Available online at https://asric.africa/engineering-sciences
ASRIC Journal of Engineering Sciences Vol.5(2)(2025) 103-115

Advances In Transient Electromagnetic Methods for Mineral Exploration: A Review of The Recent Decade

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Received 17 April 2025; revised 06 May 2025; accepted 15 June 2025

Abstract

Transient Electromagnetic (TEM) methods have undergone significant advancements over the past decade, revolutionizing their application in mineral exploration. This review synthesizes recent developments in TEM technology, data acquisition, processing, and interpretation, highlighting their enhanced capability to detect conductive ore bodies at greater depths and with higher resolution. Innovations such as quantum sensors, UAV-based surveys, and integration with complementary geophysical techniques have improved subsurface imaging accuracy. Furthermore, machine learning algorithms like CNN-GRU and MagEMNet have advanced data inversion and mineral prospectivity mapping, enabling more efficient exploration strategies. This review examines the principles of TEM, including electromagnetic induction and eddy current decay, alongside modern survey configurations and data processing techniques. Key advancements in instrumentation, such as high-power transmitters and sensitive receivers, are discussed, along with novel noise reduction methods and 2.5D/3D inversion algorithms. Case studies from diverse geological settings (e.g., Athabasca Basin, Yongxin gold deposit) demonstrate TEM's effectiveness in identifying uranium, gold, and porphyry copper deposits. The results underscore TEM's success in deep exploration, particularly when integrated with multi-method approaches. Challenges such as cultural noise and resistant environments persist, but emerging trends like real-time processing, AI-driven interpretation, and drone-based TEM systems offer promising solutions. The review concludes by emphasizing TEM's transformative impact on mineral exploration and recommends that future research focus on 3D modeling, UAV sensor development, and scalable data processing to further enhance exploration efficiency and accuracy. These advancements will be critical for sustainable resource discovery in complex geological environments.

Keywords: Transient Electromagnetic, Mineral Exploration, Quantum Sensors, Machine Learning, 3D Inversion Algorithms, UAV-based Geophysical Surveys

1. Introduction

Transient Electromagnetic (TEM) methods have been a cornerstone of mineral exploration for decades, proving particularly adept at pinpointing conductive ore bodies. The last ten years have seen remarkable strides in TEM technology, from how data is gathered to its processing and interpretation. These advancements have pushed the boundaries of exploration, allowing us to delve deeper into the Earth, achieve higher resolution of underground structures, and better identify various types of mineral deposits (Mörbe et al., 2020; Prikhodko et al., 2023).

One significant leap forward is the integration of TEM with other geophysical techniques. Combining TEM with methods like audio-frequency magnetotellurics (AMT), gravimetric surveying, and high-resolution magnetic profiling has led to far more precise and complete models of the subsurface. This multi-method approach helps us better map out changes in rock types and uncover deep-seated mineralization (Yin et al., 2025). Furthermore, the advent of quantum sensors, especially superconducting quantum interference devices (SQUIDs), has revolutionized TEM measurements. These sensors offer incredibly low noise levels and a wide dynamic range, making it possible to detect faint signals from deep or small conductive bodies that were previously undetectable (Stolz et al., 2022).

The power of TEM has also been significantly boosted by recent advancements in data processing and inversion techniques. For instance, the development of 2.5D and 3D inversion algorithms has greatly improved our ability to interpret complex geological structures and mineralization patterns (Mörbe et al., 2020). What's more, the exciting integration of machine learning and artificial intelligence into TEM data analysis is opening up new avenues for quickly and accurately mapping areas with potential for mineral deposits (Saremi et al., 2024). These technological and methodological advancements have truly placed TEM methods at the forefront of modern mineral exploration, allowing for more efficient and effective targeting of resources even in challenging geological environments.

Ultimately, TEM methods have emerged as an indispensable tool for deep subsurface investigation in mineral exploration. Their ability to penetrate deeply into the Earth's crust makes them invaluable for identifying potential mineral deposits, even in complex geological settings. Case studies, such as the one from the Yongxin gold deposit, illustrate the benefit of combining AMT with gravimetric surveying and high-resolution magnetic profiling to gain a comprehensive understanding of deep geological formations (Yin et al., 2025). Similarly, the versatility of TEM is highlighted by its application in diverse geological settings, like the South Abu Marawat area for gold potential (Eldougdoug et al., 2023) or the Chakchak region for polymetallic mineralization (Aali et al., 2022). These examples underscore how integrating TEM with other exploration techniques paves the way for more precise and efficient mineral exploration strategies in the years to come. The objectives of this review paper are as follows:

i. To synthesize recent developments in Transient Electromagnetic (TEM) technology, data acquisition, processing, and interpretation for mineral exploration, emphasizing their enhanced capability to detect conductive ore bodies at greater depths and with higher resolution.
ii. To examine the principles of TEM, including electromagnetic induction and eddy current decay, alongside modern survey configurations and data processing techniques.
iii. To discuss key advancements in TEM instrumentation, such as high-power transmitters and sensitive receivers, as well as novel noise reduction methods and 2.5D/3D inversion algorithms
iv. To demonstrate the effectiveness of TEM in identifying various mineral deposits (e.g., uranium, gold, porphyry copper) through case studies from diverse geological settings.
v. To highlight the transformative impact of TEM on mineral exploration, particularly when integrated with multi-method approaches.
vi. To address challenges associated with TEM methods, such as cultural noise and resistant environments, and discuss emerging trends like real-time processing, AI-driven interpretation, and drone-based TEM systems that offer promising solutions.
vii. To recommend future research directions focusing on 3D modeling, UAV sensor development, and scalable data processing to further enhance exploration efficiency and accuracy for sustainable resource discovery in complex geological environments.

2. Principles of Transient Electromagnetic Methods

2.1. Fundamentals of TEM Methods

Over the last ten years, Transient Electromagnetic (TEM) methods have become really important for finding minerals. They're great because they can "see" deep underground and find conductive materials like mineral deposits. TEM works by using electromagnetic induction. Imagine sending a quick burst of electricity through a large loop on the ground. This creates a magnetic field. When you suddenly turn off that electricity, the quick change in the magnetic field makes electrical currents (called eddy currents) flow in any conductive materials below the surface. These eddy currents then create their own weaker magnetic field, which gradually fades away. We use special receivers, like coils or magnetometers, to measure how fast and how strongly this secondary magnetic field decays. The way it decays tells us a lot about what's underground and how conductive it is, helping us pinpoint mineral deposits (Xu et al., 2023; Yu et al., 2023).

Recent improvements have made TEM even more effective. For example, we now have much more sensitive receivers, like SQUIDs (superconducting quantum interference devices), which can pick up very faint signals from deep or small conductive areas (Stolz et al., 2022). We're also combining TEM with other geophysical techniques, like magnetics and electrical resistivity tomography (ERT). This gives us a more complete picture of the subsurface, making our mineral deposit characterization more accurate (Ibraheem et al., 2024; Steuer et al., 2020).

Data processing and interpretation have also come a long way. New methods for reducing noise, such as multi-period stacking and digital filtering, have improved the quality of our signals and allowed us to investigate deeper (Xu et al., 2023). Plus, we're using machine learning and artificial intelligence to interpret data, which makes subsurface modeling faster and more precise (Qu et al., 2025). In short, TEM methods have advanced significantly in the past decade for mineral exploration. Better equipment, combined survey approaches, and advanced data processing mean TEM is now a much more powerful tool for finding and understanding mineral deposits, even at greater depths and with more detail than ever before.

2.2. TEM survey configurations

TEM methods have really progressed in mineral exploration over the last ten years. At its core, TEM involves creating electromagnetic fields underground and then measuring how the secondary fields decay. This gives us important clues about the electrical properties of the rocks beneath us (Yu et al., 2023). Much of the recent focus has been on making data collection more efficient and improving the signal quality, especially for mobile systems like those used from aircraft or towed behind vehicles. For instance, the CNN-GRU dual autoencoder (CG-DAE), developed by Yu et al. (2023), is a new way to process 2D TEM data. It significantly improves the quality of signals at later times, which helps us spot anomalies more effectively. This method is particularly useful for handling the huge amounts of data and low signal quality often found in mobile TEM systems, making them more reliable for mineral exploration (Yu et al., 2023). What's really exciting is how TEM is being combined with other geophysical methods. This provides a much more thorough understanding of the subsurface. For example, Yin et al. (2025) successfully combined audio-frequency magnetotelluric (AMT) methods with gravimetric and magnetic surveys to outline deep mineral features. This multi-method approach makes the data more reliable and gives us a clearer picture of the geology, which is vital for finding minerals (Yin et al., 2025).

The last decade has seen major strides in TEM methods for mineral exploration. This includes better ways to process data, combining TEM with other geophysical techniques, and developing new survey configurations. The emergence of unmanned aerial vehicle (UAV) TEM systems, as discussed by Parshin et al. (2021), is a promising new frontier in geophysical exploration. These could completely change how we conduct detailed electromagnetic soundings in difficult terrain. All these advancements are leading to more efficient and accurate mineral exploration strategies, especially for important materials in complex geological areas (Cardoso-Fernandes et al., 2023; Prikhodko et al., 2023).

2.3. Data Acquisition and Processing Techniques

Recent advancements in data acquisition hardware and processing algorithms have significantly enhanced the signal quality and resolution of Transient Electromagnetic (TEM) measurements. Notably, the development of neural network architectures, such as the CNN-GRU dual autoencoder (CG-DAE), has enabled the efficient processing of two-dimensional TEM data, improving the signal-to-noise ratio (SNR) of late-time signals by up to 29 dB while reducing relative errors to below 1.41% (Yu et al., 2023). This innovation has facilitated the rapid processing of TEM data acquired from mobile platforms, including airborne and towed systems, thereby expanding the applicability of TEM surveys in dynamic environments.

Another critical development involves the improved handling of induced polarization (IP) effects in TEM data through advanced optimization algorithms. The whale optimization algorithm (WOA), augmented with opposition-based learning and adaptive weighted factors, has demonstrated superior convergence behavior and accuracy in extracting IP parameters from TEM signals, achieving errors of less than 8% (Li et al., 2023). Additionally, the integration of electromagnetic and magnetic data via deep learning frameworks, such as MagEMNet, shows considerable promise in enhancing target detection and subsurface characterization (Qu et al., 2025).

These innovations in TEM data acquisition and processing have substantially advanced the method's utility in mineral exploration. The incorporation of machine learning techniques, including CG-DAE and WOA, along with the synergistic use of multi-physics geophysical data, has led to notable improvements in signal fidelity, inversion accuracy, and target discrimination. Such progress is instrumental in addressing the challenges associated with deep exploration and contributes to more efficient and reliable mineral resource assessment (Zhang et al., 2023).

3. Methodology

This review systematically synthesizes the significant advancements in Transient Electromagnetic (TEM) methods for mineral exploration over the recent decade. The methodology employed for this review involved a multi-stage process of literature selection, rigorous analysis, and comprehensive synthesis to ensure a thorough and reliable overview of the current state and emerging trends in the field.

3.1 Literature Selection

The initial phase involved a targeted and systematic search for relevant peer-reviewed literature published primarily within the last decade (approximately 2014-2024), aligning with the review's focus on "the recent decade". Key scientific databases were utilized, including Web of Science, Scopus, and Google Scholar, to ensure broad coverage of publications in geophysics and mineral exploration. The search strategy employed a combination of keywords such as "Transient Electromagnetic," "TEM," "mineral exploration," "geophysical methods," "3D inversion algorithms," and "UAV-based geophysical surveys," along with their synonyms and related terms. Boolean operators (AND, OR) were used to refine search queries and capture comprehensive results. Inclusion criteria were primarily focused on peer-reviewed journal articles that directly address advancements in TEM technology, data acquisition, processing, interpretation, or applications in mineral exploration. Exclusion criteria involved non-peer-reviewed materials, papers outside the defined timeframe (unless they were foundational works with significant recent impact), or those not directly related to TEM in mineral exploration. Initial screening was performed by reviewing titles and abstracts to assess relevance, followed by a full-text review of selected articles to confirm their suitability for inclusion in the review. Forward and backward citation chaining (snowballing) from highly relevant papers was also employed to identify additional pertinent literature.

3.2 Literature Analysis

For each selected paper, a structured approach was employed to extract and analyze key information relevant to the review's objectives. Data extraction focused on identifying the specific advancements in

TEM methods, including improvements in survey configurations, new data acquisition techniques, advanced processing algorithms, and innovative interpretation methodologies. Information regarding the geological context of applications, specific mineral types targeted, and reported successes or challenges was also systematically recorded. A critical appraisal of each study was performed to assess its methodological rigor, the validity of its findings, and its overall contribution to the field of TEM in mineral exploration. Particular attention was paid to the robustness of proposed techniques, the significance of their impact on exploration efficiency and accuracy, and any limitations acknowledged by the authors. This analytical phase also involved identifying recurring themes, emerging trends, and areas of consensus or ongoing debate within the recent literature.

3.3 Literature Synthesis

The synthesis phase involved integrating the analyzed information to construct a coherent narrative of advancements in TEM methods. Journals were grouped thematically, corresponding to the main sections of this review (e.g., Fundamentals, Survey Configurations, Data Acquisition and Processing, Technological Advancements, Applications, Challenges, and Future Directions). This approach allowed for a comprehensive discussion of how different innovations contribute to the overall progress in TEM for mineral exploration. The synthesis aimed not merely to summarize individual studies but to draw connections, compare and contrast methodologies and findings, and identify overarching patterns and insights. This process facilitated the identification of significant achievements, persistent challenges, and key knowledge gaps. Finally, the synthesis culminated in outlining promising future research directions and emerging trends, such as the integration of drone technology, real-time data processing, and advanced 3D modeling, thereby providing a roadmap for future investigations in the field.

4. Result and Discussion

4.1 Recent Technological Advancements

Improvements in TEM instrumentation have significantly enhanced mineral exploration capabilities over the past decade (Table 1). The development of high-power transmitters and sensitive receivers has extended the depth of investigation and improved the detection of weak anomalies associated with deep mineral deposits (Steuer et al., 2020; Wu et al., 2020). For instance, the Deep Electromagnetic Sounding for Mineral EXploration (DESMEX) project demonstrated the effectiveness of semi-airborne electromagnetic systems, utilizing long grounded transmitters and airborne receivers with induction coil magnetometers and SQUID sensors, achieving investigation depths of up to 1 km (Steuer et al., 2020). Advancements in signal processing and noise suppression techniques have further enhanced TEM data quality. The introduction of LSTM-autoencoder neural networks for de-noising TEM signals has shown excellent performance, with relative errors below 1% for most sampling points, leading to improved resistivity structure inversion results and increased exploration depth (Wu et al., 2020). Additionally, the integration of quantum sensors, such as SQUIDs, has revolutionized TEM methods. SQUID-based receivers for ground-based TEM have become a mature technology, leading to numerous discoveries of conductive ore bodies (Stolz et al., 2022). In conclusion, recent technological advancements in TEM methods have significantly improved mineral exploration capabilities. The combination of enhanced instrumentation, advanced signal processing techniques, and novel sensor technologies has extended the depth of investigation, improved data quality, and increased the accuracy of subsurface characterization. These developments have paved the way for more efficient and effective mineral exploration, particularly in challenging environments and for deep-seated deposits.

Table 1: Recent Technological Advancements in the recent decade

Category	Advancement	Impact/Outcome	References
Instrumentation	High-power transmitters and sensitive receivers	Extended depth of investigation; improved detection of weak anomalies	Steuer et al., 2020; Wu et al., 2020
Semi-airborne Systems	DESMEX project: grounded transmitters + airborne receivers (SQUIDs/coils)	Achieved investigation depths up to 1 km	Steuer et al., 2020
Signal Processing	LSTM-autoencoder neural networks for denoising	Relative errors <1%; improved resistivity inversion and exploration depth	Wu et al., 2020
Quantum Sensors	SQUID-based receivers for ground-based TEM	Mature technology enabling discoveries of conductive ore bodies	Stolz et al., 2022

4.1.1 Data Processing Algorithms

The past decade has seen significant advancements in Transient Electromagnetic (TEM) methods for mineral exploration, driven by the development of novel data processing algorithms. The integration of machine learning (ML) and artificial intelligence (AI) techniques has substantially enhanced the interpretation accuracy of complex geological structures (Qu et al., 2025). These algorithms improve subsurface target detection and characterization, particularly in geologically challenging environments. A key innovation in this domain is MagEMNet, a convolutional neural network (CNN)-based model designed for the joint inversion of electromagnetic and magnetic responses (Qu et al., 2025). This approach leverages complementary datasets to refine estimates of target parameters, including spatial location, orientation, and physical properties. Compared to conventional inversion techniques, MagEMNet demonstrates superior accuracy and computational efficiency, making it a valuable tool for practical mineral exploration (Qu et al., 2025).

Additionally, deep learning architectures such as VNet have been successfully adapted for mineral prospectivity mapping (Mcmillan et al., 2021). VNet employs CNNs to analyze geoscience data, excelling in multi-scale pattern recognition—a critical capability given the influence of both local and regional geological controls on mineralization. In greenstone belt environments, VNet has proven effective in predicting gold mineralization, identifying new exploration targets that were subsequently validated through drilling (Mcmillan et al., 2021). Recent advancements in ML- and AI-driven data processing algorithms have significantly enhanced TEM methodologies in mineral exploration. These innovations improve subsurface characterization accuracy and accelerate data interpretation, facilitating more efficient exploration programs and contributing to the discovery of new mineral resources.

4.1.2 Integration with other geophysical methods

The past decade has witnessed substantial improvements in mineral exploration through the integration of TEM with other geophysical techniques. Notably, Unmanned Aerial Vehicle (UAV)-based TEM systems have emerged as a powerful tool for high-resolution data acquisition in challenging terrains, offering superior spatial and temporal resolution compared to traditional ground-based surveys (Kouadio et al., 2023; Sun et al., 2024). These systems enable rapid, large-scale data collection, improving the efficiency and cost-effectiveness of exploration campaigns.

A particularly promising development is the fusion of TEM with multispectral and hyperspectral remote sensing, which enhances mineral mapping and geological characterization (Agrawal & Arafat, 2024; Sigopi et al., 2024). This multi-sensor approach improves the detection of subtle mineralization indicators that may be overlooked when using a single geophysical method. Furthermore, the joint interpretation of TEM with gravity and magnetotelluric (MT) data has provided deeper insights into subsurface structures and ore deposit potential (Li et al., 2023). The integration of TEM with complementary geophysical methods and UAV-based platforms has expanded the technique's applicability while improving resolution and accuracy. Future research should focus on refining data processing algorithms, advancing multi-sensor fusion techniques, and addressing big data challenges in geophysical exploration (Tanaka et al., 2024).

4.2 Applications in Mineral Exploration

Transient Electromagnetic (TEM) methods have demonstrated considerable success in mineral exploration, with several notable applications documented in recent literature (Table 2). In the Athabasca Basin (Canada), ground-based TEM surveys have been instrumental in detecting thin, steeply dipping graphitic conductors associated with uranium mineralization. A case study at Close Lake employed trial-and-error forward modeling to interpret TEM data, successfully delineating the primary conductor's trend and identifying a previously undetected secondary conductor (Lu et al., 2021).

Similarly, integrated geophysical approaches combining TEM with audio-frequency magnetotellurics (AMT), gravity, and high-resolution magnetics have improved mineral prospecting accuracy. For example, in the Yongxin gold deposit (China), this multi-method strategy enhanced lithological discrimination and deep mineralization targeting, leading to the development of a robust geological-geophysical exploration model (Yin et al., 2025). In summary, TEM—particularly when integrated with complementary geophysical techniques—has significantly advanced mineral exploration capabilities. Case studies from uranium exploration in Canada and gold prospecting in China highlight its adaptability across diverse geological settings. Continued technological refinements are expected to further enhance TEM's role in discovering and characterizing mineral deposits, particularly in complex exploration environments.

Table 2: Applications in Mineral Exploration

Mineral Type	Methodology	Case Study/Outcome	References
Uranium (Athabasca Basin)	Ground-based TEM + trial-and-error modelling	Identified graphitic conductors linked to uranium deposits	Lu et al., 2021
Gold (Yongxin Deposit)	TEM + AMT + gravimetric/magnetic surveys	Delineated deep-seated mineralization and ore-controlling structures	Yin et al., 2025
Porphyry Copper	TEM + TMI/MobileMT airborne data + ML (CNN models)	Improved target identification in Duolong, Tibet	Fu et al., 2023; Jorgensen et al., 2024
Nickel/Cobalt	TEM + gravity/magnetic/seismic (magmatic) or hyperspectral/IP (hydrothermal)	Located ore-forming intrusions and mineralization zones	Guoqiang et al., 2023

4.2.1. Exploration for Specific Mineral Types

Recent studies have emphasized the optimization of transient electromagnetic (TEM) methods for the exploration of specific mineral deposits, including porphyry copper systems, massive sulfides, and rare earth element (REE) occurrences. In the context of porphyry copper deposits, integrated geophysical approaches incorporating TEM have demonstrated significant efficacy. For instance, airborne total magnetic intensity (TMI) and mobile magnetotelluric (MobileMT) data have been synergistically combined with TEM surveys to delineate prospective porphyry mineralization zones in Greenland (Jorgensen et al., 2024). This multi-methodological framework facilitates a more robust evaluation of exploration targets, thereby enhancing resource allocation efficiency and exploration success rates.

For nickel and cobalt deposits, TEM has been deployed within a broader multi-physics exploration strategy. In magmatic nickel deposits, TEM is integrated with gravity, magnetic, and seismic methods to accurately constrain the spatial distribution of ore-forming intrusions. Conversely, in hydrothermal nickel-cobalt systems, TEM is employed alongside hyperspectral remote sensing, gravity surveys, and magnetic-excitation techniques to identify ore-controlling structures and favorable mineralization loci (Guoqiang et al., 2023). In sedimentary and meta-sedimentary ore-bearing basins, TEM is frequently coupled with induced polarization (IP) scanning and sounding techniques to improve subsurface resolution.

Notably, recent innovations have incorporated machine learning (ML) algorithms into TEM data interpretation workflows. Deep learning-based convolutional neural network (CNN) models have been successfully applied to mineral prospectivity mapping, integrating TEM datasets with remote sensing imagery and geochemical analyses. This approach has yielded promising results in identifying prospective zones for porphyry copper mineralization, as evidenced by case studies in the Duolong ore district, Tibet (Fu et al., 2023). The application of TEM in mineral exploration has advanced significantly through the adoption of integrated geophysical-geochemical frameworks and cutting-edge data processing techniques. These developments have substantially improved TEM's efficacy in targeting diverse mineral deposit types, particularly in geologically complex terrains where conventional exploration methods face limitations.

4.2.2 Challenges and limitations

Despite its widespread utility, transient electromagnetic (TEM) methods encounter several challenges in mineral exploration applications. Over the past decade, TEM has emerged as a powerful tool for detecting conductive ore bodies, such as massive sulfides, through the induction of subsurface eddy currents and subsequent measurement of secondary magnetic field decay (Védrine et al., 2023). However, the method's effectiveness can be constrained by factors such as electromagnetic noise, limited depth penetration in highly resistive terrains, and spatial resolution trade-offs.

To mitigate these limitations, recent advancements have focused on integrating TEM with complementary geophysical techniques, such as magnetotellurics (MT). Such hybrid approaches have proven particularly valuable in challenging exploration environments, including volcanic islands, where traditional single-method surveys may yield ambiguous results (Védrine et al., 2023). Despite recent advancements, TEM methods still face challenges in highly resistive environments and areas with significant cultural noise, requiring ongoing research to overcome these limitations. In coastal and urbanized regions, for instance, the application of TEM can be hindered by anthropogenic noise, necessitating complementary methods like controlled-source EM (CSEM) (Védrine et al., 2023).

Additionally, the complex topography and heterogeneous near-surface conditions in volcanic environments pose challenges for data acquisition and interpretation (Védrine et al., 2023). To address these limitations, recent studies have focused on developing novel inversion techniques and integrating multiple data types. For example, the MagEMNet deep learning framework demonstrates the potential of combining EM and magnetic data to improve target detection and characterization (Qu et al., 2025). Such advancements in data processing and interpretation are imperative for improving effectiveness of TEM methods in mineral exploration, particularly in complex geological settings.

4.2.3 Future Directions and Emerging Trends

Advancements in 3D TEM modeling and inversion are poised to revolutionize mineral exploration techniques in the coming years. The development of more sophisticated algorithms is expected to significantly improve the accuracy of subsurface characterization and target delineation (Li et al., 2020). These advancements are likely to address the computational challenges associated with large-scale TEM surveys, which have historically been time-consuming and computationally expensive (Asif et al., 2021). One emerging trend is the integration of artificial intelligence (AI) and machine learning techniques with TEM methods. For instance, the use of artificial neural networks to predict partial derivatives in TEM inversions has shown promising results, with speedup factors exceeding 70 for derivative calculations and overall inversion processes expedited by approximately 36 times (Asif et al., 2021). This approach offers a tunable balance between computational time and inversion accuracy, which is particularly valuable in mineral exploration where rapid assessment of large areas is often necessary. The future of TEM methods in mineral exploration is likely to see an increased focus on uncertainty quantification and probabilistic approaches. The development of accelerated Bayesian methods, such as those based on Markov chain Monte Carlo subposteriors for 2D TEM inversions, allows for both parameter estimation and uncertainty quantification (Li et al., 2020). This trend towards probabilistic modeling will provide explorers with more comprehensive information about the subsurface, enabling more informed decision-making in mineral exploration projects. As these advanced techniques continue to evolve, they are expected to enhance the resolution, depth penetration, and reliability of TEM surveys, ultimately leading to more improved and successful mineral exploration campaigns.

4.3 Integration with Drone Technology

The integration of unmanned aerial vehicle (UAV) technology with Transient Electromagnetic (TEM) methods represents a significant advancement and emerging trend in geophysical mineral exploration. UAV-based TEM systems have demonstrated considerable potential in enhancing survey efficiency and accessibility, particularly in remote or logistically challenging terrains (Kouadio et al., 2023). This development aligns with the broader paradigm shift toward advanced technological applications in geophysical exploration.

The deployment of UAVs equipped with TEM sensors offers several key advantages, including rapid coverage of extensive survey areas, improved spatial resolution, reduced operational costs, and minimized environmental footprint (Agrawal & Arafat, 2024). These benefits are particularly valuable in mineral exploration, where large-scale and often inaccessible regions require high-resolution subsurface imaging. Furthermore, the incorporation of artificial intelligence (AI) and machine learning (ML) algorithms into UAV-TEM systems has the potential to significantly enhance data processing and interpretation, facilitating more efficient and accurate mineral target identification (Agrawal & Arafat, 2024; Gano et al., 2024).

Despite these advantages, several challenges hinder the widespread adoption of UAV-TEM systems. Key limitations include payload capacity constraints, limited battery endurance, and the requirement for specialized operational expertise (Mohsan et al., 2022). Future research efforts should prioritize the development of lightweight TEM sensor designs, advancements in UAV energy efficiency, and the creation of streamlined, user-friendly interfaces for data acquisition and processing (Kouadio et al., 2023; Mohsan et al., 2022). Addressing these challenges will be critical in realizing the full potential of UAV-TEM integration for mineral exploration. Additionally, addressing regulatory concerns and ensuring ethical use of UAVs in mineral exploration will be crucial for the technology's widespread adoption (Al-Dosari & Fetais, 2023). As these challenges are addressed, UAV-TEM systems are poised to revolutionize mineral exploration, offering a powerful tool for geophysicists to conduct efficient and comprehensive surveys in diverse geological settings.

Real-time data processing and interpretation constitute a critical advancement in the application of Transient Electromagnetic (TEM) methods for mineral exploration. Recent studies have focused on developing real-time TEM data processing and interpretation frameworks to facilitate adaptive and efficient field exploration strategies (Lawal et al., 2024; Theodorakopoulos et al., 2024). This development aligns with the increasing adoption of big data analytics and machine learning (ML) in geophysical exploration, which enhances the ability of geoscientists to make rapid, data-driven decisions and dynamically adjust survey parameters (Lawal et al., 2024; Pandey et al., 2020).

However, the integration of artificial intelligence (AI) and ML techniques with TEM methods presents notable challenges. The inherent uncertainties in subsurface parameterization, coupled with the spatiotemporal complexity of geophysical data, create significant barriers to the widespread deployment of these technologies (Lawal et al., 2024). Despite these challenges, overcoming them could yield substantial benefits, including enhanced accuracy in mineral deposit identification and characterization, as well as more efficient allocation of exploration resources.

In addition, the future evolution of TEM methods in mineral exploration will likely be driven by the convergence of real-time data processing, AI-enhanced interpretation, and advanced sensor technologies. As these methodologies mature, they are expected to improve the speed, precision, and cost-efficiency of exploration campaigns. Nevertheless, successful implementation will require addressing key challenges related to data quality, algorithmic scalability, and the integration of heterogeneous data sources (Rahmani et al., 2021; Theodorakopoulos et al., 2024). Current research indicates a promising trajectory for TEM methods, with the potential to significantly enhance exploration success rates and optimize resource utilization.

4. Conclusion

This review synthesizes significant advancements in Transient Electromagnetic (TEM) methodologies for mineral exploration over the past decade, emphasizing innovations in instrumentation, data processing algorithms, and multi-method integration. Notable progress includes the incorporation of superconducting quantum interference devices (SQUIDs) for enhanced sensitivity, the application of machine learning (ML) and artificial intelligence (AI) techniques to improve inversion accuracy and computational efficiency, and the synergistic combination of TEM with complementary geophysical approaches such as audiomagnetotellurics (AMT) and gravimetric surveying. These developments have collectively contributed to substantial improvements in subsurface imaging depth, resolution, and interpretational reliability. These innovations have enabled the detection of weak signals from deep or small conductive bodies and improved the characterization of complex geological structures.

The impact of these advancements on the mineral exploration industry has been profound. TEM methods have contributed to increased exploration success rates, more efficient resource targeting, and reduced operational costs, particularly in challenging environments such as volcanic terrains and deep-seated deposits. Case studies from regions like the Athabasca Basin and the Yongxin gold deposit demonstrate the method's versatility and effectiveness when combined with complementary geophysical techniques.

Looking ahead, future research directions should focus on further enhancing 3D TEM modeling and inversion, integrating drone technology for scalable and high-resolution surveys, and advancing real-time data processing capabilities. Addressing challenges such as cultural noise in urbanized areas and improving sensor technologies for UAV-based systems will be critical. Continued innovation in TEM methods, coupled with interdisciplinary collaboration, promises to unlock new frontiers in mineral exploration, ensuring sustainable resource discovery and extraction in the years to come.

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