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Assessment of Near-Surface Geophysical Methods Used to Discover Karst Bauxite Deposits in the Dinarides Using the Example of Posušje Area, Bosnia and Herzegovina

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Abstract: Geophysical exploration of bauxite deposits has been carried out in the area of Posušje in Bosnia and Herzegovina, which were formed on an Upper Cretaceous carbonate substrate, whereas the hanging wall rocks can be Paleogene limestones and sedimentary clastic rocks. Karst terrains are demanding for geophysical exploration due to the relatively complex geological relationships and exceptional near-surface inhomogeneities that generate large noises and challenging conditions for taking field measurements. The fundamental question is whether geophysical research can detect exceptionally irregular karst bauxite deposits with relatively small dimensions. The basic idea is to combine several geophysical methods and a joint interpretation of several data sets to increase the efficiency of geophysical surveying in detecting complex bauxite deposits in karst terrains. Therefore, fundamental near-surface research methods, electrical tomography and seismic refraction are used. In addition, magnetometry was used to examine whether bauxite deposits yield potential magnetic anomalies that could help in detecting them. Research undertaken in the area of Posušje was carried out in the first step on already discovered and known bauxite deposits to determine whether geophysical responses correlate with the occurrence of bauxite deposits and to evaluate the effectiveness of each of the applied surface geophysical methods. Measurements were taken at several locations, and results for two micro-locations, Krstače and Mratnjača, are shown. Geophysical measurements were firstly performed on discovered bauxite deposits in order to reliably determine the possibility of identifying deposits in geophysical inverse models. Bauxite deposits were clearly recognised as characteristic geophysical responses in inversion models using both methods, electrical tomography and seismic refraction. Although the response of bauxite deposits is expressed in both models, resistivity and velocity, it is much more evident in resistivity models. The characteristic resistivity response was confirmed by the discovery of a new deposit. Therefore, the conclusion is that electrical resistivity tomography should be considered a basic method for exploring karst bauxite deposits. Seismic refraction provides a better characterisation of deposits and reduces the interpretation ambiguity. This solution can generally be applied to the problem of researching bauxite deposits in the Dinarides and similar geological models in the Mediterranean. Magnetometric measurements have shown that no magnetic anomalies could be associated with bauxite deposits, and only magnetometry was not successful in discovering bauxite deposits.

Keywords: karst; bauxite deposit; Dinarides; electrical tomography; seismic refraction

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Citation: Šumanovac, F.; Kapuralić, J.; Pavičić, I.; Perković, L. Assessment of Near-Surface Geophysical Methods Used to Discover Karst Bauxite Deposits in the Dinarides Using the Example of Posušje Area, Bosnia and Herzegovina. *Minerals* **2024**, *14*, 378. https://doi.org/10.3390/min14040378

Academic Editor: Xiaomin Zhu

Received: 8 March 2024
Revised: 30 March 2024
Accepted: 1 April 2024
Published: 3 April 2024

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1. Introduction

It is a known fact that karst terrains are characterised by relatively complex geological models, a high level of noise during field observations and challenging field conditions in dense macchia and karst surfaces. On the other side, karst bauxite deposits are exceptionally irregular with small dimensions, so the basic question is whether geophysical methods can detect such deposits.

Bauxite deposits in the Dinarides were formed during repeated emersions on the karstified carbonate substrates, and significant deposits appear on Cretaceous substrates [1]. Ordinarily, the footwall rocks are limestone, and bauxite is deposited and filled with larger and smaller depressions in the substrate. Transgressions subsequently cover these deposits with younger rocks that may be undergoing clastic or, again, carbonate development. Subsequent tectonic movements lead to the formation of complex geological structures. This development creates geological models in which complex bauxite deposits appear in lithological and structural terms and in a geophysical sense with respect to different physical parameters used in geophysical research.

Detailed geophysical exploration of bauxite deposits has been carried out in the wider area of Posušje in Bosnia and Herzegovina, which were formed on an Upper Cretaceous carbonate substrate, whereas the hanging wall rocks can be Eocene limestones as well as Eocene and Oligocene clastics [2]. Carbonate and clastic rocks and possible bauxite deposits exhibit different physical parameters in geophysical research, which also considers the use of specific geophysical methods. Carbonates and clastics have different electrical resistivities, allowing the use of electrical and electromagnetic methods in research, especially the fundamental methods of electrical tomography [3].

They also differ in seismic velocity, allowing the use of seismic methods. In contrast, the physical properties of fractured and weathered carbonates can overlap with the physical properties of certain clastic rocks. Likewise, the physical properties of bauxite deposits can be similar to clastics or carbonates exhibiting varying degrees of fracturing. Detecting potential bauxite deposits is a demanding task, and the problem of geophysical inversions that never give an unambiguous solution is another exacerbating factor.

Solving these problems and defining geological models that incorporate bauxite deposits as reliably as possible requires using several geophysical research methods that aim to limit ambiguity in geophysical inversion. Therefore, fundamental near-surface research methods, electrical tomography and seismic refraction, are used. In addition, magnetometry is used to examine whether bauxite deposits yield potential magnetic anomalies that could help in detecting them.

Electrical resistivity tomography (ERT) is based on measuring rock resistivity; hence, bodies of higher or lower resistivity are detectable from the surrounding rocks [4–6]. Given the mineralogical composition of bauxite deposits, they are expected to have a lower resistivity than carbonate rocks that form the substrate for their sedimentation. In addition, electrical tomography provides a more precise definition of lithological and structural relationships in the explored area. Electromagnetic methods, including the magnetotelluric method, especially controlled-source audio-magnetotellurics (CSAMT) [7] and the transient electromagnetic method (TEM or TDEM), can be also used in such explorations [8,9]. Both methods are also based on rock resistivity measurements, and similar results are expected as with electrical tomography methods, but they have an advantage in greater depth penetrations, those exceeding 100 m. However, their negative side is high sensitivity to electrical noises, which can often be unavoidable in shallow explorations. Clastics have significantly lower resistivity than carbonates, but the resistivity of some clastic rocks can overlap with the resistivity of bauxite deposits. Hence, they are often encountered as hanging wall rocks (Eocene and Oligocene clastics) of bauxite deposits.

Seismic refraction is based on elastic wave propagation rates in rocks, but seismic velocities in bauxite deposits and surrounding rocks are expected to differ [10,11]. Seismic velocities are lower in bauxite deposits than in footwall and hanging wall carbonate rocks, and similar velocities are expected in potential hanging wall clastic rocks. Magnetometry measures disturbances and anomalies in the Earth's magnetic field caused by rocks and certain phenomena that contain magnetic minerals, most often magnetite. Bauxite deposits are sedimentary rocks that contain minerals, including iron oxides. Hematite and limonite are usually not magnetic like magnetite, meaning they do not play any role in the formation of magnetic anomalies [3]. Other minerals can have weak magnetic properties, hence the

need to examine whether potential bauxite deposits cause magnetic anomalies and whether they can be detected from magnetic measurements.

Although bauxite deposits differ in density from substrate carbonates, gravimetry was not considered for two reasons. The expectation is that high-density variations in the surface karstified zone may conceal the action of bauxite deposits due to the relatively low-density contrast compared to substrate carbonates. Gravimetric field measurements are time-consuming and expensive because, in addition to using gravimetry, very precise geodetic measurements must be taken when precisely calculating gravimetric corrections.

Research undertaken in the area of Posušje was carried out in the first step on already discovered and known bauxite deposits to determine whether geophysical responses correlate with the occurrence of bauxite deposits and to evaluate the effectiveness of each of the applied surface geophysical methods. Measurements were taken at several locations, and Krstače and Mratnjača served as the main micro-locations. Geophysical measurements in the area of Mratnjača were taken immediately after the discovery of the deposit, which was subsequently mapped very well using a very dense network of exploration wells, helping to reliably determine possible geophysical methods to use in the explorations. Consequently, measurements were taken in an area demarcated using geophysical prospecting, where the presence of bauxite deposits had not been previously reliably established. It has been shown that bauxite deposits can be detected in geophysical surface research, where electrical resistivity tomography becomes the fundamental research method.

2. Geological Setting

2.1. General Setting

The Dinarides were formed in a subduction process of the Adriatic microplate, which is part of the African plate and the Pannonian tectonic segment, i.e., the Tisza Block, as part of Eurasia (Figure 1). Pamić [12] documents Adriatic subduction as a very long process that lasted from the Jurassic to the Paleogene and claimed that it led to the emergence of the Dinarides mountain range. However, given the length of the process, the assumption is that subduction in the Dinarides region was repeatedly renewed, and the remains of subduction processes can be found in two ophiolite zones, Sava and Dinaridic ophiolite zones [13], located along the contact line between the Dinarides and the Pannonian Basin. In geophysical models, including density and velocity models, it is expressed as a transitional zone between African and European geological units [14] and is considered a suture zone between lithospheric plates. The Dinarides can be considered a marginal and severely deformed part of the Adriatic carbonate plate and is much less distorted in the region of the Adriatic Sea. Although there has been much debate about the existence or absence of recent Adriatic subduction, newer teleseismic velocity models document its existence given that a high-velocity anomaly or "fast anomaly" appears under the Dinarides, indicating that a lithospheric plate that has sunken into the asthenosphere [15–18]. Thus, in these models, the Adriatic lithospheric plate or at least the lower part of the lithosphere, separating from the crust, sinks steeply into the asthenosphere below the Dinaridic mountain range.

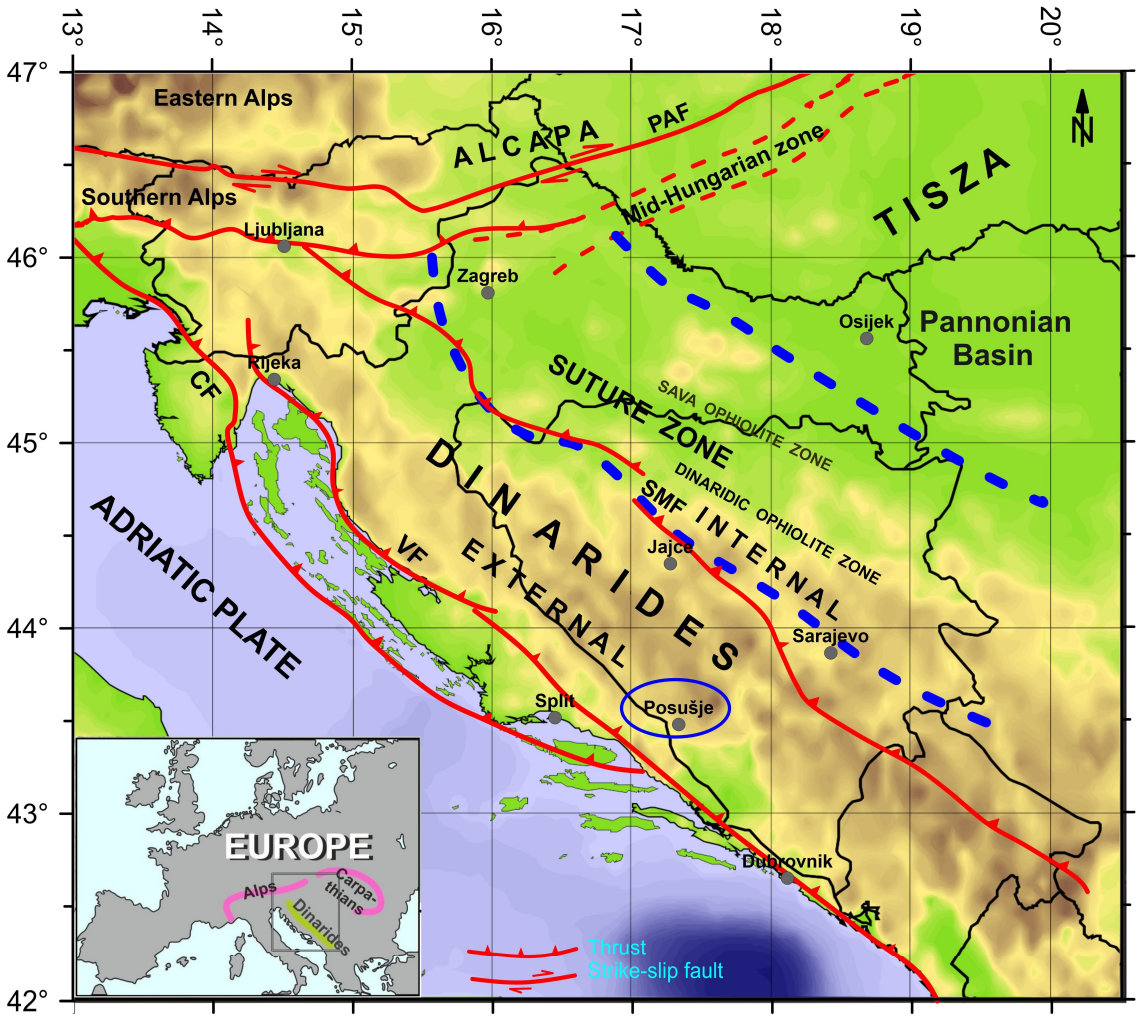


Figure 1. A coloured relief model of the Dinarides and marginal part of the Pannonian Basin with the border area of the Alcapa (Alpine–Carpathian tectonic unit). The main tectonic units and faults are superimposed on the topographic map (PAF—Periadriatic fault; CF—Ćićarija fault; VF—Velebit fault; SMF—south marginal fault of the Pannonian Basin). The suture zone (dashed blue line), which includes ophiolites zones, has been constructed following Šumanovac [14,19]. The survey area of Posušje belongs to the External Dinarides.

2.2. The Geology of Bauxite Deposits

Bauxites are deposits containing large amounts of aluminium hydroxides in the form of aluminium minerals boehmite (γ-AlO(OH)), diaspore (α-AlO(OH)) and gibbsite ($Al(OH)_3$), which are ores used to produce aluminium. Gibbsite and boehmite are the main Al-bearing minerals of the bauxites in Posušje, and diaspore was not observed. The ratio of gibbsite to boehmite varies from deposit to deposit, and in some deposits, boehmite is the only aluminium phase present. Recent petrographic, mineralogical and chemical investigations [20] have shown that the predominant Fe phase in all deposits is hematite, while goethite-rich bauxites are rare. Zircon, apatite and calcite were found as minor minerals. X-ray analysis revealed significant amounts of anatase and rutile, while kaolinite was only detected in one sample. Chemical XRF analyses revealed an Al_2O_3 content between 49.6 and 63.0 wt%, an Fe_2O_3 content between 16.5 and 33.7 wt% and a SiO_2 content between 0.5 and 4.0 wt%.

Karst bauxite deposits are deposited in depressions within a karstified carbonate substrate; hence, their shapes are very irregular, whilst their sizes can vary across a wide range from a few tens of cubic meters to tens of thousands of cubic metres [1,2].

The Posušje bauxite-bearing area, located in the External Dinarides [21], is one of the largest and most exploited in the Adriatic Carbonate Platform (AdCP) which existed from the Lower Jurassic to the end of the Cretaceous [22], Figure 1. Covering an area of 125 km, there are more than 1000 mined deposits that vary in size, volume and structural position, making the area an outstanding natural research polygon. There are numerous identified locations with shallower or deeper bauxite deposits under hanging wall deposits. Bauxite deposits have also been discovered on the surface in a dozen places. These occurrences are often small deposits preserved as erosion-related remains that have been mostly exploited.

Most of the economically valuable deposits in the AdCP, such as the bauxite deposits in Posušje, were formed during the emersion phase between the Late Cretaceous and the Paleogene (so-called Paleogene bauxites), Figure 2. The deposits were formed on the paleokarst surface of Late Cretaceous Rudist limestones and have a thickness of more than 500 m. The largest and most numerous depressions in the paleorelief contain bauxite deposits formed due to the structural conditions prior to bauxitisation [2]. Bauxites often occur in wide zones of gentle antiforms, more precisely in their hinge zones, as these are the highest points of the anticlinal structure, characterised by fracture systems and, at the same time, most exposed to weathering [1,23]. In addition to these structures, bauxites also occur in the core of gentle synclines and along pre-bauxite faults [2].

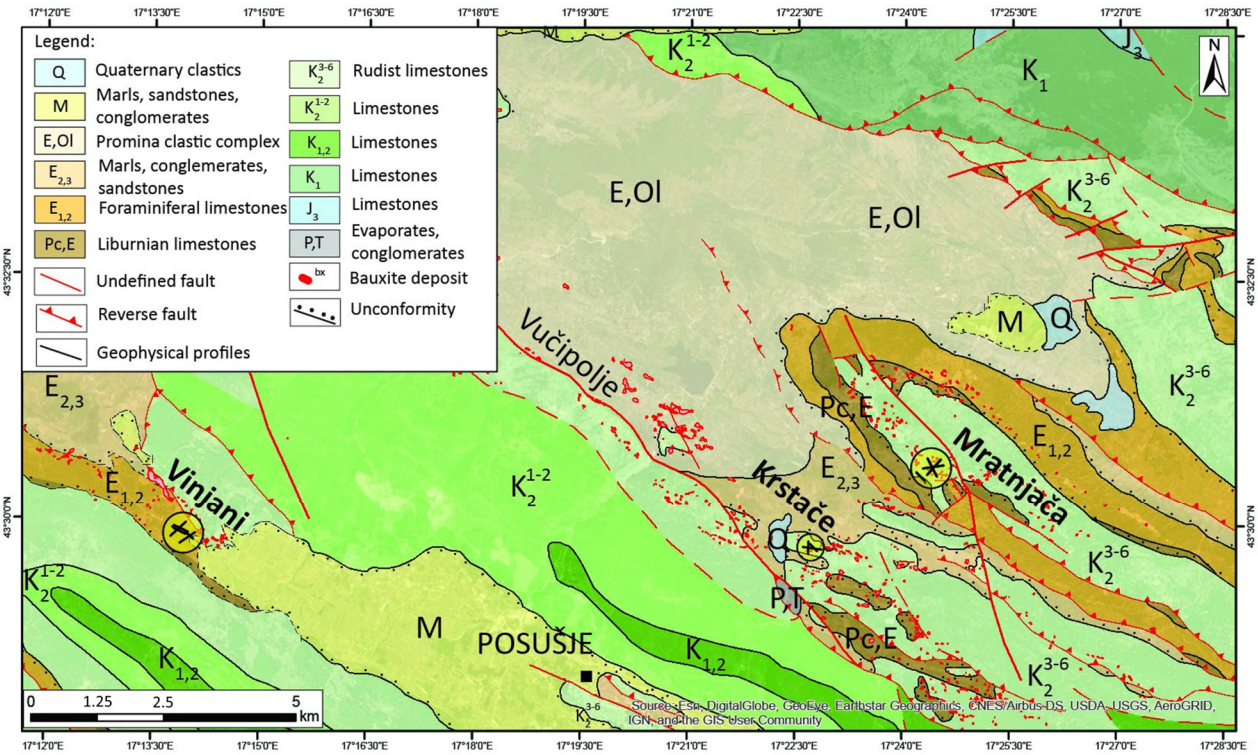


Figure 2. Geological map of the wider survey area (supplemented and constructed after Raić et al. [24]. Measured geophysical profiles at the Krstače and Mratnjača micro-locations discussed in the paper are shown as black lines (Q—Quaternary; M—Miocene; E,Ol—Eocene and Oligocene; $E_{2,3}$—Middle-to-Late Eocene; $E_{1,2}$—Early-to-Middle Eocene; Pc—Palaeocene; K_2^{3-6}—Coniacian to Mastrichtian; $K_2^{1,2}$—Cenomanian and Turonian; $K_{1,2}$—Abtian–Cenomanian; K_1—Early Cretaceous; J_3—Late Jurassic; PT—Permo-triassic).

Hanging wall deposits are represented by carbonate–clastic complexes from the Palaeocene to the Oligocene (Pc to E,Ol). The spatial and temporal distribution of hanging wall strata is very complex. In general, the hanging wall strata are divided into two lithologic types: carbonate rocks and clastic layers [24] (Figure 2). The carbonates comprise two types of limestones: Liburnian limestones and foraminiferal limestones (Pc, $E_{1,2}$). The

Liburnian rocks (Pc) consist of thin layers of shallow marine limestone that are transgressive and slightly discordant compared to the Upper Cretaceous carbonates (K_2), and their age is determined to be from the Palaeocene (Pc) to Early Eocene ($E_{1,2}$). The Liburnian limestones (Pc) consist of light brown and grey-to-dark brown, well-stratified limestones in which *Characeaes*, *gastropods* and *miliolidae* occur. The deposits have been formed throughout the bauxite-bearing area of Posušje in the form of relatively small areas and are not too widespread, which is due to the limits of their depositional environment. These deposits were deposited in the lowest parts of the paleorelief, which were first affected by the transgression, such as Snižnica, Podsniježnica, Sobač and Mranjača. The total thickness of these deposits can reach up to 200 m, but they are usually much smaller as they are largely eroded.

The deposition of the shallow marine foraminiferal limestone deposits ($E_{1,2}$) begins immediately after the deposition of the Liburnian limestones; hence, they appear together in the oldest part of the sequence. The boundary between these two units is marked by the presence of *Alveolina* which is also a characteristic of the older parts of this sequence. The upper part is characterised by a mixture of *Alveolina* and *Nummulites*. Sometimes, they are continuous on Liburnian limestones, but more often, they are transgressive to the Upper Cretaceous limestones (K_2^{3-6}). The age of this sequence is biostratigraphically dated to the Eocene (E) [23]. The thickness of the sequence is up to 420 m.

In the stratigraphic overburden and in places of lateral equivalents relating to the previously described deposits, clastic complex from Eocene marls, sandstones, conglomerates and breccias with macrofauna (molluscs, corals, gastropods and traces of coal, $E_{2,3}$) were found. Based on calcareous nanoplankton and benthic foraminifera found in the immediate cover of the bauxite, the age of these sediments was determined to be Lower and Middle Eocene and, in places, Oligocene [1,23]. This group of lithofacies is often found in the immediate hanging wall of bauxite deposits and is transgressive on Upper Cretaceous limestones (K_2^{3-6}). The total thickness of the described deposits can be up to 440 m. In the continuation of the described clastic complex, the Promina deposits (E,Ol) are dominated by conglomerates [23,24]. Conglomerates, sandstones and marls alternate vertically and laterally. Most of the carbonate conglomerates are from the Cretaceous–Eocene age with chert and dolomite clasts. These thick-bedded rocks are deposited discordantly on Cretaceous, Liburnian and foraminiferal limestones. The total thickness of these deposits was estimated to be approximately 900 m.

During the emersion phase, especially after the formation of bauxite deposits, compressional tectonic conditions prevailed, resulting in various geologic structures and bauxite positions, such as inclined, vertical and overturned positions. The wide areas are characterised by regional reverse faults and thrusts with NW-SE strike as well as NE and SW vergencies. Some of these reverse faults originate from the pre-bauxite phase and were reactivated during the formation of the Dinarides. Along with the thrusts, a series of steep to overturned synclines and anticlines were formed. The youngest structures in this area are strike-slip faults with sinistral and dextral displacement.

3. Geophysical Exploration of Karst Bauxite Deposits

Bauxite deposits in the Dinarides were most intensively explored and exploited from the 1950s to the 1980s, after which there was a lull in exploration due to Europe increasingly distancing itself from mining [1,2,24]. Before constructing exploration wells, geophysical exploration methods should play a major role in detecting bauxite deposits. However, complex geological models and difficult exploration conditions on karst terrains significantly limit geophysical exploration in detecting bauxite deposits; hence, the literature poorly covers this segment of research. Lapajne [25,26] investigated Istrian bauxites in the northwestern Dinarides using the electrical profiling method by measuring at several different depths across the same profile. Dragičević et al. [27] explored karst bauxite deposits in the Dinarides with shallow seismic reflection, but it is difficult to detect reliable

seismic reflections on a confused time seismic section, so the geological interpretation is generally unreliable.

Recent developments in geophysical methods and measurement technology have given these investigations new dimensions and possibilities. However, the application of methods varies, and recognition of geological models and bauxite deposits in particular is very questionable. Ali et al. [28] utilised the ground radiometric method as a tool to delineate the surface boundaries of buried bauxite karsts. They mapped the depletion of radioactivity in the karst overburden and estimated the boundary of the bauxite karst based on the contour lines of the depletion anomaly. However, this type of research provides no information other than the delineation of potential bauxite-bearing zones at the surface. Orfanos et al. [11] conducted an extensive integrated geophysical study in the bauxite mines of Gerolekas in Greece, where the geological conditions are similar to those in the Posušje area, with the hanging wall and footwall of the bauxite deposits consisting of limestones, but with significantly deeper deposits. They used passive geophysical methods: local earthquake tomography (LET), gravity measurements for each of the 129 seismic stations and the magnetotelluric method at points of interest as well as data from more than 4000 boreholes. The authors emphasise that the geophysical parameters used in the modelling play an important role and must be as close to reality as possible, as they influence both the forward modelling and the inversion steps. They tried to show that a credible geological model can be provided which could indicate potential for future deep borehole survey as a further reconnaissance step towards additional mining operations in that area. Due to the limited resolution of the passive methods in the near-surface models, this methodologically complex and extensive type of investigation could not provide any new insights into the shallow and small pocket-like deposits as in the karst region of the Dinarides.

In a more recent study in the same area, local earthquake tomography and transient-source seismic interferometry (TSI) were integrated. The coarse velocity model obtained by LET provided a rough estimate of where to expect the flysch–limestone boundary, and the autocorrelation-based TSI provided zero-offset virtual reflection responses under each of the recording stations [29]. This provides a 1D image of the passive seismic reflection beneath each of the recording stations, resulting in a pseudo-3D reflection image of the study area. In addition, the authors used seismic results for the reprocessing of active seismic data. From the combined interpretation of the results, they suggested the depth at which the flysch–limestone boundary is likely, followed by bauxite deposits similar to those in the surrounding area. Xue et al. [30] noted that numerous geophysical projects have been carried out in China in search of karstic bauxite deposits but with limited success. The authors propose an integration of transient electromagnetic (TEM) and gravity methods to delineate the mineralised boundaries. The gravity method was used to highlight prospective areas of bauxite mineralisation. The TEM method was then used to delineate the location and burial depth of these boundaries based on resistivity differences.

4. Data Acquisition

Geophysical measurements using electrical resistivity tomography (ERT), seismic refraction and magnetometry were performed at five micro-locations in the broader area of Posušje: Vinjani-1, Vinjani-2, Krstače, Mratnjača-1 and Mratnjača-2. Examples from the micro-locations Mratnjača-1, Mratnjača-2 and Krstače were selected in order to present the various geophysical methods in researching karst bauxite deposits (Figure 3).

At the first micro-location, Mratnjača-1, the tomographic profile TP-9 was deployed, the length of which is 240 m (Figure 3). Seismic refraction and magnetic measurements were not performed on this profile, given that exploitation began immediately after taking tomographic measurements. At the second micro-location, Mratnjača-2, three tomographic profiles were deployed, shown on the position map as TP-10, TP-11 and TP-12 (Figure 3). The profiles covered the newly discovered bauxite deposit, the outline of which is shown on the same position map. The lengths of the profiles are 400 m. Three profiles with lengths

of 240–360 m, marked as TP-6, TP-7 and TP-8, were placed at the third micro-location, Krstače (Figure 3). The evaluated outlines of the bauxite deposits, defined on the basis of geological mapping and results of exploratory drilling if they were available, are also shown on the position map.

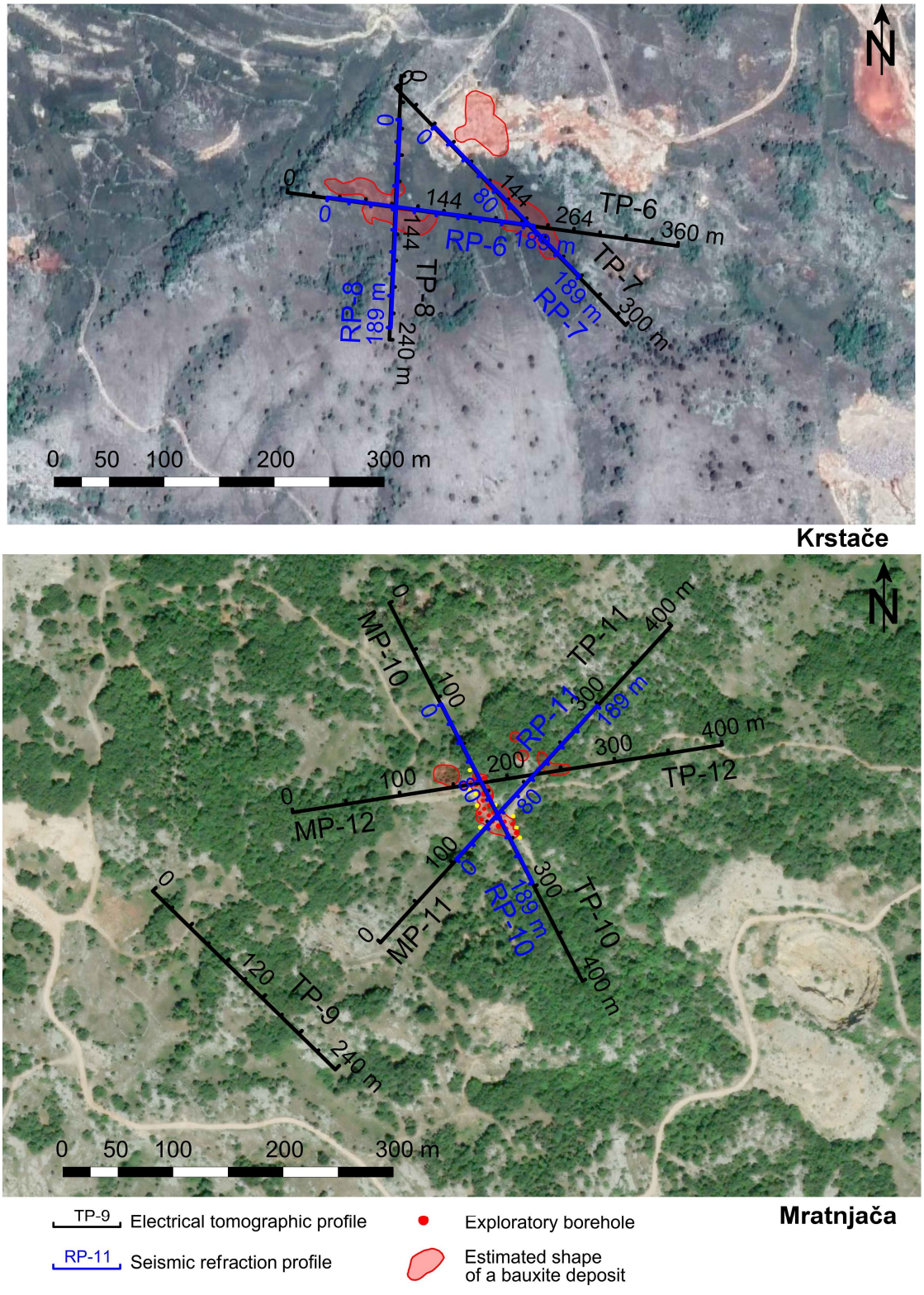


Figure 3. Positions of measured geophysical profiles in the area of Krstače and Mratnjača micro-locations.

The measurements were carried out using the Terrameter SAS 1000 and the automatic multielectrode Lund Imaging System (LIS) produced by the Swedish company ABEM. The recording geometry was determined to achieve depths of up to 40–80 m, and the unit electrode spacing was set to 3 m at the Krstače and Mratnjača-1 micro-locations and at 5 m at the Mratnjača-2 micro-location in order to be reliable to determine the relatively deep bauxite deposit. The number of electrodes used in the measurements depended on the unit electrode spacing and the length of the profile, ranging from 81 to 121 electrodes. The measurements were performed using a Wenner electrode array because it is least sensitive to noises, given that high levels of noise can always be expected in karst terrains, which adversely affect the measured data. In the area of the Krstače micro-location, the number of observed points at the profiles is in the range of 341–645, while in the area of Mratnjača, it is 259–344. Karst terrains are characterised by significantly higher electrical noises compared to sedimentary basins with clastic rocks at the surface. The noises are mainly generated by the seepage of water in the surface weathered zone and the high grounding resistances of the electrodes. Some profiles were measured after a rainy period, so the water seepage in the surface zone caused relatively large noises; on the other hand, it was favourable that the grounding resistances of the electrodes were relatively small. Other profiles were measured in a relatively dry period, so the water seepage noises in the surface zone were small, but the grounding resistances were significantly higher, which was solved by looking for a more favourable place for grounding the electrodes or by adding moisture to the soil. Although the Wenner–Schlumberger array has a declaratively better vertical and horizontal resolution, it is much more sensitive to noise than the Wenner array, which significantly reduces the quality of the measured data. According to our many experiences, this reduces the reliability and precision of determining the inverse resistivity model, which adversely affects the final geological interpretation.

Refraction profiles are set up along two tomographic profiles at the Mratnjača-2 micro-location, and they are marked with the same profile number as the tomographic profiles: RP-10 and RP-11 (Figure 2). Refraction measurements were performed on all three profiles at the Krstače micro-location (RP-6, RP-7 and RP-8). In order to achieve a high resolution, the measurements were performed with a dense geophone spacing of 3 m. In all, 64 geophones were used on the profiles; hence, the lengths of the profile were 189 m. The intention was also to cover the newly discovered bauxite deposits completely with detailed seismic refraction measurements.

At each seismic refraction profile, the measurements were made by registering the primary waves (P-waves) and were generated using a sledgehammer striking a metal plate on the ground. The seismic source was placed after every third geophone along the profile (Figure 4). Two seismic sources were placed at the ends at a distance of 1.5 m from the first and last geophones, and two were placed 6 m from the first and last geophones. Thus, there were 25 seismic source stations along the 189-metre-long refraction profiles.

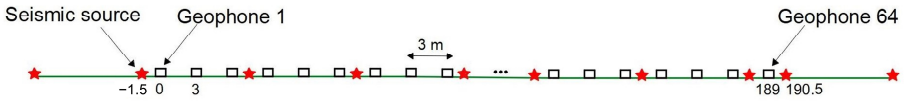


Figure 4. Geometry of P-wave recording using seismic refraction on profiles with a length of 189 m.

A digital seismograph, i.e., the DMT system, with a dynamic range of 120 dB was used for data acquisition. The system has the ability to stack signals, and signal amplification is automatically and instantaneously determined according to the input signal (IFP amplification). Vertical geophones with a resonant frequency of 12 Hz were used to receive seismic waves.

Magnetometric measurements were performed along all the tomographic profiles except for the TP-9 profile, which was excavated very quickly after tomographic measurements. The profiles are marked with the same numbers as the tomographic profiles: MP-6 to MP-12 (Figure 3). The measurements were carried out with two synchronised

magnetometers GM-19T from the company GEM System (Canada), with a resolution of 0.01 nT. The distance between magnetic observations at the profiles is 3 m.

5. Data Processing and Interpretation

The observed ERT data were processed and interpreted according to the most commonly used inversion method of Loke and Barker [31,32] using 2D geophysical inversion software Res2Dinv (version 3.71). The final shape of the interpreted resistivity model is affected by the relief of the terrain; hence, the profiles were additionally processed to take into account the altitudes determined by the geodetic survey. The software used incorporates appropriate topographic corrections for the effect of the relief of the site on the observed data, and the respective profiles are shown in Figures 5 and 6.

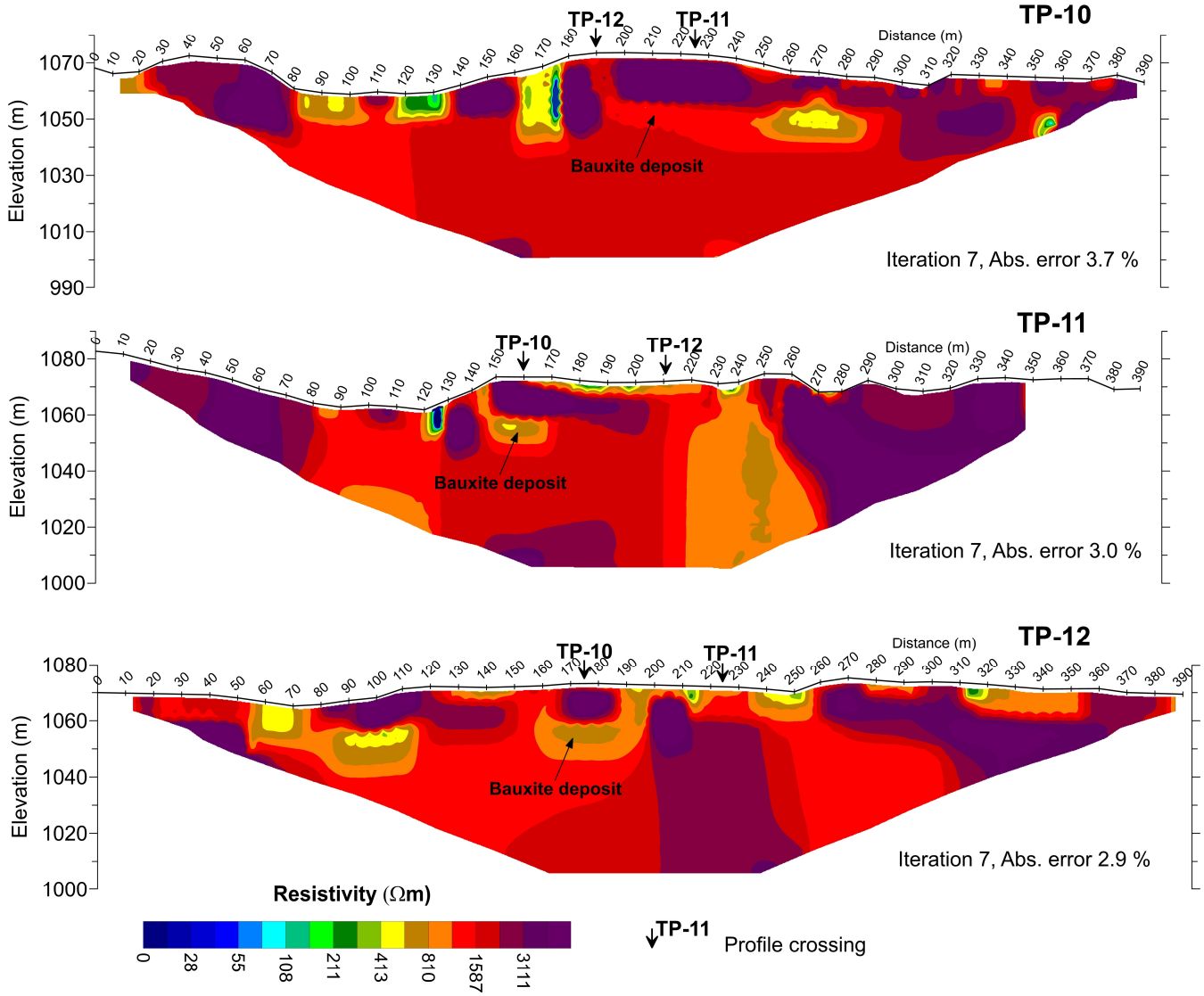


Figure 5. Inversion resistivity models for tomographic profiles measured in the area of Mratnjača. The bauxite deposit, intersected by all profiles, is expressed as a zone of lower resistivity located below very high resistivities on the surface and caused by Eocene limestones. There is no exact correspondence between the resistivity values at the intersections of the lines, since the resistivity values in geophysical sections are not only due to the deposits lying exactly vertically below the profile but are also influenced by the deposits around the profile (3D effect).

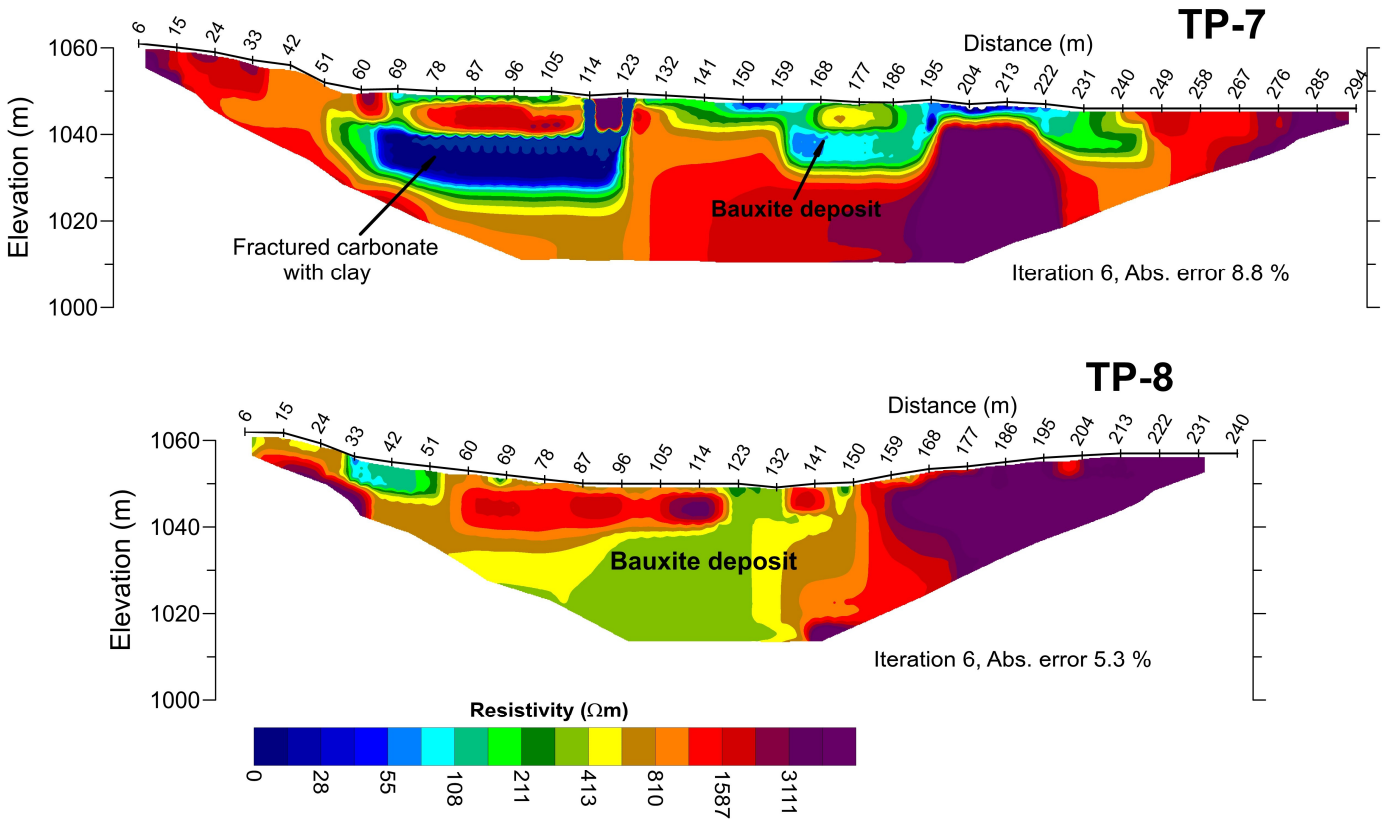


Figure 6. Inversion resistivity models for tomographic profiles measured in the area of Krstače. Bauxite deposits, in turn, are expressed as zones of lower resistivity located below very high surface resistivities caused by Eocene limestones.

The robust inversion method was applied, which emphasises the large differences in rock resistivities and gives a "sharper" picture, given that carbonate and clastic rocks with large resistivity ranges are present at the site [33]. The inversion resistivity model presents resistivities that fit the observed apparent resistivities or pseudosection. The deviations between the observed apparent resistivities and the theoretical apparent resistivities, calculated from the interpreted resistivity model, are expressed as an absolute error in percentages. The quality of the observed data is generally good, and absolute errors in the range of 2.9%–8.8% were obtained for the sixth and seventh iterations (Figures 5 and 6). Part of the observed data were loaded with high noise, which is characteristic of karst terrains, and this is discussed in the Data Acquisition Chapter, hence the need to process and filter the data additionally. Preliminary filtering of the observed data mainly involved the removal of extreme values. Although it is generally considered that a lower absolute error indicates a better fit between the observed and calculated pseudosections, which is desirable, there is no universal standard range of the absolute error that can be considered good quality results. The acceptable error may depend on several factors such as the complexity of the model, the observed data quality, the number of deleted bad data points, the inversion algorithm used and the aim of the investigation. According to previous experiences, in most cases, an absolute error of less than 10% is acceptable. Furthermore, the robust method gives less importance to data points with larger misfits, which makes the method less sensitive to bad data points [33].

The first arrivals from the onsite recordings were placed into a time–distance graph, which serves as the starting point in interpreting data from the refraction recordings. The graph was used to help in the interpretation and obtain the inverse model of seismic velocities. By applying the Delta-t-V method [34] and seismic tomography, the models for P-wave velocities were obtained, as shown in Figures 7 and 8. Depth penetration

depends on the velocity distribution underground and the length of the profile; hence, depth penetrations from several metres to about 60 m were achieved. In general, the penetration depth was greater on longer profiles and profiles with lower seismic velocities.

In the interpretation process, consideration should be given to the fact that inversion velocity models of refraction profiles provide much more reliable data in the central parts of the profile, whereas deformations may occur at the edges. The deformations depend on lateral velocity changes and the applied inversion method. It is also necessary to point out that the depth penetration is very small, only 10–20 m, for both profiles at the Mratnjača site due to Palaeocene–Eocene carbonates exhibiting very high velocities at the surface and, below them, bauxite deposits characterised by lower velocities. This situation creates a generally very unfavourable situation for the seismic refraction method, i.e., so-called "velocity inversion" because rock with lower seismic velocity exists at a greater depth. This is why seismic ray coverage in interpreted velocity models is presented in Figures 7 and 8. The rays are concentrated in zones with higher velocities, meaning that the zones with low velocities are rarely sampled, causing the zones with velocity inversion to occur in a kind of shadow of high-velocity rocks located near the surface.

The measured magnetic data were corrected for daily changes and micro-pulsations. Examples of measured magnetic profiles from the Mratnjača area are shown in Figure 9. The data were additionally edited and filtered in order to reduce the influence of surface inhomogeneities and iron objects in the soil.

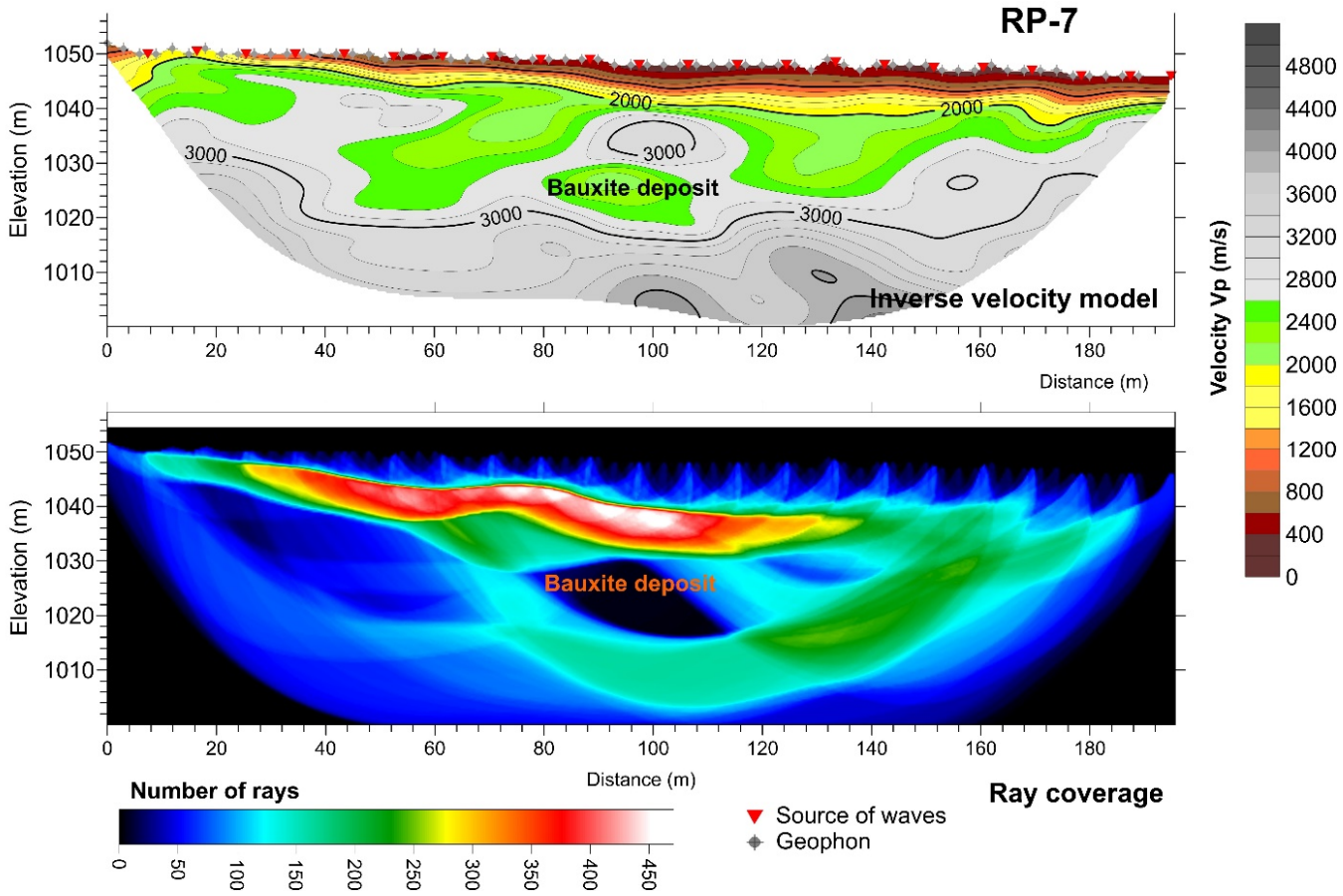


Figure 7. Inversion velocity model for the RP-7 refraction profile measured in the area of Krstače using the seismic ray coverage model. In the bauxite deposit, there is very poor ray coverage due to velocity inversion.

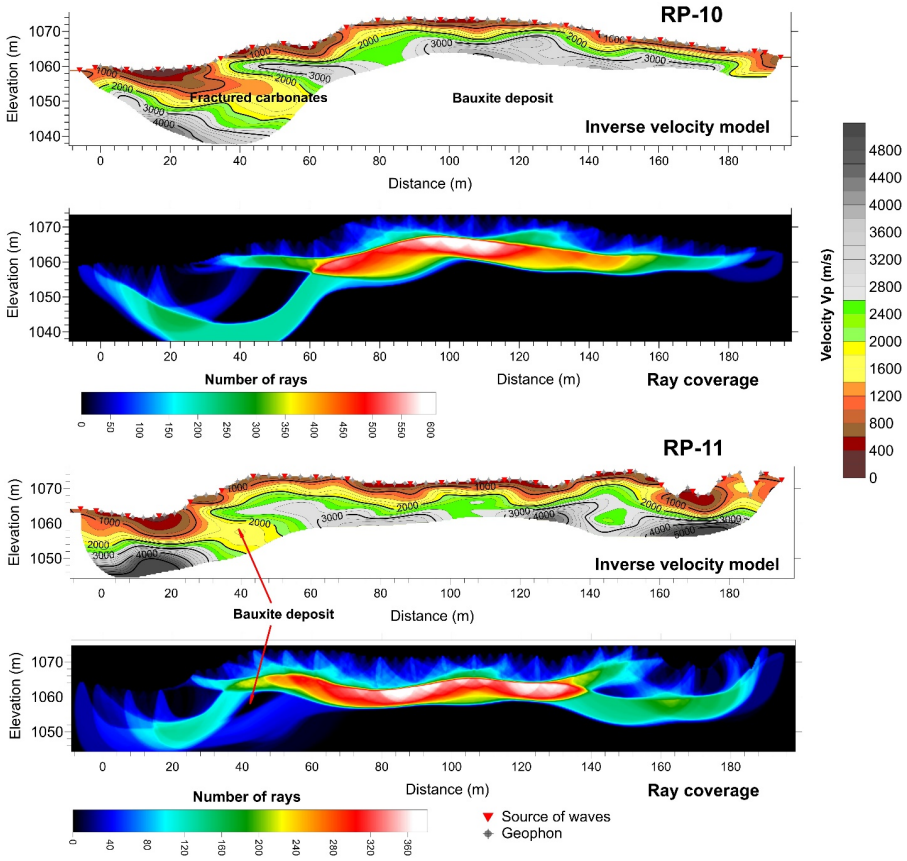


Figure 8. Inversion velocity models for refraction profile measured in the area of Mratnjača using seismic ray coverage models. A very small depth penetration is observed, given that the coverage of the bauxite deposit is very poor due to strong velocity inversion in the deposit.

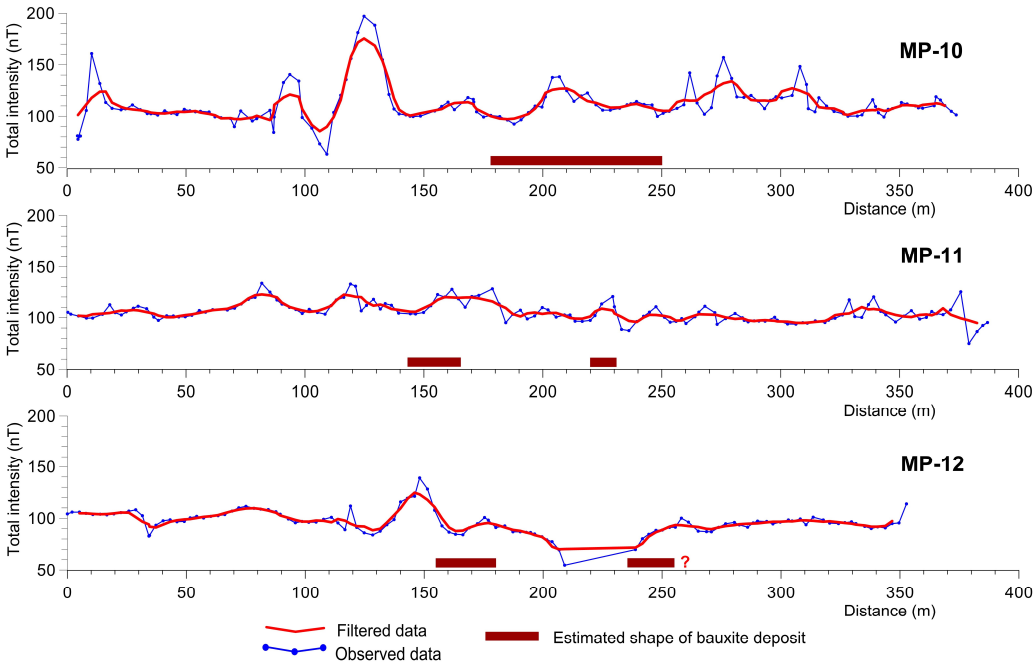


Figure 9. Measured magnetic profiles in the area of Mratnjača using measurements of the total intensity of the Earth's magnetic field. The profiles do not show magnetic anomalies originating from bauxite deposits but only anomalies from surface inhomogeneities and iron objects in the ground.

6. Results

Detecting bauxite deposits is a complex geophysical problem. The visibility of deposits depends on several parameters, primarily the mentioned contrast in the perceived physical properties, such as resistivity, seismic velocity and magnetic susceptibility. The greater the difference, the clearer the expected reflection of bauxite deposits. However, the detectability of bauxite deposits depends on their dimensions and depth of occurrence. Detectability decreases as the deposit dimensions decrease and the depth of occurrence increases. Hence, geophysical interpretation always considers the relative size of the deposit with respect to the depth of the occurrence and not its absolute size. Bauxite deposits are found in irregular pockets of weathered carbonate substrates, and the dimensions, shapes and depths of their occurrence vary across a wide range [35]. Further difficulties are caused by extensive surface inhomogeneities, characteristic of karst and carbonate terrain, given that they generate large noise levels, reducing the resolution of all applicable geophysical methods. In addition, lithological columns also contain fragmented and weathered carbonate rocks and clastic rocks, which can decrease or eliminate contrast in the physical properties, making it impossible to detect deposits. Therefore, we encountered complex geological models on karst terrains, including difficult conditions for geophysical measurements. The basic idea is to combine several geophysical methods and a joint interpretation of several data sets to increase the efficiency of geophysical surveying in detecting complex bauxite deposits in karst terrains.

Clastic deposits generally provide lower resistivity. The resistivity of clays is about 20 Ωm. More sandy and calcite components increase the resistivity. On the other hand, carbonates (limestones and dolomites) cause high resistivity, usually from several hundred to several thousand ohm-metres. If compact and dry, there is a very high resistivity, whereas an increase in fracturing leads to a decrease in resistivity because the cracks are usually filled with clay or water. That is why the resistivities of more fractured carbonate rocks can superimpose with the resistivity of certain clastic deposits. Given that bauxites are actually sedimentary rocks, the expectation is to encounter lower resistivity than in carbonate rocks but certainly more so than in clay and clay deposits.

Measurements of bauxite resistivity on outcrops revealed low resistivities compared to carbonates. The measured values vary significantly and lie within the range of 100–550 Ωm. The resistivities depend on the mineral composition, the state of the deposit (compactness–fracturing) and water saturation. The content of clay minerals and the moisture of deposits mostly lead to a reduction in resistivity. In exploring Eocene bauxites in Istria in the northwestern Dinarides, where a similar stratigraphic column is present as in the area of Posušje, ref. [25] showed that the resistivities of bauxites lie within the range of 100–300 Ωm. Thus, there is a good correlation between the resistivity of bauxites in the northwestern Dinarides and central Dinarides. The resistivity of bauxite will overlap with the resistivity of certain clastic rocks, mostly sandstone, and the resistivity of intensely fragmented and karstified zones in carbonate rocks. That is why difficulties in detecting bauxite deposits are expected when considering other phenomena, especially fractured and weathered zones in carbonates with no bauxite deposits.

Tomographic measurements at all micro-locations show that bauxite deposits correlate with low-resistivity zones located below thin zones on high-resistivity surfaces. Zones with lower resistivities clearly stand out across all profiles in the area of Mratnjača. On the TP-10 tomographic profile, the outline of the deposit is located at a position of 180–250 m (Figure 5), and the low-resistivity zone caused by the deposit is located on the tomographic profile at a position of 190–290 m. However, at a position of 250–290 m, resistivity is less than in the rest of the zone; hence, it may be due to a fractured zone of carbonates that increases the low-resistivity zone and apparently increases the size of the bauxite deposit. On the other hand, larger deposit dimensions are also possible because there are no exploration wells in this area to confirm the existence or absence of bauxite. The TP-11 profile crosses the same bauxite deposit located at a position of 147–167 m, and in the inversion tomographic model, the narrow low-resistivity zone is located at a position

of 145–170 m, all of which provides an excellent correlation (Figure 5). The same deposit is transversely intersected by the TP-11 profile and is located at a position of 155–180 m and provides a good correlation with the narrow low-resistivity zone on the tomographic profile at a position of 157–190 m (Figure 5). Second, the assumed small deposit located east of this large deposit, and not explored using wells, cannot be clearly detected in the tomographic models of the TP-11 and TP-12 profiles.

In exploring Istrian bauxites in the northwestern Dinarides using the electrical profiling method, Lapajne [25] showed that bauxite deposits are identified as clear negative electrical anomalies on resistivity profiles measured using several different depth interventions, i.e., the bauxite deposits are also identified due to decreasing resistivity on the measured profiles. The anomalies are even more expressive and pronounced than expected due to the performed forward modelling on theoretical electric models. The author explained this aspect by referring to additional geological processes that point out the decrease in resistivity of the bauxite deposit area. At that time, electrical tomography that gave a resistivity profile did not exist, that is, a cross-section of resistivity by depth; hence, the effects of hanging wall and footwall carbonates were not taken into particular consideration.

Low-resistivity zones on tomographic profiles also correlate well with detected deposits at the Krstače micro-location, where Figure 6 shows the inversion resistivity models for the two profiles, TP-7 and TP-8. The profiles do not show the outlines of the deposit, given that no exploration drilling was carried out in the dense network to provide a precise estimate of the volume of the deposit, but a rough estimate of the outline of the deposit was plotted on the position maps. On the TP-7 profile, two characteristic zones are observed, at a position of 60–125 m and 150–195 m, but on the position map, bauxite deposits are evident at a position of 140–213 m. Accordingly, the second zone correlates with the bauxite deposit. The first zone in which resistivities are exceptionally small (about 20 Ωm) indicates clay deposits, that is, a karstified clay zone within the carbonates. However, it could also be a new deposit or a remaining part, a pocket of an already excavated deposit adjacent to the profile. The characteristic zone on the TP-8 profile is located at a position of 87–150 m, and an exceptionally irregular deposit on the position map is noticeable at a position of 96–140 m. Hence, again, the conclusion is a good correlation with the bauxite deposit (Figure 6).

On all tomographic profiles in the area of the bauxite deposits, a slight decrease in resistivity was observed, given that the resistivity of bauxite is less than that of carbonates, which was observed long ago in previous studies in the Dinarides [25]. Nevertheless, another characteristic phenomenon is found in the area of bauxite deposits as high-resistivity zones in the hanging wall zone of lower resistivity. Ordinarily, the zone of lower resistivity in the area of the bauxite deposits is accompanied by a high-resistivity zone in the hanging wall, that is, at the surface of the inversion resistivity model. These phenomena correlate well with the geological model, given that the sites are Eocene limestones. In general, they are relatively poorly fractured, resulting in very high resistivities exceeding the resistivity of Cretaceous carbonates in the footwall due to stronger fracturing and karstification caused by emersion. In the middle section, there are bauxites with generally much lower resistivities at the level of certain clastic rocks, creating a zone of lower resistivity in the interpreted resistivity models.

Significantly higher seismic velocities are typical of carbonate rocks compared to clastic rocks. However, velocities in carbonate rocks can vary greatly depending on the degree of fracturing. Compact carbonate rocks allow for the highest velocities, while seismic velocities decrease with an increase in the degree of fracturing; hence, they can overlap with the velocities in clastic rocks. Given that bauxite is generally considered a sedimentary rock, the velocities through it will definitely be less than that of carbonate rocks. However, they can overlap with the velocities in fractured and karstified zones within carbonate rocks. No general experience with seismic velocities in karst bauxites was found in the literature, while Nogueira et al. [36] applied seismic refraction in Brazil, measuring velocities of 600 m/s for laterite bauxites. Such velocities indicate poorly bonded, relatively

soft deposits. Due to the relatively higher compactness, slightly higher velocities can be expected for karst bauxites.

In all inversion velocity models for refraction profiles measured in the Posušje area, there is a general increase in the velocities from the surface to greater depths, typical of the refractive responses for karst and carbonate terrains. In the karstified surface zone, the velocities are low due to significant rock fracturing and fragmentation, whereas the fractured rocks decrease with depth, leading to increased compactness and seismic velocities. Even in the area of Vinjani and Krstače, investigations have shown that the presence of bauxite deposits causes velocity inversions, given that bauxites are found in the carbonate, Cretaceous limestones in the footwall and Eocene limestones in the hanging wall. On the RP-7 profile in the area of Krstače (Figure 7), the outline of the deposit is found at a position of 85–162 m, while the characteristic velocity inversion, originating from the bauxite deposit, is evident on the profile at a position of 80–120 m. The deposit is even better outlined in the ray coverage model as a zone with minimal ray coverage due to the mentioned velocity inversion in bauxites. This zone can be defined at a position of 80–140 m, which reflects the presence of the deposit even better than the velocity inversion in the velocity model for the RP-7 profile.

The inversion velocity models for refraction profiles in the area of Mratnjača show small-depth interventions caused by high velocities in the surface zone containing Eocene limestones and velocity inversion in the bauxite deposit zone. On the RP-10 profile, the bauxite deposit is outlined at a position of 75–140 m, and in the velocity model, the zone is observed near the surface caused by relatively compact hanging wall limestones (Figure 8). Due to the concentration of rays inside the limestone at the surface and the small number of rays in the zone of low-velocity deposits, the depth intervention on the refraction profile is minimal; hence, the deposit is not shown in the velocity model. A good correlation between high resistivities on the tomographic profile and high velocities on the seismic profile caused by Eocene limestones is shown in Figure 10. A similar velocity distribution is observed on the RP-11 profile, given that high-velocity carbonate rocks at the surface again mask the effects of rocks with low seismic velocities below them (Figure 8). However, at the beginning of the RP-11 refraction profile, velocity inversion is observed, which correlates to changes in resistivity on the TP-10 tomographic profile and originates from a bauxite deposit. Although the cross-section of the deposit is relatively small on this profile, it is still clearly expressed as a velocity inversion in the inversion velocity model.

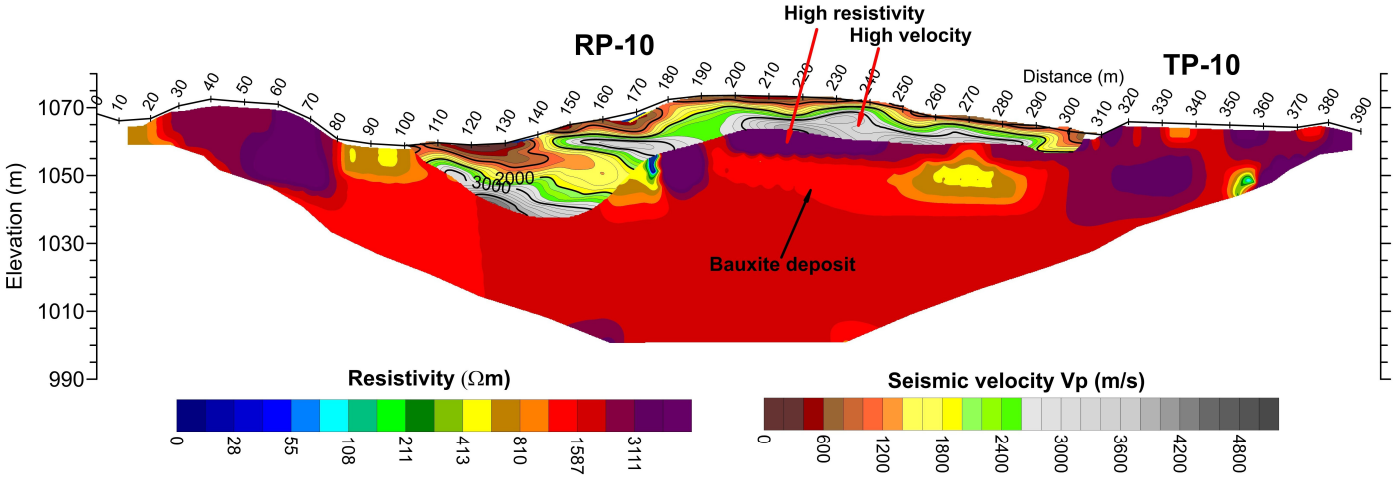


Figure 10. Folded inversion resistivity and velocity models for the TP-10 and RP-10 profiles in the area of Mratnjača. High velocities in Eocene limestones at the surface mask the action of the bauxite deposit with lower velocities below them—velocity inversion.

Thus, the response from bauxite deposits in velocity models is expressed as a velocity inversion, evident in the example for the areas of Krstače (Figure 7) and Mratnjača

(Figure 8). On the other hand, velocity inversion can cause a significant reduction in depth interventions as in the area of Mratnjača, and the bauxite deposit cannot be directly expressed, as noticeable on the RP-10 profile (Figure 8). In this case, it can only be generally ascertained that a very small depth intervention indicates the possible presence of bauxite deposits, but the position of the potential deposit on the refraction profile cannot be reliably determined. Accordingly, the response from the bauxite deposit is expressed in resistivity models for tomographic profiles and velocity models for refraction profiles, though it is much clearer in the resistivity models.

Magnetic profiles do not show any magnetic anomalies that might originate from bauxite deposits (Figure 9). Local variations in magnetisation intensities on profiles originate from surface inhomogeneities or non-geological objects, underground and above-ground steel objects and infrastructural objects. Again, it has been determined that there are no minerals in bauxite that increase its magneticity; hence, bauxite deposits are not found in magnetometric data as clear magnetic anomalies. Specifically, the main magnetic mineral is magnetite, and it can generally be said that its uneven distribution most often causes magnetic anomalies. Hematite, found in bauxite deposits, is most often not magnetic nor is limonite formed by hematite wear.

At the micro-location of Mratnjača-1 and based on some previous research, there are indications of the possible presence of a bauxite deposit; however, data and documentation were lost during the war, so accordingly, tomographic measurements were made on the TP-9 profile. The resistivity model clearly demonstrates the characteristic response from the bauxite deposit in the centre of the profile (Figure 11). On the surface at a position of 99–144 m, there are very high resistivities that indicate carbonate hanging wall rocks, Eocene rocks, which are relatively poorly fragmented. Below them, a zone of low resistivity can be observed at a position of 100–160 m, originating from bauxite deposits. In contrast, the resistivity in the Cretaceous carbonate substrate is expected to increase in the case of a larger depth intervention. The inversion resistivity model indicates larger dimensions of a deposit compared to roughly estimated limits based on recollections from previous studies. Unfortunately, refractive measurements could not be performed due to poor weather conditions, and subsequently, no additional drilling was conducted, but the deposit was immediately exploited for technological reasons.

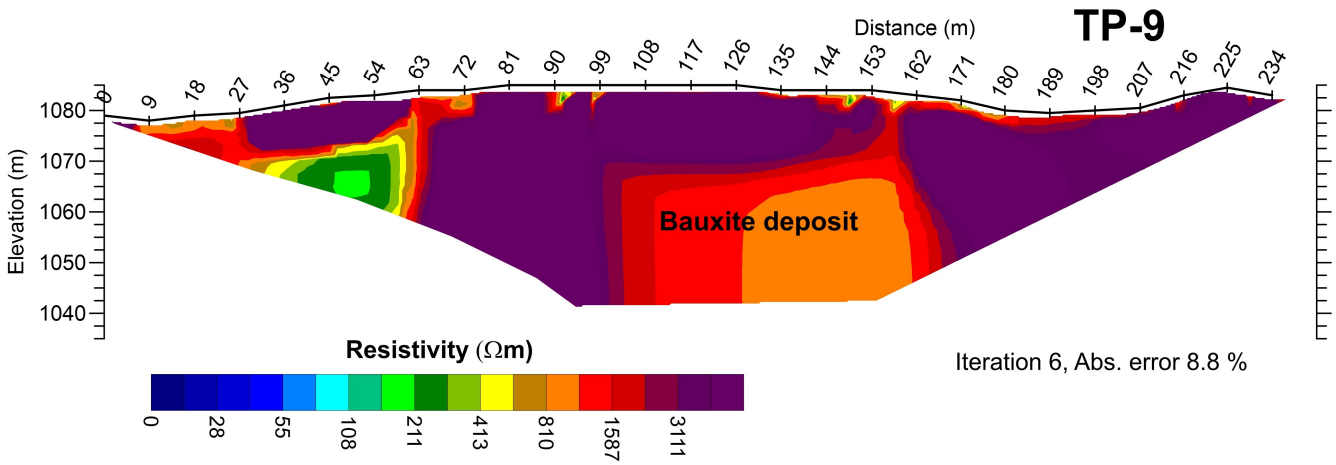


Figure 11. Inversion resistivity model for the TP-9 profile in the area of Mratnjače-1. The bauxite deposit is noticeable as a zone of lower resistivity, while the hanging wall contains Eocene limestones of very high resistivity.

This example suggests that the characteristic resistivity response observed during tomographic measurements on known bauxite deposits can be used to discover new bauxite deposits. However, this is no easy task due to the ambiguity of interpretation using inversion models. Fragmented and karstified zones in carbonates also cause the appearance of low-resistivity zones, such as bauxite deposits. If such zones do not have high resistivity

in the hanging wall, they can be written off as a potential deposit since, in such cases, there are no hanging wall carbonates. Examples of such zones are those at a position of 220–245 m on the TP-7 profile (Figure 6) and at 160–180 m on the TP-10 profile (Figure 5). The biggest problem is deeper fragmented and karstified zones in the carbonates, with less fragmented rocks at the surface, resulting in a response similar to a potential bauxite deposit. Examples of such zones can be seen at a position of 55–125 m on the TP-7 profile (Figure 6) and at 85–115 m on the TP-12 profile (Figure 5). The first zone can perhaps be eliminated due to the very low resistivities that are more indicative of clay fractured zones, while the second zone causes very similar bauxite resistivities, so only exploration drilling will be able to determine whether it is a bauxite deposit or a newly fractured zone. Although the characteristic resistivity response cannot be unambiguously attributed to a bauxite deposit, geophysical surveying allows the extraction of resistivity anomalies and targeted exploration drilling on such anomalies, unlike the previous approach, where locations were determined based on specific surface indications, which we could generally call a "blind" approach. This situation significantly reduces the number of required exploration wells in detecting bauxite deposits and significantly increases exploration efficiency while reducing associated costs.

7. Conclusions

Bauxite deposits are found in exceptionally complex geological models in the Dinarides and are deposited in depressions and pockets in the carbonate substrate of karst terrains. In the hanging wall of the deposit, there may be carbonate rocks or clastic rocks. Due to complex lithological and structural relationships, irregular outlines of deposits and their relatively small dimensions, detecting a karst type of bauxite ore deposits is a demanding geophysical task. That is why the published literature lacks solutions to this complex problem.

Geophysical surveying was carried out on karst bauxite deposits in the area of Posušje in Bosnia and Herzegovina, which generally represents the problem of researching bauxite deposits in the Dinarides and similar geological models in the Mediterranean. The problem associated with the geophysical inversion of data, that is, the general problem of interpretation, is the ambiguous interpretation or the absence of a single solution, meaning that several possible solutions meet the measured data set. One of the ways of narrowing the boundaries of ambiguity or increasing the precision of interpretation is the application of several geophysical research methods. This is why basic near-surface geophysical methods were applied in researching the karst bauxite deposits, which proved to be very effective when a series of surface research, electrical tomography and seismic refraction, and magnetometric measurements were performed. Electrical tomography and seismic refraction facilitate research within relatively short deadlines in a cost-effective manner. Other methods may also be effective in this research, such as gravimetry and passive seismology. However, research using these methods takes longer due to the longer collection of field data (passive seismology) and additional precise geodetic measurements (gravimetry) and is thus somewhat more expensive. These are significant exacerbating circumstances in practical research that most often require solving problems within very short timeframes.

Geophysical measurements were performed on already discovered bauxite deposits in order to reliably determine the possibility of identifying deposits on geophysically inversion-interpreted models. In inversion models using both methods, electrical tomography and seismic refraction, resistivity and velocity models, bauxite deposits were clearly recognised as characteristic geophysical responses. The characteristic resistivity response was confirmed by the discovery of a new deposit that was exploited soon after its discovery. Unfortunately, magnetometric measurements have shown that no magnetic anomalies could be associated with bauxite deposits, meaning there are no magnetic minerals in the deposit or magnetite minerals that caused such anomalies.

In all inversion resistivity models, a slight decrease in resistivity is observed because the resistivity of bauxite is less than that of carbonates in the area of the bauxite deposits, whereas above the deposits, in the near-surface rocks, there is a zone of very high resistivity. In general, the zone of lower resistivity in the area of the bauxite deposit is accompanied by a zone of very high resistivity in the hanging wall. These phenomena correlate very well with the geological model given that the hanging wall rocks in these sites are Eocene limestones, mostly poorly fragmented with very high resistivities. The resistivity of Cretaceous carbonates in the deposit footwall is somewhat less due to greater fracturing and karstification caused by emersion.

In the inversion velocity models of refraction profiles, the response of bauxite deposits is expressed as velocity inversion because bauxite deposits are characterised by lower seismic velocities than hanging wall carbonates. Also, under the deposit are again higher velocities due to the carbonate substrate of the deposit. Velocity inversion can cause a significant decrease in depth interventions, and the bauxite deposit can sometimes not be directly measured. In this case, it can generally be said that a very small depth intervention indicates the possible presence of bauxite deposits.

Accordingly, the response of bauxite deposits is expressed in resistivity models for tomographic profiles and velocity models for refraction profiles, though it is much more evident in resistivity models. Therefore, the conclusion is that electrical resistivity tomography should be considered a basic method for exploring karst bauxite deposits. Seismic refraction provides a better characterisation of deposits and reduces the ambiguous interpretation, thus increasing the effectiveness of geophysical research. As a last resort, electrical tomography can be independently applied to give satisfactory research results. On the other hand, seismic refraction should be combined with electrical tomography because, in some cases, the depth penetration is greatly reduced due to the pronounced velocity inversions; hence, the bauxite deposit cannot be directly expressed in the inversion velocity model.

However, some other phenomena in inversion models cause similar responses to bauxite deposits, namely fragmented and karstified zones in carbonates, creating low resistivity zones. Some of these zones do not have high resistivity in the hanging wall, so they can be written off as a potential deposit given that, in this case, there are no hanging wall carbonates. However, significant difficulties are caused by deeper fractured and karstified zones in the carbonates above, with less fragmented rocks, resulting in a similar response as with potential bauxite deposits. This problem can only be solved by exploration drilling to determine whether the characteristic geophysical response is caused by a bauxite deposit or a newly fractured carbonate zone. However, targeted exploration drilling in detected geophysical anomalies, unlike the previous approach where locations were determined "blindly", greatly reduces the number of necessary exploration wells for detecting bauxite deposits and significantly increases exploration efficiency.

Author Contributions: Conceptualisation, F.Š.; methodology and software, F.Š.; validation, F.Š.; formal analysis, F.Š. and J.K.; investigation, F.Š., J.K., I.P. and L.P.; resources, F.Š.; data curation, F.Š., J.K., I.P. and L.P.; writing—original draft preparation, F.Š. and J.K.; writing—review and editing, F.Š. and J.K.; visualisation, supervision and project administration, F.Š., J.K. and I.P.; funding acquisition, F.Š., J.K., I.P. and L.P. All authors have read and agreed to the published version of the manuscript.

Funding: EU Horizon Europe project Agile Exploration and Geo-modelling for European Critical Raw materials—AGEMERA, Grant agreement ID: 101058178. Seismic equipment was supported by the Virtulab project (KK.01.1.1.02.0022), co-funded by the European Regional Development Fund.

Data Availability Statement: The raw data supporting the conclusions of this paper will be made available by the corresponding author on request due to internal policy.

Acknowledgments: We thank Saša Kolar and Ana Brcković, who participated in the field measurements.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of this study; in the collection, analyses, or interpretation of data; in the writing of this manuscript; or in the decision to publish the results.

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