

DCIP tomography for delineation of Zn-Pb sulfide mineralization and estimation of mineral resources

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Abstract

Purpose. This study aims to evaluate the effectiveness of direct current resistivity and induced polarization (DCIP) tomography in delineating Zn–Pb sulfide mineralization and estimating mineral resources at the Nash Creek deposit in Canada. The investigation seeks to identify mineralized zones, characterize their geoelectrical properties, and assess their economic potential.

Methods. A quasi-3D DCIP survey was conducted over an area of approximately 21.5 km², using 17 parallel survey lines spaced 200 m apart. The acquired data were processed and interpreted using two-dimensional and three-dimensional inversion techniques. The resulting resistivity and chargeability models were integrated with geological, petrophysical, borehole, and mineralogical information to delineate mineralized zones and estimate potential mineral resources.

Findings. The inversion results revealed subsurface resistivity ranging from 20 to 4500 Ω·m and chargeability from 0 to 14 mV/V. Mineralized zones were identified at approximately 180 m depth and were characterized by resistivity of 1500 to 2000 Ω·m and chargeability exceeding 8.5 mV/V. Three-dimensional visualization confirmed the spatial continuity of massive sulfide occurrences within the study area. Validation using borehole records and mineralogical analyses showed strong agreement with the geophysical interpretation. The identified mineralized bodies were subsequently used to estimate probable mineral resources.

Originality. The study demonstrates the use of quasi-3D DCIP tomography as an integrated approach for detecting, characterizing, and estimating resources in Zn-Pb sulfide deposits.

Practical implications. The results provide a cost-effective framework for mineral exploration, resource evaluation, and mine planning, supporting informed decision-making for future mining operations.

Keywords: DCIP tomography; induced polarization; electrical resistivity; sulfide deposit; mineral resource estimation; geoelectrical exploration

1. Introduction

The exploration of minerals is critical to economic development, the creation of new technologies, and the sustainable management of resources. As demand for infrastructure, manufacturing, renewable energy systems, and advanced technologies grows, there is an ever-increasing need for efficient exploration methods to identify mineral deposits that can be developed in a commercially viable manner [1]–[5]. Therefore, the development of reliable exploration methodologies will help ensure a secure long-term supply of resources and minimize the negative environmental impacts of mining operations.

Among the various types of ore deposits, volcanogenic massive sulfide (VMS) deposits are among the most important sources of zinc, lead, copper, silver, and gold worldwide [6]–[10]. These deposits form through hydrothermal processes in submarine volcanic environments and are characterized by high concentrations of economically valuable sulfide minerals. Owing to their significant metal content and economic value, VMS deposits have attracted considera-

ble attention from both industry and academia [11]. Canada hosts more than 350 VMS deposits, which contribute substantially to national metal production, accounting for approximately 27% of Cu, 49% of Zn, 20% of Pb, 40% of Ag, and 3% of Au production [10]–[13]. The abundance of Zn-Pb and Cu-Zn VMS deposits in Canada is largely related to the extensive development of primitive oceanic arc environments during the Precambrian era [11].

Exploring sulfide deposits remains challenging because of the complex geometry of ore bodies, geological heterogeneity, and low-grade mineralization. Consequently, geophysical methods have become indispensable tools for mineral exploration, providing rapid, cost-effective, and non-invasive information about subsurface conditions. Seismic [14], [15], electromagnetic [16], [17], magnetic, gravity, and electrical methods [18] have been widely used to identify potential mineralized zones and improve geological interpretations. These techniques significantly reduce exploration risks and optimize drilling programs [19]–[24].

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Direct current (DC) resistivity and induced polarization (IP) geophysical methods are effective for exploring sulfide deposits, as reported in the literature [6], [9], [25] [26]. Resistivity indicates how electrically conductive the subsurface is at various depths. In contrast, induced polarization indicates the charge-storage capacity of the rocks and minerals. The combination of the DC and IP methods is a powerful tool, as disseminated and massive sulfide minerals exhibit different chargeability behaviors than the surrounding host rock [27], [32], thereby allowing the differentiation of sulfides from their host rock. Because of this ability, the combined DC and IP approach is one of the most widely used techniques for locating, mapping, and characterizing sulfide mineralization.

The success of DCIP methods depends heavily on survey design and the dimensionality of the collected data. Standard one-dimensional (1D) methods provide only profile information and limited ability to assess where lateral changes occur [33]-[36]. Two-dimensional (2D) equipment increases confidence in subsurface characterization by combining measurements from multiple profiles, thereby improving the representation of identified geological structures and mineralized zones [37]-[40]. However, 2D interpretations often assume limited variability perpendicular to the survey line, so they do not provide a complete depiction of complex 3D geological environments [6], [41], [42]. Full three-dimensional (3D) surveys overcome these limitations by providing detailed volumetric models of the subsurface and improving the delineation of ore bodies [43], [45]. Nevertheless, acquiring and processing dense 3D datasets are often associated with high operational costs and increased logistical complexity.

Quasi-3D DCIP surveys offer an effective compromise between the spatial resolution of full 3D investigations and the cost-efficiency of 2D surveys [7]. In this approach, data are collected along parallel survey lines and then integrated via interpolation and three-dimensional inversion [46]-[48]. The resulting models provide improved visualization of subsurface structures and mineralization patterns while keeping acquisition costs reasonable. Despite these advantages, the application of quasi-3D DCIP tomography to Zn-Pb VMS deposits remains limited, and additional case studies are needed to evaluate its effectiveness for mineral resource assessment.

2. Materials and methods

2.1. Study area and geological setting

The study area lies within the Nash Creek (NC) Zn-Pb deposit in northeastern New Brunswick, Canada, along the southwestern margin of the Jacquet River Graben. Geologically, the area is part of the Chaleur Bay Synclinorium (CB), one of the major tectonostratigraphic belts of northern New Brunswick and a component of the northern Appalachian Orogen [49]-[54] (Fig. 1).

The NC deposit is hosted primarily in volcanic and sedimentary rocks of the Lower Devonian Dalhousie Group, which comprises the Mitchell Settlement, Jacquet River, Archibald Settlement, Sunnyside, and Big Hole Brook formations.

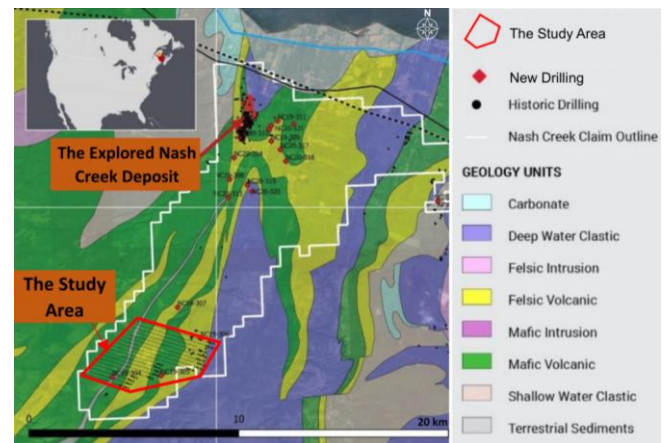


Figure 1. The location and geological units of the study area [54]

Mineralization occurs mainly within the bimodal volcanic sequences of the Archibald Settlement and Sunnyside formations, with minor extension into the sedimentary rocks of the Jacquet River Formation. These formations generally exhibit sub-horizontal to gently eastward-dipping attitudes.

Previous geological studies suggested that the NC deposit formed in a failed-rift environment with hydrothermal activity linked to extensional fault systems [50], [51]. The deposit is classified as a VMS system and consists predominantly of sphalerite, galena, pyrite, and minor chalcopyrite. Drilling programs have identified Zn-Pb mineralization at depths of approximately 150 m below the ground surface [52]. Despite extensive geological, geochemical, and drilling investigations, the three-dimensional distribution of the sulfide mineralization remains poorly constrained.

2.2. Research framework

The methodology used in this study comprised five consecutive stages (Fig. 2).

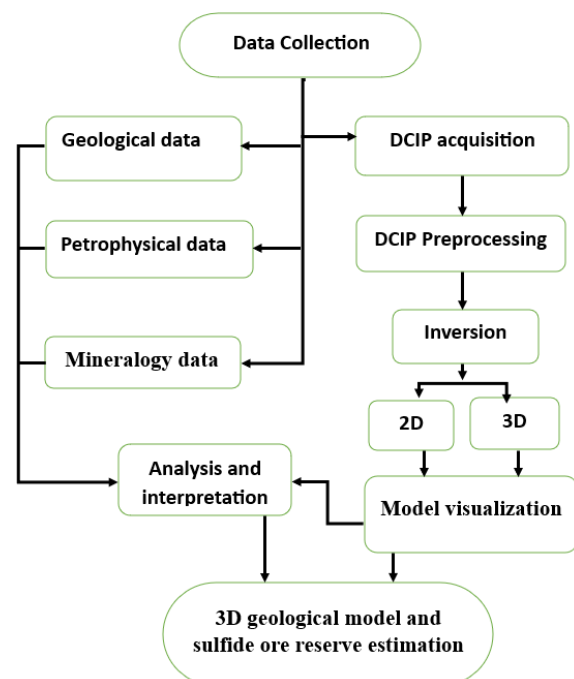


Figure 2. Flowchart of the DCIP methodology employed in this study

As illustrated in Figure 2, the methodological workflow comprised five consecutive stages:

- compilation of geological and exploration data;
- acquisition of quasi-3D DCIP data;
- quality control and preprocessing of geophysical data;
- two-dimensional and three-dimensional inversion modeling;
- geological interpretation, validation, and mineral resource estimation.

The workflow was designed to integrate geophysical observations with available geological, mineralogical, and borehole data to improve delineation of Zn-Pb sulfide mineralization and to assess its resource potential.

2.3. DCIP survey design and data acquisition

A large-scale quasi-3D DCIP survey was conducted over the NC deposit to investigate the spatial distribution of sub-surface sulfide mineralization. The survey covered approximately 21.5 km² and comprised seventeen nearly parallel survey lines distributed throughout the study area (Fig. 3).

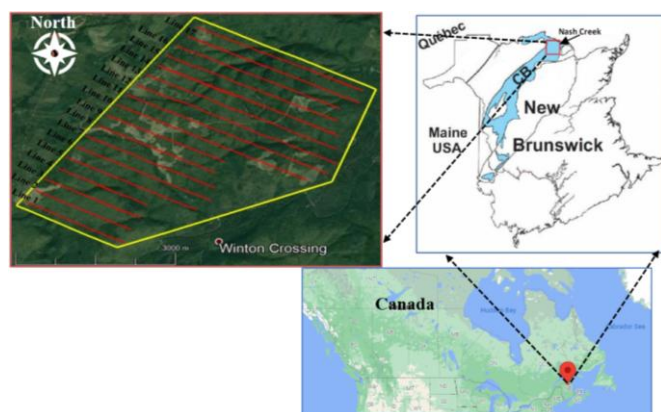


Figure 3. Map of DCIP survey lines (from line 1 to line 17) in the study area

The profile lengths ranged from approximately 2.0 to 4.6 km, with a constant line spacing of 200 m. Data were acquired using a Syscal Pro resistivity and induced polarization system (IRIS Instruments). A pole-dipole electrode configuration was selected for its favorable depth penetration and lateral resolution in mineral exploration.

A minimum electrode spacing of 50 m was used, and measurements were collected at ten investigation levels. Geographic coordinates and elevation data were recorded with a GPS receiver to enable topographic correction during inversion. The principal acquisition parameters are summarized in Table 1.

Table 1. Main DCIP acquisition parameters

Parameter	Value
Instrument	Syscal Pro
Survey type	Time-domain IP
Electrode array	Pole-Dipole
Minimum electrode spacing	50 m
Number of survey lines	17
Line spacing	200 m
Number of levels	10
Injection time	240 sec.
Off-time windows	20 gates
Measurement interval	80 sec.

2.4. Data processing and inversion

Before inversion, all DCIP datasets underwent quality-control procedures to remove erroneous measurements and minimize the effects of cultural and environmental noise. Specifically, pre-inversion quality-control procedures were performed during data acquisition and initial data processing, including data screening, consistency checking, filtering, and topographic correction.

Using RES2DINV (Version 4.08), we inverted the processed data for each profile in our survey to produce two-dimensional (2D) resistivity and chargeability sections. The inversion used the Gauss-Newton optimization method in NLP (Non-Linear Programming) with a robust L1-norm constraint to enhance the recovery of sharp geological contacts consistent with the resurgence of sulfide minerals.

The raw apparent resistivity and chargeability datasets from all 2D survey profiles were compiled into a unified 3D dataset and imported into RES3DINV (Version 3.14) for quasi-3D inversion. The inversion used a voxel-based finite-element method that subdivided the subsurface into a 3D grid of rectangular cells. The algorithm iteratively calculated resistivity and chargeability for each cell until the calculated responses matched the observed field measurements.

Final model selection was based on the degree of inversion stability and the model's geological validity; therefore, the final model presented in this study represents the fifth inversion iteration, at which the balance between reducing misfit and maintaining geological accuracy was at the maximum achievable level.

2.5. Interpretation and validation

The resulting resistivity and chargeability models were jointly interpreted to identify potential zones of Zn-Pb sulfide mineralization. Areas with elevated chargeability values and moderate-to-high-resistivity anomalies were considered prospective targets for sulfide mineralization.

To improve the reliability of the interpretation, the geophysical models were integrated with available geological maps, drilling records, lithologic logs, and mineralogical analyses. The interpreted mineralized zones were then used to delineate ore-bearing bodies and estimate probable mineral resources in the study area.

The validation process enabled an independent assessment of the geophysical results and instilled confidence in the applicability of quasi-3D DCIP tomography for mineral exploration and resource evaluation in VMS environments.

3. Results

3.1. Two-dimensional DCIP inversion results

The seventeen DCIP survey lines were inverted individually to generate two-dimensional resistivity and chargeability models. For example, Figures 4-7 show the pseudo-sections and 2-D inversion results for resistivity and chargeability of the Line 1 and Line 2 datasets, respectively. The quality of the inversion results was evaluated using absolute and RMS errors, indicating satisfactory convergence and model stability. Detailed RMS statistics are shown in Figure 8.

Resistivity imaging provided subsurface data to a depth of approximately 250 meters, with resistivity values ranging from 20 to 4500 ohm-meters. This data showed considerable spatial variability across the study area, consistent with lithologic variability and structural complexity.

Resistivity generally decreases from the southern to the northern part of the survey area, with several localized high-resistivity areas identified along several profiles, especially on the west side of the survey lines.

The chargeability models ranged from 0 to 14 mV/V. Compared with the resistivity sections, chargeability anomalies were generally more discrete, laterally continuous, and had better-defined boundaries. Most high-chargeability zones occurred in the western portion or near the central sections of

the profiles. Several of these anomalies coincided with moderate- to high-resistivity features, suggesting potential sulfide mineralization. A consistent geoelectrical signature was identified across multiple profiles. These prospective zones were characterized by resistivity of approximately 1500-2000 $\Omega \cdot m$ and chargeability exceeding 8.5 mV/V. The anomalies were detected at depths of approximately 50 to 200 m below ground level, indicating potentially continuous mineralized bodies throughout the survey area.

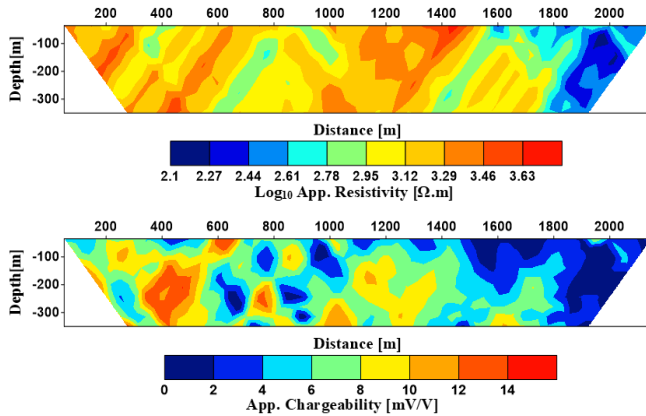


Figure 4. The pseudo-sections of the Line 1 DC&IP dataset

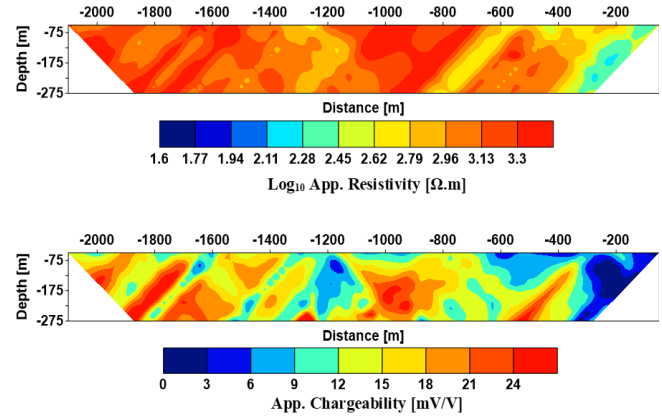


Figure 6. The pseudo-sections of the Line 2 DC&IP dataset

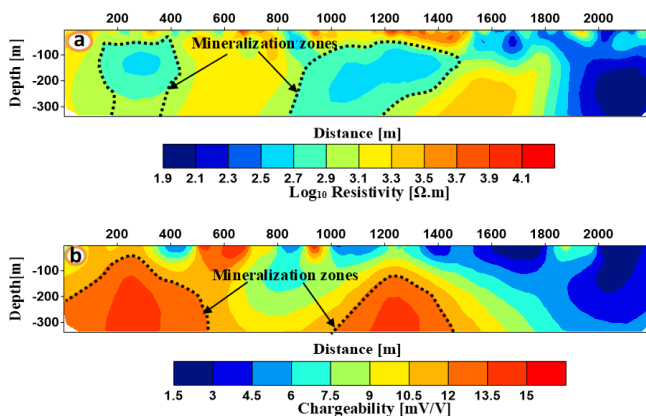


Figure 5. 2-D inversion results of resistivity and chargeability sections a and b for Lines 1, respectively

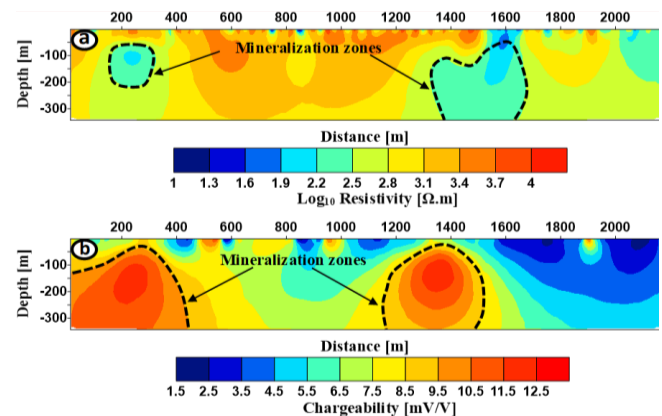


Figure 7. 2-D inversion results of resistivity and chargeability sections a and b for lines 2, respectively

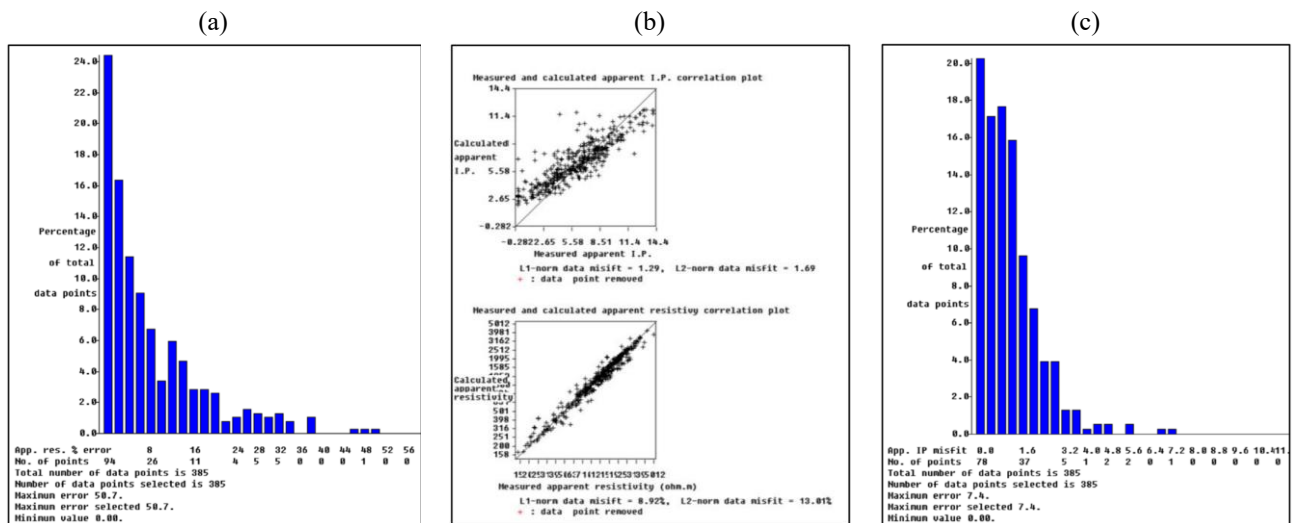


Figure 8. Results of 2D inversion analysis for Line 1: (a) distribution of apparent resistivity percentage errors; (b) scatter plots comparing measured and calculated apparent resistivity and IP values; (c) distribution of apparent IP errors

3.2. Three-dimensional DCIP inversion results

The quasi-3D inversion results are presented as horizontal resistivity and chargeability slices (Fig. 9-11). In addition, detailed RMS statistics for the 3D-DCIP inversion results are shown in Figure 12. Six depth intervals, extending from the surface to approximately 227 m depth, were generated to investigate the three-dimensional geometry of the subsurface anomalies.

The resistivity slices revealed narrow anomalies near the surface that progressively expanded with depth. The deepest slices showed highly consistent spatial patterns, suggesting the presence of continuous geological structures within the volume investigated. Similar behavior was observed in the

chargeability model, where the dimensions and continuity of the anomalies increased with depth.

The strongest chargeability responses (> 8.5 mV/V) were concentrated in several distinct zones that overlapped substantially with moderate- to high-resistivity anomalies. Although the spatial coincidence was imperfect, the overall agreement between the two datasets strongly suggests the presence of sulfide mineralization.

Compared with the individual 2D sections, the 3D models provided a more comprehensive view of the geometry, continuity, and spatial extent of the mineralized zones. The volumetric representation improved delineation of potential ore bodies and facilitated resource estimation.

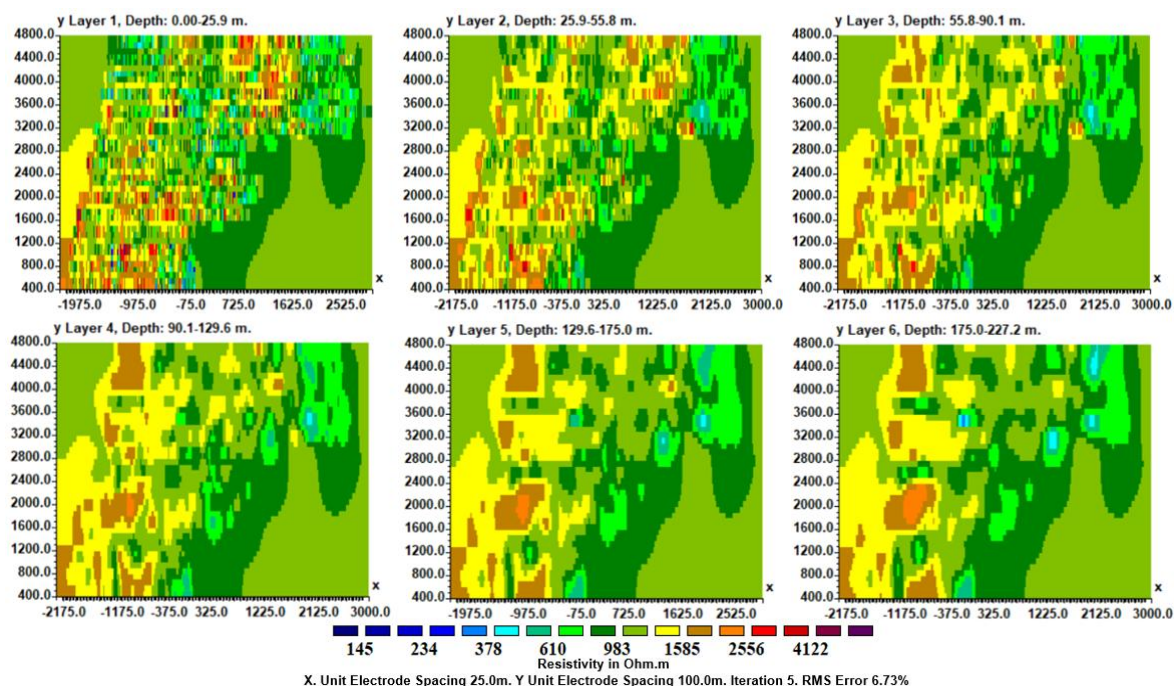


Figure 9. Horizontal slices (on the x-y plane) of the 3D resistivity inversion result (from 0 to 227.2 m depth)

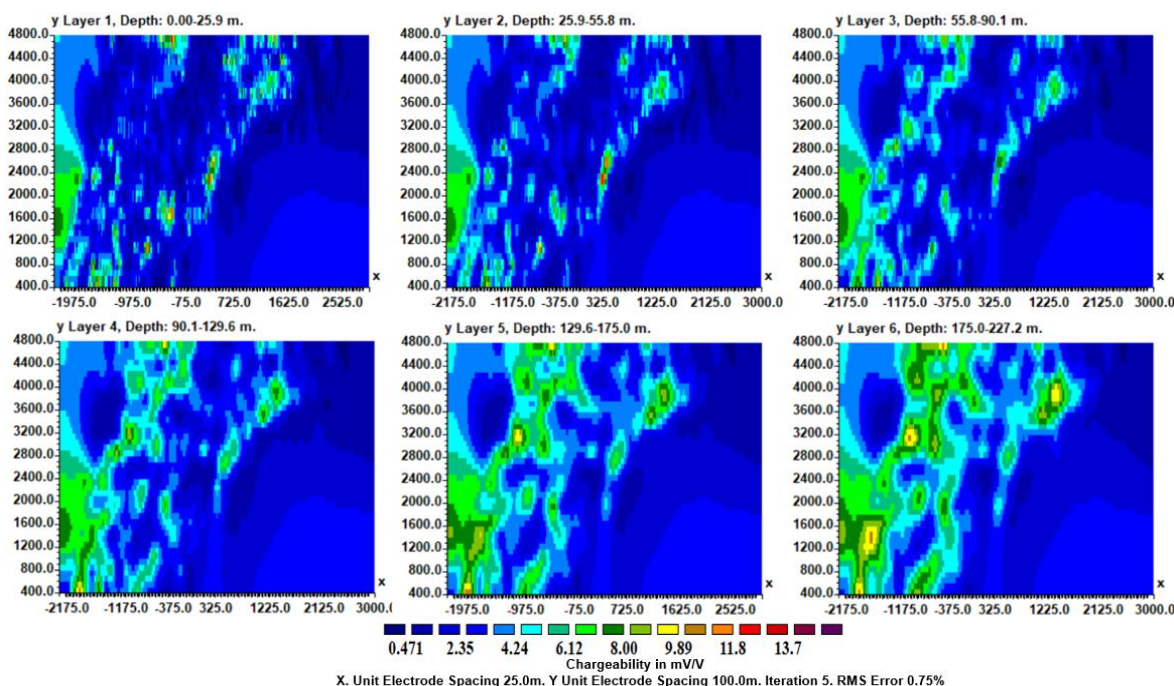


Figure 10. Horizontal slices (on the x-y plane) of the 3D chargeability inversion result (from 0 to 227.2 m depth)

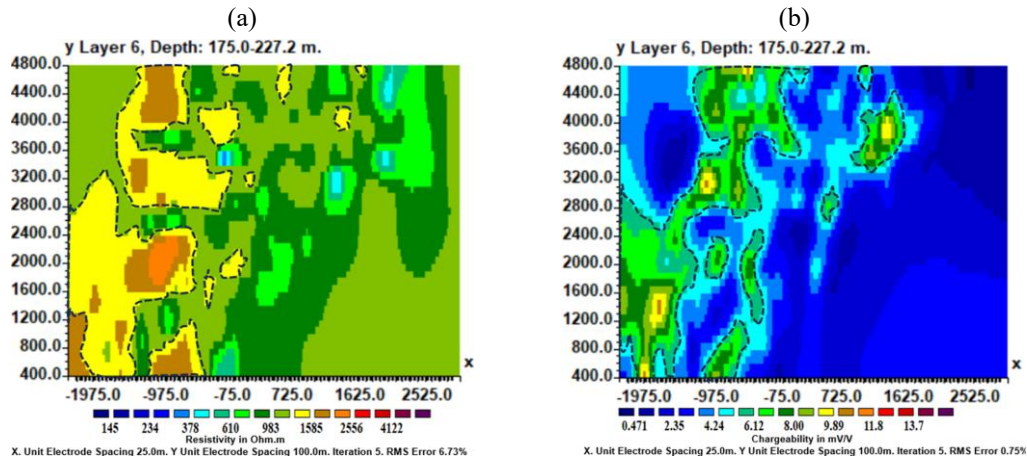


Figure 11. Horizontal slices of the 3D inversion model at depths of 175-227 m: (a) resistivity model; (b) chargeability model. Dashed lines indicate corresponding anomalies (i.e., interpreted mineralization zones)

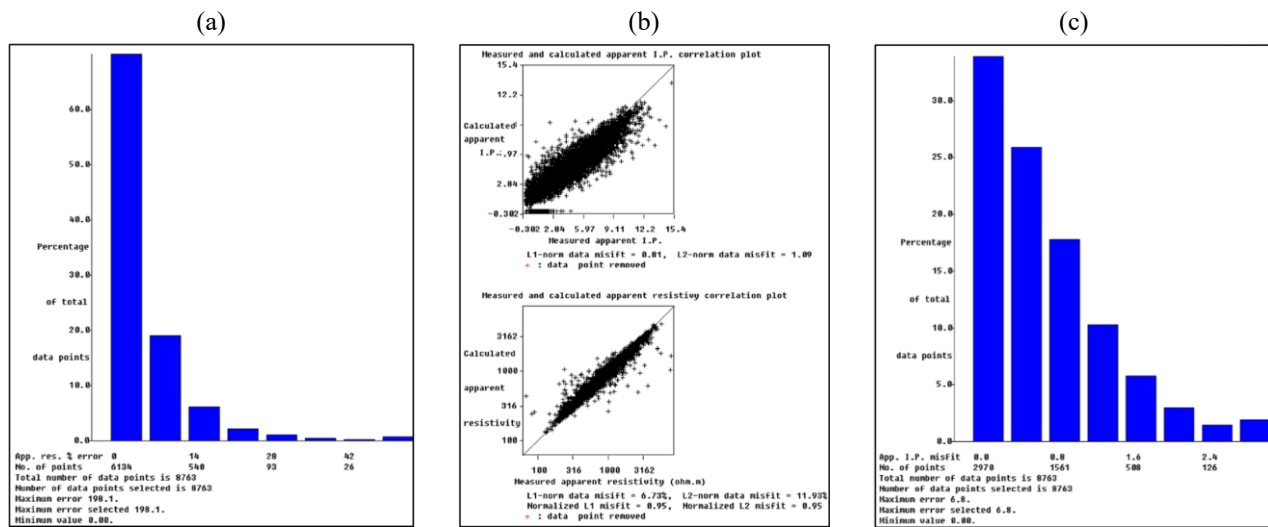


Figure 12 Results of 3D inversion analysis: (a) distribution of apparent resistivity percentage errors; (b) scatter plots of measured vs. calculated apparent resistivity and IP values; (c) distribution of apparent IP errors

3.3. Delineation of mineralized zones and resource estimation

The interpretation of the DCIP models was integrated with geological information, petrophysical measurements, and borehole records, as shown in Figure 13. The combined analysis indicated that mineralization is associated with chargeability values greater than 8.5 mV/V and resistivity values between 1500 and 2000 $\Omega \cdot m$.

Three-dimensional visualization of the chargeability model revealed several continuous mineralized bodies, particularly at depths of 175 to 227 m. An isosurface generated with a chargeability cutoff of 8.5 mV/V was used to estimate the volume of the mineralized zones (Fig. 14-a).

The volume of the interpreted sulfide mineralization enclosed by the 8.5 mV/V chargeability isosurface was estimated using Voxler 4.0 3D modeling (Fig. 14a) and was calculated to be approximately 1363301.5 m³. An average density of 3.5 g/cm³ was adopted based on available petrophysical information from previous borehole investigations [53]. The preliminary geophysical tonnage was calculated using:

$$M = V \cdot \rho, \quad (1)$$

where:

- M – estimated mass, t;
- V – mineralized volume, m³;
- ρ – the density, t/m³.

Thus preliminary geophysical tonnage is equal to ≈ 4.8 Mt. This value is a preliminary geophysical tonnage estimate based on the interpreted 8.5 mV/V chargeability volume and the adopted density. It should not be considered a formal mineral resource or reserve estimate.

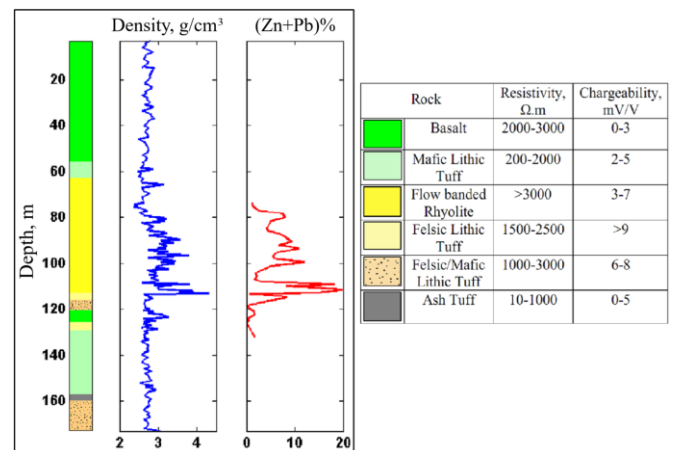


Figure 13. Petrophysical characteristics of the investigated rocks: (a) borehole density and Zn + Pb assay logs; (b) resistivity and chargeability of the main lithologic units [13], [52], [55]

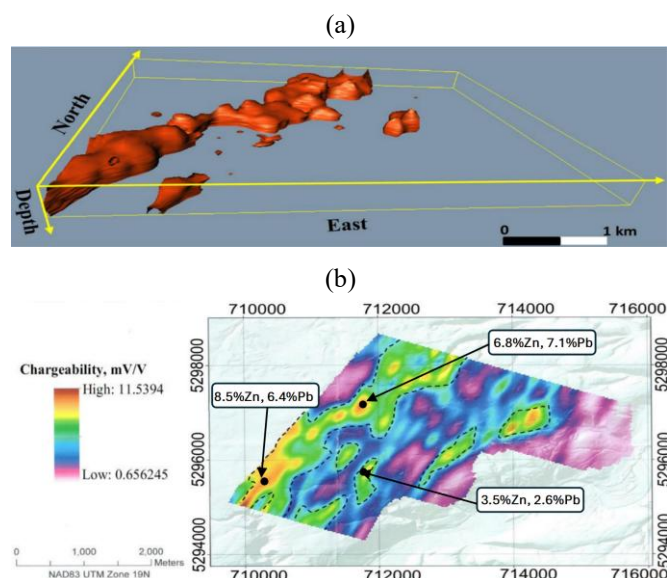


Figure 14. 3-D models of sulfide zones in the southern region at a chargeability cut-off of 8.5 mV/V; (a) 3-D isosurface of mineralization zones, (b) a slice of the 3-D inversion model of the chargeability data at depths between 175 and 227 m

To provide independent geological support for the geophysical interpretation, data from three previously drilled boreholes from earlier exploration campaigns [52], [53] at locations corresponding to major chargeability anomalies (Fig. 14b) were examined. Mineralogical analyses of the recovered core samples confirmed the presence of Zn-Pb sulfide mineralization. The samples analyzed contained Zn and Pb concentrations of 8.5% Zn and 6.4% Pb, 6.8% Zn and 7.1% Pb, and 3.5% Zn and 2.5% Pb, respectively. The agreement between the borehole results and the interpreted DCIP anomalies provides independent support for the geophysical interpretation and demonstrates the potential of quasi-3D DCIP tomography to identify sulfide mineralization.

4. Discussion

Integrating resistivity and chargeability data proved essential for delineating Zn-Pb sulfide mineralization within the Nash Creek deposit. Although resistivity anomalies reflect variations in lithology, structure, porosity, and fluid content, they do not uniquely identify mineralized zones. Consequently, resistivity data alone are insufficient for reliable sulfide exploration.

Petrophysical analyses indicate that Zn-Pb mineralization is primarily associated with felsic rhyolite and felsic-mafic tuff units. These lithologies show moderate-to-high resistivity and elevated chargeability relative to the surrounding volcanic rocks. The observed geoelectrical signatures align with the known characteristics of disseminated and semi-massive sulfide mineralization reported in previous studies.

Compared with resistivity models, the chargeability models delineated the mineralized zones more clearly. The zone of high chargeability values is due to polarization from metal sulfide minerals such as sphalerite, galena, and pyrite, with insignificant amounts of chalcopyrite. Therefore, the chargeability anomaly area was more reliable than the resistive area alone for delineating sulfide mineralization. This agrees with other studies, which have shown that induced polarization methods are superior to other methods for detecting sulfides.

The interpreted sulfide zones occur at depths of 50 to 200 meters and show good lateral continuity across multiple surveys. The agreement between the 2D and 3D inversions, along with strong correlation with borehole data and mineralogy, supports the robustness of the interpretation.

One of the key accomplishments of this research is that quasi-3D DCIP tomography accurately estimated mineral resources. In contrast to traditional two-dimensional methods, the three-dimensional models provided a much more accurate portrayal of ore body shapes and continuity, leading to a significantly better estimate of mineralized volumes. Although it is expected that as many as 4.8 million tons of material will be extracted from the ground, this estimate should be treated as a likely geological resource rather than a formal reserve estimate. This result shows that DCIP tomography has great potential as a low-cost (compared to traditional methods) preliminary investigation method for estimating resources.

In addition, this study demonstrates that integrated quasi-3D imaging of DCIP can enhance the detection, characterization, and volumetric assessment of deposit areas containing zinc and lead sulfides. Furthermore, the methodology provides a viable exploration framework for volcanogenic massive sulfide settings, assisting in the design of drilling programs, resource assessments, and future mine development.

5. Conclusions

This research established the suitability of quasi-3D DCIP tomography for locating Zn-Pb sulfide deposits and estimating mineral resources in New Brunswick, Canada.

The geophysical data set, collected along 17 parallel survey lines over an area of about 21.5 km², was successfully analyzed using both 2D and 3D inversion algorithms. The resulting geoelectrical models indicate subsurface resistivities ranging from 20 to 4500 Ω·m, with chargeabilities ranging from 0 to 14 mV/V. Geology, petrophysics, and borehole data were integrated with the inversion results to identify prospective mineralized areas characterized by resistivities of approximately 1500 to 2000 Ω·m and chargeabilities greater than 8.5 mV/V.

It appears that the Zn-Pb mineralization occurs primarily between 110 and 200 m below the surface, with considerable horizontal and vertical continuity. Three-dimensional visualization of the chargeability volume provided a clear depiction of mineralized geometries and spatial distribution, thereby creating a realistic model of the deposit in the subsurface.

Using a chargeability cutoff of 8.5 mV/V, the mineralized volume is estimated at about 1.36×10^6 m³. Based on an average ore density of 3.5 g/cm³, the estimated geological resource is approximately 4.8 million tonnes.

The assessment used borehole and mineralogical data to independently validate the interpretation and confirm the presence of Zn-Pb sulfide mineralization within the identified geophysical anomalies. The strong correlation between the datasets demonstrates the validity of the proposed method.

Overall, the findings of this study confirm that quasi-3D DCIP tomography is a cost-effective and accurate tool for detecting, delineating, and characterizing sulfide deposits. This methodology can be used for mineral exploration, resource estimation, and drill/target selection in volcanogenic massive sulfide systems and similar geological settings.

Author contributions

Conceptualization: MAHA; Data curation: ASM; Formal analysis: MAHA, MAY, ASM; Methodology: MAHA; Project administration: MAY, SAM; Resources: MAY, SAM; Software: SAM; Supervision: MAY, SAM; Validation: ASM; Visualization: MAHA; Writing – original draft: MAHA, ASM; Writing – review & editing: MAY. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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DCIP-томографія для оконтурення Zn-Pb сульфідної мінералізації та оцінювання мінеральних ресурсів

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Мета. Оцінити ефективність томографії електричного опору постійного струму та викликаної поляризації (DCIP) для оконтурення Zn-Pb сульфідної мінералізації та оцінювання мінеральних ресурсів родовища Nash Creek у Канаді. Дослідження спрямоване на виявлення мінералізованих зон, визначення їх геоелектричних характеристик та оцінювання економічного потенціалу.

Методика. На площі близько 21.5 км² виконано квазі-3D DCIP-знімання з використанням 17 паралельних профілів, розташованих з інтервалом 200 м. Отримані дані оброблено та інтерпретовано із застосуванням двовимірного та тривимірного інверсійного моделювання. Побудовані моделі електричного опору та поляризованості інтегровано з геологічними, петрофізичними, свердловинними та мінералогічними даними для оконтурення мінералізованих зон і оцінювання потенційних мінеральних ресурсів.

Результати. Результати інверсійного моделювання показали, що електричний опір порід у межах досліджуваної ділянки змінюється від 20 до 4500 Ом·м, а поляризованість – від 0 до 14 мВ/В. Мінералізовані зони виявлено на глибині близько 180 м; вони характеризуються електричним опором 1500-2000 Ом·м і поляризованістю понад 8.5 мВ/В. Тривимірна візуалізація підтвердила просторову безперервність масивних сульфідних утворень у межах досліджуваної ділянки. Перевірка за свердловинними даними та результатами мінералогічного аналізу засвідчила їх високу узгодженість із геофізичною інтерпретацією. Виявлені мінералізовані тіла надалі використано для оцінювання ймовірних мінеральних ресурсів.

Наукова новизна. Продемонстровано можливість використання квазі-3D DCIP-томографії як комплексного підходу до виявлення, характеристики та оцінювання ресурсів Zn-Pb сульфідних родовищ.

Практична значимість. Отримані результати формують економічно ефективну основу для пошуку корисних копалин, оцінювання ресурсів і планування гірничих робіт, сприяючи обґрунтованому прийняттю рішень щодо подальшого освоєння родовища.

Ключові слова: DCIP-томографія; викликана поляризація; електричний опір; сульфідне родовище; оцінювання мінеральних ресурсів; геоелектрична розвідка

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