THE DYNAMICS OF RECENT GEOMORPHIC PROCESSES
IN THE ALPINE ZONE OF THE TATRA MTS

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Abstract: The energy of high-mountain georelief is evidently transformed into intensity and range of impact of gravitational, water- or snow-induced processes, cryogenic processes, solifluction and deflation. The altitude and climatic conditions of the alpine zone allow for the conservation of some relict or development of some recent processes in the periglacial environment. This paper presents the results of direct measures of some geomorphic processes acting, or said to be active, in the alpine area of the Tatra Mountains. Measurements of debris flows and debris slides, as well as of eolian-nivalional, solifluction and ploughing boulder processes, have been conducted at 25 sites distributed across: the Jalovecká valley in the Western Tatra Mts, as well as the source area of the Predné Medodoly and Zadné Medodoly Valleys in the Belianske Tatry. The results have been compared with those from previous observations.

Key words: debris flows; debris slides; deflation; nivation; ploughing boulder; alpine zone; the Tatra Mountains; Slovakia

INTRODUCTION

A geomorphic process is one entailing a change of state that immediately causes changes in georelief (Minár 1995). The term includes particular material flows and changes in the matter-energetic balance, as well as complex changes of georelief (Urbánec 1974). Recent geomorphic processes are those being observed, or at least considered probable, in a specific region, within the last few decades. The processes usually act together within temporal and/or spatial complexes, thus creating morpho-dynamic systems (Hreško 1994, 1997).

In relation to the intensity and effect of the aforementioned process on humans and the environment geomorphic hazards may also be identified. These are understood to be phenomena entailing the rapid triggering and transport of a great amount of material over a relatively long distance. These most often cause distinct changes in relief, as
Figure 1. Locations of research plots.

The aim of the paper is to present the current state of research as regards recent geomorphic processes, on the basis of direct field measures of the dynamics to these processes.

STUDY AREA

The research sites are located within the alpine zone of the Slovakian Tatra Mts, being distributed across two separate areas distant from one another, i.e. the Jalovecká valley (in the Western Tatras) and the divide area between the Predné Medodoly and Zadné Medodoly Valleys, which is partly in the contact zone between the eastern part of the High Tatras and the Belianske Tatry.

Within the Jalovecká Valley, measurements were made at 14 sites of altitudes 1750–1930 m a.s.l. Geologically, the area falls within the region of crystalline rocks (schist, gneiss and migmatite) and of granitoids (granodiorite). One site is located in the marginal Mesozoic part of the territory in which limestones, dolomites and various slates are dominant (Nemčok et al. 1993, 1994). Depending on the elevation and topography, climates here oscillate between the moderately cold and the cold (Konček 1974). Total annual precipitation varies from 950 to 2000 mm. The long-term means for annual temperature range between +3°C and 0°C. Shallow alpine soil types, podzols and podzolic leptosols are dominant here. Vegetation cover consists of natural alpine grasslands with a prevalence of the Juncion trifidi association. Small clumps of dwarf pine (in Pinion mugi) diversify this relatively homogeneous vegetation structure at lower elevations.

The measurements in the Belianske Tatry were conducted at 10 sites of altitudes 1600–1850 m a.s.l. Mesozoic rocks (limestones, dolomites and Werfenian slates) dominate in this part of the mountains. Climatically, the territory comprises moderately cold or cold mountainous areas with mean annual temperatures ranging from +2°C to +4°C (Konček 1974). Mean annual precipitation is in turn of 900–1200 mm. Soils reflect the natural conditions close to a periglacial environment. The typical vertical zonation of soils is not developed here. The structure of soil cover is represented by lithic leptosols, leptosols, rendzinas, cambic rendzinas, podzolic cambisols and some other azonal subtypes (Bedrna et al. 2000). Vegetation reflects more fertile soil conditions on calcareous substrates through the presence of varied grassland communities of Class Elyno-Seslerietea, while communities of the Juncetea trifidi association occupy the less-fertile areas. Small clumps, or rarely larger areas, of dwarf pine stands complete the vegetational mosaic.

METHODS

While fieldwork to measure the intensity of recent geomorphic processes has been in progress in both areas since 2001, the Jalovecká Valley research follows work conducted in the 1990s (Hreško 1997). Frequency of measurement has depended on the type of process but has not taken place more rarely than once a year. A chronological database of photographs has been created for each site. A set of direct measuring methods has been used in the research: a) the method of one moving and one fixed point; b) the method of one moving between two fixed points; c) the method of coloured lines and squares.

The first method is based on the measurement of distances between one fixed and one “moving” point. The fixed point (a steel rod in the earth, or a mark on a stable boulder)
has to be set in a position in which much more limited geodynamic activity is assumed (even no activity at all). The “moving” point is located in a position in which activity is expected again taking the form of a steel or wooden stick, or else a mark on an unstable boulder. This method is used in the measurement of solifluction-gravitational processes, as well as the activity of ploughing boulders.

The method of a moving point between two fixed ones is used in measuring the edges of eolian-nivalitional niches and changes therein. The method is based on the measuring of the distance from a fixed point located outside the niche to the niche edge (the moving point) in the direction of the next fixed point inside the niche area.

The method of coloured lines and squares is used to measure the activity of the accumulated material within debris flows and debris slides, gravitational creep, or eolian deflation of debris particles. By means of the coloured straight lines sprayed (between two fixed points) on debris perpendicularly to the flow direction shifts of debris fragments can be measured over a specific time period. The coloured sampling squares (50 x 50 cm) are of 3 size categories according to the size of debris particles, with diameter limits up to 0.5 cm, 2 cm, and 5 cm, sprayed on the debris surface. They have been used to measure both shift distances and the amount of moved material (recalculated to square metres or as percentages). Where wind activity is concerned, only the shifts aside of the gravitationally conditioned flow direction can be taken into account. In addition to the distance measures, prevailing wind directions and wind intensity can also be estimated.

**DEBRIS FLOWS**

Debris flows can transport a considerable amount of saturated fragments of weathered
rock being accumulated below crags, furrows and gullies, often without any noticeable motion for several years or decades. The causes of debris flows can vary, but a frequently postulated triggering mechanism is the influence of water and the resulting increase of pore-water pressure (Hürlimann et al. 2003). In the Western Carpathians, the intensity of these processes have been investigated and evaluated by several studies (Lukniš 1973, Mahr 1973, Nemčok 1982, Midriak 1983, 1993, Kotarba 1996, Hreško 1994, 1996a, 1996b, 1997, Barka 2005, Rączkowska 2006).

In the area of the Jalovecká Valley it has proved possible to identify 47 debris flows, mostly located at altitudes of 1700–2100 m a.s.l., on slopes of 20–50° both north and south facing. The methods used do not entail measurement of the frequency of occurrence, size and dynamics of the debris flows in the strict definition of this phenomenon. Direct measures have focused on the dynamics of accumulated material after the real process of debris flow has become relatively stabilised. In line with the relationship between the transport dynamics and sizes of rock fragments, the material of debris flows has been categorised into (A) a group in intensive motion (mean size of fragments less than 2 cm); and (B) a group without or with less intensive motion (mean size of fragments greater than 5 cm). Mean annual movements of some centimetres (group B) up to 4 metres (group A) have been measured.

In the area of the Belianske Tatry Mts., the observed debris flows are located at altitudes of 1650–1750 m a.s.l., on SW-facing slopes with inclinations of 25–45°. The measured values of the shift (for mean size of debris fragments = 5 cm) in the source zone are 0.5–1.5 m/year; cf. 1.5–10 m/year in the transport zone and 0.3–1 m/year in...
the accumulation zone. The most intensive transport activity is observed each year after the spring melt, as well as at various times during heavy rainstorms, when it is mainly the finer debris that moves down—prevailingly along the centreline of the debris flow (Plate 2).

DEBRIS SLIDES

It is displacement of a soil profile including weathering mantle and, possibly, periglacial debris that creates debris slides. Unlike the debris flows, these gravitational forms accumulate coarser material in bottom parts (Mazúr 1955). The generation of debris slides is associated with smooth hillsides with slope angles over 30°, once a waterlogged debris layer becomes separated from the subsoil and begins to move down (Plesník 1971, Lukniš 1973). This process nevertheless resembles that involved with debris flows in being conditioned by water supply and gravitation. Debris slides mainly affect shallow layers of fine debris.

In the Jalovecká Valley, the occurrence of the latter has been registered on slopes with angles in the range 20–50°, at altitudes of 1600–2100 m a.s.l. generally in south-facing areas. The measurements of debris dynamics have been made by means of coloured lines (distance measures) and squares (distance and area measures). Differences in dynamics in relation to the size of fragments have been determined as well. While the fragments of mean size greater than 5 cm have been transported up to 1 metre, rarely 2 metres per year, those smaller than 2 cm moved 2–4 metres per year. Results of measurements from the 1990s (Hreško 1997) reveal shifts of 0.4–1.2 metres per year.

EOLIAN-NIVATIONAL PROCESSES

Wind activity represents a significant phenomenon in an alpine environment (Midriak 1983). The effect of wind erosion is expressed mainly in deflation that causes the transport of fine debris particles on (or above) the surface, with larger residual frag-
The intensity of the process can increase when the ice crystals drift in the wind. Indirect eolian activity is connected with snow transfer from windward to leeward sides of crests, thus forming snowdrifts as sources for either avalanche triggering or the nivation processes characteristic of long-term snow patches.

The erosive effect of snow accumulations (nivation niches) on the surface is significant in areas with discontinuous vegetation cover, though it differs in relation to slope type, in that there is lithologically-controlled fragment-size composition of cover. The role of melt water is thus different in various lithological types of niches (Rączkowska 1995).

Observations on snow dynamics in relation to snow redistribution by eolian drift and its role in water balance have also been made in the Jalovecká Valley (Holko, Koštka and Parajka 2003).

Plate 4. Installation of coloured squares
(a) on the surface of the eolian-nivational niches (at 1925 m a.s.l.) below the plateau of the western branch of Mt. Salatín;
(b) displacement of debris fragments after 5 months (in the May-October period).

Patches affected by eolian deflation and nivation have been identified at 114 sites in the Jalovecká Valley, these occupying a total area of 1.8 ha. They are usually located on crest positions, close to the edges of summit plateaus or saddles at altitudes of 1800–2100 m a.s.l., on gentle slopes of various aspects, if with a prevalence of N-NW and S-SW sectors.

Measurements were made at 7 sites (see Table 1 and Fig. 2). The results from observations based on coloured squares reveal losses of fine (less than 0.5 cm) particles equal to 50–70% of the square area. This compares with 0–30% a year in the case of coarse debris of up to 5 cm. The distance measurements as regards debris transport by nivation have detected shifts of 10–200 cm/year depending on slope inclination and the size of debris fragments. Drifts of fine particles by means of wind action have reached 10–110 cm/year, while drift angles indicate the prevalence of the S-SE wind directions.
Measurements of the degree of widening of niches by means of abrasion of edges have been made at 2 sites. Average shifts of 0.5 up to 2.5 cm per year have been reported. Previous research (Hreško 1997) reported values of 0.5–1.5 cm/year, or 5–10 cm/year in sporadic cases.

Average values from measurements made at sites in the Belianske Tatry Mts. vary from 0.5 to 2 cm/year. Kotarba (1976) gives values

Table 1. Characteristics of sampling sites.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Process/Form</th>
<th>Altitude [m a.s.l.]</th>
<th>Mean slope [deg.]</th>
<th>Aspect</th>
<th>Soil and/or Lithology</th>
<th>Land Cover (in site / vicinity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Jalovecká valley</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>1</td>
<td>ploughing boulder</td>
<td>1725</td>
<td>35</td>
<td>SE</td>
<td>dolomitic block</td>
<td>grassland / dwarf pine</td>
</tr>
<tr>
<td>2</td>
<td>eolian-nivalional</td>
<td>1920</td>
<td>5</td>
<td>SW</td>
<td>fine granitoid debris</td>
<td>debris / grassland</td>
</tr>
<tr>
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<td>eolian-nivalional</td>
<td>1920</td>
<td>15</td>
<td>SW</td>
<td>granitoid debris</td>
<td>debris / grassland</td>
</tr>
<tr>
<td>4</td>
<td>eolian-nivalional</td>
<td>1920</td>
<td>5</td>
<td>SW</td>
<td>granitoid debris</td>
<td>debris / grassland</td>
</tr>
<tr>
<td>5</td>
<td>eolian-nivalional</td>
<td>1925</td>
<td>3</td>
<td>SW</td>
<td>granitoid debris</td>
<td>debris / grassland</td>
</tr>
<tr>
<td>6</td>
<td>eolian-nivalional</td>
<td>1890</td>
<td>7</td>
<td>SW</td>
<td>fine granitoid debris</td>
<td>debris / grassland</td>
</tr>
<tr>
<td>7</td>
<td>solifluction lobes</td>
<td>1880</td>
<td>30</td>
<td>SW</td>
<td>Podzolic Leptosols</td>
<td>grassland / coarse granitoid debris</td>
</tr>
<tr>
<td>8</td>
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<td>1875</td>
<td>30</td>
<td>SW</td>
<td>granitoid block</td>
<td>grassland</td>
</tr>
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<td>9</td>
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<td>1875</td>
<td>30</td>
<td>SW</td>
<td>granitoid debris</td>
<td>debris / grassland</td>
</tr>
<tr>
<td>10</td>
<td>debris shift</td>
<td>1850</td>
<td>32</td>
<td>SW</td>
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<td>debris / grassland</td>
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<tr>
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<td>granitoid debris</td>
<td>debris / grassland</td>
</tr>
<tr>
<td>12</td>
<td>debris flow</td>
<td>1930, 1800</td>
<td>35</td>
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<td>debris / grassland</td>
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<td>1935</td>
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<td>N</td>
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<td>debris / grassland</td>
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<tr>
<td>15</td>
<td>debris flow</td>
<td>1675, 1700, 1725</td>
<td>35</td>
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<td>debris, tufts of grass / grassland</td>
</tr>
<tr>
<td>16</td>
<td>debris flow</td>
<td>1740</td>
<td>35</td>
<td>S</td>
<td>coarse dolomitic debris</td>
<td>debris / grassland, dwarf pine</td>
</tr>
<tr>
<td>17</td>
<td>debris flow</td>
<td>1720</td>
<td>35</td>
<td>S</td>
<td>coarse dolomitic debris</td>
<td>debris / grassland</td>
</tr>
<tr>
<td>18</td>
<td>debris creep</td>
<td>1916</td>
<td>40</td>
<td>SW</td>
<td>dolomitic debris</td>
<td>debris, tufts of grass / grassland</td>
</tr>
<tr>
<td>19</td>
<td>debris creep</td>
<td>1780</td>
<td>35</td>
<td>SW</td>
<td>coarse dolomitic debris</td>
<td>debris / grassland</td>
</tr>
<tr>
<td>20</td>
<td>eolian niche</td>
<td>1763</td>
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<td>N</td>
<td>fine slate debris</td>
<td>debris / grassland</td>
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<tr>
<td>21</td>
<td>eolian niche</td>
<td>1830</td>
<td>15</td>
<td>N</td>
<td>fine slate debris</td>
<td>debris / grassland</td>
</tr>
<tr>
<td>23</td>
<td>eolian niche</td>
<td>1825</td>
<td>3</td>
<td>NW</td>
<td>fine slate debris</td>
<td>debris, tufts of grass / grassland</td>
</tr>
<tr>
<td>24</td>
<td>solifluction lobes</td>
<td>1920</td>
<td>30</td>
<td>E</td>
<td>Podzolic Cambisols</td>
<td>grassland / coarse debris</td>
</tr>
<tr>
<td>25</td>
<td>solifluction lobes</td>
<td>1760</td>
<td>30</td>
<td>S</td>
<td>Cambic Rendzinas</td>
<td>grassland / coarse calcareous debris</td>
</tr>
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</table>
of 3–16 cm/year for limestone area at sites at similar altitudes. Our results also indicate seasonal retrograde fluctuations, in that, for example, the direction of the shift between May and August 2001 was counter to the total annual shift between May 2001 and June 2002. It is assumed that this is caused by soil cohesion and volume changes during periods of freezing and thawing.

**SOLIFLUCTION**

Solifluction, broadly defined as slow mass wasting resulting from freeze–thaw action in fine-textured soils, involves several components: needle ice creep and diurnal frost creep originating from diurnal freeze–thaw action; annual frost creep, gelifluction and plug-like flow originating from annual

Plate 5. The Jalovecká valley. Sequence of solifluction-gravitational lobes (highlighted by white dashed lines) on the SW slope of the Mt. Brestová side branch (at 1875 m a.s.l.). Black arrow indicates position of “moving point” on garland vertex.
freeze–thaw action; and retrograde movement caused by soil cohesion (Matsuoka 2001). Lukniš (1973) described solifluction lobes as elongated steps on slopes inclined by more than 22° on which turf soil is pushed up into arched ramparts at the front. The lower limit of solifluction activity in the Western Carpathians is to be found at altitudes of about 1700–1800 m a.s.l. (Kotarba 1976).

Relevant measurements in this case were made at 3 sites: one in the Jalovecká Valley (at an altitude of 1875 m a.s.l.), and two in a region of the Belianske Tatry Mts (at 1920 m

and 1760 m a.s.l.). The heights of lobes vary from 0.5 m to 1.5 m, while lengths are of 3 up to 5 metres. Values measured in the Belianske Tatry Mts. indicate displacements of 1–2.5 cm/year; in the Jalovecká valley the average values are 0.5–2 cm/year. Previous observations (Hreško 1997) have not been recorded any displacements.

A complex form consists of three elements—the boulder itself (usually of 1–1.5 m in diameter), and its frontal mound and upslope furrow as evidence of displacement. Mean annual shifts are generally of less than 1 cm, only sporadically exceeding 2 cm/year (Kotarba 1976, Hreško 1997). Measurements made in the period 2001–2007 revealed shifts of 0.5–1.5 cm/year on average.

PLoughing BOULders

Ploughing boulders represent a relatively common phenomenon in the periglacial environment. They occur in areas of active solifluction, on frost-susceptible soils with low plastic and liquid limits allowing for the frost heaving and creeping of blocks. During movement these rotate to adopt an alignment of least resistance (Berthling et al. 2001, Ballantyne 2001). The co-occurrence of ploughing boulders and stony lobes has been confirmed (Lukniš 1973, Garcia-Ruiz et al. 1990).

Plate 6. Measuring ploughing boulder (site no. 10) displacement on the SW slope of Mt. Brestová.
CONCLUSION

Research on periglacial processes assumes particular importance in light of the need to identify climate change. The activity or passivity of the process, or else signs of changing intensity can point to both long-term climatic shifts and short-term fluctuations. Detailed monitoring-like observation supports the evaluation of such environmental problems as erosional processes, changes in the structure of vegetation associations and the possible invasion of allochtonous species into disturbed patches.

The results presented here confirm that processes have been maintained at relatively constant intensity. However, since 2000, the alpine environment has experienced a moderate increase in fluviation and more frequent activity as regards processes linked to nivation. However, final confirmation of this trend will require testing of the correlations with climatic data.

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Paper first received: February 2008
In final form: May 2008