

Review

Case Studies of Magnetic and Electromagnetic Techniques Covering the Last Fifteen Years

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Abstract: Magnetic and electromagnetic techniques have a long history of application in mineral exploration to detect deposits and their surroundings. Their implementation over the last fifteen years has been affected by strong variations in the mining market in parallel with important technological developments. During this period, both methods were the subject of numerous documented case studies all over the globe, which is a sign of popularity and longevity of these techniques. Through a review of case histories from the main geophysical journals, we analyze the principal usage of these methods when applied to mineral exploration, while the majority of documented cases originate from North America, Asia, and Australia. There are more case studies describing the use of the magnetic method and we attribute this popularity to direct and indirect use of this method for mineral exploration. In particular, there is an increasing number of magnetic surveys conducted with drones. Combining magnetic and electromagnetic techniques is also common. The number of magnetic and EM technique case histories range by descending order from gold, porphyry copper, polymetallic, massive sulfides, uranium, Ni-Cu-PGE, iron ore, kimberlite, and iron-oxide copper-gold, with a number of single continent-specific applications.

Keywords: magnetic exploration; electromagnetic exploration; case studies



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1. Introduction

Magnetic techniques are mainly based on the measurement of the Earth's magnetic field [1] over a given area and the associated geographical variations with changes in the magnetic susceptibility of the subsurface [2]. Electromagnetic methods (EM) [3] use natural or artificial, electric or magnetic sources to generate secondary signals due to the presence of conductivity/resistivity subsurface variations [4]. Both techniques, either ground, borehole, or airborne, are widely used in mineral exploration [1,5] either to directly detect mineralization or to characterize the geology surrounding a potential deposit. The last fifteen years were an active period for the development of these techniques. Years 2010–2012 saw a significant allocation for exploration budgets [6]. However, these years were followed by four years of decreasing exploration budgets that slowly recovered after 2017 without reaching their previous peak. Worldwide production reached a plateau around 2013 [7] and has been stable since. During the same period, technology improvements have had an profound impact on society [8,9], and in particular exploration geophysics.

Technological advances in the application and interpretation of these techniques have been numerous over the last fifteen years, since the seminal works of [1,5,10,11] covering the first decade of the XXIst century, and are difficult to relate succinctly. For this reason, we refer the reader to the reviews of [12–20] which cover acquisition and interpretation. Thus, the focus of this paper is on case studies of magnetic and EM techniques, since they are an important part of the geophysical literature that reflects technological advances and their usage. We mainly rely on papers published in the last fifteen years in *Geophysics*, *Exploration Geophysics*, *Geophysical Prospecting*, *Minerals*, and *Australian Society of Exploration Geophysicists (ASEG) Extended Abstracts*, as these publications can be easily found on the

internet. For developers, these publications are opportunities to justify claimstaking while also celebrating success sometimes. Consequently, case studies published since 2010 highlight the achievements of the last fifteen years. First, we start with applications of aeromagnetic drone techniques, followed by publications of magnetic and EM techniques, classified by continent, knowing that our choice of publications may bias the geographical distribution of our results. Magnetic surveys are often conducted with gravity surveys and in this circumstance classified as potential field surveys.

2. Drones

During the period covered, various studies were conducted to compare unmanned airborne vehicle (UAV) measurements with ground or airborne measurements. Ref. [21] conducted a simulated magnetic UAV survey and compared the results with ground and airborne surveys. The results have higher resolution than airborne surveys and are similar to ground survey data. Ref. [22] compares the responses of UAV magnetic data with airborne data over a hilly area in China. The results compare favorably. Ref. [23] compares measurements collected with a rotary-wing UAV magnetometer and with fixed-wing aeromagnetic data over iron-oxide deposits in central Sweden. The two data sets outline the mineralization similarly. Ref. [24] conducted an UAV survey over mineralization in New Brunswick, Canada, whose results compare favorably with upward continued ground magnetic data. Ref. [25] compares the response of ground, helicopter and UAV magnetic data over a prospective gold area in northern Québec. UAV data are of the same quality as traditional methods. Ref. [26] conducts a combined ground and UAV magnetic survey in northern Sweden, where the ground and airborne surveys were compared. Strong correlation is observed between the two surveys. Ref. [27] describes trials of an UAV sub-audio magnetics (SAM) survey at Forrestania Electromagnetic Test Range in Western Australia.

Several drone case studies were conducted over known mineralizations. Ref. [28] presents the results of a magnetic UAV survey conducted in the Shebandowan Greenstone Belt, northwest of Thunder Bay, Ontario, Canada. Ref. [29] describes a magnetic UAV survey over a gold property in northern Québec, Canada, and after repeatability tests for validating the data, these data were inverted with Geosoft VOXI toolbox. Ref. [30] presents a case study of helimagnetic survey for regional exploration and UAV for high-resolution exploration of iron ore located in Pocheon, Korea. Ref. [31] developed a new iterative imaging technique applied to UAV magnetic data for achieving high resolution and identifying weak anomalies to be applied over an iron deposit in China. Other UAV studies include a survey of the Bjerkreim-Sokndal layered intrusion in southwestern Norway with custom multirotor magnetic UAV, in an area with challenging environmental conditions [32]. The UAV added information about the important geological contacts and, with multiple flight altitudes, helped in the construction of the anomaly. Ref. [33] describes a combined ground-UAV TDEM survey carried out over a gold prospect in eastern Russia. Ref. [34] presents the results of an UAV magnetic gradiometry survey over a little iron ore deposit in western Iran.

3. Magnetism

3.1. Africa

Ref. [35] presents a potential field study of kimberlites in Botswana, where geometrical properties of two of the pipes were estimated using gravity and magnetic analysis, and modelling. Ref. [36] applies digital edge detector operations on magnetic data to enhance the delineation and interpretation of geological features within the Middle Benue Trough of northern Nigeria. Ref. [37] applies a joint inversion to combined gravity and magnetic datasets collected over kimberlite pipes, also in Botswana. Ref. [38] combines aeromagnetic data and geochemical analysis to map related gold ore mineralization deposits around the Wadi El-Saqia area in the Central Eastern Desert of Egypt. Ref. [39] presents magnetic data processing and interpretation for exploration of rutile from the Minta area, in Haute-Sanaga,

Cameroon. Using magnetic data, Ref. [40] establishes connections between geological structures and precious and base metal deposits of the Pangar-Djérem Zone, Cameroon. Ref. [41] analyzes aeromagnetic data, transformations, and geological information for the structural interpretation of the location of precious stones from the mineral-rich zones in parts of Lafiagi and Pategi areas of Bida basin, central Nigeria. Ref. [42] integrates ground geophysical methods (ground magnetics, electrical resistivity, and induced polarization) in conjunction with fire assay and inductively coupled plasma-atomic emission spectrometry techniques to delineate orogenic gold mineralization potential zones in the Kushaka greenschist belt, Nigeria. Using ground magnetic data, Ref. [43] characterizes anomalous bodies in the manganese-rich mining zone situated in Bouarfa, Morocco. Ref. [44] analyzes geological and geophysical data to assess the structural trends affecting phosphate distribution near Wadi El-Nakheel, Egypt. Ref. [45] presents an integrated geophysical investigation for potential gold mineralized zones located in northwestern Nigeria. Ref. [46] applies surface geometry inversion to a magnetic dataset acquired over two kimberlite pipes located in north-central Botswana. Ref. [47] describes ground and airborne geophysical data collected over a gold deposit located in Guinea.

3.2. Asia

Using gravity and magnetic data, Ref. [48] develops an integrated geological model for the polymetallic Shizishan ore field in Anhui Province of China. Ref. [49] presents an interpretation of aeromagnetic data collected over a north-east trending orogenic gold belt of the Piranshahr-Sardasht-Saqquez Zone, Iran. Ref. [50] presents the geophysical signatures of the Beldih mine in eastern India, known for Nb–rare-earth-element–uranium mineralization. Ref. [51] proposes a combination of magnetic data filters to locate porphyry copper deposits in the tertiary magmatic belts of Iran. Ref. [52] applies constrained inversion to the interpretation of the Macheng iron deposit in China. Ref. [53] presents the case of a large magnetic anomaly detected by airborne geophysics at Gadarwara Madhya Pradesh, in north-central India. Drilling shows that this anomaly, which can be fitted with 2D models, is caused by an iron formation. Ref. [54] applies factorial kriging to regional–residual separation of magnetic data collected over the Bashmaq area, an Iron Oxide Copper-Gold (IOCG) deposit, in northwestern Iran. Ref. [55] integrates aeromagnetic, radiometric, and satellite imagery data over the Chahargonbad area in the Kerman province of Iran, prone to Cu-bearing mineralization. Ref. [56] discusses aeromagnetic exploration methods applied to exploration of iron deposits located in the Hubei province of China. Ref. [57] applies a methodology to analyze and fuse information (Landsat, aeromagnetic data, geological data, and geochemical stream sediment analysis) over an area known for copper indices and mines in Iran. Ref. [58] presents a study of ground magnetic and electrical resistivity/chargeability data from Kerala, India, known for vein-type gold mineralization. Ref. [59] employs 3D magnetic susceptibility inversion of aeromagnetic data over lead-zinc polymetallic deposits in Yichun, China. Ref. [60] interprets magnetic anomalies of the Galinge iron polymetallic deposit in western China.

3.3. Australia

Ref. [61] presents the results of an aeromagnetic and radiometry survey over the Carrapateena iron-oxide copper-gold deposit located in South Australia. Ref. [62] describes various magnetic data collection and processing over the magnetite iron ore resource Hawsons Iron project in western New South Wales. Ref. [63] applies the method developed by [64] to analyze magnetic data over a gold-mineralized system in Queensland. Ref. [65] studies the anisotropy of the Monakoff carbonate-hosted IOCG in Queensland and surrounding banded iron formations to differentiate the structural and metallogenic controls. Ref. [66] compares magnetic responses from an iron-rich gossan in a volcanic environment and a limestone-hosted manganese deposit of Papua New Guinea. Ref. [67] applies geological constraints to the inversion of magnetic data over the Darlot-Centenary Gold Mine of Western Australia. Ref. [68] presents airborne magnetic inversions over the

Wallaby gold deposit of Western Australia. Ref. [69] applies petrology and petrophysics to the interpretation of airborne magnetic surveys conducted over the Mt Leahy Tenement porphyry copper project in Papua New Guinea. Ref. [70] integrates drill core geochemistry, spectral and petrophysical logs, and geophysical data to characterize the Punt Hill Copper-Gold prospect and IOCG system of South Australia. Ref. [71] interprets magnetic, radiometric, and gravity data from the Stanthorpe region, Australia, with a particular interest on hydrothermal alteration. Ref. [72] presents interpretation of potential field data over the Darlot gold mine located in the Yilgarn Craton. Ref. [73] studies the region of Heazlewood-Luina-Waratah, a prospective region for minerals in northwestern Tasmania, Australia, by combining the results of potential field (geometry and property) inversion, petrophysical measurements, and updated field mapping. Ref. [74] presents an integration modelling and associated machine learning targeting of the Jaguar Massive Sulfide (MS) deposit of Western Australia using potential field and geological information.

3.4. Europe

Ref. [75] analyzes the results of magnetic and electric surveys completed to extend known Fe-rich emery horizons and to locate new deposits in the Elmacik area, Yatagan, Turkey. Ref. [76] develops and applies a joint inversion algorithm on 3D potential field data collected over a gabbro intrusion in northern Sweden. Ref. [77] investigates, using potential fields, Slingram moving loop data and rock's physical properties the geological geometry in the Gällivare mining area, Sweden.

3.5. North America

Ref. [78] inverts magnetic and gravity data with geological and geophysical constraints over the Rambler Rhyolite in Newfoundland, Canada. Ref. [79] applies an automatic lineament network extraction method to identify magnetic lows that may represent faults from Wopmay Orogen in northwestern Canada, an area with promising polymetallic hydrothermal mineral occurrences. Ref. [80] derives constraints from a geophysical–geological feedback process and applies these constraints on inversion models for interpreting the northeast Amer belt located in Nunavut, Canada. Ref. [81] uses the normalized source strength for interpretation of potential field tensor data collected for exploration of nickel, copper and platinum group element (Ni-Cu-PGE) deposits in the McFaulds Lake area, northern Ontario, Canada. Ref. [82] analyzes aeromagnetic data to locate intrusives near the Pebble deposit in Alaska, USA. In Canada, the Sudbury structure in Ontario, which is host to several ore deposits, has been the subject of various studies. Ref. [83] models airborne gravity and magnetic profiles, while constraining the results based on seismic sections, geological contacts, and petrophysical data of the Sudbury area. Ref. [84] predicts the 3D geological setting of the Sudbury structure by integrating available geophysical and geological information using 3D GeoModeller software. Ref. [85] builds a litho-prediction model from potential field data-constrained inversions over the Victoria property, in Sudbury. Ref. [86] analyzes potential field data covering the southwest Thelon Basin, Northwest Territories, Canada, a prospective area for uranium and other economic metals. Ref. [87] applies magnetization inversion at the regional scale and cooperative inversion of DC/IP and magnetics at the local scale over the Newton Au-Ag deposit in British Columbia, Canada. Ref. [88] compares unconstrained and constrained inversions applied on potential field data collected from three different mining sites in Canada. Constrained inversion provided more meaningful results in the three cases. Ref. [89] compares the results of three different inversions programs applied on the same dataset, Highland Valley copper district in British Columbia, Canada, with unconstrained and constrained models. Variations in the results are attributed to the intrinsic errors in producing images from different programs. Ref. [90] proposes, based on 3D magnetic data inversion, computation of an alteration index to estimate porphyry copper alteration at depth at Highland Valley. Ref. [91] presents a case study of potential field joint inversion collected over the McArthur River area of the eastern Athabasca Basin in western Canada. Airborne and ground gravity and magnetic data over

one of the Tli Kwi Cho kimberlites in Northwest Territories, Canada, were interpreted with petrophysically and geologically-guided joint inversions by [92]. Ref. [93] images oxide-apatite deposits located in eastern Adirondack Highlands, upstate New York, USA, using aeromagnetic, aeroradiometric, ground gravity, petrophysical and geochemical data. Ref. [94] applies self-organizing maps (SOMs) to magnetic, radiometric and gravity data sets from the Baie Verte Peninsula, in Newfoundland, Canada. Ref. [95] incorporated 3D magnetic inversion in the structural study of Sixtymile Gold district, Yukon, Canada. Ref. [96] performs joint potential field inversion and geology differentiation to obtain a quasi-geological model of the Elk Creek Carbonatite complex, southeast Nebraska, USA, an area hosting niobium and rare earth element mineralization.

3.6. South America

Ref. [97] uses the SOM approach to analyze airborne geophysical data collected over the Brazilian Amazon. Ref. [98] analyzes aeromagnetic data collected over the Morro do Leme nickel deposit, Brazil, with an initial model based on magnetic source parameter estimation techniques. Ref. [99] presents a study characterizing geology from inverted potential field data over an iron formation in Minas Gerais, Brazil. Ref. [100] inverts magnetic data above the Furnas southeast IOCG deposit at a low magnetic latitude in Carajás Mineral Province, Brazil. Ref. [101] analyzes the geophysical data above the Catalão I alkaline–carbonatite complex, located in central Brazil, which is one of the main producers of niobium and phosphates in the world. Ref. [102] studies and delineates, through various geophysical parameters, the source of a magnetic anomaly near the Buracao da Velha copper deposit in Brazil. Ref. [103] develops an interpretation scheme based on geophysical models obtained from 2D and 3D inversion of geophysical and sparse geological data. This scheme was applied to the interpretation of geophysical data collected over the Cristalino iron oxide copper-gold deposit, in northern Brazil. Ref. [104] applies a new technique for airborne magnetic topography correction on data collected over the Río Blanco-Los Bronces and El Teniente porphyry copper districts (Andes of central Chile). Ref. [105] utilizes 3D litho-constrained inversion of potential field data to define a region with good potential for iron ore deposits in the Sierra Grande region of northern Patagonia, Argentina. Ref. [106] compares four techniques for removing spatial aliasing artifacts in aeromagnetic surveys completed over southeastern Minas Gerais, Brazil. Using the Poisson theorem relating magnetization and density, Ref. [107] interprets a pseudo potential field survey covering the Serra Sul of the Carajás Mineral Province, Brazil, area known for iron deposits. An analysis by [108] of the geophysical data collected at the Cristalino IOCG deposit in Carajás, Brazil, reveals that magnetic rocks are not fully mapped by the total magnetic gradient if the strike of the rocks direction and Earth's magnetic field direction coincide. Furthermore, brecciated massive sulfides are found to be weakly magnetic. Ref. [109] presents results of 2D modelling and 3D inversion of airborne magnetic data flown over the Serra das Éguas Complex, (in Brumado, Bahia, northeastern Brazil), a geological structure containing lenses of magnesite. Ref. [110] uses gravity and magnetic methods for the investigation of an iron ore deposit, namely East Deposit, of Sierra Grande Formation, Río Negro Province, Argentina.

3.7. Mixed Continents

Ref. [111] reviews the practice of gravity, magnetic, and radiometric methods to the study of igneous intrusions, notably carbonatitic–alkalic intrusions, peralkaline intrusions, and pegmatites, rich in rare-earth metals, with North American and Australian examples.

4. Electromagnetics

4.1. Africa

Ref. [112] compares four different AEM system data sets from the Sunnyside nickel deposit in southeast Botswana. Ref. [113] presents filtered and enhanced Airborne Electromagnetic (AEM) time domain data acquired over the Ilesha Shist Belt in southwestern

Nigeria. Ref. [114] presents a study, using ground geophysical methods, aimed at detecting sulfide mineralization possibly associated with radioactive bostonite rocks located in the Central Eastern Desert, Egypt.

4.2. Asia

Ref. [115] describes the results of high-resolution heliborne magnetic and time domain EM surveys conducted over a fracture-controlled uranium deposit located in the Sikar district, Rajasthan, India. Ref. [116] describes the results of a controlled source audio-frequency magnetotelluric (CSAMT) survey carried out to evaluate potential iron (Fe) and polymetallic (Pb-Zn-Cu) deposits in Longmen region, southern China. Ref. [117] attributes to polarizable conductive zones negative responses in heliborne EM data recorded over uranium deposits in the Cuddapah Basin, India. Ref. [118] evaluates a chromite exploration case history using CSAMT, located in southern Tibet, China. Ref. [119] compares broadside (perpendicular) and inline ground time domain EM methods over the Caosiyao porphyry molybdenum deposit in China. Ref. [120] presents 3D MT inversions in the central Luzong basin ore district of eastern China which is well known for porphyry iron deposits. Ref. [121] describes the results of an AMT survey conducted over a gold polymetallic deposit in the Qinling Metallogenic Belt of North China Craton. Ref. [122] 3D inverts AMT data over the Cimabanshuo porphyry copper deposit in Tibet. Ref. [123] analyzes the application of the AMT technique to a metallic deposit located in the northwestern Guizhou province of China.

4.3. Australia

Ref. [124] compares 3D inversions of AEM systems ZTEM and AirMT collected over the Nebo-Babel Ni-Cu-PGE deposit, in West Musgrave, Western Australia. Ref. [125] presents airborne EM results of surveys over known and new manganese deposits located in Western Australia. Ref. [126] presents results of airborne and borehole EM surveys at Hallandaire copper deposit in Western Australia. Ref. [127] integrates inverted AEM data with the initial model of a 2D MT inversion conducted over the Cariewerloo Basin, a region of unconformity-type uranium deposit, in South Australia. Ref. [128] presents and interprets sub-audio magnetics data over the Far South gold project located in Western Australia. Ref. [129] describes airborne and ground EM surveys which led to the discovery of the Musket and Camelwood nickel sulfide deposits located in Western Australia. Ref. [130] presents drill hole EM surveys that led to the discovery of the Eureka massive sulfide lens located in Victoria. Ref. [131] describes the discovery of the Artemis Cu-Au-Zn-Ag deposit, located in northwest Queensland, using historical geophysical and geological data complemented by new airborne and ground EM. Ref. [132] presents and discusses AEM results over banded iron formation in the Hamersley Province of Western Australia. Ref. [133] attributes second-order effects in concentric-loop AEM system responses at Lewis Ponds in New South Wales, Australia, to polarizable material mapped with a Cole–Cole model as ground dipole–dipole array data accurately imaged disseminated sulfides surrounding ore-grade massive sulfides. Ref. [134] compares AEM responses collected over the Nebo Babel Ni-Cu-PGE deposit located in Western Australia. Ref. [135] delineates cobalt targets using the sub-audio magnetics method deployed over cobalt high-grade mineralization of the Carlow Castle project of Western Australia. Ref. [136] compares three inversion methods applied to greenfield AEM data. CDI3D, Maxwell codes, and underdetermined 3D voxellated inversion were used over a volume surrounding the conductor at the test site in Forrestania, Western Australia. The first two methods provide satisfactory results in comparison with the third method, which computes using significant computer resources but without satisfactory results. Ref. [137] presents results of borehole EM surveys associated with the mineralization in the Bellevue Gold Mine in the Agnew-Wiluna greenstone belt. Ref. [138] presents observations and interpretations from an AEM survey conducted over Mississippi valley-type lead-zinc (MV Pb-Zn) sulfide occurrences of the Canning Basin. Ref. [139] presents AEM data collected over PGE-Ni-Cu sulfide zones of the Julimar

Region of Western Australia. Ref. [140] presents the application of airborne passive EM for targeting hidden mineralization near the Telfer gold–copper deposit. Ref. [141] describes a discovery of nickel sulfide mineralization in the Yilgram region found by recovering AEM data’s weakly conductive features, originally masked by IP effects.

4.4. Europe

Ref. [142] describes seismic reflection and MT surveys carried out in northwestern Skellefte District, Sweden, with the objectives of explaining the geological relationship between the mineralizations in the Adak mining camp and the Kristineberg area. Ref. [143] describes ground electric and EM surveys conducted over the Pb-Zn deposit of Lontzen-Poppelsberg, Belgium. Ref. [144] describes audio 2D MT inversion results from data collected over the Outokumpu belt in eastern Finland, characterized by several polymetallic (Cu-Co-Zn-Ni-Ag-Au) sulfide ore deposits. Ref. [145] presents the results of ground-based long-offset transient-electromagnetic data in eastern Thuringia, Germany. Plate models derived for AEM data are compared by [146] with drilled sections of the massive sulfide volumes from the Touro copper deposit in Spain, which showed excellent correlation. Ref. [147] presents results from ground electrical and electromagnetic surveys carried out at Koillismaa Layered Intrusion Complex in northeastern Finland. Ref. [148] presents a Deep EM Sounding for Mineral Exploration (DESMEX) investigation in a graphite mining district in eastern Bavaria, Germany, where IP effects were observed in 3D inversions.

4.5. North America

Ref. [149] compares resistivity maps estimated from ground and various AEM surveys conducted over the Midwest uranium deposit located in Saskatchewan, Canada. Ref. [150] contrasts SPECTREM fixed-wing and ZTEM natural audio-frequency inversion results from surveys flown over Pebble deposit in Alaska, USA. Ref. [151] presents the results of helicopter natural EM field measurements over the low sulfidation epithermal gold–silver vein systems at Gold Springs located in southeastern Nevada, USA. Ref. [152] presents inversion and interpretation of airborne natural EM field data over the Silver Queen polymetallic vein system located in BC, Canada. Ref. [153] compares results and interpretations of passive and time-domain helicopter surveys flown over the 501 project (Cu-Zn volcanogenic massive sulfide) at McFault’s Lake in northern Ontario, Canada. Ref. [154] presents airborne, ground, and borehole EM measurements over the Hood 10 volcanogenic hosted massive sulfide located in Nunavut, Canada. Ref. [155] analyzes the response of ground electromagnetic surveys conducted over the former Opemiska mine in Québec, Canada, where petrophysical studies, geological and geophysical data have been compiled. Ref. [156] presents a case study of a ZTEM survey conducted over sedimentary exhalative (SEDEX) lead-zinc deposits in Selwyn Basin, Yukon, Canada. Ref. [157] describes the results of the HELITEM system flown over the Lalor deposit in Manitoba, Canada. Ref. [158] investigates nine inversion strategies applied to co-located seismic and MT data sets from one of the Carlin gold deposit districts of north-central Nevada, USA. Ref. [159] analyzes AEM data for Lac Brûlé, Québec, Canada, over an anorthosite intrusion, and is able in some areas to distinguish, in the data, superparamagnetic (SPM) effects from IP effects. Ref. [160] compares 3D inversions of ZTEM and ground MT data over a Ag-Au-rich epithermal system in Canada, while Ref. [161] compares the same AEM system inversions over the Morrison porphyry Cu-Au-Mo deposit, both of which are located in British Columbia, Canada. Ref. [162] presents results of AEM time-domain and natural field data over the Dolly Varden Mine region of BC, which hosts silver and gold deposits. Ref. [163] presents airborne and ground, radiometric and EM, surveys collected over the Patterson Lake South uranium deposit located in Saskatchewan, Canada. Trial-and-error interpretation is attempted on EM data from the uranium rich Athabasca Basin, Saskatchewan [164,165]. Ref. [166] presents an interpretation of AEM methods using the moment Gaussian model developed by [167] from the Athabasca Basin, Canada. Ref. [168] presents a study of forward modelling and 3D EM inversion from the McArthur

River uranium deposit in the Athabasca Basin, Canada, integrating the finding about the quaternary geological cover impact on EM measurements.

4.6. South America

Ref. [169] presents 3D audiomagnetotelluric inversions over the Regis kimberlite pipe in Minas Gerais, Brazil. Ref. [170] evaluates a method of cooperative inversion on airborne TEM, controlled source magnetotellurics, and direct current resistivity data from the Antonio gold deposit in Peru. Ref. [171] presents Airborne Induced Polarization (AIP) inversions for data collected over the Lamego gold mine of the Quadrilátero Ferrífero area in Minas Gerais State, Brazil. Ref. [172] presents a review of historical ground and downhole EM data, identifying strong correlations with known nickel intersects from the Jaguar Nickel Project, a hydrothermal Iron-Oxide Nickel Copper (IONC) deposit located in the Carajas Mineral Province of Brazil.

4.7. Mixed Continents

Ref. [173] outlines an approach to extract IP information from AEM data using the Cole–Cole model on VTEM data collected from Mt Milligan, BC, Canada and Amakinskaya kimberlite pipe, Russia. Ref. [174] interprets in terms of Cole–Cole parameters AIP surveys conducted over various geologies and exploration targets, with examples of diamond, gold, and base metals deposits in northern Canada, Oman, and Australia. Ref. [175] compares 1D and 2D AEM inversion algorithms applied over areas of rough terrains in Iran and Norway. Ref. [176] presents case studies of application of AEM natural fields in exploring for various minerals across sites located in Canada and Kazakhstan.

5. Magnetism and Electromagnetics

5.1. Africa

Ref. [177] presents a robust airborne natural source processing approach, which is applied to data from the Kalahari-Copper-Belt in Namibia.

5.2. Asia

Ref. [178] describes geological mapping and detailed geophysical surveys for chromite exploration at Tangarparha, India. Ref. [179] presents airborne and ground geophysical measurements over the Elang Cu-Au porphyry deposit in Indonesia. Ref. [180] presents results of helicopter natural EM fields and magnetics flown over the Ad Duwayhi intrusion-related gold deposit in Saudi Arabia. Ref. [181] presents advanced processing and interpretation, for AEM, magnetic, and radiometric data from the Mohar cauldron, India, with uranium potential. Ref. [182] compares magnetic and electromagnetic (EM) results from time-domain (VTEM) and AFMAG (ZTEM) flown over the Nuqrah SEDimentary EXhalative (SEDEX) massive sulfide deposits located in the Kingdom of Saudi Arabia. Ref. [183] presents the results of audio MT and ground magnetic surveys which help image the alteration and mineralization system of the epithermal gold deposit, Tuoniuhe, in northeast China. Ref. [184] presents results of a comprehensive analysis of 2D CSAMT imaging over an important copper polymetallic ore field in Zhongxington area, Inner Mongolia, China. From 2D profile CSAMT inversions, Ref. [185] investigates the electrical resistivity structure of the Zhaishang gold deposit, in West Qinling, China. Ref. [186] combines magnetism, TEM, and magnetotellurics to locate an iron ore body from southern Liaoning province, China. Ref. [187] uses potential field and electromagnetic data interpretation to provide new information on the copper-zinc Xiaorequanzi deposit, in northwest China. Ref. [188] presents a study analyzing magnetic and VLF-EM data to delineate anomalous zones related to gold-associated sulfide mineralization in the North Singhbhum Mobile Belt of eastern India. Ref. [189] presents results of ground magnetic and VLF-EM surveys conducted over the Hatinitor Pahar and Kadwara areas of India, which are probable kimberlite zones.

5.3. Australia

Ref. [190] reviews the various geophysical methods that have been tested over the high grade Ag-Zn-Pb Cannington deposit located in Queensland. Ref. [191] reviews integrated interpretation of geophysical surveys with geological data applied in the interpretation and exploration of detrital iron deposits in Western Australia. Ref. [192] describes ground EM, magnetic, and gravity surveys obtained over the Gurubang volcanogenic massive sulfide (VMS) deposit located in New South Wales. Ref. [193] present results of ground and airborne surveys conducted over the Wafi-Golpu porphyry system.

5.4. Europe

Ref. [194] analyzes the geophysical characteristics of a strongly-conductive horizon in northern Sweden, associated with thin layers of pyrrhotite and graphite. Ref. [195] derives a 3D conductivity volume from 2D MT-inverted sections of data collected over the Kevitsa Ni-Cu-PGE deposit in Finland. Ref. [196] develops a new boundary detection technique that identifies and removes uniform layers from the 3D model, leaving edges. The method allows for the visualization of property edges, which are generated from the geophysical inversion of data from the Kevitsa Ni-Cu-PGE deposit in Lapland, Finland.

5.5. North America

Ref. [197] presents an application of lithoclassification using the self-organizing maps (SOM) technique, which uses EM, gravity and magnetic data from the Reid–Mahaffy test site in Ontario, Canada. Ref. [198] characterizes the Cu-Au-Mo Pebble porphyry deposit in Alaska, USA, using geophysical data, drillhole information, and physical properties.

Ref. [199] presents results and preliminary interpretation of AEM and magnetic surveys over the massive sulfide Lalor deposit in Manitoba, Canada, while [200,201] present inversion results of EM and airborne magnetic data collected over the same deposit. Ref. [202] presents an integration of inversion of aeromagnetic, gravity, and MT data with physical property measurements and geological information, thus facilitating a better understanding of the NICO Au-Co-Bi-Cu deposit, Northwest Territories, Canada. Ref. [203] combines MT, magnetics, and gravity to study the geophysical response of the Mountain Pass carbonatite, in California.

Ref. [204] presents results of joint inversions of two VTEM datasets and associated aeromagnetic datasets, from two surveys flown six years apart over a VMS gold prospect in northern Ontario, Canada. Results of inversions over Tli Kwi Cho kimberlites from Northwest Territories, Canada, are presented for potential field data [205], airborne AEM conductivity [206] and chargeability data [207]. Ref. [208] compiles historical apparent resistivity and induced polarization data combined with recent AEM surveys to infer structurally complex zones in the gold-rich, Canadian Malartic district, from Québec, Canada. Ref. [209] uses a supervised machine learning algorithm to classify rock types throughout the Kliyul porphyry prospect in British Columbia, Canada. Ref. [210] inverts magnetic and frequency-domain EM data over gold-rich, Canadian Malartic district, and interprets the results in terms of lithologies. Ref. [211] presents modelling and analysis of helicopter EM data resulting in physical property models and magnetic derivatives which characterize shallow parts of the Stillwater Complex, USA, rich in PGE, nickel, copper, and chromium. Ref. [212] describes data, interpretation, and targeting approach of a helicopter time domain EM, magnetic, and radiometric survey over epithermal Au-Ag deposits in north central BC, in Canada. Ref. [213] describes the results of airborne natural EM field and magnetic survey conducted over porphyry copper occurrences near Houston, also in BC.

5.6. South America

Ref. [214] compares ground resistivity/IP, airborne EM, and magnetic responses, supported by 3D inversions, over the Romero and Romero South Au-Cu-Zn-Ag epithermal deposit area of Dominican Republic. Ref. [215] describes the data and interpretation of

an airborne EM, magnetic, and radiometric survey flown over the Cerro Quema high sulfidation epithermal gold deposits in Panama. Ref. [216] describes airborne EM and magnetic survey results from the Panama Cobre porphyry copper camp, which includes the Balboa deposit.

6. Discussion

The numerous references presented show that magnetic and EM techniques are still popular for mineral exploration and that this field represents an active area of research with many papers published in various scientific journals. In particular, drone magnetic surveys have gained popularity. We have compiled the different case studies (drone studies excluded) by target type and continents for the magnetic technique in Table 1, the EM technique in Table 2, and a combination of magnetic and EM techniques in Table 3.

Table 1. Compilation of case studies by application of magnetics (IOCG: Iron-Oxide Copper-Gold, MS: Massive Sulfides).

Deposit Type	Africa	Asia	Australia	Europe	North America	South America
Apatite		[50]			[93]	
Carbonatite			[111]		[96,111]	[101]
Copper		[51,55]				[102]
Gemstones	[41]			[77]		
Gold	[38,42,45,47]	[49,58]	[63,64,67,68,71,72]		[87,88,95]	[97]
IOCG		[54]	[61,65,70]			[100,103,108]
Iron ore		[52,53,56]	[62]	[75]		[99,105–107,110]
Kimberlite	[35,37,46]				[91,92]	
Lateritic Ni						[98]
Magnesite						[109]
Manganese	[43]		[66]			
MS			[74]			
Ni-Cu-PGE					[81,83–85]	
Phosphate	[44]					
Polymetallic	[36,40]	[48,59,60]	[73]	[76]	[78,79,94]	
Porphyry Cu		[57]	[69]		[82,88–90]	[104]
Rutile	[39]					
Uranium					[80,86,88]	

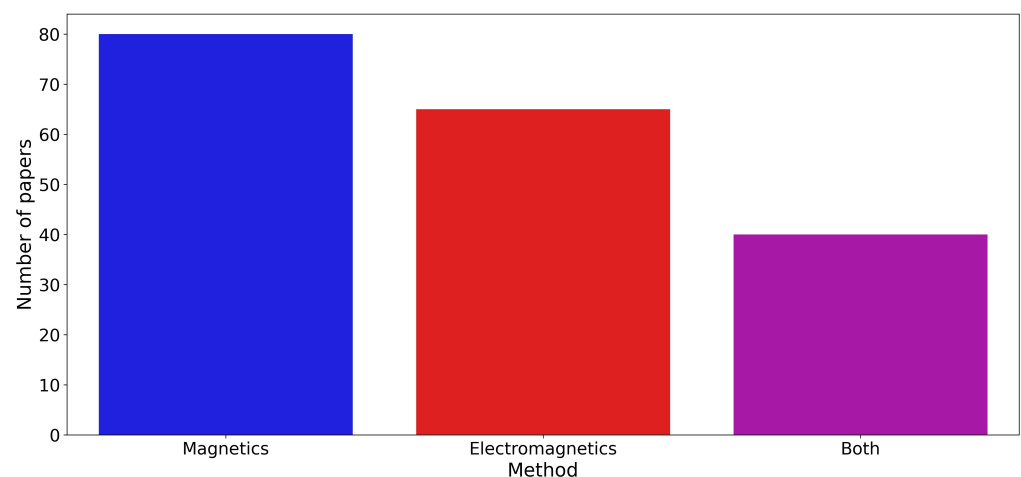
Table 2. Compilation of case studies by application of electromagnetics (IONC: Iron-Oxide Nickel-Copper, MS: Massive Sulfides, MVLZ: Mississippi Valley Lead-Zinc, SEDEX: SEDimentary EXhalative lead-zinc).

Deposit Type	Africa	Asia	Australia	Europe	North America	South America
Bostonite	[114]					
Chromite		[118]				
Cobalt			[135]			
Copper			[126]	[146]		
Gold	[113]	[121]	[137,140,174]		[151,158,174]	
Gold & zinc					[156,157]	[170,171]
Graphite				[148]		
IONC						[172]
Iron ore		[120]	[132]			
Kimberlite		[173]			[173]	[169]
Manganese			[125]			
Molybdenum		[119]				
MS			[128,130,133,136]	[142]	[153–155]	
MVLZ			[138]	[143]		
Ni-Cu-PGE	[112]		[124,129,134,139,141]	[147]		
Polymetallic		[116,123]	[131]	[144]	[152]	
Porphyry Cu		[122]			[150,161]	
Rutile					[159]	
SEDEX					[156]	
Silver					[160,162]	
Uranium		[115,117]	[127]	[145]	[149,163–165,167,168]	

Table 3. Compilation of case studies on application by magnetics and electromagnetics (IOCG: Iron-Oxide Copper-Gold, MS: Massive Sulfides, SEDEX: SEDimentary EXhalative lead-zinc).

Deposit Type	Africa	Asia	Australia	Europe	North America	South America
Carbonatite					[203]	
Chromite		[178]				
Copper	[177]					
Copper-zinc		[187]				
Detrital iron			[191]			
Epithermal gold					[212]	[214,215]
Gold		[180,183,185,188]			[208,210]	
Graphite				[194]		
IOCG					[202]	
Iron ore		[186]				
Kimberlite		[189]			[205–207]	
MS			[192]		[197,199–201,204]	
Ni-Cu-PGE				[195,196]	[211]	
Polymetallic		[184]				
Porphyry Cu		[179]	[193]		[198,209,213]	[216]
SEDEX		[182]				
Silver			[190]			
Uranium		[181]				

These results can be used to produce various histograms and only the most meaningful are presented. The simplest one presented in Figure 1 shows the number of research papers for each method while Figure 2 shows the number of papers by continent. The majority of case studies are compiled for the magnetic method and describes surveys conducted in North America, followed by Asia and Australia, while other continents have smaller but similar numbers of papers. The popularity of the magnetic technique may be a reflection of the fact that this technique is used both as a direct and an indirect method of exploration. Magnetic surveys can be conducted to directly detect magnetic material like iron ore, while during the search of other deposits they are used mainly to map the geology, using the rock magnetite content as a geological indicator or structural marker. In general, EM surveys directly detect the conductive mineralization, although in uranium exploration they detect conductors associated with the mineralization.

**Figure 1.** Number of case studies by method.

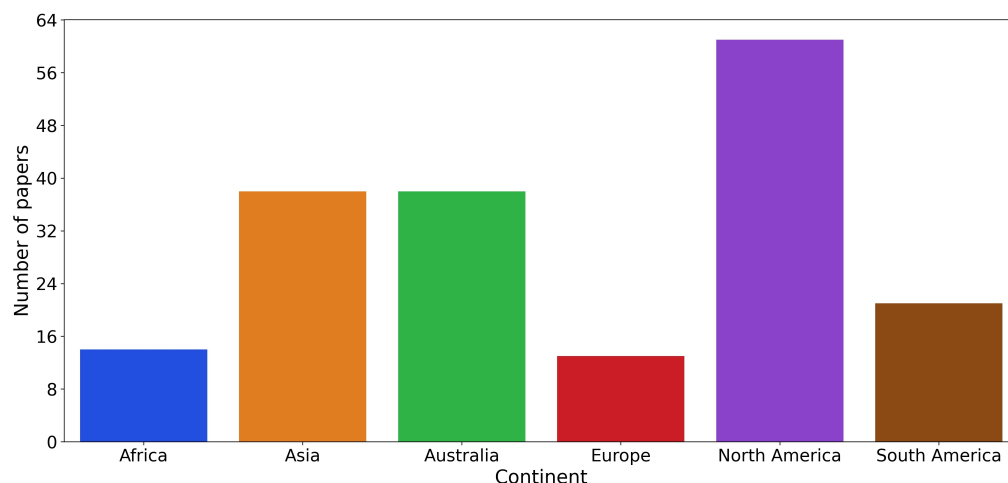


Figure 2. Number of case studies by continent.

Going into more detail, an histogram of the number of papers by method and continent (Figure 3) shows distinct patterns. Electromagnetic and magnetic paper numbers are the same in North America, while magnetic methods are more popular in other continents except Europe, where EM methods are favored. The combination of magnetic and EM techniques is popular in North America and Asia. Although the number of case studies documented in a particular continent is function of various factors such as the geography and metallogeny, the mining market, the exploration activity, the number of researchers in each continent, and the bias of the scientific journals that were used for this study, it is, therefore, a first-order indication of the preference for each method in these continents.

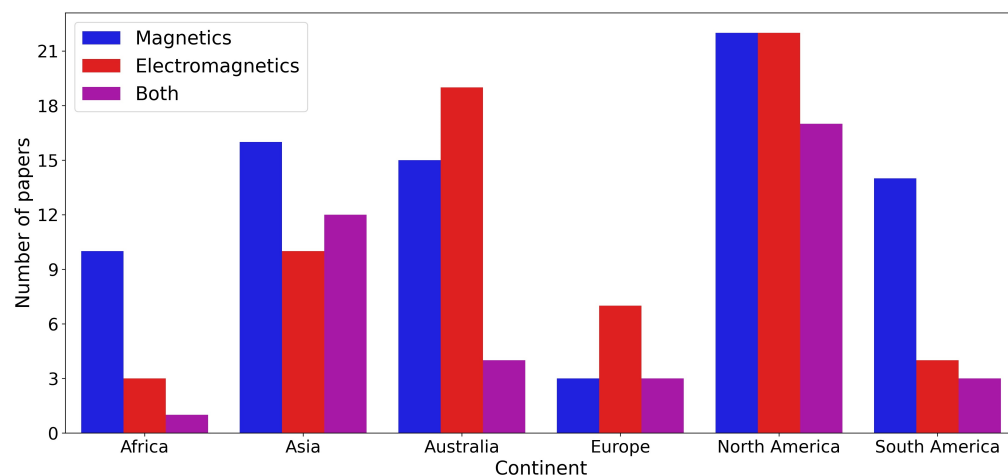


Figure 3. Number of case studies by continent and method.

The following figures illustrate the distribution of the various deposit types documented. In Figure 4, the total number for each target type is presented. The classification of the deposits was based on the information provided by the authors of the case studies and is sometimes more commercial than geological. However, characteristic features can be observed. Gold mineralizations are the most popular, followed by porphyry copper, polymetallic, massive sulfides, uranium, Ni-Cu-PGE, iron ore, kimberlite, and IOCG.

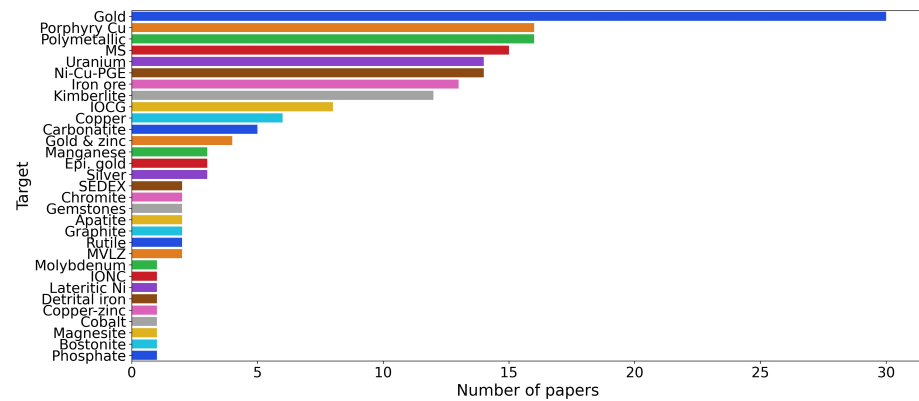


Figure 4. Number of case studies by types of mineralization (IOCG: Iron-Oxide Copper-Gold, IONC: Iron-Oxide Nickel-Copper, MS: Massive Sulfides, MVLZ: Mississippi Valley Lead-Zinc, SEDEX: SEDimentary EXhalative lead-zinc).

In Figure 5, these types of mineralization are classified by methods. Magnetic techniques are favored for gold, iron ore, and polymetallic, while electromagnetic methods are used for uranium, massive sulfides, and gold. Both methods characterize porphyry copper, massive sulfides, and gold.

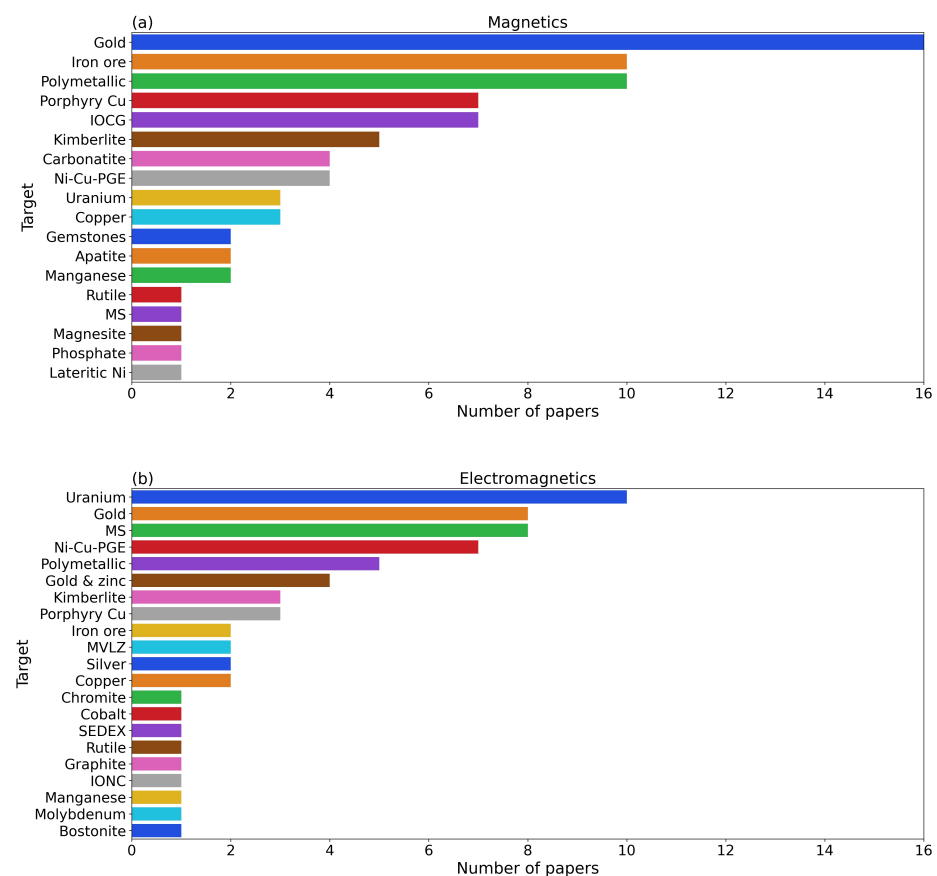


Figure 5. Cont.

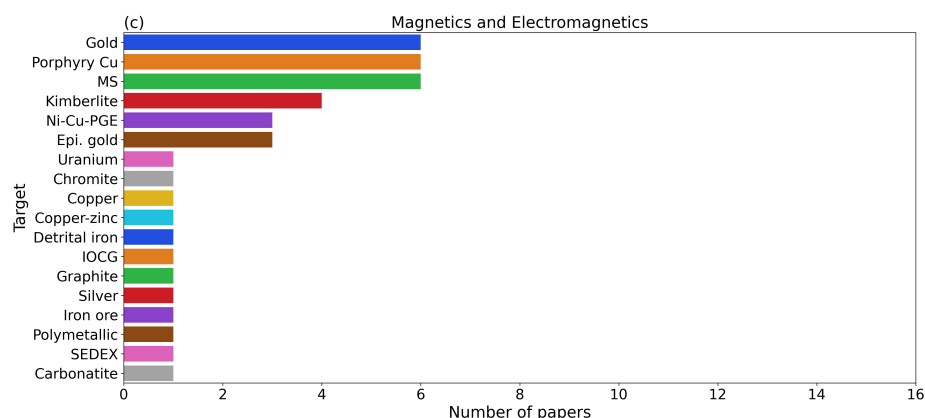


Figure 5. Types of mineralization by method: (a) magnetics, (b) electromagnetics, and (c) magnetics and electromagnetics (IOCG: Iron-Oxide Copper-Gold, IONC: Iron-Oxide Nickel-Copper, MS: Massive Sulfides, MVLZ: Mississippi Valley Lead-Zinc, SEDEX: SEDimentary EXhalative lead-zinc).

Figure 6 presents the same information by continents. Gold and polymetallic-style mineralization are studied in Africa, while gold, polymetallic, and kimberlite are studied in Asia. In Australia, gold and massive sulfides are studied geophysically, while in Europe, case studies for Ni-Cu-PGE, polymetallic, and graphite are more popular. In North America, studies have been conducted predominantly on uranium, porphyry copper, massive sulfides, gold, kimberlite, and others. In South America, iron ore, IOCG, and porphyry copper mineralizations have been studied.

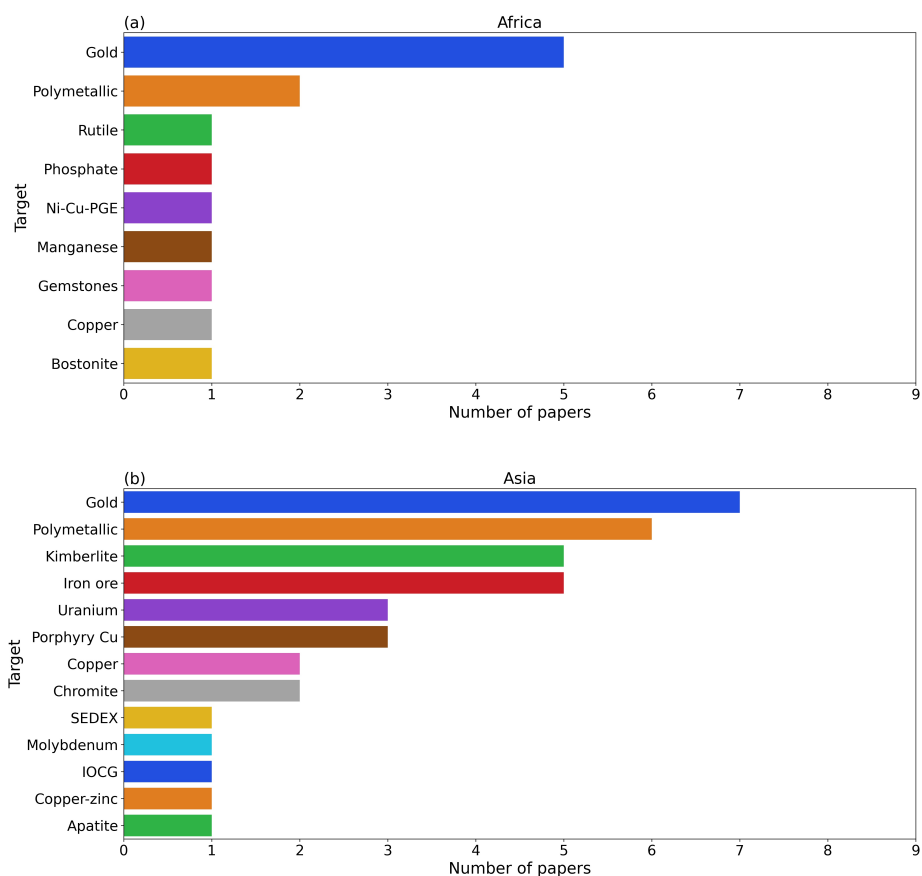


Figure 6. Cont.

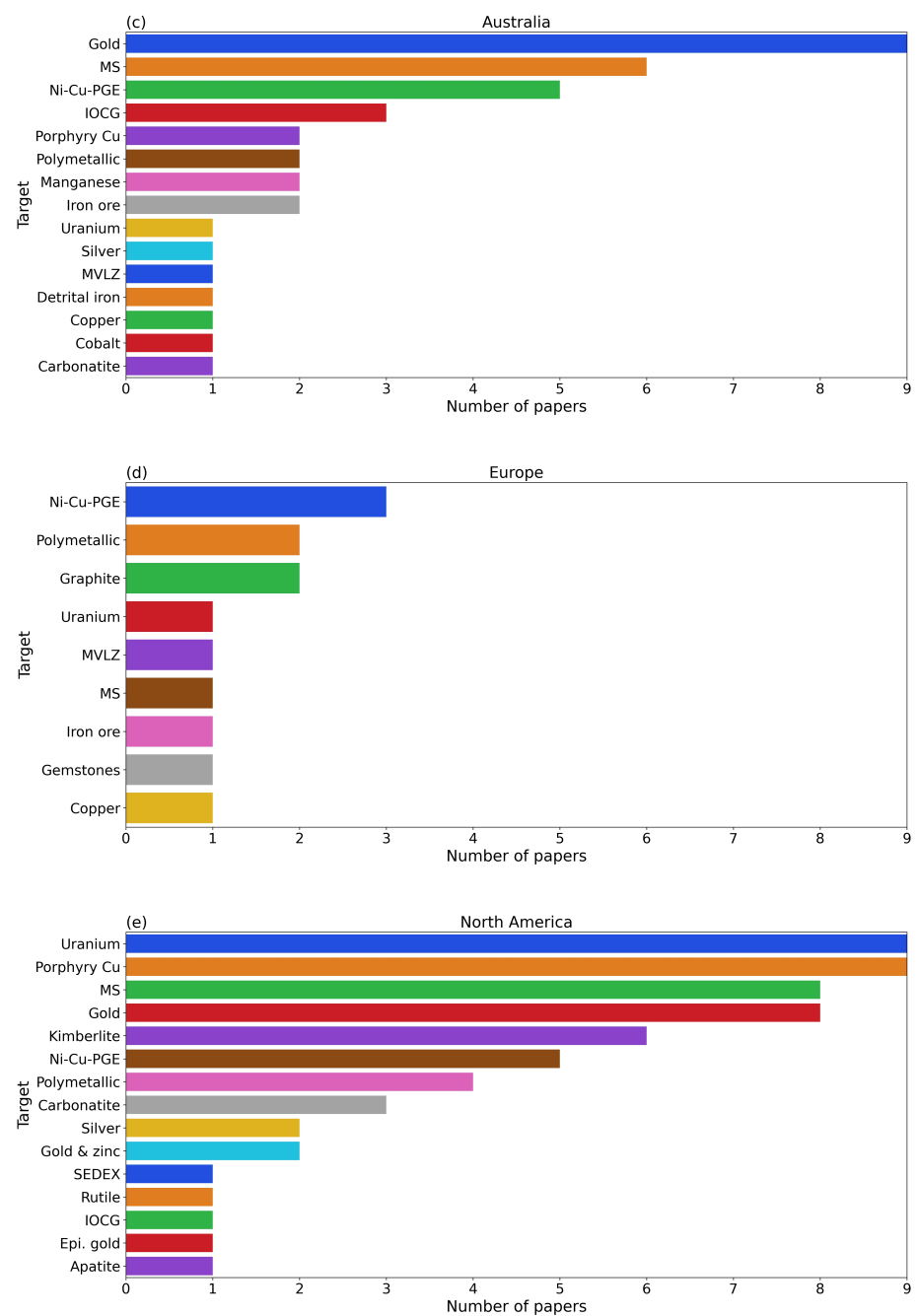


Figure 6. Cont.

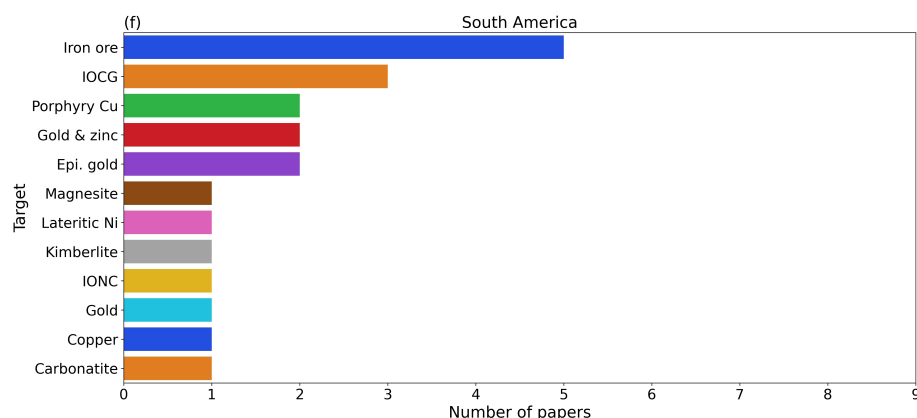


Figure 6. Types and numbers of mineralizations by continent: (a) Africa, (b) Asia, (c) Australia, (d) Europe, (e) North America, and (f) South America (IOCG: Iron-Oxide Copper-Gold, IONC: Iron-Oxide Nickel-Copper, MS: Massive Sulfides, MVLZ: Mississippi Valley Lead-Zinc, SEDEX: SEDimentary EXhalative lead-zinc).

7. Conclusions

The field of geophysical exploration for mineral deposits is very active with a constant flow of new developments, in particular in magnetic and EM techniques, as developers have been eager to adapt new technologies to new geophysical applications. Our review of the documented case studies over the last fifteen years is unfortunately an incomplete compilation of the geophysical activity around the world during this period, as not all geophysical activity is documented in the reviewed papers. First, case studies provide an incomplete description of the technological developments. Furthermore, in our review, applications of the magnetic and electromagnetic techniques in North America, Asia, and Australia predominate over applications in other continents. This predominance is attributed to different factors, ranging from academic and metallogeny, to mining market, and journals selected. Despite these limitations, this review provides detailed information about the usage of magnetic and EM techniques, encompassing a wide range of geological environments. The magnetic method is slightly more popular and this popularity is attributed to the fact that it can be both a direct and an indirect indicator of mineralization. Magnetic and EM techniques were utilized for many different target types, with a preference for gold, porphyry copper, polymetallic, massive sulfides, uranium, Ni-Cu-PGE, iron ore, kimberlite, and iron-oxide copper-gold. They are also popular for a range of small applications which are continent-specific. The variety of case studies presented in this review should help in selecting and designing geophysical surveys in a new area or domain as well in helping to better elucidate the challenges encountered in a specific geological environment, given the limitations of each technique.

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