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ORIGINAL PAPER

COULD LONG VALLEY GLACIERS HAVE BEEN EXTENDED IN THE BOHEMIAN FOREST? GEOPHYSICAL INSIGHTS FROM GROßER RACHEL REGION

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ABSTRACT

The Bohemian Forest was glaciated during Pleistocene cold periods. However, opinions on the extent of the glaciation of this mountain range are divided and vary throughout the scientific communities on either side of the Czech/German border. There is the hypothesis of a more extensive glaciation, which is to some extent supported on the Bavarian side, but Czech researchers rather incline to the existence of individual cirques or small valley glaciers. We present the results of geophysical analyses using electrical resistivity tomography carried out in the vicinity of Kleiner Rachelbach cirque. The aim was to examine the extent of the glacial sediments and thus, prove or disprove the hypothesis of a more extensive glaciation. We were seeking to find geophysical manifestations of the glacial sediments (determined on the basis of a literature review, the official geological map and our research) in a moraine complex and beyond it, where long valley glaciers are assumed to have extended. We observed such a manifestation only in the moraine complex. We can thus disprove the hypothesis of an extensive glaciation in the vicinity of Kleiner Rachelbach cirque.

INTRODUCTION

The question of the extent of glaciation in the Bohemian Forest has not yet been satisfactorily resolved. The hypothesis of a more extensive glaciation is still accepted (Ergenzinger, 1967; Hauner, 1980; Pfaffl, 2010; Hauner et al., 2019) mainly on the German side. The German authors have dated the more extensive glaciation to the last (Würm) or penultimate (Riss) glacial period. The outputs of these works are glaciation maps of the Bavarian part of the Bohemian Forest in particular (Ergenzinger, 1967; Hauner, 1980; Pfaffl, 2010; Hauner et al., 2019). These maps present the most extensive possible glaciation of the mountains in the form of a glacial cap or firn field with individual (up to 6 km long) valley glaciers and glacial tongues. The studies from the area of the Kleiner Arbersee (Raab and Völkel, 2003; Reuther, 2007; Reuther et al., 2011) represent an exception on the German side. These authors lean towards glaciation linked only to a north-oriented glacial cirque with a maximum extent in the Last Glacial Maximum (LGM). In more recent work, Czech authors do not usually emphasise the idea of a more extensive glaciation (Mentlík et al., 2010; Křížek et al., 2012; Mentlík et al., 2013; Vočadlová et al., 2015; Vondrák et al., 2021). These studies focus on chronologies in the vicinity of the north- or northeast-oriented cirques (Černé, Prášilské, Plešné and Laka lake cirques), where the oldest moraines correspond to the LGM. An exception is the work by Czech authors presenting an analysis of LIDAR data for the whole mountain range (Krause and Margold, 2019). This also posits the hypothesis of a more extensive glaciation of the whole Bohemian Forest, but without supporting field research.

More extensive glaciation is also described in other European Hercynian mountain ranges. Seret at al. (1990), Mercier et al. (1999) and Hemmerle et al. (2016) describe ice cap and up to 25 km long outlet glaciers in the Vosges. Hofmann et al. (2021) dated moraines which limit the glacier more than 3 km long in the Black Forest. Engel et al. (2014) discuss moraines 4 km from the cirque in the Giant Mountains. Cirque glacier is only expected in the Jizerské hory Mountains (Engel et al., 2017). According to Vočadlová (2011), the evidence of older and possibly more extensive glaciation than the LGM in the Bohemian Forest is only indirect (glacial accumulation at low altitudes or fossil soils from the last interglacial overlain by a solifluction horizon), but its existence cannot be excluded. Hypothetical glacial relics are reported from altitudes up to 720 m a.s.l. (Ergenzinger, 1967; Hauner, 1980; Raab, 1999; Hauner et al., 2019). In addition to sedimentary and

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geological findings older (and possibly more extensive) glaciations can be inferred from significant remodelling of glacial cirques (Křížek et al., 2012; Barr and Spagnolo, 2015).

This paper aims to examine the extent of glacial sediments in the vicinity of Kleiner Rachelbach cirque by comparing the subsurface manifestations of the area of more extensive glaciation (according to Hauner, 1980; Hauner et al., 2019) with the subsurface manifestations of the area of moraine complex (according to Duffek et al., 2023b). As the site is located in the protected area of the Bavarian Forest National Park (designation for the Bohemian Forest on the German side), a non-destructive and non-invasive research method had to be used

Geophysical methods are both non-invasive and non-destructive (Kearey et al., 2002). The multi-electrode resistivity method and its processing by electrical resistivity tomography (ERT) were used due to its considerable versatility and time efficiency. ERT is widely used in geomorphology (Šilhán and Pánek, 2007; Reynolds, 2011; Tábořík, 2012; Viles, 2016; Špaček et al., 2017; Břežný et al., 2018). Its suitability has been proven in investigations of the thickness of weathered mantle or sediments (Pellicer and Gibson, 2011; Tábořík, 2012; Duffek et al., 2023a) as well as glacial and periglacial landforms and permafrost (Kneisel, 2006; Hilbich et al., 2008; Krautblatter, 2010; Mentlík et al., 2010; Tábořík, 2012; Onaca et al., 2013; Engel et al., 2017; Duffek et al., 2023b). According to Tábořík (2012), the method can be used in glacially remodelled relief to determine the extent and thickness of glacial sediments and cirque and valley fills. This is confirmed, among others, by the research of Kneisel (2006), Mentlík et al. (2010), Thompson et al. (2012), Zamosteanu et al. (2014), Duffek and Mentlík (2022), Duffek et al. (2023b). These investigations (Kneisel, 2006; Mentlík et al., 2010; Thompson et al., 2012; Zamosteanu et al., 2014; Duffek and Mentlík, 2022) carried out in areas of mountain glaciation have shown that most glacial sediments of mountain glaciation exhibit extreme resistivity values and often show a two-layered structure on 2D models of the subsurface resistivity distribution. For older accumulations, the structure on the 2D subsurface resistivity model may be slightly different (Duffek and Mentlík, 2022).

REGIONAL SETTINGS

The Kleiner Rachelbach cirque is located on the northern slope of the Großer Rachel Mountain in the central part of the Bohemian Forest (Fig. 1a). The depression itself is significantly overdeepened, similar to other sites in the Bohemian Forest (Křížek et al., 2012) where glacial remodelling has been demonstrated (Vočadlová et al., 2015; Mentlík et al., 2010; Reuther et al., 2011; Mentlík et al., 2013). There are accumulation landforms adjacent to the cirque (similarly to other localities in the Bohemian Forest), which are assumed to be of glacial origin (Pfaffl, 2010; Hauner et al., 2019; Duffek et al., 2023b). These accumulations are morphologically distinct in the terrain (Duffek et al., 2023b) and can be seen in the detailed digital elevation model (DEM) as well. The detailed LIDAR based DEM was loaned by the Bavarian Forest National Park Authority (LDBV, 2022). The morphologically distinct accumulations associated with the overdeepened depression thus confirm the glacial remodelling of the site as reported in the literature (Křížek et al., 2012; Hauner et al., 2019; Duffek et al., 2023b). Duffek et al. (2023b) described the geophysical-based manifestations of these accumulations even below the surface. These landforms are most distinctive north of the cirque (Fig. 2), where they form a kind of moraine complex. This moraine complex (Fig. 1) has been mapped in other works (Ergenzinger, 1967; Hauner, 1980; Hauner et al., 2019). Hauner et al. (2019) identify three retreat moraines in this complex, but Duffek et al. (2023b) do not confirm this hypothesis by detailed geomorphological mapping and only refer to a random assemblage of ridges and depressions, which they refer to as hummocky moraine relief. Hauner (1980) and Hauner et al. (2019) delineate the limits of more extensive glaciation at the site (Fig. 2), and these were used in this work.

According to the 1 : 25000 geological map (Fig. 1b, LFU, 2021), the wider surroundings of this area are built of mainly metamorphic cordierite-sillimanite and biotite paragneiss complexes. Only rarely do formations of Variscan granite plutons rise to the surface. The near-surface is composed of unbroken Pleistocene consolidated slope sediments up to an elevation of approximately 1050 m a.s.l. to 1100 m a.s.l., (LFU, 2021). According to Bauberger (1977), these slopes are composed of sand or gravel with numerous larger stones. Overall, this substratum is relatively consolidated and may reach a thickness of more than 10 metres (Bauberger, 1977).

METHODS

The fieldwork was carried out in the summer of 2022, during which a total of 4 ERT profiles were measured. The individual profiles were set to cross at least the field boundary of the moraine complex (defined by Hauner et al., 2019; Duffek et al., 2023b and DEM) or the more extensive glaciation boundary defined in Hauner (1980) and Hauner et al. (2019). The profiles crossing the more extensive glaciation boundary were below the assumed equilibrium line altitude (ELA) (1060 m a.s.l.) of the historical more extensive glaciation given by Ergenzinger (1967) and Hauner et al. (2019). Thus indications of both glacial accumulations and boundaries of more extensive glaciation could be considered on the resulting geophysical (GF) models. The positions of the profiles (P1 - P4) are shown in Figure 2, and the locations (stationing) of the boundary crossings in Table 1.

The ARES II automatic geoelectric system (GF Instruments, Brno) was used for the GF survey.

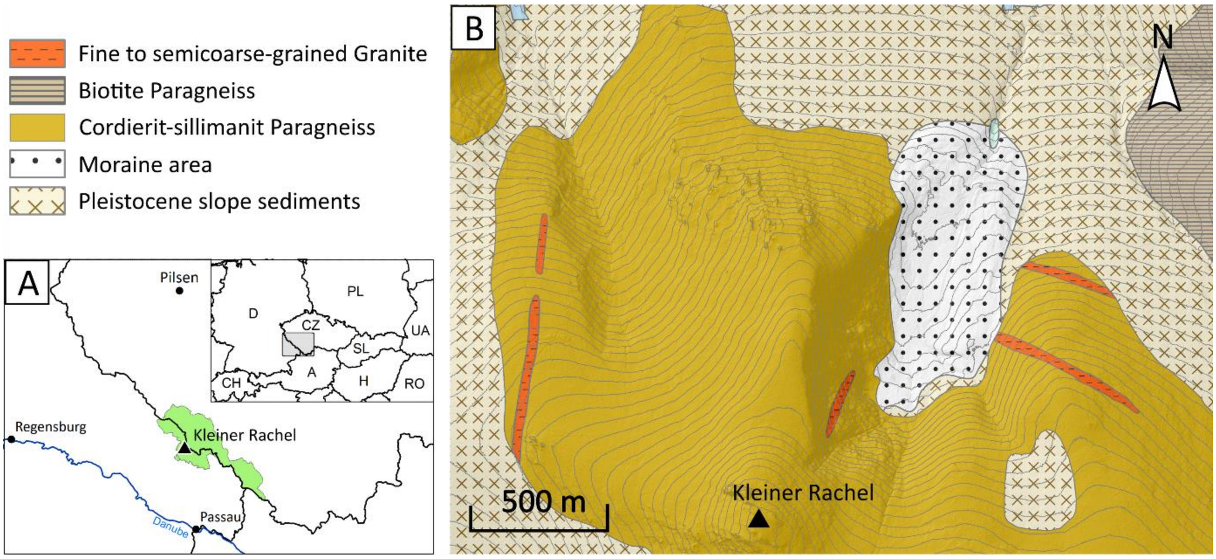

Fig. 1 a) position of the site within Bavarian Forest close to the Czech – Bavarian (German) borderline, b) geological map of the site (LFU, 2021).

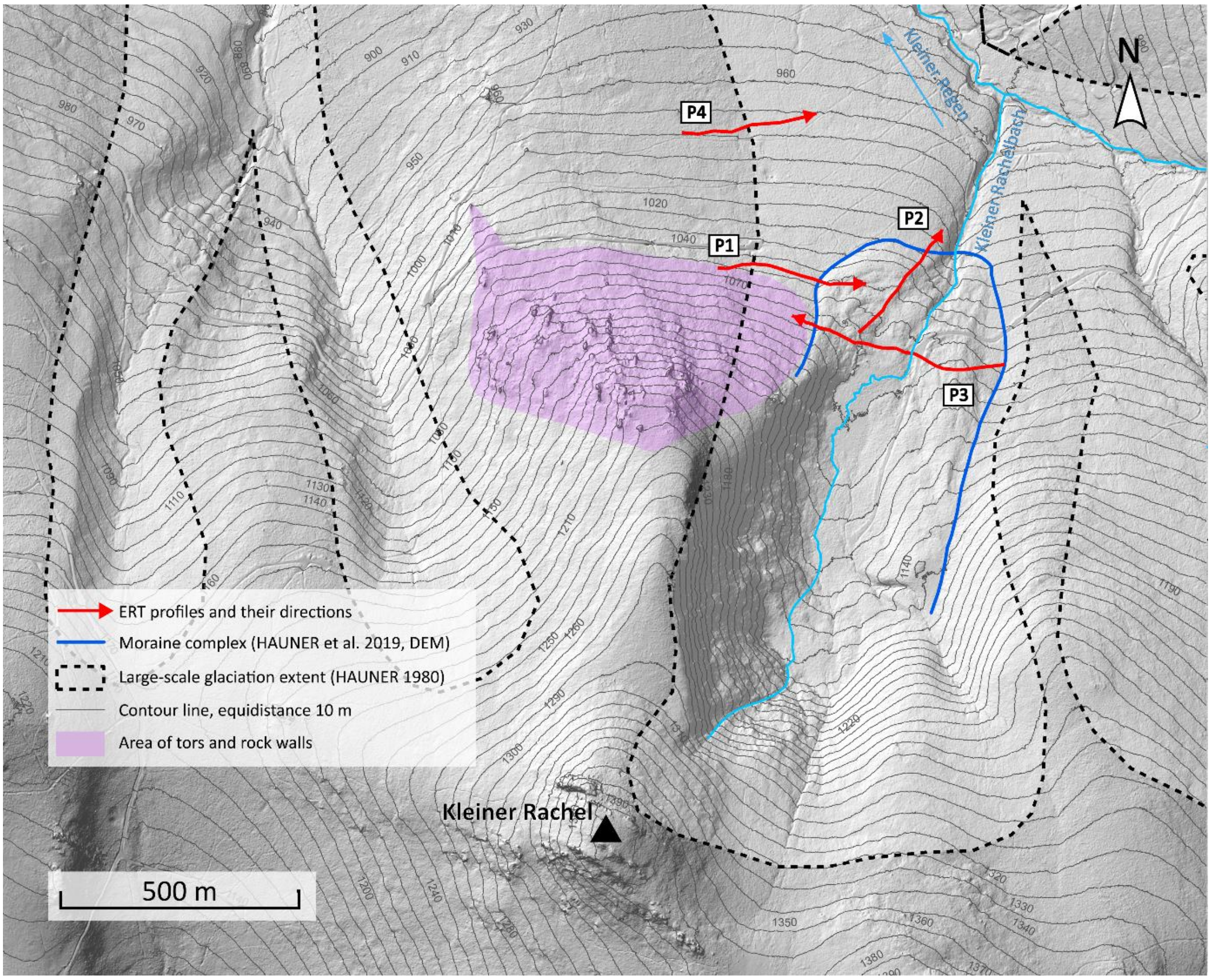

Fig. 2 Individual ERT profiles at the site. The extent of the moraine complex is identified on the basis of DEM (LDBV, 2022), Hauner et al. (2019), Duffek et al. (2023b).

Table 1 ERT profiles and their attributes.

Profile	Length (m)	Terrain boundaries of the moraine complex (m)	Boundary according to HAUNER, 1980 (m)	RMS error	Present geology (LFU, 2021)
P1	355	240	80	3.0	paragneiss - moraine area
P2	315	245	-	3.3	moraine area - consolidated Pleistocene slopes
P3	515	0 and 455	-	6.9	moraine area – paragneiss
P4	315	-	150	2.4	consolidated Pleistocene slopes

Considering the expected structure of the glacial sediments (given in the introduction), the Wenner-Schlumberger electrode array was selected for all profiles. This configuration has sufficient sensitivity and therefore resolution for both horizontal and vertical structures (Loke, 2000). An electrode spacing of 5 m was used for all profiles.

RES2DINV software (Loke, 2000) was used to invert the data using two-dimensional tomographic inversion. The standard computational method of the inverse problem was chosen using least squares model discretization, as robust inversion is more suitable for simplifying complicated models and exploring interfaces (Loke, 2000; Tábořík, 2012). Five iterations were used for each model. Topographic corrections were applied into the inversion calculation (Loke, 2000).

The structure of the glacial sediments was interpreted based on 2D models of the subsurface resistivity distribution (high resistivity and two-layered structure). The data were interpreted in the context of defined more extensive glaciation boundaries (Hauner, 1980; Hauner et al., 2019) and the geological map (LFU, 2021). The individual ERT profiles were also compared with each other and with ERT profiles from other studies (Kneisel, 2006; Mentlík et al., 2010; Tábořík, 2012; Thompson et al., 2012; Zamosteanu et al., 2014; Duffek and Mentlík, 2022; Duffek et al., 2023b). The resistivity scale was unified for all the resistivity models to enable the interpretation and mutual comparison of the ERT profiles.

RESULTS AND DISCUSSION

The ERT results (Fig. 3) in the moraine complex show resistivity values that correspond to glacial accumulations. At the end of P1 (240-350 m) and the whole of P2 and P3 (A_m in Fig. 3), we observe high resistivities near the surface, which is characteristic for glacial sediments (Mentlík, et al. 2010; Tábořík, 2012; Zamosteanu et al., 2014; Duffek and Mentlík, 2022; Duffek et al., 2023b). The resistivity reaches values >10 000 Ω·m. In the same portions of the profiles we also observe two-layered subsurface conditions, which is also characteristic for glacial accumulations (Kneisel, 2006; Mentlík et al., 2010; Tábořík, 2012; Thompson et al., 2012; Zamosteanu et al., 2014; Duffek and Mentlík, 2022). At the end of P2 and P3, a continuation of the characteristics described above can be observed beyond the mapped boundaries of the moraine complex. These results suggest that the glacial sediments extend at the front and probably at the sides of the accumulation outside the moraine complex. This would suggest either a greater extension of the sediments supporting the hypothesis of more extensive glaciation (Hauner, 1980; Hauner et al., 2019), or degradation of the bounding accumulations by geomorphological (slope) processes (Pluktonen and O'Neal, 2006; Morgan and Pluktonen, 2022). The second hypothesis is supported by the fact that at P1 (from 0 to 240 m (Fig. 3)) the characteristics of accumulations are not typical for glacial accumulation (Mentlík et al., 2010; Zamosteanu et al., 2014; Duffek and Mentlík, 2022). In all portions of the profiles that intersect the moraine complex (the end of P1 and the whole of P2 and P3), a low-resistivity layer (Pg in Fig. 3) with values <2 000 Ω·m can be observed under layers of high resistivities. This layer probably represents the bedrock paragneiss. Low resistivities can also be observed at the surface at P3 around 230 m (Fig. 3), where there is a local decrease in resistivity, probably due to water flow and higher saturation (Mentlík et al., 2010; Tábořík, 2012; Duffek and Mentlík, 2022).

The results correspond to the geological map (LFU, 2021). The characteristics and the extent of the moraine complex are described above and correspond to the moraine area on the geological map (LFU, 2021). P1 (Fig. 3) crosses the bedrock consisting of the paragneiss up to about 240 metres and a significant change in subsurface conditions can be observed at this stationing (where the subsurface paragneiss changes to moraine on the geological map). Bodies of extreme resistivity (> 15 000 Ω·m) at P1 (bPBa in Fig. 3) could represent glacial accumulations (Mentlík et al., 2010; Tábořík, 2012; Zamosteanu et al., 2014; Duffek and Mentlík, 2022; Duffek et al., 2023b). However, we do not observe the classic two-layered subsurface conditions (Kneisel, 2006; Mentlík et al., 2010; Tábořík, 2012; Thompson et al., 2012) seen at the end of this profile (240-350 m) in the moraine complex. Thus, the extreme resistivities more likely represent the now buried block accumulations formed in the periglacial zone. Analogues of these buried

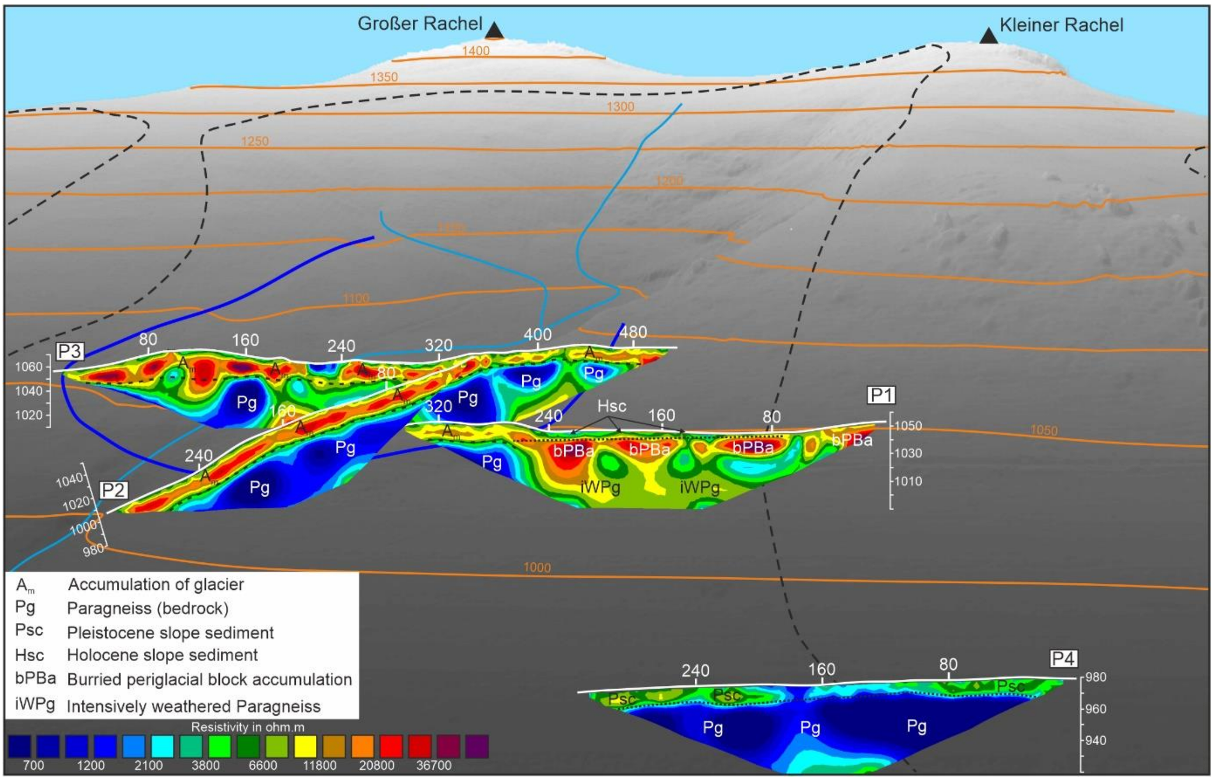

Fig. 3 ERT results in the context of the detailed DEM, moraine complex boundaries (blue line) and more extensive glaciation boundaries (black dashed line) reported in Hauner (1980) and Hauner et al. (2019).

accumulations in the Bohemian Forest region were presented, for example by Duffek et al. (2023a) who, based on geophysical analysis, lean towards a periglacial origin of these accumulations. The hypothesis of the occurrence of periglacially originated block accumulations is supported by the fact that the high resistivity bodies on P1 are located at the same level as the bedrock in the moraine complex (black dotted line on P1 Fig. 3). The bedrock in the moraine complex was most likely protected from periglacial weathering by the overlying glacier and, after the glacier retreated, by moraine sediments whose present thickness exceeds 10 m. The hypothesis of buried block accumulations is also supported by the extent of rock walls and tors (Fig. 2) which also originated in the periglacial zone (Goodfellow et al., 2014) and which are located higher up the slope. Below the layer of buried block accumulations, we find apparently strongly periglacially weathered bedrock paragneiss (iWPg in Fig. 3). From about 120 m to 240 m a not very thick near-surface layer of intermediate resistivities (from 3 000 to 7 000 Ω·m) burying block accumulations can be observed at P1 (Hsc in Fig. 3). Based on the above, these are Holocene slope layers that overlie the block accumulations. Compared to P1, P2 and P3, we observe completely different resistivity characteristics at P4 (Fig. 3). The two-layered subsurface conditions at P4 probably do not represent glacial sediments, because we do not observe extreme resistivity values for the top layer (Kneisel, 2006; Mentlík et al., 2010; Thompson et al., 2012; Duffek and Mentlík, 2022), such as at P2. Extreme values could be reduced by higher water saturation (Loke, 2000; Mentlík et al., 2010; Thompson et al., 2012). However, the position on the slope and location approximately 90 metres above the valley floor precludes a higher water table, and water in the stream would decrease resistivities only locally (Loke, 2000), similar to P3 (Fig. 3). Despite the reduction in resistivity may be caused by groundwater and not by a change in sedimentary facies, the interpretations are based on the fact that these sediments are referred to as a moraine complex by other authors (Hauner, 1980; Pfaffl, 2010; Hauner et al., 2019; Duffek et al., 2023b). This was also supported by field mapping focused on the glacial landforms. Qualitative (geophysical-geological) interpretations, were thus 'calibrated' on the basis of such an assumption, and a certain resistivity pattern could have been followed during the interpretations. Therefore, it is very likely that the subsurface resistivity distribution model depicts the Pleistocene slope sediments (Psc in Fig. 3) that can be identified on the geological map (LFU, 2021). Bauberger (1977) describes this material as "sediment consisting of sand or gravel with clay and dust mixed in and with numerous larger stones", which likely corresponds to intermediate resistivity values (from 3 000 to 7 000 Ω·m). The thickness of this layer corresponds to the thickness of the slope cover reported for example in Turner (1996). The deeper layer of low resistivities (Pg in Fig. 3) is likely to represent the bedrock of the paragneiss, which was protected in the periglacial zone by older sediment (Psc) deposited above it.

Thus, the electrical resistivity tomography results do not support the more extensive glaciation hypothesis presented in Hauner (1980) and Hauner et al. (2019). We do not find high resistivities at P4 that would suggest the existence of glacial sediments (Kneisel, 2006; Mentlík et al., 2010; Thompson et al., 2012; Duffek and Mentlík, 2022). The high resistivities at P1 outside the moraine complex (bPBa) probably represent buried block accumulations rather than glacial accumulations (see above). The low-resistivity layers found in all the profiles could also be indications of older and more extensive glaciation. These layers would thus represent material that was deposited by historical glaciation and is now highly compact and saturated with water, which increases its conductivity (Loke, 2000). However, this hypothesis is ruled out by P1, where we observe a low-resistivity layer only from 250 m, which roughly corresponds to the boundary of the moraine complex.

Although the geophysical results are consistent with geomorphological mapping (Duffek et al., 2023b) and the geological map (LFU, 2021), they must be treated with caution due to the nature of geophysics (Otto and Sass, 2006; Schrott and Sass, 2008). The results could be combined with other geophysical methods (Sass, 2006; Tábořík et al., 2017; Břežný et al., 2021; Duffek et al., 2023a) such as shallow seismic refraction as recommended by e.g. Schrott and Sass (2008) or Duffek et al. (2023a). On the other hand, geophysical profiling in protected areas is probably the only option for the non-destructive investigation of subsurface conditions.

CONCLUSION

The results of the presented research correspond very well with the geological map (LFU, 2021) and confirm the occurrence of older Pleistocene slope sediments as well as bedrock consisting predominantly of paragneiss. This bedrock shows signs of varying intensity of periglacial weathering and thus actually indirectly confirms the extent of glaciation. The area now formed by the glacial moraine complex (and formerly covered by a glacier) has different resistive properties to the area outside the moraine complex, where intense periglacial weathering probably occurred and at considerable depth. Paradoxically, the bedrock, which was first overlain by a glacier and later by several metres of moraine material, does not seem to have been subject to such intense frost weathering. Similarly, the relatively poorly weathered paragneiss, protected by up to several metres of older Pleistocene slope sediments, can be interpreted on the basis of the observed resistivity values.

ERT analysis near the Kleiner Rachelbach cirque has yielded important results that contribute to clarifying the extent of glaciation in the study area. Despite certain pitfalls of using a single geophysical method, we lean towards the hypothesis of less extensive glaciation as presented by Duffek et al. (2023b). This is because the subsurface conditions in the area of the more extensive glaciation (defined by Hauner (Hauner, 1980; Hauner et al., 2019) do not reflect the geophysical manifestation of glacial sediments. It should be noted, however, that the hypothesis of more extensive glaciation cannot be unequivocally refuted by the presented research. In order to resolve the question of more extensive glaciation in the Bohemian Forest, similar research would need to be carried out at other sites where the boundaries of the hypothetical, more extensive glaciation are defined to an extent (area-wise) significantly beyond the moraine complexes mapped in the field. These results could then be complemented by additional research methods.

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