1. Introduction

Rock glaciers are tongue- or lobate-shaped landforms resulting from downslope creeping of ice-rich debris in mountain permafrost conditions (e.g. Barsch, 1996; Berthling, 2011; Kääb, 2013). Most rock glaciers exhibit characteristic surface morphology consisting of steep frontal and lateral slopes (for active rock glaciers mostly steeper than the angle of repose) enclosing rugged upper surface with frequent longitudinal and transversal ridges and furrows emerging due to the compression of debris-ice mixture associated with the rock-glacier flow, closely resembling lava streams (Kääb, 2013). Because of high portion of non-ice component, rock glaciers are usually able to retain much of their morphology long after the permafrost body has completely thawed (Hughes, Gibbard, & Woodward, 2003), meaning they can be identified even in a relict state and under vegetation cover if high-resolution remotely sensed imagery or digital elevation models are available (e.g. Colucci, Boccali, Žebre, & Guglielmin, 2016; Kellerer-Pirklbauer, Wagner, & Winkler, 2016).

Active and inactive rock glaciers represent important component of mountain cryosphere because they contain significant volumes of ground ice and act as long-term stores of water, even in arid or semi-arid regions (e.g. Azócar & Brenning, 2010; Brenning, 2005; Burger, Degenhardt, & Giardino, 1999; Millar, Westfall, & Delany, 2013). Analogously, relict rock glaciers indicate the existence of large amounts of ground ice in the past (e.g. Barsch, 1996; Kääb, 2013) and because of a high storage capacity they noticeably affect current hydrology of mountain watersheds as well (e.g. Wagner, Pauritsch, & Winkler, 2016; Winkler et al., 2016). Furthermore, rock glaciers are highly sensitive indicators of both present and past climate and permafrost evolution (e.g. Barsch, 1996; Frauenfelder & Kääb, 2000; Haeberli et al., 2006), which can be mapped rapidly and at low cost to build-up extensive databases of permafrost evidence over large spatial scales. Consequently, there is a worldwide interest to compile rock-glacier inventories for a number of both purely scientific and practical reasons. In Europe, these investigations have been realized in larger scale particularly in the Alps (e.g. Baroni, Carton, & Seppi, 2004; Colucci et al., 2016; Kellerer-Pirklbauer, Lieb, & Kleinfetterner, 2012; Krainer & Ribis, 2012; Nyenhuis, Hoelzl, & Dikau, 2005; Scotti, Brardinoni, Alberti, Frattini, & Crosta, 2013; Seppi et al., 2012), the Pyrenees (e.g. Chueca, 1992; Serrano, Agudo, & Martinez de Pison, 1999), the Scandinavian Mts. (e.g. Lileøren & Etzel-müller, 2011; Sollid & Sorbel, 1992) and the Southern Carpathians (e.g. Onaca, Ardelean, Urdea, & Magori, 2017; Urdea, 1992).

Unlike the above regions, rock-glacier mapping in the Western and High Tatra Mts., Western Carpathians (Slovakia and Poland), has been much less intensive. Rock glaciers in the study area were first noted by Partsch (1923) who reported their occurrence in the High Tatra Mts. Later on, Klimaszewski (1948, 1988) and Jahn (1958) described rock glaciers in the Polish territory of the region and called them ‘debris
glaciers’ and ‘patch rock glaciers’, respectively. In the Slovak territory, many rock glaciers were described by Lukniš (1973) throughout the entire area of the High Tatra Mts., but they were referred to as ‘firm moraines’. A year later, Nemčok and Mahr (1974) published the most extensive rock-glacier inventory to date, in which they reported 13 and 18 sites with rock-glacier occurrence in the Slovak territory, many rock-glacier studies have emerged since the turn of the eighties and nineties (Baumgart-Kotarba & Kotarba, 2001; Dzierżek, Lindner, & Nitychoruk, 1987; Dzierżek & Nitychoruk, 1986; Kaszowski, Krzemień, & Libelt, 1988; Kociuba, 1996; Kotarba, 1986, 1988, 1991–1992, 1992; Kotarba, Kaszowski, & Krzemień, 1987; Libelt, 1988), but exclusively from the Polish side of the mountains. This imbalance began to equalize from 2004 when Kędzia, Kotarba, and Mościcki (2004) published their case study of a single rock glacier located near the Velké Honcovo pleso Lake in the Slovak High Tatra Mts. and since then, a large amount of work related to rock glaciers has been carried out in both Slovak (Klaptya, 2009, 2010, 2011, 2012, 2013a, 2013b; Pánek et al., 2015; Pánek et al., 2016; Zasadni & Klaptya, 2014) and Polish territory (Klaptya, 2008, 2013b, 2015; Klaptya & Kołaczek, 2009; Kotarba, 2007, 2013; Makos, Rinterknecht, Braucher, Żarnowski, & Aster Team, 2016; Zasadni & Klaptya, 2016) of the mountain ranges. In a surprising contrast, no rock glaciers have been reported in the regional overview of periglacial landforms occurring in the Western and High Tatra Mts. compiled by Rączkowska (2007). Most rock glaciers in the region are thought to be relict landforms (Kędzia, 2014) of the Late Glacial or the early Holocene age (e.g. Kaszowski et al., 1988; Klaptya, 2011, 2013a; Kotarba, 1988, 2007).

Despite a considerable effort resulting in the above extensive list of literature, there still remain large areas both in the Western and High Tatra Mts., where rock glaciers have not been mapped yet. Furthermore, many previous investigations are only descriptive, incomplete and do not enable to determine the rock-glacier occurrence precisely or to extract their morphological attributes. Finally, none of the above rock-glacier studies have focused on the entire area of the Western and High Tatra Mts. Accordingly, the aim of our study is to complete the information on rock-glacier occurrence based on remotely sensed mapping, validated by field and literature data, and to introduce the first detailed map of rock glaciers covering the entire area of the Western and High Tatra Mts.

2. Study area

The Western and High Tatra Mts. are c. 42 km and c. 26 km, respectively, long mountain ranges, located in the northernmost part of the Carpathian arc and stretching longitudinally along the Slovak-Polish border (Figure 1). They reach their maximum elevations of 2248 m asl and 2655 m asl at the top of Bystrá Peak and Gerlachovský štít Peak, respectively. Geology of the mountain ranges is dominated by Carboniferous-Permian granitic rocks, enriched with Palaeozoic metamorphic rocks, such as gneisses, migmamites or amphibolites in the Western Tatra Mts. On northern sides of the mountain ranges, the crystalline core is overlaid by thrust sheets of Mesozoic sedimentary rocks, particularly limestones and dolomites. The foothills have an extensive cover of Cretaceous-Palaeogene fylch rocks, such as claystones, siltstones, sandstones, conglomerates and breccias (Jurewicz, 2007; Nemčok et al., 1994; Figure 2).

Extensive glaciers recurrently evolved during the cold phases of the Pleistocene (Figure 3), which resulted in typical alpine-type topography with numerous cirques, U-shaped valleys and distinct moraine ridges in both mountain ranges (e.g. Křížek & Mida, 2013; Makos, Nitychoruk, & Zreda, 2013a, 2013b; Zasadni & Klaptya, 2014), but all pronouncedly more developed in the High Tatra Mts. Currently, the mountains host no glaciers, but perennial snowfields and firm-ice patches can be found in suitable locations (Gadék, 2014). In the period 1981–2010, the mean annual air temperature (MAAT) at the top of Lomnický štít Peak, at 2635 m asl, was –3.4 °C and mean annual precipitation amounted 1653 mm (Slovak Hydrometeorological Institute). The present-day climatic snowline has been calculated at c. 2500–2600 m asl and c. 2700–2800 m asl on northern and southern slopes, respectively (Zasadni & Klaptya, 2009), and the lower limit of discontinuous permafrost has been estimated at 1930 ± 150–200 m asl based on the analysis of air thawing and freezing indices and complementary geophysical soundings and measurements of bottom temperature of snow (Dobiński, 1997a, 2004, 2005).

3. Methods

3.1. Areal extent and coordinate system

The map focuses on the Western and High Tatra Mts. in a scale of 1 : 40 000 and covers the area of 838.34 km² between c. 49°06′–49°17′ N and c. 19°39′–20°15′ E (Figure 1). The map is projected in the coordinate system WGS 1984 UTM Zone 34N. Accordingly, some layers, originally acquired in the coordinate system S-JTSK (based on Bessel ellipsoid), had to be transformed into the map projection. Considering the medium map scale, we converted the data using the transformation tools implemented in ESRI ArcMap 10.3. We employed the most accurate transformation algorithm (c. 1 m error) according to our own testing of the conversion accuracy between the above two coordinate systems (Křížek, Uxa, & Mida, 2016).
3.2. Topography and additional map content

3.2.1. Digital elevation model

We used the existing digital elevation model (DEM) with a horizontal resolution of 10 m produced by stereo photogrammetry from aerial images (Tatra National Park, 2009) as a primary topographic base for the Main Map and as a supplementary source of information for mapping of rock glaciers, delineation of their contributing areas and extraction of elevation attributes. The model represents the most detailed and most widely utilized DEM covering the entire study area to date. Nonetheless, it contains elevation errors and other defects, such as straight break lines, which are mostly located in lower elevated areas unoccupied by rock glaciers, particularly along the alpine treeline and adjacent forest belt located on southern slopes (cf. Zasadni & Klapyta, 2014). Therefore, the model was adjusted prior to final map compilation so that the defective parts and their immediate surroundings (accounting for c. 11% of the DEM area) were replaced by a supportive co-registered 10 m DEM constructed from contour data with equidistance of 10 m provided by the Geodetic and Cartographic Institute Bratislava (GCIB). Both models were merged together and filtered by averaging within a moving window of 5 × 5 cells to ensure smooth transition at the contact of the models. Subsequently, shaded relief and contours with equidistance of 50 m were generated based on this updated and smoothed DEM and thereafter used in the final map.

3.2.2. Other topographic features

Beside the above DEM-based elements, we also added a set of elevation points into the map to provide complementary elevation information. In addition, other topographic features, such as watercourses, lakes, roads, railways, cable cars, built-up areas and state boundary, were integrated into the map for better orientation.

The elevation points and cable cars were obtained by digitizing the national topographic map series in a scale of 1 : 25 000 and 1 : 50 000 accessible on geoportals of the GCIB (geoportal.sk) and the Head Office of Geodesy and Cartography (HOGC; geoportal.gov.pl). In the Slovak territory of the study region, watercourses and lakes were taken from the database SVM 50, which is based on the Basemap of Slovak Republic in a scale of 1 : 50 000. In the Polish territory, these topographic features were acquired by manual digitization of the topographic map accessible at the geoportal of HOGC. Roads, railways and built-up areas for the entire area were extracted from the freely available OpenStreetMap database (download.geofabrik.de).

The topographic layers were checked for quality and particularly their mutual consistency and, if necessary, they were manually adjusted, for example, watercourse directions were slightly changed to appropriately fit the contour lines.

3.2.3. Additional map content

We included a schematic geological map (Figure 2) based on Nemčok et al. (1994) and Bezák et al.
as a background layer in the Main Map in order to infer bedrock lithology of rock glaciers, with division into five geological units: Palaeozoic gneiss rocks, migmatite and amphibolite; Carboniferous-Permian granitic rocks; Mesozoic limestone, dolomite, sandstone, shale and quartzite; Cretaceous-Palaeogene claystone, siltstone, sandstone, conglomerate and breccia; and Palaeogene sandstone, limestone, conglomerate and breccia. Furthermore, the above layer was complemented with both proved and assumed faults based on the same data sources.

We also added the Last Glacial Maximum glacier extent in the Tatra Mts. (Figure 3) after Zasadni and Klapyta (2014) to provide information about the relationship between rock glaciers and former glaciation limit.

Finally, as rock glaciers are widely accepted indicators of the lower limit of discontinuous mountain permafrost (Barsch, 1996), we show the level of 1930 m asl in the Main Map, which corresponds to the average minimum elevation of discontinuous permafrost occurrence in the Tatra Mts. suggested by Dobiński (1997a, 2004, 2005).

3.3. Rock glaciers
3.3.1. Rock-glacier mapping
We mapped rock glaciers (Figure 4) throughout the entire area of the Western and High Tatra Mts. using aerial photographs from years 2010–2015 with a resolution of 0.1, 0.25, 0.5 and 1 m accessible on geoportals of the GCIB and HOGC and on Google Earth. Rock glaciers were identified and double-checked by both authors based on their typical surface morphological features visible on aerial imagery (Figure 5), such as steep frontal and lateral slopes and longitudinal and/
or transverse ridges and furrows. In areas with closed or semi-closed vegetation cover, we followed vegetation patterns associated with the rock-glacier surface morphology as well (Barsch, 1996). The mapping was also supported by field inspections in 2014, 2015 and 2016, during which c. 22% of the mapped landforms, mostly located in the High Tatra Mts., were visited and their occurrence and delineation was verified. The survey was supported by previous literature reports and maps as well (Dzierżek & Nitychoruk, 1986; Klapyta, 2008, 2009, 2010, 2011, 2012, 2013a, 2013b, 2015; Klapyta & Kolaczek, 2009; Kotarba, 1988, 1991–1992, 2007; Nemčok & Mahr, 1974; Zasadni & Klapyta, 2016) that enable to extract precise information about the location of rock glaciers. However, we did not take over the literature information completely in all cases because the above mappings have emerged over several decades and had inconsistent data sources and mapping methodologies. Consequently, there is occasionally no consensus among researchers regarding the landform identification or classification. An excellent example of this inconsistency is the debris accumulation located near the Zadni Staw Polski Lake in the Pięciu Stawów Polskich Valley in the Polish High Tatra Mts., which was classified as a rock glacier (Dzierżek et al., 1987), a moraine ridge (Makos et al., 2013a) as well as a rock avalanche (Zasadni & Klapyta, 2016). Therefore, we carefully considered the integration of each individual previously mapped landform into the database mainly based on its appearance on aerial imagery in order to ensure the consistency of the inventory in terms of landform identification, classification and delineation throughout the whole region.

Each rock glacier was manually delineated along the foot of its frontal and lateral slopes towards the rooting zone (Figure 5) based on aerial photographs (c.f. Baroni et al., 2004; Colucci et al., 2016; Kellereer-Pirklbauer et al., 2012; Krainer & Ribis, 2012; Nyenhuis et al., 2005; Onaca et al., 2017; Scotti et al., 2013). In the lower part, the interface between the rock glacier and its surroundings was in most cases clearly discernible. On the contrary, a distinction between the rock-glacier rooting zone and the above-lying contributing area was often much more difficult to differentiate (c.f. Colucci et al., 2016; Krainer & Ribis, 2012). In such cases, the boundary was identified by both visual inspection of aerial images and searching for a sudden change in the DEM-derived slope inclination. Places with gradient exceeding the angle of repose of c. 35° (Barsch, 1996) were implicitly considered as parts of the contributing area, probably corresponding to debris-free rock slopes or rock walls (sensu Gądek, Grabiec, Kędzia, & Rączkowska, 2016). The layers of slope inclination

Figure 4. (A) Intact talus rock glacier near the Pusté pleo Lake in the Velká Studená Valley, High Tatra Mts.; (B) relict talus rock glacier in the Kobylia Valley, Western Tatra Mts.; (C) fronts of intact and relict debris rock glaciers in the Slavkovská Valley, High Tatra Mts.; (D) densely vegetated relict talus rock glacier in the Furkotská Valley, High Tatra Mts.; note the person in the foreground for scale.

Note: White dashed lines delineate rock-glacier fronts.
and shaded relief were also employed to refine the delineation of some large rock-glacier outlines. In cases where more rock-glacier bodies merge to form so-called multipart rock glacier (Barsch, 1996), we delineated each of these distinguishable parts individually (c.f. Falaschi, Castro, Masiokas, Tadono, & Ahumada, 2014; Kellerer-Pirklbauer et al., 2012).

3.3.2. Rock-glacier classification

After completion of the rock-glacier mapping, we classified rock glaciers according to the main source of material, permafrost presence and activity, and bedrock lithology.

Two rock-glacier categories, talus rock glaciers and debris rock glaciers (Barsch, 1996; Figure 4), were adopted to differentiate the landforms based on the main source of material. As talus rock glaciers are regarded those landforms, which are unambiguously related to talus slopes situated above, delivering frost-shattered rock fragments for rock-glacier formation, and do not significantly extend down to the bottom of the valley. By contrast, debris rock glaciers are usually more extensive debris deposits, mostly covering valley floors, which evolve particularly from moraine-derived materials. We also include the most distinct landforms referred to as protalus (pronival) ramparts into the first category for two main reasons. Firstly, these landforms are usually very difficult to differentiate from talus rock glaciers not only from aerial imagery, but also in the field (e.g. Hedding, 2016; Hedding & Sumner, 2013). Secondly, these geomorphic features are largely genetically related to talus rock glaciers and

Figure 5. Aerial photographs showing the delineation of rock glaciers and their fronts (white solid lines) as well as contributing areas (white dashed lines); note well-defined ridge-and-furrow topography on some of the rock glaciers. (A) Relict debris rock glacier in the Spálená Valley, Western Tatra Mts.; (B) relict debris rock glacier in the Świstówka Roztocka Valley, High Tatra Mts.; (C) intact talus and debris rock glaciers forming a multipart rock glacier in the Batizovská Valley, High Tatra Mts.; (D) intact and relict talus and debris rock glaciers forming a multipart rock glacier in the Slavkovská Valley, High Tatra Mts. All the figures have a northern orientation.

Note: Parts of other rock glaciers and their contributing areas extending into the images are not highlighted.
many researchers describe them as embryonic stage of rock glaciers, that is, a kind of developmental continuum, closely resembling them in morphology, internal structure, ice content and morphodynamics (e.g. Barsch, 1996; Haeberli, 1985; Scapozza, 2015).

Intact and relict classes were set to differentiate the rock glaciers according to the presence of permafrost and activity (Barsch, 1996). Intact rock glaciers (including both active and inactive landforms) host permafrost inside and may (active rock glaciers) or may not (inactive rock glaciers) move due to permafrost creep. In contrast, permafrost has completely thawed within relict rock glaciers. Borehole drilling, ground temperature measurements, geophysical soundings and/or monitoring of rock-glacier movements are particularly helpful to distinguish between the intact and relict rock glaciers (e.g. Haeberli et al., 2006). Some of the above methods have been employed in the High Tatra Mts., suggesting probable permafrost presence in several rock glaciers (Kędzia, 2014), but the data are available for a limited number of landforms (Dobiński, 1997b; Gądek & Kędzia, 2008, 2009; Kędzia et al., 2004; Uxa & Mida, 2016, 2017). Consequently, the classification is largely based on morphological attributes discernible on aerial imagery that are widely accepted to be indicative of ground ice presence or absence and were adopted in many recent rock-glacier inventories as well (e.g. Colucci et al., 2016; Falaschi et al., 2014; Onaca et al., 2017; Scotti et al., 2013). Intact rock glaciers are characterized by steep frontal and lateral slopes, which often exceed the angle of repose of c. 35°, exhibit well-defined ridge-and-furrow topography, and completely lack or have sparse vegetation cover. In contrast, relict rock glaciers are typical of subdued topography with gentler slopes caused by permafrost degradation, and usually have extensive vegetation cover.

The bedrock lithology of individual rock glaciers was inferred from the schematic geological map (see section 3.2.3; Figure 2) based on rock-glacier outlines. In total, three geological units were identified for the mapped rock glaciers: Palaeozoic gneiss rocks, migmatite and amphibolite; Carboniferous-Permian granitic rocks; and Mesozoic limestone, dolomite, sandstone, shale and quartzite.

### 3.3.3. Rock-glacier contributing areas

Contributing area of each rock glacier, that is, the zone where source material for its formation is collected (Figure 5), was computed using the Hydrology tools (e.g. Bolch & Gorbunov, 2014) implemented in ESRI ArcMap 10.3 based on the void-filled DEM (see section 3.2.1.). Because this debris-contributing area (sensus Janke & Frauenfelder, 2008) may not be identical to the hydrological catchment of a rock glacier (particularly in the case of debris rock glaciers), only those parts of the respective rock glaciers, which presumably received material directly from the source zone (i.e. not secondarily through the rock-glacier flow), were used as the lower modelling limit. Several lines of evidence, such as the orientation of ridges and furrows and the connection between the outer edge of a rock glacier and neighbouring slope, were considered to determine these rock-glacier parts. The delineated contributing areas are essentially based on calculations confined to locations outside the rock glaciers, and therefore no problems that could be expected on rugged rock-glacier topography, such as flow divergence or presence of sinks with undefined flow direction, have been encountered. The contributing areas of lower-lying rock glaciers forming parts of multipart rock glaciers were set to include both the area of all the above-lying and genetically related rock glaciers and their contributing areas.

### 4. Mapping results and interpretation

The inventory contains a total of 383 rock glaciers occupying the area of 13.84 km², which are supplied by rock material from 51.81 km² of contributing areas (Table 1). Hence, the total rock-glacier-affected area in both mountain ranges constitutes 65.65 km², which comprises c. 16% of the area above 1375 m asl (~lower limit of rock-glacier occurrence). The average rock-glacier density above this limit is 0.93 landforms per km² and the average specific rock-glacier area accounts for 3.34 ha per km². Less rock glaciers, 183 (c. 48%), occur in the Western Tatra Mts. than in the High Tatra Mts. where 200 rock glaciers (c. 52%) are located. However, this does not translate into the difference in the total rock-glacier area, which is by 0.45 km² larger in the Western Tatra Mts. On the other hand, the total contributing area is by 2.60 km² more extensive in the High Tatra Mts. (Table 1).

Talus rock glaciers predominate in both mountain ranges, with c. 63% and c. 74% in the Western Tatra and High Tatra Mts., respectively, but their total area represents only c. 25% and c. 42% of all the rock glaciers. Accordingly, debris rock glaciers are substantially larger in size, which is on average around four to five times the average size of talus rock glaciers (Table 1). Debris rock glaciers also have substantially larger contributing areas (Table 1), which are capable to supply these voluminous landforms with a sufficient amount of material necessary for their development. Most rock glaciers are considered as relict; only seven landforms were classified as intact in the Western Tatra Mts. (c. 4%) and other forty nine in the High Tatra Mts. (c. 25%), representing c. 15% of the total number of rock glaciers in the entire study region and covering the total area of 1.34 km² (Table 1). Relict landforms extend down to 1375 m asl and 1414 m asl in the Western and High Tatra Mts., respectively, with the average front elevation of 1644 ± 119 m asl and 1731...
± 143 m asl, respectively (Figure 6). Lower limit of intact rock glaciers occurs at 1761 m asl and 1831 m asl in the Western and High Tatra Mts., respectively, and their front elevation averages 1812 ± 30 m asl and 2011 ± 92 m asl, respectively. The discrepancy of nearly 200 m between the mountain ranges in the latter parameter results from wider elevation range where intact rock glaciers occur in the High Tatra Mts., and also from the limited number of intact landforms in the Western Tatra Mts. Consistently with the distribution patterns observed elsewhere (see Barsch, 1996), both relict and intact rock glaciers have their lower limits located higher in southern aspects than in northerly exposed places. In the Western Tatra Mts., the average front elevation of relict and intact rock glaciers facing the NW–NE directions is at 1599 ± 107 m asl and 1823 ± 37 m asl, respectively, while landforms oriented to the SW–SE are at 1723 ± 103 m asl and 1819 ± 18 m asl, respectively. In the High Tatra Mts., the respective elevations are 1692 ± 159 m asl and 1943 ± 63 m asl for the NW–NE sectors and 1768 ± 116 m asl and 2018 ± 88 m asl for the SW–SE. Intact rock glaciers are mostly of talus type, with c. 86 % and c. 78 % in the Western and High Tatra Mts., respectively, and have on average around one and a half to two times smaller size than relict landforms (Table 1).

Rock glaciers occur in three different geological units (Table 2), which represent 100 % and c. 97 % of the area above 1375 m asl in the Western and High Tatra Mts., respectively. The total numbers and areas of rock glaciers built by different substrates well correlate with the areal proportion of these materials in the study region. Granitic rocks predominate here (Figure 2), and therefore c. 65 % and 96 % of rock glaciers, covering the total area of 4.84 km² and 6.46 km², are formed within these substrates in the Western and High Tatra Mts., respectively (Table 2). More diverse geology of the Western Tatra Mts. promotes c. 27 % of rock glaciers (2.00 km²) consisting of Palaeozoic metamorphic rocks (particularly gneisses and migmatites) and c. 8 % of the landforms (0.31 km²) developed within Mesozoic
limestones, dolomites, sandstones, shales and quartzites. On the contrary, only 1 % and 3 % of rock glaciers (0.07 km² and 0.17 km²) in the High Tatra Mts. are formed by these materials (Table 2). In total, the non-granitic rock glaciers cover the area of 2.31 km² and 0.24 km² in the Western and High Tatra Mts., respectively.

Rock glaciers consisting of Mesozoic limestones, dolomites, sandstones, shales and quartzites have the smallest average size and also show the lowest rock-glacier density as well as the lowest specific rock-glacier area in both mountain ranges (Table 2), which suggests that these materials are less favourable for rock-glacier formation in the study region. In contrast, rock glaciers built by granitic rocks and Palaeozoic metamorphic rocks are substantially larger and occur more frequently within the hosting geological units (Table 2). Their average sizes are almost identical in the individual mountain ranges, but in total the latter landforms are slightly larger, which is associated with both comparatively greater abundance of Palaeozoic metamorphic rocks in the Western Tatra Mts. and more extensive rock glaciers occurring there. On the other hand, the average rock-glacier density in the entire study region is distinctly the highest for granitic rocks, 1.12 landforms per km², as is the average specific rock-glacier area, which in these substrates equals 4.07 ha per km².

Intact rock glaciers can be utilized to approximate the contemporary lower limit of discontinuous permafrost on a regional scale, and relict rock glaciers can indicate the variations in discontinuous permafrost extent in the past (e.g. Barsch, 1996; Haeberli et al., 2006). The average front elevation of intact rock glaciers calculated collectively for both mountain ranges is at 1986 ± 109 m asl, which on average represents the area of 60.45 km² above this level in the entire study region. The average value of 1986 m asl is 56 m above the previously proposed average discontinuous permafrost boundary of 1930 m asl (Dobiński, 1997a, 2004, 2005). Undoubtedly, the difference is principally affected by distinct methodologies. The former investigations (Dobiński, 1997a, 2004, 2005) assessed the permafrost occurrence in principle via the elevation of zero isotherm of air temperature, while the present study builds on the visual inspection of rock-glacier activity based on aerial imagery. Active rock glaciers typically exist in areas where MAAT is −2 °C or less (Barsch, 1996). However, internal ice core may persist inside inactive rock glaciers even under positive MAAT because coarse blocky materials of rock glaciers tend to be substantially colder than outside air (e.g. Gorbunov, Marchenko, & Seversky, 2004; Harris & Pedersen, 1998). Because inactive rock glaciers dominate the intact category in the Western and High Tatra Mts. and the cooling effect has been extensively observed here as well (Uxa & Mida, 2016, 2017), the average elevation of the intact rock-glacier front and the zero isotherm of air temperature should likely be reversed. This issue may be attributed to climate warming because the earlier estimates of permafrost distribution (Dobiński, 1997a, 2004, 2005) were mostly based on air temperature series two to three decades older (from 1985–1989 or 1985–1994) than our aerial images. The air temperature at Kasprowy Wierch (1991 m asl), located almost exactly in the middle of the study region, has been increasing on average by 0.02 °C per year (Żmudzka, 2011) during 1966–2006 and has continued to rise at least until 2010 (Gądek & Leszkiewicz, 2012). Such a warming rate would elevate the zero isotherm level by 73–109 m in 20–30 years, assuming the average temperature lapse rate of 0.0055 °C per m that is based on 1951–1970 data from the eight highest elevated stations in the Western and High Tatra Mts. (Niedzwiedz, 1992). In that case, the zero isotherm of air temperature would be at 2003–2039 m asl, which much better fits the presumed relation between air temperature and distribution of mostly inactive rock glaciers. In addition, the contemporary zero isotherm level may lie even higher because the warming apparently accelerated in the eighties of the last century (see e.g. Gądek & Leszkiewicz, 2012; Żmudzka, 2011).

Because the lowest fronts of relict rock glaciers descend to around 1400 m asl (Figure 6), the lower boundary of discontinuous permafrost in the Western and High Tatra Mts. in the Late Glacial or the early Holocene probably occurred around this level, provided that the rock glaciers could fully develop under the given climate conditions. In that case, discontinuous

### Table 2. Areal extent of geological units above 1375 m asl (∼lower limit of rock-glacier occurrence) and rock-glacier presence in the Western and High Tatra Mts.

| Geological unit | Area (km²) | Number | Total area (ha) | Mean area (ha) | Mean specific area (ha/km²) | Density (n/km²) |
|-----------------|-----------|--------|-----------------|---------------|---------------------------|----------------|
| **Western Tatra Mts.** | | | | | | |
| Gneiss rocks, migmatite, amphibolite | 69.59 | 50 | 199.75 | 4.00 | 2.87 | 0.72 |
| Granitic rocks | 102.48 | 119 | 483.82 | 4.07 | 4.72 | 1.16 |
| Limestone, dolomite, sandstone, shale, quartzite | 38.34 | 14 | 30.66 | 2.19 | 0.80 | 0.37 |
| **High Tatra Mts.** | | | | | | |
| Gneiss rocks, migmatite, amphibolite | 1.06 | 2 | 6.83 | 3.42 | 6.44 | 1.89 |
| Granitic rocks | 175.08 | 192 | 645.53 | 3.36 | 3.69 | 1.10 |
| Limestone, dolomite, sandstone, shale, quartzite | 21.04 | 6 | 17.14 | 2.86 | 0.81 | 0.29 |

Note: Only the geological units hosting rock glaciers are listed.
permafrost would occupy the area of c. 393 km$^2$ in the entire study region, that is, around six and a half times more than the estimated contemporary discontinuous permafrost extent, and the MAAT at 1400 m asl could be −2 °C or less if we accept this value to be valid for active rock glaciers to develop (Barsch, 1996). The contemporary MAAT at this elevation is estimated to be +3.4 °C based on the 1981–1996 temperature record from Lomnický štít Peak and the present average lapse rate of 0.0055 °C per m. Consequently, the temperature at the time of the rock-glacier formation was probably at least 5.4 °C lower than at present.

The spread between the average front elevation of intact and relict rock glaciers in the Western and High Tatra Mts. is well within the ranges observed in most surrounding regions, but local rock glaciers occur on average about 400–600 m lower than in the European Alps (Table 3). The decline in the front elevation is similar to that reported from some of the easternmost sub-regions of the European Alps and the Southern Carpathians (Table 3), which has been attributed to less precipitation towards the east (e.g. Onaca et al., 2017), causing thinner snow cover during winter, and thus lower ground temperatures (sensu Gruber & Haeberli, 2009). About 100 m lower average front elevation of the intact rock glaciers in the Western and High Tatra Mts. than in the Southern Carpathians is most likely due to latitudinal temperature decrease, and is close to the previously reported difference in the contemporary lower limit of discontinuous permafrost of 70 m between these two Carpathian regions (Dobiński, 2005).

Table 3. Overview of front elevations of intact and relict rock glaciers in the European Alps and the Carpathians.

| Region                  | Lon/° | Lat/° | Number | Front elevation | Lon/° | Lat/° | Number | Front elevation | Source                        |
|-------------------------|-------|-------|--------|-----------------|-------|-------|--------|-----------------|-------------------------------|
| Grazian Alps, Italy     | 6°52’ | 45°50’| –      | 2484’           | –     | –     | –      | –               | –                             |
| Prealps, Vaud, Switzerland | 7°08’ | 46°24’| 0      | –               | 25    | 1761 ± 165 | –      | 226             | Guglielmin and Smiraglia (1998) |
| Maritime Alps, Italy    | 7°11’ | 44°14’| –      | 2179’           | –     | –     | –      | –               | Guglielmin and Smiraglia (1998) |
| Entremont, Valais, Switzerland | 7°12’ | 45°56’| 166    | 2626 ± 132      | 155   | 2400 ± 168 | 226   | Delaloye and Morand (1998) |
| Cottian Alps, Italy    | 7°15’ | 44°40’| –      | 2458’           | –     | –     | –      | –               | Guglielmin and Smiraglia (1998) |
| Printse Valley, Valais, Switzerland | 7°19’ | 46°06’| 40     | 2715 ± 165      | 31    | 2342 ± 166 | 373   | Reynard, Lambiel, and Wenker (1998) |
| Turtmannalp, Valais, Switzerland | 7°42’ | 46°12’| 62     | 2621 ± 119      | 21    | 2496 ± 145 | 125   | Nyenhuis et al. (2005) |
| Bernese Alps, western Switzerland | 7°47’ | 46°28’| 41     | 2515 ± 136      | 41    | 2183 ± 330 | 332   | Imhof (1998) |
| Pennine Alps, Italy    | 7°52’ | 45°56’| –      | 2457’           | –     | –     | –      | –               | Guglielmin and Smiraglia (1998) |
| Fletschhorn area, Valais, Switzerland | 7°58’ | 46°11’| 51     | 2617 ± 177      | 25    | 2508 ± 203 | 109   | Frauenfelder (1998) |
| Lepontine Alps, Italy  | 8°08’ | 46°24’| –      | 2168’           | –     | –     | –      | –               | Guglielmin and Smiraglia (1998) |
| Upper Engadin, Switzerland | 9°49’ | 46°28’| 144    | 2637 ± 135      | 26    | 2370 ± 205 | 267   | Hoelzle (1998) |
| Central Italian Alps, Italy | 9°52’ | 46°10’| 639    | 2590° ± 129°    | 875   | 2203° ± 149° | 385   | Scotti et al. (2013) |
| Rhaetian Alps, Italy   | 10°00’| 46°48’| –      | 2319’           | –     | –     | –      | –               | Guglielmin and Smiraglia (1998) |
| Adamello-Presanella Massif, Italian Alps, Italy | 10°37’| 46°07’| 88     | 2485 ± 186      | 128   | 2058 ± 149 | 427   | Baroni et al. (2004) |
| Tyrolean Alps, Austria | 10°53’| 47°01’| 1432   | 2573            | 1713  | 2279  | 294   | Kainer and Ribis (2012) |
| Alpes, Italy           | 10°56’| 46°36’| –      | 2438’           | –     | –     | –      | –               | Guglielmin and Smiraglia (1998) |
| Eastern Italian Alps, Italy | 11°12’| 46°05’| 173    | 2632 ± 205      | 532   | 2169 ± 211 | 463   | Seppi et al. (2012) |
| Dolomites, Italy       | 11°51’| 46°26’| –      | 2236’           | –     | –     | –      | –               | Guglielmin and Smiraglia (1998) |
| Carnic Alps, Italy     | 12°53’| 46°36’| –      | 1744’           | –     | –     | –      | –               | Guglielmin and Smiraglia (1998) |
| Eastern European Alps, Austria | 14°19’| 47°20’| 347    | 2515 ± 106°     | 1300  | 2102 ± 171° | 413   | Kellerer-Pirkbauer et al. (2012) |
| Southeastern Alps, Italy | 14°28’| 46°09’| 4      | 1827’           | 49    | 1778° ± 69° | 49    | Colucci et al. (2016) |
| Western and High Tatra Mts., Slovakia and Poland | 19°57’| 49°12’| 56     | 1986 ± 109      | 327   | 1684 ± 137 | 302   | This study |
| Southern Carpathians, Romania | 23°42’| 45°25’| 48     | 2088 ± 49°      | 258   | 1930 ± 99° | 158   | Onaca et al. (2017) |

Note: Averages and standard deviations are reported if not defined otherwise.

Unweighted average of mean front elevations of active and inactive rock glaciers.

Median subtracted from boxplot diagram.

Half of the interquartile range subtracted from boxplot diagram.

5. Conclusions
The map includes a total of 383 rock glaciers, making it the most comprehensive rock-glacier inventory for the entire area of the Western and High Tatra Mts. to date. Relict rock glaciers account for 85% of the database
and cover the total area of 12.50 km². These landforms have their lowest limit around 1400 m asl, and thus the lower boundary of discontinuous permafrost zone in the Late Glacial or the early Holocene probably lied at this level, and covered the total area of around c. 393 km². Intact rock glaciers constitute 15 % of the inventory and cover the total area of 1.34 km². Their average front elevation of 1986 ± 109 m asl delineates the contemporary lower limit of discontinuous permafrost zone on a regional scale that occupies the total area of 60.45 km².

The rock-glacier inventory adds to the current state of knowledge about the occurrence of these permafrost landforms in less investigated high-mountain regions located east of the European Alps. However, it must be emphasized that the inferred permafrost limits and extents should be understood as rather tentative in nature. Rock glaciers can provide a first-order evaluation of potential permafrost distribution, which generally tends to overestimate the permafrost extent at places without debris cover. Consequently, the present work is rather a starting point towards more thorough analyses of rock-glacier distribution and morphology and modelling of discontinuous permafrost distribution, which will substantially improve the understanding of present and past environmental conditions in the Western and High Tatra Mts.

Software

The mapping, digitizing, analyses of DEM and map compilation were all carried out using ESRI ArcMap 10.3. Final merger of vector and raster map elements was done in Adobe Acrobat Pro DC.

Data availability

The shapefiles of rock-glacier outlines and contributing areas are available on request by the authors. Data users are requested to inform the data owners about the planned activities and invite them to contribute to any work that would lead to a co-authorship.

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