AN INTEGRATED APPROACH FOR MAPPING THE NEAR-SURFACE SECTION IN KARST TERRAINS

Banush Banushev, Stefan Dimovski, Nikolay Stoyanov

University of Mining and Geology “St. Ivan Rilski”, 1700 Sofia; E-mail: banushev@mgu.bg

ABSTRACT. The proposed integrated approach for mapping the near-surface section in karst terrains combines various geophysical, borehole, and geological and petrographic methods and techniques, including electrical resistivity tomography (ERT), exploration core drilling, macroscopic and microscopic studies of rock samples. The electrical resistivity sections obtained along the surveyed lines are transformed into spatial models of the near-surface geologic structures with an emphasis on the spread of layers and zones with different degree of karstification, characterised by different water saturation and/or water permeability. Data from core drilling, geological and petrographic analysis, and published tables containing values of resistivity for different rock types are used as transformation keys. The proposed integrated approach has been approbated in the karst terrain of a site selected for the construction of a small hydropower plant on the Arda River in the area of the village of Potochnitsa, Southern Bulgaria.

Keywords: geophysical methods, geological and petrographic methods, karst, surveys over karst terrains, Southern Bulgaria.

КОМПЛЕКСЕН ПОДХОД ЗА КАРТИРАНЕ НА ПРИПОВЪРХНОСТНИЯ РАЗРЕЗ В КАРСТОВИ ТЕРЕНИ

Бануш Банушев, Стефан Димовски, Николай Стоянов

[1]Минно-геоложки университет „Св. Иван Рилски“, 1700 София

РЕЗЮМЕ. Предложеният комплексен подход за картиране на приповърхностния разрез в карстови терени използва различни геофизични, сондажни и геолого-петрографски методи и техники, включително електросъпротивителна томография, проучвателно ядково сондиране, макроскопски и микроскопски изследвания на скални образци. Получените по профили електросъпротивителни разрези са трансформирани в пространствени модели на съставните геоложки формации с акцент върху очертанията на пластове и зони с различна степен на карстификация, различна водонаситеност и/или водопропускливост. Като трансформационни ключове се ползват данни от ядковото сондиране, геолого-петрографските определения и таблични стойностти на електричните съпротивления на скалите. Предложеният комплексен подход е апробиран в карстов терен на строителна площадка, определена за изграждане на малка ВЕЦ на р. Арда в района на с. Поточница, Южна България.

Ключови думи: геофизични методи, геолого-петрографски методи, карст, картиране на карстови терени, Южна България.

Introduction

Karst and karst terrains are not only the subject of scientific research, but are also a common objective of detailed studies in engineering practice. Good knowledge of this geological phenomenon helps to find optimum solutions in the fields of construction, extraction of rock raw materials, water resources management, environmental protection, and a number of other human (economic) activities conducted in karst regions.

Our previous experience shows that the method of electrical resistivity tomography (ERT) can be successfully applied for studying the near-surface section in karst terrains. (Dimovski and Stoyanov, 2010, 2016; Stoyanov and Dimovski, 2016; Dimovski et al, 2017, 2020). The ERT method uses standard equipment, optimum measurement arrays, and srecific software (Griffiths and Barker, 1993; Loke, 1999, 2001). The obtained distribution of specific electrical resistivity unambiguously reflects the ionic electrical conductivity in the studied section (Daniels and Alberty, 1966) and on this basis, one can differentiate lithological and tectonic boundaries, areas with different degree of cracking and/or karstification, zones characterised by different level of water saturation, etc. The determination of these boundaries and zones is indirect (fairly accurate) because in the interpretation of the derived electrical resistivity sections, published tables are used most often that contain values of resistivity for the main types of rocks, taking into account their secondary alternation, degree of water saturation and TDS in groundwater.

The proposed integrated approach makes it possible to identify the established boundaries in the near-surface section more precisely, as the interpretative procedure uses data from geological surveys of the specific rock varieties present in the studied area. These data are obtained by investigations accompanying electrical resistivity tomography, including elucidation of the spatial position and distribution of rocks in the geological section, as well as of the contacts and transitions between the separate rock types, exploratory core drilling, and petrographic studies of core samples. The detailed petrographic characteristic is essential for clarifying the composition and the structural and textural peculiarities and thus, for determining the rock type. The effectiveness of the proposed approach is illustrated by the results presented in this article. These results are from the performed studies in the karst terrain of a site selected for the construction of a small hydropower plant on the

Arda River in the area of the village of Potochnitsa, Southern Bulgaria. A similar multidisciplinary approach has been employed for the determination of low-rank hydrogeological units in the volcanic and sedimentary complex near the town of Haskovo, Southern Bulgaria (Stoyanov et al, 2010).

Geological setting

Regionally, the studied site falls within the Rila-Rhodope massif, belonging to the Moravian-Rhodope zone, part of the Alpine orogenic system (Dabovski and Zagorchev, 2009). This heterogeneous tectonic unit includes Precambrian high-metamorphic rocks, Paleozoic, Late Cretaceous and Oligocene granitoids, Paleogene volcanic rocks, and sedimentary rocks.

The region of the studied area and its adjacent territories have a very variegated structure. A large number of geological formations of Precambrian Paleogene and Quaternary age have outcrops in the field (Fig. 1).

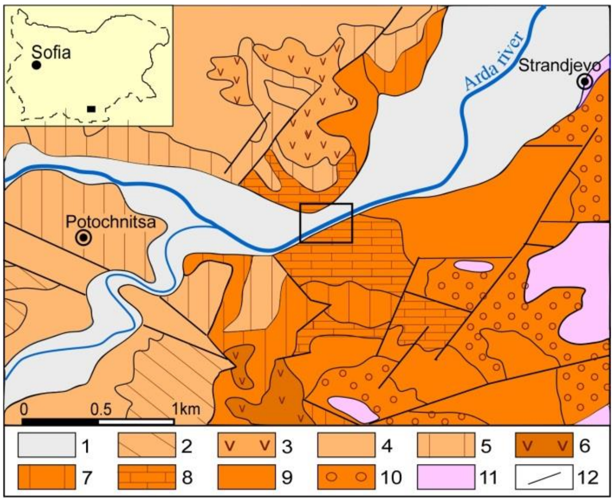

Fig.1. Geological map of the region of the studied site (after Kozhuharov et al., 1992)

1 – Quaternary alluvial deposits; 2-10 – Paleogene: 2 – Lithologic units of the 2nd acid volcanic phase (rhyolite and rhyodacite tuffs, tuffites and a packet of organogenic limestones); 3-4 Lithologic units of the 2nd intermediate volcanic phase: 3 – Andesites, basaltic andesites, latites, shoshonites, 4 – Intermediate tuffs, tuffites and organogenic limestones; 5 – Lithologic units of the 1st acid volcanic phase (acid tuffs, tuffites, organogenic limestones, sandstones and conglomerates); 6-7 – Lithologic units of the 1st intermediate volcanic phase: 6 – Andesites and basaltic andesites, 7 – Intermediate tuffs, tuffites, marls and organogenic limestones; 8 – Marl-limestone formation (organogenic limestones, marls), 9 – Coal-bearing sandstone formation (conglomerates, sandstones, siltstones (aleurolites), clays, coal seams); 10 – Breccia-conglomerate formation (breccia-conglomerates, conglomerates, gravelites, sandstones); 11 – Precambrian: Vacha Variegated Formation (amphibole-biotite, biotite and two mica gneisses, gneiss-schists, schists, marbles, amphybolites, quartzites); 12 – Fault.

The formations, in which the studied site selected for the construction of a small hydropower plant is located, are directly related to the performed survey – these are the Paleogene marl-limestone formation and the Quaternary alluvial deposits. The marl-limestone formation has a thickness of up to 90-100 m and includes organogenic reef limestones and marls (Goranov et al., 1995). It has outcrops along the northern and southern banks of the Arda River in the area of the studied site. This formation is overlying a variegated rock assemblage and in most cases is located normally, with a rapid transition on the materials of the coal-bearing sandstone formation, and is covered by the lithologic units of the 1st intermediate volcanic phase. The alluvial deposits compose the beds and river terraces of the Arda River and its tributaries. They have a thickness of 2-10 m and consist of gravels, sands and clays.

Methods and instruments

The integrated approach for mapping the near-surface section in karst terrains, applied in the studied area, includes a combined usage of the ERT method, exploratory core drilling, and geological and petrographic methods.

The ERT surveys performed along 4 electrical resistivity lines (ERL), located in the floodplain and the terrace of the Arda River (Fig. 2), study the near-surface section down to a depth of 22-25 m. The total length of the surveying lines is 810 m. The field measurements are accomplished using a Schlumberger array with the help of a large number of electrodes connected to a multi-core cable (Griffiths and Barker, 1993). Two sets of 12-core cable with a distance between the electrodes of 5 m (24-electrode array) are used. After finishing each series of measurements, the array is moved forward along the surveying line by a step of 60 m. The registration is achieved with the help of the *Terrameter SAS 300 B* equipment, manufactured by the Swedish company ABEM. The field data are processed with the RES2DINV program (Loke, 2001).

The exploratory core drilling involves the construction of six boreholes (BH), each down to a depth of 20 m. Their precise location is illustrated in Fig. 2.

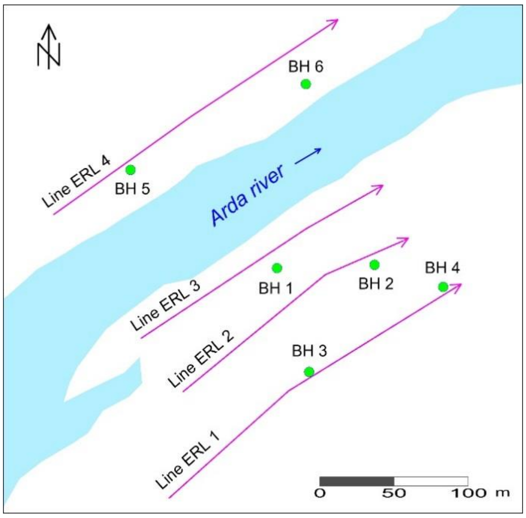

Fig.2. Location of the boreholes and the electrical resistivity surveying lines

The lithology sections and groundwater levels established by the drilling operations are documented in detail. Core samples are gathered for petrographic examinations under laboratory conditions.

The geological and petrographic methods include fieldwork and rock sampling in the region of the study area. Laboratory observations are made with an Olympus binocular stereo microscope that is designed to allow faster adjustment of magnification through the use of a rotating drum to change lenses inside the barrel. Polarised light microscopy is performed using NIKON Eclipse LV100ND. This motorised microscope with episcopic/diascopic illumination enables control of objectives and light intensity from the camera control unit and automatically detects the observation method. The composition and the structural and textural characteristics of the rocks are determined. Photomicrographs are taken with an Olympus Camedia C-5060 Wide Zoom digital camera. The classification and nomenclature of the rock samples is clarified.

The transition from an electrical resistivity section to a geological or hydrogeological model is performed by correlating the solutions obtained by the RES2DINV program with data from exploratory core drilling, the results of the geological and petrographic determinations, and published values of resistivity for different types of rocks (Daniels and Alberty, 1966; Keller and Frischknecht, 1981).

Results and interpretation

Electrical resistivity sections

The electrical resistivity distribution along the four studied lines acquired with the RES2DINV program is illustrated in Fig. 3.

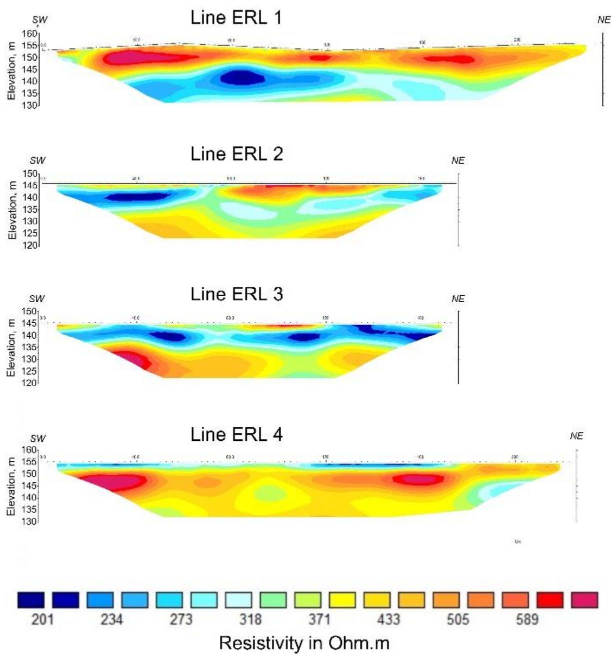

Fig.3. Geoelectrical sections along the surveyed lines

Geological-petrographic characteristics

The rock composition in the area of the studied site includes Paleogene sedimentary rocks (organogenic limestones and conglomerates) and Quaternary deposits (sands, gravels, boulders and sandy clays). The biomorphic (organogenic) limestones are represented by two clearly distinguishable macroscopic types - gray to light gray relatively dense limestones in the bottom part of the geological section and light yellow to yellowish karstified limestones, separated from the former by a layer of conglomerates (Fig. 4a,b).

The limestones in the bottom part of the geological section are thick-layered to massive, biomorphic, with many macroscopically visible organic remnants (Fig. 4a). Minor manifestations of karstification can be observed relatively rarely – single, unevenly distributed caverns, having size of 0.5-1 cm. In some areas, mainly around the cracks, dark brown and black deposits of Fe and Mn hydroxides are present. Microscopically, many organic remnants (about 60%) are found, embedded within a micro-grained calcite matrix. The organic remnants are represented by foraminifera, bryozoa, crinoidea, and mollusk shell sections. The foraminifera are single-, double-, triple- and multi-chambered, having size of up to 1 mm. Their shells are composed of fine-grained calcite in the central parts and micro-grained in the peripheral ones. Sometimes, recrystallised clear calcite is noted in the chambers (Fig. 4c). The bryozoa have chamber-cell texture, and the crinoidea have a well-defined microporous texture. The mollusk shell sections are elongated, with a complex multi-layered texture (Fig. 4e). The clastic minerals are very rare (under 1 %). They are represented by quartz and sericitised plagioclase with a size of up to 0.08 mm. The matrix is composed of micro-grained calcite and fills the space between the organic remnants. About 20-30% of it is recrystallised, with well-formed crystals (up to 0.1-0.35 mm), with perfect cleavage in one or two directions.

These limestones are covered by a layer of conglomerates having massive structure and psephytic texture. Their thickness is between 1.20 and 4.70 m and decreases in the direction of the southeastern bank of the Arda River. They are composed of isometric or rounded coarse fragments of pre-existing rocks (shales, marbles, quartzites, gneisses, amphibolites, granites) held together by a finer-grained clastic matrix and cemented by calcium carbonate.

The conglomerates are covered by light yellow, yellowish to beige karstified biomorphic limestones, with massive structure and biomorphic (zoogenic) texture, locally colored by rust-brown Fe hydroxides (Fig. 4b). A noticeable stylolite structure is observed in some places, with characteristic interlocked, tooth-like surfaces, making a zigzag suture across the face of the stone. The limestones in these zones are denser and less karstified. The maximum limestone layer thickness is on the northwestern bank of the Arda River (7.70 m). The minimum thickness is registered in borehole BH1 and then it increases again. Single caverns, having size of 4-6 cm, are present (in some of them well-formed calcite crystals have crystallised), as well as many smaller ones, with a size of about 1-2 cm. The performed survey shows that these are some of the most permeable rocks in the area. The limestones are composed of organic remnants embedded in fine- to micro-grained calcite, with a size of 0.01-0.1 mm. The organic remnants (foraminifera, bryozoa, crinoidea, occasionally ostracoda and mollusk shell sections) are unevenly distributed. The foraminifera are found ubiquitously in all samples. They are single-, double-, triple- and multi-chambered, from 0.1 to 0.8 mm in size. Their shells are composed of fine-grained calcite, passing to micro-grained in the peripheral parts. Sometimes, one or several larger calcite crystals are observed in the central part of tests (Fig. 4d). The bryozoa are represented by fragments (up to 0.6 x 0.15 mm in size) with a chamber-cell structure, with isometric, spherical and elongated shape. The chambers have rectangular and oval cross-sections. Their walls are single-layered, built of micro-grained calcite. The crinoidea are isometric (0.6-1.3 mm) or elongated (up to 1.5 x 0.25 mm), recrystallised to single crystals, with a distinct micro porous texture (Fig. 4f). The clastic minerals (quartz and feldspar) are very rare, discovered only in a few samples. Their predominant size is between 0.02 and 0.04 mm.

The matrix is micro-grained, in some places recrystallised calcite.

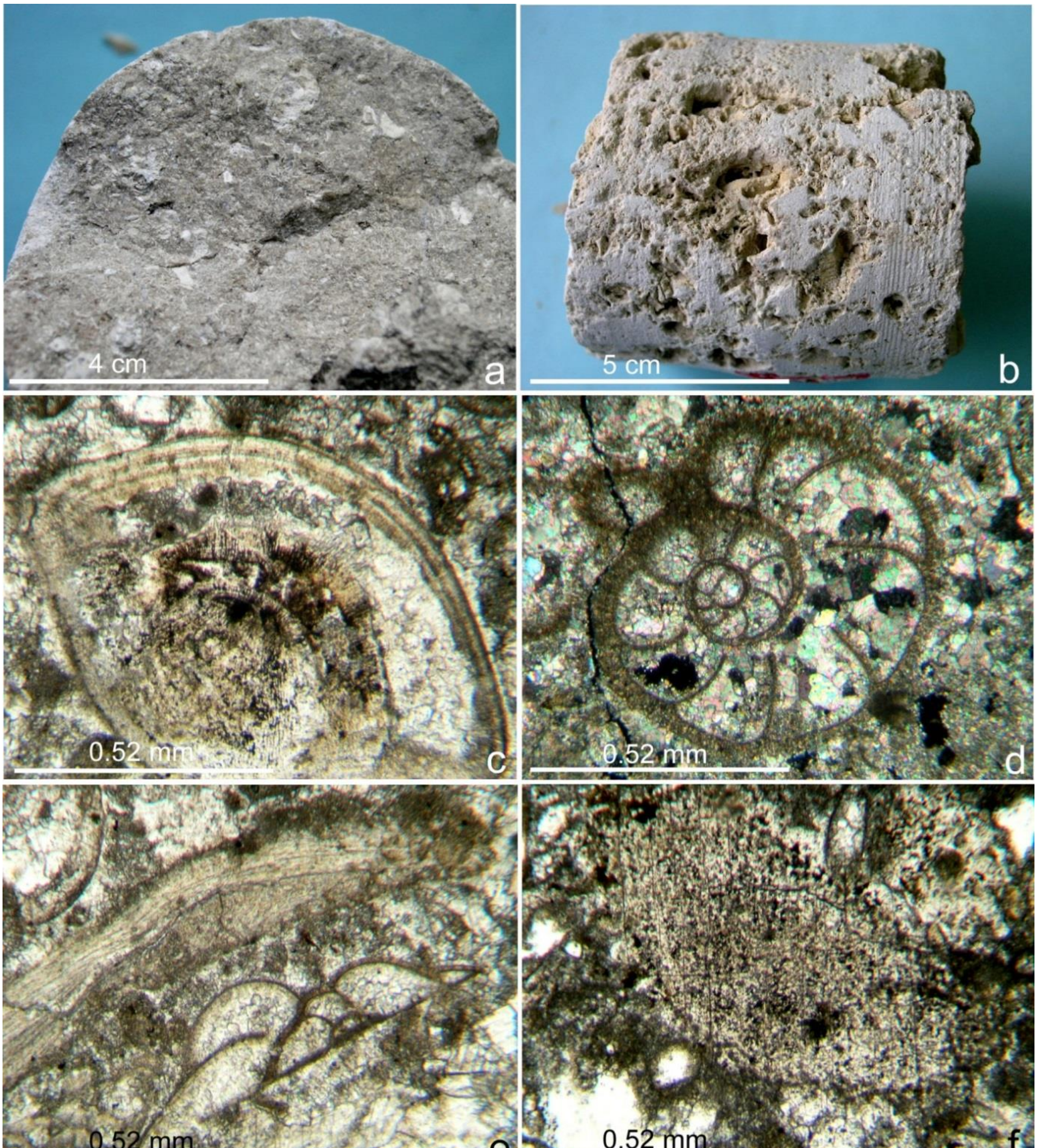

Fig.4. Macro photos and photomicrographs of limestones from the study area. Macro photos (a, b): a – Limestone from the bottom part of the geological section; b – Karstified limestone; Photomicrographs (c-f): c-d – Foraminifera; e – Mollusk shell sections; f – Crinoidea with micro porous texture; c, e, f II N; d +N.

A small conglomerate lens is overlying the organogenic limestones. It has a thickness of 2-2.20 m and is revealed only in boreholes BH1 and BH2. The conglomerates composing this lens and those of the first relatively consistent layer have similar structural and textural features, composition, and properties.

The Quaternary is represented by a variety of deposits – gravels, sands, boulders, and sandy clays. The gravels have a thickness of 1-2.20 m. They are at the base of the Quaternary section and overlay the karstified organogenic limestones.

The gravels are found in boreholes BH5 and BH6, in the northern part of the region, and are not present in the other boreholes. Above them, in borehole BH6, there is a soil layer, and in borehole BH5 – sandy clays. The sands are characteristic for the central part of the area (boreholes BH1 and BH2). Their thickness is between 6.80 and 8.50 m. They contain pieces (gravels and boulders) of various pre-existing rocks. Sandy clays are present in the southeastern part (boreholes BH3 and BH4) and the northwestern part of the region (borehole BH5). They are light brown to dark brown, with inclusions of limestone pieces.

Spread and characteristics of the geoelectrical media. Hydrogeological conceptual model

The electrical resistivity sections obtained by the RES2DINV computer program are transformed into spatial models of the complex geological formations and zones characterised by different degree of karstification, water saturation, and water permeability. The lithologic descriptions and groundwater levels documented during the exploratory core drilling, the results of the geological and petrographic determinations, and published values of resistivity for different types of rocks, taking into account their secondary alterations and degree of water saturation, are used as transformation keys. As a result, xthree main zones and ten low-rank electrical resistivity media (sub-zones) are differentiated in the near-surface section of the study area. They reflect the spread of the main geological formations and outline layers and zones characterised by different degree of karstification, water saturation, and water permeability (Fig. 5).

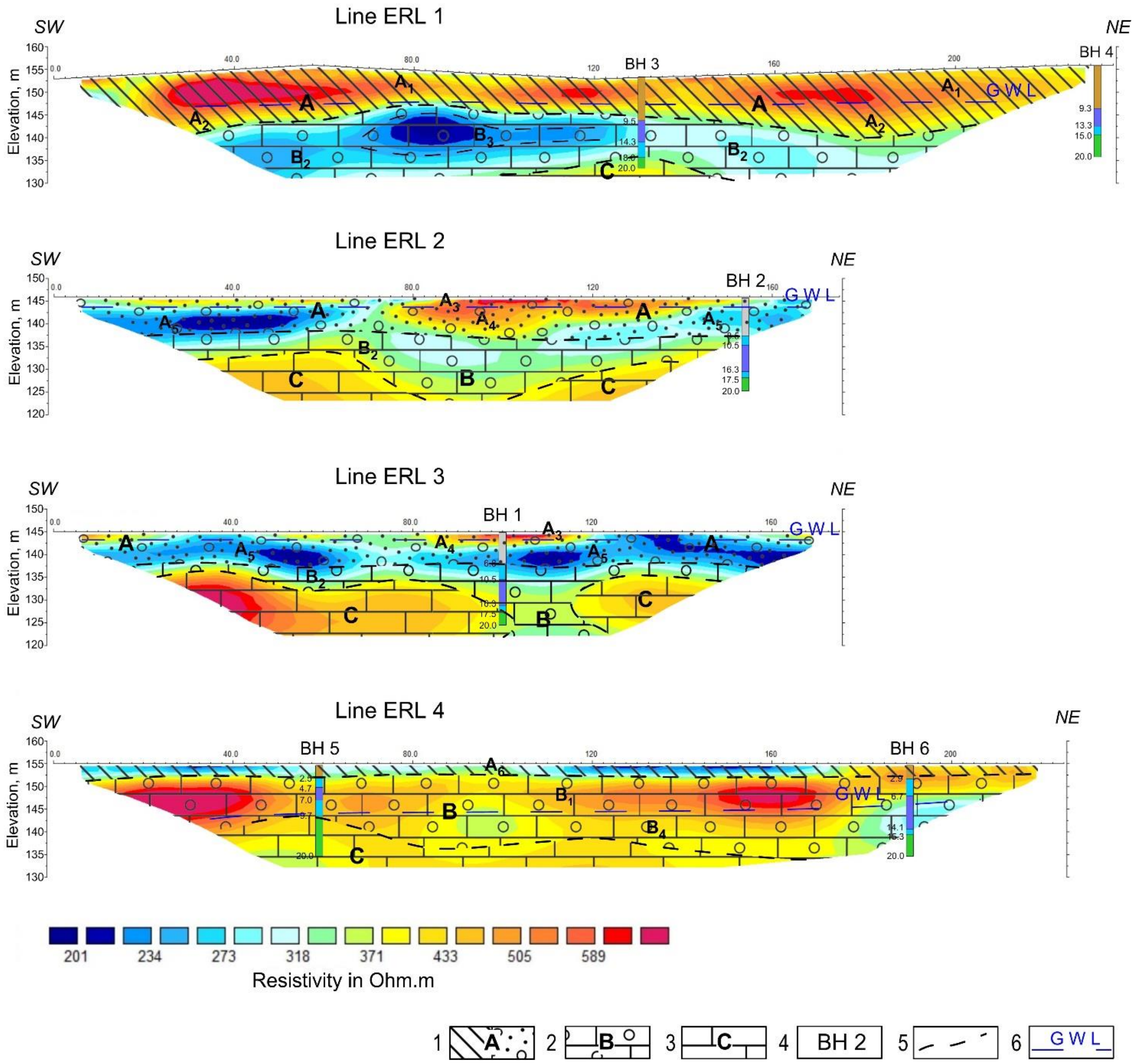

Fig.5. Spread of the geoelectrical media (zones). Hydrogeological units

1 – First electrical resistivity medium (Zone A) – a. Clays, b. Boulders, gravels, sands; 2 – Second electrical resistivity medium (Zone B) – Karstified limestones, conglomerates; 3 – Third electrical resistivity medium (Zone C) – Limestones, relatively dense; 4 – Borehole; 5 – Boundaries between the main electrical resistivity media; 6 – Groundwater level.

The first electrical resistivity medium (Zone A) is typified by electrical resistivity values ranging from 200 to 1000 Ohm.m, rarely over. It outlines the spread of the Quaternary deposits represented by gravels, sands, and clays. Six low-rank electrical resistivity media can be separated in the structure of Zone A – sub-zones A_1, A_2, A_3, A_4, A_5 and A_6.

The second electrical resistivity medium (Zone B) is characterised by a similar range of electrical resistivity values – from 220 to 1000 Ohm.m. Most likely, it maps the conglomerates and the karstified limestones, light yellow to beige. Four low-rank electrical resistivity media can be separated in the structure of Zone B – sub-zones B_1, B_2, B_3 and B_4.

The third electrical resistivity medium (Zone C) has values of electrical resistivity between 350 and 1000 Ohm.m, rarely over. It probably outlines the dense, gray to light gray, limestones at the bottom part of the studied geological section.

The main characteristics of the electrical resistivity media differentiated in the section are presented in Table 1. This table also illustrates the accepted concept for their transformation into corresponding hydrogeological units.

Table 1. *Main characteristics of the electrical resistivity media (zones). Hydrogeological conceptual model*

Zone	Sub-zone	Resistivity, Ohm.m	Lithology	Water permeability	Hydrogeological unit (zone)	ERL No
A	A1	350-1000	Clays, sandy, with inclusions of limestone pieces	low	Vadose zone	1
	A2	350-500	Clays, sandy, with inclusions of limestone pieces	low	Aquitard	1
	A3	250-1000*	Sands, gravels and boulders	high	Vadose zone	2,3
	A4	350-600	Sands with gravels and boulders	high	Aquifer	2,3
	A5	200-350	Boulders, gravels and sands	high	Aquifer	2,3
	A6	220-450	Sandy clays and soil layer	low	Vadose zone	4
B	B1	350-1000	Highly karstified limestones and conglomerates	average	Vadose zone	4
	B2	300-1000	Karstified limestones and conglomerates	average	Aquifer	1,2,3
	B3	220-350	Highly karstified limestones	high	Aquifer	1
	B4	220-500	Karstified limestones and conglomerates	average	Aquifer	4
C	-	350-1000	Limestones, relatively dense	very low	Aquiclude / Aquitard	1,2,3,4

** The high values of resistivity are typical for sectors where gravels and boulders have a predominant presence*

Conclusions

The results of the performed study show that over the entire study area, in the near-surface section down to a depth of 20-25 meters, the limestones are karstified to highly karstified, which presupposes high water permeability in the rocks underlying the very permeable alluvial deposits in the terrace of the Arda River. This was the main argument for not realising the investment intention to build a small hydropower plant in the area of the village of Potochnitsa.

The presented multi-disciplinary research proves the applicability and high efficiency of the proposed integrated approach for mapping karst terrains. The same approach can be successfully used for detailed studies of near-surface sections in regions having similar geological conditions.

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