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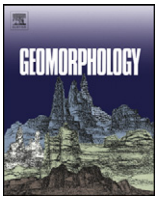

Reflection of climate changes in the structure and morphodynamics of talus slopes (the Tatra Mountains, Poland)

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ABSTRACT

Talus slopes beside glaciers are among the best objects to research on climate change. In the Tatra Mountains, the highest mountains of central Europe, no glaciers remain, only glacierets and permafrost. For that reasona complex investigation of talus slopes was conducted there in the years 2009–2010. This paper presents the results of GPR and lichenometric measurements of the talus slopes in six glacial cirques located in the High and Western Tatras. The thickness and internal structure of talus slopes were identified along with the variability and conditions of their development. Maximum thickness of the talus slopes ranges from 20 to 35 m, reaching higher values in the High Tatras. The diversity of the thickness of the talus slopes within the Tatras is mostly explained by differences in the relief conditioned by lithology. The diverse altitudinal locations of the talus slopes, and the exposure and inclinations are not reflected in the size and thickness. The thickness of the studied slopes depends primarily on the activity of the processes supplying rock material and on the size and shape of the sediment supply area. The results of the lichenometric testing together with the analysis of the long-term precipitation data imply a several hundred-year-long deterioration of the climate during the Little Ice Age, which is reflected in the increased activity of morphogenetic processes on the talus slopes across the whole massif of the Tatras. In the last 200 years, the talus slopes of the Tatras were most active in three periods: at the end of the Little Ice Age, in the 1930s and 1940s, and in the early 1970s.

1. Introduction

Talus slopes are among the most widespread elements of high-mountain relief. Their development is conditioned by the geological structure and relief of the sediment supply area (e.g., Densmore et al., 1997; Hetu and Gray, 2000) as well as by the processes of weathering, erosion, transport and accumulation of rock debris (e.g., Kotarba and Strömquist, 1984; Kotarba et al., 1987; Sass and Krautblatter, 2007; Fort et al., 2009; Krautblatter et al., 2012). The former factors are generally invariable over time, whereas the dynamics of geomorphological processes depend on hydrometeorological conditions whose variability reflects characteristics of the climate. Therefore, the thickness, internal structures and microrelief of the surface of debris slopes in glacial cirques may reflect the type of morphogenetic processes and changes in climatic conditions since deglaciation; however, the knowledge of this record is still limited (Sass and Krautblatter, 2007). More about the activity of the slopes may be concluded on the basis of the results of lichenometric dating of the surface of talus slopes, whose time frame is limited, however, merely to the recent centuries (e.g., Bull et al., 1994; Kotarba, 1989, 1995, 2004; McCarroll et al., 2001). On the other hand, correlating the results of lichenometric dating is possible with the results of instrumental meteorological measurements and thus deducing the impact of climate change on the morphodynamics of the slopes.

Frost weathering is the major process responsible for the supply of debris material building the talus slope. This material may be transported to talus slopes by various processes, mainly by debris flows, topplings and snow avalanches. These processes, along with weathering, determine the development of talus slopes. Therefore, various models of the accumulation on debris slopes have been developed to match the conditions in different regions of the world (e.g., Caine, 1969; Statham and Francis, 1986; Rapp and Nyberg, 1987). However, the model of accumulation designed for one region only may be different in time and within a limited space, i.e., at different places located in close vicinity to each other (Whitehouse and McSaveney, 1983).

Many researchers express the opinion that the development of debris slopes is the consequence of the interaction of the processes of detachment by rockfall and redistribution of debris material mainly by debris flows (e.g., Francou, 1991; Kotarba, 1992; Hinchliffe et al., 1998). Over time, the segmentation of rockwalls with couloirs also favours reworking of talus by channeling the water flow onto the talus,

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which causes debris flows and gully incision and increases sediment connectivity (Fryxell and Horberg, 1943; Becht et al., 2005; Sass and Krautblatter, 2007; Heckmann et al., 2012). The beginning of the formation of talus slopes is also disputable. According to Ballantyne (2002), they were formed in the periglacial climate during the period of deglaciation, and later on they were given mere 'retouches' mainly by the debris flow activity. Also Curry and Morris (2004) pointed out a change in the processes shaping high mountain slopes in the period between the Late Glacial and Holocene, emphasizing the increasing role of debris flows in the transformation of the slope and the decreasing importance of microgelivation in the temperate climate zone in the Holocene.

The impact of the last, conspicuous cooling of the climate during the Little Ice Age on the development of debris slopes manifested itself in an increased supply of the material through rockfall (e.g., McCarroll et al., 2001; Kotarba and Pech, 2002) or an increase in the activity of debris flows (e.g., Nyberg and Lindh, 1990; Strunk, 1992; Kotarba, 1995;). The subsequent climate warming resulted in an escalation of catastrophic processes in the mountains (e.g., Evans and Clague, 1994; Fort et al., 2009). Many researchers in recent years have shown the impact of climate changes, including an increase in the number of intense rainfall events and/or in temperatures on the activity of debris flows (e.g., Haeberli et al., 1990; Zimmerman and Haeberl, 1990; Kotarba, 1997; Rebetez et al., 1997; Jomelli et al., 2004; Pelfini and Santilli, 2008).

In the Tatra Mountains, talus slopes have been the subject of numerous studies (e.g., Kotarba et al., 1983, 1987; Kaszowski et al., 1988; Klimaszewski, 1988; Krzemień et al., 1995; Ferber, 2002; Kotarba, 2004). They concerned the origin and contemporary morphodynamics of the slopes. Models of the formation of the talus slopes of this region were presented by Kotarba et al. (1987).

Currently in the Tatras, the most extensively modified slopes are those within an altitude of about 1500 m asl, the upper limit of timberline, and about 1950 m asl. The highest accumulation of loose gravitational deposits (mainly in the form of talus slopes) and glacial and glacifluvial sediments occurs in this area, which are easily displaced under the influence of extreme hydrometeorological events. Because of the morphogenetic role (evidenced by new landforms) and the amount of dislocated material, debris flows belong to the most important processes (Kotarba, 1992, 1995, 1997; Rączkowska, 2006; Rączkowska et al., 2012; Kotarba et al., 2013). Above and below the aforementioned range of altitude, the intensity of geomorphological processes becomes lower partly because of less frequent freeze–thaw cycles (Kotarba et al., 1987).

However, because the thickness and internal structure of talus slopes were unknown, it was not possible to recognize the variability and conditions of the development. This paper presents the results of GPR and lichenometric measurements of the talus slopes in six glacial cirques located in the High and Western Tatras (Fig. 1). The slopes are different regarding altitude, size, and exposure as well as the geological structure and relief of the sediment supply area (Table 1). It was the first time that in such diverse sites within one mountain range of the temperate zone, information concerning internal structure, morphogenesis, and morphodynamics of the talus slopes had been collected; and for the purpose of its interpretation, multidecadal data on the intensity of rainfall had been employed. This allows us to present the complexity of the post-glacial evolution of high mountain talus slopes in the temperate zone, which is the main objective of this work.

2. Regional setting

2.1. Geology and relief

The Tatra Mountains are of alpine character, elevated up to 2655 m asl (Gerlachovský štít peak). The Tatra Mountains are composed of a crystalline core formed of intrusive Carboniferous granitoids of the High Tatras and metamorphic rocks (Paleozoic rocks: gneiss, amphibolite, metamorphic shale) occurring mainly in the Western Tatras. The core is rimmed by allochthonous High Tatric Nappe and Sub-Tatric Nappes, consisting of quartzites, dolomites, limestones, marls, shales, and sandstones of the Triassic-Middle Cretaceous age (Książkiewicz, 1972; Nemčok et al., 1994; Oszczypko, 1995). The entire Belianske Tatras are built up of nappes of Mesozoic sedimentary rocks (Bezák et al., 1993; Nemčok et al., 1994).

In the Neogene, the Tatras were dissected by fluvial–denudational valleys, which underwent rejuvenation in the Pleistocene mainly through glacial and periglacial processes (Klimaszewski, 1988; Baumgart-Kotarba and Kotarba, 2001). As a result, in the High Tatras a system of glacial cirques was formed, often arranged in tiers, and glacial troughs, both with very steep and rocky slopes, deeply incised by couloirs. At the outlets of the couloirs, large talus cones developed, which are currently modified mainly by debris flows (Kotarba 1992, 1997). In the Western Tatras only the upper sections of the valleys underwent glaciations. The bottoms of the cirques are not overdeepened, and the rocky slopes and rock walls are shorter than in the High Tatras and often replaced by debris-mantled slopes (Klimaszewski, 1988). Currently, in the Tatras only glacierets and

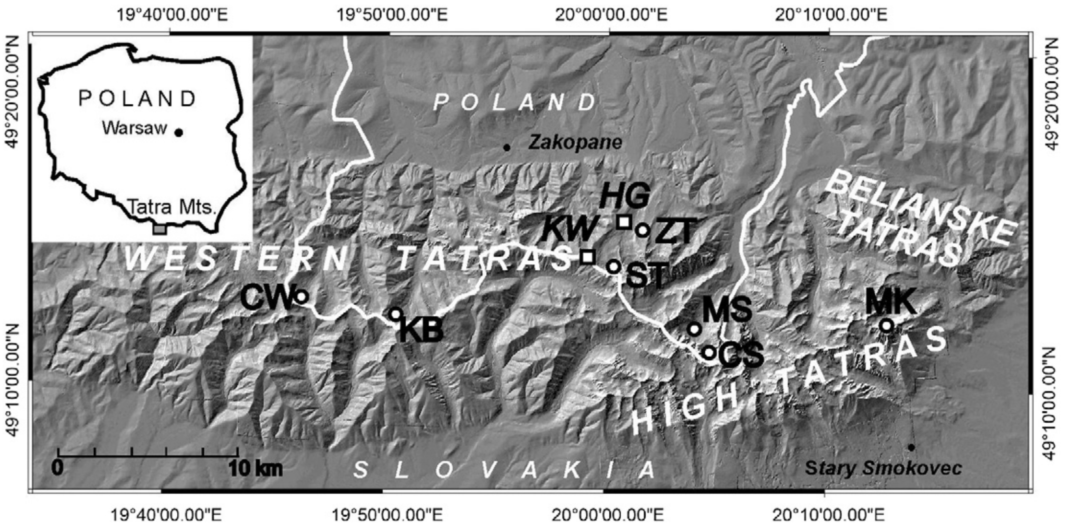

Fig. 1. Study area. Dots — location of studied slopes: CW — Szeroki Piarg on N slope of Wołowiec peak, KB — N slope of Błyszcz peak, ST — N slope of Skrajna Turnia peak, ZT — W slope of Żółta Turnia peak, MS — Szeroki Piarg over Morskie Oko lake, CS — Wielki Piarg over Czarny Staw pod Rysami lake, MK — Medená kotlina valley. Quadrats — location of meteorological stations: KW — Kasprowy Wierch, HG —Hala Gąsienicowa.