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The influence of aspect and altitude on the size, shape and spatial distribution of glacial cirques in the High Tatras (Slovakia, Poland)

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ABSTRACT

The shape of glacial cirques is generally considered to result from the combined actions of climate, topography, and geology. The goal of this article was to determine the dependence of cirque morphology on mesoclimatic conditions defined by altitude and aspect in the highest part of the Carpathians — the High Tatras. The morphology of each of 116 analyzed cirques was described using a set of 12 morphometric characteristics. The relationships between the obtained data were evaluated using simple and multivariate statistical methods. The results indicate that cirques in the High Tatras are scale-specific landforms with allometric development. Their occurrence increases with altitude, but their size decreases. The shape of the cirques is determined by altitude only to a small extent, with the exception of an increase in the degree of incision with altitude. The spatial distribution of cirques is negatively influenced by incoming solar radiation and positively influenced by moisture sources, which came mainly from the NW to N during the cold phases of the Pleistocene. For this reason, north-facing cirques have proportionally stronger representation and are more incised with steep slopes. Thus, cirques have proportionally stronger representation on the northern slopes and represent more developed glacial erosion landforms than those on the southern slopes. Although some relationships were detected between cirque morphology and mesoclimatic factors (such as altitude and aspect), a general discriminant analysis showed that these environmental factors did not explain variations in cirque morphology with sufficient cogency.

1. Introduction

After the European Alps, the High Tatras were the second most glaciated mountain range in central Europe during the Pleistocene, but knowledge of the timing and course of the glaciations and associated landforms in this mountain range remains weak in comparison with that of surrounding mountain ranges (the Alps: e.g., Ivy-Ochs et al., 2008; the Giant Mts.: e.g., Engel et al., 2010; the Bohemian Forest: e.g., Mentlík et al., 2010; Romanian Carpathians: e.g., Reuther et al., 2007). The occurrence of Pleistocene mountain glaciers in the area is documented by the presence of erosional and accumulational glacial landforms on the Slovakian and on the Polish side of the mountains (e.g., Lukniš, 1973; Klimaszewski, 1988; Baumgart-Kotarba and Kotarba, 1997, 2001; Lindner et al., 2003). These authors focused especially on morphostratigraphy or the dating of glacial and glaciofluvial accumulations. However, studies of glacial erosion and its associated landforms are scarce or unavailable.

Optimal conditions for the development of local mountain glaciation vary among different parts of the world (see e.g., Evans, 1977; García-Ruiz et al., 2000; López-Moreno et al., 2006). The nature of glaciation and the shape of related landforms are generally taken to reflect the combined effects of climate (resulting from regional and global climatic patterns, altitude, and aspect), mountain topography, and geological conditions (Owen et al., 2009; Thompson, 2009).

Cirques are defined as hollows formed at glacier source areas in mountains that are partly enclosed by steep, arcuate slopes commonly known as headwalls (Evans, 2004, 2007). Many studies have evaluated the relationship between the morphology of cirques and altitude, aspect, lithology, and other environmental factors. Some of these studies (Haynes, 1968; Olyphant, 1977; Federici and Spagnolo, 2004; Hughes et al., 2007) have confirmed the influence of geological conditions, aspect, and/or altitude on the size and shape of glacial cirques. Nevertheless, in other studies (Klimaszewski, 1964; Evans and Cox, 1995; García-Ruiz et al., 2000; Ruiz-Fernández et al., 2009), no particular relationship among cirque morphology and climatic factors (which depend on altitude and aspect) or geological conditions was confirmed. In these cases, apparently the development of cirque shape is probably controlled rather by the type of preglacial relief (e.g., planation surfaces, avalanche channels, and ravines), the presence of initial hollows (acting as agents for primary cirque formation), or structural predispositions (e.g., fissures, variable inclination of the strata, or the presence of outcrops of different resistance). Morphological differences between cirques also appear to reflect various stages of cirque development rather than differences in environmental factors (Aniya and Welch, 1981; Brook et al., 2006). In any particular region,

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a range of cirques exist, each of which may have been initiated at a different time or developed at a different rate; and consequently, the spatial variation of cirque morphology within the area will provide insight into how cirques evolve through time (Bennett and Glasser, 2009). Many studies (e.g., Olyphant, 1981; Evans and Cox, 1995; Federici and Spagnolo, 2004; Evans, 2006a) have shown that cirque headwall retreat is usually faster than its downward erosion. This is related to the concept of the allometric development of glacial cirques introduced by Olyphant (1981) and reevaluated by Evans and Cox (1995) and Evans and McClean (1995). Regional variability in cirque morphology has also been interpreted in terms of paleoclimatic reconstructions (e.g., Evans, 1977; Dahl and Nesje, 1992; Mîndrescu et al., 2010); cirque floor altitudes may be used to reconstruct the equilibrium line altitude of former glaciations (Benn and Lehmkuhl, 2000; Carrivick and Brewer, 2004).

The cirques of the High Tatras, which are located in the valley heads, represent the source areas of local valley glaciers and therefore essentially influence the nature and dynamics of the local glaciation (Fig. 1). These cirques have not yet been analyzed in terms of their morphometric characteristics, unlike many cirques in other regions of the world. Previous studies concerned with cirque morphometry and its relation to environmental factors have mostly examined regions with maritime climates (the Pyrenees, the Cantabrian range, the British Isles, etc.). In contrast, the High Tatras are located in an interesting transitional area (from a paleoenvironmental and paleogeographical viewpoint) between oceanic Western Europe and the continental East European lowlands (Kotarba, 1992; Niedzwiedz, 1992). Furthermore, as the most northerly part of the Carpathian arc and of the entire Alpine–Carpathian–Dinaric orogen, these mountains were located near the margin of the Fennoscandinavian ice sheet margin during the cold stages of the Pleistocene. The lack of data on cirque morphometry in the unique region of the High Tatras and the importance of the region for understanding the factors that controlled the development of cirques in the context of the Central-European Pleistocene glaciation were the major reasons for this study.

The aim of the study was to determine the dependence of cirque morphology (as described by morphometric characteristics) on the basic environmental factors influenced by altitude and aspect (which define mesoclimatic conditions). The objectives were to analyze and classify the cirques morphometrically and to examine their spatial distribution variability.

2. The study area

The High Tatras form the highest part of the Carpathian arc. This mountain range is located at the border between Poland and Slovakia, and the highest peak is Gerlachovský štít (2655 m asl) (Fig. 2). These typical alpine mountains consist of granitoid rocks, primarily quartz diorites to granodiorites; on the northern slopes, the crystalline core is unconformly overlain by Mesozoic sedimentary rocks, mainly limestones (Nemčok et al., 1994). During the Miocene, Pliocene, and Quaternary, the High Tatras were lifted to the surface by northerly tilting and rotational uplift along the sub-Tatra fault (Janák et al., 2001; Baumgart-Kotarba and Kráľ, 2002; Jurewicz, 2007); therefore, the mountain massif rises very abruptly in the south from its foreland, and the highest summits are located on the southern parts of the ridge. Consequently, the southern valleys are steep and short; comparatively, the northern valleys are wider, deeper, and more gently inclined.

Local mountain glaciation occurred in the High Tatras during several cold phases of the Pleistocene. Many different and contradictory opinions have been voiced regarding the age and extension of glaciations in this area (e.g., Lukniš, 1968, 1973; Klimaszewski, 1988; Halouzka, 1992; Lindner et al., 1993; Halouzka and Horniš, 1995; Baumgart-Kotarba and Kotarba, 1997, 2002; Lindner et al., 2003; Birkenmajer, 2009). Glacial landforms have rarely been dated using radiometric methods in the High Tatras, and this has only been performed on the northern side of the mountains (Lindner et al., 1993; Dzierzek et al., 1999; Baumgart-Kotarba and Kotarba, 2001; Makos et al., 2013). Traditionally, three main glaciations have been recognized and related to the alpine nomenclature: Mindel (correlated with MIS 12), Riss (MIS 6–10), and Würm (MIS 5d-2) (Lukniš, 1973; Klimaszewski, 1988). The older glacials are represented only in the form of glaciofluvial deposits (Lindner et al., 2003). Lukniš (1973) determined that the penultimate glaciation was the most extensive; in contrast, Klimaszewski (1988) and Kotarba (1992) stated that the last glaciation was the most extensive.

Although the climatic snowline averaged between 1550 m asl on the northern slopes and 1650 m asl on the southern slopes during the local last glacial maximum (Lukniš, 1973), longer glaciers with greater volumes of ice were situated on the southern slope (Lukniš, 1973; Klimaszewski, 1988). This was determined mainly by the fact that the area above the climatic snowline was larger on the southern slope than on the northern slope.

Fig. 1. One of the cirques of the Zlomisková Dolina valley. The Dračie pleso tarn is visible on the cirque floor.

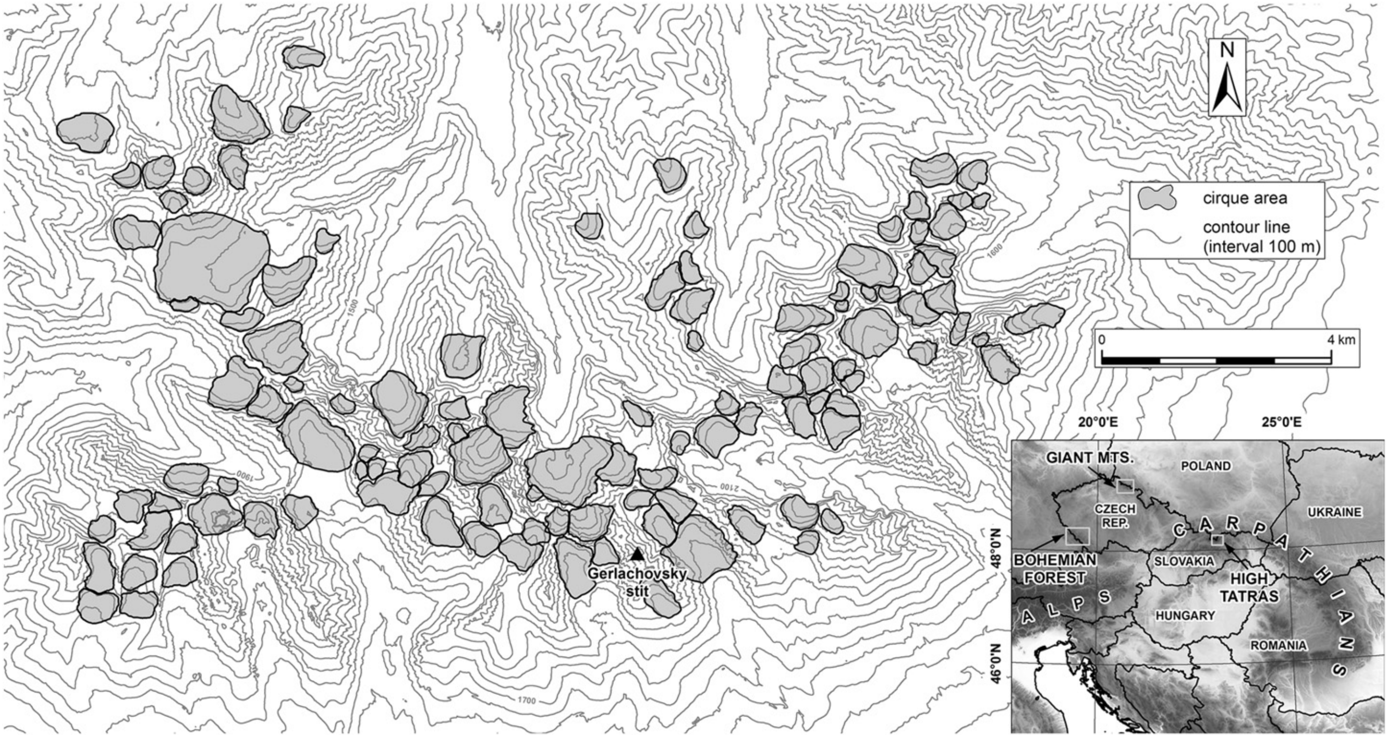

Fig. 2. Position of the High Tatras within the Carpathian range and the cirque delimitation map.

Glaciers in the High Tatras disappeared during the early Holocene (the Preboreal and Boreal phases); and the last substantial cold oscillation, which preserved the last small glaciers in some uppermost hanging cirques above 1950 m asl, corresponded with the Venediger stage (9.2 ka BP) in the Austrian Alps (Baumgart-Kotarba and Kotarba, 1995). Postglacial modeling has modified these glacial landforms mainly by flattening the overdeepening of the cirques and troughs and by reshaping and eroding glacial and glaciofluvial sediments. Among recent geomorphic processes, the most effective have been mass movements (rockfalls, rock sliding, debris flows, creep, and solifluction) and nivation and periglacial processes (frost weathering and freeze-thaw processes) (Kotarba, 1992; Kalvoda, 1998; Midriak, 2001; Hreško et al., 2008). Currently, the High Tatras are free of glaciers, and the climatic snow line lies on the northern slopes at ~2500–2600 m asl and on the southern slopes at ~2700–2800 m asl (Zasadni and Kłapyta, 2009). The ecotone of the alpine timberline is located at ~1500 m asl on the northern slopes and at ~1600 m asl on the southern slopes (Plesník, 1971). In suitably shaded locations, perennial snowfields and firn-ice patches can be found (Gądek and Kotyrba, 2007; Gądek, 2008), and discontinuous permafrost has also been documented in the High Tatras (Dobiński, 2004, 2005; Gądek and Kędzia, 2008).

3. Methods

The cirques were identified using a geomorphological map of the area (Lukniš, 1968), aerial photography maps, previous literature (Lukniš, 1973; Klimaszewski, 1988), DEM with a spatial resolution of 10 × 10 m (Marcin Guzik, Tatrzański Park Narodowy), and fieldwork. Morphometric analyses were performed on the basis of the DEM using ArcMap 10.0 (ESRI Inc., 2010).

Compound cirques and cirque complexes (*sensu* Benn and Evans, 1998) are quite frequent in the study area. Therefore, all of the identifiable simple 'sub-cirques' within compound cirques or cirque complexes were separately evaluated and morphometrically analyzed. In total, 162 cirques were delimited. Nevertheless, some of the cirques originally described by Lukniš (1973) and Klimaszewski (1988) were in the field recognized as upper ends of troughs; some cirques were indistinct or unidentifiable neither in the field nor in the DEM. These cirque-like landforms did not match the morphological definition of a cirque (their headwall gradient was too low or their floor gradient was too high) and represented the results of mass movements rather than the effects of glacial erosion. Such disputable landforms were excluded from further work, and the remaining 116 cirques are analyzed in this work (Fig. 2).

The implemented morphometric characteristics describing the size and shape of cirques are consistent with the usual methods (Graf, 1976; Gordon, 1977; Aniya and Welch, 1981; Evans and Cox, 1995; García-Ruiz et al., 2000; Federici and Spagnolo, 2004; Brook et al., 2006; Hughes et al., 2007; Ruiz-Fernández et al., 2009) (Table 1). Apart from these characteristics, each cirque was also determined by the minimum cirque floor altitude (E_{min}) and the maximum cirque headwall altitude (E_{max}). Five altitudinal cirque classes were distinguished using Jenks' natural breaks classification method (Jenks, 1967) based on a histogram of minimum cirque floor altitudes (E_{min}): A (1529–1629 m asl), B (1630–1814 m asl), C (1815–1960 m asl), D (1961–2069 m asl), and E (2070–2211 m asl). These altitudinal classes were used to calculate the index of spatial distribution (see below). Aspect was calculated as the intersection angle of the median axis (*sensu* Evans and Cox, 1995) with the geographical north. Eight aspect categories were considered: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW). The effect of lithological structure was not considered because of its uniformity in the study area (see Nemčok et al., 1994). Of 116 analyzed cirques, 114 were formed in granodiorites and only 2 were formed in limestone; therefore, it was not possible to examine the effect of lithology on cirque morphology in this article.

The dependence of the spatial distribution of cirques on altitude and aspect was determined based on the ratio of a proportional representation of cirques (in terms of total area) in a particular category of the mentioned phenomenon and its participation in the total studied area, i.e., $W_{ij} = X_i/Y_j$, where W is the index of spatial distribution, X is the proportional areal representation of cirques in a particular category, and Y is the proportional part of this category in the total

Table 1
Directly measured morphometric characteristics of cirques and their derived features.

Morphometric characteristic	Description
Length (*L*)	Length of median axis. Median axis represents the line starting from middle of cirque treshold (cirque focus) and dividing the cirque plan area into two equal halfs (*sensu* Evans and Cox, 1995).
Width (*W*)	Width of the longest line perpendicular to median axis (*sensu* Evans and Cox, 1995).
Height (*H*)	Difference between minimum altitude of cirque floor (E_{min}) and maximum altitude of cirque headwall (E_{max}) (*sensu* Aniya and Welch, 1981; García-Ruiz et al., 2000; Federici and Spagnolo, 2004).
L/*W* ratio	Describes planimetric shape of a cirque, implies cirque elongation.
L/*H* ratio	Inverse of overall cirque gradient. Describes a cirque vertical development and is a measure of cirque incision.
W/*H* ratio	Similar as the *L*/*H* ratio; describes a cirque vertical development and is a measure of cirque incision (Hughes et al., 2007).
Circularity ratio (*CR*)	The ratio between the perimeter of a cirque and the circumference of a circle that has the same area as the cirque plan (*sensu* Aniya and Welch, 1981) and is a measure of cirque indentation.
Volume (*V*)	Cirque volume (*sensu* Olyphant, 1981). $V = L \times W \times H$.
Planar area (*2D*)	Area of a cirque plan. Calculated in GIS.
Surface area (*3D*)	Real surface area of a cirque. Calculated in GIS.
3D/*2D* ratio	Reflects an area-relative elevation relationship of a cirque.
Mean slope gradient (*S*)	Mean inclination in degrees. Calculated in GIS on the basis of slope map as a mean of gradient values of all raster cells within particular cirque.
Allometric exponents (a, b, c)	Defined as $L = V^a$, $W = V^b$, $H = V^c$. The exponents are indices of relative rates of dimensional increase with over-all cirque enlargement. If the exponents differ from one-third, then the population of cirques within studied area exhibit allometric development (*sensu* Olyphant, 1981; Evans, 2006a).

studied area (*sensu* Křížek, 2007). Total studied area was defined as surface area above the lowest-lying cirque floor (i.e., entire area above 1529 m asl) and was calculated from the hypsometric curve. Similarly, surface areas of individual altitudinal classes were calculated from the hypsometric curve. Surface areas of slopes of individual aspect classes were derived in GIS. If $W = 1$, then the proportional representation of cirques in a relevant category corresponds to the proportion of this category in the total area. The greater is the value of *W* above 1, the stronger is the representation of cirques in the particular category with respect to its proportional part in the total area.

All statistical analyses were performed using STATISTICA (StatSoft, Inc., 2009). Correlations among the morphometric characteristics of the cirques were detected using Pearson correlation coefficients, and their significance was tested using the *t*-test at a significance level $p = 0.05$. Significant differences in the means of morphometric characteristics between independent variables were analyzed using one-way ANOVA and tested using the *F*-test at a significance level $p = 0.05$. Morphologically similar groups of cirques were identified by cluster analysis based on Ward's method and Euclidean distances (*sensu* Kaufman and Rousseeuw, 2005). An important assumption when using the cluster analysis is the mutual independence of input features (Meloun et al., 2005); therefore, all morphometric characteristics (Table 1) were tested for multicollinearity. Subsequently, uncorrelated morphometric characteristics (called the basis; *sensu* Křížek et al., 2012) represented the input features for the cluster analysis. The mathematical basis of the morphometric characteristics was defined as the largest set of independent morphometric characteristics (i.e., those characteristics that were not mutually correlated) (Křížek et al., 2012). The first member of the basis was defined as the characteristic with the smallest number of significant correlations with the other morphometric characteristics. The next members of the basis were defined in the same way from the set of remaining morphometric characteristics. The basis of the morphometric characteristics (in accordance with the above described procedure) consists of the *3D*/*2D* ratio (1st member), *L*/*W* ratio (2nd member), and cirque volume (*V*, 3rd member). The basis represents quite an apposite subset of all morphometric characteristics because it contains parameters describing cirque size (*V*), cirque plan shape (*L*/*W* ratio), and the vertical relief segmentation of a cirque (*3D*/*2D* ratio). Associations among morphologically similar groups of cirques and aspect categories were determined using correspondence analysis (*sensu* Manly, 2005), which estimates linkages between the categories of nominal variables using scores. General discriminant analysis (GDA) was used to assess the effects of altitude and aspect (independent variables — predictors) on the classification of cirques into morphologically similar groups based on the cluster analysis (dependent — grouping variables). Discrimination accuracy was defined using a cross-validation method (Huberty, 1994) that assessed the predictive accuracy of a model in a test sample (*sensu* STATISTICA; StatSoft, Inc., 2009).

4. Results

4.1. Cirque size and shape

The mean planar area (*2D*) of cirques in the High Tatras was 29.8 ha, and 80% of them were between 8.1 and 55.9 ha (Table 2). Most of the cirques (80%) had a length (*L*) between 283 and 915 m, a width (*W*) between 290 and 851 m, and a cirque height (*H*) from 191 to 456 m. For

Table 2
Summary statistics of morphometric characteristics and altitudinal indicators for 116 cirques in the High Tatras.

	Mean	Median	Minimum	Maximum	10 Percentile	90 Percentile	Standard deviation
E_{max} (m asl)	2232	2251	1787	2560	2019	2421	151.81
E_{min} (m asl)	1921	1929	1529	2211	1704	2109	159.37
H (m)	311	300	103	603	191	456	99.00
L (m)	570	515	179	1961	283	915	270.90
W (m)	550	477	206	1905	290	851	258.47
CR	1.14	1.12	1.04	1.41	1.07	1.22	0.07
L/*H*	1.87	1.77	0.69	4.25	1.12	2.83	0.68
L/*W*	1.09	1.03	0.41	2.30	0.67	1.67	0.39
W/*H*	1.82	1.72	0.54	3.71	1.07	2.72	0.65
V (10^6 m^3)	134.20	76.50	6.11	1916.42	21.46	268.06	214.29
2D area (ha)	29.75	23.23	3.73	319.80	8.10	55.92	35.29
3D area (ha)	37.51	29.27	5.24	356.30	10.06	68.61	41.60
3D/*2D*	1.28	1.26	1.02	1.76	1.13	1.45	0.13
S (°)	35	34	21	55	27	42	6.09

Table 3
Correlation matrix for morphometric characteristics and altitudinal indicators for 116 cirques in the High Tatras; marked (**bold**) correlations are significant at the significance level $p = 0.05$.

	E_{max}	E_{min}	H	L	W	CR	L/H	L/W	W/H	V	$2D$	$3D$	$3D/2D$	S
E_{max}	1.00	**0.80**	**0.25**	0.02	−0.13	−0.01	**−0.19**	0.18	**−0.38**	−0.03	−0.07	−0.05	**0.30**	**0.25**
E_{min}	**0.80**	1.00	**−0.39**	**−0.36**	**−0.46**	−0.17	−0.09	0.06	**−0.21**	**−0.39**	**−0.38**	**−0.41**	0.03	0.11
H	**0.25**	**−0.39**	1.00	**0.61**	**0.55**	**0.26**	−0.16	0.16	**−0.23**	**0.58**	**0.51**	**0.57**	**0.41**	**0.20**
L	0.02	**−0.36**	**0.61**	1.00	**0.71**	**0.41**	**0.65**	**0.41**	**0.27**	**0.82**	**0.85**	**0.86**	−0.17	**−0.42**
W	−0.13	**−0.46**	**0.55**	**0.71**	1.00	**0.37**	**0.33**	**−0.29**	**0.64**	**0.84**	**0.87**	**0.88**	−0.17	**−0.39**
CR	−0.01	−0.17	**0.26**	**0.41**	**0.37**	1.00	**0.23**	**0.20**	**0.23**	**0.38**	**0.40**	**0.40**	−0.10	**−0.23**
L/H	−0.18	−0.09	−0.16	**0.65**	**0.33**	**0.23**	1.00	**0.42**	**0.55**	**0.37**	**0.47**	**0.44**	**−0.61**	**−0.73**
L/W	0.18	0.06	0.16	**0.41**	**−0.29**	**0.20**	**0.42**	1.00	**−0.45**	0.01	0.01	0.01	−0.06	−0.11
W/H	**−0.38**	**−0.21**	**−0.23**	**0.27**	**0.64**	**0.23**	**0.55**	**−0.45**	1.00	**0.37**	**0.46**	**0.43**	**−0.60**	**−0.66**
V	−0.03	**−0.39**	**0.58**	**0.82**	**0.84**	**0.38**	**0.37**	0.01	**0.37**	1.00	**0.98**	**0.98**	−0.06	**−0.26**
$2D$	−0.07	**−0.38**	**0.51**	**0.85**	**0.87**	**0.40**	**0.47**	0.01	**0.46**	**0.98**	1.00	**0.99**	−0.14	**−0.35**
$3D$	−0.05	**−0.41**	**0.57**	**0.86**	**0.88**	**0.40**	**0.44**	0.01	**0.43**	**0.98**	**0.99**	1.00	−0.08	**−0.30**
$3D/2D$	**0.30**	0.03	**0.41**	−0.17	−0.17	−0.10	**−0.61**	−0.06	**−0.60**	−0.06	−0.14	−0.08	1.00	**0.87**
S	**0.25**	0.11	**0.20**	**−0.42**	**−0.39**	**−0.23**	**−0.73**	−0.11	**−0.66**	**−0.26**	**−0.35**	**−0.30**	**0.87**	1.00

80% of the cirques, the L/W ratio was between 0.67 and 1.67, and the mean value and median of the L/W ratio were 1.09 and 1.03, respectively. Thus, cirque length (L) was approximately equal to cirque width (W) in most cases, and the mean and median values of the circularity ratio (CR) were 1.14 and 1.12, respectively (Table 2). Neither cirque area ($3D$, $2D$) nor cirque volume (V) correlated with the L/W ratio (Table 3). Thus, the shapes of the cirques were nearly circular, and this was not dependent on cirque size ($3D$, $2D$, V).

The values of the L/H and W/H ratios for 80% of the cirques were included in the intervals 1.12–2.83 (mean value of 1.87) and 1.07–2.72 (mean value of 1.82), respectively (Table 2). Cirque height (H) increased with cirque size ($3D$, $2D$, V); however, the rate of cirque height (H) increase was smaller than the cirque length (L) increase and width (W) increase. This finding was confirmed by increased values of Pearson's correlation coefficients (r) of the length (L) – size ($3D$, $2D$, V) correlations and the width (W) – size ($3D$, $2D$, V) correlations in comparison to those of the height (H) — size ($3D$, $2D$, V) correlations (Table 3). More rapid cirque headwall retreat with respect to deepening of the cirque floor was associated with the allometric development (*sensu* Olyphant, 1981; Evans, 2006a) of cirques in the High Tatras (Fig. 3). This finding was also confirmed by the mean values and 95% confidence intervals of the allometric exponents: $a = 0.343 \pm 0.002$, $b = 0.341 \pm 0.002$, and $c = 0.316 \pm 0.003$ (see Table 1 for explanations).

4.2. Cirque morphological types

Based on selected morphometric characteristics (see Methods section), the cirques in the High Tatras were classified into homogenous groups using cluster analysis. Three main clusters of the cirques were recognized at the standardized Euclidean linkage distance of 23 (see also Table 4).

Group 1 (51 cirques) comprises almost circular cirques (mean L/W ratio of 1.04, mean CR of 1.12) with moderate vertical development (mean L/H ratio of 1.95) and above-average size (mean planar area ($2D$) of 38 ha). This group represents the most frequent morphological cirque type in the High Tatras.
Group 2 (34 cirques) comprises wide cirques (mean L/W ratio of 0.70) with high overall gradient (mean L/H ratio of 1.38, mean $3D/2D$ ratio of 1.32), steep slopes (mean slope gradient (S) is 37°), and moderate size (mean planar area ($2D$) is 23.45 ha).
Group 3 (31 cirques) comprises long and rather narrow cirques (mean L/W ratio of 1.61) with low vertical development (mean

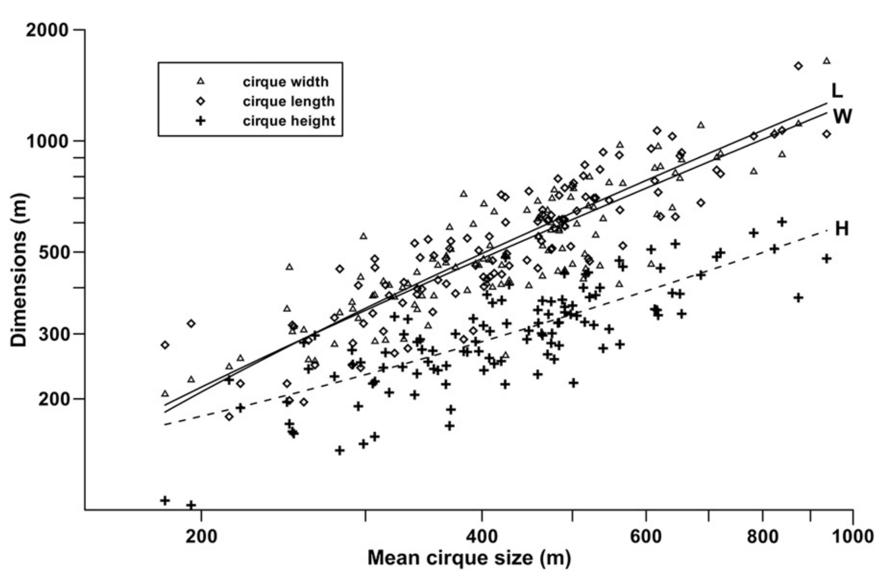

Fig. 3. Power relationships (*sensu* Evans and Cox, 1995) of cirque length, width, and height to mean cirque size (the cube root of cirque volume (V)). The smaller inclination of the regression curve for cirque height (H; dashed line) in comparison to the curves for cirque length (L) and width (W) implies that cirque shape varies with size — the cirques exhibit static allometry (this is static because the data refer to one time period).

Table 4
Summary statistics for morphometric characteristics and altitudinal indicators for cirque groups obtained from the cluster analysis.

	Group 1 (51 cirques)			Group 2 (34 cirques)			Group 3 (31 cirques)		
	Mean	Median	Standard deviation	Mean	Median	Standard deviation	Mean	Median	Standard deviation
E_{max} (m asl)	2217	2250	157.99	2226	2223	166.14	2261	2282	122.95
E_{min} (m asl)	1897	1923	170.22	1924	1917	173.39	1956	1956	117.30
H (m)	320	309	102.76	302	287	86.02	305	299	107.51
L (m)	623	535	316.06	412	395	166.36	656	650	209.30
W (m)	607	510	312.01	594	605	218.53	407	408	111.34
CR	1.12	1.10	0.06	1.14	1.11	0.08	1.16	1.16	0.06
L/H	1.95	1.83	0.67	1.38	1.26	0.45	2.27	2.13	0.59
L/W	1.04	1.03	0.14	0.70	0.72	0.12	1.61	1.57	0.27
W/H	1.91	1.79	0.66	2.01	1.79	0.66	1.46	1.32	0.49
V (10^6 m^3)	184.30	96.70	305.80	93.90	62.45	84.86	95.97	90.59	68.03
2D area (ha)	38.00	23.61	49.60	23.45	18.14	16.54	23.11	22.52	12.89
3D area (ha)	47.55	31.16	57.91	29.93	23.11	20.49	29.29	29.44	16.69
3D/2D	1.28	1.24	0.12	1.32	1.32	0.16	1.25	1.24	0.10
S (°)	34	34	5.67	37	38	7.56	33	33	4.05

L/H ratio of 2.27) and moderate size (mean planar area (*2D*) of 23.11 ha).

4.3. Cirque altitude

More than half of the cirques (62) were situated in altitudinal classes C (1815–1960 m asl) and D (1961–2069 m asl) (Table 5). According to the index of spatial distribution, the largest proportional representation of the cirques was within altitudinal class D, and the smallest proportional representation of the cirques (six cirques) was within altitudinal class A (1529–1629 m asl). Cirques were preferentially situated in altitudinal classes C, D, and E; i.e., above 1960 m asl (the values of the index of spatial distribution were >1) (Table 5).

Negative correlations between minimal cirque floor altitude (E_{min}) and characteristics describing cirque size (H, L, W, and planar area (*2D*), surface area (*3D*), and cirque volume (V)) were statistically significant (Table 3). This implies that cirques in the High Tatras were smaller at higher altitudes. No significant correlations were found between the altitudinal parameters (E_{min}, E_{max}) and the characteristics describing cirque shape (L/W ratio and CR). Likewise, correlations between the minimal cirque floor altitude (E_{min}) and the L/H ratio, *3D/2D* ratio, and mean slope gradient (S) were insignificant (Table 3). This finding is related to the fact that the mean and median values of E_{min} and E_{max} among the morphological groups of cirques were very similar (Table 4). Therefore, the shapes of the cirques in the High Tatras were not determined by their altitude.

4.4. Cirque aspect

The spatial distribution of the cirques respecting aspect depended on the course of the main ridge of the High Tatras. The main ridge runs in a WSW–ENE direction, resulting in a higher frequency of cirques (and their approximate numerical equality) belonging to opposite aspect categories (N–S, NW–SE, and NE–SW) than W and E aspect categories.

The largest number of the cirques (21) faces SE; in contrast; only five cirques face W (Table 5). According to the index of spatial distribution (Table 5), the largest proportional representation of cirques is on N- and NW-facing slopes. In general, the northern quadrant (NW, N, NE, i.e., shaded aspects) was more preferred for cirque formation (higher values of the spatial distribution index) than the southern quadrant (SE, S, SW, i.e., sunny aspects).

One-way ANOVA testing showed that cirques with shaded aspects (NW, N, and NE) and cirques with an E aspect were located at significantly lower altitudes (according to E_{max} and E_{min}) than cirques with sunny aspects (SE, S, SW) (Table 6, see also Table 5).

Only cirques facing N were wider than longer (mean L/W ratio of 0.80); cirques facing all other directions were rather longer than wider (mean L/W ratios between 1.02 and 1.26). Using a one-way ANOVA, significant differences were found in the L/H ratio, *3D/2D* ratio, and mean slope gradient (S) between cirques facing NW, N, and NE and those facing S (Table 6, see also Table 5). Generally, the cirques with shaded aspects (NW, N, and NE) were more

Table 5
Mean values of the studied morphometric characteristics with respect to the altitudinal classes and cirque aspects; mean values of E_{max} and E_{min} for the altitudinal classes were not computed with respect to the method used to determine the classes.

	Altitudinal classes					Aspect categories							
	A	B	C	D	E	N	NE	E	SE	S	SW	W	NW
No. of cirques	6	27	34	28	21	15	15	11	21	18	12	5	19
Index of distribution	0.113	0.734	1.469	2.694	1.652	1.610	0.761	0.181	0.311	0.270	0.253	0.243	1.130
E_{max} (m asl)	–	–	–	–	–	2164	2152	2172	2302	2287	2313	2310	2181
E_{min} (m asl)	–	–	–	–	–	1851	1806	1871	1977	2025	2034	1960	1851
H (m)	409	335	328	298	241	312	345	301	325	262	279	350	329
L (m)	941	606	595	572	375	467	581	592	602	634	536	628	540
W (m)	1059	609	557	488	399	616	553	529	531	562	501	555	545
CR	1.20	1.13	1.14	1.13	1.12	1.12	1.14	1.16	1.13	1.12	1.15	1.21	1.12
L/H	2.23	1.83	1.88	1.94	1.69	1.49	1.69	2.13	1.88	2.38	1.96	1.79	1.62
L/W	0.94	1.03	1.12	1.22	0.99	0.80	1.09	1.26	1.17	1.14	1.16	1.19	1.02
W/H	2.49	1.89	1.79	1.71	1.71	1.94	1.69	1.81	1.68	2.17	1.81	1.74	1.66
V (10^6 m^3)	606.95	156.93	124.12	94.48	39.15	143.89	220.01	117.63	123.73	126.47	82.28	123.61	122.84
2D area (ha)	102.62	34.16	28.09	24.29	13.25	30.24	40.00	28.42	28.18	32.02	22.11	27.84	26.98
3D area (ha)	123.92	44.23	35.61	30.45	16.66	38.48	49.54	35.73	36.58	38.34	27.26	35.68	35.47
3D/2D	1.26	1.29	1.29	1.28	1.29	1.31	1.34	1.24	1.32	1.19	1.23	1.29	1.33
S (°)	31	35	34	35	36	38	38	33	35	30	33	35	36

Table 6
Statistical significance (p) of the ANOVAs for the chosen morphometric characteristics and altitudinal indicators with respect to the cirque aspects; marked (**bold**) relations are significant at the significance level $p = 0.05$.

		SW	S	SE	NW	N	NE	W	E
SW	E_{max}	x	0.6311	0.8288	**0.0121**	**0.0072**	**0.0038**	0.9704	**0.0180**
	E_{min}	x	0.8669	0.2598	**0.0006**	**0.0010**	**0.0001**	0.3214	**0.0063**
	L/H	x	0.0781	0.7247	0.1443	0.0585	0.2715	0.6244	0.5213
	$3D/2D$	x	0.4443	**0.0325**	**0.0290**	0.0825	**0.0204**	0.3465	0.8343
	S	x	0.1408	0.2690	0.1330	**0.0228**	**0.0211**	0.4311	0.8218
S	E_{max}	0.6311	x	0.7537	**0.0226**	**0.0132**	**0.0066**	0.7527	**0.0337**
	E_{min}	0.8669	x	0.2820	**0.0003**	**0.0006**	**0.0000**	0.3570	**0.0048**
	L/H	0.0781	x	**0.0154**	**0.0004**	**0.0001**	**0.0023**	0.0703	0.3051
	$3D/2D$	0.4443	x	**0.0012**	**0.0011**	**0.0068**	**0.0009**	0.1213	0.3311
	S	0.1408	x	**0.0036**	**0.0010**	**0.0001**	**0.0001**	0.0567	0.0937
SE	E_{max}	0.8288	0.7537	x	**0.0075**	**0.0045**	**0.0020**	0.9064	**0.0145**
	E_{min}	0.2598	0.2820	x	**0.0055**	**0.0093**	**0.0005**	0.8094	**0.0452**
	L/H	0.7247	**0.0154**	x	0.1933	0.0726	0.3764	0.7888	0.2893
	$3D/2D$	**0.0325**	**0.0012**	x	0.9191	0.7565	0.7072	0.5741	0.0641
	S	0.2690	**0.0036**	x	0.6229	0.1480	0.1386	0.9702	0.4101
NW	E_{max}	**0.0121**	**0.0226**	**0.0075**	x	0.7293	0.5507	0.0697	0.8699
	E_{min}	**0.0006**	**0.0003**	**0.0055**	x	0.9961	0.3538	0.1252	0.7071
	L/H	0.1443	**0.0004**	0.1933	x	0.5669	0.7415	0.5774	**0.0346**
	$3D/2D$	**0.0290**	**0.0011**	0.9191	x	0.6917	0.7836	0.5351	0.0571
	S	0.1330	**0.0010**	0.6229	x	0.3321	0.3155	0.7849	0.2234
N	E_{max}	**0.0072**	**0.0132**	**0.0045**	0.7293	x	0.8123	**0.0464**	0.8849
	E_{min}	**0.0010**	**0.0006**	**0.0093**	0.9961	x	0.3778	0.1363	0.7231
	L/H	0.0585	**0.0001**	0.0726	0.5669	x	0.3938	0.3554	**0.0124**
	$3D/2D$	0.0825	**0.0068**	0.7565	0.6917	x	0.5258	0.7347	0.1393
	S	**0.0228**	**0.0001**	0.1480	0.3321	x	0.9742	0.3607	**0.0462**
NE	E_{max}	**0.0038**	**0.0066**	**0.0020**	0.5507	0.8123	x	**0.0312**	0.7165
	E_{min}	**0.0001**	**0.0000**	**0.0005**	0.3538	0.3778	x	**0.0357**	0.2446
	L/H	0.2715	**0.0023**	0.3764	0.7415	0.3938	x	0.7475	0.0821
	$3D/2D$	**0.0204**	**0.0009**	0.7072	0.7836	0.5258	x	0.4314	**0.0404**
	S	**0.0211**	**0.0001**	0.1386	0.3155	0.9742	x	0.3489	**0.0432**
W	E_{max}	0.9704	0.7527	0.9064	0.0697	**0.0464**	**0.0312**	x	0.0711
	E_{min}	0.3214	0.3570	0.8094	0.1252	0.1363	**0.0357**	x	0.2424
	L/H	0.6244	0.0703	0.7888	0.5774	0.3554	0.7475	x	0.3280
	$3D/2D$	0.3465	0.1213	0.5741	0.5351	0.7347	0.4314	x	0.4424
	S	0.4311	0.0567	0.9702	0.7849	0.3607	0.3489	x	0.5463
E	E_{max}	**0.0180**	**0.0337**	**0.0145**	0.8699	0.8849	0.7165	0.0711	x
	E_{min}	**0.0063**	**0.0048**	**0.0452**	0.7071	0.7231	0.2446	0.2424	x
	L/H	0.5213	0.3051	0.2893	**0.0346**	**0.0124**	0.0821	0.3280	x
	$3D/2D$	0.8343	0.3311	0.0641	0.0571	0.1393	**0.0404**	0.4424	x
	S	0.8218	0.0937	0.4101	0.2234	**0.0462**	**0.0432**	0.5463	x

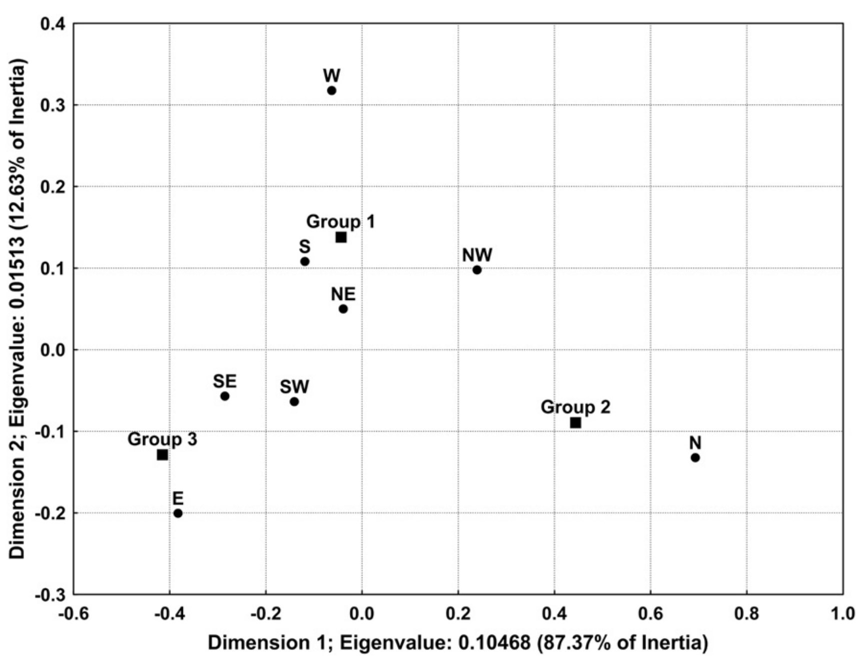

Fig. 4. Correspondence analysis of the distribution of cirque morphological groups in relation to aspect categories. The distribution of scores is shown for the first two dimensions. The first dimension extracts the most information (i.e., it has the highest eigenvalue) and explains 87.37% of the total inertia.

vertically developed (based on their *L/H* ratio), had higher vertical relief segmentation (based on their *3D/2D* ratio) and had higher mean slope gradients (*S*) than cirques with sunny aspects (SE, S, and SW) (Table 5). However, the differences in these characteristics (*L/H* ratio, *3D/2D* ratio, and mean slope gradient (*S*)) among individual aspect categories were not statistically significant in all cases (Table 6). Cirques facing NE and N were also the largest (based on cirque volume (*V*) and cirque surface area (*3D*)), but the differences in cirque-size characteristics (*3D*, *2D*, *V*) among individual aspect categories were not statistically significant.

The first dimension of correspondence analysis (Fig. 4) showed that cirques belonging to group 2 were associated with N and NW aspects and differed from cirques belonging to groups 1 and 3. A synergic effect between the first and second dimensions separated cirques belonging to group 3 and linked them with sunny aspects (E, SE, and SW). Most cirques of the High Tatras belonged to group 1, which was associated mainly with NE, S, and W aspects, and thus the group was associated with neither sunny nor shaded aspects.

A general discriminant analysis (GDA) showed that the classification of the cirques based on their morphometric characteristics (groups obtained by tree clustering) had 43% conformity with the classification based on altitude and aspect (Table 7). This finding implies a relatively limited influence of these two environmental factors on cirque morphology in the High Tatras.

5. Discussion

5.1. Cirque size and shape

In the High Tatras, cirque length (*L*) and cirque width (*W*) did not exceed 2 km, and cirque height (*H*) did not exceed 1 km. From this point of view, the cirques of the High Tatras are similar to the cirques of the English Lake District (Evans and Cox, 1995), the Cantabrian range (Ruiz-Fernández et al., 2009), the Bohemian massif (Křížek et al., 2012), and Mt. Smolikas and Mt. Vasilitsa (Hughes et al., 2007) (Fig. 5). However, according to the mean values and range of cirque planar areas (*2D*), the studied cirques are similar to the cirques of the central Spanish Pyrenees (García-Ruiz et al., 2000), the Maritime Alps (Federici and Spagnolo, 2004) (Fig. 5), and the Romanian Carpathians (mean planar area (*2D*) 43.7 ha; I.S. Evans, Durham University, personal communication, 2012). In general, the means of the chosen morphometric characteristics of cirques in the High Tatras are comparable with corresponding values for cirques in other discussed regions (with the exception of cirques in the Victoria Valley system, which exhibit notably higher values; Fig. 5); higher variability is observed for the total range of individual characteristics. This finding supports the statements of Evans and McClean (1995) and Evans (2003) that cirques are scale-specific landforms (with a limited range of sizes), commonly between 0.2 and 4 km broad and long with a minimum size that is related to the threshold for glacier formation and an upper limit that is governed by valleyhead spacing.

The cirques in the High Tatras were approximately circular (according to the mean *L/W* ratio and mean circularity ratio, Table 2), similar to the situation in the Maritime Alps (mean *L/W* ratio of 1.07; Federici and Spagnolo, 2004), in the Romanian Carpathians (mean *L/W* ratio of 0.96; I.S. Evans, Durham University, personal communication, 2012), and in the Bohemian massif (mean *L/W* ratio of 1.16; Křížek et al., 2012). The finding of almost no correlation between the *L/W* ratio and cirque size (*3D*, *2D*, *V*) ($r = 0.01$, Table 3) in the High Tatras contrasts with the findings in the Victoria valley system (Aniya and Welch, 1981), in the central Spanish Pyrenees (García-Ruiz et al., 2000), and in Wales (Evans, 2006a) where cirque length increases more rapidly than cirque width (thus, the *L/W* ratio increases with cirque size in the latter areas, caused by more rapid backwall than sidewall erosion; see Evans, 1997, 2007, 2010). This cirque headwall retreat toward the main ridge of a mountain chain and its importance for shaping the general topography of glaciated mountains has been highlighted by Oskin and Burbank (2005) and by Mitchell and Montgomery (2006). In the High Tatras, the increase in cirque width or possible lateral coalescence of cirques most likely balances the increase in cirque length, resulting in the almost circular shape of the cirques regardless of their size. This is similar to the situation in Sangre de Cristo Mountains (Olyphant, 1981), where nearly equal increases in cirque length and width can be observed.

A similar overall cirque gradient (based on the mean *L/H* ratio) to cirques in the High Tatras has been found in the Maritime Alps (mean *L/H* ratio of 1.93) (Federici and Spagnolo, 2004) and in the Sierras in southwest Asturias, Cantabrian range (mean *L/H* ratio of 1.95) (Ruiz-Fernández et al., 2009). The mean *L/H* ratio of cirques in the central Spanish Pyrenees is lower (1.48) (García-Ruiz et al., 2000). Higher mean values of the *L/H* ratio (i.e., lower overall cirque gradient) have been found in the Kintail–Affric–Cannich area of northwest Scotland (2.21) (Gordon, 1977), in New England (mean values between 2.7 and 4.7) (Davis, 1999), in the Highlands of Britain (3.00) (Embleton and Hamann, 1988), and in the Bohemian massif (2.96) (Křížek et al., 2012). Although the compared *L/H* ratios refer to geographically distinct regions with different geologic structures and geomorphological histories, the cirques of the High Tatras (similar to cirques in other mountain ranges built up during the Cenozoic) have higher overall cirque gradient (based on *L/H* and *W/H* ratios) than cirques from old Palaeozoic mountain systems. This pattern has been already noted previously (see Federici and Spagnolo, 2004; Ruiz-Fernández et al., 2009).

Static allometry (*sensu* Olyphant, 1981; Evans, 2006a) was confirmed for the cirques in the High Tatras; this finding accords with findings in other regions (e.g., Gordon, 1977; Olyphant, 1981; Evans and Cox, 1995; Federici and Spagnolo, 2004; Ruiz-Fernández et al., 2009). If the cirque size is considered as a proxy for cirque maturity (i.e., stage of cirque development), then more rapid increase of cirque horizontal dimensions (headwall retreat) than cirque floor incision (i.e., decreasing vertical development with increasing size) appears to be a common rule that describes the evolution of cirque morphology in time.

5.2. Cirque altitude

Based on the index of spatial distribution, cirque formation is preferred at altitudes > 1960 m asl (altitudinal classes C, D, and E); this is caused mainly by the prevalence of climatic conditions more suitable for cirque glacier formation at this altitude and the longer time during which these cirques were located above the climatic snowline. Most of the cirques surveyed were located somewhere in the middle of the altitudinal range of the High Tatras (altitudinal classes C and D); the number of cirques in the lowest and the highest locations is lower. This pattern is in good agreement with the altitudinal distribution of cirques in other ranges (e.g., García-Ruiz et al., 2000; Federici and Spagnolo, 2004; Ruiz-Fernández et al., 2009).

Altitude determined cirque size in this study (decreasing cirque size with increasing altitude) but had only a slight influence on their shape. A modest decrease of cirque size with increasing altitude

Table 7
Classification matrix for the cirque groups observed (i.e., obtained from cluster analysis) and predicted by discriminant analysis; the rows show the real (observed) classification of the cirques, and the columns show the classifications predicted by discriminant analysis.

Classes	C	B	A	Total	Percent correct
C	31	10	10	51	60.78
B	17	12	5	34	35.29
A	18	5	8	31	25.81
Total	66	27	23	116	43.97

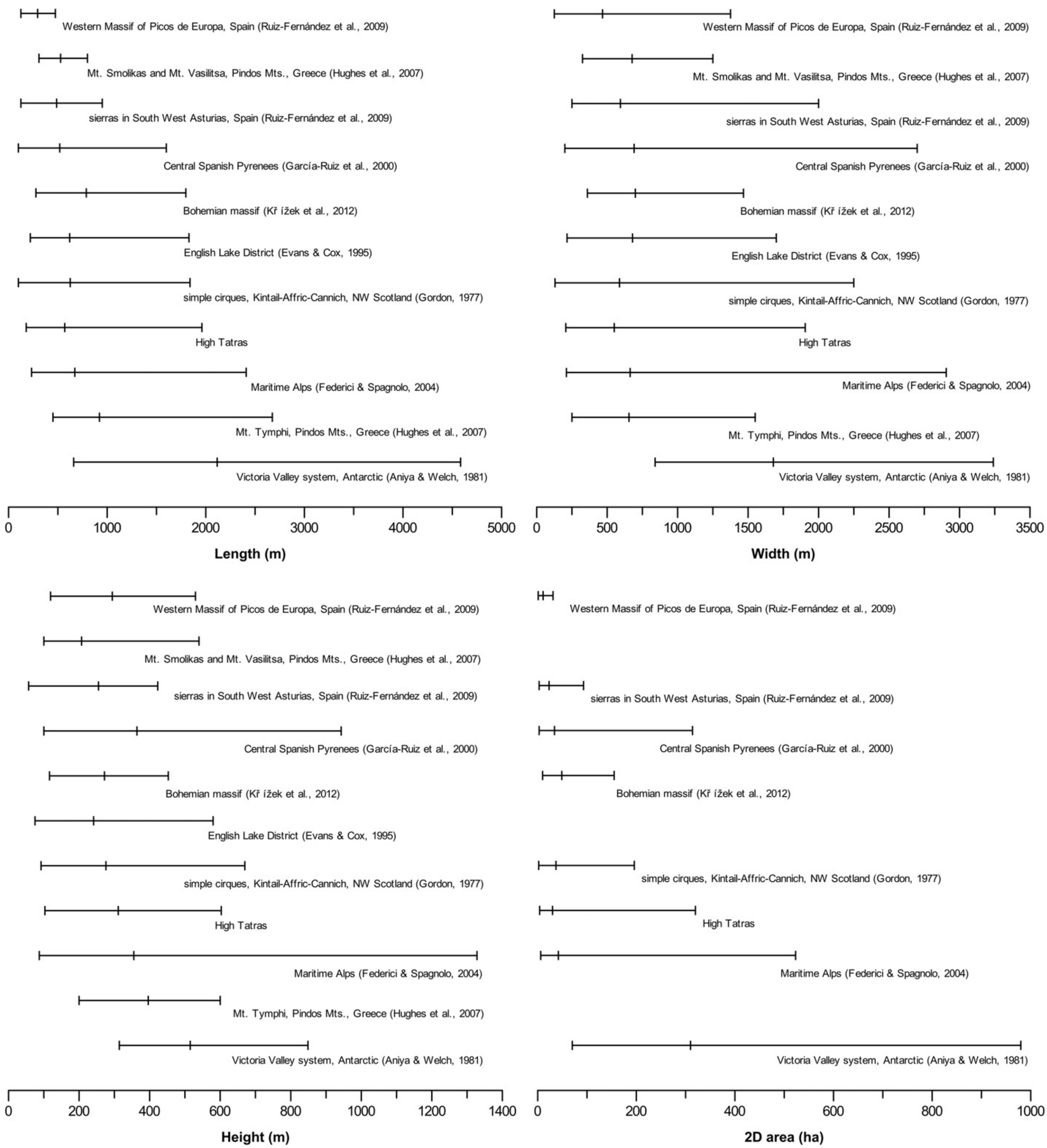

Fig. 5. Comparison of the dispersion and means of chosen morphometric characteristics for cirques in the High Tatras with corresponding morphometric characteristics of cirques in some European alpine areas, the Bohemian Massif, the British Isles, and the Victoria valley in the Antarctic.

was also observed in the central Spanish Pyrenees (García-Ruiz et al., 2000), which contrasts with the situations in the Maritime Alps (Federici and Spagnolo, 2004) and in the Sierras in southwest Asturias, Cantabrian range (Ruiz-Fernández et al., 2009). Only a small effect of altitude on cirque size was found in the English Lake District (Evans and Cox, 1995). One possible explanation for the decrease in cirque size with increasing altitude in the High Tatras is that cirques at higher altitudes had limited space for lateral growth (narrower ridges were located in the upper crest of the mountains) in comparison with cirques at lower altitudes. Moreover, where erosion causes the back-to-back coalescence of cirques, a deep col is formed (Evans, 2007); and strong winds (the jet effect) associated with the cols inhibit snow accumulation and further cirque growth.

Similar mean altitudinal values (E_{max}, E_{min}) of morphological groups of cirques and the existence of only a few significant correlations among these altitudinal indicators and morphometric characteristics describing cirque shape showed that altitude had limited influence on cirque shape in the High Tatras. Only the *W*/*H* ratio correlated significantly with both of the altitudinal indicators (increased overall cirque gradient with increasing altitude), which accords with the concept of allometric development in the studied cirques that is linked with decreasing size with increasing altitude. The finding that cirque shape is unrelated to altitude was also observed for the Maritime Alps (Federici and Spagnolo, 2004), the English Lake District (Evans and Cox, 1995), and the Western Massif of Picos de Europa in the Cantabrian range (Ruiz-Fernández et al., 2009). The relative independence of cirque shape on altitude suggests the existence of another factor that influences cirque shape in the High Tatras. For example, Klimaszewski (1964, 1988) proposed that the conditions for glacial erosion and cirque formation are determined by the character of the preglacial relief of the valley heads and differential rates in their rejuvenation, but a more likely explanation appears to be influence of the width and direction of mylonite zones on cirque shape (Kalvoda, 1974).

5.3. Cirque aspect

In the High Tatras, the spatial distribution of cirques respecting their aspect and altitude was substantially determined by general topography (the latitudinal direction of the main ridge and the higher altitudes of the south part of the range). An effect of general mountain topography on cirque aspect distribution was also found in the Maritime Alps (Federici and Spagnolo, 2004), the central Spanish Pyrenees (García-Ruiz et al., 2000), and in the Cantabrian range (Ruiz-Fernández et al., 2009). However, for a sufficiently large set of cirques located in a range with ridges at various orientations, it is believed (*sensu* Evans, 1977; Mîndrescu et al., 2010) that climatic factors affect the spatial distribution and morphology of cirques more than topographic factors.

The degree of cirque frequency symmetry in opposite aspect categories is usually in direct proportion to the number and intensity of glaciations in an area (the 'law of decreasing glacial asymmetry with increasing glacier cover'; *sensu* Evans, 1977), and locally symmetrical glaciation tends to be found where either the climatic snowline fell well below the elevation of the main ridge or the climate was neither sunny nor very windy (Evans, 2006b). Consequently, several generations of cirque glaciers (or subsequently, larger valley glaciers) probably developed in the High Tatras. Multiple glaciations of the High Tatras are also recognized by other researchers (e. g., Lukniš, 1973; Lindner et al., 2003); however, these findings were based on the study of moraine remnants and glaciofluvial sediments, not of glacial erosional landforms.

Based on the index of spatial distribution, cirques in the High Tatras developed preferentially on slopes facing N, NW, and possibly NE (shaded aspects), thus confirming the importance of incoming solar radiation on cirque formation. This finding accords with the situation in the Maritime Alps (Federici and Spagnolo, 2004) and in the Cantabrian range (Ruiz-Fernández et al., 2009) and agrees with the findings of Evans (1977, 2006b), who showed that the northern quadrant is the most favorable for the development of local mountain glaciation (and thus cirques) in the majority of mountain ranges in the northern hemisphere.

Southern-slope cirques are located at higher altitudes than northern-slope cirques because the southern part of the High Tatras is asymmetrically uplifted horst and that is why there are the highest summits here. However, the influence of climatic factors on cirque altitudinal distribution in relation to their aspect cannot be totally neglected. During the cold phases of the Pleistocene, wind directions in the High Tatras mainly resulted from the strong effect of a stationary anticyclone over the Fennoscandian Ice Sheet and a north-south climatic gradient (see Huijzer and Vandenberghe, 1998; Florineth and Schlüchter, 2000). Wind directions (i.e., moisture sources) above the study area contained a stronger NW-to-N component than did ranges located farther to the south (the Alps and the mountains of the Balkan Peninsula). For example, prevailing west winds caused the eastward rise of cirque floor altitudes in the Romanian Carpathians (Mîndrescu et al., 2010).

Accordingly, in the High Tatras, significantly higher incision (based on the *L*/*H* ratio) and higher relative relief (based on the *3D*/*2D* ratio) of cirques are associated with NW, N, and NE aspects in comparison to SE, S, and SW aspects. Moreover, most excavated cirques with steep slopes (morphological group 2) were associated with N and NW aspects. Thus, cirques of the northern slopes represent more developed glacial erosion landforms; therefore, these cirques had to endure more intensive or longer glaciation than cirques of the southern slopes of the High Tatras. This contradicts the accepted model of the course of glaciations in the High Tatras. Based on the better preserved and lower lying moraine residuals of the southern slopes, it is considered (e.g., Lukniš, 1973; Lindner et al., 2003) that the glaciations of the southern slopes were more numerous and more intensive than those of the northern slopes. A possible explanation for this discrepancy is that only small cirque glaciers existed on the northern slopes (the southern slopes were nonglaciated) during the earlier stages of the Pleistocene. However, the sedimentary evidence of these northern-slope cirque glaciers was erased by the activity of successive glaciers during succeeding glaciations; hence, their occurrence is no longer recognizable. Another explanation is that although the southern-slope glaciers were larger and longer during the maximum glaciation stages, the preservation of small glaciers was favored only on the northern slopes of the High Tatras during the earlier and latest glaciation phases. This emphasizes the role of the anaglacial and cataglacial phases of glaciation for cirque floor incision (see Evans, 1999) when rather wet-based or polythermal glaciers with higher erosive potential are present in cirques. In both cases, this finding demonstrates the considerable variability of glaciation conditions in the High Tatras during the cold phases of the Pleistocene.

5.4. The dependence of cirque morphology on environmental factors

The GDA demonstrates only weak conformity (43%) between the morphologic classification of cirques and the classification of cirques based on altitude and aspect. For the cirques in the central Spanish Pyrenees (García-Ruiz et al., 2000), altitude, aspect, and lithology explained the classification of 66% of the cirques. In this respect, altitude and aspect have an even more limited influence on cirque morphology in the High Tatras than in the central Spanish Pyrenees. Weak connections between specific cirque morphology and particular environmental conditions were also found in the English Lake District (Evans and Cox, 1995) and the Cantabrian range (Ruiz-Fernández et al., 2009). Although it is possible to detect and examine certain relations among cirque morphology and altitude, aspect, or other environmental factors, these factors do not explain the morphologic variability of cirques with sufficient precision.

Previous morphometry studies of cirques in different regions of the world (Aniya and Welch, 1981; Evans and Cox, 1995; García-Ruiz et al., 2000; Federici and Spagnolo, 2004; Hughes et al., 2007; Ruiz-Fernández et al., 2009) have shown that not all relationships between the above-mentioned factors (altitude and aspect) and cirque morphology can be generalized. The higher degree of cirque incision within young (Mesozoic and Cenozoic) mountains than in older (Palaeozoic) massifs highlights the role of initial forms and preglacial relief in determining the morphology and development of cirques (see Evans and Cox, 1995; Federici and Spagnolo, 2004) and, contrarily, diminishes the influence of climatic conditions. The alpine relief type evolves differently in tectonically active young mountains than in old massifs that have not been substantially rejuvenated by Neogene and Quaternary tectonics (Benn and Evans, 1998). Therefore, it is more suitable to compare cirque morphometry (morphology) within regions with similar tectonic history and topography and, ideally, with similar lithology. If this premise is fulfilled, then variations of cirque morphology in distinct regions can be examined in relation to mesoclimatic factors, which are given mainly by altitude and aspect.

However, separation of the long and complex development of the natural environment from the isolated influences of several environmental factors (e.g., altitude and aspect) remains very difficult. It is important to note that morphological differences within the given cirque population may reflect various stages in their development rather than the differential influences of environmental factors. On the other hand, it may be useful to define new morphometric characteristics and indexes that can describe cirque morphology variability in relation to altitude and aspect more cogently. Nevertheless, further comparative studies regarding other glaciated regions are needed for a better understanding of the relationships between cirque morphology and climate, geology, and topography.

6. Conclusions

Analysis and subsequent evaluation of 116 High Tatras' cirques showed the following:

– High Tatras cirques are scale-specific landforms with allometric development.
– Three morphological groups of the cirques are recognized. The most common morphological type (group 1) is circular and exhibits moderate incision and above-average size relative to the entire set of studied cirques.
– Cirque formation was favored at elevations > 1960 m asl, indicating a positive influence of increasing altitude in connection with mesoclimatic conditions (decreasing temperature, rising precipitation) on the spatial distribution of the cirques. On the other hand, although the cirques occur more frequently at higher altitudes, cirques are larger at lower altitudes than at higher altitudes. However, this relationship is not generally valid.
– Cirque shape is only slightly related to altitude, with the exception of an increase in incision with altitude. If cirque size is considered a substitute for cirque age, pertinent to the concept of the allometric development of cirques, then smaller, more incised and younger cirques are formed above (at higher altitudes) than larger, less incised and older cirques and cirque amphitheatres in the High Tatras.
– The spatial distribution of the cirques is negatively influenced by incoming solar radiation and positively influenced by moisture sources, which came mainly from the NW to N during the cold phases of the Pleistocene. This is the reason why north-facing cirques have proportionally stronger representation and are more incised with steep slopes (group 2) than the cirques of the southern quadrant. North-facing slopes represented the best location for the development (more intensive or longer glaciations) of glaciation in the High Tatras. On the other hand, higher altitudes and the larger area above the climatic snowline on the southern part of the High Tatras allowed the formation of a greater number of south-facing cirques. Therefore, in the High Tatras, the southward rise of cirque floor altitudes appears to be a result of a synergetic effect of topography, exposure to moisture sources coming from the NW to N and differences in incoming solar radiation.
– Based on this study of cirque morphology, several glaciation phases occured in the High Tatras. This finding is consistent with the results of studies of glacial accumulation landforms and the 'law of decreasing glacial asymmetry with increasing glacier cover' (*sensu* Evans, 1977).
– Although some relationships and dependencies among morphometric characteristics and altitude and aspect were determined, according to the results of the GDA, these environmental factors are unable to explain variations in cirque morphology with sufficient cogency.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.geomorph.2013.05.012. These data include Google map of the most important areas described in this article.

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