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1. Introduction

Reliable information about the occurrence of past mountain glaciations is the key to the assessment of regional environmental responses to Quaternary climate oscillations. Previous studies have shown that climate conditions during the Last Glacial Maximum (sensu Hughes et al., 2013) favoured local mountain glaciations in high elevated mountain relief (~1200–1600 m asl) across the mid-European Variscan belt (e.g., Diedrich, 2013; Mentlík et al., 2013; Engel et al., 2014; Glotzbach et al., 2014; Mercier, 2014; Vočadlová et al., 2015). In contrast, possible glaciation of lower Variscan ranges has been considered controversial; and the existence of local mountain glaciers in the Rhön (950 m), Thüringer Wald (983 m), Schwäbische Alb (1015 m), Fichtelgebirge (1051 m), or Isergebirge/Jizerské hory Mountains (1126 m) has only been tentatively suggested based on indirect geomorphological evidence (e.g., Fiebig et al., 2004; Nývlt et al., 2011). However, more details about former glaciers within these ranges could change significantly the current view of Quaternary mountain glaciations in central Europe and improve our understanding of the regional climate evolution across a large area between the Fennoscandinavian ice sheet and the Alps during past glaciations (e.g., Heyman et al., 2013).

In order to test the hypothesis of past glaciation in low elevated mountain regions, we present new evidence from the sediment record of the Pytlácká jáma Hollow in the Jizerské hory Mountains, an eastern segment of the mid-European Variscides. The mountain range is located at the southern limit of middle Pleistocene advances of the Fennoscandinavian ice sheet in the western Sudetes (Černá et al., 2012, and references therein). Hypothetical mountain glaciation was initially proposed by Králík and Sekyra (1989) for the northern flank of the range that is deeply dissected by cirque-like (semicircular) valley heads. However, the low elevation of these landforms (~600–1000 m asl) appears to contradict the field evidence for glaciers located significantly higher in the adjacent Krkonoše (Giant) Mountains (e.g., Migoń, 1999). Recent geomorphological investigations have revealed that shallow hollows on the NE to SE side of high altitude ridge areas may have been glaciated by small ice fields (Pilous, 2006). If this hypothesis is valid, then the Pytlácká jáma Hollow (the best-developed cirque-like landform with a peat bog on its floor) represents a key site to solve the question of hypothetical mountain glaciation in the range (Traczyk et al., 2008).

In this study, we analyse the morphology and structure of the Pytlácká jáma Hollow and a 460-cm-long sediment core collected from its floor. The primary objectives of this study are to ascertain whether morphological features of this mountainside hollow are consistent with the glacial hypothesis and whether glacial sediment is preserved in the core profile. In addition, we detected shallow geological structures using geophysical methods.

2. Study area

The study area is located in the Jizerské hory Mountains (the highest point at 1126 m asl), which belong to the eastern zone of the Variscan orogenic belt in central Europe. The central part of the range comprises three gently undulating ridges (1000–1100 m asl) separated by the wide valleys (820–880 m asl) of the Jizera and Jizerka rivers (Fig. 1) directed to the southeast. The divide between the two valleys has the form of a large planation surface that rises toward SE and forms the middle Jizera Ridge (1018 m asl). The slopes of the ridge are steeper (22–24°) on the northeast side compared to the southwest side (12–18°; Traczyk et al., 2008). The asymmetry of the ridges and valleys was attributed to Cenozoic tilting and uneven uplift of individual blocks within the range (Migoń and Potocki, 1996).

The Pytlácká jáma Hollow is incised into the northeastern slope of the middle Jizera Ridge, which is built of mid-Carboniferous, medium-grained porphyritic granite (Žák et al., 2013). The valley-side hollow has arcuate steep slopes and a flat floor gently inclined to NE. A peat bog covers the floor, and a reverse bedslope closes its lower part separating the hollow from the Jizera valley below. The arcuate shape of the hollow (Fig. 2) and its location in the lee of prevailing winds has been attributed to the enhanced accumulation of snow and the formation of a small glacier (Pilous, 2006; Traczyk et al., 2008). It has also been hypothesised that a shallow lake filled the hollow prior the formation of the *Sphagnum* bog on its floor (Pilous, 2006).

The climate in the range is influenced mainly by mid-latitude air masses moving from the Atlantic Ocean. The mean annual precipitation (1961–1990) increases with altitude to 1300–1800 mm in the central part of the range (Kulasová et al., 2006). The number of the days with snow cover reaches ~150/y at 780 m asl (Bubeníčková and Kulasová, 2009). The mean annual air temperature varies from 3.5 °C in the bottom parts of the upper Jizera and Jizerka valleys to 5 °C at the valley sides (Sobik and Urban, 2000; Balcar et al., 2012). Because of the local topography, these valleys experience frequent temperature inversions and occasional frost days even during the summer months (Bubeníčková and Kulasová, 2009; Sobik and Błaś, 2010). Winds are mostly southerly to southwesterly (Balcar et al., 2012).

3. Methods

3.1. Landform analyses

The morphometric characteristics of the Pytlácká jáma Hollow were determined and used to ascertain its hypothetical glacial origin. The shape and size characteristics of the landform were acquired from the digital terrain model of the Czech Republic (DMR 5G), which is based on stereophotogrammetry and airborne laser scanning. The total standard error of 0.18 and 0.3 m indicates a vertical accuracy of the model in the bare and forested terrain, respectively (Czech Office for Surveying, Mapping and Cadastre, 2015). The landform borders were delineated according to the gentle surrounding relief threshold. A range of eight landform features were determined from the model: height (H), length (L), width (W), mean slope and aspect of the median axis, planar (2D) and surface area (3D), volume (V; calculated as $V = 0.5(H \times L \times W)$ sensu Gordon, 1977). Based on these features, the following ratios that describe the shape of cirques (e.g., Evans and Cox, 1995) were calculated: L/H, L/W, W/H and 3D/2D. The valley head overdeepening was expressed using the k-curve (sensu Haynes, 1968) and the $k_{h/s}$ values (sensu Křížek et al., 2012).

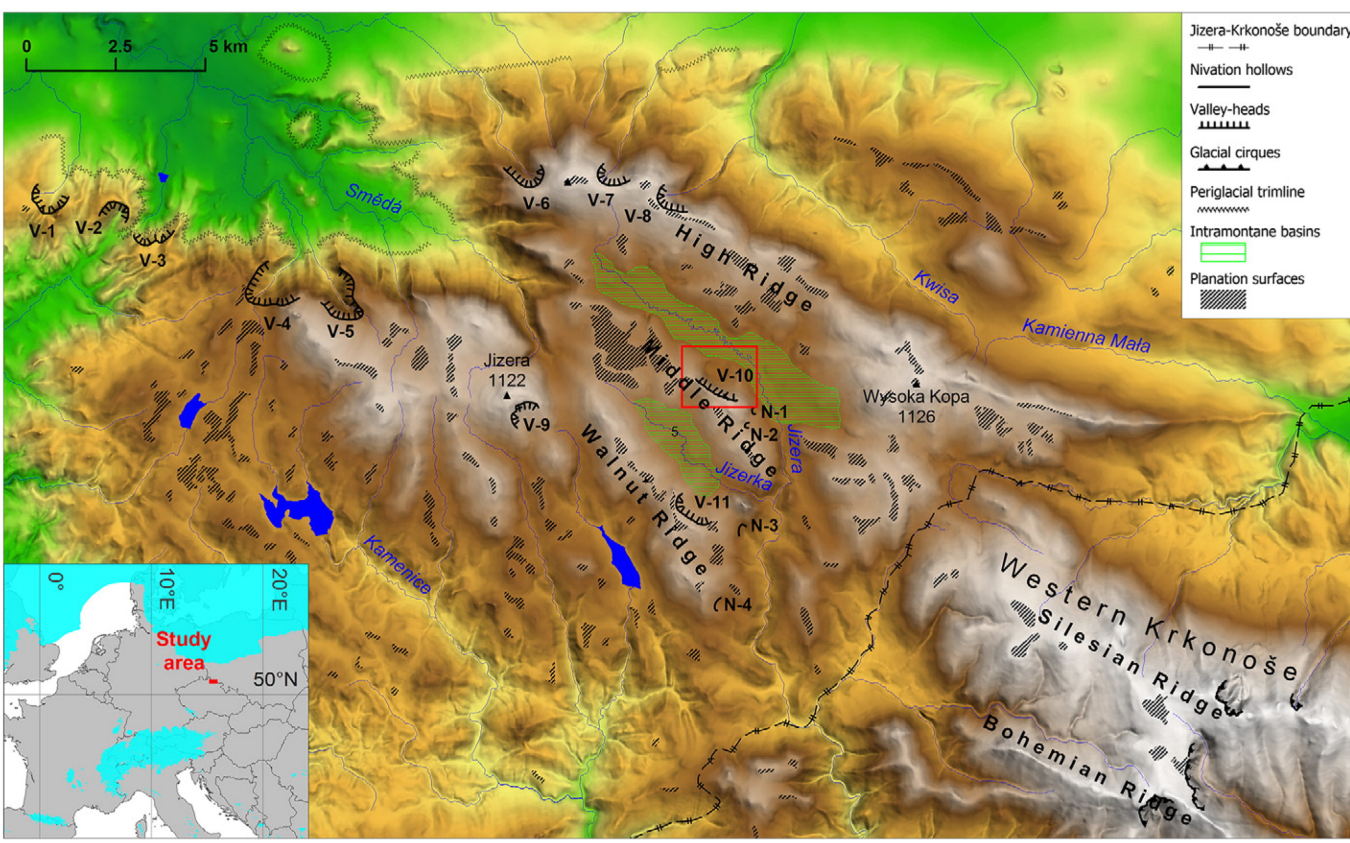

Fig. 1. Location of the study site (red rectangle) in the Jizerské hory Mountains and its position in central Europe (inset). The valley heads (codes V-1 to V-11) and nivation hollows (N-1 to N-4) are adopted from Králík and Sekyra (1989) and Pilous (2006). The LGM extent of glaciers (blue shades) in the inset is after Ehlers et al. (2011).

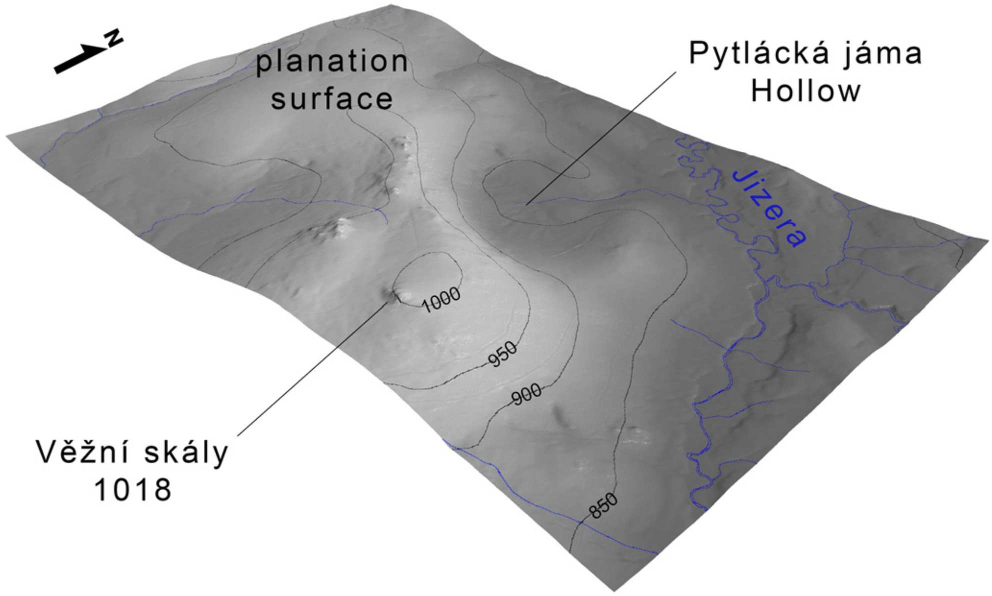

Fig. 2. Three-dimensional view of the Pytlácká jáma Hollow. 1.5× vertical exaggeration.

The morphometric characteristics were compared with the morphologic indices of 27 cirques described by Křížek et al. (2012) in the nearby Krkonoše Mountains and other ranges within the Bohemian Massif. The group of valley heads was divided into groups using cluster analysis (tree clustering) based on Ward's method and Euclidean distances (sensu Kaufman and Rousseeuw, 2005), with the appropriate values of *L*/*W*, *H*, 3D/2D as the input variables (as these form the basis of morphometric characteristics for cirques in the Bohemian Massif defined by

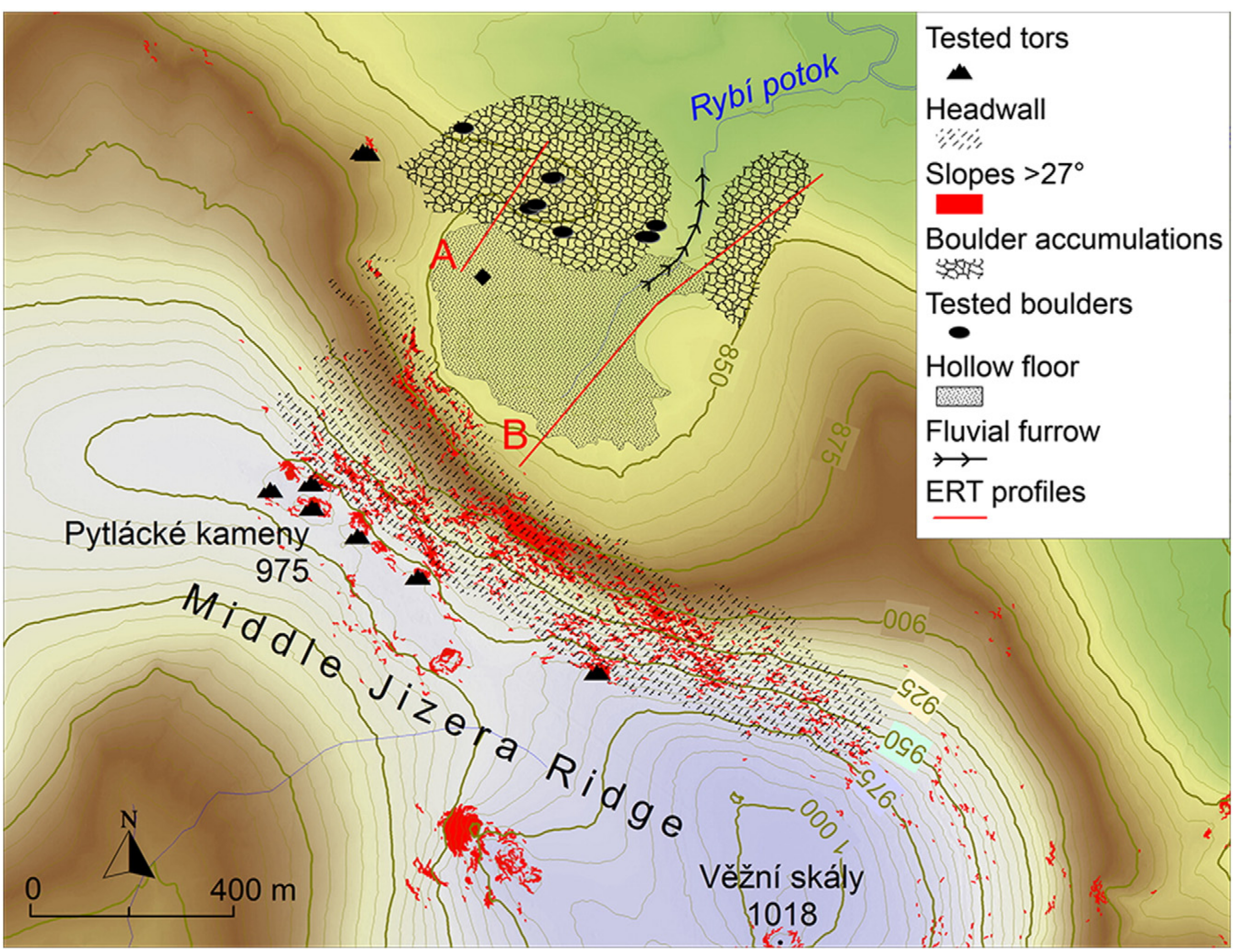

Fig. 3. Morphology of the Pytlácká jáma Hollow. The diamond represents the position of the core described in this study.

Křížek et al., 2012). This analysis allows for determination of the morphology of the Pytlácká jáma Hollow relative to the range of cirques in the same morphogenetic region. The morphology of the Pytlácká jáma Hollow was also compared with morphometric characteristics of 14 mountainside hollows (Fig. 1) reported by Králík and Sekyra (1989) and Pilous (2006) from the Jizera range. The cluster analysis was applied to morphometric features (H, L, W) and position characteristics (maximum altitude of the valley head: alt_{max}; hollow floor altitude: alt_{floor}; aspect of the valley head axis). All statistical operations were performed using the STATISTICA programme (StatSoft, Inc., 2009).

The thickness and internal structure of the bottom deposits and moraine-like landforms at the downslope side of the Pytlácká jáma Hollow were determined using electrical resistivity tomography (ERT). Soundings were carried out along the central longitudinal axis of the hollow and across the boulder accumulation that closes the western part of the hollow (Fig. 3). The ERT was applied at multiple four-electrode arrays with 5-m spacing between the electrodes using the Wenner-Schlumberger measuring method (Loke, 2000; Milsom, 2003). The obtained apparent resistivity data were subjected to the geophysical inversion procedure (L1-norm) in RES2DINV software (Geotomo, Malaysia).

The Schmidt hammer (SH) method was applied on bedrock outcrops in the study area and the boulder accumulation in front of the Pytlácká jáma Hollow to allow an approximate determination of their ages. Subhorizontal surfaces of eight tors and nine boulders were measured with the SH, each with 25 impacts, following Moon's (1984) guidelines. The obtained *R*-values were averaged separately for the boulder accumulation, the valley-side tors, and the summit tors. The resulting mean values were compared with the published *R*-values obtained for glacial surfaces in the western Sudetes, and the relative chronology of the tested surfaces was suggested (Engel, 2007; Černá and Engel, 2011; Engel et al., 2014). Analysis of variance was used to determine if any differences exist in the mean *R*-value among the surfaces. The significance of the relationship was tested by the *F*-test with *p*-level of 0.05.

3.2. Analyses of sediment core samples

Sediment from the floor of the Pytlácká jáma Hollow was cored in the western part of the mountainside hollow where the largest thickness of peat accumulation was probed. The core site (50°50′51″N, 15°20′16″E, 848 m asl) was located about 60 m from the bog limit, and its surface was slightly inclined to the E (Fig. 3). A 450-cm-long core was sampled using Eijkelkamp percussion gouges with diameters of 100 and 75 mm. A sample of plant tissue was selected from the lower section of the peat-dominated part (0–192 cm) of the core for dating at the AMS Radiocarbon Laboratory, Erlangen, Germany. The sample was prepared with the acid-alkali-acid method, using HCl and NaOH, and centrifuged with a $ZnCl_2$ solution. Conventional ^{14}C age of the sample was calibrated using the OxCal 4.2.3 software (Bronk Ramsey, 2009) and IntCal09 (Reimer et al., 2009).

The sedimentary succession in the core was divided into the units defined by textural differences and colour changes. The colour of the sediments was determined using the Munsell Soil Color Chart (2000). The particle-size and shape analyses were applied to the samples from the minerogenic units, which were described according to the classification of Moncrieff (1989). The grain size distribution was measured with the dry sieving method, following the guidelines of Gale and Hoare (1991). The orthogonal axes of 50 gravel clasts from each unit were measured with a vernier calliper, and clast roundness was assessed using the Powers (1953) scale. The TRI-PLOT spreadsheet method of Graham and Midgley (2000), ternary diagrams, and histograms were used for the presentation of clast morphology. Two samples, from 206 and 276 cm depth, were selected for analysis of quartz grain micromorphology in order to determine the mode of transport. The grains were rinsed in 10% HCl and washed using distilled water. Fifty to seventy

Table 1
Landform features of the Pytlácká jáma Hollow and cirques in central European mountains.

Area (n. of cirques)	Elevation (m asl)			Axis aspect	Mean gradient (°)	Height (m)	Length (m)	Width (m)	*L/H*	*L/W*	*W/H*	Volume (10^6 m^3)	Area (10^6 m^2)		Surface/Planar	k_h	k_s
	Max	Min	Mean										Planar	Surface			
Pytlácká jáma	984	838	881	32°	11	146	820	1290	5.62	0.64	8.84	32.5	0.95	0.99	1.04	0.56	0.72
Bohemian Massif (27)	1061–1500	907–1246	999–1334	N-E-S	15–34	116–453	278–1798	360–1467	1.50–5.33	0.50–1.97	0.95–3.92	11.2–353.8	0.10–15.45	0.12–17.15	1.02–1.22	0.35–1.00	0.30–1.21
mean	–	–	–	–	26	271	788	700	2.98	1.16	2.66	95.6	0.49	0.56	1.15	0.65	0.74
Sudetes (14)	1303–1500	1018–1246	1124–1334	N-E-S	23–34	185–453	278–1507	360–1300	1.50–5.33	0.50–1.97	0.95–3.73	11.8–230.3	0.10–10.18	0.12–11.46	1.13–1.22	0.56–1.00	0.64–1.21
mean	–	–	–	–	30	284	682	620	2.46	1.27	2.29	72.3	0.38	0.44	1.19	0.74	0.84
Bayerischer Wald/Šumava mountains (13)	1061–1437	907–1085	999–1213	N-E-S	15–26	116–374	407–1798	382–1467	2.28–4.98	0.82–1.70	2.31–3.92	11.2–353.8	0.11–15.45	0.12–17.15	1.02–1.16	0.35–0.89	0.30–0.79
mean	–	–	–	–	22	258	902	788	3.54	1.22	3.08	120.8	0.62	0.69	1.15	0.56	0.60

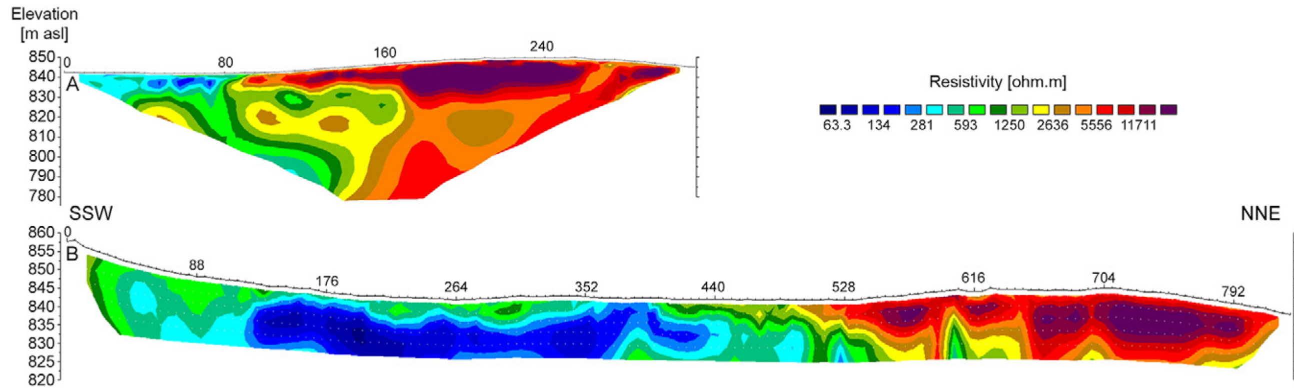

Fig. 4. Resistivity tomograms performed at the flat ridge on the downslope side of the Pytlácká jáma Hollow (A) and along the central axis of the valley head (B; 2.5× vertical exaggeration). Electrode spacing is 5.5 m. The distances above each profile are in metres.

grains of medium-grained (with diameter of 250–500 μm) quartz sand were selected from each sample using a light microscope. Grains were fixed on a carbon tape, gilded, and analysed using electron microscopes (JEOL 6380 LV and Hitachi TM3030) and the atlas of Mahaney (2002).

4. Results

4.1. Study site morphology

The Pytlácká jáma Hollow is located at an elevation range of 984–838 m asl, and its longitudinal axis is oriented to the NE. The indistinct upper limit of the hollow ascends from ~940 m asl in the western part of the landform to 985 m asl in its eastern section. The best-developed headwall is located in the central part of the hollow where it is about 110 m high (Table 1). The mean gradient of the headwall reaches 20°, but locally it increases up to 70°. The lower part of the headwall is covered by slope deposits that descend from 860 to 845 m asl The hollow floor at 850–840 m asl is inclined to the NE, and its mean gradient reaches 2.7°. The floor surface is the flattest in the western peat-covered part of the hollow. The *k*-coefficient, which indicates the degree of cirque overdeepening, reaches the values of 0.56 for k_h and 0.72 for k_s (k_{mean} is 0.64). The maximum (hypothetical) depth of the cirque floor (thus the thickness of sedimentary fill of the cirque bottom) derived from the *k*-curve equation reaches nearly 20 m.

Flat elongated landforms border the lower part of the hollow at ~ 845–850 m asl (Figs. 2 and 3). A ridge-shaped form rises 6 m above the surface of the floor and extends over ~400 m along its western part. The ridge consists of poorly sorted clasts with the predominance of coarse rounded debris. The long axis of the largest boulders on its surface ranges between 2 and 5 m. A counterpart terminal deposit in the eastern part of the hollow is more restricted, flat, and poorly delimited against the surrounding relief.

The ERT inversion models show the internal structure of terminal ridges and deposits on the hollow floor to a depth of ~60 m (Fig. 4). Northern sections of the investigated survey lines with resistivity values >30.000 Ω m reflect accumulations of granite boulders in the ridge areas. The boulder accumulations are imaged through upper areas of the models, reaching 10–20 m below the topographic surface. Southern parts of the profiles show a low-resistivity zone (<1000 Ω m) that extends to a depth of 15–20 m. Electrical resistivity decreases with depth in this zone, ranging from ~1000–400 Ω m in the subsurface layer to values <200 Ω m in the lower sections. The relatively high resistivity values in the upper 2–2.5 m layer correspond with peat deposits and an extremely low-resistivity section with waterlogged minerogenic sediments identified in the core (see Section 4.2. for details). Moreover, the ERT model shows that the boundary between sediments and bedrock is at a depth of about 20–25 m in the central part of the hollow floor.

The Schmidt hammer *R*-values measured on the boulder accumulation range between 25.2 and 33.5, yielding the highest mean *R*-value (29.6 ± 0.8) among the tested surfaces (Fig. 5). The *R*-values obtained on the valley-side tors range between 25.1 and 26.6, yielding a mean value of 25.9 ± 0.8. The *R*-values measured on the summit tors fall within the range 21.8–30.8, but the highest individual *R*-value may be identified as an outlier (Fig. 5). The mean *R*-value for the summit tors amounts to 25.4 ± 1.4 (24.4 ± 1.1 without the outlier).

4.2. Succession of clastic sediments in the core

Two contrasting sedimentary sections were identified in the core (Fig. 6). The upper section down to 192 cm depth consists of biogenic deposits dominated by *Sphagnum* peat. This section accumulated since the onset of the Holocene as indicated by the ^{14}C age of 11,424 ± 129 cal. y BP obtained for the peat sample (Erl-15999) from a depth of 190 cm. Beneath the deposits of peat, a sequence of minerogenic (clastic) sediments occurs. The boundary between these sections is sharp.

The uppermost minerogenic subunit (192–200 cm) is the most gravelly section of the core with the gravel fraction of 78.2%. The sand and fine-earth fractions account for 20.9 and 0.7%, respectively. The median particle size reaches the highest value ($\varphi = -3.15$), and the particle-size distribution is polymodal. The poorly sorted sediment ($\sigma = 1.94$)

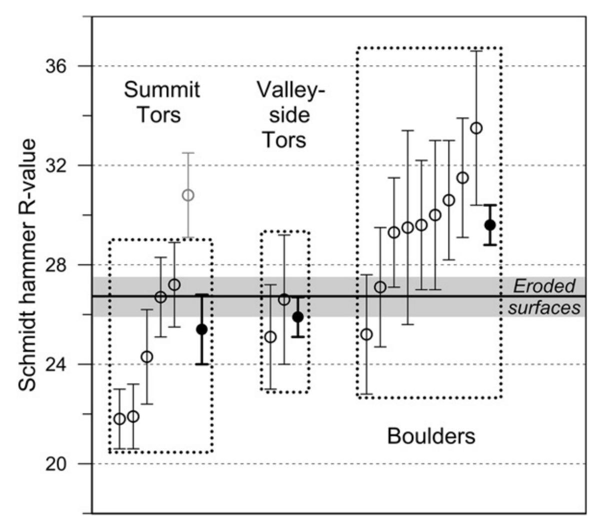

Fig. 5. Schmidt hammer *R*-values for the three groups of surfaces in the Pytlácká jáma Hollow. The mean *R*-values for individually tested surfaces and three groups are marked with open and full circles, respectively. An outlier value is shown in grey. The mean *R*-value (black line) and standard deviation (grey rectangle) for the bedrock surfaces located below the upper limit of continental glaciation in the Jizera range calculated from the data reported by Černá and Engel (2011).

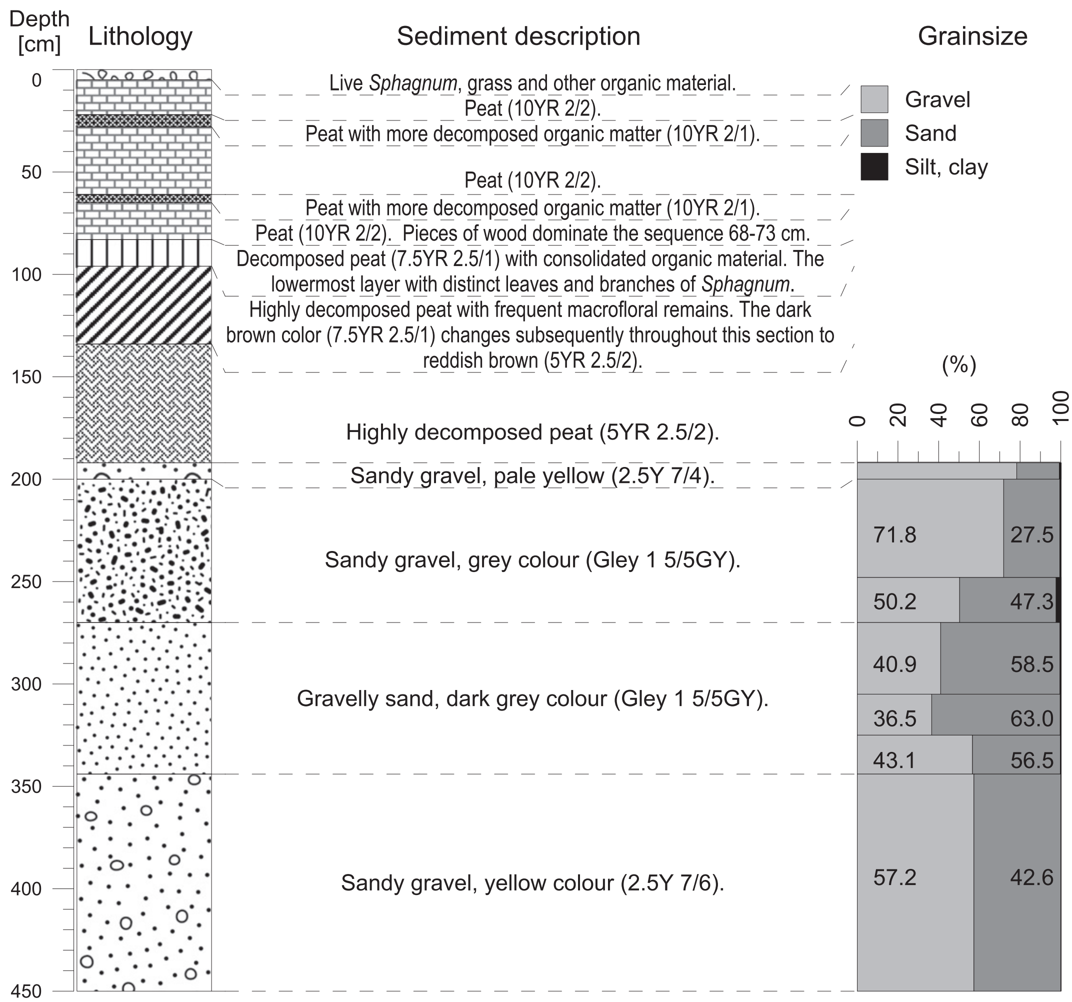

Fig. 6. Sedimentary log of the core from the Pytlácká jáma Hollow, depicting lithologic units and inferred sedimentary conditions.

consists of predominantly very angular to angular clasts (RA = 96). The C_{40} index reaches the lowest value (2) within the analysed sample set (Fig. 7).

The minerogenic unit between 200 and 270 cm consists of two sandy gravel subunits. The upper subunit (200–248 cm) is characterised by the unimodal particle-size distribution and the poorly sorted clasts of predominantly angular or subangular shapes (the RA value of 53 is the smallest within the core). In the lower subunit (248–270 cm), the weight proportion of silt and clay particles (2.5%) is largest within the minerogenic core section. The particle-size distribution is characterised by a polymodal shape, the sediment is very poorly sorted, and very angular to angular clasts are predominantly compact. Quartz grains from the depths of 206 and 276 cm have subangular and angular shapes with low and medium relief. Quartz grains of both samples are very weathered with abraded edges and silica precipitations covering them. In some cases, we see that silica precipitations overlap older microtextures, e.g. parallel striations and curved grooves were filled by silica precipitations. Meandering ridges, fracture faces, straight steps, and adhering particles are very frequent microtextures developed on grains (Fig. 8). The absence of oriented etched pits and quartz crystal overgrowths on grains is a common feature for both samples.

The minerogenic unit between 270 and 344 cm consists of three subunits that are characterised by the highest amount of sand-size particles within the core (Fig. 6). The particle-size distribution of the sediment is unimodal to bimodal (middle subunit), the poorly sorted clasts are angular or very angular, and the C_{40} index amounts to the highest values within the profile (Fig. 7). Gravel-size particles dominate the lowermost unit (344–450 cm) identified in the core. The amount of silt and clay particles (0.2%) is the lowest among all the examined samples. The particle-size distribution is bimodal, and the poorly sorted clasts are characterised by high angularity and a low C_{40} index.

5. Discussion

5.1. Origin of the Pytlácká jáma hollow

Cirque-like depressions evolve from a variety of preexisting mountainside hollows under different climate conditions. The enlargement of hollows can occur by glacier erosion, nivation processes, rock-slope failures, deep chemical weathering, and dissolution of carbonate rocks or collapse of volcanic craters (e.g., Barr and Spagnolo, 2015). According to the bedrock conditions in the study area, the origin of the Pytlácká jáma Hollow may be associated with glacier erosion, nivation, or chemical weathering.

The investigated hollow reveals most of the morphological features of glacial cirques, notably an arcuate headwall, a well-delimited gently sloping floor, and a convex threshold at its lower margin. By contrast, any section of the upper limit of the hollow has a form of a sharp edge that is a characteristic feature of cirques in nearby Variscan mountain regions (Křížek et al., 2012). Moreover, only 16% of the headwall area has a gradient >27°, which is sometimes used to define the lower limit of the cirque headwall (Barr and Spagnolo, 2015). The blocky headwall is significantly less steep compared to cirques in the Bohemian Massif (i.e., the high Sudetes and Šumava mountains; Table 1) and

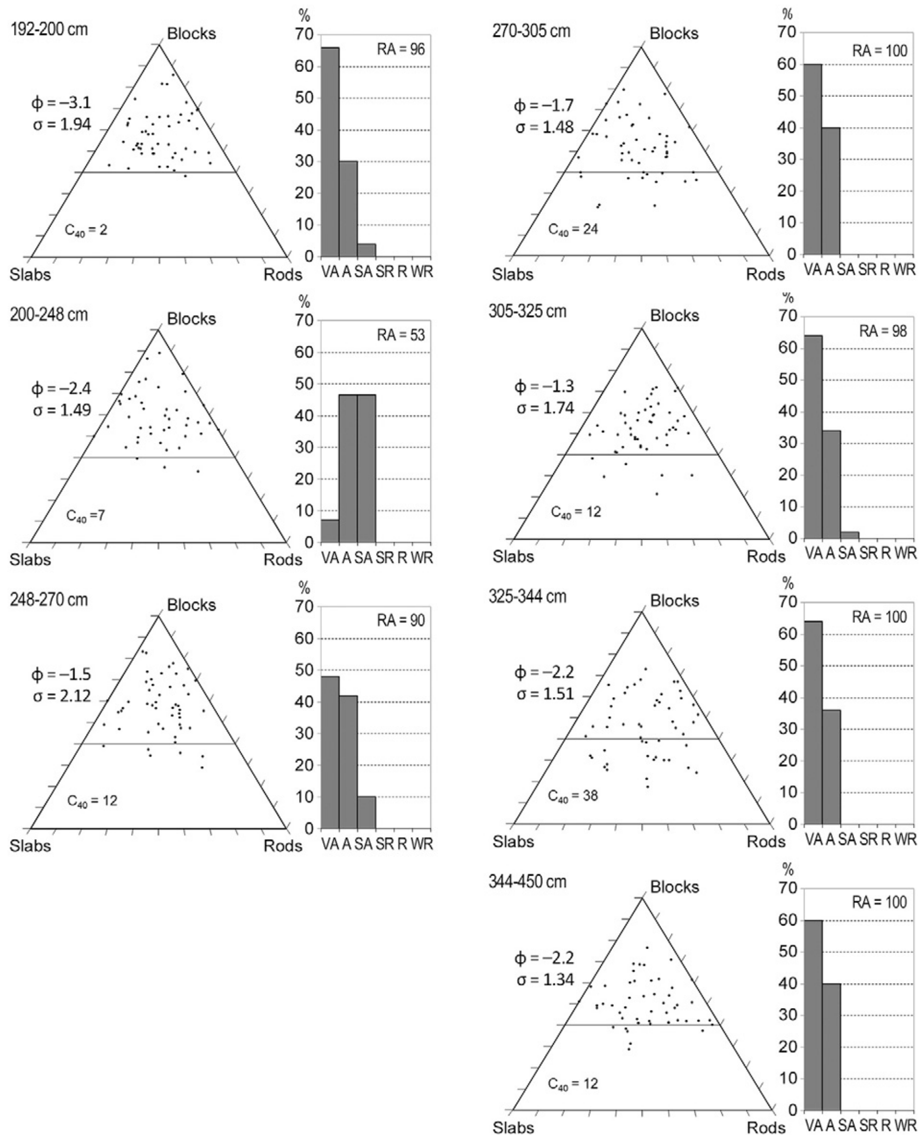

Fig. 7. Clast shape and roundness diagrams for sediments from mineral sequences in the lower part of the core (192–450 cm). φ – median particle size; σ – sorting; C_{40} – percentage of clasts with a c/a ratio of <0.4; RA – percentage of very angular and angular clasts; VA – very angular; A – angular; SA – subangular; SR – subrounded; R – rounded; WR – well-rounded.

sporadic bedrock outcrops in the lower headwall lack indications of subglacial erosion, an integral part of the cirque definition (Evans and Cox, 1974). On the other hand, the headwall is high enough to allow the accumulation of sufficiently thick snow required for glacier ice formation. Assuming the maximum snow surface at the line that connects the top of the headwall and the lip of the hollow, the thickness of snow ranged up to 45–55 m (Fig. 9). Because glacier ice in mid-latitudes forms under a pressure of ~30 m of overlying snow (Vallon et al., 1976), the ice was probably present in the Pytlácká jáma Hollow. Moreover, the distance from the headwall to toe (450–820 m) is an order of magnitude greater than the threshold length of 30–70 m between snow patches and glaciers (Ballantyne and Benn, 1994). The deepening of the floor is lower compared to well-developed, overdeepened cirques but well within the range of deepening observed in cirques without steep headwalls (e.g., Barr and Spagnolo, 2015). The comparable degree of valley head deepening within the eastern Variscan ranges is indicated by similar *k*-values (Table 1, Fig. 9) that represent the cirque longitudinal profile's concavity (Haynes, 1968). The equation-curve based depth of bedrock below the cirque floor surface is consistent with the value derived from the ERT survey. The length, the volume, and the surface area are within 1σ of the mean values for cirques in the Bohemian Massif, but other morphometric features differ significantly from the mean values. However, large variability can be observed between individual features, which differ significantly between cirques in the northern (the high Sudetes) and the southern (the Šumava Mountains) parts of the Bohemian Massif (Fig. 10).

An alternative hypothesis for the landform origin may be associated with the weathering and mass movement processes related with perennial snow. This solution was proposed for the formation of many slope niches in the Bohemian Massif (e.g., Prosová and Sekyra, 1961), including the Jizerské hory Mountains (Pilous, 2006; Balatka and Pilous, 2009). However, these landforms are generally much smaller and less arcuate than the Pytlácká jáma Hollow, which is nearly 150 m deep and 1300 m across. By contrast, characteristic nivation hollows in the Jizera range are up to 50 m deep and 400 m wide (Pilous, 2006). Similar dimensions were reported from the Krkonoše Mountains (Křížek, 2007) and other mountain regions (Christiansen, 1998; Rączkowska, 2007). The Pytlácká jáma Hollow is also more circular (0.6 *L*/*W* ratio) than reported cirque-like hollows in the Jizera range (mean ratio of 0.4 for the nivation hollows reported by Pilous, 2006). Finally, the floor of the hollow is less inclined, and a rock basin beneath sedimentary infill has a reversed slope toward the lip of the depression (Fig. 4). This is

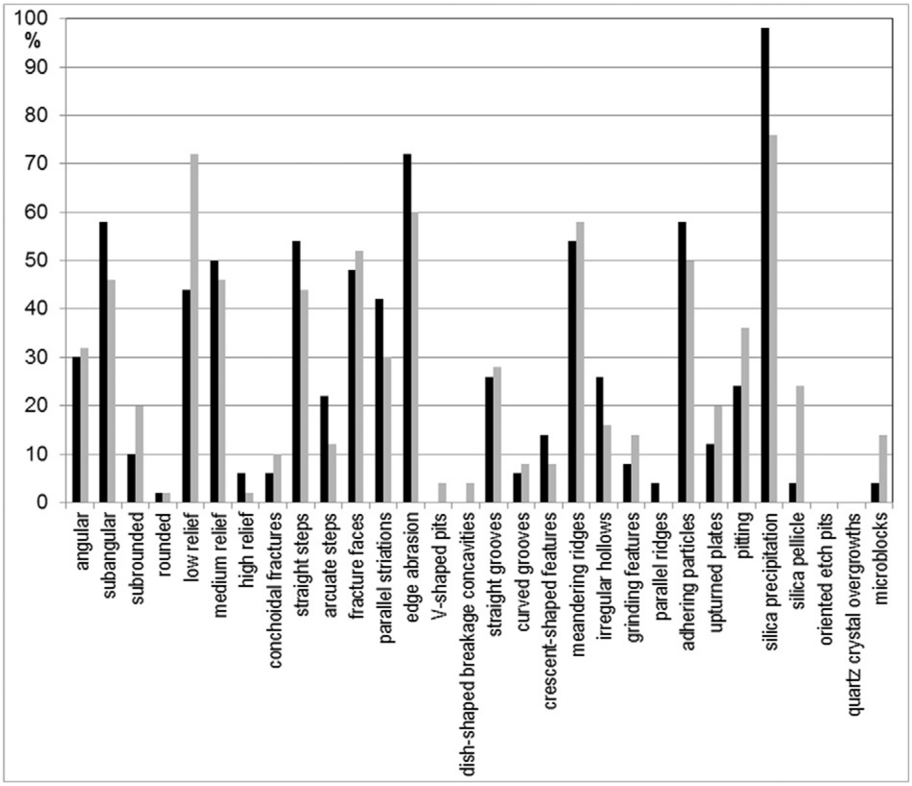

Fig. 8. Occurence of microtextures on quartz grains in the RL core samples from a depth of 206 cm (black) and 276 cm (grey).

probably the most important argument against nivation origin of the form as nivation hollow lacks reversed floor slope (Embleton and King, 1975). The different origin of the Pytlácká jáma Hollow is also indicated by the results of cluster analysis as this form belongs to a different group than nivation hollows (Fig. 11).

The hypothesis of chemical weathering origin could be rejected based on the distribution of cirque-like hollows in the Jizera range. If the landforms have originated from deep (chemical) weathering, which has played a major role in the study area during the Paleogene (Migoń and Lidmar-Bergström, 2001), they should be located on old planation surfaces far from incised valleys. However, the location of mountainside hollows only partly matches planation surfaces (Fig. 1). The largest cirque-like hollows in the northwestern part of the range are incised in a fault-generated scarp of Neogene to Quaternary age (Migoń and Potocki, 1996). Small hollows in the central part of the range are located on young valley slopes that formed as a result of neotectonic movements and differential surface uplift (Migoń and Potocki, 1996; Danišík et al., 2010).

The observed morphological features suggest that the Pytlácká jáma Hollow is probably a glacial cirque at an early stage of development (sensu Evans and Cox, 1995). The geomorphologic position, an arcuate headwall, and a well-defined flat floor and threshold imply the glacial origin of the hollow. Other morphological characteristics are weak, but cirques in marginal conditions are rarely developed with all typical features (Derbyshire and Evans, 1976). Following the reasoning by Evans

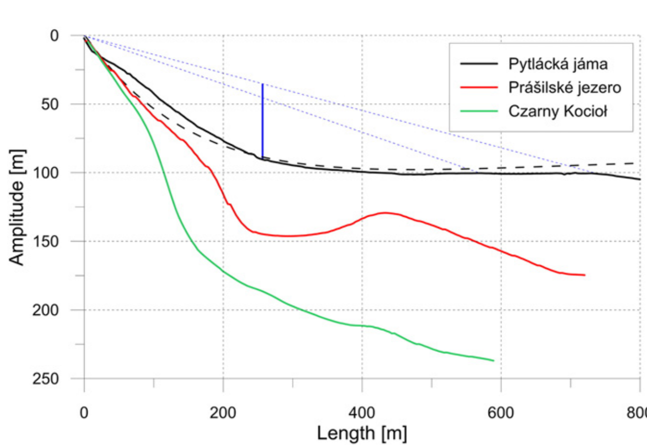

Fig. 9. Comparison of the longitudinal profiles (2× vertical exaggeration) of the Pytlácká jáma Hollow and two morphological types of cirques in the Bohemian Massif (modified from Křížek et al., 2012). Exponential curve for $k = 0.75$ (Haynes, 1968) fitted to the Pytlácká jáma Hollow profile. Dotted and bold blue lines indicate the maximum snow surface and thickness, respectively.

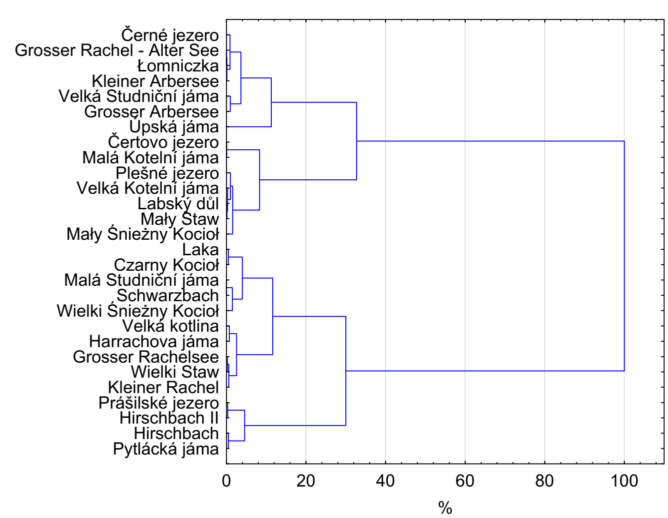

Fig. 10. Tree clustering of the Pytlácká jáma Hollow and cirques in the Bohemian Massif according to L/W, H, 3D/2D. Euclidean distance measures and amalgamation rule by the Ward's method.

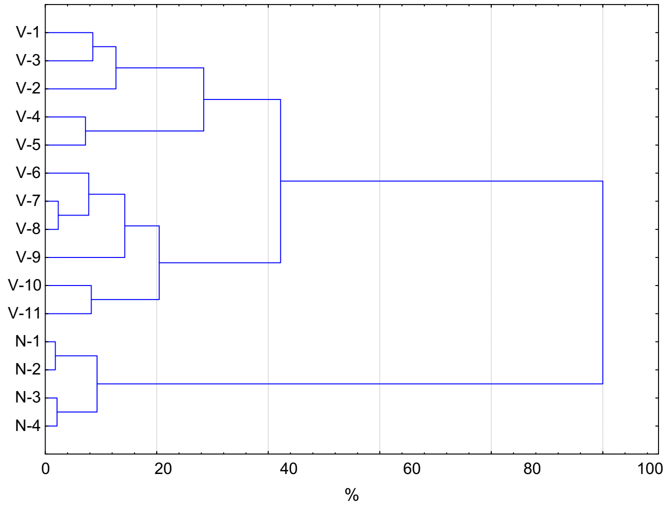

Fig. 11. Ward's dendrogram of mountainside hollows in the Jizera range according to *H*, *L*, *W*, alt_{max}, alt_{floor}, and aspect. The location of the valley heads (V-1 to V-11) and nivation hollows (N-1 to N-4) is marked in Fig. 1.

and Cox (1995), well-developed characteristics of the Pytlácká jáma Hollow compensate for weak ones, confirming its cirque status proposed by Pilous (2006).

Grain size distribution and micro/morphology of clasts from the lower part (460–190 cm) of the sedimentary record in the bottom of the Pytlácká jáma Hollow add further evidence of former glaciation in the region albeit not unambiguous. Grain size, sorting, clast roundness, quartz grain shape, and microtextures preclude aeolian sections within the sedimentary profile (Mahaney, 2002). Predominantly angular to very angular clasts together with the angular shape of quartz grains, dish-shaped breakage concavities, and the absence of V-shaped pits and crystal overgrowths (Fig. 8) exclude longer fluvial transport (Cremer and Legigan, 1989; Helland et al., 1997). By contrast, the high frequency of meandering ridges and grains with edge abrasion, together with the presence of crescent-shaped features, indicates frequent mutual collision of grains caused by the motion of slope sediments or in the environment of a small glacier (a low kinetic energy environment sensu Krinsley et al., 1976). The analysed grains reveal all mechanical microtextures arising from glacier transport, such as curved grooves, straight grooves, conchoidal fractures, crescent-shaped features, straight and arcuate steps, upturned plates, and adhering particles (e.g., Mahaney, 2002; Strand et al., 2003). Moreover, the high representation of fracture faces (48–52%) corresponds to the values (21–80%) found on glacial grains from the Łomnica Valley in the Krkonoše Mountains (Engel et al., 2011). On the other hand, the representation of other microtextures is considerably smaller compared to samples transported by glaciers over a similar length, and the number of quartz grains with high relief (Fig. 8) is also small (Krinsley and Doornkamp, 1973; Mahaney, 2002; Engel et al., 2011).

Boulder accumulations at the downslope side of the hollow are located at the characteristic position of terminal moraines of cirque glaciers. The thickness of these accumulations (10 to 20 m) indicated by the ERT measurements is well within the range of vertical dimensions of terminal moraines deposited by small cirque glaciers (e.g., Anderson et al., 2014). Moreover, the arcuate ground plan of the western accumulation is consistent with the shape of moraines that close cirques. By contrast, the flat morphology, small height, and the absence of slope asymmetry differ from accepted moraines in the central European Variscides. If we accept the glacial origin of the accumulation, a significant period of denudation would need to occur since the deposition. The difference between the current morphology of this accumulation and the moraines of the last glacial period in the Vosges, Harz, Krkonoše, and Bayerischer Wald/Šumava Mountains (e.g., Reuther et al., 2011; Diedrich, 2013; Engel et al., 2014; Mercier, 2014) implies its pre-Weichselian origin. This is also evidenced by the *R*-values measured on the boulders, which are significantly lower than the values reported from late Weichselian moraines and Holocene rock surfaces in the western Sudetes (Table 2). The mean *R*-value calculated for the flat accumulation is close to the *R*-value obtained by Černá and Engel (2011) for roches moutonnées in the Smědá Valley at the northern part of the Jizerské hory Mountains. This suggests that the flat ridge formed around the same time when ice-sheet eroded bedrock in the northern foothills of the range.

The *R*-values measured on the flat ridge at the downslope side of the hollow are significantly higher than those measured on the valley-side and summit tors confirming the succession of landform formation (Fig. 5). The significant difference between the *R*-values from the boulders and the valley-side tors at the western margin of the Pytlácká jáma Hollow indicates boulder deposition in a pre-existing hollow that formed after a period of slope lowering. The mean *R*-value obtained for the valley-side tors is well within the uncertainty of the mean *R*-

Table 2
Timing of granite surfaces in the study area (in bold) based on R-values and exposure ages from the Sudetes Mountains.

Tested surfaces	Altitude [m asl]	Granite	Range of *R*-values	Mean *R*-value	Age [ka]	Reference
Summit tors above the Smědá valley	965	Porphyritic	17.7 ± 1.2 to 20.9 ± 2.9[a]	19.1 ± 0.8	Pre-Quaternary	Traczyk and Engel (2006)
Valleyside tors above the trimline of ice-sheet glaciation	518–596	Porphyritic	19.7 ± 1.8 to 25.1 ± 1.6	22.5 ± 0.5	> MIS 12	Černá and Engel (2011)
Summit tors on the Middle Jizera Ridge	**956–974**	**Porphyritic**	**21.8 ± 1.2 to 30.8 ± 1.7**	**25.4 ± 1.4**	–	**This study**
Valleyside tors by the Pytlácká jáma Hollow	**869–871**	**Porphyritic**	**25.1 ± 2.1 to 26.6 ± 2.6**	**25.9 ± 0.8**	–	**This study**
Glacially-transformed bedrock surfaces below the trimline of ice-sheet glaciation	346–496	Porphyritic	21.0 ± 2.7 to 34.4 ± 2.1	26.8 ± 0.7	< MIS 12	Černá and Engel (2011)
Boulders in front of the Pytlácká jáma Hollow	**843–852**	**Porphyritic**	**25.2 ± 2.4 to 33.5 ± 3.1**	**29.6 ± 0.8**	–	**This study**
Moraine boulders of the last glaciation in the Krkonoše Mts.	825–1250	Biotite/porphyritic	25.4 ± 1.4 to 44.3 ± 5.6	35.1 ± 0.5	21.3–12.7	Engel et al. (2014)
Channel of the Smědá River	365–366	Porphyritic	43.5 ± 5.4 to 46.6 ± 4.7 [a]	45.0 ± 1.6	Holocene	Traczyk and Engel (2006)
Foot of cirque headwalls in the Krkonoše Mts.	1170–1254	Biotite	42.8 ± 2.7 to 60.9 ± 3.9	52.3 ± 3.7	14.4–9.5	Engel et al. (2011, 2014)
Pronival ramparts in the Krkonoše Mts.	1285–1300	Porphyritic	37.3 ± 4.5 to 60.4 ± 3.9	54.2 ± 5.6	Mid to Late Holocene	Margold et al. (2011)

[a] *R*-values are recalculated using the procedure described in the current paper.

value of the summit tors around the Pytlácká jáma Hollow. However, the geomorphological position suggests that the valley-side tors were formed somewhat later than the bedrock surfaces on the top of the ridges. The range and mean of *R*-values for tors coincide with those reported from valley-side and summit tors in the western part of the Jizerské hory Mountains (Table 2). The summit tors are considered to be relics of paleosurfaces that likely formed after ~75 Ma in the western Sudetes (Danišík et al., 2010). The *R*-values reported by Traczyk and Engel (2006) from bedrock surfaces located above the trimline of ice-sheet glaciation probably constrain the upper age threshold for the tors that are definitely older than the Elsterian glaciation, i.e., marine isotope stages (MIS) 16 and 12 (Nývlt et al., 2011).

5.2. Implications for quaternary mountain glaciations in Central Europe

The morphology of the Pytlácká jáma Hollow and sedimentological characteristics of the sedimentary infill indicate that the central part of the range was probably glaciated. This conclusion contradicts the prevailing view of glacier-free conditions in the range during the Quaternary (e.g., Migoń, 1999). The cirque altitudinal range implies a glaciation limit around 1000 m asl and an equilibrium line altitude (ELA) between 890 and 900 m asl when the toe-to-head altitude ratio of 0.35–0.40 is taken into account (Meierding, 1982). The calculated ELA is 100–175 m lower than the paleo-ELA in the Krkonoše Mountains during the LGM (990–1075 m asl; Engel, 2003). The difference in altitude is wide taking into account the close proximity of both ranges (the Pytlácká jáma Hollow is located 17 km from the nearest cirques in the Krkonoše Mountains). Considering a low uplift rate in the Sudetes in the late Cenozoic (Danišík et al., 2010), it may be inferred that the proposed low glaciation limit represents pre-LGM (and probably pre-Weichselian) glaciation. It is likely that during the last glacial period only perennial snow patches occurred in the Pytlácká jáma Hollow. Snow patches have recently been frequent in the cirques within the Krkonoše Mountains well outside the present glaciation limit (Margold et al., 2011).

The existence of pre-Weichselian glaciation was hypothesised more than a century ago for the highest range (the Krkonoše Mountains, 1602 m asl) within the eastern Variscides (Partsch, 1894). This view was suggested on the basis of local river terrace stratigraphy and tentatively confirmed by weathering characteristics (Králík and Sekyra, 1989; Traczyk, 1989) and sedimentological investigations (Carr et al., 2002). However, the hypothesis of pre-Weichselian glaciation has not been confirmed yet by numerical-age dating. The geomorphological analysis of the Pytlácká jáma Hollow and sedimentological evidence from its bottom further validate the model of such old glaciation. Moreover, the evidence comes from a relatively low-elevated range.

The proposed glacial origin of the Pytlácká jáma Hollow has implications for the extent of Quaternary mountain glaciations in central Europe. The significant depression of ELA during the middle Quaternary implies (i) more extensive glaciations of mid-mountain regions prior to the last glaciation and (ii) formation of pre-late Quaternary glaciers in locations lower than currently accepted. The hypothesis of extensively glaciated mid-mountain areas is in accordance with the field evidence for the existence of ice-cap glaciation in the Harz (e.g., Diedrich, 2013), Vosges (Flageollet, 2002), Schwarzwald (Glotzbach et al., 2014), and Bayerischer Wald (Reuther, 2007). The formation of ice fields has also been suggested for high altitude plateau areas well above the cirques and the troughs in the Krkonoše Mountains (Sekyra and Sekyra, 2002). Moreover, outlet glaciation extending onto the foreland of the Harz and the Krkonoše Mountains has recently been suggested (Carr et al., 2002; Diedrich, 2013). The inferred glaciation limit at ~1000 m asl and ELA around 900 m asl have likely led to the glaciation of lower mountain ranges in central Europe. Within the eastern Variscides, ranges with extensive summit areas at 900–1100 m asl (e.g., Erzgebirge, Fichtelgebirge, and Thüringer Wald) were likely covered by ice. According to the strong longitudinal temperature gradient in central Europe during the last glacial (Allen et al., 2008; Heyman et al., 2013) and corresponding lowering of ELA toward the west (Reuther, 2007), glaciation of even lower ranges must be assumed in the western part of central Europe.

6. Conclusions

The geomorphological and sedimentary evidence suggests that the Pytlácká jáma Hollow in the Jizerské hory Mountains was probably formed by a cirque glacier. An arcuate headwall and a convex lower threshold delimit the depression. The gently sloping floor is clearly delimited against the adjacent slopes, and a slope reversal is present in the western section of the downslope margin. The deepening of the floor is moderate as indicated by the *k*-curve (sensu Haynes, 1968) coefficients that are comparable to the values observed in the cirques within the eastern Variscides in central Europe. The morphological features of the hollow are well within the range of values reported for these cirques, but they differ from the morphology of nivation hollows in the Jizera range. The absence of well-defined upper margins and the predominantly less steep headwall suggest that the Pytlácká jáma Hollow is a glacial cirque at an early stage of development (sensu Evans and Cox, 1995). The probable maximum snow thickness of 45–55 m estimated for the hollow favours the presence of glacier ice in the depression. Grain size distributions of clasts and the micromorphology of quartz grains from the hollow bottom indicate the glacial environment of a small glacier, with short transport distance; and boulder accumulations at the downslope side of the hollow have a characteristic position, ground plan, and thickness of terminal moraines deposited by cirque glaciers.

The Schmidt hammer *R*-values and their comparison with other records provide indication of the relative age of the landform. The paleo-ELA reconstructions and the Schmidt hammer data cannot resolve the problem completely, but they are able to constrain the age of the cirque in a way that has not been attempted before. The comparison of the paleo-ELA calculated for the Pytlácká jáma Hollow (~900 m asl) with the reported ELA in the Krkonoše Mountains during the LGM implies that the proposed glaciation limit represents pre-Weichselian glaciation. Moreover, the likely age of the boulder accumulation at the downslope side of the cirque inferred from the *R*-values constrains the post-Elsterian timing of the Pytlácká jáma Hollow formation.

The suggested presence of a small glacier in a relatively low-elevated range well above the limits of the Scandinavian Ice Sheet has important implications for the reconstructions of Quaternary mountain glaciations in central Europe. The glaciation limit (1000 m asl) and paleo-ELA (900 m asl) proposed for the Jizerské hory Mountains implies that substantially lower ranges than previously considered were probably glaciated during the Quaternary. Therefore, the recent consensus that local ranges lower than 1100 m asl remained unglaciated during all Quaternary glacial periods requires careful revision.

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References

Allen, R., Siegert, M., Payne, A.J., 2008. Reconstructing glacier-based climates of LGM Europe and Russia – part 2: a dataset of LGM precipitation/temperature relations derived from degree-day modelling of paleo glaciers. Clim. Past 4, 249–263.

Anderson, L.S., Roe, G.H., Anderson, R.S., 2014. The effects of interannual climate variability on the moraine record. Geology 42 (1), 55–58.

Balatka, B., Pilous, V., 2009. Geomorfologické poměry Jizerských hor. In: Karpaš, R. (Ed.), Jizerské hory. O mapách, kamení a vodě. Nakladatelství RK, Liberec, pp. 267–296.

Balcar, V., Špulák, O., Kacálek, D., Kuneš, I., 2012. Klimatické podmínky na výzkumné ploše Jizerka. II – teplota, vítr a sluneční svit. Zprávy lesnického výzkumu 57 (2), 160–172.

Ballantyne, C.K., Benn, D., 1994. Glaciological constraints on protalus rampart development. Permafr. Periglac. Process. 5 (3), 145–453.

Barr, I.D., Spagnolo, M., 2015. Glacial cirques as palaeoenvironmental indicators: their potential and limitations. Earth-Sci. Rev. 151, 48–78.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51 (1), 337–360.

Bubeníčková, L., Kulasová, A., 2009. Podnebí a počasí Jizerských Hor. In: Karpaš, R. (Ed.), Jizerské Hory. O mapách, kamení a vodě. Nakladatelství RK, Liberec, pp. 342–383.

Carr, S.J., Engel, Z., Kalvoda, J., Parker, A.G., 2002. Sedimentary evidence to suggest extensive glaciation of the Úpa valley, Krkonoše Mountains, Czech Republic. Z. Geomorphol. 46 (4), 523–537.

Černá, B., Engel, Z., 2011. Surface and sub-surface Schmidt hammer rebound value variation for a granite outcrop. Earth Surf. Process. Landf. 36 (2), 170–179.

Černá, B., Nývlt, D., Engel, Z., 2012. A buried glaciofluvial channel in the Anděl Col, Northern Bohemia: new evidence for the Middle Pleistocene ice sheets extent in Western Sudetes. Geografie 117 (2), 127–151.

Christiansen, H.H., 1998. Nivation forms and processes in unconsolidated sediments, NE Greenland. Earth Surf. Process. Landf. 23, 751–760.

Cremer, M., Legigan, P., 1989. Morphology and surface texture of quartz grains from ODP site 645, Baffin Bay. In: Srivastava, S.P., Arthur, M., Clement, B., et al. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results 105, pp. 21–30.

Czech Office for Surveying, Mapping and Cadastre, 2015. Digital Terrain Model of the Czech Republic of the 5th Generation (DMR 5G). ČÚZK, Praha.

Danišík, M., Migoń, P., Kuhlemann, J., Evans, N.J., Dunkl, I., Frisch, W., 2010. Thermochronological constraints on the long-term erosional history of the Karkonosze Mts., Central Europe. Geomorphology 117, 78–89.

Derbyshire, E., Evans, I.S., 1976. The Climatic Factor in Cirque Variation. In: Derbyshire, E. (Ed.), Geomorphology and Climate. Wiley, London, pp. 447–494.

Diedrich, C., 2013. Impact of the German Harz Mountain Weichselian ice-shield and valley glacier development onto Palaeolithic and megafauna disappearances. Quat. Sci. Rev. 82, 167–198.

Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), 2011. Quaternary Glaciations - Extent and Chronology: A Closer Look. Developments in Quaternary Science. Elsevier, Amsterdam.

Embleton, C., King, C.A.M., 1975. Periglacial Geomorphology. Edward Arnold, London.

Engel, Z., 2003. Pleistocénní zalednění české části Krkonoš. Przyroda Sudetów Zachodnich 6, 223–234.

Engel, Z., 2007. Measurement and age assignment of intact rock strength in the Krkonoše Mountains, Czech Republic. Z. Geomorphol. 51 (Suppl. Iss. 1), 69–80.

Engel, Z., Traczyk, A., Braucher, R., Woronko, B., Křížek, M., 2011. Use of ^{10}Be exposure ages and Schmidt hammer data for correlation of moraines in the Krkonoše Mountains. Z. Geomorphol. 55 (2), 175–196.

Engel, Z., Braucher, R., Traczyk, A., Laetitia, L., ASTER team, 2014. ^{10}Be exposure age chronology of the last glaciation in the Krkonoše Mountains, Central Europe. Geomorphology 206, 107–121.

Evans, I.S., Cox, N.J., 1974. Geomorphometry and the operational definition of cirques. Area 6 (2), 150–153.

Evans, I.S., Cox, N.J., 1995. The form of glacial cirques in the English Lake District, Cumbria. Z. Geomorphol. 39 (2), 175–202.

Fiebig, M., Buiter, S.J.H., Ellwanger, D., 2004. Pleistocene glaciations of South Germany. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations – Extent and Chronology. Part I: Europe. Elsevier, Amsterdam, pp. 147–154.

Flageollet, J.-C., 2002. Sur les traces des glaciers vosgiens. CNRS, Paris.

Gale, S., Hoare, P., 1991. Quaternary Sediments: Petrographic Methods for the Study of Unlithified Rocks. Belhaven, London.

Glotzbach, C., Röttjer, M., Hampel, A., Hetzel, R., Kubik, P.W., 2014. Quantifying the impact of former glaciation on catchment-wide denudation rates derived from cosmogenic ^{10}Be. Terra Nova 26, 186–194.

Gordon, J.E., 1977. Morphometry of cirques in the Kintail-Affric-Cannich area of northwest Scotland. Geogr. Ann. A 59 (3/4), 177–194.

Graham, D.J., Midgley, N.G., 2000. Graphical representation of particle shape using triangular diagrams: an Excel spreadsheet method. Earth Surf. Process. Landf. 25, 1473–1477.

Haynes, V.M., 1968. The influence of glacial erosion and rock structure on corries in Scotland. Geogr. Ann. A 50 (4), 221–234.

Helland, P.E., Huang, P.H., Diffendal, R.F., 1997. SEM analysis of quartz sand grain surface textures indicates alluvial/colluvial origin of the quaternary “glacial” boulder clays at Huangshan (Yellow Mountain), East-Central China. Quat. Res. 48, 177–186.

Heyman, B.M., Heyman, J., Fickert, T., Harbor, J.M., 2013. Paleo-climate of the central European uplands during the last glacial maximum based on glacier mass-balance modelling. Quat. Res. 79 (1), 49–54.

Hughes, P.D., Gibbard, P.L., Ehlers, J., 2013. Timing of glaciation during the last glacial cycle: evaluating the meaning and significance of the ‘last glacial maximum’ (LGM). Earth-Sci. Rev. 125, 171–198.

Kaufman, L., Rousseeuw, P.J., 2005. Finding groups in data: an introduction to cluster analysis. Wiley, Hoboken.

Králík, F., Sekyra, J., 1989. Paleogeografický vývoj v terciéru a kvartéru. In: Chaloupský, J. (Ed.), Geologie Krkonoš a Jizerských Hor. Ústřední ústav geologický, Praha, pp. 171–175.

Krinsley, D.H., Doornkamp, J.C., 1973. Atlas of Quartz Sand Surface Textures. Cambridge University Press, New York.

Krinsley, D.H., Friend, P.F., Klimentidis, R., 1976. Eolian transport textures on the surface of sand grains of Early Triassic age. Geol. Soc. Am. Bull. 87, 130–132.

Křížek, M., 2007. Periglacial landforms above alpine timberline in the High Sudetes (Czech Republic). In: Kalvoda, J., Goudie, A. (Eds.), Geomorphological Variations. P3K, Praha, pp. 313–337.

Křížek, M., Vočadlová, K., Engel, Z., 2012. Cirque overdeepening and their relationship to morphometry. Geomorphology 139–140.

Kulasová, A., Pobříslová, J., Jirák, J., Hancvencl, R., Bubeníčková, L., Bercha, Š., 2006. Experimentální hydrologická základna Jizerské hory. J. Hydrol. Hydromech. 54 (2), 163–182.

Loke, M.H., 2000. Electrical imaging surveys for environmental and engineering studies. A Practical Guide to 2-D and 3-D Surveys. Geotomo, Malaysia.

Mahaney, W.C., 2002. Atlas of Sand Grain Surface Textures and Applications. Oxford University Press, Oxford.

Margold, M., Treml, V., Petr, L., Nyplová, P., 2011. Snowpatch hollows and pronival ramparts in the Krkonoše Mountains, Czech Republic: distribution, morphology and chronology of formation. Geogr. Ann. A 93, 137–150.

Meierding, T.C., 1982. Late Pleistocene glacial equilibrium-line altitudes in the Colorado Front Range: a comparison of methods. Quat. Res. 18 (3), 289–310.

Mentlík, P., Engel, Z., Braucher, R., Léanni, L., ASTER team, 2013. Chronology of the Late Weichselian glaciation in the Bohemian Forest in Central Europe. Quat. Sci. Rev. 65, 120–128.

Mercier, J.-L., 2014. Glacial imprint on the main ridge of the Vosges Mountains. In: Fort, M., André, M.-F. (Eds.), Landscapes and Landforms of France. Springer, Dordrecht, pp. 161–169.

Migoń, P., 1999. The role of preglacial relief in the development of mountain glaciation in the Sudetes, with the special reference to the Karkonosze Mountains. Z. Geomorphol. Suppl.-Bd. 113, 33–44.

Migoń, P., Lidmar-Bergström, K., 2001. Weathering mantles and their significance for geomorphological evolution of central and northern Europe since the Mesozoic. Earth Sci. Rev. 56, 285–324.

Migoń, P., Potocki, J., 1996. Rozwoj morfotektoniczny centralnej części Gor Izerskich. Acta U. Wratisl., 1808. Prace Inst. Geogr., Seria A, Geografia Fizyczna 8, pp. 69–79.

Milsom, J., 2003. Field Geophysics. Wiley, Chichester.

Moncrieff, A.C.M., 1989. Classification of poorly-sorted sedimentary rocks. Sediment. Geol. 65, 191–194.

Moon, B.P., 1984. Refinement of a technique for determining rock mass strength for geomorphological purposes. Earth Surf. Process. Landf. 9 (2), 189–193.

Munsell® Soil Color Charts, 2000. GretagMacbeth, New Windsor.

Nývlt, D., Engel, Z., Tyráček, J., 2011. Pleistocene glaciations of Czechia. In: Ehlers, J., Gibbard, P.L., Hughes, P.D. (Eds.), Quaternary glaciations - extent and chronology: a closer lookDevelopments in Quaternary Science vol. 15. Elsevier, Amsterdam, pp. 37–46.

Partsch, J., 1894. Die Vergletscherung des Riesengebirges zur Eiszeit. Forsch. Dt. Landes-u. Volksk. 8, 103–194.

Pilous, V., 2006. Pleistocénní glacigenní a nivační modelace Jizerských hor. Opera Corcontica 43, 21–44.

Powers, M.C., 1953. A new roundness scale for sedimentary particles. J. Sediment. Res. 23, 117–119.

Prosová, M., Sekyra, J., 1961. Vliv severovýchodní expozice na vývoj reliéfu v pleistocénu. Čas Mineral Geol. 6 (4), 448–463.

Rączkowska, Z., 2007. Współczesna rzeźba Peryglacjalna Wysokich gór Europy. PAN IGiPZ, Warszawa.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51 (4), 1111–1150.

Reuther, A.U., 2007. Surface Exposure Dating of Glacial Deposits from the Last Glacial Cycle. Schweizerbart, Stuttgart.

Reuther, A.U., Fiebig, M., Ivy-Ochs, S., Kubik, P.W., Reitner, J.M., Jerz, H., Heine, K., 2011. Deglaciation of a large piedmont lobe glacier in comparison with a small mountain glacier — new insight from surface exposure dating. Two studies from SE Germany. Quat. Sci. J. 60 (2–3), 248–269.

Sekyra, J., Sekyra, Z., 2002. Former existence of a plateau icefield in Bílá louka Meadow, eastern Giant Mountains: hypothesis and evidence. Opera Corcontica 39, 35–43.

Sobik, M., Błaś, M., 2010. Wyjątkowe zdarzenia meteorologiczne. In: Migoń, P. (Ed.), Wyjątkowe zdarzenia przyrodnicze na Dolnym Śląsku i ich skutkiRozprawy Naukowe Instytutu Geografii i Rozwoju Regionalnego 14. Uniwersytet Wrocławski, Wrocław, pp. 35–80.

Sobik, M., Urban, G., 2000. Thermal condition of the Kamionek catchment in the Izerskie Mountains. Acta Univ. Wratisl. 2269, 143–157.

StatSoft, Inc., 2009. STATISTICA (data analysis software system), version 9.0. www.statsoft.com.

Strand, K., Passchier, S., Näsi, J., 2003. Implications of quartz grain microtextures for onset Eocene/Oligocene glaciation in Prydz Bay, ODP site 1166, Antarctica. Palaeogeogr. Palaeoclimatol. Palaeoecol. 198, 101–111.

Traczyk, A., 1989. Zlodowacenie doliny Łomnicy w Karkonoszach oraz poglady na ilość zlodowaceń pleistoceńskich w średnich górach Europy. Czas. Geogr. 60, 19–199.

Traczyk, A., Engel, Z., 2006. Maximální dosah kontinentálního zalednění na úpatí Ořešníku a Poledníku v severním svahu Jizerských hor. Geografie – Sborník ČGS 111(2), pp. 141–151.
Traczyk, A., Engel, Z., Janásková, B., Kasprzak, M., 2008. Glacjalna morfologia wierzchowiny Gór Izerskich w świtle badań w rezerwacie "Rybí loučky" (Republika Czeska). Landf. Anal. 9, 129–133.
Vallon, M., Petit, J.R., Fabre, B., 1976. Study of an ice core to the bedrock in the accumulation zone of an alpine glacier. J. Glaciol. 17, 13–28.
Vočadlová, K., Petr, L., Žáčková, P., Křížek, M., Křížová, L., Hutchinson, S.M., Šobr, M., 2015. The Lateglacial and Holocene in Central Europe: a multiproxy environmental record from the Bohemian Forest, Czech Republic. Boreas 44 (4), 769–784.
Žák, J., Verner, K., Sláma, J., Kachlík, V., Chlupáčová, M., 2013. Multistage magma emplacement and progressive strain accumulation in the shallow-level Krkonoše-Jizera plutonic complex, Bohemian Massif. Tectonics 32, 1493–1512.