**Advanced Engineering Science**
http://publish.mersin.edu.tr/index.php/ades
**e-ISSN 2791-8580**

# Exploration of the carbonate-hosted Pb-Zn deposit via using IP/Resistivity and ground penetrating radar (GPR) methods in Yahyalı (Kayseri-Türkiye)

**Cihan Yalçın** *[1], **Hurşit Canlı** [2]

[1]Ministry of Industry and Technology, World Bank Project Implementation Unit, Ankara, Türkiye, cihan.yalcin@sanayi.gov.tr
[2]Haliç Mineral Exploration and Drilling, İstanbul, Türkiye, hursitcanli@gmail.com

Cite this study: Yalçın, C., & Canlı, H. (2023). Exploration of the carbonate-hosted Pb-Zn deposit via using IP/Resistivity and ground penetrating radar (GPR) methods in Yahyalı (Kayseri-Türkiye). Advanced Engineering Science, 3, 125-136

**Keywords**
Carbonates
Pb-Zn
IP/Resistivity
Ground Penetrating Radar
Mining

**Research Article**
Received:31.08.2023
Revised: 28.09.2023
Accepted:10.10.2023
Published:17.10.2023

**Abstract**
In the field of mineral exploration, the identification and characterization of economically viable ore deposits are key challenges. Lead (Pb) and zinc (Zn) deposits are of great importance in global metal supply chains, and the exploration of these resources requires innovative and reliable methodologies. Efficient and accurate exploration methods are essential for locating and assessing Pb-Zn deposits. These methods help determine the potential of ore deposits, optimize resource utilization, and support sustainable mining practices. By employing advanced techniques and technologies, mineral exploration endeavors can effectively identify and evaluate Pb-Zn deposits, contributing to the global metal supply chain and ensuring the availability of these critical resources. This paper presents a comprehensive study on the exploration of Pb-Zn deposits using the induced polarization (IP) and resistivity methods. The aim of this study is to improve the accuracy and efficiency of mineral resource assessment in order to contribute to sustainable mining practices and resource management. The Taurus Orogenic Belt is known for its significant Pb-Zn mineralization, and the Aladağ-Zamantı province within this belt has been a major area of mining activities. The Yahyalı Region, located within this belt, exhibits Pb-Zn ore mineralization in Devonian-aged carbonates. Geophysical studies were conducted in the Yahyalı Region using IP/Resistivity and Ground Penetrating Radar (GPR) methods. Measurements were taken along specific profiles and evaluated in combination to determine the ore geometry and potential in the area. These visual representations provide crucial information for effective planning and coordination of mining operations in the region. The utilization of IP/Resistivity and GPR methods and the generated visual information contribute significantly to the success of mining activities in the Yahyalı Region, facilitating the exploration and extraction of Pb-Zn deposits. By employing innovative geophysical techniques, this study aims to enhance the efficiency and sustainability of mining practices in this mineral-rich area.

## 1. Introduction

The geological community has been actively searching for reliable methods to locate and assess mineral deposits for a long time. Traditional exploration techniques like geological mapping and drilling have limitations in terms of coverage, cost, and potential environmental impact. Consequently, geophysical methods have gained significant attention as valuable tools for mineral exploration. Among these methods, induced polarization (IP) and resistivity techniques have proven to be effective in identifying and characterizing mineral deposits beneath the Earth's surface. The exploration of Pb-Zn ore systems holds great significance due to their economic value and wide distribution. Copper, lead, and zinc are crucial elements used in various industries such as electronics, construction, and transportation. Therefore, developing efficient techniques to locate and evaluate these deposits is of utmost importance in order to meet global demand and optimize resource utilization.

Electrical resistivity tomography (ERT) is a widely used geophysical method for characterizing subsurface structures and understanding geological settings [1-2]. It provides valuable information about the distribution of electrical resistivity in the subsurface, allowing for the identification of different geological features and potential mineralization zones.

Induced polarization (IP) is another geophysical technique that can provide valuable insights into subsurface conditions. It has the capability to detect small conductive rocks that may not be readily observable through other methods. IP measurements can be used to identify the presence of sulfur in minerals, mineral deposits, and soils, as well as to characterize the polarizability of subsurface materials [3].

This is a powerful combination of methods, as it can provide information about both the electrical conductivity and the polarizability of the subsurface materials. This information can be used to identify areas where sulfide minerals are likely to be present, as these minerals typically have low resistivity and high chargeability.

Ground penetrating radar (GPR) is a technique that uses radio waves to detect underground objects. GPR can be used to determine the location, size, and depth of underground objects. GPR is used in a variety of applications, including archaeology, engineering, geology, and construction [4]. GPR applications for mining geophysics have received a lot of attention [5].

GPR works by sending a radar transmitter into the ground surface. The radar transmitter sends radio waves into the ground. The radio waves reflect off of underground objects and are received by a radar receiver. The radar receiver uses the reflected radio waves to determine the location, size, and depth of underground objects.

Geological structures where sulfide minerals occur often exhibit low resistivity and high chargeability responses [6-7]. These geophysical signatures can be indicative of the presence of sulfide mineralization, including lead-zinc (Pb-Zn) deposits. Successful applications of resistivity and IP methods have been documented in various studies related to mineral exploration, including Pb-Zn exploration [8-9].

Pb-Zn mining in Türkiye has a long history dating back to the Roman period [10]. The Taurus Orogenic Belt, particularly the Aladağlar-Zamantı province in the Eastern Taurus Mountains, is known for its significant carbonated Zn-Pb production in Türkiye [11-13]. The study area in the southeast of Yahyalı region is located within this belt and has attracted the interest of researchers due to its potential for Pb-Zn deposits.

In this study, geophysical investigations were conducted to assess the ore potential of the Pb-Zn deposit in the southeast of Yahyalı, Kayseri, Türkiye. The study aimed to obtain important data specific to the region and contribute to the existing literature on the subject. By utilizing geophysical methods such as ERT, GPR, and IP, valuable insights can be gained regarding the subsurface characteristics and potential mineralization zones in the study area.

## 2. Material and Method

Using the induced polarization principle, the IP/Resistivity approach maps the distribution of subsurface resistivity and chargeability.

The ratio of the voltage obtained after the current is stopped to the voltage measured during the current supply is known as true chargeability and is indicated by the symbol (M"). It normally falls between 0 and 1000 mV/V and is measured in millivolts per volt (mV/V).

A stainless-steel electrode is driven into the ground to inject an electric current during applications of the resistivity (electrical resistivity) method. Two electrodes are then installed at various points to measure the voltage differential within the ground. The measured voltage is recorded in volts (often millivolts), and the applied current is measured in amperes (typically milliamperes). These figures, along with the electrode array's geometric factor K (array factor), are used to determine the apparent resistivity (in ohm-m) at the precise measurement site. Below the electrode array system's middle, the determined value is assigned.

In the study area, an AGI brand, 8-channel, 84-electrode resistivity, and IP measurement device with 84 electrodes was utilized. The Dipole-Dipole Gradient method was applied, and a total of 19 profiles were generated with electrode spacing ranging between 20-10-7 meters. The line was prepared using a Magellan handheld GPS with a positioning accuracy of 3 meters. The collected data were analyzed using the Earth Imager 2D evaluation program. For this study, data from six profiles are presented.

The IP/Resistivity method is a powerful tool for mineral exploration, as it can be used to map the distribution of sulfide minerals, which are often associated with economic mineral deposits.

Here are some additional details about the IP/Resistivity method:

- The IP/Resistivity method is based on the principle that certain rocks exhibit capacitive behavior, retaining some electric current for a period of time after the current is turned off. This capacitive behavior is caused by the presence of polarizable minerals, such as sulfide minerals.
- The IP/Resistivity method is typically used in conjunction with other geophysical methods, such as magnetics and gravity, to provide a more complete picture of the subsurface geology.
- The IP/Resistivity method is a relatively non-intrusive method, as it does not require the drilling of boreholes. This makes it a cost-effective method for mineral exploration.

GPR works by transmitting high-frequency electromagnetic pulses into the ground via an antenna. These pulses travel through various materials and are detected and recorded by the same or different receiving antennas. Geophysicists and researchers can create detailed subsurface profiles and identify subsurface features such as buried objects, geological layers, voids, or even potential hazards by analyzing the time and amplitude of these reflected signals.

GPR has proven to be a valuable geophysical tool in the exploration and characterization of subsurface deposits, including the exploration of Pb-Zn (lead-zinc) deposits. GPR provides a non-destructive means of investigating the geological composition and structural features associated with Pb-Zn mineralization due to its non-invasive nature and high-resolution imaging capabilities.

GPR studies were conducted over an 8-kilometer area using Python and Zond devices. It is a significant benefit that these devices are portable, have no negative environmental impact, can collect data much faster than other geophysical methods, and can perform high-resolution underground imaging.

The study area includes Kayseri's southeastern part of Yahyalı.

Dark blue and light blue tones dominate the elevation color contour map of the study area (Figure 1), while green, yellow, orange, red, and white tones indicate steep slopes and high elevations such as hills or mountains. The geophysical surveys were carried out at an average elevation of 1700-1900 meters, as shown on the map (Figure 1), and the points represent the IP/Resistivity coordinates of the study area.

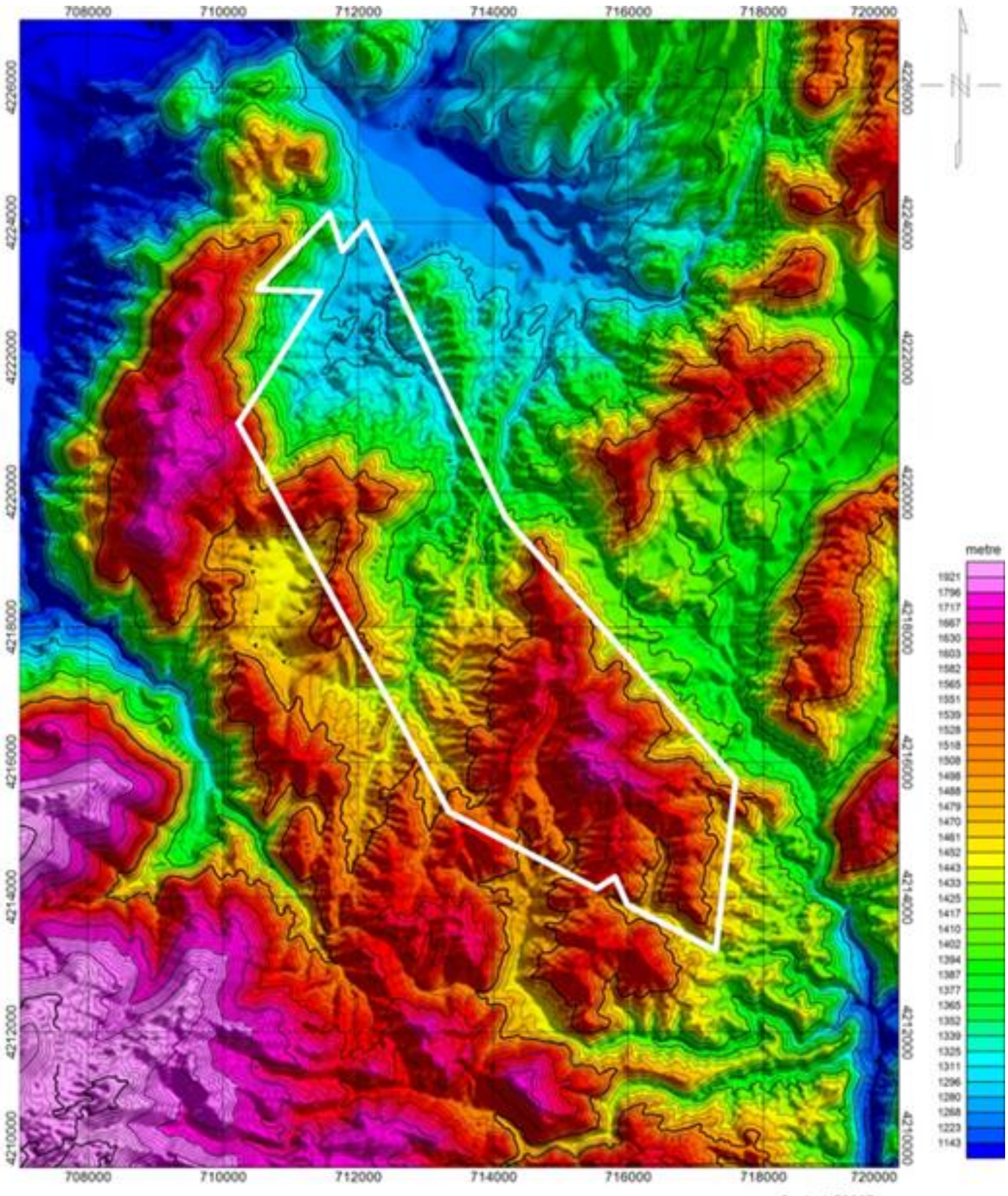


**Figure 1.** Colour, contour (topography) map of the study area and its surroundings with elevation data, and geophysical profiles of the study area.

### 2.1. Geological framework and mineralization

The study area is in an area with a high concentration of nap tectonic fractures and faults in the Eastern Taurus Mountains. Aladağ and Yahyalı nappes are found together in this region [10]. Both tectonostratigraphic units have similar lithological characteristics and host Pb-Zn mineralization in different places [10]. This region is also known as the "Aladağ-Zamantı Zn-Pb Belt" and plays an important role in Turkish Zn-Pb mining. Mineralization in the Aladağ Nappe is linked to Devonian-aged carbonates. Smithsonite, anglesite, cerusite, and other alteration minerals can be found near the surface of the ore zone, which is formed by veins and veinlets running east-west. The primary ore minerals are galenite and sphalerite [14].

## 3. IP-Resistivity applications

In order to obtain a more accurate geological representation, the resistivity and chargeability data collected from the profiles were compiled and inverted. To correct for topographic effects in the inverse analysis, the GPS elevation data of the profiles were utilized.

The inverse solutions of the profiles resulted in chargeability and resistivity graphs. These graphs were color-coded to provide a visual representation of the data. Warm red-purple colors were used to indicate high chargeability and resistivity values, while cool colors like green and blue were used to represent low values. The areas with high resistivity, which are associated with karstic sinkholes, were considered important targets in this study.

Most of the profiles measured in the field exhibited normal chargeability values. However, there were certain areas where high chargeability values were obtained, indicating the possible presence of sulfide ores. These high chargeability values suggest the potential for significant mineralization in those areas.

High resistivity and chargeability were observed in the first profile at an electrode spacing of 20 meters. There was a partial correspondence between chargeability and resistivity values at the 4$^{th}$ electrode (65 meters) depth, indicating the potential presence of a low-grade ore body with relatively small reserves (Figure 2). This area may be worth further exploration and evaluation to determine the mineralization's economic viability.

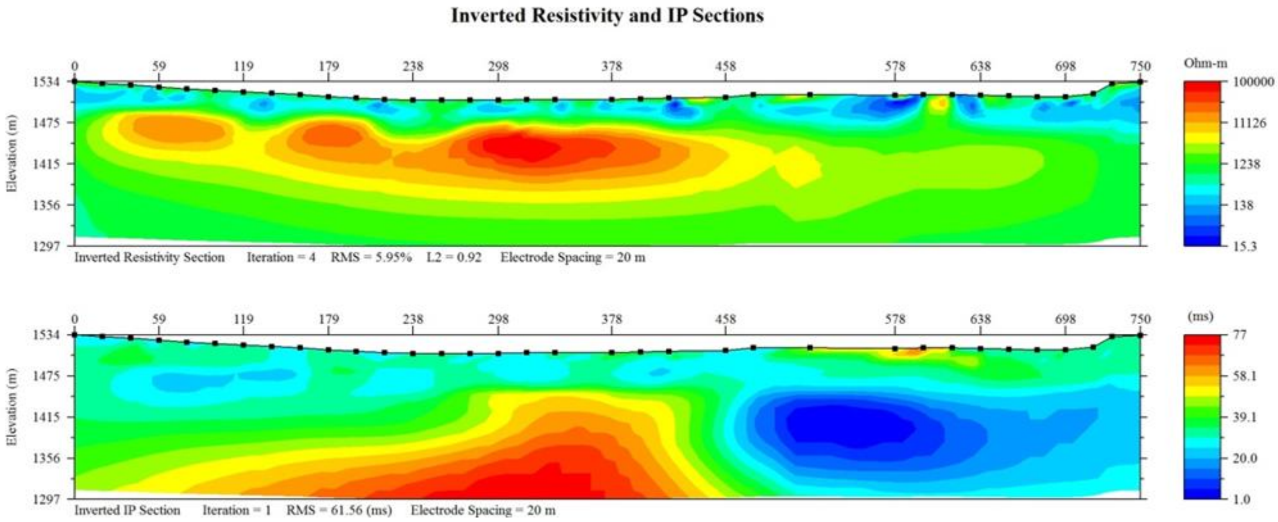


**Figure 2.** The inverted resistivity and IP sections of the 1$^{st}$ profile.

In the 2$^{nd}$ profile, similar to the 1$^{st}$ profile, the results of the IP/Resistivity surveys in the second profile suggest the presence of a low-grade ore body with small reserves. The high resistivity and high chargeability values at the electrode spacing of 20 meters and the partial correspondence between chargeability and resistivity values at the 4$^{th}$ electrode (65 meters) depth are consistent with the presence of a sulfide mineral deposit (Figure 3).

These findings further support the potential mineralization in this area, and it may warrant further investigation and exploration to assess the economic feasibility of extracting the ore.

An anomaly was discovered in the third profile at a depth of 32 meters and an electrode spacing of 10 meters (Figure 4). This anomaly is distinguished by high resistivity and chargeability values, indicating the presence of a significant mineral deposit in the subsurface. The occurrence of sulfide minerals, which are commonly found in ore deposits such as lead-zinc mineralization, is often associated with the combination of high resistivity and high chargeability.

The presence of this anomaly suggests that there may be a substantial mineralized zone at the indicated depth. Further investigation and exploration are recommended to fully understand the extent and economic viability of the mineral deposit in this area. Proper assessment and planning based on this anomaly can contribute to more efficient and sustainable mining practices in the region.

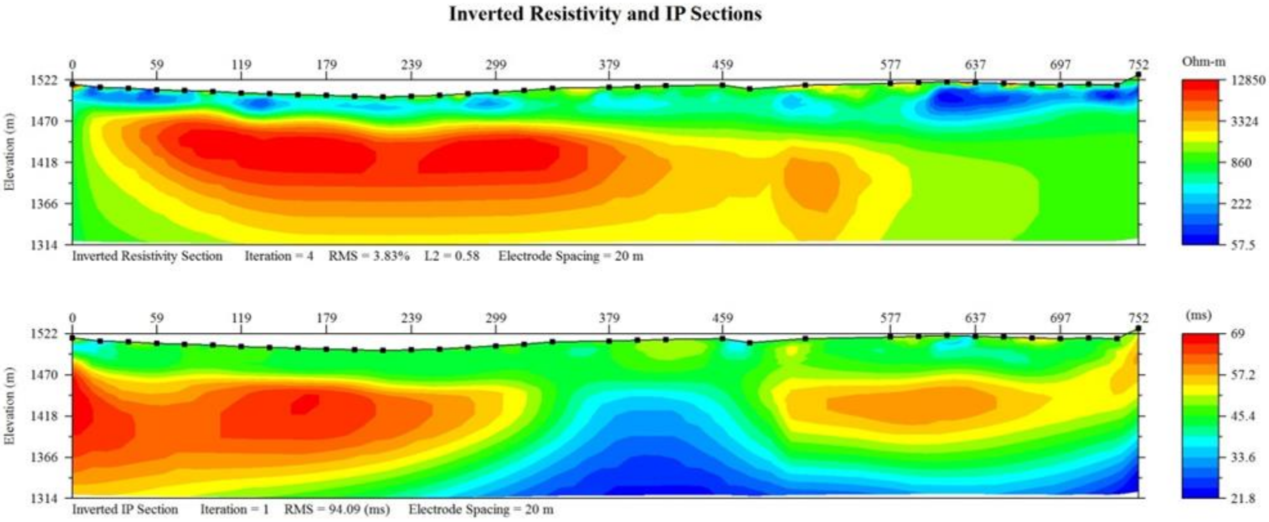


**Figure 3.** The inverted resistivity and IP sections of the 2nd profile.

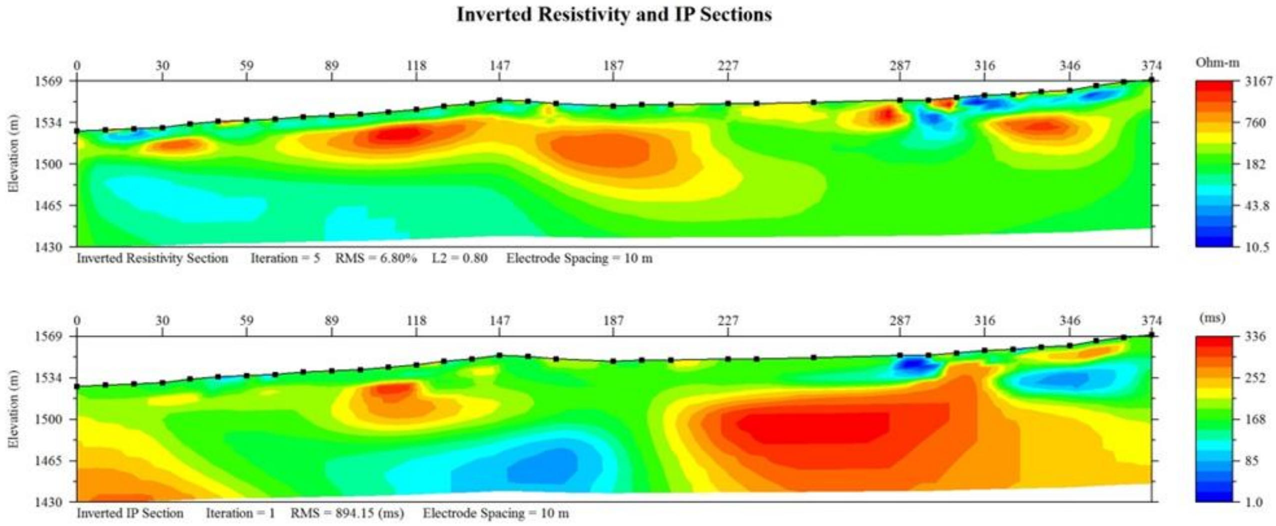


**Figure 4.** The inverted resistivity and IP sections of the 3rd profile.

In the 4th profile with an electrode spacing of 20 meters, the dominant feature observed is low chargeability, which gradually decreases towards the end of the profile. Additionally, resistivity values were observed to be high throughout the profile (Figure 5).

The low chargeability along the profile suggests that there is a lower concentration of polarizable sulfide minerals in this section. This could indicate a potential transition zone where the mineralization becomes less significant or starts to diminish.

On the other hand, the high resistivity values observed along the profile indicate the presence of more resistive rocks or materials. These resistive rocks may act as barriers or confining units for the mineralization, affecting its lateral extent or continuity.

It is important to note that geophysical anomalies are complex, and further investigations, including additional geophysical surveys and drilling, would be required to fully understand the geological structures and potential mineralization in this area. The combination of geophysical data and other geological information will provide a more comprehensive picture of the subsurface and aid in the assessment of the mineral potential in the 4th profile of the study area.

Significant anomalies were observed at a distance of 146 meters along the profile and at a depth of 40 meters in the fifth profile with an electrode spacing of 10 meters (Figure 6).

The detected anomalies could be indicative of potential mineralization or subsurface features that differ from the surrounding geological formations. The anomalies could be caused by the presence of polarizable sulfide minerals or other conductive materials, implying the presence of ore bodies or mineralized zones.

The location and depth of these anomalies are crucial information for further exploration and targeted drilling activities. Follow-up investigations, such as core drilling and geological sampling, should be conducted in the vicinity of the observed anomalies to confirm the presence and extent of mineralization. Additionally, integrating the geophysical data with geological and geochemical data can help to better understand the nature and economic potential of the mineral deposits in the 5th profile of the study area (Figure 6).

In the 6th profile with an electrode spacing of 10 meters, a significant anomaly was observed at a distance of 336 meters along the profile and at a depth of 32 meters (Figure 7).

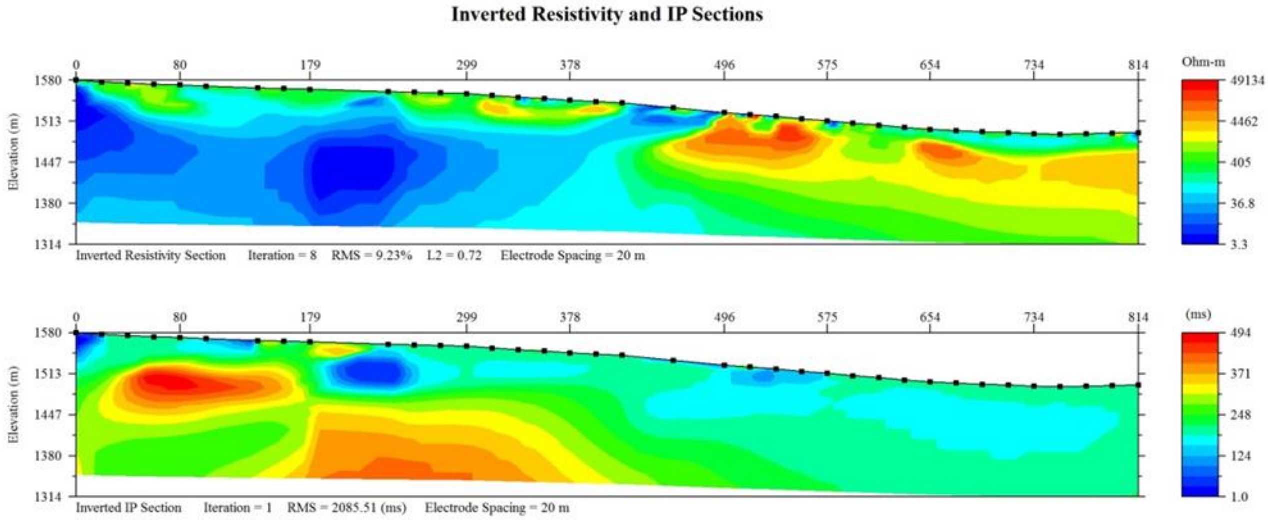


**Figure 5.** The inverted resistivity and IP sections of the 4th profile.

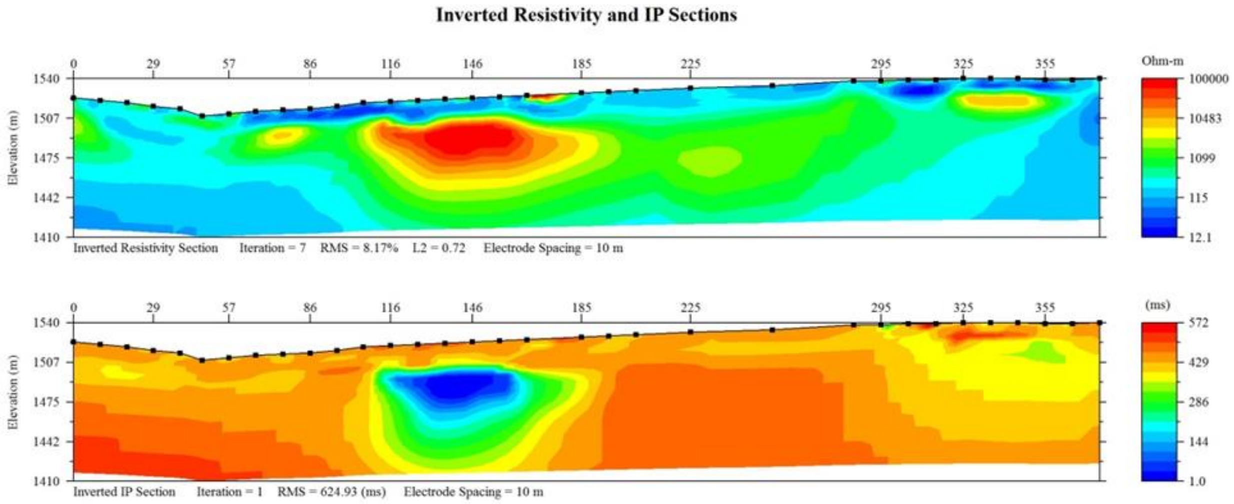


**Figure 6.** The inverted resistivity and IP sections of the 5th profile.

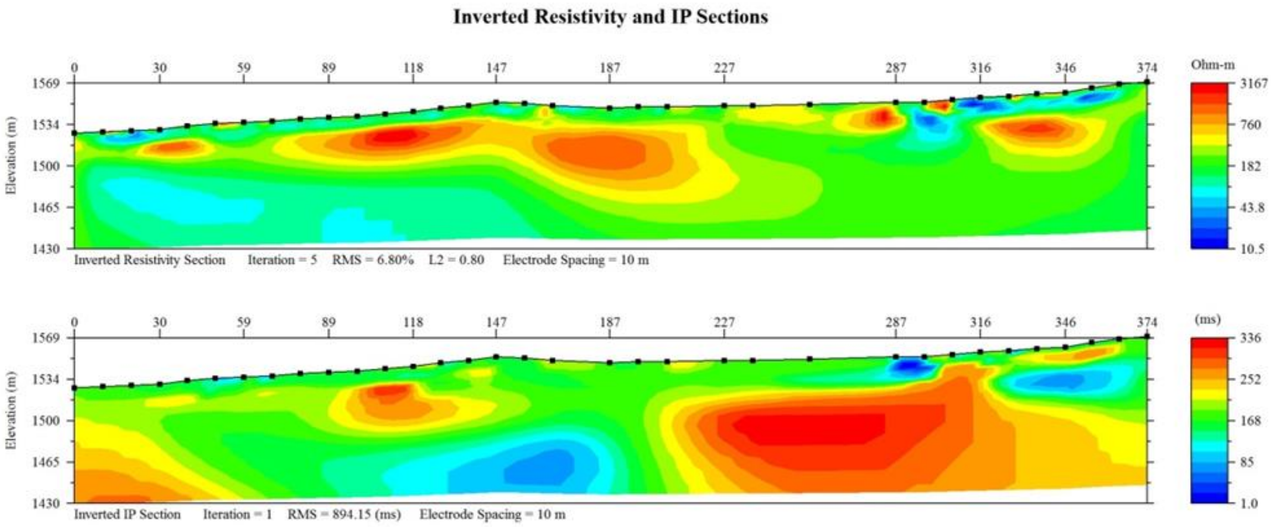


**Figure 7.** The inverted resistivity and IP sections of the 6th profile.

The observed anomaly could indicate the presence of mineralization or a subsurface feature that differs from the surrounding geological formations. The anomaly may be associated with the presence of polarizable sulfide minerals or other conductive materials, which could suggest the presence of ore bodies or mineralized zones.

The location and depth of this anomaly are valuable information for further exploration efforts. Additional investigations, such as core drilling and geological sampling, should be conducted around the identified anomaly to verify the presence and extent of potential mineralization.

By integrating the geophysical data with geological and geochemical information, a comprehensive understanding of the subsurface geology and potential mineral deposits in the 6th profile can be achieved. Such integrated studies play a crucial role in guiding mineral exploration activities and optimizing resource exploration and development in the study area.

## 4. GPR Applications

The georadar systems, Python GPR and Zond were used in the study area to gather subsurface data. While the data obtained from the Python GPR system was reliable and provided clear information, the data collected from the Zond-branded georadar system appeared to be noisy and difficult to interpret.

In the Python GPR images (Figure 8, 9, and 10), the fracture and fracture systems are well represented, and the most significant fracture crack system in the drilling area was identified. These images offer valuable insights into the subsurface structures and potential fractures, which can be crucial for understanding the geological setting and identifying potential mineralization zones.

On the other hand, the Zond-branded georadar data (Figure 11 and 12) were not suitable for a clear interpretation. The noise in the data may have resulted in limited visibility of subsurface features, making it challenging to analyze and interpret the images effectively.

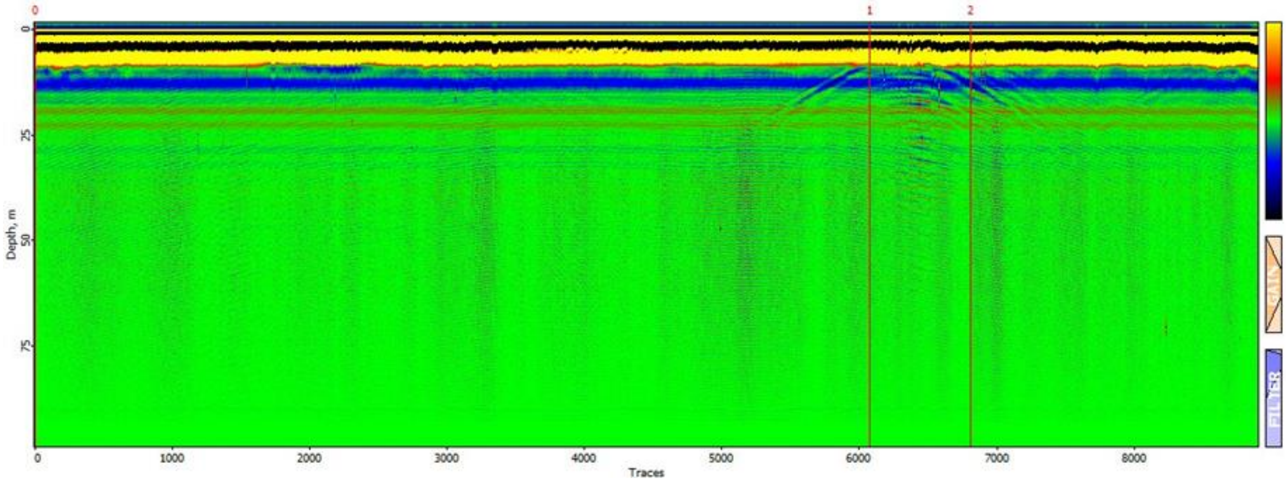


**Figure 8.** Representative Python GPR image (1 and 2 drilling points).

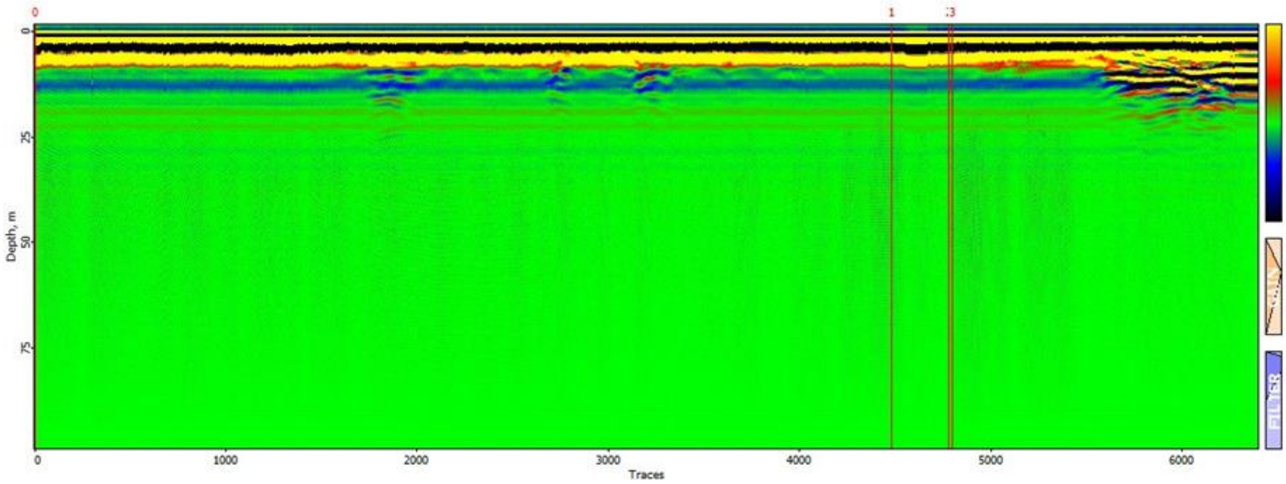


**Figure 9.** Representative Python GPR image (drilling points).

Despite the limitations of the Zond georadar data, the Python GPR system proved to be a valuable tool in providing reliable subsurface information, especially regarding fracture and fracture systems in the drilling area.

Overall, the combination of geophysical techniques like electrical resistivity tomography (ERT), induced polarization (IP), and georadar (such as Python GPR) can offer a comprehensive approach to mineral exploration, helping to improve the accuracy and efficiency of identifying potential ore deposits and understanding the subsurface geology in the study area.

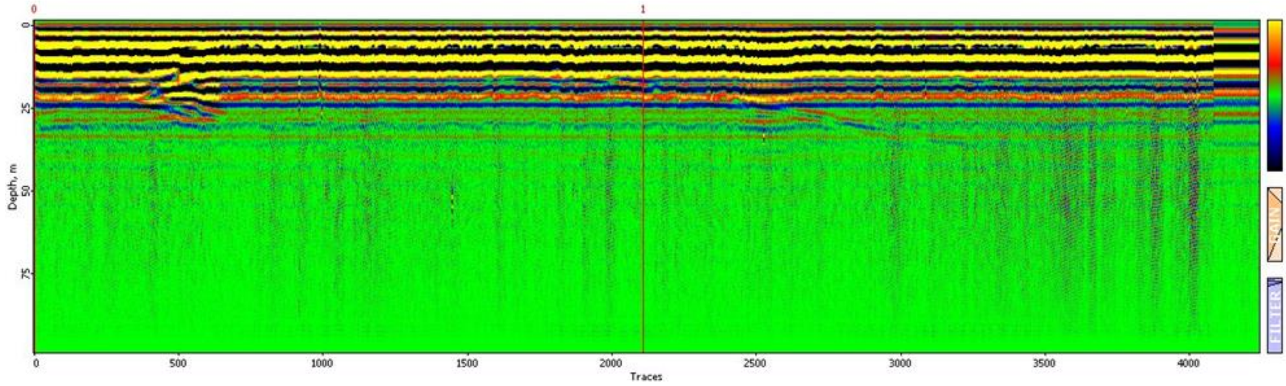


**Figure 10.** Representative Python GPR image (1 drilling point).

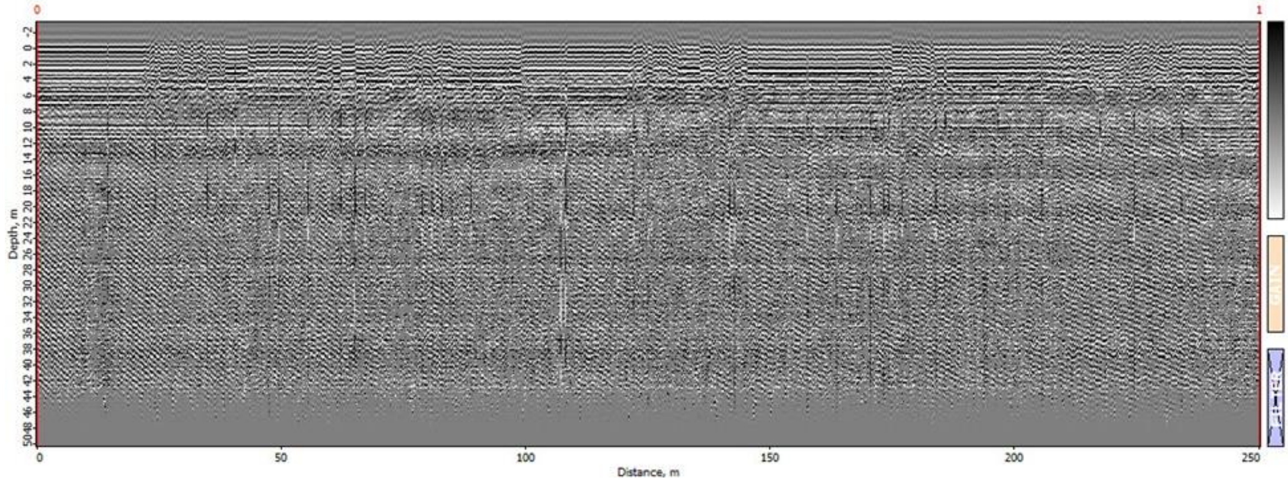


**Figure 11.** Representative Zond GPR image.

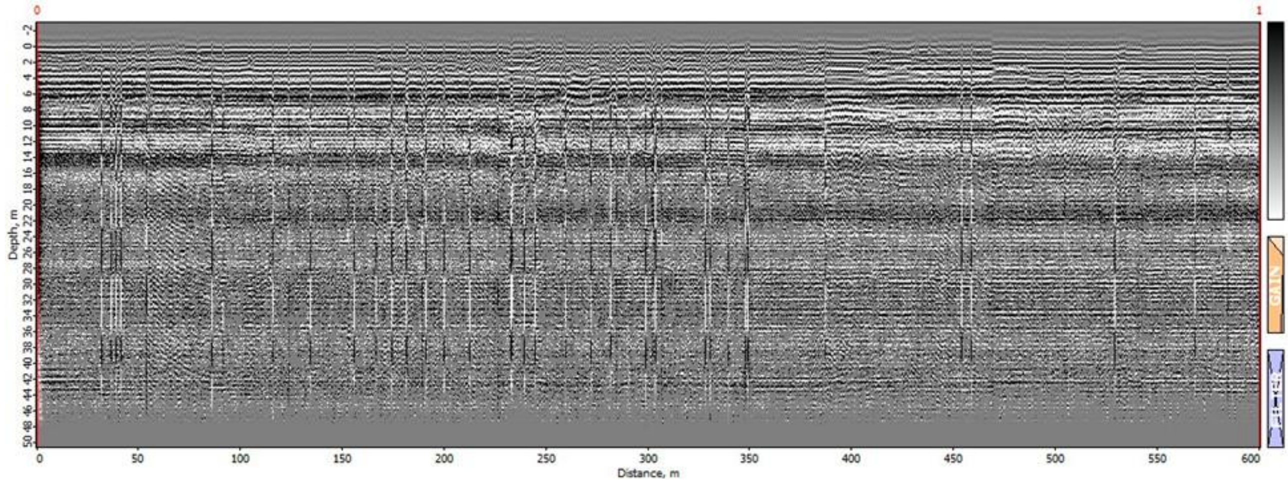


**Figure 12.** Representative Zond GPR image.

## 5. Results and Discussion

The induced polarization (IP) method is a valuable enhancement to electrical methods in mineral exploration [15]. It assesses the chargeability of soil materials, which provides insights into the soil's capacity to store and restore electric currents when injected and interrupted [16-18]. This information is essential for identifying potential mineralization zones and understanding the subsurface geology.

On the other hand, resistivity tomography examines the horizontal and vertical distributions of the soil's electrical properties, specifically the resistivity [19-20]. By passing an electric current through the soil using a pair of electrodes and measuring the resultant potentials via another pair of electrodes, it quantifies the resistivity of the ground. This method allows for the assessment of different subsurface layers and their electrical properties.

In the study area, both the induced polarization and resistivity tomography methods were implemented, and previous exploration drillings were conducted in two different areas with suspected mineralization. By analyzing the data from these methods and the drillings, several important findings were revealed:

The potential mineralization in the study area is located northeast of the present drilling area. This indicates that there might be untapped mineralization zones in that direction, which warrants further investigation.

Young sedimentary units and altered sedimentary rocks in the study area have lower densities compared to their surroundings. This information can help in identifying specific rock formations that are more likely to host mineralization.

Priority should be given to the areas with Paleozoic-aged carbonate rocks in the study area. These rocks are more likely to contain mineral deposits and can be potential targets for further exploration.

Areas with high chargeability characteristics have been identified as potential areas. The high chargeability values suggest the presence of polarizable sulfide minerals, which are often associated with mineralization.

Overall, the integration of induced polarization and resistivity tomography data with the results from exploration drillings has provided valuable insights into the potential mineralization zones and the geological characteristics of the study area. These findings can guide future exploration efforts and help in optimizing mineral resource assessment and exploration activities.

Geophysical methods such as resistivity, induced polarization (IP), and self-potential (SP) have proven to be effective tools in the exploration and confirmation of sulfide deposits. These methods allow for the mapping and delineation of potential mineralization zones, which is crucial for successful mineral exploration and resource assessment [21-22].

One such example is the integrated geoelectrical study conducted in Umuobuna, Uburu, Ohaozara local government area, southeastern Nigeria, where electrical resistivity tomography (ERT) and induced polarization (IP) were combined to identify potential zones of Lead-Zinc mineralization [23]. The integration of these geophysical techniques provides a comprehensive understanding of the subsurface geology and helps identify areas of interest for further exploration and drilling campaigns.

Similarly, in the Bolkardağı region of the Central Taurus, geophysical measurements were performed to identify potential areas for bauxite mineralization using resistivity and induced polarization (IP) measurements [24]. The results showed that areas with low resistivity and high chargeability values were associated with potential bauxite mineralization. This correlation between geophysical measurements and mineralization indicates that combining IP and resistivity data can be a powerful tool for locating metallic mineral deposits.

Yalçın et al. [25] studied in the Kavşut (Göksun-Kahramanmaraş) region is an important application of the IP and resistivity methods for detecting polymetallic enrichments. Polymetallic mineral deposits, such as those containing copper, lead, and zinc, are economically significant and necessary in a variety of industries. Overall, Yalçın et al. [25] emphasize the importance of geophysical methods such as IP and resistivity in the exploration and detection of polymetallic enrichments, thereby contributing to the advancement of mineral exploration practices and resource development in the Kavşut region and beyond.

As geophysical survey technology continues to advance, we can expect even more accurate and detailed maps of the subsurface geology. This will lead to a better understanding of the distribution of mineral deposits, allowing for more successful exploration and mining operations worldwide. The use of compatible IP and resistivity values in mineral exploration has proven to be a valuable approach, and it is likely to continue being a prominent method in the field.

The use of compatible IP and resistivity values is a powerful tool for mineral exploration, and it is being used in many different parts of the world. As the technology for geophysical surveys continues to improve, we can expect to see even more accurate and detailed maps of the subsurface geology. This will lead to a better understanding of the distribution of mineral deposits, and ultimately to more successful exploration and mining operations. As the technology for geophysical surveys continues to improve, we can expect to see even more accurate and detailed maps of the subsurface geology. This will lead to a better understanding of the distribution of mineral deposits, and ultimately to more successful exploration and mining operations.

One of the key benefits of using GPR for Pb-Zn deposit exploration is the ability to visualize and delineate subsurface structures with high resolution. Geologists and mineral exploration experts can use this information to identify potential ore bodies, geological structures, and mineralization patterns. Geoscientists can gain insights into the depth, shape, and distribution of the Pb-Zn deposits by analyzing GPR data, assisting in the development of targeted exploration strategies, and resource estimation.

Furthermore, GPR is a non-destructive, low-cost alternative to traditional exploration methods. GPR does not disturb the site, unlike drilling or excavation, making it environmentally friendly and suitable for sensitive or protected areas. Furthermore, GPR surveys can cover large areas quickly, allowing for efficient preliminary evaluations of potential Pb-Zn mineralization zones.

Indeed, Ground Penetrating Radar (GPR) is a valuable geophysical method that has found applications in various fields, including mineral exploration. Erten et al. [26] focused on the application of GPR in bauxite deposits, showcasing its supportive role in conjunction with other geophysical methods.

GPR works by emitting high-frequency electromagnetic waves into the subsurface and recording the reflected signals. This technique is particularly useful for investigating shallow subsurface layers and identifying buried structures, such as fractures, voids, and geological boundaries. In the context of mineral exploration, GPR can help identify and delineate potential mineralization zones, providing valuable information to complement other geophysical methods like resistivity and induced polarization.

The combination of GPR with other geophysical techniques can enhance the overall effectiveness of exploration efforts, as each method offers unique insights into the subsurface. By integrating GPR data with data obtained from resistivity, IP, and other methods, geologists and exploration teams can obtain a more comprehensive understanding of the geological features and potential mineralization in the study area.

The use of GPR in mineral exploration has become more prevalent due to advancements in technology and data processing techniques. As a non-destructive and non-invasive method, GPR allows for efficient data collection and high-resolution imaging, making it a valuable tool in the modern mineral exploration toolbox. Its ability to provide subsurface details with high accuracy and spatial resolution makes it an important complement to other geophysical methods and contributes to the successful identification and characterization of mineral deposits.

## 6. Conclusion

Indeed, geophysical studies, particularly those utilizing the IP/Resistivity and Ground Penetrating Radar (GPR) methods, can be beneficial in the exploration of Pb-Zn (lead-zinc) mineral deposits, particularly those associated with sulfide mineralization. These methods can provide critical information about the ore's subsurface potential and geometry, allowing mining operations to be more effective and efficient.

As previously discussed, the IP/Resistivity method can assist in identifying areas with potential mineralization by measuring the chargeability and resistivity of the subsurface. Sulfide mineralization frequently has distinct geophysical signatures, and high chargeability values indicate the presence of potential sulfide ores. The combination of these methods can help to define target areas for future exploration and drilling campaigns.

Additionally, the GPR method, as a supportive tool, can provide high-resolution imaging of the subsurface. It is especially useful in identifying shallow structures, fractures, and voids that may be associated with mineralization. GPR data can help guide exploration efforts, refine geological models, and optimize drilling locations, enhancing the overall efficiency of the mining operation.

In the context of the operational mine southeast of Yahyalı, geophysical studies can be crucial for monitoring and evaluating the underground potential, verifying the extension of known mineralization, and identifying new targets for future mining activities. The combination of IP/Resistivity and GPR methods can provide valuable information about the subsurface geology, assisting in resource evaluation, mine planning, and decision-making processes.

By integrating geophysical data with geological and drilling data, mining companies can gain a comprehensive understanding of the deposit's characteristics and distribution. This holistic approach can lead to more sustainable and efficient mining practices, as it helps optimize resource utilization and minimize environmental impact.

Overall, geophysical studies, including IP/Resistivity and GPR, are essential tools for exploring and characterizing Pb-Zn mineral deposits, and their successful application can significantly contribute to the success of mining operations.

However, GPR does present some challenges in the exploration of Pb-Zn deposits. The method's effectiveness could be limited by the electromagnetic properties of the subsurface, as highly conductive materials can attenuate radar signals, reducing penetration depth and resolution. Furthermore, accurate differentiation of Pb-Zn deposits from other geological features requires expertise in geophysics and mineralogy when interpreting GPR data.

Finally, Ground Penetrating Radar (GPR) is a powerful and non-invasive tool for exploring and characterizing Pb-Zn deposits. Because of its high-resolution imaging capabilities and non-destructive nature, it is an appealing option for mineral resource exploration. Geologists and mineral exploration professionals can improve their understanding of Pb-Zn deposits and make informed decisions in their exploration efforts by leveraging GPR's strengths and understanding its limitations.

**Acknowledgement**

This study was partly presented at the 6$^{th}$ Advanced Engineering Days [27].

**Funding**

This research received no external funding.

**Author contributions**

**Cihan Yalçın:** Writing-Reviewing and Editing, Geology, Methodology, **Hurşit Canlı:** Editing, IP/Resistivity and GPR.

**Conflicts of interest**

The authors declare no conflicts of interest.

**References**


1. Loke, M. H., & Barker, R. D. (1996). Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method1. Geophysical prospecting, 44(1), 131-152. https://doi.org/10.1111/j.1365-2478.1996.tb00142.x
2. Dusabemariya, C., Qian, W., Bagaragaza, R., Faruwa, A. R., & Ali, M. (2020). Some experiences of resistivity and induced polarization methods on the exploration of sulfide: A review. Journal of Geoscience and Environment Protection, 8(11), 68-92. https://doi.org/10.4236/gep.2020.811004
3. Olowofela, J. A., Ajani, O. O., & Oladunjoye, M. A. (2008). Application of induced polarization method to delineate sulphide ore deposit in Osina area of Benue state, Nigeria. Ife Journal of Science, 10(1), 137-150.
4. Daniels, D. J. (2004). Ground Penetrating Radar, IEE Radar, Sonar and Navigation Series. 15, 2nd ed.; IEE: London, UK, 725. ISBN 0863413609.
5. Francke, J. (2010). Applications of GPR in mineral resource evaluations. In Proceedings of the XIII International Conference on Ground Penetrating Radar, 1-5. IEEE. https://doi.org/10.1109/ICGPR.2010.5550188
6. Langore, L., Alikaj, P., & Gjovreku, D. (1989). Achievements in copper sulphide exploration in Albania with IP and EM Methods. Geophysical Prospecting, 37, 975-991. https://doi.org/10.1111/j.1365-2478.1989.tb02243.x
7. Yoshioka, K., & Zhdanov, M. S. (2005). Three-dimensional nonlinear regularized inversion of the induced polarization data based on the Cole–Cole model. Physics of the Earth and Planetary Interiors, 150(1-3), 29-43. https://doi.org/10.1016/j.pepi.2004.08.034
8. Sono, P., Nthaba, B., Shemang, E. M., Kgosidintsi, B., & Seane, T. (2021). An integrated use of induced polarization and electrical resistivity imaging methods to delineate zones of potential gold mineralization in the Phitshane Molopo area, Southeast Botswana. Journal of African Earth Sciences, 174, 104060. https://doi.org/10.1016/j.jafrearsci.2020.104060
9. Moreira, C. A., Lopes, S. M., Schweig, C., & da Rosa Seixas, A. (2012). Geoelectrical prospection of disseminated sulfide mineral occurrences in Camaquã sedimentary basin, Rio Grande do Sul state, Brazil. Brazilian Journal of Geophysics, 30(2), 169-179. http://dx.doi.org/10.22564/rbgf.v30i2.90
10. Hanilçi, N., Öztürk, H., & Kasapçı, C. (2019). Carbonate-hosted Pb-Zn deposits of Turkey. Mineral Resources of Turkey, 497-533. https://doi.org/10.1007/978-3-030-02950-0_10
11. Ayhan, A., & Erbayar, M. (1985). Batı Zamantı (Aladağlar-Yahyalı) karbonatlı Pb-Zn yataklarının jeokimyasal prospeksiyonu. MTA Dergisi, 105, 75-84.
12. Hanilçi, N., & Öztürk, H. (2003). Aladağlarda karbonatlar içindeki Pb-Zn yataklarında duraylı kükürt izotopu ve mikrotermometrik incelemeler, Doğu Toroslar, Türkiye. 56. Türkiye Jeoloji Kurultayı, Bildiri Özleri Kitabı, Ankara, 112–114.
13. Hanilçi, N., & Öztürk, H. (2005). Aladağlar-Zamantı (Doğu Toroslar) bölgesinde Misisipi Vadisi tipi (MTV) Zn-Pb yatakları: Ayraklı ve Denizovası Zn-Pb Yatakları, Türkiye. İstanbul Yerbilimleri Dergisi, 18(1), 23-43.
14. Hanilçi, N., & Öztürk, H. (2011). Geochemical/isotopic evolution of Pb–Zn deposits in the Central and Eastern Taurides, Turkey. International Geology Review, 53(13), 1478-1507. https://doi.org/10.1080/00206811003680008
15. Burger, R. H., Sheehan, F. A., & Jones, C. H. (2006). Introduction to applied geophysics: exploring the shallow subsurface. Norton & Company, Inc., New York, 265-347.
16. Seguin, M. K. (1974). The use of geophysical methods in permafrost investigation: iron ore deposits of the central part of the Labrador Trough, northeastern Canada. Geoforum, 5(2), 55-67. https://doi.org/10.1016/0016-7185(74)90006-2
17. Sumner, J. S. (1976). Principles of induced polarization for geophysical exploration. Elsevier, Amsterdam, 227
18. Béhaegel, M., & Gourry, J. C. (2003). Investigation de pollutions organiques par méthodes géophysiques. Rapport BRGM/RP-52642-FR, 89.
19. Gouet, D.H., Ndougsa-Mbarga, T., Meying, A., Assembe, S.P. & Man-Mvele Pepogo, A.D, (2013). Gold mineralization channels identification in the Tindikala-Boutou Area (Eastern-Cameroon) using geoelectrical (DC& IP) methods: A case study. International Journal of Geosciences, 4(3), 643-655. https://doi.org/10.4236/ijg.2013.43059

20. Parasnis, D. S. (1997). Principle of Applied Geophysics. Springer Netherlands, 429.
21. Adejuwon, B. B., Obasi, I. A., & Salami, A. A. (2021). Integrated geophysical study for mapping Pb–Zn sulfide deposits in Asu River Group shales in Nkpuma-Ekwoku, Abakaliki Area, southeastern Nigeria. Arabian Journal of Geosciences, 14, 1385. https://doi.org/10.1007/s12517-021-07770-4
22. Elem, J. C., & Anakwuba, E. K. (2022). Application of ground magnetics and geoelectrical methods in delineating sulphide deposit in Oshiri Area, southeastern Nigeria. Global Journal of Geological Sciences, 20(1), 69-82.
23. Ikegbunam, I. C. (2022). Delineation of potential zones of lead-zinc mineralization in Uburu Ohaozara LGA South Eastern Nigeria, using electrical resistivity tomography and induced polarization methods. International Journal of Physical Sciences, 17(3), 121-130. https://doi.org/10.5897/IJPS2022.5013
24. Yapici, N., Güneyli, H., & Karakilçik, H. (2016). Fakılar boksit cevher özellikleri ve potansiyeline ait ilk bulgular (Çamlıyayla/Mersin). Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi, 30(2), 55-64. https://doi.org/10.21605/cukurovaummfd.242768
25. Yalçın, C., Canlı, H., Haznedaroğlu, K., & Akbulut, F. (2023). Investigating the Kavşut (Göksun-Kahramanmaraş) Cu-Pb-Zn deposit by using IP/Resistivity methods. Advanced Engineering Days (AED), 7, 73-76.
26. Erten, O., Kizil, M. S., Topal, E., & McAndrew, L. (2013). Spatial prediction of lateral variability of a laterite-type bauxite horizon using ancillary ground-penetrating radar data. Natural resources research, 22, 207-227. https://doi.org/10.1007/s11053-013-9210-z
27. Yalçın, C., & Canlı, H. (2023). Investigating the Yahyalı (Kayseri, Türkiye) Pb-Zn deposit by using IP/Resistivity methods. Advanced Engineering Days (AED), 7, 69-72.