Surface geophysical surveys and LiDAR DTM analysis combined with underground cave mapping – an efficient tool for karst system exploration: Jaskinia Niedźwiedzia case study (Sudetes, SW Poland)

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Abstract—**The paper presents results of last studies in karst area of Kleśnica valley in the Sudetes (SW Poland), known for spectacular discoveries of new cave passages in 2012–2014. We used airborne laser scanning data (LiDAR based DTM 1×1 m) and geophysical measurements (ground penetrating radar and 2-dimensional electrical resistivity tomography), combined with detailed underground mapping, representing a new multi-facet approach focused on the examination of karst voids distribution in Kleśnica valley. The confrontation and comparison of spatial data from different measurement techniques allowed us to determine the range of crystalline limestones and distribution of karst voids, including the voids previously unknown and not explored by speleologists.**

I. INTRODUCTION

Niedźwiedzia (Bear) Cave with entrance location at 50°14'03"N, 16°50'03"E, discovered on 14th October 1966, belongs to one of the biggest cave in Poland, at the same time being a leading one within the Sudetes Mts. (SW Poland). Since the 1983 middle level of karst voids might be reached by tourists, and its surrounding is protected within a natural reserve. For last tens of years, Kleśnica basin and Niedźwiedzia Cave within, have been a subject of intensive geological, geomorphological, hydro-geological and geophysical research, e.g. [1, 2, 3, 4, 5, 6]. Last few years have brought new facts, being an impulse for a new chapter in cave area research. During the years, 2012–2014 speleologists from the Wrocław Caving Section explored 1979 metres of new cave passages, with some spectacular speleothems inside (e.g. *Mastodont Hall* and *Humbaki Hall*). In this period underground cave passages were re-examined, resulting in new high-precision cave map [7, 8]. Simultaneously since 2013 land surface airborne laser scanning (ASL) data are available for Poland and distributed by Documentation Centre of Geodesy and Cartography. The LiDAR data with density of 4–6 points per square metre and vertical accuracy ≤ 0.15 m allow building digital terrain model (DTM) with a resolution of 1×1 m, making field work precise and convenient. Moreover new geophysical equipment is available, which gives an opportunity for leading a high-resolution near surface surveys. With this study, we present a new multi-facet approach focused on the examination of karst voids distribution in Kleśnica valley (Śnieżnik Massif). We combined electrical resistivity tomography (ERT), high-resolution DTM data and cave underground mapping.

II. METHODS

Geophysical ERT works done during spring and autumn seasons 2014, have been preceded by ground penetrating radar (GPR) study, which is commonly applied approach, e.g. [9, 10, 11, 12, 13]. Shallow GPR sounding of geological basement was made with 250 MHz shielded antenna for eight profiles located perpendicularly to the ridge axis of Mt. Stroma (1166 m a.s.l.). Next, we conducted 8 ERT profiles, 5 of them oriented perpendicularly to Kleśnica valley, last three lengthwise to this axis (Fig. 1). Profiles length range from 265 to 596 metres made with Wenner-Schlumberger electrode array and 5 m spacing between electrodes. ERT measurements were led over known karst voids, newly discovered parts as well as further to the south in the area of unknown underground structure.

We referenced all geophysical profiles with two GPS receivers and precision of 3–5 m and 0.5–1.5 m respectively

In: Geomorphometry for Geosciences, Jasiewicz J., Zwoliński Zb., Mitasova H., Hengl T. (eds), 2015. Adam Mickiewicz University in Poznań - Institute of Geoecology and Geoinformation, International Society for Geomorphometry, Poznań

(differential GPS). Subsequently we used high-resolution LiDAR based DTM image for crystalline limestone identification (Fig. 2), which form unobvious slope micro features, mainly in the contact zone of mica schist and karstic rocks [14]. Topography data also allowed integration with ERT

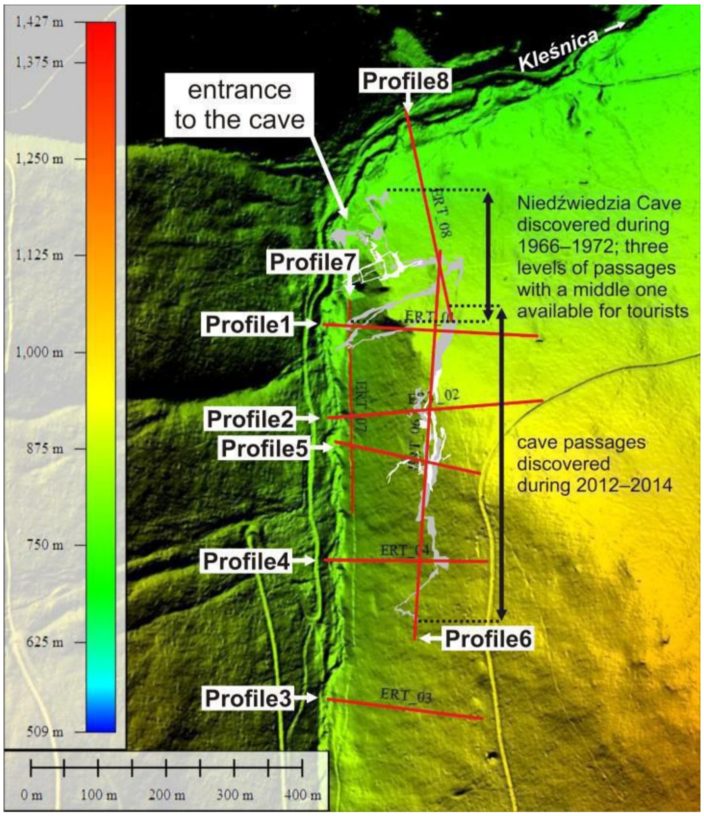

Figure 1. Electrical resistivity tomography profiles in the Kleśnica valley.

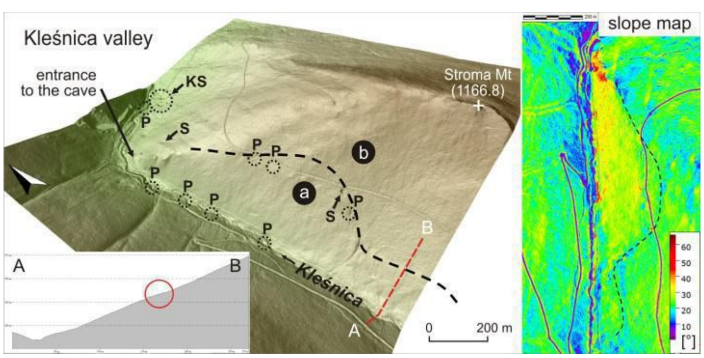

Figure 2. DTM analysis for detection crystalline limestones range on slope surface in the Kleśnica valley: a – crystalline limestones, b – mica schists and paragneisses, KS – karst spring, P – ponor zone [1], S – sinkhole.

measurements and latter spatial interpretation. We computed geophysical data with RAMAC Ground Vision 2 (MALÅ Geoscience) and RES2DINV (Geotomo) software for GPR and ERT respectively. We applied SAGA GIS (by O. Conrad) and MicroDEM (by P. Guth, PETMAR Trilobite Breeding Ranch) software for DTM analysis, and Voxler 3 (Golden Software) for three-dimensional visualising of geophysical and topography data. We used electronic cave surveying device (Leica Disto) with millimeter accuracy laser measurements feature for underground mapping, with magnetic declination correction included [8].

III. RESULTS & RESEARCH PERSPECTIVES

Geophysical tomograms revealed existence of three levels of karst voids in the Niedźwiedzia Cave, being in accordance with previously reported data (Fig. 3). First horizon appears at the reference level of modern Kleśnica river valley floor. Second one, located higher and further to the east, is located 30–60 m above river floor (a.r.f.), latter one ranging from 70 to 80 a.r.f respectively. Above-mentioned values are of approximate meaning. Furthermore, crystalline limestone lens contains numerous minor karst voids, building highest underground level with still undiscovered passages therein. ERT profiling reached several recently discovered prominent underground features: *Zdzichu Gangway* and *Mastodont Hal*l (profile 1), *Piętrowa Hall* (profile 2), *Humbaki Hall* (profile 5) and *Kutaśnik* (profile 4). On the profile no. 3, located furthest to the east, we unequivocally confirmed existence of unknown karst voids, representing Kleśnica upstream continuation of the Niedźwiedzia Cave system (Fig. 4). Reported passages remain still undiscovered for speleo-

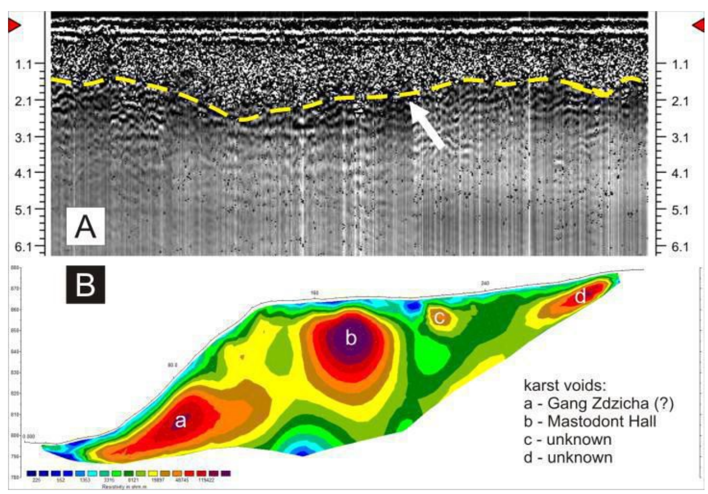

Figure 3. Examples of crystalline limestones imaging by ground penetrating radar (A) and 2-dimensional electrical resistivity tomography (B) – profile 1. Yellow line shows a boundary between solid and weathered rocks.

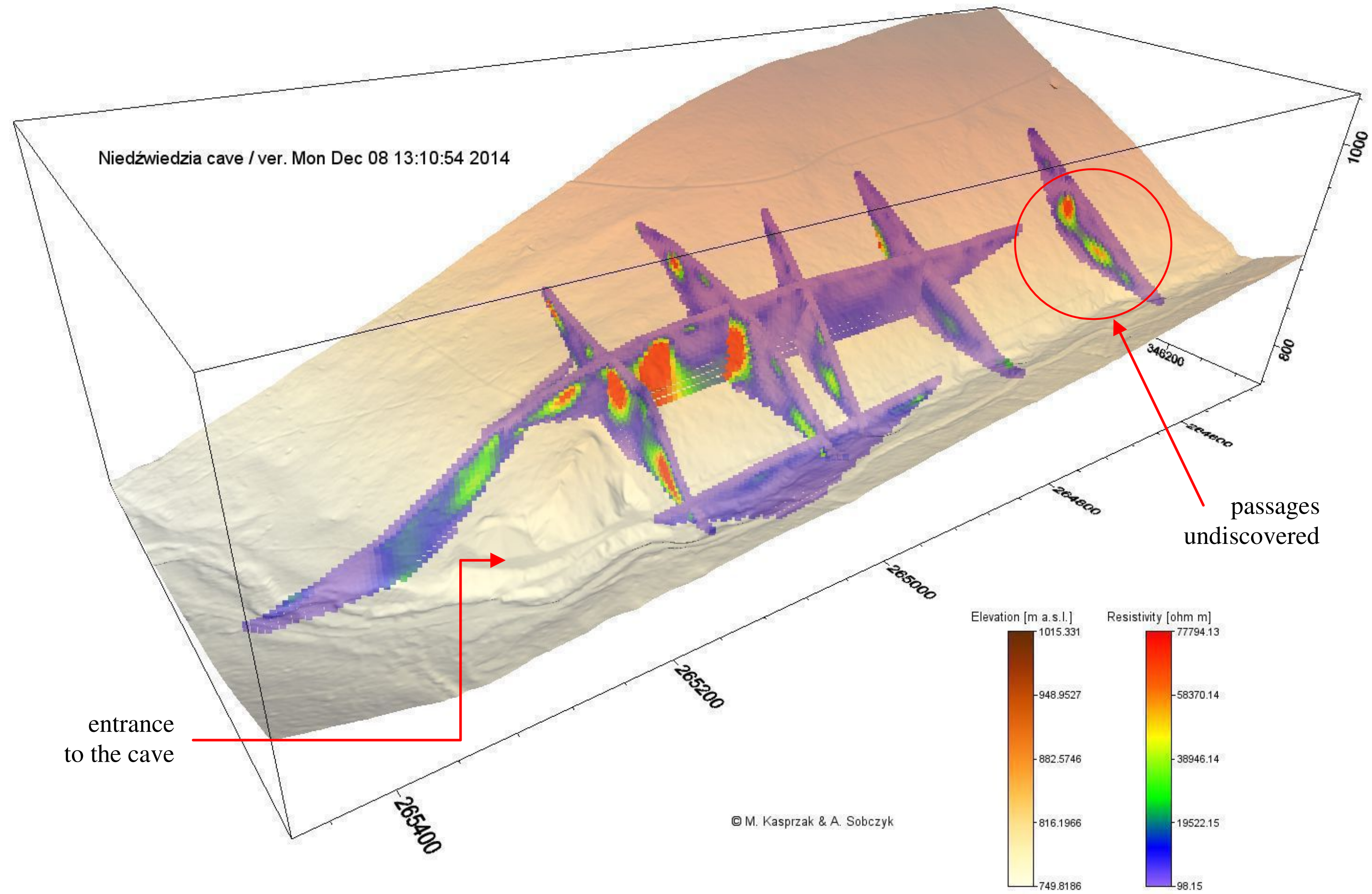

Figure 4. 3-dimensional image of karst voids detected by electrical resistivity tomography in the Kleśnica valley. Fields in ERT profiles, marked with "warm" colors, indicate a location of high resistivity areas – karst voids.

logists. According to tomograms performed, we reached the limestone lens floor, suggesting total thickness below 100 m. Moreover, we suggest its spatial distribution to be re-examined since we investigated the existence of crystalline limestone further to the east and south, out of mapped outcrops known from available geological maps [15, 16]. Presented initial remarks on Niedźwiedzia Cave system supported by multi-facet study, prove theirs high potential in a detailed study of karst areas. Nevertheless further works coupling geophysical methods, geomorphology and underground speleological explorations, should allow better understand origin and evolution of the Śnieżnik Massif in wider regional context [17]. The greatest difficulties of this research are an exploration and mapping inside the cave and slope ≥ 30° during surface geophysical surveys.

ACKNOWLEDGMENT

Fieldworks were partially supported by the project *Rozpoznanie systemu pustek krasowych w dolinie Kleśnicy (Masyw Śnieżnika) przy pomocy tomografii elektrooporowej,* award no 2170/M/IGRR/14, financed by statutory funds for the development of young scientists of Faculty of Earth Sciences and Environmental Management, University of Wrocław. Authors are grateful for the Regionalny Dyrektor Ochrony Środowiska we Wrocławiu for a permission to work in the nature reserve *Jaskinia Niedźwiedzia w Kletnie*. We would like to inform, that

LiDAR data used for this study, have been purchased and used with academic license DIO.DFT.DSI.7211.1619.2015_PL_N, according to the Polish law regulations in the administration of Główny Urząd Geodezji i Kartografii.

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