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The application of the 2D/3D electrical resistivity tomography (ERT) method in investigating the carbonate karst of the Zakrzówek Horst

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Abstract: A characteristic features of the geological structure of the Krakow area are tectonic horsts and grabens. The Zakrzówek Horst is one of the seven horst structures within the Krakow area, located in the south-western part of the area. It is built of Upper Jurassic limestones, where numerous karst caves have been developed. The caves of the Zakrzówek Horst probably form a system of interconnected caves. This hypothesis has been tested in the western region of the Zakrzówek Horst using the electrical resistivity tomography (ERT) method. The investigations were conducted in the parallel profile configuration as well as with the data processing procedure based on the 2D and 3D inversion. The results of these studies are an attempt to locate additional voids as well as fractured zones in carbonate rock mass. The studies confirmed the hypothesis that the Jasna Cave is probably only a fragment of a vast cave system developed within the Zakrzówek Horst. As a result of the research carried out with the ERT method, the most prospective directions for future speleological research have been determined.

Keywords: 2D/3D ERT methods, karst structures, Zakrzówek Horst, Jasna Cave

INTRODUCTION

Karst structures are characterized by a high degree of heterogeneity and considerable spatial variability, which is due to the presence, inter alia, voids and fractured zones. These features are difficult to be detected by conventional geological and speleological exploration. Geophysical methods can significantly help to improve and direct the exploration. The electrical resistivity tomography (ERT) method is widely recognized as the one of most effective one in this respect (Pasierb et al. 2020, Verdet et al. 2020, Pasierb 2021, Amanatidou et al. 2022). Resistivity data are acquired through measurements and processing conducted with the application of two-dimensional (2D) and three-dimensional (3D) techniques. In the case of monitoring tasks, the 4D technique is applied, where measurements are repeated in the time domain (Lapenna & Perrone 2022). In the 2D technique, where measurements are performed along the linear profile it can be difficult to identify the spatial extent of heterogeneities in geological structures (Aizebeokhai 2010, Hung et al. 2019). Therefore, measurements based on the 3D technique provide more accurate and reliable results, especially in the case of inhomogeneities existing under the surface.

In the electrical resistivity tomography method, the classical approach makes use of a 3D array of electrodes placed in a rectangular grid, where data are collected from all available directions

(Loke 2010). Moreover, innovative data acquisition procedures based on the parallel, orthogonal and diagonal profiles arrangements are used in various configurations, e.g., cross-diagonal, horse-shoe and star-shaped and other geometries (Chávez et al. 2014, Tejero-Andrade et al. 2015, Van Hoorde et al. 2017). The above measurements, carried out with the electrical resistivity tomography method in the 3D scheme, are extremely laborious and time-consuming and also need a large number of cables (Aizebeokhai 2010) due to the geometry of measurements. It requires maintaining a fixed electrode spacing as well as the same distances and directions of the profiles. This is possibly the main reason for the low interest and infrequent use of this kind of investigation, especially for commercial purposes.

Therefore, an alternative is the 2D/3D ERT method (another name: pseudo-3D ERT) (Kidanu et al. 2020, Singh & Sharma 2022); in which the measurements are performed in the grid of parallel and/or orthogonal profiles. This method enables a flexible design of surveys, an easy selection of measurement systems, and the ease of adjusting data acquisition to 3D inversion (Torrese 2020, Okafor et al. 2021).

This paper presents the possibility of using the 2D/3D ERT research on karst structures located in the western part of the Zakrzówek Horst.

GEOLOGY OF STUDY AREA

The Zakrzówek Horst is one of the seven horst structures, situated approximately 4 km away from the center of Krakow to the south-west (Fig. 1). It lies within the Skały Twardowskiego Park, which belongs to the Bielańsko-Tyniecki Landscape Park. It was created as a result of Palaeogene tectonic movements (Szelerewicz & Górny 1986, Felisiak 1992). This is a huge tectonic structure having an area of approximately 1 km^2 with a flat plateau, which is an abrasive surface (Gradziński 1972) and is dismembered by a system of stair-stepped fault in its western part (Jędrys & Krajewski 2002). The Zakrzówek Horst is built mainly of Upper Jurassic limestones which in this area are about 225 m thick (Krajewski & Olchowy 2021). They have developed as three lithological types: i) banded limestones, ii) dominant sheet limestones (thick- and narrow-bedded), containing numerous silica concretions, and iii) occasionally, rocky limestone (Gradziński 1962).

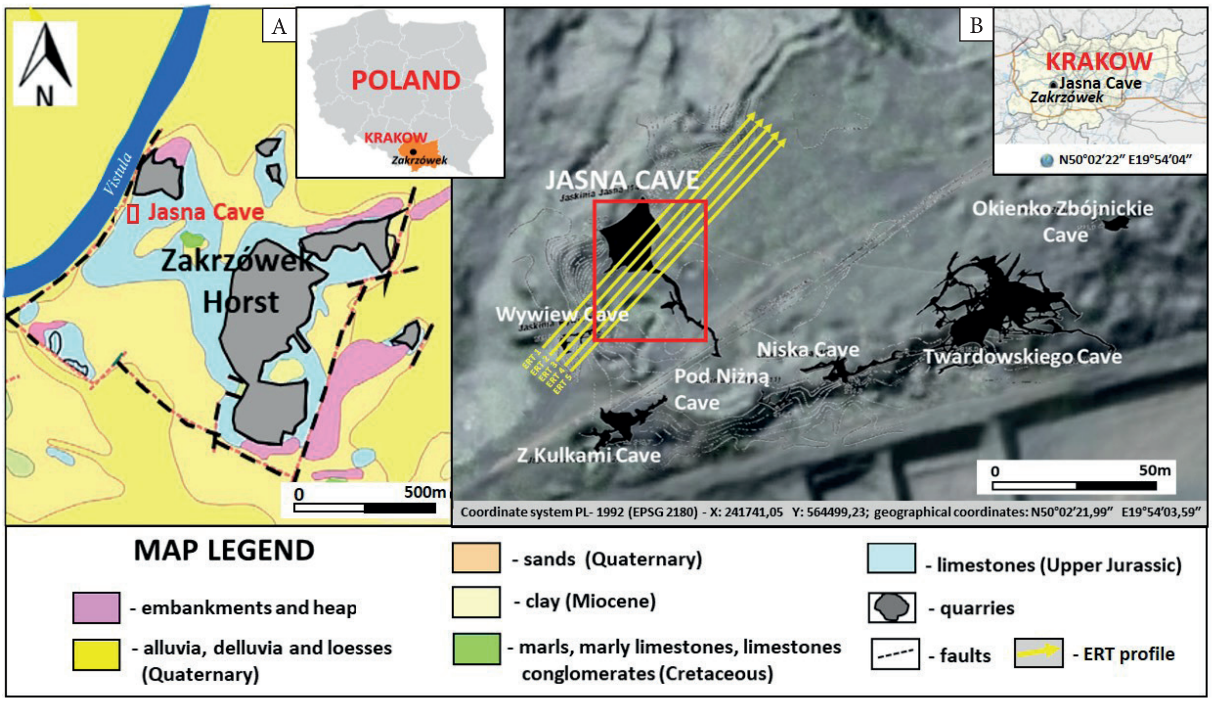

Fig. 1. *The location and geology of the study area above the Jasna Cave (PL-1992 X: 241 741.05 Y: 564 499.23) (A). The yellow lines mark the position of the ERT profiles on the DEM (digital elevation model) background (B) (after Migała 2001, Motyka et al. 2003, Polska.geoportal2.pl, n.d.)*

They are covered by Upper Cretaceous formations, such as marls, marly limestones, and limestone conglomerates (Krajewski & Olchowy 2021) The grabens between the horsts are also filled with Miocene formations represented mainly by clay and covered by Quaternary sediments, like sand, gravel, loams, alluvia, delluvia and loesses (Motyka & Postawa 2004, Sermet & Rolka 2013). In Jurrasic as well as in Cretaceous formations, groundwater occurs in limestone fissures and karst voids. The free water level is located at a depth of a few to several metres below the ground level (Naborczyk & Wacławski 2002).

Within the area of the Zakrzówek Horst, there are dormant quarries and numerous karst caves, such as the Twardowski Cave, the Niska Cave, the Z Kulkami Cave, the Pod Niżną Cave, the Wywiew Cave and the Jasna Cave (Fig. 1B). Caves have developed primarily in those zones that are densely dissected by faults in the NE-SW direction (Jędrys & Krajewski 2002). The caves of the Zakrzówek Horst probably represent a system of interconnected caves. This hypothesis has been tested, inter alia, by the research group of Prof. Jacek Motyka and a team of speleologists headed by Andrzej Górny (Motyka & Postawa 1998). They proved that the markers (NaCl and fluorescein) introduced over the Z Kulkami Cave appeared in the Jasna and Twardowski Caves. Also, geophysical research conducted with the application of the georadar method in the northern region of the Twardowski Cave by the Jędrys & Krajewski team (2002), confirmed the assumption of the existence of a vast karst system in this part of the horst. In order to verify the above hypothesis, as well as to more fully explore the bedrock and the existing karst systems, geophysical investigations using the electrical resistivity tomography (ERT) method were conducted in the western part of the Zakrzówek Horst.

The investigated area is located above the Jasna Cave, whose entrance lies within the western edge of the horst at the bottom of the rocks, on the side of the Vistula River. On the surface, numerous karst forms are visible, mostly sinkholes and funnels with a depth of 1–2 m (Fig. 1). The Jasna Cave is connected with a network of karst channels supplied by the water from the Vistula River, which was observed during the flood of 1997 when the bottom of the cave chamber was flooded with water. The cave has developed in the Upper Jurassic bedded limestone, and the entrance to the cave has developed in chalky limestone, which blends into knobby limestone towards the top. Karst caves formed in this type of limestone are rare (Krajewski 2001). Apart from the layers of silicate blobs in horizontal fissures and interbedding fissures, on the cave walls, there are anastomosis channels. According to the explorers (Górny et al. 1997, Krajewski 2001, Szelerewicz & Górny 2013, Krajewski et al. 2016), the cave is 82 m wide, and the opening is located at a height of approximately 210 m above sea level. The entrance is approximately 13 m wide and 5 m high. In the rear part, the main chamber changes into a tight channel. It is 40 m in length. Approximately in the middle of the channel length, corridors branch off, ultimately changing into narrow fissures. At the end of the main channel, there is a chimney blocked by large boulders. The cave floor is overlain by stone rubble and large limestone boulders that have fallen off the cave roof. This is one of the reasons why the non-invasive, surface electrical resistivity tomography (ERT) method was used to determine the shape of the Jasna Cave.

ERT SURVEY AND DATA PROCESSING

In measurements using the ERT method, the basic parameter is electrical resistivity of rocks (Loke 2010). Electrical resistivity values are related to lithology, water saturation, porosity, pore connectivity, permeability, clay content, fluid/water nature and are used to map the subsurface and identify the geological structure and properties of the medium, e.g., location of sinkholes, cracks, voids, groundwater, etc. (Zonge 1972, Everett 2013). The ERT measurements are performed in successive sequences along a particular profile, each time increasing the electrodes spacing, thereby increasing the depth range of the method. Resistivity data are registered using complex combinations of current and potential electrode pairs arranged along the measurement profile. In the presented investigations, the electrode array was designed to enable data interpretation with the 3D inversion method. To this end, five parallel

94-metre-long profiles were run above the cave, at a distance of 4 m. Roll-along mode was used to increase the profile length. The profiles ran from NE to SW perpendicular to the cave axis. Due to difficulties in placing straight profiles along the edge of the escarpment above the cave entrance and the negative impact of the proximity of the escarpment edge, causing disturbances in the current flow, the profiles were moved away from the escarpment above the cave entrance by 7 m. The dipole-dipole array was used because it can obtain a higher data coverage than standard arrays, such as the Wenner array or Wenner–Schlumberger array (Loke 2010) and it is regarded as having the highest horizontal resolution and a satisfactory vertical resolution (Dahlin & Zhou 2004, Szalai et al. 2009). The ERT measurements were performed with the standard electrode spacing of $\Delta x = 2$ m, lengths of current and potential dipoles $a = 1, 3, 5, 7, 9\ \Delta x$, whereas the separation rate n, being the ratio of the distances between a current dipole and a potential dipole was equal to $n = 1, 2, 3, 4$. The measurement error was assumed at a level of 2%, which mean that observations with a standard deviation error of more than 2% were repeated or discarded. The ERT survey was carried out using an ARES equipment (Gf Instruments). To optimize the processing parameters, the 2D inversion process was carried out using the robust data constraint option (L_1 norm optimization), which tends to create models with a considerably more distinct and straighter boundary between media characterized by different resistivity values (Loke et al. 2014), which can be expected in karstic environments. The applied method (using the Res2Dinv program, Geotomo Software, now Aarhus GeoSoftware), minimizes the absolute difference (Abs – absolute error) between the measured and calculated apparent resistivity values (Loke et al. 2003, Pasierb 2015). Before the inversion process itself, the "exterminate bad datum points" option was used. The refinement of the mesh model with widths of half the unit spacing was used due to large changes in resistivity near the surface. An extended model of rectangular shape with the blocks up to the edge of the survey line with two nodes between adjacent electrodes was also assumed. The option to reduce the effect of the side block was also selected, which limits the impact of very high or very low resistivity values at the sides of the model. The topographic adjustment was also introduced, based on the data from the RTK GNSS measurements and digital elevation model (DEM). The generated Abs error was no more than 4.3% for the maximum of seven conducted iterations. The files in the 2D format were converted into one data file in the format used in the 3D inversion process, and a full inversion program Res3Dinv was used. In this case, the robust inversion method was also applied to the reconstruction of the 3D resistivity-depth models below the surface. The matching error (Abs error) was 9.36%. The error obtained is partly attributed to the error characteristics of the parallel 2D data sets collated to the 3D data set. The amount of error in the 3D model is also affected spacing of the profile lines in relation to the spacing of the electrodes as well as the 3D inversion type used in the data processing (Aizebeokhai & Singh 2013). The Abs errors obtained as a result of the 2D and 3D inversion can be considered as a reliable results under the conditions of the karst bedrock.

RESULTS AND DISCUSSION

The investigations conducted using the electrical resistivity tomography (ERT) method provided: after the 2D inversion, (i) electrical resistivity cross-sections (Fig. 2D, E); after the 3D inversion: (ii) electrical resistivity cross-sections (vertical sections in the X-axis direction (Fig. 2F), (iii) horizontal slices from subsequent depth intervals (up to a depth of 20 m) showing the resistivity distribution on a horizontal plane (Fig. 2A–C); and (iv) a spatial visualization of the image in the form of a 3D model of a karst medium (Fig. 3).

A spatial visualization of a subsurface medium based on the results obtained from the 3D inversion can recently be carried out with the Res3Dinv software (Aarhus GeoSoftware), where model values can be saved in a file with VTK text used by the Paraview 3D plotting package. The results after 3D processing can also be exported to the graphics software Voxler (Golden Software) and, using it, a 3D image visualization (Fig. 3) can be performed. Analyzing the obtained results made it possible to identify the subsurface conditions in the western part of the Zakrzówek Horst.

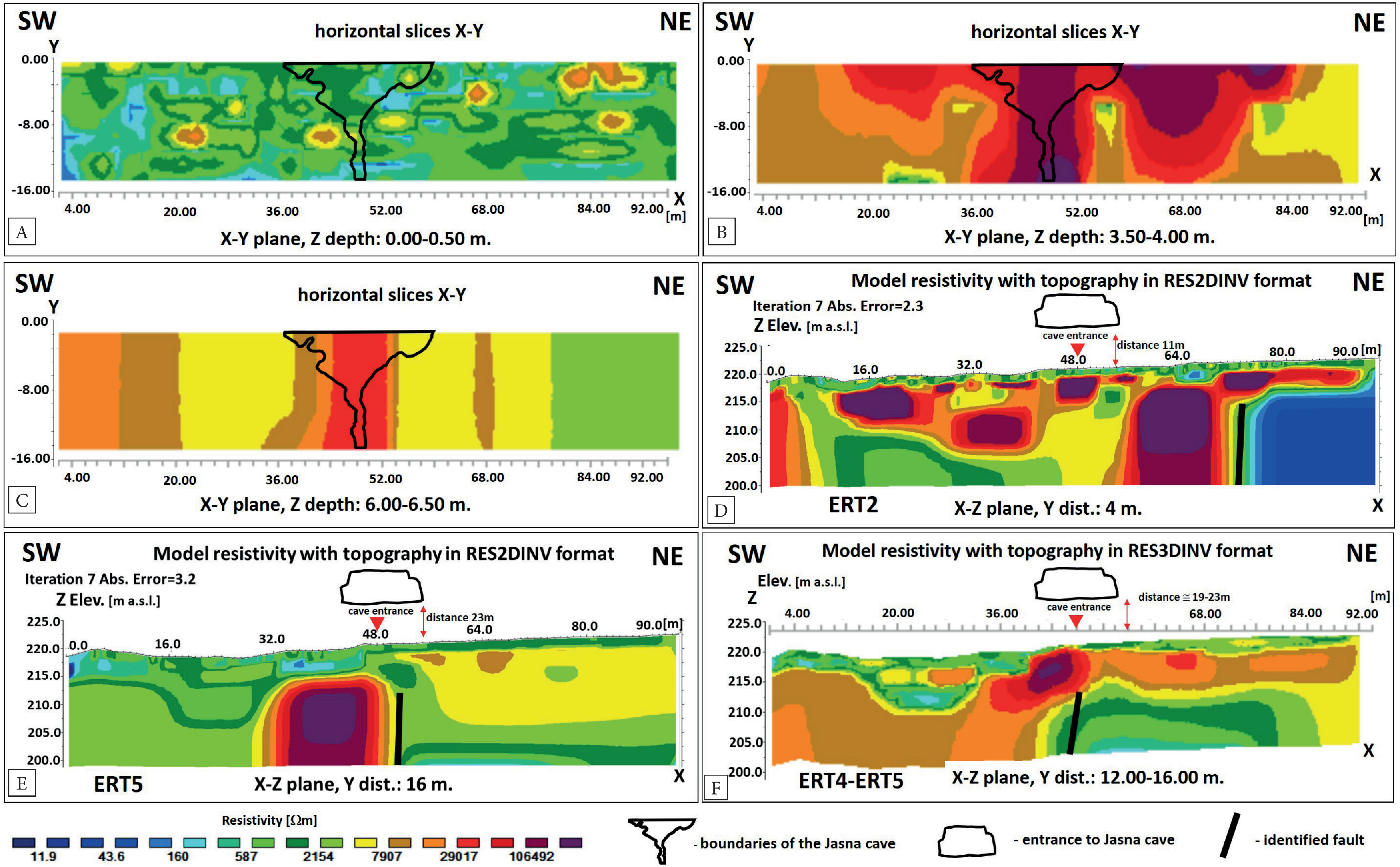

Fig. 2. *Results of 2D and 3D ERT survey: horizontal slices obtained from the 3D inversion from the 0.00–0.50 m depth interval (A); horizontal slices obtained from the 3D inversion from the 3.50–4.00 m interval (B); horizontal slices obtained from the 3D inversion from the 6.00–6.50 m interval (C); ERT2 cross-sections obtained from the 2D inversion (D); ERT5 cross-section (vertical section in the X-axis direction) obtained from the 3D inversion (E); ERT4-5 cross-section (vertical section in the X-axis direction) obtained from the 3D inversion (F)*

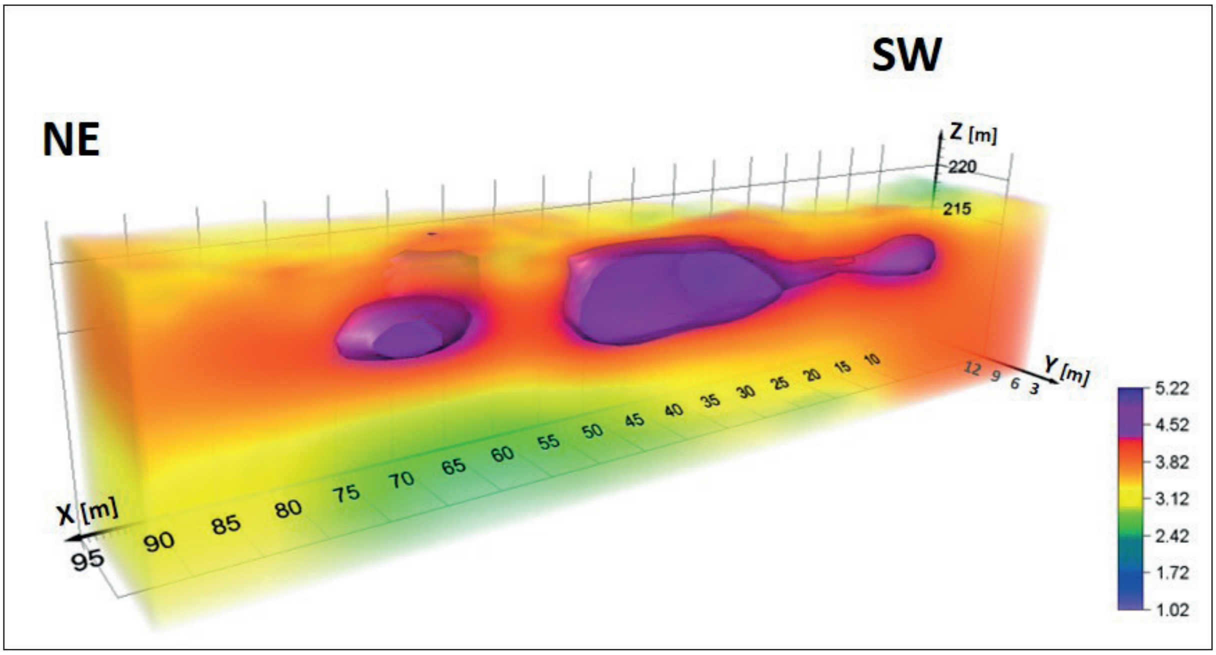

Fig. 3. *The 3D visualization model of the karst structure generated with the logarithm scale of the interpreted resistivity*

The Jasna Cave, located in this area, lies at an elevation between 210 and 218 m, below a 2-metre overlayer. On the basis of geological data (Gradziński 1972, Reynolds 2011, Sermet & Rolka 2013, Krajewski & Olchowy 2021) and the obtained ERT cross-sections (Fig. 2), it can be concluded that the overburden is very differentiated in terms of its lithology and structure. In the near surface layer, there is a considerable diversity of resistivity values, reaching even up to 3000 Ωm (Fig. 2A), which is related to the occurrence in this layer weathered, loesses, and carbonate-silica rubble, as well as lower lying Cretaceous formations developed in the form of marlaceous limestones, marls, limestone conglomerates and clay deposits. Sinkholes and karst funnels occurring in this layer, which are connected with the surface of the area, are visible as high-resistivity anomalies, especially on the horizontal slices from the 0.00–0.50-metre interval (Fig. 2A), which was obtained as a result of the 3D inversion. In the surface karst zones, anomalies of low resistivity are related mostly to the infiltration of precipitation water, which percolates through a layer of loose sediments to the karstified bedrock (e.g., near the 10th and 65th metre of the length of ERT2 profile (Fig. 2D) or near the 38th metre of the length of ERT5 profile (Fig. 2E). The contour of the carbonate bedrock roof occurring at of approximately 218 m is reflected by the morphology of the overlayer. The sinkhole sites correspond to weathering and fissured zone. It is more clearly visible on the ERT4-5 cross-section (Fig. 2F) extracted from the 3D inversion model than in the ERT5 cross-section (Fig. 2E) obtained from the 2D inversion model, where near the 20th metre of the profile length, an over 5-metre lowering of the roof of the carbonate rocks can be clearly seen. Carbonate formations are characterized by high resistivity values in excess of 7000 Ωm. The high-resistivity anomalies of over 29,000 Ωm, visible on the 2D vertical cross-sections (Fig. 2D–F), the horizontal slices from the 3.50–4.00-metre interval (Fig. 2B), and the 3D model (Fig. 3) are probably related to the karst void system and fractures. In the images, it is possible to distinguish an anomaly originating from the main chamber of the cave and additional anomalies – on both sides of the cave, most likely reflecting similar karst chambers, which have not been identified by speleologists due to their lack of any connections with the main chamber as well as the lack of unobstructed passages. It is very likely that one of the chambers registered from the SW side may be the Wywiew Cave, marked on the map (Fig. 1). The entire identified karst structure in this part of the Zakrzówek Horst is probably approximately 60 m wide (the X-axis), up to 8 m high (the Z-axis), and its length exceeds the profile grid (the Y-axis). In Figure 2B, showing the distribution of resistivity on the horizontal slice, the high-resistivity anomaly images the outline of the cave with the surrounding fracture zone. This anomaly disappears at a depth of about 6 m below the ground (Fig. 2C). Almost vertical boundaries between the high- and low-resistivity deposits, visible on the cross-sections (Figs. 2D–F) and the 3D model (Fig. 3), indicate discontinuity zones, thus confirming the existence of the system of "stair-stepped" faults, mentioned in the literature (Jędrys & Krajewski 2002). A particularly distinct boundary can be distinguished on the visible ERT2 profile (from the 70^{th} metre in Figure 2D), where the horst structure probably changes into a tectonic fault trough filled with low-resistivity deposits, according to the literature data – clayey deposits (Sermet & Rolka 2013). Some of the voids visible as high-resistivity anomalies are also developed on faults. At the bottom, there are deposits with lower resistivity values in the 550–4000 Ωm range, indicating more solid and compact limestones.

Interpretation of the obtained images made it possible to distinguish the main chamber of the cave together with the fracture zone surrounding it and the well-developed karst system, determine the probable spatial shape and presumed dimensions of the examined part of the karst structure, as well as to analyse the conditions within the investigated medium.

CONCLUSIONS

The electrical resistivity tomography (ERT) survey has provided new data on the karst structure of the Zakrzówek Horst. The investigations of the carbonate karst of the Zakrzówek Horst using the 2D/3D ERT methods allowed to identify probably additional chambers and voids beyond the main chamber of the Jasna Cave, which have been as yet inaccessible for explorers and may now provide prospective directions for their future research. The structure of the near surface layer using the ERT method was also identified. The depth boundaries between the overlayer and the bedrock, as well as between the lithologically differentiated layers were identified. The investigations enabled the identification of the contour of the carbonate bedrock roof and locating fissured zones. Moreover, the fault zones that confirm the tectonic character of the structure, as well as the boundary between the north-western part of the horst and the tectonic trough filled with clayey soils were determined. The 3D inverse resistivity models obtained from these studies are considered reasonable. The 3D image of the medium enabled to contour of the probable karst structure shape along the orthogonal horizontal axes (X, Y) and the vertical axis (Z). The 3D investigations based on the technique of assembling parallel 2D profiles and converting them to create 3D profiles are an alternative to classical 3D studies in the case of problems with data acquisition and processing. As a result of the ERT investigations, the main directions for future speleological explorations were indicated, aimed at reaching the discovered voids. The hypothesis that the cave Jasna is part of the larger void system in Zakrzówek Horst and might be connected with the other caves located in the study area seems to be highly probable.

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