Journal of the Geological Survey of Brazil vol 8, n1, 65 - 75, April 2025

Journal of the Geological Survey of Brazil

Geophysical methods in graphite exploration: A review

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Abstract

Graphite, with its unique thermal, electrical, and chemical properties, is crucial for technologies like energy storage and advanced materials. However, exploring graphite deposits is challenging due to the variability in crystallinity, purity, and distribution within host rocks, which complicates geophysical data interpretation. This study reviews 20 articles on geophysical methods for graphite exploration, analyzing their advantages and limitations, in addition to incorporating insights from 53 other articles to support discussions on graphite properties and geophysical techniques. Electrical methods, such as resistivity and induced polarization, effectively delineate mineralized zones but are constrained by limited spatial coverage. In contrast, magnetic and electromagnetic techniques provide broader survey coverage and greater cost-efficiency, making them valuable for regional exploration, despite their lower resolution in distinguishing graphite from other minerals. Effective exploration requires integrating regional geological surveys with high-resolution investigations by academia and industry. Understanding the geophysical signatures of different graphite deposit types — like lump, flake, and amorphous graphite — is essential for refining exploration strategies and improving discovery rates. By combining large-scale data with focused studies, exploration efforts can be optimized, enhancing the identification and assessment of graphite resources.

Article Information

Publication type: Review Article
Received 16 December 2024
Accepted 29 March 2025
Online pub. 25 March 2025
Editor: David Castro

Keywords:
Graphite exploration
Geophysical methods
Airborne geophysics
Electrical surveys
Electromagnetic surveys

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1. Introduction

Graphite, one of the polymorphs of carbon, is prized for its unique petrophysical and chemical properties, including high thermal and electrical conductivity, chemical stability, and lubricity (Keeling 2017; Jara et al. 2019; Burchell and Pavlov 2020). In recent years, graphite has become increasingly important due to its critical role in emerging technologies like energy storage systems, electric vehicle batteries, and advanced materials such as graphene (Sousa and Matos 2020; Duan et al. 2023; Gautneb et al. 2023). The growing demand for sustainable energy solutions and high-performance materials has made graphite a strategic mineral, necessitating the development of more efficient exploration methods to locate and develop new deposits (Conly and Moore 2015; Al-Ani et al. 2022; Scherba et al. 2018).

In graphite exploration, indirect geophysical methods are essential for acquiring subsurface data without extensive drilling (Soupios and Kokinou 2016; Rey et al. 2024; Kana et al. 2015). Airborne geophysics, especially when combined with methods like magnetic, radiometric, and electromagnetic surveys, provides an efficient means of covering vast areas. However, the challenge remains in correlating the mineral's specific properties—such as crystallinity, purity, and distribution—with clear geophysical signatures. Unlike commodities like hydrocarbons, where fluid percolation structures produce distinct geophysical responses, graphite's varied petrophysical characteristics complicate such correlations. A notable success in overcoming these challenges is the work of Legault et al. (2015), who used airborne electromagnetic (AEM) surveys in Ontario, Canada, to identify a rare hydrothermal graphite deposit (Figure 1). Their findings demonstrate the effective application of AEM systems in detecting graphite mineralization, further supported by detailed ground-based follow-up surveys. This case underscores how geophysical methods can provide critical insights into graphite deposits, particularly when combined with local investigations.

Another significant example is the work of Loukola-Ruskeeniemi et al. (2023), who integrated magnetic, radiometric, and electromagnetic data with petrophysical and

ISSN: 2595-1939
https://doi.org/10.29396/jgsb.2025.v8.n1.4
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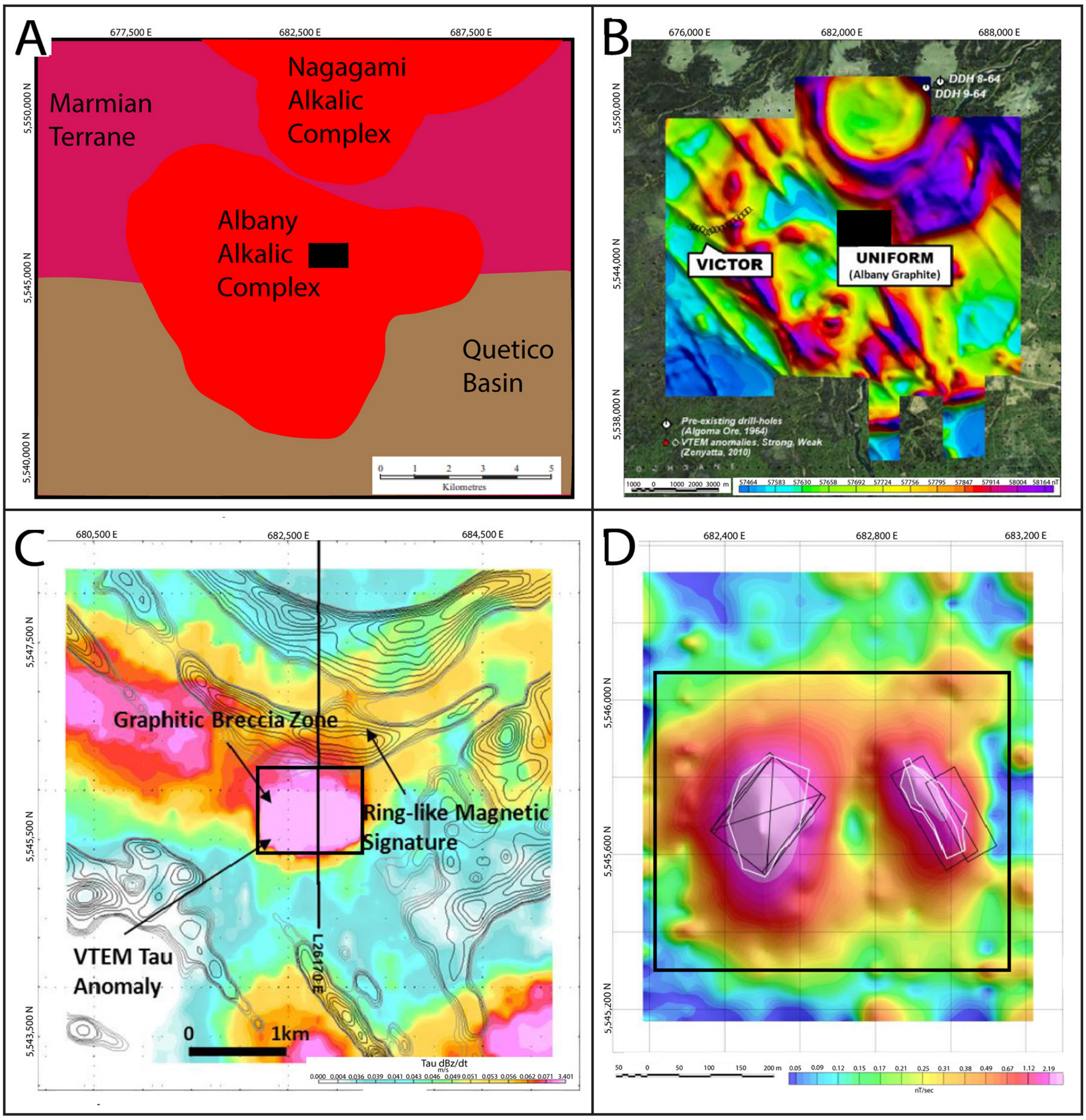

FIGURE 1. Albany graphite discovery, Ontario, Canada — exemplifying successful data integration for mineral exploration. (A) Basement geology of the property; (B) Reduced-to-pole (RTP) magnetic image; (C) Late-channel VTEM dBz/dt time constant overlaid with magnetic gradient contours; (D) Late-time (channel 22) total field for Loop 1, showing modeled conductive plates (black) and surface deposit outline (white). Black squares locate the deposit area (Adapted from Ross and Masun 2014; Legault et al. 2015).

geochemical measurements to delineate multiple graphitic bodies. This multi-method approach was particularly effective in mapping graphite zones in Finland, showcasing the value of combining different geophysical techniques with detailed geological data to improve exploration accuracy. The success of these integrated methods highlights the importance of adopting a multi-pillar approach—combining geological surveys, academia, and the private sector—to enhance graphite exploration efforts.

This article synthesizes findings from 20 key studies on graphite exploration using geophysical methods, analyzing their applications, challenges, and effectiveness across different geological settings. Additionally, insights from 53 other articles were integrated to provide a comprehensive discussion on the geological characteristics of graphite deposits and the principles underlying geophysical techniques. The review illustrates how geophysical methods, such as resistivity, induced polarization, and magnetic surveys, have been employed to locate and characterize graphite deposits. By providing practical examples, including the work of Legault et al. (2015) and Loukola-Ruskeeniemi et al. (2023), this article aims to guide future graphite exploration, emphasizing the importance of integrating multiple geophysical techniques to overcome the challenges posed by graphite mineralization. Such integration significantly enhances the reliability and efficiency of mineral exploration, driving the discovery of new graphite resources.

2. Materials and Methodology

This review is based on an analysis of 20 scientific studies specifically focused on the application of geophysical methods in graphite deposit exploration. However, to provide a more comprehensive assessment of the topic, a total of 71 references were examined. The selected studies were identified through a systematic search on Google Scholar, using keywords such as "graphite," "geophysical methods," and "mineral exploration." The search was not limited to a certain period of time, in this sense the articles selected were published between 1983 and 2024, ensuring the inclusion of recent advancements and diverse case studies.

The analysis focused on several key parameters: type of publication, year of publication, study area, country, scale of investigation, geophysical techniques employed, underlying motivations for the surveys, type of graphite mineralization being targeted (according to Simandl et al. 2015; Robinson et al. 2017; Sun et al. 2018), detection effectiveness of the geophysical method, and authorship or responsible party for the geophysical studies.

To conduct a more effective analysis of geophysical methods applied to graphite exploration, it is essential to understand the fundamental characteristics of graphite, including its petrophysical and geochemical properties, as well as its different types of mineralization. These factors play a crucial role in determining the geophysical response of graphite, as they can influence the detectability and interpretation of geophysical data. Therefore, a detailed examination of these aspects is necessary to enhance the accuracy and reliability of geophysical exploration techniques.

This structured approach enabled a comprehensive evaluation of the methodologies and their contextual relevance to graphite exploration.

3. Petrophysical and Geological properties of Graphite

To effectively analyze the geophysical methods used in graphite exploration, it is essential to first understand the petrophysical and geological properties of graphite. These properties influence the suitability of specific geophysical methods (Reynolds 2011; Kana et al. 2015; Romero-Ruiz et al. 2018). The petrophysical characteristics of graphite determine how it interacts with geophysical signals, making certain techniques more appropriate for detecting, mapping, and characterizing graphite mineralization. From a geological perspective, understanding the types of graphite mineralization is crucial, as different mineralization styles exhibit distinct petrophysical and structural characteristics that affect their geophysical responses (McCann et al. 1997).

Graphite mineralization occurs in three primary forms: flake, vein, and amorphous. Flake graphite is typically found in high-grade metamorphic rocks such as gneisses and schists and forms through the metamorphism of carbonaceous material in sedimentary sequences. It consists of isolated, flat, plate-like crystals with high crystallinity, which enhances its electrical and thermal conductivity (Burchell and Pavlov 2020). Vein graphite, also known as lump graphite, occurs in fissures, fractures, and shear zones, often in association with hydrothermal activity. This type exhibits the highest purity and crystallinity, forming through precipitation from carbon-rich fluids at high temperatures and pressures (Luque et al. 1998). Amorphous graphite, despite its name, consists of very fine-grained graphite formed by the low-grade metamorphism of coal or organic-rich sedimentary rocks. It has lower crystallinity and conductivity compared to flake and vein graphite but is still valuable for industrial applications.

The crystal size of graphite is strongly linked to its formation temperature and metamorphic grade. Larger, well-ordered graphite crystals indicate higher-temperature conditions during metamorphism, whereas smaller crystals, characteristic of amorphous graphite, reflect lower-grade metamorphic conditions (Wilde et al. 1999; Pasteris 1999). This variation in crystal size and crystallinity directly influences the geophysical responses of graphite deposits, affecting properties such as electrical conductivity, thermal behavior, and magnetic susceptibility.

The primary distinction between diamond and graphite, both polymorphs of carbon, lies in their bonding: diamond features sp^3 (tetrahedral) hybridization, while graphite exhibits sp^2 (trigonal) hybridization. As a result, diamond has a three-dimensional crystal structure (covalent network solid), whereas graphite consists of carbon layers (with covalent bonding within each layer) linked by weak van der Waals interactions produced by delocalized π-orbitals. The carbon layers in graphite are known as graphene layers (Burchell and Pavlov 2020; Chung 2002). Due to its anisotropic structure, graphite can undergo intercalation reactions, where reactant species, known as intercalates, insert themselves between graphene layers without significantly disrupting the crystal lattice. This process forms intercalation compounds, which alter the petrophysical and chemical properties of graphite (Inagaki 1998; Dresselhaus and Dresselhaus 1994). Intercalation compounds occur naturally under specific geological conditions, such as in hydrothermal environments enriched with reactive elements.

The thermal behavior of a solid material is controlled by interatomic forces through the vibrational spectrum of the crystal lattice (Burchell and Pavlov 2020). As graphite is anisotropic due to differences in its crystal axes, it is a good electrical and thermal conductor within the layers (due to the in-plane covalent bonding) and a poor electrical and thermal conductor perpendicular to the layers (due to the weak van der Waals forces between the layers). Therefore, the conductivity measured parallel to the cleavage is much higher than that measured normal to the cleavage (Dentith and Mudge 2014).

Graphite's electrical conductivity enables its use as electrochemical electrodes and in electric brushes. Due to its layered structure, carbon layers can slide easily relative to one another, making graphite an effective lubricant and a key material in pencil production (Chung 2002). Additionally, its high conductivity makes it highly effective for electromagnetic interference (EMI) shielding (Harris et al. 1999; Chung 1987). Compression of exfoliated graphite flakes without a binder results in mechanical interlocking, forming a flexible and resilient sheet known as flexible graphite—a widely used gasket material (Chung 2000).

In the context of geophysical exploration, identifying graphite deposits requires a focus on the petrophysical properties that distinguish graphite from its surrounding rocks. One of the most distinctive characteristics is its remarkable electrical conductivity, which frequently serves as a key indicator in geophysical surveys. Graphite can significantly enhance the conductivity of the host rocks, commonly schists and gneisses, elevating their values to levels comparable to those of massive sulfide mineralization (Dentith and Mudge 2014).

Understanding these attributes is crucial for selecting and optimizing geophysical methods, as they directly influence the response and effectiveness of techniques such as electromagnetic surveys, resistivity tomography, and magnetic measurements. By leveraging these distinctive characteristics, geophysics becomes a powerful tool not only for detecting graphite but also for mapping its distribution and understanding the geological processes associated with its formation.

4. Results and Discussion

Table 1 provides a comprehensive summary of the key findings, including the scale of investigation, geophysical techniques employed, underlying motivations for the surveys, type of graphite mineralization being targeted, authorship or responsible party for the geophysical studies, study location, and the year of publication. This table serves as a reference for understanding the scope and focus of previous research efforts in graphite exploration using geophysical methods.

Figure 2 visually represents these data, categorizing the studies based on the year of publication, type of geophysical survey conducted, country where the deposit or study is located, scale of investigation, and the authorship or institution responsible for the geophysical surveys. This visualization helps to identify trends over time and regional variations in the application of geophysical techniques for graphite exploration.

The analysis of the selected articles shows that graphite deposits are investigated using a wide range of geophysical methods, each targeting specific petrophysical properties of the mineral. The choice of the most appropriate method depends not only on the physical properties of the graphite but also on the deposit type, lithostructural setting, and mineralization style. This relationship becomes particularly important when considering the different graphite types — lump, flake, and amorphous — as their distinct textures, grain sizes, and fixed carbon content influence how they respond to geophysical techniques.

Among the most utilized methods are geoelectrical surveys, such as resistivity, induced polarization (IP), and spontaneous polarization (SP) (Bhattacharya et al. 1984; Jödicke et al. 2007; Rakoto et al. 2019; Baranwal et al. 2024; Batista 2021; Fentaw et al. 2000; Yang et al. 2022; Wu and Peruzzo 2020; Stenberg 2024; Ramazi et al. 2009; Rønning et al. 2017), followed by aeromagnetic surveys (Hedin and Bergman 2020; Baranwal et al. 2024; Batista 2021; Molak and Cool 2018; Leinonen 2019; Gomes et al. 2022; Liimatainen 2022) and electromagnetic surveys, including frequency-domain (FTEM), time-domain (TDEM), and very low frequency (VLF) approaches (Hedin and Bergman 2020; Legault et al. 2015; Baranwal et al. 2024; Fentaw et al. 2000; Leinonen 2019; Liimatainen 2022; Loukola-Ruskeeniemi et al. 2023; Biswas and Sharma 2015; Rønning et al. 2017). Additional methods, such as gamma spectrometry, gravimetry, and magnetotelluric are also employed, though less frequently (Hedin and Bergman 2020; Batista 2021; Gomes et al. 2022), reflecting the diversity of approaches used to characterize graphite deposits.

Electrical methods stand out as the preferred choice for graphite analysis due to their ability to explore characteristic petrophysical properties such as high electrical conductivity and anisotropy (Klein 1962; Zondlo 2012). Resistivity measures the opposition of a material to electrical current flow, aiding in identifying variations that indicate possible graphite zones (Loke et al. 2021). Induced polarization (IP), in turn, evaluates the temporary storage of electric charge in materials, making it especially useful for identifying disseminated graphite in rock matrices (Martinho 2023). Disseminated flake graphite, when present at even 1% by volume, exhibits high chargeability, which justifies the use of this method (Dentith and Mudge 2014). A successful example comes from the Vesterålen district in Northern Norway, where helicopter-borne electromagnetic (HEM) and magnetic surveys successfully detected both known and previously undiscovered flake graphite deposits, later confirmed through drilling and laboratory analyses (Baranwal et al. 2024). This highlights how combining airborne geophysical methods with ground-based techniques can effectively map graphite mineralization in complex terrains.

Spontaneous polarization (SP) measures natural electric potentials generated by chemical or thermal gradients, which are particularly useful in hydrothermally altered environments (Sarma 2014). Graphite, especially amorphous types formed from high-grade metamorphism or hydrothermal processes, is an excellent target for SP surveys due to its conductivity (Dentith and Mudge 2014). However, these methods are not without limitations — for instance, in regions with thick overburden or complex subsurface conditions, electrical resistivity and IP methods may yield inconclusive results due to signal attenuation or interference (Suzuki et al. 2000). This can be especially problematic for lump graphite deposits, where mineralization may be confined to narrow veins or pockets, making detection challenging without complementary techniques like ground magnetics or electromagnetic surveys.

These methods offer high resolution in the subsurface and effectively differentiate mineralized zones from surrounding materials. Still, they come with constraints, including high implementation costs and restricted spatial coverage (Soupios and Kokinou 2016). Studies employing electrical techniques are typically confined to localized sections near the deposit, making their application on larger scales, such as district or province levels, challenging (Rakoto et al. 2019). Consequently, while they offer high accuracy for specific areas, they are less suitable for regional investigations aiming to understand the geological extent of deposits or identify new occurrences over broader areas (Sternberg 1991).

The magnetometric method also stands out as an essential tool in graphite exploration, especially due to its significant advantage over electrical methods: its relatively lower cost and feasibility for airborne surveys using aircraft or drones (Molak and Cool 2018). This capability allows for efficient coverage of extensive areas in a short time, making it particularly valuable in preliminary exploration stages, where the objective is to delineate broad structural features that may host mineralization. In graphite deposit analysis, magnetometry is widely used to identify geological structures such as fault zones, folds, and lithological contacts, which are critical for understanding the tectonic evolution of graphite deposits. These structures often act as conduits for fluid flow, promoting the remobilization and reconcentration of graphite, especially in the case of flake and lump graphite formed through high-grade metamorphism (Luque et al. 1992).

Magnetometry measures variations in the Earth's magnetic field caused by differences in rock magnetic susceptibility (Nabighian et al. 2005). While graphite is diamagnetic, it

TABLE 1. Summary of reviewed studies on the use of geophysical methods in graphite deposits exploration: Key parameters and characteristics.

Reference	geophysical survey	motivation	mineralization – Lithostrucutural context	study area	country	scale	authorship of the surveys
Bhattacharya et al., 1984	SP, Resistivity	Locate graphite Deposits	Lump graphite in Gneissic and Khondalite belt	Balagir District, Orissa	India	1:10,000	Private Sector
Jödicke et al., 2007	SP, Resistivity	Understand the electrical conductivity in rocks at depth.	Amorphous graphite in Graphite-rich quartzite, metapelitic unit	Serre San Bruno, Calabria	Italy	1:5,000	Academy
Hedin & Bergman, 2020	Gravimetric, Magnetometric and VLF	Assess graphite potential	Amorphous graphite in Paragneiss	Gilltjärn–Skrammelfall, Norberg	Sweden	1:50,000	Geological Survey
Heritiana et al., 2019	SP, electrical resistivity tomography (ERT), IP	Evaluation of flake graphite ore	Flake Graphite in Paragneiss	Toamasina and Brickaville cities	Madagascar	1:5,000	Academy
Dentith & Barrett, 2003	IP	Reevaluation of flake graphite ore	Flake Graphite in Graphite-Schist	Uley, South Australia	Australia	1:10,000	Private Sector
Legault et al., 2015	TDEM	Exploration program targeting nickel (Ni), copper (Cu), and platinum group metals (PGMs)	Lump epigenetic graphite in Alcalic Complex	Albany Deposit	Canada	1:10,000 1:5,000	Private Sector
Baranwal et al., 2024	aero FTEM, aero magnetic, conductivity, ERT, IP, CP, SP	Find hidden graphite deposits	Flake graphite in Gneiss and migmatites	Vesterålen province	Norway	1:50,000 to 1:5,000	Geological Survey
Batista, 2021	Magnetometry, Gamma spectrometry, resistivity, IP	Establish a geophysical-geological workflow for exploring graphite deposits in granulite metamorphic areas.	Flake Graphite in Graphite-Schist	Pintadas, Bahia	Brazil	1:100,0000 to 1:5000	Geological Survey, Academy
Fentaw, 2000	IP/Resistivity, GENIE EM	Evaluate graphite body	Flake Graphite in Graphite-Schist	Moyale Deposit	Ethiopia	1:10,000	Geological Survey
Yang et al., 2019	SP and magnetotelluric	Optimize the effective geophysics methods in graphite exploration	Flake Graphite in Graphite-Schist	Panzhihua deposit	China	1:20,000	Geological Survey
Molak & Cool, 2018	drone magnetometry	Locate graphite Deposits	Lump Graphite in Syenite	Feagan Lake West	Canada	1:2000	Private Sector
Leinonen, 2019	FTEM, TDEM, magnetometry	Locate graphite Deposits	Flake Graphite in Graphite-Schist	Vaajasalmi	Finland	-	Private Sector
Wu & Peruzzo, 2020	IP	Understand the effects of salinity and pH on the spectral induced polarization signals of graphite particles	-	-	-	-	Academy
Gomes et al., 2022	Gamma spectrometry, magnetometry	Identify Graphitic Signature Patterns	Flake Graphite in Paragneiss	Quatis, Rio de Janeiro	Brazil	1:100,000 1:5,000	Geological Survey, Academy
Liimatainen, 2022	FTEM , magnetometry	Locate graphite anomalies	Flake Graphite in Migmatite and paragneiss	Korsnäs region	Finland	1:25,000	Geological Survey
Ruskeeniemi et al., 2023	magnetometry, FTEM	Country-wide exploration studies	Flake Graphite in Graphite schists, Graphite-sulphide schists, Black schists and Black shales	Kajaani, Lahnaslampi, Talvivaara, Sotkamo	Finland	1:50,000	Geological Survey
Stenberg, 2024	Conductivity	To understand the role of graphite in electrical conductivity	Flake Graphite in Graphite-Schist and Gneiss	Takkula Deposit, Pälkäne	Finland	1:1,000	Geological Survey
Ramazi et al., 2009	SP, Resistivity	To explore the graphite deposit	Lump graphite in Graphite-Schist and Gneiss	Khenadarreh, Arak	Iran	1:1,000	Academy
Biswas & Sharma, 2015	VLF	To determine the sub-surface graphite deposit and their structural control	Amorphous Graphite in Graphite-Schist	Daltangan, Jharkhand	India	1:10,000	Academy
Rønning et al., 2017	HEM, CP, SP, ERT, IP	Part of the MINN project (Minerals in Northern Norway)	Flake Graphite in Graphite-Schist	Senja	Norway	1:10,000	Geological Survey

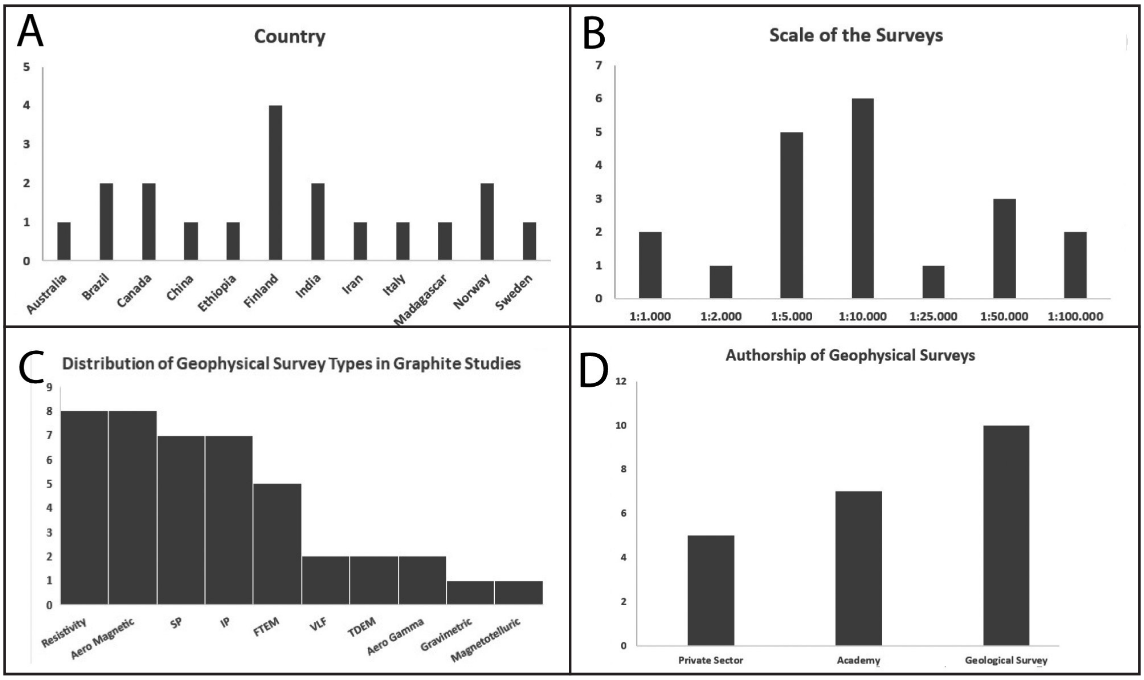

FIGURE 2. Overview of Geophysical surveys for graphite exploration: categorized by country, scale, and authorship. In panel (A), Wu and Peruzzo 2020, was excluded as it covers multiple graphite samples. Panel (B) presents the scale of the 20 articles reviewed. In panel (C), all geophysical surveys are included, with some studies utilizing more than one method. Panel (D) reflects multiple authorships per study, as many were conducted by various institutions.

can carry remanent magnetism, especially in lump graphite (Hansen et al. 2005). Graphite is often associated with ferromagnetic minerals, such as magnetite and pyrrhotite, which produce strong magnetic anomalies. For example, in the Albany graphite deposit, Ontario, airborne surveys successfully mapped high-grade flake graphite by detecting deep-seated structures (Legault et al. 2015). However, graphite's high conductivity can complicate interpretations, as the presence of other conductive minerals, like pyrite, may influence resistivity and induced polarization responses.

Magnetometry has limitations, particularly in deposits with amorphous graphite or low concentrations of magnetic minerals. In the state of Bahia, Brazil, it was ineffective for directly detecting graphite due to the scarcity of magnetic minerals and the complexities of metamorphism. However, when integrated with gamma spectrometry data, it improved mineralization mapping, demonstrating the value of a multi-method approach (Susin et al. 2019). In such cases, combining magnetic surveys with other techniques, such as EM or IP, is crucial to prevent misleading interpretations and optimize exploration costs, especially in complex deposits where different graphite types exhibit distinct geophysical responses (Verduzco et al. 2004; Baranwal et al. 2024).

Electromagnetic methods are widely used in graphite exploration due to their ability to identify conductive materials in the subsurface, such as graphite, which exhibits high electrical conductivity (Chung 2002). These methods are based on the generation of primary electromagnetic fields and the measurement of secondary responses induced in conductors (Zhdanov 2009). Techniques like time-domain (TDEM), frequency-domain (FTEM), and Very Low Frequency (VLF) are commonly used to detect materials with varying conductive properties, with VLF being particularly useful for shallow investigations (Giannino and Leucci 2021; Biswas and Sharma 2015). In the context of graphite, these methods can effectively map mineralized zones, particularly in regions where flake and lump graphite are present. These graphite types, which form in specific geological conditions—flake graphite in high-grade metamorphic environments and lump graphite in areas influenced by regional metamorphism—tend to show strong conductive responses, making them ideal targets for electromagnetic surveys.

Electromagnetic methods, particularly when employed in airborne surveys using aircraft or drones, are revolutionizing the way data is collected by enabling the rapid coverage of vast areas (Baranwal et al. 2024; Leinonen 2019; Rønning et al. 2017; Loukola-Ruskeeniemi et al. 2023). While their high cost remains a limiting factor, the use of advanced technologies, such as airborne sensors and drones, significantly enhances the efficiency and scope of exploration. Integrating TDEM data with satellite imagery, for example, can offer a more robust and comprehensive analysis, providing a deeper understanding of the geological structures associated with mineralization. These methods are especially valuable in identifying structural features like faults and folds, which often act as conduits for the formation of graphite, particularly lump and flake graphite.

Rønning et al. (2017) describe a frequency-domain helicopter-borne electromagnetic survey conducted by the Geological Survey of Sweden. This survey successfully mapped potential graphite mineralizations across a broad area, identifying zones with high exploration potential. This was followed by electrical surveys for higher-resolution data, which led to the precise mapping of graphite mineralizations. This example highlights the integration of electromagnetic methods with other techniques to refine exploration efforts.

Loukola-Ruskeeniemi et al. (2023) describe a similar airborne frequency-domain electromagnetic survey conducted by the Geological Survey of Finland (GTK), where the 3 kHz frequency was used for its nationwide coverage and minimal interference from environmental factors. This approach enabled efficient mapping of areas likely to host graphite deposits, further demonstrating the usefulness of electromagnetic methods in graphite exploration, particularly in identifying geological structures that host flake and lump graphite.

Despite the advantages of electromagnetic methods, they can face limitations, especially when dealing with amorphous graphite deposits, which typically exhibit lower conductivity compared to flake or lump graphite. In regions where amorphous graphite predominates, these methods may not provide clear responses, making it essential to combine electromagnetic surveys with other geophysical techniques, such as magnetometry or IP, for more comprehensive exploration strategies.

In addition to electrical and electromagnetic methods, other geophysical techniques, such as gamma spectrometry, also play complementary roles in studying graphite deposits. Gamma spectrometry, like magnetometry, can be performed using aircraft, allowing it to efficiently cover large areas (Uyttenhove 2005). This method is particularly useful for mapping lithologies and identifying subsequent rock alterations, as the primary control of graphite mineralizations is lithological (Batista 2021). While its direct application for locating graphite deposits is limited, gamma spectrometry serves as a regional tool for identifying promising graphite targets. It provides valuable data on the concentrations of potassium (K), thorium (Th), and uranium (U), as well as total gamma counts, which are essential for understanding the geological context of graphite mineralizations.

Graphite mineralizations, particularly flake and lump graphite, are often linked to specific geological processes, with flake graphite commonly associated with high-grade metamorphism and lump graphite forming in regions with strong tectonic activity. In contrast, amorphous graphite tends to form in low-grade metamorphic settings or through hydrothermal alteration processes (Batista 2021). The mapping of elements such as thorium and uranium through gamma spectrometry can help identify areas where these types of graphite are likely to occur. For instance, the Wadi Al-Allaqi region in the southeastern desert of Egypt, known for its graphite and uranium occurrences, features areas with high values of the F parameter (Gobashy et al. 2024). This parameter, calculated using the formula $F = K \cdot U/Th$, highlights regions where graphite, especially lump and flake varieties, may be concentrated.

In the Bissett Creek graphite deposit in Canada, there is a positive correlation between graphitic carbon and uranium (Drever et al. 2023), a relationship that could be indicative of the structural and lithological conditions favoring graphite mineralization. Similarly, the Liu Mao graphite deposit in China is associated with the metamorphism of uranium- and vanadium-rich black shales (Xu 1989; Chai and Liu 1992; Wilde et al. 1999), suggesting that high-grade metamorphic conditions, typical of flake and lump graphite deposits, are key to its formation. In Alaska, the Graphite Creek flake graphite deposit is located in areas with elevated concentrations of thorium and strontium, further demonstrating the relationship between geochemical elements and graphite mineralization (Case et al. 2023).Several studies have highlighted the positive correlation between carbon and uranium contents in graphite deposits (Parnell et al. 2021; Cheng et al. 2022). The International Atomic Energy Agency (IAEA 2018) has also noted that graphitic rocks are useful indicators for uranium exploration. Consequently, uranium and thorium can be effectively employed as pathfinder elements in graphite prospecting.

Gravimetry, which measures variations in rock density, is valuable for mapping large-scale geological structures associated with graphite deposits, especially in areas with pronounced density contrasts between graphite-rich rocks and their host lithologies (Wenyong et al. 2012). This method excels in identifying regional features, such as folds and faults, that can act as structural traps for lump and flake graphite, commonly formed in high-grade metamorphic settings. However, its effectiveness becomes limiting when targeting smaller, discrete mineralized zones, particularly in deposits of amorphous graphite, which often occur in more homogeneous, lower-density environments (Dentith and Mudge 2014). Since graphite is generally less dense than many other minerals, gravimetry could, in some cases, help highlight the presence of graphite by revealing contrasts with denser host rocks. Nonetheless, its ability to effectively detect graphite mineralization is compromised in such cases, and complementary geophysical techniques are needed to improve exploration precision. Magnetotellurics, valuable for studying deep geological structures and regional tectonic contexts, are less effective for graphite deposits due to their high cost and inability to resolve detailed features at the deposit scale, especially for amorphous graphite (Chave and Jones 2012; Yang et al. 2022). These methods, however, can complement other geophysical techniques to better understand the broader geological setting of graphite occurrences.

4.1. Lithostructural Analysis of Graphite Mineralization Types and Corresponding Geophysical Methods

An analysis of the reviewed articles reveals that successful graphite exploration requires not only an understanding of its petrophysical properties but also a careful selection of geophysical surveys suited to the geological setting and type of graphite mineralization. Each type of graphite deposit occurs in distinct geological environments with specific structural controls, which directly influence the effectiveness of different geophysical methods. Therefore, aligning the survey approach with these factors is crucial for accurately detecting and delineating graphite mineralization.

Flake graphite is typically found in high-grade metamorphic terrains, particularly within paragneisses, schists, and marbles derived from organic-rich sediments. Its mineralization is strongly controlled by ductile deformation zones, where folding, shearing, and faulting influence its distribution. Given these characteristics, geophysical methods must be capable of detecting both conductive graphite-bearing horizons and the structural features associated with their formation. In Baranwal et al. (2024), for the northern region of Norway, frequency-domain helicopter EM (HEM) and airborne magnetic surveys were employed to identify conductive anomalies and structural trends indicative of graphite mineralization. These methods were particularly effective in high-grade metamorphic settings, where graphite's conductivity and associated structural features create distinct electromagnetic and magnetic signatures. To refine the interpretation, ground-based methods such as electrical resistivity tomography (ERT), charged-potential (CP), self-potential (SP), ground EM, and geological surveys were conducted, confirming the presence and extent of graphite mineralization.

A similar geophysical approach was applied to flake graphite deposits in central Madagascar, though adapted to the region's specific geological conditions. Heritiana et al. (2019) studied mineralization within the Antananarivo tectonic block, where graphite follows a NNE-SSW structural trend in highly weathered gneissic rocks. Due to intense laterization, the mineralized zones exhibit significant heterogeneity, requiring methods capable of distinguishing conductive graphite layers from the altered host rocks. To achieve this, self-potential (SP), electrical resistivity tomography (ERT), and induced polarization (IP) surveys were used, effectively mapping subsurface conductivity variations and refining the delineation of graphite-rich units. While both studies focused on flake graphite in metamorphic environments, the contrasting geological conditions—structurally complex, high-grade terrains in Norway versus laterized, highly altered gneiss in Madagascar—necessitated different combinations of geophysical techniques to optimize exploration outcomes. Regarding amorphous graphite, it forms through the low-grade metamorphism of coal or carbonaceous sedimentary rocks and is commonly found in sedimentary basins. Compared to flake graphite, these deposits exhibit limited structural complexity. In Hedin and Bergman (2020), in northwestern Sweden, gravimetric, magnetometric, and very low-frequency electromagnetic (VLF) measurements were conducted along nine profiles to enhance graphite exploration in this well-known graphite-bearing region. The magnetometric survey was specifically employed due to the known presence of sulfides associated with graphite in the area, allowing for the detection of magnetic anomalies that could indicate mineralized zones. These surveys were carried out to characterize subsurface density and conductivity variations, aiding in the identification and delineation of graphite-rich zones while distinguishing them from surrounding barren lithologies.

Vein-type graphite deposits, such as the Albany graphite deposit in the Superior Province of the Canadian Shield, are typically hosted within intrusive complexes and structurally controlled by deep-seated fluid migration pathways. The Albany deposit is specifically found within the Albany Alkalic Complex, consisting of gneissic to unfoliated syenite, granite, diorite, and monzonite, intruded by younger felsic to mafic dykes. These basement rocks are overlain by Paleozoic sedimentary sequences and thick overburden, which pose challenges for direct geological mapping. Given these geological characteristics, geophysical methods played a crucial role in delineating the deposit. An airborne electromagnetic survey conducted by Geotech Ltd. in 2010 using the prototype VTEMMAX time-domain EM system identified key anomalies, which were later validated through drill testing. In 2013, Crone Geophysics & Exploration Ltd. conducted surface time-domain EM (TDEM) surveys, specifically targeting the drill-confirmed East and West graphitic breccia pipes. The use of in-loop and out-of-loop configurations allowed for effective coupling with the top and steeply dipping edges of these pipes, successfully outlining their lateral extents. These geophysical methods were particularly suited for detecting the strong conductivity contrasts associated with vein-type graphite mineralization, where graphite is concentrated in structurally controlled breccia zones within intrusive bodies (Legault et al. 2015).

4.2. Source of the Data

The analysis of the selected articles reveals key distinctions in the types and scales of geophysical data collected by geological agencies, private companies, and academia, highlighting the essential roles each entity plays in mineral exploration. Approximately half of the studies rely on geological survey data, which are crucial for regional mapping and mineral potential assessments. These surveys, typically conducted at scales ranging from 1:100,000 to 1:5,000, provide broad, generalized data that lay the foundation for more focused investigations by academia or private enterprises. Geological surveys primarily focus on providing comprehensive, large-scale datasets that help define broad geological features, such as faults, folds, and lithological contacts, which are essential for identifying potential mineralization zones. These datasets are vital for subsequent, more detailed studies conducted by academia and private enterprises, who use them to target specific mineralized areas. Typically, geological agencies concentrate on regional-level data collection, while more detailed, site-specific studies are generally handled by academia and private companies (Hedin and Bergman 2020; Loukola-Ruskeeniemi et al. 2023).

In Baranwal et al. (2024), a geological survey initiated a project with airborne electromagnetic and magnetic surveys at a regional scale, followed by ground-based electrical and electromagnetic studies to identify and characterize mineral deposits. While this comprehensive approach illustrates the potential of geological surveys to guide entire exploration processes, it is more common for these agencies to focus on broader investigations, leaving detailed exploration to academia and private companies. Academia and private enterprises tend to apply advanced technologies to conduct high-resolution surveys, focusing on specific areas identified by regional data (Batista 2021). These investigations provide deeper insights and targeted exploration, complementing the regional datasets from geological surveys.

An example of such a collaboration is seen in the discovery of a rare hydrothermal graphite deposit, where airborne electromagnetic (AEM) systems played a pivotal role in identifying the deposit (Legault et al. 2015). The initial regional aeromagnetic survey by the Ontario Geological Survey (Stott 2008) revealed a promising area for further investigation, and subsequent interpretative mapping guided the detailed exploration process. This highlights the critical importance of regional surveys carried out by geological agencies in identifying promising exploration targets, which academia and private enterprises can then explore in greater detail. The integration of regional data with more localized studies ensures a robust, multi-layered approach to graphite exploration. This collaboration between geological surveys, academia, and private companies creates a synergistic environment where each pillar brings its strengths to the table—geological surveys provide the broad, foundational knowledge, while academia and private companies apply advanced technologies to refine the search for mineral deposits and enhance the understanding of mineral systems. This integrated approach ultimately leads to more efficient, cost-effective, and successful exploration projects.

5. Conclusions

The exploration of graphite deposits, like many mineral deposits, faces unique challenges due to the variability in petrophysical and chemical properties, such as crystallinity, purity, and distribution within host rocks. These factors complicate the establishment of distinct geophysical signatures for graphite, making data interpretation particularly challenging. Despite these complexities, geophysical methods—particularly electrical, magnetic, and electromagnetic techniques—have proven valuable for identifying and characterizing graphite mineralization. Electrical methods, such as resistivity and induced polarization, offer high accuracy in delineating mineralized zones, though their spatial coverage is often limited, requiring complementary methods for regional mapping. In contrast, magnetic and electromagnetic surveys provide broader coverage and are cost-effective, making them indispensable for regional reconnaissance and preliminary exploration.

Graphite exploration typically relies on a multi-pillar approach involving geological surveys, academia, and the private sector. Geological surveys play a critical role by providing foundational regional mapping, while academia and the private sector conduct more localized, high-resolution investigations. To ensure successful exploration, it is crucial for each pillar to fulfill its role: geological surveys offer comprehensive data that inform targeted, detailed studies by academia and industry. The relationship between geological features, such as lithostructural behavior, deposit types, and geophysical responses, must also be considered to refine exploration strategies. Understanding how different graphite deposit types—such as lump, amorphous, and flake—respond to various geophysical methods is essential for optimizing data interpretation and identifying mineralization zones.

The lithostructural setting of graphite deposits dictates the effectiveness of geophysical exploration methods. Flake graphite, found in metamorphic terrains, benefits from electromagnetic and induced polarization techniques. Amorphous graphite in sedimentary basins is best detected using resistivity and seismic methods, while vein graphite, structurally controlled by fault networks, responds well to electromagnetic and resistivity surveys. Understanding these geological and structural parameters enhances the efficiency of graphite exploration programs.

In conclusion, overcoming the challenges of graphite exploration requires integrating multiple geophysical methods and fostering collaboration between geological surveys, academia, and the private sector. By combining broad-scale regional data with focused, high-resolution investigations, graphite exploration can be enhanced, contributing to the efficient identification of new resources and advancing exploration strategies.

Acknowledgements

We would like to express our sincere gratitude to the reviewers for their valuable suggestions and contributions to the text. The proposed changes have undoubtedly helped to enhance the clarity and consistency of the work, making it more robust and well-structured. We deeply appreciate the time and effort dedicated to the review.

Authorship credits

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C - Data Interpretation/ Validation **D** - Writing
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