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APPLICATION OF GEOPHYSICAL INVESTIGATIONS FOR DETECTING THE GROUNDWATER SPRINGING IN THE SIRAČ LIMESTONE QUARRY, MINING FIELD ČELINA

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Abstract

Natural resources, such as rock material, gravel and sand, are the most important mineral raw materials used in construction. Limestone rocks are exploited in the Sirač quarry Čelina, which is then processed into two types of products: crushed stone and stone aggregates. In 2021, during the excavation process, a new feature of water accumulation appeared on the quarry floor (208 m.a.s.l.) and water pools were formed, which tended to flow towards the northern part of the excavation floor. In the same year, an exploratory well with a depth of 50 meters was drilled near the place where the water appeared. Artesian water came to the surface from the mentioned well, which confirmed the presence of groundwater. Given that the inflow of water did not decrease over time, research had to be carried out with the aim of solving the problem so that the quarry could be properly managed as a natural resource of rock material. In addition to geological prospecting, three different methods of geophysical investigation were applied at the end of 2023 to detect the source and extent of groundwater springing: electrical resistivity tomography (ERT), multichannel analysis of surface waves (MASW) and ground penetrating radar (GPR). A fault zone was detected by interpreting the research results, which probably represents a groundwater aquifer. It was determined that the bedding planes of the Triassic carbonate rocks in the deposit have low water permeability therefore the fault zone allows drainage of seepage and groundwater. In addition, impermeable grey-green Triassic sedimentary elements of clastic rocks were identified in the sublayer of Triassic carbonates, which probably represents a barrier to the percolation and movement of groundwater.

Key words

limestone quarry, groundwater spring, exploratory well, geophysical investigations, fault zone.

1 Introduction

The complicated structure of the rock mass with its defects and inhomogeneity and the wide range of its applications cause challenges and problems in rock engineering and construction, which often involve considerations that are of relatively little or no concern in most other branches of engineering (Palmström, 1995). Together with sand and gravels, quarried rocks are essential raw materials for the construction industry. Construction rock material generally refers to rock blasted in quarries and commonly crushed and screened before use. Such rock is used mainly as aggregate for road surfaces, aggregates for concrete and asphaltic concrete, for constructing road bases and sub-bases, and as a basic raw material for producing building materials (e.g. plasters and adhesives).

All of the above also applies to the Sirač limestone quarry Čelina. However, during the exploitation and the progress of mining works in the aforementioned quarry, a problem arose in the water management activities (dewatering the quarry).

Generally, water in quarry excavations collects from precipitation or from groundwater seeping through fractures in quarry walls. Methods for calculating the groundwater inflow into the mining pit have mostly been worked out (Marinelli and Niccoli, 2000; Sobko et al., 2019). In addition to calculations, it is also possible to carry out hydrogeological modelling to assess the groundwater inflow into limestone mining pits (Surinaldu et al., 2011). Quarry operators pump out inflowing water from the excavation to allow for extraction (blasting and recovering the bedrock) on a dry quarry floor. Groundwater seeping into the excavation from water-bearing breaks (fractures) in the bedrock lowers the water table to the depth of the fracture break, releasing the water into the quarry. Except for the fractures, the bedrock prevents water movement (OSSGA, 2016). However, it is a general statement and it should be kept in mind that there are rocks that have a high primary permeability.

Problems with water management in the specific case (Čelina mining field) studied in this paper began in 2021. A new feature of water accumulation in the form of water pools appeared on the quarry floor (208 m.a.s.l.), where the water had a tendency to flow towards the northern part of the excavation floor (Figure 1.). Given that the inflow of water did not decrease over time, it was not possible to continue the management of the quarry as a natural resource of rock material. Such an unfavourable situation could have been prevented by carrying out detailed investigations before the quarry started working. Such extensive studies would assess the local impact on groundwater flow systems. However, considering that research was not carried out before, detailed geophysical and geological investigations were carried out at the end of 2023 to detect the source and extent of groundwater springing. In addition to geological prospecting, three different methods of geophysical investigation were applied: electrical resistivity tomography (ERT), multichannel analysis of surface waves (MASW) and ground penetrating radar (GPR). Input data for research planning was obtained from the results of exploratory drilling with a depth of 50 meters that was performed near the place where the water appeared. Artesian water came to the surface from the well, confirming groundwater's presence.

Figure 1. Panoramic photo of the research floor, 208 m.a.s.l.

The application of geophysical measurements for detecting the groundwater inflow in the quarry has already been recorded in the literature. Abd El-Gawad et al. (2018) applied geoelectrical measurements to detect groundwater seepage in a clay quarry. In order to detect the source and extension of the groundwater seepage, a geoelectrical resistivity technique in the form of vertical electrical soundings (VES, 1D method) was applied. About the above example, the research carried out in the Sirač limestone quarry, and presented in this paper, is upgrade of the application of geophysical research methods for the detection of groundwater inflow into the quarry, considering that several 2D geophysical methods are combined.

2 Methods

2.1 Geological investigations

All available geological reports and data, including satellite photographs, topographical maps, basic maps, legislative boundary maps, etc., were reviewed. Input data for research planning was obtained from the results of exploratory drilling with a depth of 50 meters that was performed in 2021 near the place where the water appeared. Exploratory drilling was performed by Kufner Group (2021) using a wireline system. Wireline core drilling is a special type of core drilling that is most commonly used for mining operations. Wireline coring allows rapid placement and withdrawal of the core barrel within the drill rods therefore the rods do not need to be removed to recover each individual core sample. Geological research was conducted in the field to collect additional data. These data were collected in the form of photographs, measurements and notes. Figure 2 shows the borehole log up to a depth of 25 m and other observations made during exploratory drilling and geological mapping.

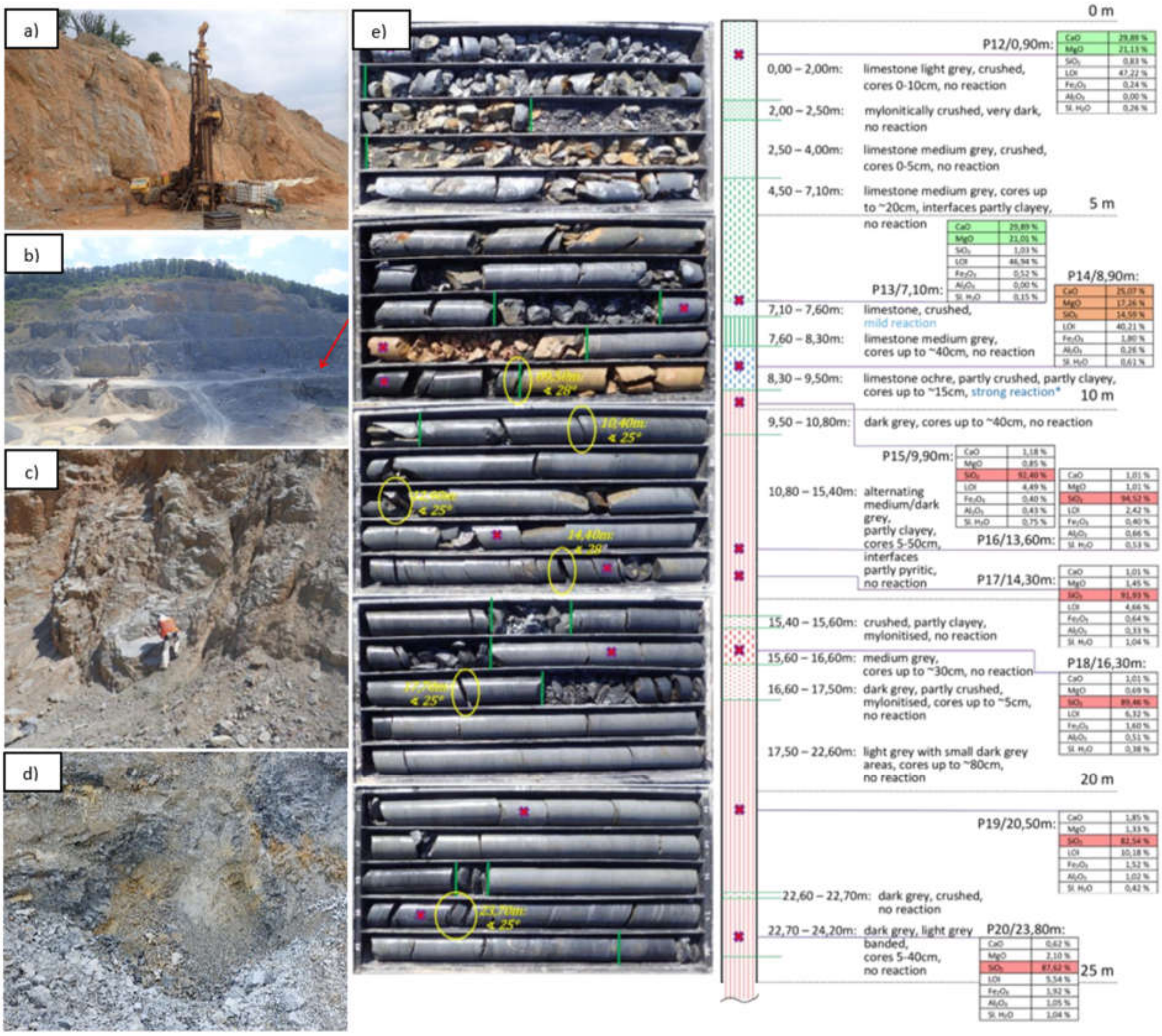

Figure 2. Input data for geological investigations: a) Drilling machine with wireline system; b) Exploratory well position marked with a red arrow; c) Geological maping; d) Cavern near a well location; e) Borehole log up to depth of 25 m (Kufner Group, 2021).

2.2 Geophysical investigations

The geophysical investigations were performed using three techniques: Electrical Resistivity Tomography (ERT), Multichannel Analysis of Surface Waves (MASW) and Ground Penetrating Radar (GPR). The position of the geophysical surveys is shown in Figure 3a.

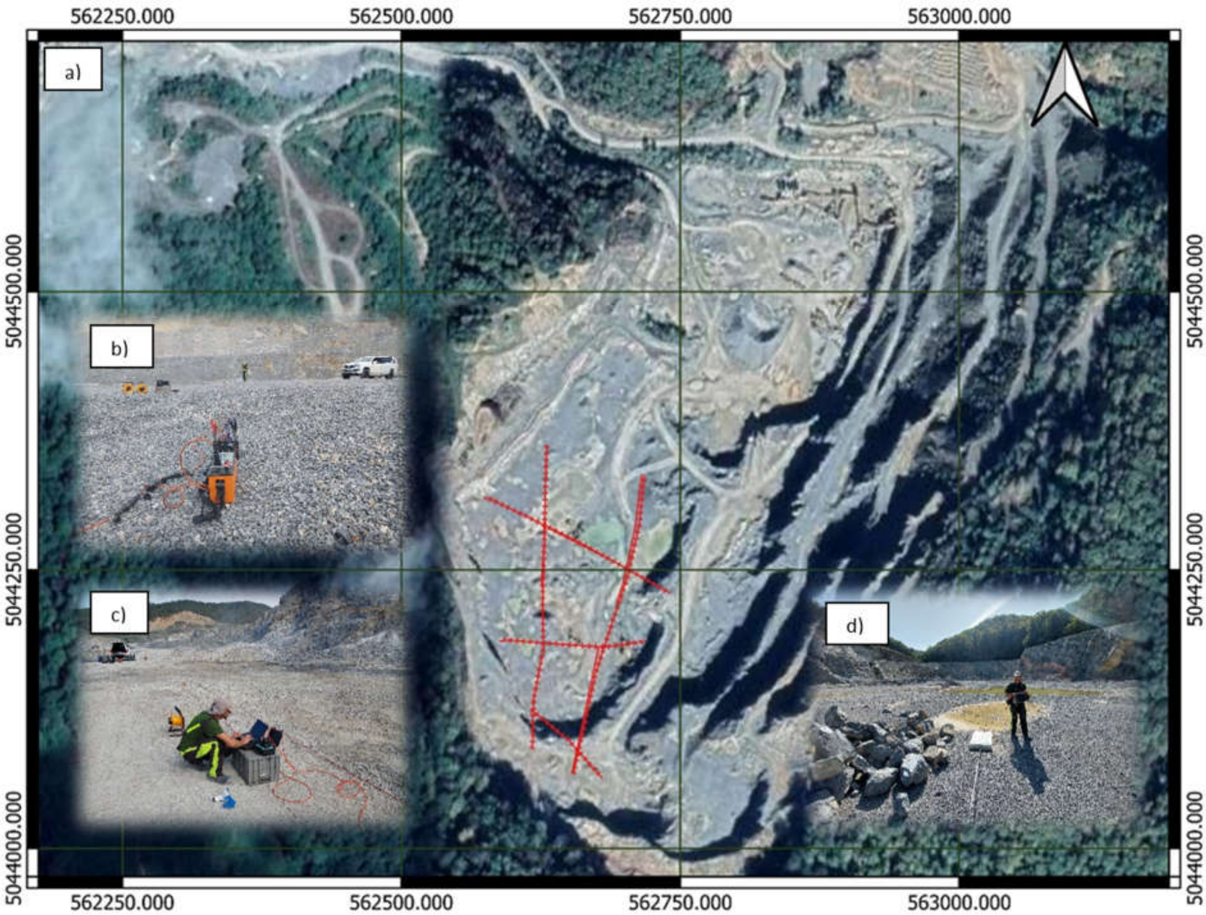

Figure 3. Geophysical investigations: a) Location of geophysical profiles on the satellite image from DGU Geoportal; b) ARES system for ERT; c) PASI GEA 24 investigation seismograph for MASW; d) ZOND12e GPR system.

2.2.1 Electrical Resistivity Tomography (ERT)

ERT is a geophysical technique that generates 2D pictures depicting electrical resistivity distribution in the subsurface (Strelec et al., 2017). The ARES system (Figure 3b) was used for field measurements (Czech manufacturer GF Instruments), a multi-electrode system used for 2D electric study. This technique utilises an array of electrodes interconnected by multicore cable to generate a linear depth profile, or pseudo section, of the resistivity variation along the survey line and at different depths. Loke (2011) describes this procedure. The analysis and interpretation of tomograms enable the detection of variations in resistivity, which can be caused by differences in lithological material or changes in water content within specific areas. The inversion of the resistivity profile was successfully performed via the RES2DINV software, which is based on Loke's methodology (2019).

2.2.2 Multichannel Analysis of Surface Waves (MASW)

MASW, first introduced in 1999 (Park et al., 1999), is a seismic exploration technique for mapping the subsurface. The MASW technique initially detects seismic Rayleigh surface waves created by different seismic sources, analyses the velocities at which these surface waves propagate, and later indicates variations in shear wave velocity (v_S) below the surveyed zone. Foti et al. (2011) briefly described field techniques and data processing steps. The PASI GEA 24 investigation seismograph (PASI SRL) and 12 single-component geophones with a frequency of 4.5 Hz with a spacing of 5 meters are utilised for imaging in Sirač (Figure 3c). The collected data was analysed using the PC software SeisIMAGER 4.0.1.6. developed by OYO Corporation.

2.2.3 Ground Penetrating Radar (GPR)

Rock quality could be well investigated using electromagnetic techniques (Jug et al., 2020). Electromagnetic waves propagate through a medium of blocky limestone, thus reflecting inhomogeneity with different parameters, such as layer boundary. The receiving signal, however, in addition to the reflected wave, also contains a direct wave that travels the shortest distance directly from the transmitting to the receiving antenna. Therefore, the receiver's output signal combines the transmitter's pulse followed by reflected pulses. Field GPR profiling was done using the ZOND12e GPR system, Radar System, Inc. Latvia and a 300 MHz shielded antenna (Figure 3d), for which the expected investigation depth in the carbonate rock mass is 20 to 30 m. Acquiring was done with the Prism2 software.

3 Results

3.1 Results of geological investigations

As part of these detailed investigations, the lithological composition of the deposits was determined. In addition, tectonic elements (cracks and faults) were recorded. According to the basic geological map L33-95 Daruvar, the study area comprises Triassic and Jurassic deposits (Jamičić, 1989). The thickly layered grey dolomitic limestone (T_3) represents a lithological unit in which stone is exploited. Thinly layered clastites are locally found within these carbonate rocks. A sequence of grey-green clastites occurs in the base of the Triassic carbonates. During the investigations carried out in the southern part of the deposits on the terrain surface, a distinct fault zone extending NW-SE with a paraclase inclination of about 75° to the southeast was registered, which was later confirmed by the results of geophysical investigations. On already formed carbonate rocks of Triassic age, sedimentation continuously took place throughout the Jurassic (J) period, and thus thin-plate gray limestones were formed. In the quarry area, they were developed in the form of a narrow zone on the northern flank of the deposit. The mentioned deposits are not significant for the research presented in this paper. The described geological relationships are shown on a characteristic geological cross-section (Figure 4).

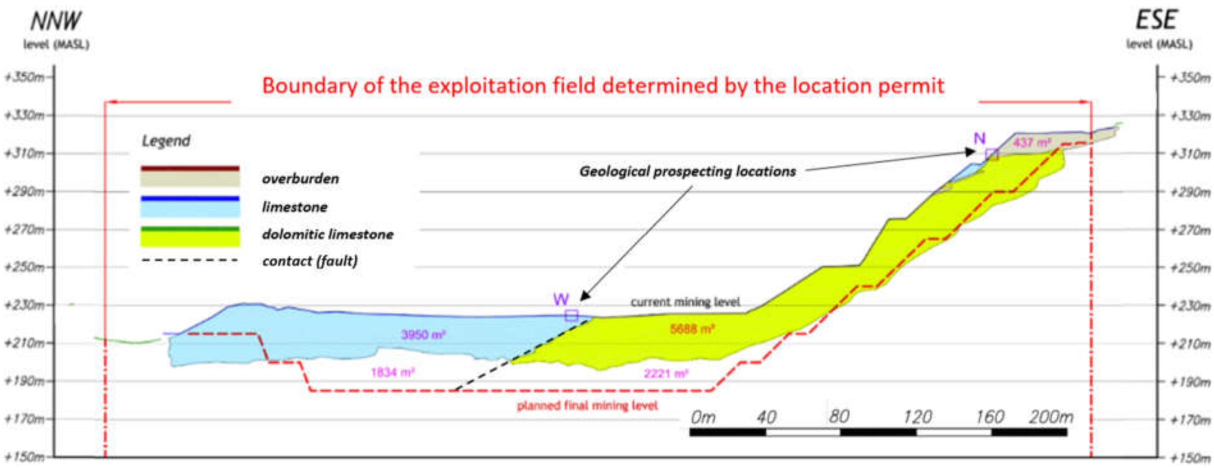

Figure 4. Characteristic geological cross-section - southern part of the Čelina mining field.

3.2 Results of geophysical investigations

3.2.1 Results of ERT investigations

In the Sirač quarry area, Čelina mining field, five 2D profiles were made by electrical resistivity tomography, with a length of 90 to 276 m and an interpretive depth of up to a maximum of 50 meters. The profiles were made using the Wenner electrode arrangement with an electrode spacing of 6 meters. The results of electrical resistivity measurements are shown in Figure 5.

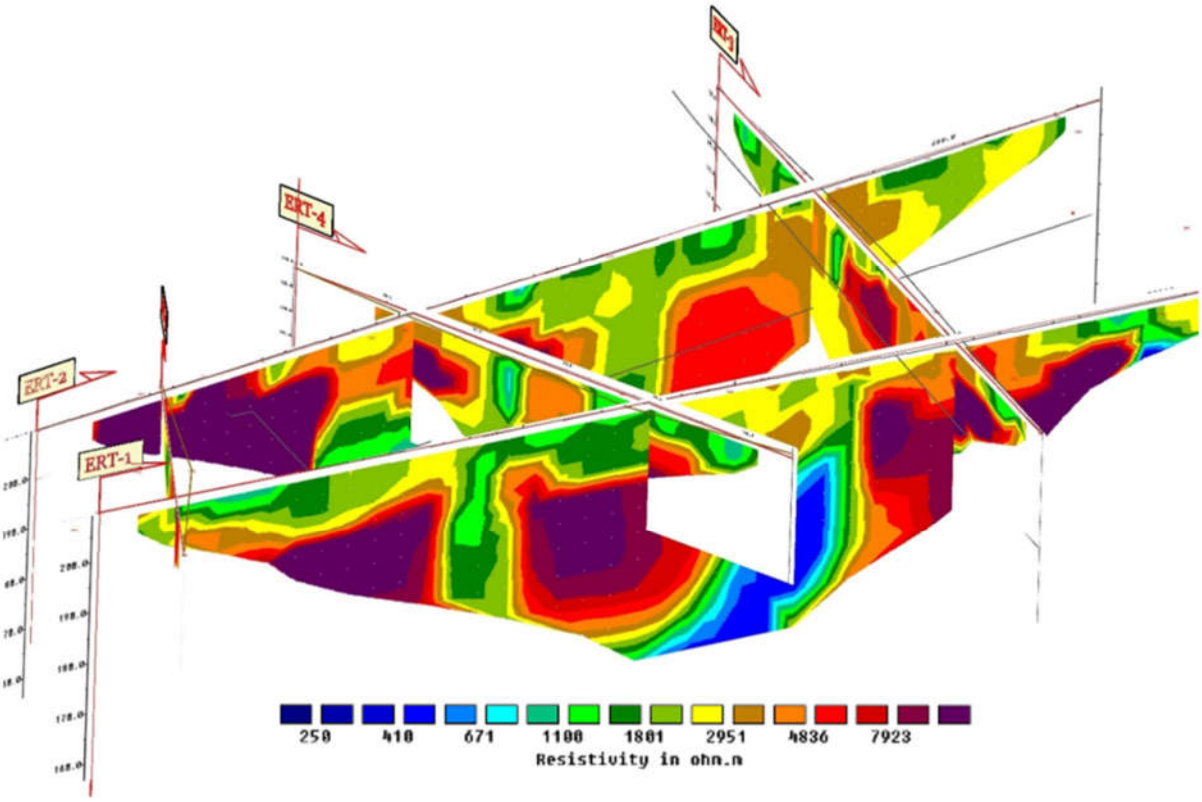

Figure 5. Results of ERT profiling in 3D view.

On the interpreted ERT profiles, based on electrical resistivities, it is possible to assume two lithological zones generally. Jurassic limestones and weathered rocks have lower resistivities, from 500 to 2000 Ωm (blue and green colour shades). According to these resistivities, younger limestones are represented in this zone, presumably saturated with water. The same resistivities can also represent a water-permeable zone as clastite in the fault area. Triassic dolomitic limestone has higher electrical resistance (red, yellow and brown colour shades), the resistivities range from 2800 to 10000 Ωm. According to the resistance of the rocks, it is more or less weathered. The mentioned materials on the tomography profiles alternate in depth and laterally.

3.2.2 Results of MASW investigations

The MASW data generated 2D shear wave velocity (v_s) profiles. Recorded seismograms were processed by the widely used MASW technique for picking the amplitude maximum in 2D spectral representations of the wavefield. A total of four seismic profiles were performed, each 115 meters long. Figure 6 shows the interpreted results of MASW-1 and MASW-2 profiling. The mentioned profiles follow the research line of the ERT-1 geoelectrical profile and are intersected by profiles ERT-3, ERT-4 and ERT-5. Seismic measurements detected lower shear wave velocities at the end of the MASW-1 profile and the beginning of the MASW-2 profile (v_s = 800-1400 m/s). Given that the mentioned area is surrounded by a more compact rock mass (v_s = 1500-2200 m/s), it is obviously a discontinuous and weathered rock mass in the fault zone.

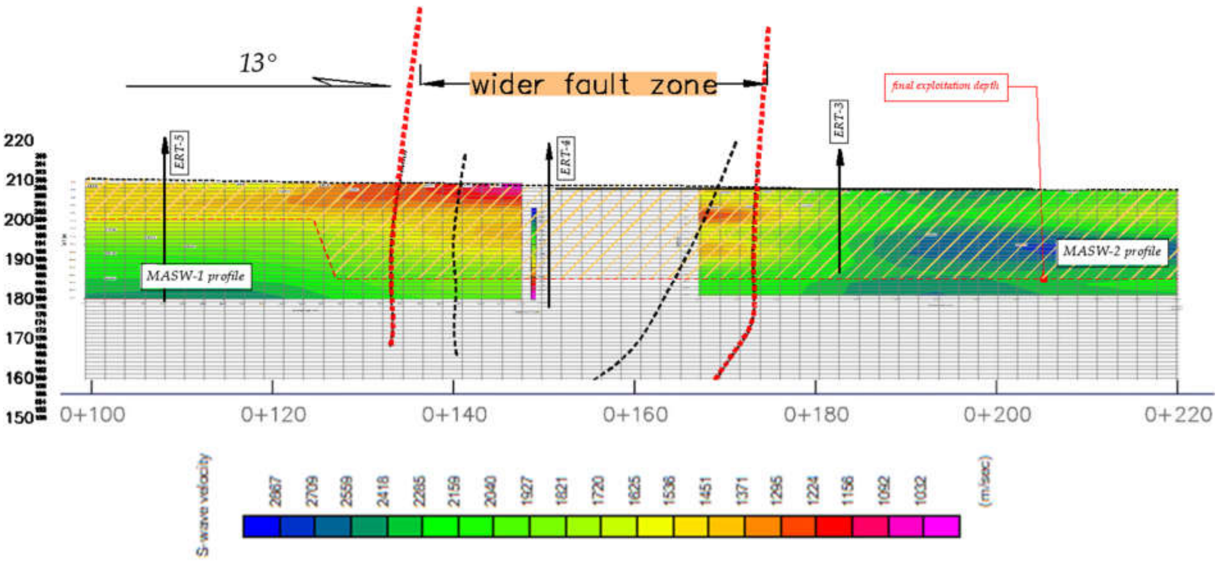

Figure 6. Results and interpretation of MASW profiling.

3.2.3 Results of GPR investigations

In the Čelina mining field, seven 2D profiles were made with ground penetrating radar, with an interpretive depth of up to a maximum of 20 meters. The section of the recorded GPR-2 radargram is shown in Figure 7, while the section of GPR-1 is shown in Figure 8 as a superimposed composite view with other geophysical investigation results. Detected crack systems within the investigated rock mass were interpreted on the radargrams. A dielectric permeability value of 6 was chosen for a time-depth conversion procedure in blocky limestones for all GPR recordings. The GPR-2 profile (Figure 7) also covers the fault zone detected by the MASW survey, and it is marked on the profile with black dashed lines. The main crack systems are also marked with dashed lines, and the depth and angle of the discontinuity are recorded.

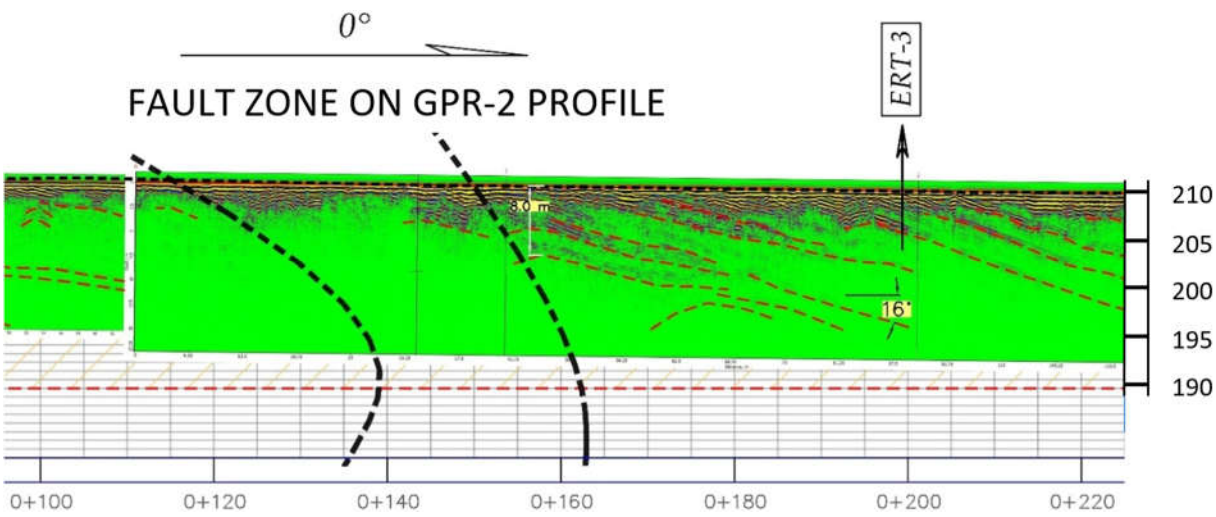

Figure 7. Results and interpretation of GPR profiling, from station 0+100 to 0+220.

4 Discussion

Based on the interpreted geoelectrical models, a significantly reduced electrical resistance zone was identified in the ERT-1 profile in stations 0+140 to 0+165 m. Figure 8 shows that the mentioned anomaly is part of a wider disturbed zone from station 0+080 m to 0+165 m, which is additionally confirmed by the GPR radiogram recorded on the same geophysical profile. On the GPR radiogram, in the parts outside the disturbed zone, layer discontinuities with a layer inclination in the direction of the geophysical profile axis of 12° are visible, while inside the disturbed zone, the cracks are irregularly distributed and have approximately horizontal inclinations. For this zone, it can be assumed that it results from a fault, where the marginal areas along the fault wings are significantly eroded (Figure 8). In the hydrogeological sense, the detected fault zone represents a more significant weathering zone that can represent an accumulator, an underground water aquifer. It is known that the dolomitic rock in the reservoir has weakly permeable bedding planes. Therefore, the space of the fault enables the drainage of seepage and underground water. That is why it is recommended to drill a new well within the mentioned fault zone (Figure 9).

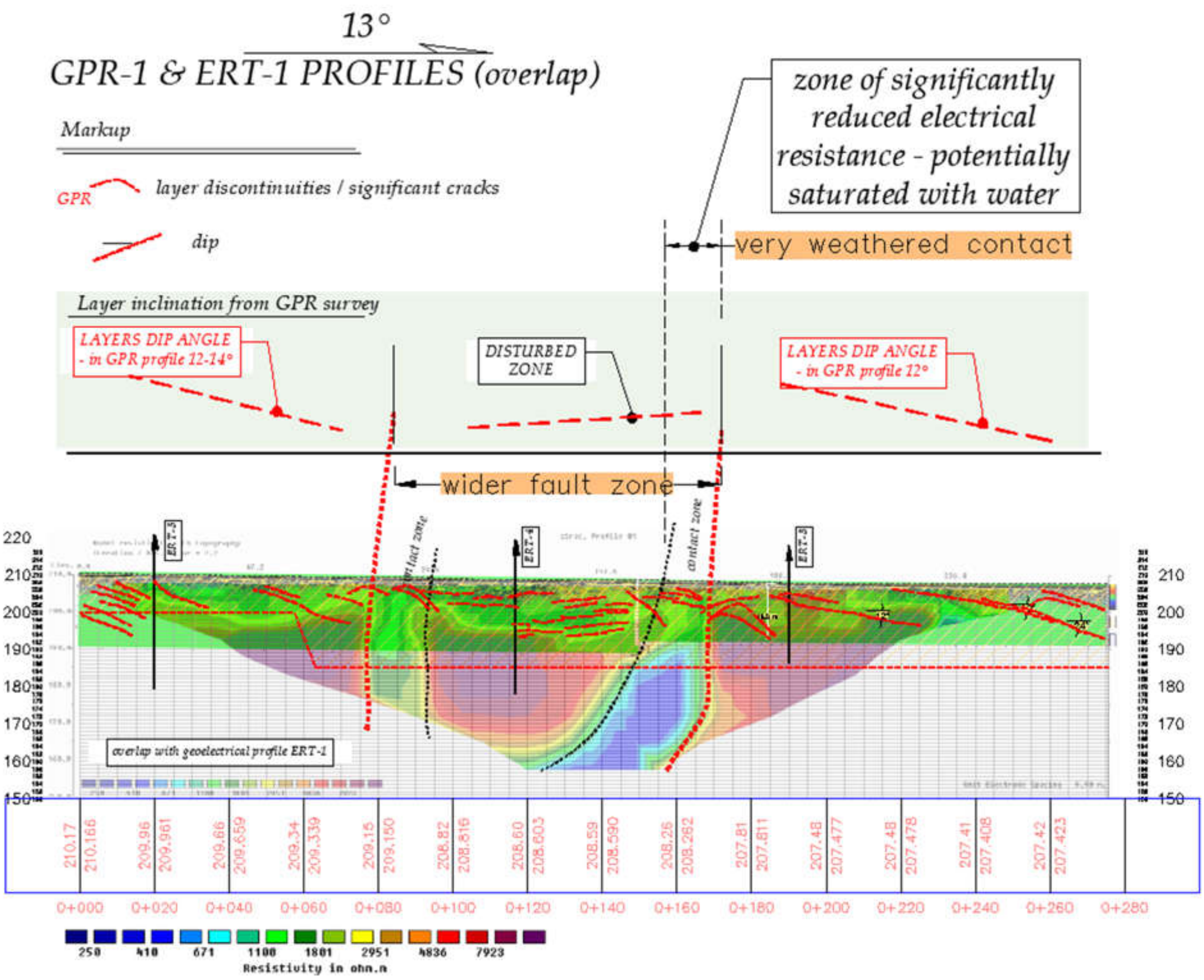

Figure 8. Composite ERT-1 electric tomography profile superimposed on GPR-1 georadar profile.

5 Conclusion

In the southern part of the Čelina exploitation field, geophysical surveys were carried out to locate the place of accumulation and discharge of underground water into the surface mine. Based on the results of the geophysical tests, a fault zone was detected, and the drilling of an exploration-exploitation well is recommended. The drilling depth will not be designed in advance, but will be defined during drilling, depending on the structure of the aquifer.The recommended position of the well coincides with the location of the established rupture along the edge of the fault wing. The purpose of the exploratory well at the proposed micro-location is to confirm the presence of water within the fault contact. In the case of confirmation that these are permeabe water bearing rock bodies, the well would be equipped as a pumping well from which it would be possible to pump significant amounts of water. The assumption is that by pumping the well, the piezometric pressures within the aquifer around the well will be sufficiently reduced, resulting in a decrease in saturation and water spilling over a wider area of the disturbed fault zone.

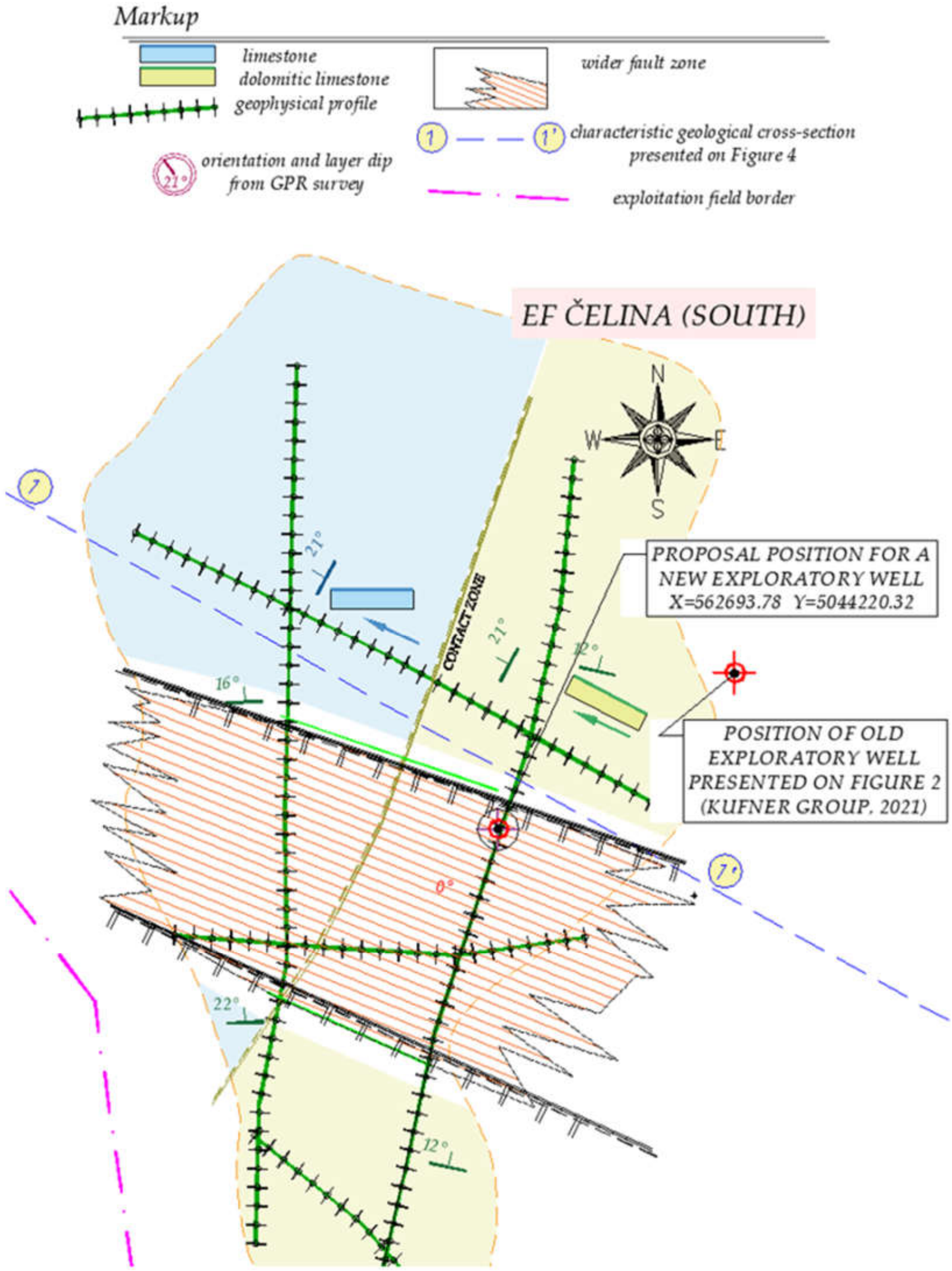

Figure 9. Recommended position for drilling of an exploration-exploitation well.

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