Comparison of morphometric characteristics of cirques in the Bohemian Forest

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Abstract
This study analyses selected morphometric characteristics of seven glacial cirques in the Bohemian Forest. Firstly, a glacial system of a glacial cirque typical of the Bohemian Forest was postulated. Then, morphometric characteristics were counted and compared for components of the system (cirque floor, headwall, deflation plateau, etc.). It is probable that the total altitude (mainly the position of deflation plateaus) was an important factor for the development of glaciers. The following hypothesis was postulated based on connections between morphometric characteristics and genesis of the cirques: (1) the lengthening of the cirques occurred primarily during the cold stages of the Pleistocene depending on the size and position of the deflation plateau, (2) development of the cirques continued after the disappearance of the glaciers by other (particularly periglacial) processes, and (3) fluvial and gravitational processes reshaped the cirques during the warmer stages of the Pleistocene. Two types of ELA (equilibrium line altitude) were calculated: the TP-ELA was probably ca. 1290 m a.s.l and the TPW-ELA in ca. 1021 m a.s.l.

Key words: morphometry, glacial landform, cirque, ELA, Bohemian Forest (=Šumava Mts.)

INTRODUCTION

Two main concepts dealing with the glaciation of the Bohemian Forest (= Šumava Mts.) during the cold stages of the Pleistocene have been postulated. Firstly, BAYBERG (1886) as well as PREIHÄUSSER (1934) stated the hypothesis of an extensive glaciation (an ice cap was developed in the Šumavské Pláně plateau and the outlets filled the valleys of the bigger rivers such as Vydra and Otava). The snouts of these glaciers probably finished at low altitudes (475 m a.s.l.).

Secondly, RATHSBURG (1928, 1932) argued that the glaciers were located just at their cirques and their snouts just overlapped the sills. This hypothesis seems to be true in the light of the results of research carried out after the Second World War (VOTÝPKA 1979) and consequently after 1989 (MENTLÍK 2002, 2005, 2006, RAAB & VÖLKEL 2003, VOČADLOVÁ & KŘÍŽEK 2005, etc.), when the Iron Curtain in the Bohemian Forest was removed.

Eight glacial cirques, which are occupied by lakes lying in glacial cirques exist in the Bohemian Forest at present. Furthermore, a filled lake was found in the Stará Jímka area (BŘÍZOVÁ & MENTLÍK 2005) and also the depression on the north flanks of the Grosser Rachel Mt. is thought to be a filled lake (PFAFFL 1988). Thus, comparison of their morphometry would be a good source of information about their origin and development.

A comprehensive study dealing with morphometry of the cirques has not been published yet, however, PFAFFL (1992) investigated some characteristics of the lakes and deflation pla-

teaus. He concluded that summits lying between 1300–1400 m a.s.l. had special importance for glaciation of the mountains and very significant glacial forms developed in their surroundings.

Nevertheless, studies dealing with the morphometry of glacial cirques have been carried out in other mountains ranges all around the world. Definition of the basic characteristics of glacial cirques and comparison of the data from various regions was made by Evans (1977) and Evans & Cox (1974, 2005). Recently, Aniya & Welch (1981) analysed the morphometry of cirques in Antarctica, García-Ruiz et al. (2000) dealt with a morphometric analysis of glacial forms in the central Spanish Pyrenees, and also Federici & Spagnolo (2004) studied the morphometry focusing on the size, shape and spatial distribution of cirques in the Maritime Alps. Gordon (1977) analysed the morphometry of cirques in the Kintail-Affric-Cannich area of Northwest Scotland.

The study of morphometry and development of cirques was connected in a paper dealing with glacial cirques in the Ben Ohau Range, New Zealand (Brook et al. 2006). The authors argued that glacial cirques create an evolutionary model of morphological changes depending on time. According to this model, the cirques developed from relatively shallow forms (with respect to the variability of the sites where cirques began forming – gullies, landslide scars etc.) to deeper and longer forms. They also stated the rate of the development of the cirques over time. According to the results (Brook et al. 2006) the development of a "classic – fully developed cirque" takes ca. 750 ka of glacial occupancy. Nevertheless, the landforms approaching the morphology of a glacial cirque develop after ca. 400 ka of glacial occupancy.
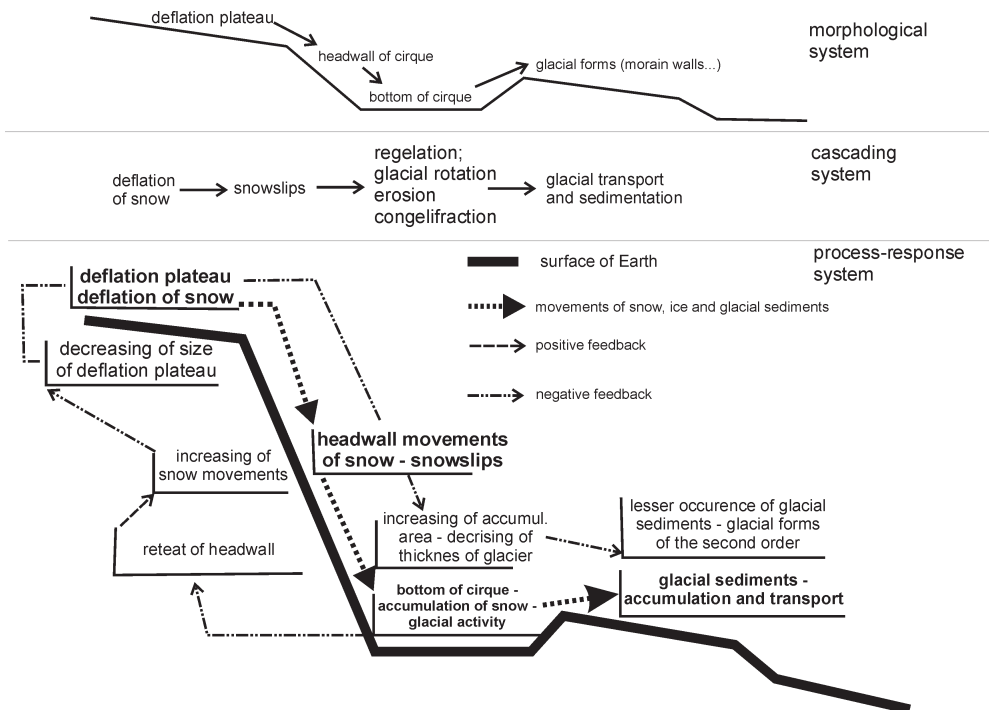

Fig. 1. Model of a system of a "typical glacial cirque of the Bohemian Forest".

It is assumed according to research of glacial landforms (especially accumulation forms – Votýpka 1979, Mentlík 2002, 2005, 2006, Raab & Völkel 2003) that the glaciation of the Bohemian Forest took place just in the last glacial period (the Würm) of the Pleistocene. We only have numerical data for the end of the last glaciation from the surroundings of Prášilské and Grosser Arbersee lakes (Raab & Völkel 2003). It is probable, that these areas were ice free before the Younger Dryas. Moreover, the beginning of the glaciation was dated by Raab & Völkel (2003) by IRSL (infrared stimulated luminescence) at 32.4 ka BP. The analysis of morphometry of the destruction of glacial landforms, however, suggests the occupancy of the cirques by glaciers longer than 100 ka (Mentlík 2006). Therefore, more detailed research of morphometry of the cirques and its comparison may provide a useful view of the glaciation in the whole mountain range.

Another problem which may be solved by analysing of cirque morphometry is the position of the former equilibrium line altitude (ELA). Some authors have used the morphometry of glacial cirques (precise altitude of the cirque floor) in an attempt to reconstruct the ELA of former glaciations (Federici & Spagnolo 2004).

According to a model of a "typical glacial cirque of the Bohemian Forest" (Fig. 1), it is possible that the position of a deflation plateau was important for the development of the glacial cirques. Thus, two types of ELA were probably important for the development of glaciations in the Bohemian Forest. Firstly, the locally topographic ELA defined by the position of cirque glaciers on slopes with colder aspect. Secondly, the regional ELA (influenced by temperature and precipitation) with a higher position. The plateaus on ridges, working as deflation plateaus, were an important factor determining the lowering of the local ELA (cf. examples from Norway, Nesje & Dahl 1992). Hence, morphometry (mainly the size) of the plateaus, which are connected with the cirques, should be important for the development of the cirques.

According to the assumptions stated above the aims of this paper may be summarized as follows: (i) To analyse glacial cirques in the Bohemian Forest and to compare the results with data from other mountain ranges (mainly with respect to their age). (ii) To postulate a probable position of the ELA (local and regional) for the Bohemian Forest. (iii) To test the following hypothesis: the size of a deflation plateau influences the development and morphometry of cirques.

Selected glacial cirques and their basic characteristics

All glacial cirques in this study lie in the Bohemian Forest: cirques of Prášilské, Černé, Čertovo, Plešné, and Laka lakes in the Czech part and cirques of Rachelsee and Grosser Arbersee lakes in the German part (Fig. 2).

According to Mentlík (2006), two significant glaciations took place in the surroundings of Prášilské Lake. The older and also larger probably finished at ~1000 m a.s.l. The younger, on the other hand, was bound to the steep slope with colder (East) aspect and was less extensive.

The main bedrock in the area is strongly magmatized cordierite-biotitic paragneiss, medium-grained to coarse-grained porphyric-biotitic granite, chlorite-muscovite mica schist and gneiss (Zbořil 1996).

The cirque of Laka Lake lies in the Debrnická Hornatina highland. Although gneiss and migmatite are the most extensive bedrock there, the small belt of granodiorite occurs in the NW part of the cirque. The probable extent of the older (more wide-ranging) glaciation is marked by the glacial sediments at a height of about 1000 m a.s.l. (Mentlík 2005). However, a glacier probably existed just in the area of the present lake basin during the second phase
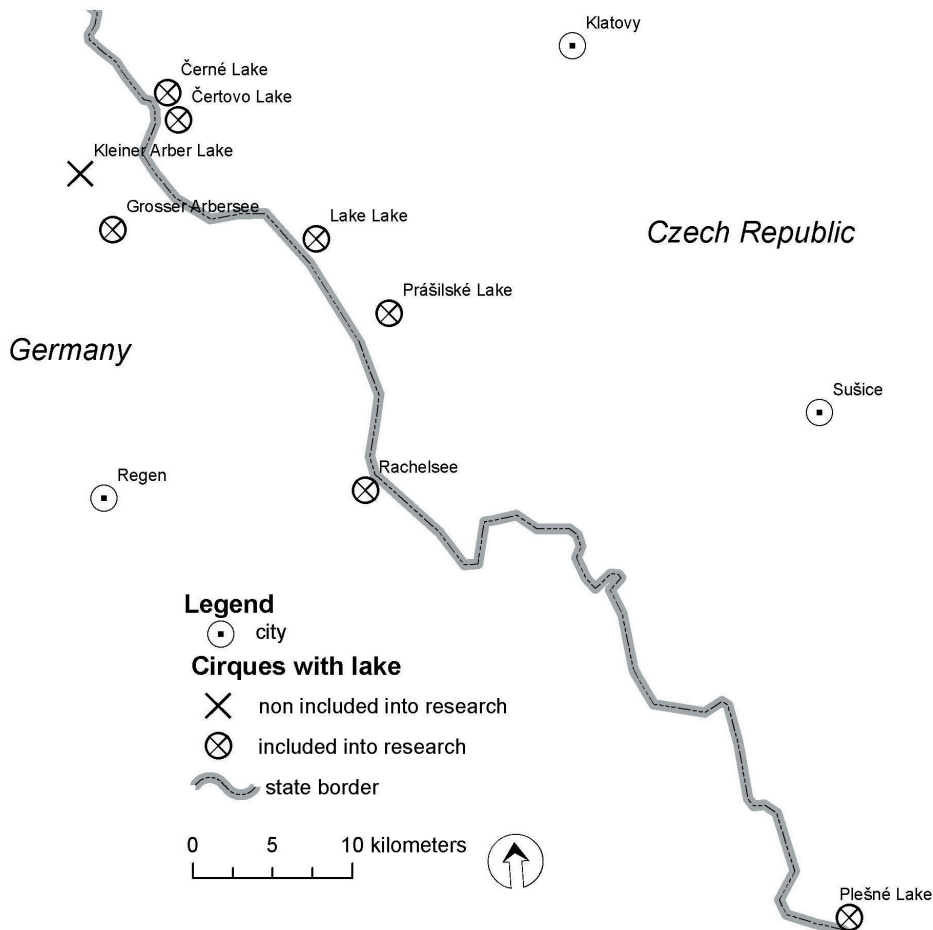
Fig. 2. Localization map of studied cirques.

of glaciation (Mᴇɴᴛʟíᴋ 2005).

The cirques of Černé and Čertovo lakes belong to the geologically monotonous unit of the Královský Hvozd highland, which is composed of medium coarse-grain garnet-biotitic-muscovitic mica schist.

Knowledge of the geomorphology of the surroundings of the cirque of Čertovo Lake is very poor. Conversely, Vᴏčᴀᴅʟᴏᴠá & Křížᴇᴋ (2005) carried out research in the surroundings of the cirque of Černé Lake, where they identified at least three groups of moraine walls.

The cirque of Plešné Lake lies on the SE and NE flanks of the Plechý Mt. (1378 m a.s.l.). The cirque is formed by eisgarn granite with muscovitic-garnet diorite. Biotitic porphyric medium-grained grandiorite of the weinsber type is situated on the west side of the lake. The centre of the massif is composed of a rastenber type of amphibolic-biotitic porphyric medium-grained granite (Jᴀɴsᴋý et al. 2005). Based on the analysis of glacial accumulations in the surroundings of Plešné Lake, Vᴏᴛýᴘᴋᴀ (1979) concluded that two phases of the Würm glaciation occurred there. These results were probably based on the geomorphological position of the glacial landforms and are not supported by other methods of numerical or relative dating.

From a geological point of view, the cirques of Grosser Arbersee and Rachelsee lakes are created by metatetic garnet-cordieritic-sillimanitic gneiss (PFAFFL 1988).

METHODS AND DATA

The authors dealing with glacial cirques in the Bohemian Forest recently (HOUSAROVÁ & MENTLÍK 2004) used basins of the lakes for analysing morphometry. However, glacial cirques are not necessarily delimited by the basin of the lake. Thus, the delimitation of the cirques according to contour line analysis (scale 1 : 10000 and DEM – digital elevation model) was used in this paper. Many authors have used the same approach in other regions (e.g. GARCÍA-RUIZ et at. 2000, FEDERICI & SPAGNOLO 2004).

A glacial cirque is defined (according to EVANS & COX 1974) as a hollow open downstream and bounded upstream by a steep headwall (backwall) surrounding a gently sloping floor. The cirque floor is situated between the headwall and an accumulation area (the area of occurrence of glacial sediments). The transition between the gentle part to the very steep part of the headwall (on the lower end) may be very pronounced or it can form as an almost horizontal ledge. This is described as a "schrundline" lying at the former boundaries of the ice (freeze-and-thaw erosion took place above this line) (VILBORG 1977, 1984).

The headwall is defined as a place limited by the border between the gentle slope and the steep slopes at the top and the "schrundline" at the bottom.

Table 1. Selected morphometric characteristics of investigated cirques.

Morphometric characteristics	Units	Denotation in the text
Area 2D	ha	A 2D
Area 3D	ha	A 3D
3D/2D ratio	dimensionless	A 3D/A 2D
Minimum altitude	m a.s.l.	Minimum altitude
Maximum altitude	m a.s.l.	Maximum altitude
Height	m	H
Length	m	L
Width	m	W
L/H ratio	dimensionless	L/H
L/W ratio	dimensionless	L/W
Mean altitude	m a.s.l.	Mean altitude
Mean slope gradient	°	Mean slope gradient
Headwall gradient	°	Headwall gradient
Deflation plateau area 2D	ha	DPA 2D
Azimuth of median axis	°	Azimuth of median axis[*]

[*]cirque median axis passes through the middle of the sill and divides the cirque map area into two equal parts (definition according to EVANS 1977)

The glacial cirques in the Bohemian Forest have some special features in comparison with cirques in higher mountain ranges where "a classical" glacial landscape with cirques, arêtes and matterhorns is developed. Extensive deflation plateaus were probably important for lowering the local topographic ELA and development of the glaciers. Nesje & Dahl (1992) described a similar situation in Norway. They distinguished the local topographical ELA (TPW-ELA – influenced by temperature, precipitation, wind) and the regional ELA (TP-ELA – depending on temperature and precipitation).

The model of a glacial cirque typical for the Bohemian Forest was developed (Fig. 1). Consequently, parts of the system were used as features of the morphometrical analysis. The main parts of the system were defined as follows: (i) deflation plateau, (ii) headwall (backwall), (iii) bottom of cirque. and (iv) accumulation area.

Unfortunately, it was not possible to obtain data from detailed terrain research from the all areas. Therefore, it was impossible to incorporate features of accumulation areas into the analysis, because its delimitation (in contrast to the bottom of the cirques) was very ambiguous. Conversely, deflation plateaus were defined as plateaus situated near the cirques with gradient 0–12° (without consideration of aspect).
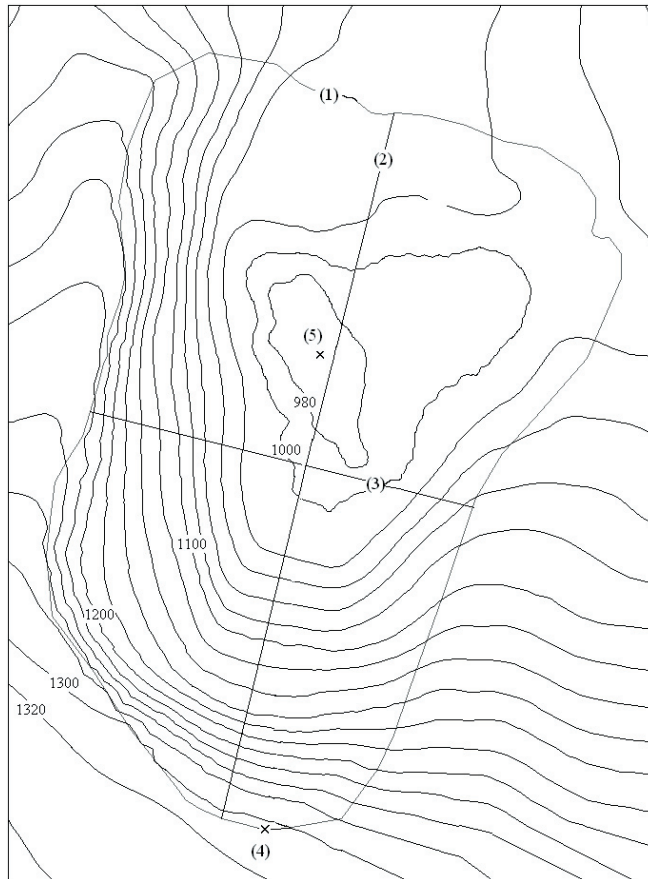
Fig. 3. Definition of the measured variables in the cirque of Černé Lake: (1) area [ha], (2) length [m], (3) width [m], (4) maximum altitude [m a.s.l.], (5) minimum altitude [m a.s.l.].
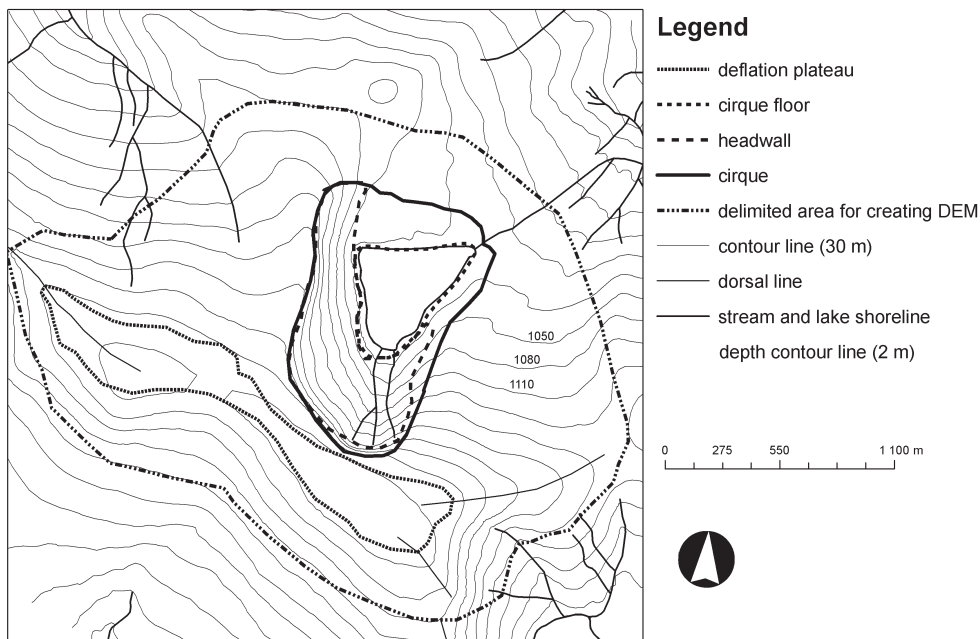
Fig. 4. Defined forms in the cirque of the Černé Lake with the deflation platform.

Elevation data (contour line, elevation of defined points) were obtained from digital contour line maps of DMÚ (1998) (Digital Landscape Model) 1 : 25 000 and ZABAGED® (2006) (Fundamental Base of Geographic Data) 1 : 10000. Depth contour lines of lakes (bottom of cirques) were geocoded and manually vectorized from bathymetric maps (Janský et al. 2005).

According to Gordon (1977), the analysis of morphometry is divided into three main parts: analysis of size descriptors, shape descriptors, and additional parameters. The measures of size descriptors were: height, length, width, area of the cirque 2D and 3D, 3D/2D ratio and deflation plateau area 2D (Table 1, Fig. 3). Shape descriptors comprised mean slope gradient, headwall gradient, L/H ratio and L/W ratio. Additional parameters were minimum altitude, maximum altitude, mean altitude and azimuth of median axis (Table 1).

The area of a cirque and the size of a deflation plateau were identified by analysis of DEM in ArcGis 9.1 (Fig. 4). The length was measured as the longest line splitting a cirque into two equal parts. The cirque width was drawn as the longest line inscribed in a cirque and the perpendicular to the length line. The area together with the minimum, mean and maximum altitudes were automatically derived from DEM in the extension 3D Analyst. Mean steepness and headwall gradient were obtained by the analysis of morphometric maps; steepness and aspect of slopes from the DEM. The azimuth of the median axis was considered to be the angle between the North and the length line (Evans 1974). This parameter was used especially to create the cumulative vector diagram (Fig. 5), where each azimuth of median axis represents one vector line. Finally, the ruggedness of the landscape was expressed by the A3D/A2D ratio.

The relationship between mean steepness of slopes and altitude was analyzed using zonal statistic tools in ArcGis 9.1. The altitude maps were divided into zones with an interval of 20 meters for this analysis and the results were compared (Fig. 6).
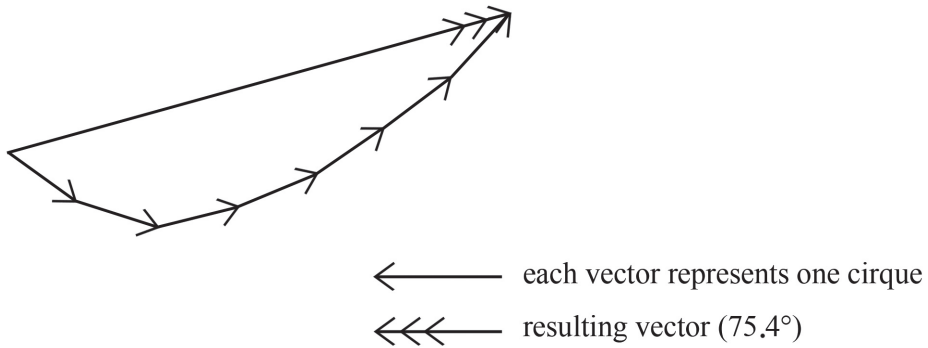
each vector represents one cirque

resulting vector (75.4°)

Fig. 5. Cumulative vector diagram of cirques in the Bohemian Forest (Czech and German part).
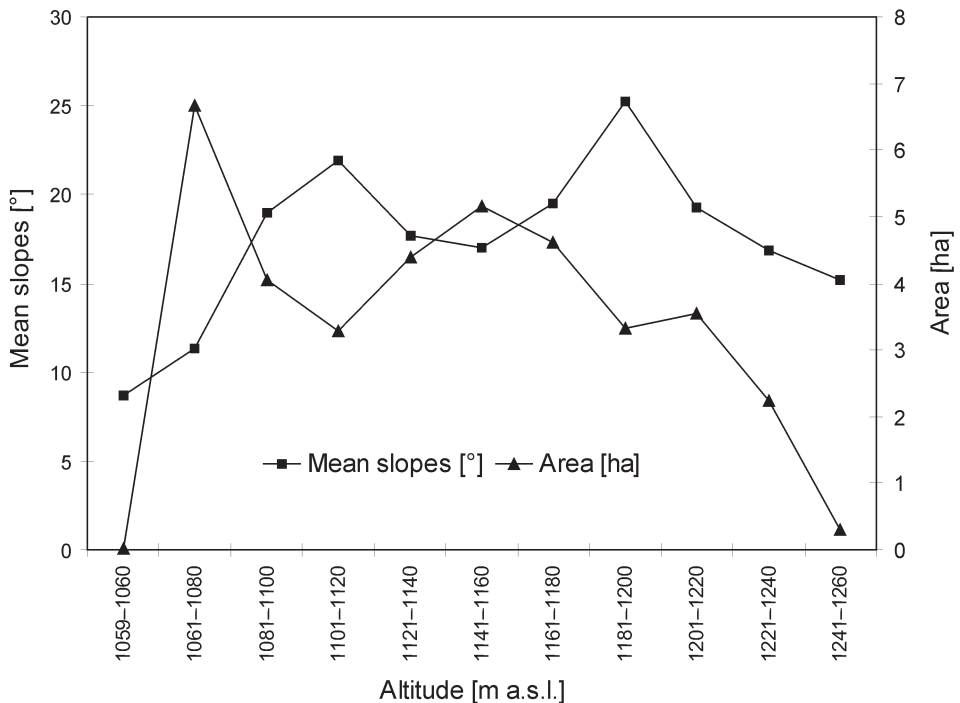

Fig. 6. Relationship between mean slopes, area (2D) and altitude; the example from the cirque of Prášilské Lake.

Finally, the Pearson's correlation coefficient between the parameters was calculated (Table 2). We used this analysis despite the low number of the items (7), so it is probable that the results are not so significant. It is necessary to verify them by other methods (see below). This calculation was firstly used for finding connections between the size of deflation plateaus and other parameters. However, interesting results were obtained when all datasets were included (Table 3).

RESULTS

The cirques lying in the German part of the Bohemian Forest have the highest values of the size descriptors. The cirque of Rachelsee is the widest (1352.2 m) and the deepest (384.5 m). It also covers the largest area (112.3 ha). The cirque of Grosser Arber Lake, however, was found to be the longest (1237.3 m). In comparison, the cirque of Prášilské Lake has the smallest depth (186.9 m) and length (677.0 m) (Table 2).

Generally, all the studied cirques have a mean slope gradient between 16–24°. Slopes ranging between 12–25° occupy the largest part of the total area of the cirques. The slopes with the highest gradient (between 55–90°), on the other hand, are very rare (Fig. 7). Con-

Table 2. Summary of the cirques size data.

Morphometric characteristics	Černé	Čertovo	Grosser Arbersee	Laka	Plešné	Prášilské	Rachelsee
H [m]	340	277	361	200	262	187	385
L [m]	1177	974	1237	1120	917	677	1179
W [m]	907	1263	1090	608	783	638	1352
A 2D [ha]	84.4	96.2	106	54.7	53.1	36.9	112
A 3D [ha]	97.1	104	119	57.4	60.6	39.4	125
A 3D/A 2D	1.15	1.08	1.13	1.05	1.14	1.07	1.12
DPA 2D	49.6	33.7	47.6	95.5	27.8	17.0	66.9
A 2D [ha]	84.4	96.2	106	54.7	53.1	36.9	112
L/H	3.46	3.52	3.43	5.6	3.5	3.62	3.07
L/W	1.3	0.77	1.14	1.84	1.17	1.06	0.87

Table 3. Results of correlation analysis between the morphometric characteristics of the investigated cirques.

	H	L	W	A 2D	A 3D	A 3D/A 2D	DPA 2D	L/H
H								
L	0.7440							
W	0.7948	0.4655						
A 2D	0.9014	0.7471	0.9236					
A 3D	0.9285	0.7552	0.9141	0.9975				
A 3D/A 2D	0.7425	0.4097	0.3454	0.4241	0.4860			
DPA 2D	0.1233	0.6783	−0.0041	0.2281	0.2039	−0.2505		
L/H	−0.6278	0.0452	−0.6256	−0.4730	−0.5073	−0.6767	0.6564	
L/W	−0.4176	0.2191	−0.7294	−0.4668	−0.4671	−0.6767	0.6430	0.8694

versely, many flat areas were found in all the glacial cirques. Mainly moraine plateaus and smooth moraine ridges as well as parts of deflation plateaus create a significant part of the total area of all the cirques. For example, the cirque of Prášilské Lake has 64.3% of the area in the interval of 0–12°.

According to the results of comparison of mean steepness of slopes by area, the glacial cirques were divided into three groups with the following features: (i) Two significant peaks of mean steepness of the slopes and inversely the minimum area (A2D) occurr in the cirques of Černé and Prášilské lakes (Fig. 6). (ii) The mean steepness is increasing with altitude. This trend is typical for the cirques of Laka and Rachelsee lakes. (iii) Relatively very steep upper parts of the headwall are in the cirques of Plešné, Čertovo and Grosser Arbersee lakes.

L/H and L/W are other characteristics of the slope steepness (FEDERICI & SPAGNOLO 2004). The L/H ratio varies from a minimum value of 3.07 (the cirque of Rachelsee Lake) to a maximum value of 5.60 (the cirque of Laka Lake). The L/W ratio ranges from 0.77 (the cirque of Čertovo Lake) to 1.84 (the cirque of Laka Lake) (Table 2).

FEDERICI & SPAGNOLO (2004) classified the cirques into three categories. If we try to place the cirques from the Bohemian Forest into this system, we realize that the cirques of Čertovo and Rachelsee lakes fit into the group of the cirques, which were (or are) occupied by a cirque glacier (0.5 < L/W < 1). Other investigated cirques belong to the group in which cirques were (or are) occupied by a valley glacier with a long ablation tongue (L/W > 1) (Table 2). This discrepancy may mean that the investigated forms have different morphometric characteristics than "normal" glacial cirques (in fact they are longer and/or not as wide as the cirques in the other mountain ranges).

Five cirques have aspects between the North and East. Only the cirques of Rachelsee and Čertovo lakes are oriented to the SE. The cumulative vector diagram (Fig. 5) expresses the predominant aspects of studied cirques. The direction of the resulting vector was 75.4°.

Generally, two cirques (the cirques of Prášilské and Grosser Arbersee lakes) have this aspect. Although it is possible to assume that this direction was the most appropriate for development of a glacial cirque in the Bohemian Forest, the cirque of Rachelsee Lake developed on slopes with a distinctly warmer aspect.

Significant correlation was found between the size of the deflation plateaus and the length of the cirques (L, L/H and L/W) (Table 3) – all these features are derived from the length
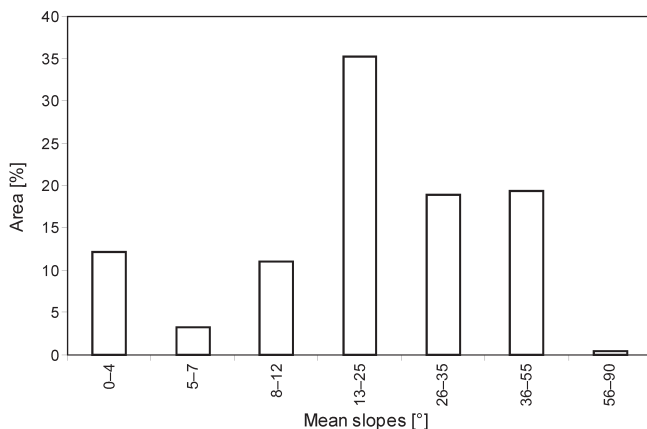

Fig. 7. Mean slopes of the Grosser Arbersee cirque in relation to the area (2D).

(L). No significant correlation was investigated between the area of the deflation plateaus and width or height of the cirques.

The TP-ELA (regional ELA) of the study areas was determined as an arithmetic mean of the mean altitude of the deflation plateaus – 1290.1 m a.s.l. with variation coefficient 2.92. The TPW-ELA, on the other hand, was calculated as an arithmetic mean of the lowest place in the cirques – 1021.42 m a.s.l. with variation coefficient 6.02.

DISCUSSION

In comparison with results from other mountain ranges (FEDERICI & SPAGNOLO 2004), just the two cirques have a "classical" cirque form. Moreover, although the cirques are quite long, they are not so deep in comparison with the results of BROOK et al. (2006); however, the shape of the cirques in the Bohemian Forest (mainly their overdeepening of their cirque floor, which is confirmed by the presence of the lakes and size characteristics) corresponds with very old landforms (older than 400 ka). Thus, it is possible that the forms are old glacial cirques and/or other complicated polygenetic landforms influenced by other geomorphological processes.

When we analyzed the results of comparison of the correlation of all the measured characteristics (Table 3), the highest correlation was found between the height of the headwall and the other six features. Correspondingly, the width of the cirques correlates with five other characteristics. Although both these characteristics correlate to each other, low correlation was observed between them and the length of the cirques. The length, on the other hand, correlates significantly with the size of the deflation plateaus (Table 3).

BROOK et al. (2006) argued that the cirques lengthen at a faster rate than they deepen, and also that cirques broaden at a much slower rate compared to lengthening. Therefore, it is possible to postulate the following assumptions:

(i) The lengthening of the cirques occurred during the cold stages of the Pleistocene when the conditions were appropriate for the development of glaciers. Conversely, the broadening and deepening were much slower. It is possible that the presence of a deflation plateau induced the development of longer cirques in comparison with the cirques in other mountains (snow was carried from the back side of the cirque more significantly, while avalanches accumulated it from all sides in the alpine landscape).

(ii) The broadening of cirques continued in the absence of glaciers by other processes (congelifraction, nivation etc.). The height of the headwall influenced their intensity, because the higher headwall shaded the depression and perennial snowfields (sources of water for various geomorphological processes) could be preserved there for a longer time.

(iii) Fluvial and gravitational processes reshaped the cirques during the warmer stages of the Pleistocene.

CONCLUSIONS

The results of the analysis of morphometric characteristics of the glacial cirques in the Bohemian Forest can be summarized as follows:

The cirques in the German part of the Bohemian Forest are bigger than the same forms on the Czech side of the mountain range. Thus, it is probable that the total altitude was an important factor for the development of glaciers (Grosser Arber Mt. 1456 m a.s.l., Grosser Rachel Mt. 1453 m a.s.l.). Most deflation plateaus lie above ~1300 m a.s.l. and their total area and alignment towards the predominant direction of wind influenced the origin and development of the glaciers. Furthermore, the height of headwalls was important.

The TP-ELA was probably ~1290 m a.s.l. The TPW-ELA (crucial for the development of the cirque glaciers in the Bohemian Forest) was ~200 m lower than the regional ELA – in ~1021 m a.s.l.

According to the connections between morphometric characteristics and genesis of the cirques it is possible to postulate the following hypothesis:

(i) The lengthening of the cirques occurred primarily during the cold stages of the Pleistocene depending on the size and position of the deflation plateau (the position of TP-ELA). The lengthening was quicker than the broadening and deepening of the cirques.

(ii) Development of the cirques continued when the glaciers did not exist by other (particularly periglacial) processes. The height of the headwall influenced their intensity by shading the depression.

(iii) Fluvial and gravitational processes reshaped the cirques during the warmer stages of the Pleistocene – changing their morphometric characteristics.

Generally, the age of the cirques (according to comparison of development of their shape) is probably more than 100 ka. Thus, they are obviously older than the Würm on the both flanks of the mountain.

These assumptions and hypothesis should be verified by detailed research in the areas of interest (results from the surroundings of Čertovo, Plešné, and Rachelsee lakes are particularly indispensable). It is also necessary to pay attention to other places in the Bohemian Forest where glaciation could occur (cf. HAUNER 1980).

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