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RESEARCH ARTICLE - SPECIAL ISSUE

Application of the ERT to recognise the geological structure of frost-riven cliffs localised in the Skalny Potok (Hrubý Jeseník Mts.)

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Abstract
In the area of the Skalni Potok Nature Reserve (Hrubý Jesenik), studies of gneissic cliffs were carried out to determine the role of lithology in the process of their formation. The research included geometric measurements of vertical discontinuity zones of selected rock outcrops and the electrical resistivity tomography (ERT) measurements of strongly weathered subsurface layers. As a result of the measurement, the orientation of the main crack systems (NW–SE and NE–SW) responsible for the location of cliffs within the Skalni Potok Valley was obtained. In addition, the main crack directions for the gneiss occurring in the studied mountain region were identified. Interpretation of the ERT models allowed to characterise the structure of the rock mass, including the reach of the rainwater infiltration level and the depth of the weathering front.

Keywords Cliffs · ERT · Weathered subsurface · Eastern Sudetes

Introduction

The Skalní Potok Nature Reserve is located within the highland range of Hrubý Jeseník Mts. (Eastern Sudetes) in geomorphological subunit the Medvědská hornatina and vincinity of west of Vrbno pod Pradědem (Fig. 1).

It is the second highest mountain range in the Czech Republic, located in the north-eastern part of the Bohemian Massif. The climate of the reserve area is slightly cool, with an average annual temperature of 4–6 °C and an average rainfall of 900–1200 mm per year. The winds predominate most often SW and NW directions (Agentura ochrany přírody a krajiny České Republiki). This area with the highest peak of the Lysý vrch (1128 m a.s.l.) is drained by the Skalni Potok stream, which flows into Středni Opava forming its left tributary. The mountain valley Skalni Potok has a variable course of the riverbed, and the stream creates numerous rapids, i.e. a set of cascades and several smaller waterfalls. The slopes within the reserve are steep (up to 35°) with many springs and outcrops of crystalline rocks, with a predominant majority of gneisses (Proterozoic) (Prosová 1954; Fediuková and Aichler 2004). The complex tectonic activity, the Upper Devonian folding and metamorphic processes led to transformations of the region's rocks with the older rocks (Stupnicka 1997) and development of discontinuities such as crack structures, fissures, mineral and rock veins (Liszkowski and Stochlak 1976; Kuzak and Żaba 2011). In order to understand the morphology of the studied area, particular attention should be paid to the process of creating any discontinuities associated with the structure of rock massifs acquired under the influence of endogenous factors. They have become weak zones predisposing directions of potential disintegration. The tertiary displacements of rock masses along faults led to the creation of a diversified sculpture with high lithological variability, including the shape of the main leveling surfaces (Czudek 2005). The warming up of the climate and the increase in humidity have triggered the processes of deep weathering by producing the significantly thick weathered cover (Goodfellow 2007; Hall et al. 2012). The changing climatic conditions in the Pleistocene due to the immediate vicinity of both the Scandinavian glacier (during Elsterian and Saalian glaciations) as well as local mountain glaciers (including alpine glaciers) coursed the exposure of the crystalline bedrock and transformations within it (Nývlt et al. 2011; Goodfellow 2007). As a result of progressive weathering along the primary surfaces of the discontinuity associated with the processes of swelling and shrinkage, freezing and thawing during cyclic cooling and heating, progressive crumbling of rocks occurred not only

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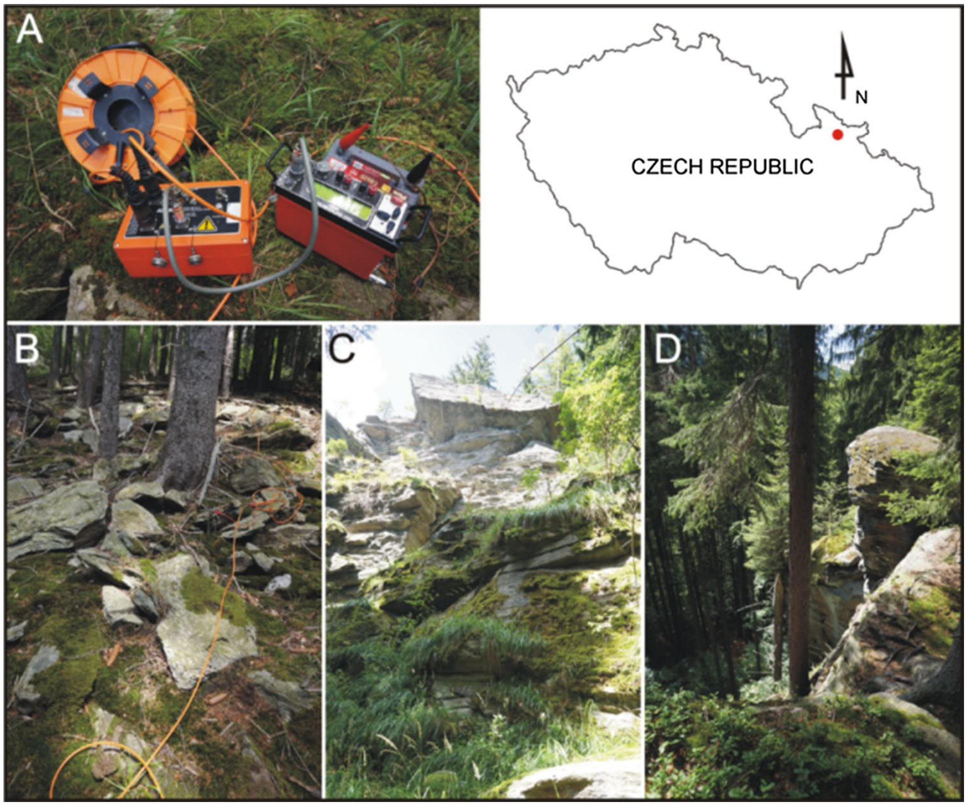

Fig. 1 Localisation of the Skalní Potok Nature Reserve in Czech Republic. **a** ABEM Terrameter LUND Imaging System, **b** ERT profile, **c**, **d** examples of cliffs

at the surface, but also included the subsurface zone (Harris et al. 2009). Unlike the endogenous fractures that create a repetitive spatial system unique for a particular rock mass weathering, the exogenous cracks are generally characterised by irregular shape and instability of directions (Liszkowski and Stochlak 1976). The successive discharge of the weathered material in the periglacial climatic conditions in the area with limited vegetation led to the preservation of the most resistant to deep weathering outcrops with poorly developed divisibility of the rock.

The presence of bare surfaces under the influence of high climatic variability, including the activity of water and/or ice, constantly shaped the morphology of the mountain slopes and valleys regardless of the type of rocks that built them (Migoń and Lidmar-Bergström 2001; Traczyk and Migoń 2003; Lowe and Walker 1997). As a consequence, it resulted in a rich variety of landforms (Pánek and Kapustová 2016) which currently are the Pleistocene relics (Demek 1968, 1969; Křižek 2016). Therefore, in view of the above, direct measurements of cracks have been carried out to determine the role of lithology and rock structure occurring in the Skalni Potok Reserve in the relief formation. The structure of the residual frost-riven cliffs was study using the electrical resistivity tomography (ERT).

Geophysical methods such as the electrical resistivity tomography (ERT), the ground penetrating radar (GPR) or the seismic refraction tomography are used in the study of cliffs. Deparis et al. (2011) used geophysical methods such as seismic, electric and electromagnetic to study three limestone cliff sites located around Grenoble (French Alps). Authors underlined that applicability of geophysical techniques depends on the site characteristics, but they, however, significantly contributed to delineate the geometry and the volume of the potential unstable blocks. Jeannin et al. (2004) using geophysical methods (GPR, ERT and seismic) mapped the fractures seen on the cliff, delineated the geometry of potential unstable rock mass and determined its volume. Examples of such research can be found in the literature, but it should be noted that they also concern the study of sea cliffs (Leucci 2007; Udphuay et al. 2011; Van Dam 2012).

Methods

In the studied area, in the period from August to September 2017 and from July to September 2018, geomorphological mapping and geological mapping were performed to identify the highland forms. On the basis of visible outcrops and available exposures, such as frost-riven cliffs and isolated rocks, the rock types were recognised. The fracture measurements were taken on available rocks and cliffs. The strike azimuth and the dip angle were measured by a geological compass on randomly selected cracks in the exposure walls. From 30 to 100, cracks were measured at each measurement point. Their number is associated primarily with the availability of the studied outcrops and the uneven distribution of the crack set assemblies in the measured morphological forms. This allowed to obtain a representative sample and the measured dip azimuth as well as to determine the directions of main crack systems occurring in the studied rock mass. In order to illustrate the subsurface structures of rock, the electrical resistivity tomography (ERT) was used as a non-destructive and non-invasive method of measurement (Schrott and Sass 2008; Akca 2016; Amini and Ramazi 2016; Kowalczyk et al. 2017; Szczygieł et al. 2019). The measurements were taken with the ABEM Terrameter LUND Imaging System applying the Wenner–Schlumberger array. Three profiles P1 (725 m a.s.l.), P2 (690 m a.s.l.) and P3 (680 m a.s.l.) were made with the spacing of electrodes at 2.5 m, 4 m and 5 m, respectively, which were dictated by area conditions (Fig. 2). The profiles were made on a steep, southern slope of the valley in accordance with the counter line. The interpretation was carried out using the RES2DINV software. As a result, two-dimensional (2D) geoelectric cross sections were obtained (Loke 2003).

Results and discussion

In the area of the Skalní Potok Nature Reserve, there are cliffs formed in the gneiss with the following orientation: NW–SE (3 cliffs) NNW–SSE (6 cliffs), NE–SW (1 cliff), W–E (1 cliff) and WSW–ENE (4 cliffs). Their orientation is related to the occurrence of primary discontinuity zones. The measured crack systems with NNE–SSW and NW–SE directions do not explain the directions of all cliffs within the reserve, but it should be noted that the measured cracks are almost vertical cracks with a dip angle above 70° (Liszkowski and Stochlak 1976). The analysis does not take into account cracks resulting from primary partibility (schistosity). Another factor affecting their current location is quartz veins and lenses occurring in the studied massif, which undoubtedly increase the resistance to weathering processes (Schön 2015). In the highest parts of the valley, the cliffs with WSW–ENE and W–E orientation exist, where their formation is very likely determined by bedding, not vertical cracking. These cliffs most probably represent the primary surface being the oldest forms within the valley. The development of forms within the study rock mass, apart from the orientation of cracks, was also influenced by the processes of selective mechanical weathering (frost), especially during the impact of the cold periglacial climate. The relief of the Hrubý Jeseník mountain range is represented by numerous diverse landforms regardless of the type of rocks that build them. The obtained results from the Skalni Potok Reserve were compared with the measurements of cracks in the gneissic cliffs located within the Medvědí vrch (1216 m.a.s.l) (Stan and Stan-Kleczek 2014). Two systems of vertical cracks with the directions NW–SE and NE–SW also occur in this massif. It should be stated that the comparison of the crack directions in both locations is compatible with predicting cliffs for weathering in these directions. On this basis, the authors conclude that the NW–SE and NE–SW fracture systems are gneiss dominant directions in this area, and thus, they are responsible for the current valley morphology. In order to identify subsurface discontinuity zones within the gneissic cliffs, measurements of ERT were taken.

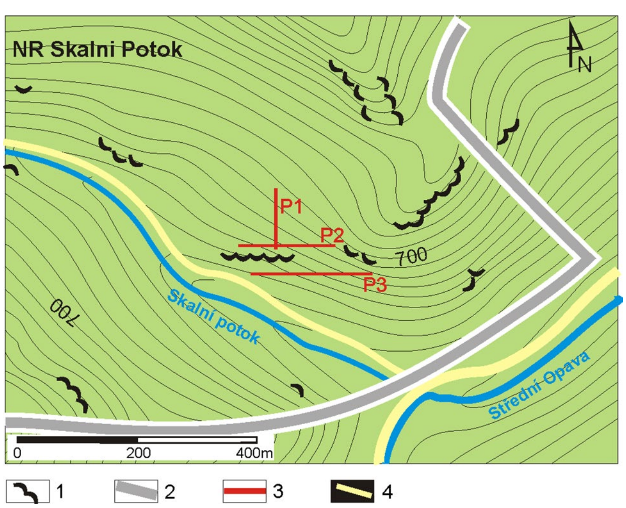

Fig. 2 Location of ERT profiles: 1- frost-riven cliffs, 2- the boundary of the Skalní Potok Nature Reserve, 3- ERT profiles, 4- roads

The first, near surface layer with the electrical resistivity from 9 to 12 kΩm (Fig. 3) is a layer consisting of blocks partially filled with air (the middle part of the profile). In the remaining part, loosely packed rock material was stabilised with fine-grained material and partially covered with vegetation. The next layer with the electrical resistivity values from 1.2 to 3 kΩm has a diversified thickness, strongly cracked and is also a layer of infiltration of water initiating further development of erosion processes. The third layer with the electrical resistivity of 4 to 9 kΩm is less cracked. The P1 profile perpendicular to the P2 profile intersecting it at 68 m represents a three-layer rock mass.

The P2 profile made on the roof of the cliff has a two-layer structure of the rock mass (Fig. 4). The first layer with the electrical resistivity from 1.2 to 3 kΩm achieves an average thickness of up to 15 m. The thickness of this layer increases from 120 m, which is related to the thickening of the vegetation cover, in particular woody, which is represented by decreasing electrical resistivity values. The middle part of the profile lens of much smaller resistivity values (0.7–1 kΩm) than the surrounding medium can be noticed pointing to water infiltration. At the beginning of the profile, the electrical resistivity values above 11 kΩm can be observed. They are connected with the occurrence of a fracture of up to 15 cm opening, separating the cliff. The first layer is underlain by a less cracked layer with the electrical resistivity values up to 9 kΩm.

The P3 profile was located parallel to the P2 profile at the foot of the studied cliff. The length of the profile was 200 m and the depth was up to 40 m. The floor of weathered layer was not reached (Fig. 5). Despite the fact that the profile

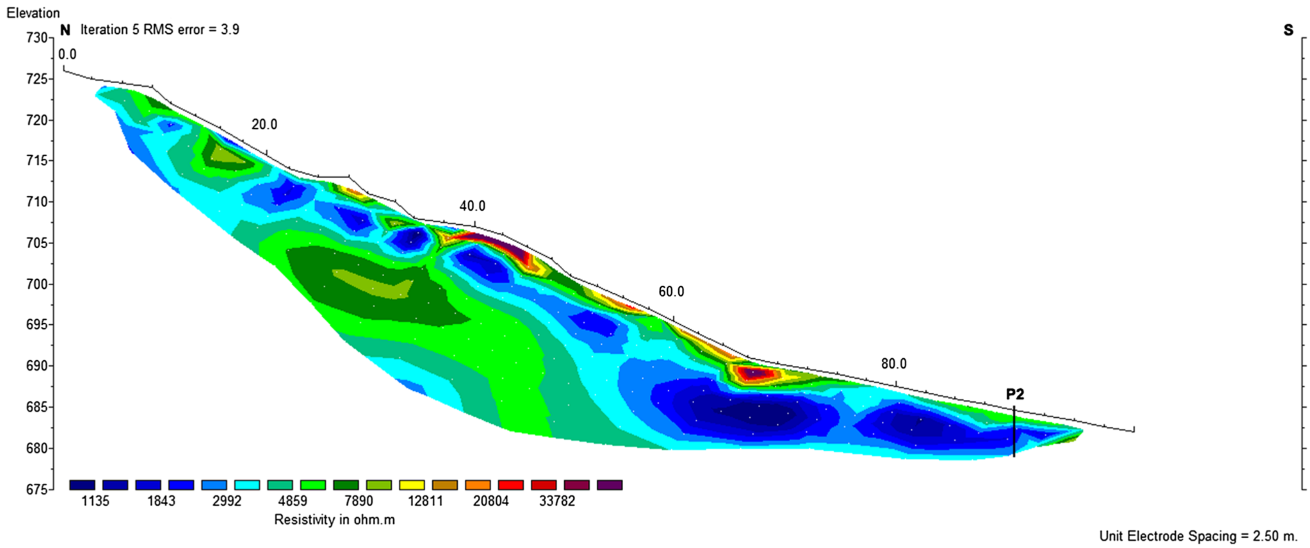

Fig. 3 Electrical resistivity tomography of the profile P1

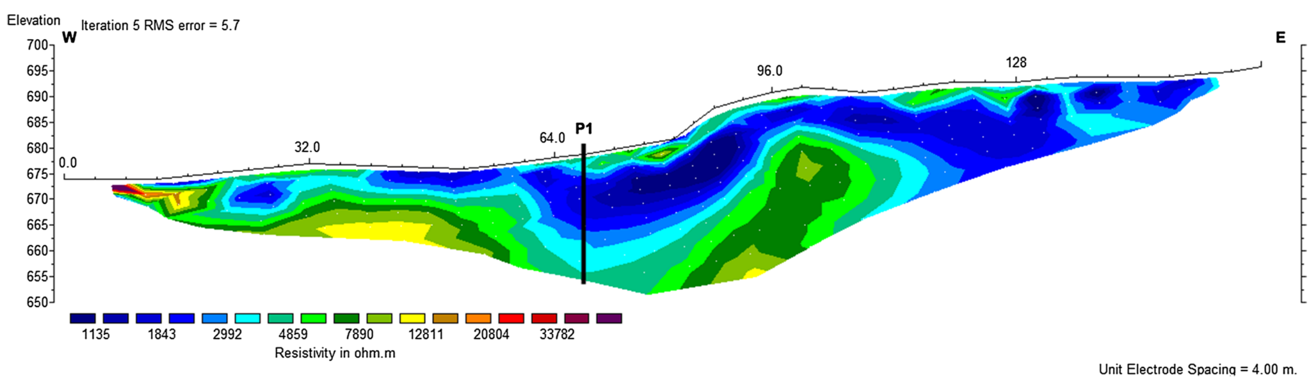

Fig. 4 Electrical resistivity tomography of the profile P2

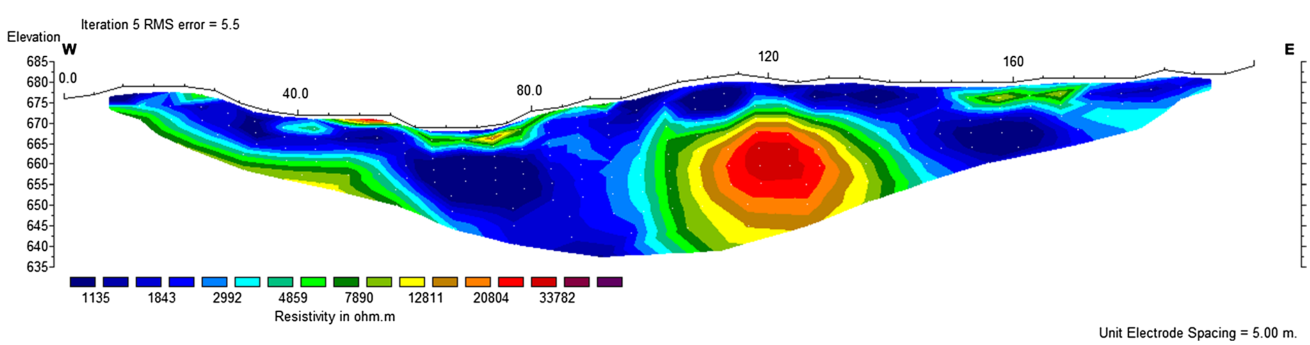

Fig. 5 Electrical resistivity tomography of the profile P3

was carried out at the foot of the slope, the thickness of the weathering cover (regolith) did not exceed 40 cm (compare with Stan and Stan-Kleczek 2014) confirming the high activity of recent slope processes in the studied area. Compared to previous profiles, the P3 profile does not have a layered structure. The layer with the electrical resistivity from 1.2 to 3 kΩm is dominant. On its surface, remains of the 4 kΩm layer are visible as a less cracked layer (see profiles P1 and P2). Similarly, to the P2 profile, the waterlogged places are noticeable as an accumulation of water feeding neighbouring watercourses. In the central part of the profile, the intrusion of the metagranitoid with a high quartz content with the electrical resistivity values above 15 kΩm is most likely recognised. The changes in the measured values of the electrical resistivity on the Skalni Potok cliffs are related to the degree of weathering of the stratum, that is, the compact distribution of cracks and the occurrence of water within the rock layer, as well as the intrusion of quartz intrusions occurring within them (Martín-García et al. 2015). On the P1 and P2 profiles made on the cliffs, the cracks zone has a smaller thickness than at the foot of the cliff, which is a water reservoir transported down the slope. The activation of both primary (tesktural) and secondary (tectonic) areas of discontinuity in directly exposed outcrops depends both on temperature and humidity. The gneiss occurring in the studied area, as a crystalline rock of increased resistance due to the fact that it was exposed to cyclic freezing and thawing during the Pleistocene period (Czudek 2005), significantly reduced its mechanical strength (Rapp 1960) by increasing porosity and microcracks (Le Pera et al. 2001; Ehlen 2002). This led to the fragmentation and increase in the weathering front and, as a consequence, the disappearance of some of the drained outcrops. The evolution of the Skalni Potok landforms did not end with the decline of the Ice Age. As a result of global warming, the decisive factor responsible for the frequency and size of changes within the crack set is the presence of water (compare with the S3 profile) which, in the form of rain (dissolution) or snow and/or ice (microgelivation) (Matsuoka 2001, 2008), plays a key role in contemporary weathering processes shaping the relief of the studied rock landforms.

Conclusion

The electrical resistivity tomography ERT measurements indicated that despite the occurrence of primary discontinuity zones, the reactivated secondary fractures played a decisive role in the evolution of the valley, i.e. the development of the cliffs. The ERT method was not used before in this area in the study of relict relief. This method proved to be excellent in the study of metamorphic rocks with a dense crack system and allowed to determine the depth of the weathering frontage and water infiltration zones. The research of cliffs located within the Skalní Potok Nature Reserve let authors to define the main crack systems (NW–SE and NE–SW), which are responsible for the current valley morphology, confirming the superior role of the crack systems in their formation. Thus, the carried out comparative analysis enables to specify dominant directions of the main crack systems for gneiss in the studied region of the Hrubý Jeseník (compare Stan and Stan-Kłeczek 2014). Studies also claimed that not insignificant in the presence and location of the measured rock outcrops are quartz intrusions that determine the selective way of sharp weathering. It should be remembered that the obtained results are qualitative and it is difficult to determine the exact thickness of the layer or the degree of the cliff weathering, and therefore, it would be worth completing the obtained results with other available information (e.g. drilling a borehole or using a other geophysical method).

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