafrost, their present-day activity being due to diurnal and seasonal freeze-thaw cycles (Rączkowska 2007).

The aim of this paper has been to discuss—by reference to the Tatra Mountains—the relationship between landform development and the presence of permafrost in mountains in which the latter is only present in isolated patches. To that end, answers were sought to the following questions:

- Are there any geomorphic indicators of permafrost being present?
- Does permafrost influence present-day relief development?
- Does permafrost influence slope morphodynamics?

Answers to the above questions were expected to arise from examinations of slope morphology and morphodynamics in those areas of the Tatra Mts. in which permafrost could be detected. Three sites with permafrost—the Kozia Dolinka Valley, the Medena Kotlinka Valley and the Kasprowy Wierch summit—were investigated geomorphologically by author. In this, detailed geomorphological mapping was used as the basic technique.

SLOPE MORPHOLOGY AT PERMAFROST SITES

THE KOZIA DOLINKA VALLEY SITE

The Kozia Dolinka Valley is the uppermost glacial cirque in the Sucha Woda Valley of the Polish High Tatras (Figs. 4 and 5). Permafrost was evidenced there using indirect methods, mainly geophysical and BTS. Isolated patches of permafrost exist in the lower part of shadowed talus slopes (Fig. 4) below the high rockwall of the Kozi Wierch summit. The depth of the active layer is an estimated 2 m (Kędzia *et al.* 1998; Mościcki and Kędzia 2001; Kędzia 2004). Fig. 5 presents a geomorphological sketch of the Kozia Dolinka Valley at the scale 1:10 000. High rockwalls surround a relatively narrow valley bottom,

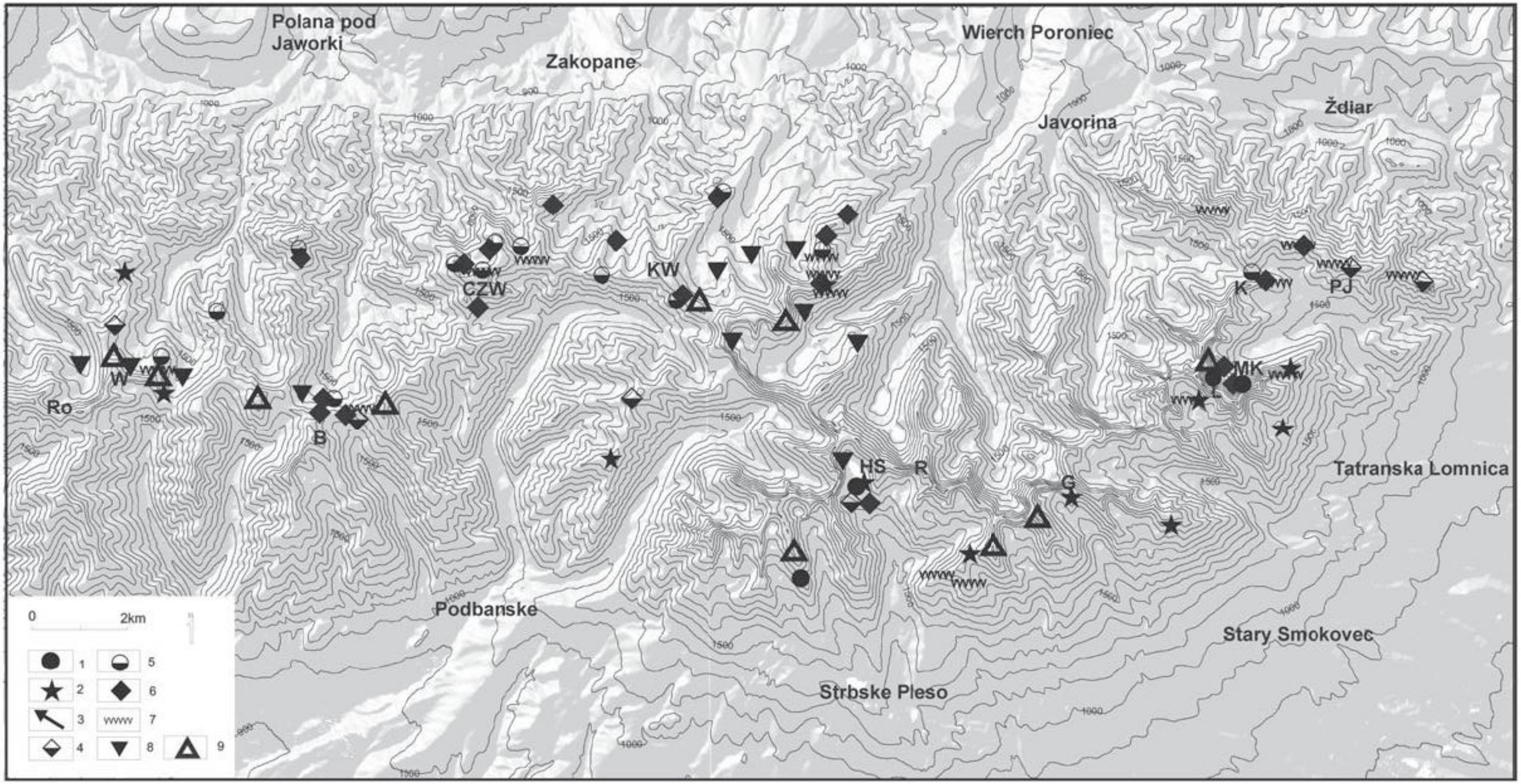

Figure 3. Periglacial landforms in the Tatra Mts. 1- sorted circles, 2—sorted polygons, 3—sorted strips, 4—miniature patterned ground, 5—thufurs, 6—solifluction lobes, 7—solifluction garlands, 8—rock glaciers, 9—blockfields (after Rączkowska 2007).

Figure 4. View of the Kozia Dolinka Valley and northern slopes of the Kozi Wierch summit (2291 m a.s.l.) (by S. Kędzia).

filled with glacial drift deposits, which in the southern parts consist mainly of an accumulation of giant boulders. Talus slopes between rockwalls and the valley bottom form heaps and cones. Permafrost was found at altitudes between 1900 and 2000 m a.s.l. on north-facing talus slopes, which are very much shaded year-round. Slopes there are of about 25–35°, and there upper parts have perennial snow patches with nival niches developing (Rączkowska 1997). The slopes are modelled by gravitational processes like falling, rolling or sliding, as well as by the accumulation of debris. The effects of debris-flow activity are visible in the eastern part. There are no other distinct periglacial forms beside the nival niches (Fig. 5).

THE KASPROWY WIERCH SITE

Kasprowy Wierch summit was indicated by W. Dobiński (1997) as an area whose climatic features are such as to sustain a presumption that permafrost is even now present. The results of geophysical soundings confirm this, and point to their being two permafrost layers (Dobiński 2004).

The slopes of Kasprowy Wierch are smooth and debris mantled, sustaining the vegetation cover of alpine meadows (Fig. 6). Coarse, angular boulders are significant components of slope covers. The relief in the area was analysed on the basis of a morphodynamic map of the Kocioł Gąsienicowy basin (Fig. 7), as devised within the framework of 1:1000-scale geomorphological mapping (Rączkowska 1999). The Kocioł Gąsienicowy basin is located on the north-eastern slope of Kasprowy Wierch. Bare crystalline rocks visible at the very summit are not portrayed on the map. Patches of relict blockfields are typical features, especially of the western slopes of Kasprowy Wierch, though small blockfields also occur on the eastern slopes (Fig. 6). Periglacial processes, mainly solifluction, dominate on the upper parts of slopes, while soil and debris creep prevail in the remaining parts. It is contended that both processes model slopes

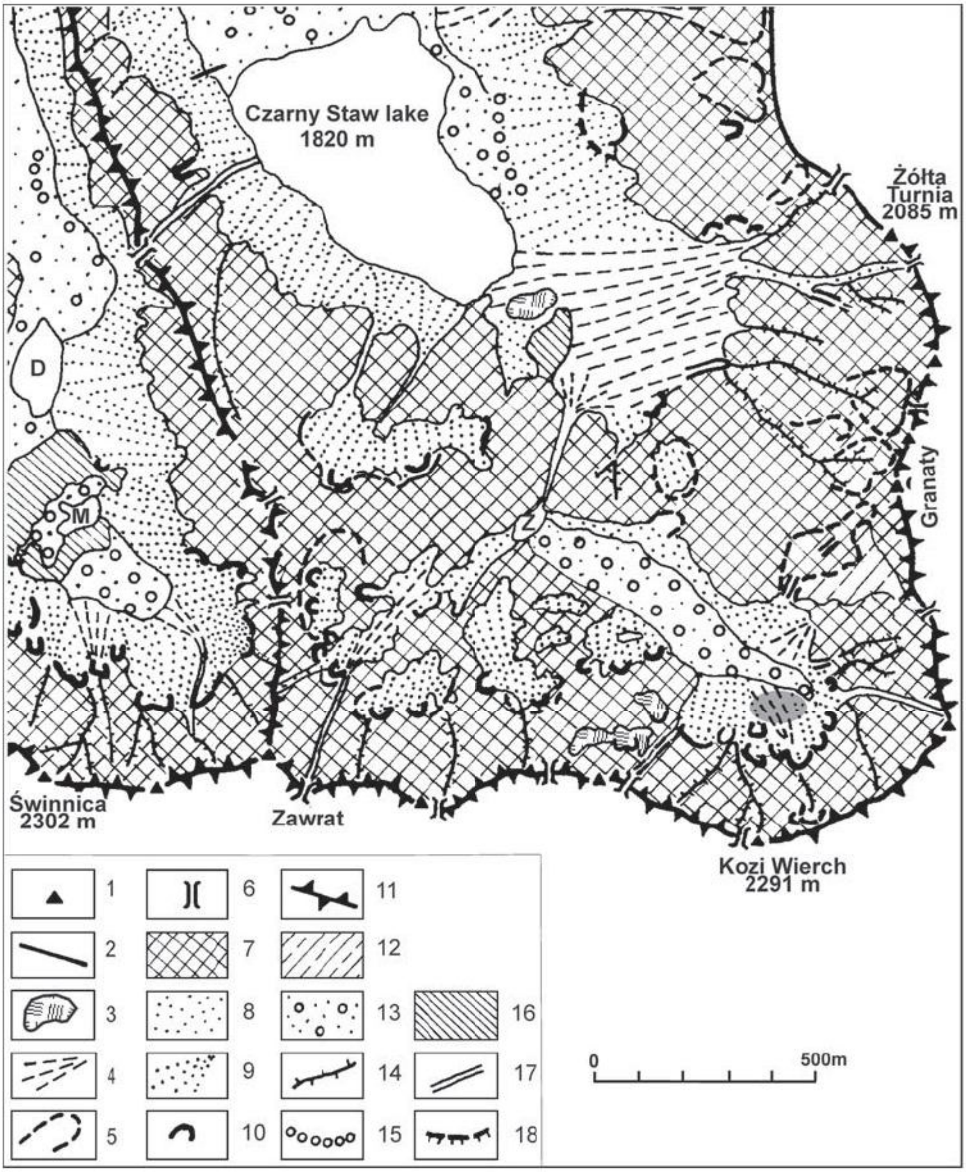

Figure 5. Geomorphological sketch of the upper part of the Sucha Woda Valley. Permafrost was found on the north-facing talus slope below the Kozi Wierch summit.
1—summit, 2—rounded ridge, 3—long-lasting snow patch, 4—alluvial-talus slope or cone, 5—relict nival niche, 6—pass, 7—rockwalls and rocky slope, 8—debris slope, 9—talus cone, 10—active nival niche, 11– knife-like ridge, 12—debris-mantled slope partly covered by vegetation, 13—glacial drift deposit, 14—chute, 15—moraine ridge, 16—roche moutonée, 17—debris flow gully, 18—protalus rampart; D—the Długi Staw lake, Z—the Zadni Staw lake (after Rączkowska 1997, modified).
Grey ellipse denotes area with permafrost found by S. Kędzia (2004).

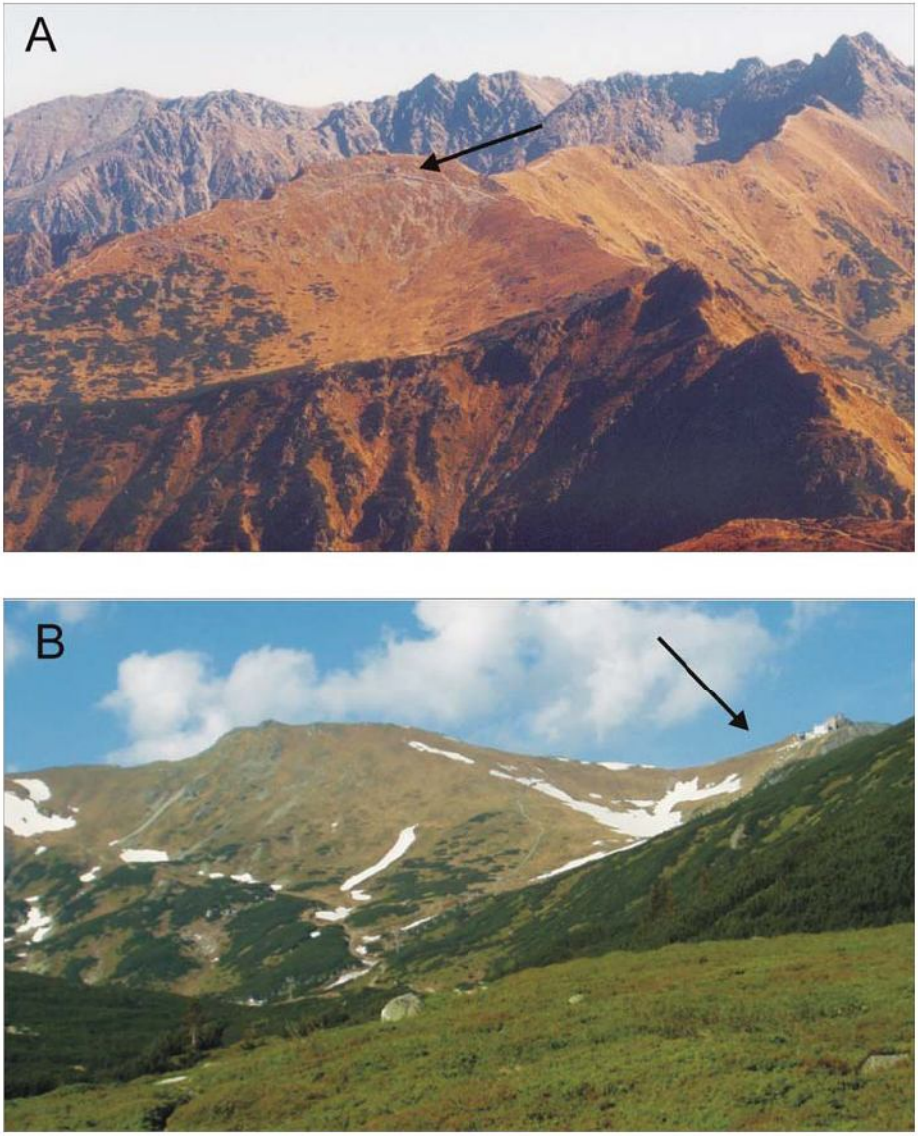

Figure 6. Slopes of Kasprowy Wierch (1987 m a.s.l).
A—western, B—eastern. Arrows show summit,
on which permafrost is said by W. Dobiński (1997, 2004) to occur
(by Z. Rączkowska).

intensively. Rates of movement, evaluated on the basis of measurements for a few years are of 0.0–5.3 cm yr^{-1}. Solifluction has only resulted in the generation of microforms such as terracettes. Their development is not linked with permafrost, unlike that of the large solifluction lobes, which are even treated as geomorphic indicators of permafrost, if not very substantial ones (Etzelmüller *et al.* 2001). Unfortunately, solifluction lobes

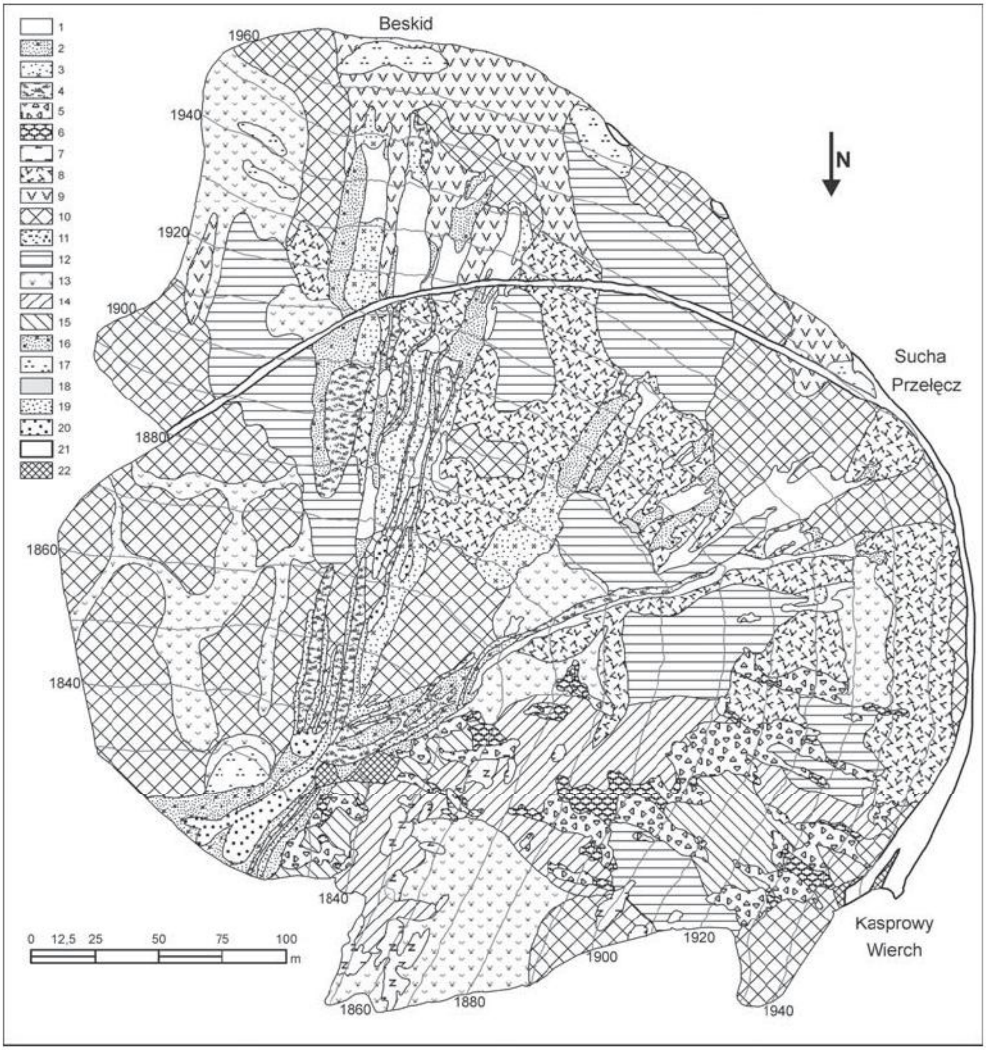

Figure 7. Morphodynamic map of the Kocioł Gąsienicowy area.
1—slope modelled by erosional processes, mainly sheetwash and rill erosion (I), 2—slope modelled by erosional processes, mainly sheetwash and rill erosion, with some sparse grasses, (II), 3—slope modelled by erosional processes, mainly sheetwash and rill erosion, partly stabilized by vegetation (III), 4—slope modelled by erosional processes, mainly sheetwash and rill erosion, stabilized by vegetation (IV), 5—slope modelled by creep of weathering cover (II), 6—slope with block cover modelled by creep of soil and vegetation layer over blocks (II), 7—slope with block cover modelled by creep of vegetation layer over blocks (III), 8—slope modelled by soil creep and solifluction (III), 9—slope with terractes modelled by solifluction (II), 10—slope modelled by solifluction (II), 11—nival niches modelled by nivation, 12—smoothed, stable slope modelled by deflation (III), 13—inactive slope (IV), 14—slope stabilized by *Pinus mugo* (IV), 15—stable slope with block cover (IV), 16—stable slope with block cover occupied by vegetation during period 1975–1995 (IV), 17—slope with fresh accumulation at debris flow levee (II), 18—stable slope with accumulation at debris flow levee (IV), 19—stable slope with accumulation at debris flow tonque (IV), 20—accumulation on alluvial cone and plane (IV), 21—slope with anthropogenic erosional and accumulational processes (II), 22—buildings. Roman numerals I to IV denote intensity of processes from very low to high.

Figure 8. The Medena Kotlinka Valley with glacierette at the bottom indicated by the arrow (by B. Gądek).

are not found in the area. Apart from solifluction, nivation in the vicinity of the snow patches persisting until June that are present in small hollows on the upper parts of slopes has contributed to the development and simultaneous preservation of the above hollows. Erosional niches and fresh accumulation in the form of alluvial cones account for just small fragments of slopes, though erosional processes are presently involved in the significant modification of slope morphology. Overall, forms indicative of the presence of permafrost have been not found in association with slope morphology.

THE MEDENA KOTLINKA VALLEY SITE

The Medena Kotlinka Valley is a small, hanging, glacial cirque in the upper part of the Kežmarska Biela Voda Valley, in the Slovak part of the High Tatra Mts. (Fig. 8). Narrow and surrounded by c. 500 m high rockwalls, the valley opens up to the north. A small firn/ice body—a glacierette—rather than a perennial snow patch—is present at altitudes 2020–2350 m a.s.l. The glacierette is the largest form of this type in the Tatra Mts. A layer of ground ice was detected in the bottom of the valley, just to the right of the glacierette, at depths ranging from 2–5 m near the moraine ridge to 10 m at the talus cone. The presence of massive ground ice was evidenced by different geophysical methods (Gądek and Kotyrba 2003; Gądek and Żogała 2005). Moreover, ground ice outcropped at the surface even in an extremely hot summer (Fig. 2).

The analysis of slope morphology in the area under study was based on detailed geomorphological mapping at 1:1000 (Fig. 9). Gravitational processes, alluviation, avalanche activity and periglacial processes all model debris slopes at the bottom of the Medena Kotlinka Valley (Rączkowska 2005). Large alluvial cones and distinct talus cones occur at the valley bottom. Fresh debris flow gullies of various sizes dissect not only the alluvial cone but also those of gravitational and avalanche origin. Avalanche

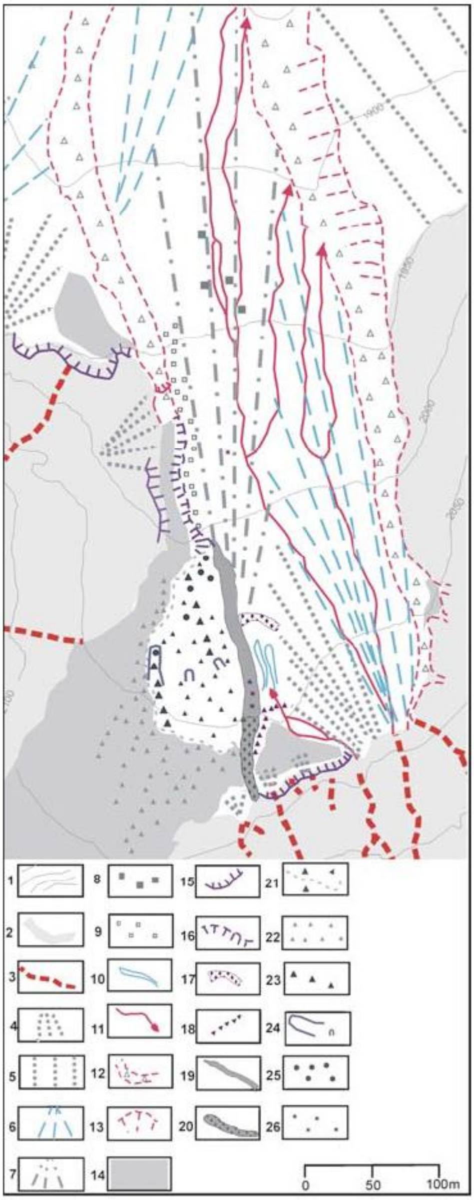

Figure 9. Geomorphological map of the Medena Kotlina Valley. 1—contour lines, 2—rockwall and rocky slopes, 3—chutes, 4—talus cones, 5—talus heaps, 6—alluvial cones, 7—debris slope modelled by avalanches, 8—rocky blocks (height >1 m), 9—accumulation of fresh debris, 10—debris flow tongues, 11—small gullies of debris flows (0.3–1.0 m depth, up to 3 m wide), 12—large gullies of debris flows (up to 6 m wide), 13—erosional edges, height >5 m, 14—perennial snow patches and tiny glacier (glacierette), state in summer 2003, 15—nival niches, 16—edges of nival niches cut in debris cover, 17—relict protalus ramparts, 18—active protalus ramparts, 19—ridge of frontal-lateral moraine, formed in the Little Ice Age, at present modelled by frost action, 20—active ridge of frontal-lateral moraine, 21—surface moraine, 22—periodical surface moraine, 23—moraine ridges within surface moraine, 24—lobes of free solifluction, 25—thermokarst hollows with diameters from 1 to a few metres, 26—patterned ground.

activity significantly affects the whole valley bottom through the transportation and accumulation of large amounts of debris and the simultaneous smoothing of the debris slope. Periglacial processes are at present resulting in the development of landforms. Nivation niches of different types and sizes with a distinct protalus rampart up to 1–1.5 m high are most common. Small polygons, 0.4–0.5 m in diameter, and miniature structural soils also exist, especially on the 7–10 m high moraine ridge rising along the right side of the glacierette. On the surface of the ridge it was possible to observe small crevasses (a few centimetres deep) related to ground thawing, as well as a large (> 1 m diameter) boulder that had plunged into the moraine deposits and been split into two pieces by frost weathering. In this case the occurrence of latest forms or phenomena can be linked with processes in the active layer, as the presence of permafrost in the morainic ridge was documented by the two-year BTS study (Gądek and Kędzia 2006). Morphological indicators of permafrost presence are found on the surface moraine covering the right half of the glacierette with a layer more than 3 metres thick. Small thermokarst hollows and a relatively large lobe of free solifluction have developed there. The thermokarst hollows are one to a few meters in diameter and less than 1 m thick. The fresh debris lobes are over ten metres long and a few metres wide, and have fronts more than 1 m high. Aside from the surface moraine, similar forms have not been found in the Medena Kotlinka Valley, even in the area in which the existence of permafrost patches is stated. The situation thus resembles that in the Tatra Mountains as a whole.

The results of the morphological analysis reveal either a weak relationship or almost no relationship at all between slope morphology and the presence of permafrost in the area. This is also confirmed by the results of the studies on slope morphodynamics and slope cover texture. The nature of the disturbances to the lines marked on the debris combine with the distance travelled by debris to point to frost creep or avalanche activity (Rączkowska 2004, 2007). The analysis of clast microfabric on the debris slope also indicates the possibility that permafrost is only present in surface moraine (Fig. 10). The azimuths of the clast longest axes and directions of clast axis dip vary from 0 to 360°. The slope of the superficial moraine generally faces north and is inclined to around 20°. The angle of inclination of debris ranges from 15° up to 90°. Clast microfabric on the debris slope, occurring below

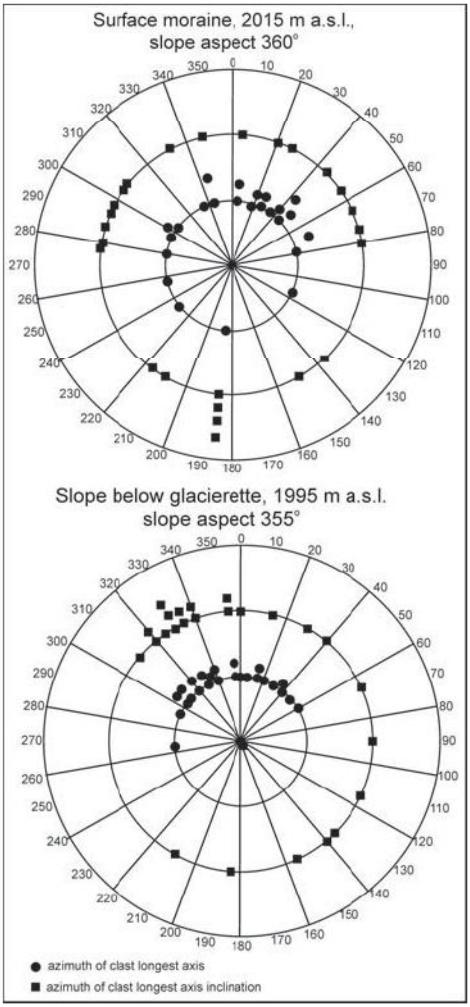

Figure 10. Microfabric of clast on a debris slope in the Medena Kotlinka Valley (after Rączkowska 2007, modified).

the glacierette, indicates that the debris slope is mainly modelled by avalanches. There is a definite difference in clast microfabric on the slope below the glacierette and on the superficial moraine. Azimuths of the clasts longest axes are between 260° and 60°, and are in good agreement with the slope orientation. Axes of 25% of clasts on this slope are inclined in opposite directions. This suggests that, while the slope is modelled by debris creep or maybe frost creep, it is not modelled by permafrost creep.

DISCUSSION AND CONCLUSION

The analysis of the slope relief at the three discussed permafrost sites does not provide unequivocal evidence as to the presence of permafrost and its influence on slope morphology or morphodynamics. Neither permafrost-indicative landforms nor large periglacial forms were found, other than the fragments of glacierrette covered by surface moraine.

Relatively large sorted polygons (the best developed examples anywhere in the Tatra Mts.) occur in the Mengusovska Valley, at an altitude similar to that at which permafrost has been found in other locations (i.e. 1950 m a.s.l.). However the polygons are zonal forms (Fig. 11), their contemporary activity being related to seasonal and diurnal freeze–thaw cycles, as documented by experimental studies (Rączkowska 2007). Active, indicative permafrost landforms are not found at other permafrost sites in the Tatra Mts.

Generally, the periglacial landforms developing in the Tatra Mts. are small, and only

Table 2. Occurrence of active periglacial forms in the high mountains of Europe. (after Z. Rączkowska 2007, modified).

Forms	High Tatras	Western Tatras	Belanske Tatras	Scandinavian Mountains	Alps	Retezat	Fagaraš
Blockfields	–	–	–	±	+	–	–
Rock glaciers	–	–	–	+	++		–
Ice-cored moraine	–	–	–	+	±	–	–
Palsas	–	–	–	+	–	–	–
Non-sorted polygons	–	–	–	+	±	–	–
Sorted polygons	+	–	–	++	++	–	–
Sorted circles	+	–	–	++	++	±	±
Sorted strips	+	+	+	++	+	–	–
Miniature patterned grounds	+	+	+	+	+	+	+
Thufurs	+	+	+	+	+	+	+
Solifluction lobes	±	+	+	++	++	±	+
Solifluction sheets	–	–	–	+	–	–	–
Solifluction garlands	±	+	+	+	+	+	+
Terraccettes	+	++	++	+	++	+	++
Ploughing blocks	+	+	+	++	+	+	+
Gelideflation forms	–	+	±	+	+	–	–
Nival niches	+	+	+	++	+	+	+
Protalus ramparts	±	–	–	+	+	±	±

"–"—absent, "±"—sporadic, "+"—common, "++"—very common

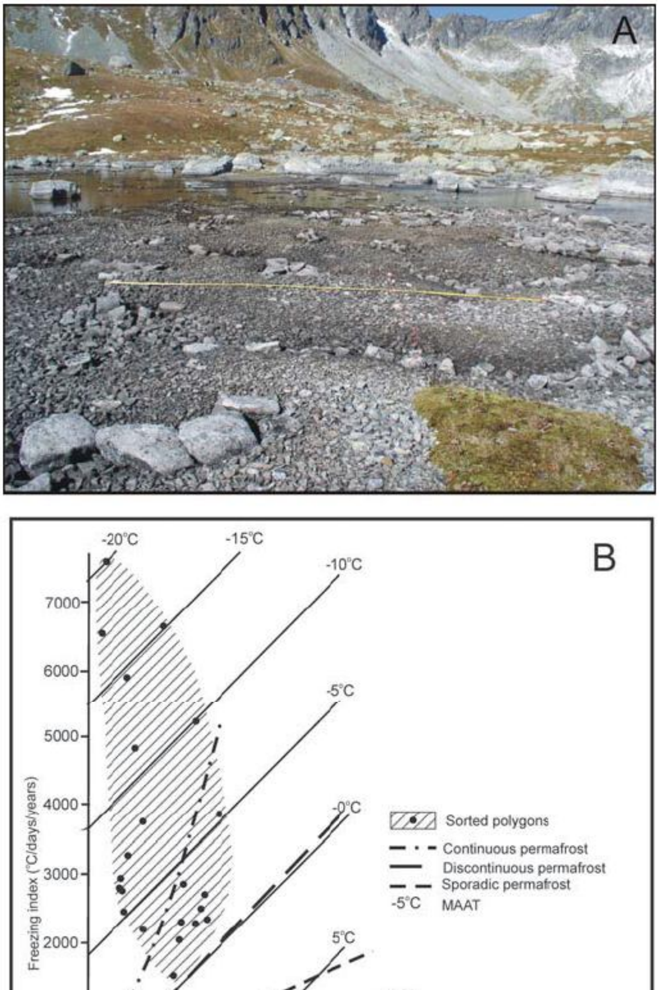

Figure 11. A. sorted polygons in the Hińczowe Oko lake at 1950 m a.s.l., Mengusovska Valley, south slope of the High Tatras, Slovakia (Photo. Z. Rączkowska);
B. Zonality of patterned ground in the Mengusovska Valley, on the diagram of S. Harris (1981);
X—sorted polygons at the Hińczowe Oko lake.

occasionally large, as is the case for mountains in which the presence of permafrost was only suggested, rather than evidenced, as in the Retezat or Făgraš Massifs of the southern Carpathians. The types of periglacial forms are less diversified/numerous than in the mountains where permafrost is more widespread and comprises a variety of forms from isolated patches to a continuous layer, as in the Alps or the Scandinavian Mountains (Table 2).

The high activity of geomorphic processes observed in the areas with permafrost is likely to be another reason for the absence of geomorphic evidence regarding the presence of permafrost. The activity of avalanches and gravitational processes seems to efface the results of periglacial morphogenesis on debris slopes.

It is the nature of permafrost that causes related active landforms to be absent from the Tatras, as well as other mountain regions in which similarly developed permafrost can be found. According to Kędzia (2004) and Dobiński (2004), the patches of permafrost are small. Therefore, they seem inadequate to set permafrost creep in motion, for example. Only a loosening of soils can be stated. The relatively great (2–6 m) depth of the active layer might also help explain why permafrost does not affect slope morphology.

The absence of active permafrost-related forms from the Tatra Mts. is not exceptional. There are other mountain regions with isolated patches of permafrost occurring or suggested to occur (i.e. Urdea 1992; Kern *et al.* 2004; Gude *et al.* 2003; Julián and Chueca 2007; Zacharda *et al.* 2007) in which no distinct geomorphic evidence of the presence of permafrost is reported. Thus, geomorphic forms are not particularly useful identifiers of the existence of permafrost in mountains in which the latter forms nothing more than isolated patches. Even the presence of periglacial zonal forms could not always offer a basis for a determination of the extent of permafrost in given areas, as S. Harris (1981) suggested.

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