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Electromagnetic Induction Methods in Mining Geophysics from 2008 to 2012

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Abstract In the period from 2008 to 2012, the topic of electromagnetic (EM) induction methods applied to mineral exploration has been the subject of more than 50 papers in journals and more than 300 extended abstracts presented at conferences (about 100 of which contain developments worthy of mentioning). Most of the work at the universities has been on modelling, inversion and data processing, and most of this material is published in the refereed literature. However, academia has also undertaken work on system geometry changes, system calibration and sensor design. There have been papers describing new systems developed for mineral exploration and case histories describing the use of EM methods to directly discover mineral deposits or to map the geology. Most of this work is by the service companies and mining companies and reported in the unrefereed literature. Since 2008, the pace of development of helicopter time-domain systems has slowed and more effort has been directed to developing natural source magnetic systems and to modelling and inverting this data. A number of studies comparing the results from natural source methods with the results from artificial source methods conclude that the natural source methods can see large-scale geological structures usually when there is a weak conductivity contrast with the surrounding material, but the natural source methods are unable to see small features that have a very large conductivity contrast with the country rock. Hence, they are not a good detector of mineral deposits unless one is looking for a large porphyry system.

Keywords Mining · Mineral exploration · Electromagnetic induction · Controlled source · Natural field

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1 Introduction

Electromagnetic (EM) methods were developed in the 1920s and initially deployed for mineral exploration (de Beer 2011). Recent reviews that discuss EM methods as applied to mineral exploration include Sheard et al. (2005), Zhdanov (2010) and Vallée et al. (2011). These papers concentrated on the early part of the period 2000–2010, so this review will concentrate on the years 2008–2012, following the global financial crisis, when the work undertaken has had a different emphasis.

Mineral exploration is a specific industrial application of electromagnetic methods. The users of the technology are the exploration companies; these companies are sometimes reluctant to publish their data as it will reveal to their competitors the exploration strategy that the companies are following.

The suppliers of the technology are most frequently the geophysical service companies. These companies are also reluctant to publish their technology as this will allow their competitors to offer comparable products. Furthermore, none of the employees of the service companies or the exploration companies are under any pressure to "publish or perish", so not all research makes its way into the formal scientific literature. However, there are some mining companies who have employees who believe that, for the good of the science and the industry, some material should be published. Also, the service companies want to advertise their capability and their technology, so there is some impetus to publish cases when electromagnetic methods have been used successfully.

The junior mining companies want to advertise their capability as explorers and the value of the properties they hold, so they are interested in having case histories published. However, they often do not have in-house experts capable of documenting this information in a way that would be acceptable in the scientific literature. The willingness of the junior companies to release example data and the desire for the service companies to publish examples that showcase their technology bring these two parties together, and there are many of examples of these types of papers that are available. Unfortunately, these case histories are not what some people would call "scientific studies". They are rarely systematic in any way or rigorous and reproducible. Hence, these also rarely make the refereed literature.

The other category of workers that publish in the literature are the academics that have experience in the mining industry or are funded by the mining industry in some way. These scientists are driven by a need to publish and therefore their work is well documented and available in the refereed literature.

I have chosen to structure this review according to the institution that employed the authors, as this provides a different perspective on the nature of the work being done. As usual, I will cover the refereed literature, but in order to cover all the important developments and the applications of electromagnetic methods in mineral exploration, it is also necessary to cover the unrefereed literature, which is primarily extended abstracts from conferences and workshops.

2 Refereed Work Emanating from Academia

2.1 Modelling and Inversion of EM Data

The strongest capability of academia has been in developing codes for modelling and inverting electromagnetic data. This work is primarily being done at the University of

British Columbia (UBC), the Memorial University of Newfoundland (MUN) and the University of Utah, with other work in the reporting period being done at the Universities of Freiberg and Tasmania, and at the Indian Institute of Technology.

Airborne electromagnetic surveys that are commonly used in mineral exploration have multiple transmitter positions, which increase the computation time linearly. The UBC approach to reduce the computation time is described by Yang and Oldenburg (2012) who use a coarse grid and a limited number of transmitters to get an approximate conductivity structure and then refine the conductivity estimate on a finer grid using additional transmitter positions. This workflow was demonstrated on a synthetic example that has a number of anomalies in a simple background. The algorithm has not yet been tested on field data where the background is usually more complex or varies systematically. The approach taken by Börner et al. (2008) to speed up the inversion is to use Krylov subspace projection.

There has been some debate as to whether 3D inversions are necessary. Yang and Oldenburg (2012) argue that the necessity for 3D modelling depends on the scale length of the current flow compared with the scale length of conductive features. Hence, a 1D assumption might be adequate for a frequency-domain system, whereas the larger current flow patterns associated with time-domain EM systems are more likely to require 3D inversion.

The University of Utah group has made a contribution to modelling mining data by proposing a method of 3D inversion that only considers the contribution from the ground within a “footprint” that is proximal to the transmitter location (Cox et al. 2010; Wilson et al. 2010). For moving source surveys where there are multiple transmitter positions, this strategy does make the inversions significantly faster, and Cox et al. (2010) argue that the computation times are comparable to those required by laterally constrained 1D inversion. Unfortunately, the area they chose to demonstrate the method was largely a one-dimensional environment, so Viezzoli et al. (2010) argued that 1D inversion is better in this instance. Since then, Wilson et al. (2012) have presented some airborne EM (AEM) inversion examples where the geology is more strongly 3D and the results are impressive. See the unrefereed section below for further discussion.

One of the issues with inversions is that they can be unstable and nonunique. The standard approach is to regularize the results by ensuring that the final model is smooth. However, in mineral exploration, the conductivity structure is rarely smooth, with the target geological structure often having a sharp and large contrast with the surrounding host material. Farquharson (2008), of MUN, tried looking for piecewise constant models and illustrated his approach using MT and gravity data. At the UBC, the approach has been to constrain the smooth model with surface and borehole data and dip information. For potential field data (Lelièvre et al. 2009), this gives good results proximal to the constraints or if the dip does not change; however, a short distance away the model can become diffuse. Knowing the electrical properties of the earth will help constrain this type of EM inversions; Smith et al. (2012) discuss how these physical properties can be collected and some of the challenges involved.

In EM modelling, the earth is traditionally discretized into cubes or rectangles. A novel approach described by Lelièvre et al. (2012) is to use unstructured tetrahedral meshes, which have the potential to better represent the geology, but this does have disadvantages by adding complexity to (a) coding the forward and inverse modelling and (b) the mesh specification and manipulation process.

The work at the University of Tasmania has involved methods to calculate the resistive-limit response of a half-space model from data that covers a limited range of delay times

(Schaa and Fullagar 2012). Inversion and modelling work that use this resistive-limit is described below in the unrefereed section.

The modelling of airborne audio frequency magnetic (AFMAG) data is less demanding computationally, as (a) multiple transmitter locations do not have to be modelled and (b) only a few frequencies have to be modelled. The results obtained by Holtham and Oldenburg (2010a), which nonetheless took 3 days to compute, show that large-scale structures can be imaged quite well.

Work on magnetotelluric (MT) systems has traditionally been strong at universities. In the period 2008–2012, there are two examples of MT and AMT methods being applied to mineral exploration data. La Terra and Menezes (2012) collected a 111-station AMT survey and input this data into the WSINV3DMT program to derive an impressive 3D model of a kimberlite pipe that is consistent with the drill information. This work shows that AMT data could be used to delineate a kimberlite once discovered and potentially reduce the cost of delineation drilling. Another 3D inversion was applied to AMT data collected for uranium exploration in the Athabasca Basin (Farquharson and Craven 2009). The inversion results clearly identified a linear conductor at depths of 1–2 km depth that is consistent with the known depth and strike of a graphitic zone. Uranium deposits are often associated with alteration zones proximal to these conductors; the weakly conductive alteration that occurs above the highly conductive graphite was not identified clearly in the inversions, perhaps because of the smooth nature of the inversion model. Zhdanov (2009) also presents the results of 3D inversion methods applied to synthetic MT data.

Work at the Indian Institute of Technology by Sharma and Baranwal (2011) found that having VLF data at multiple frequencies improved the interpretation, as conductors of different sizes and depths gave larger responses at different frequencies. A study by Sharma and Verma (2011) shows that the incorporation of EM data with resistivity data into an inversion problem can help to solve the problem of resolving both the resistivity and the thickness in just a few iterations.

2.2 Calibration of EM Systems and Changes in System Geometry

One of the focuses of the group at the RMIT University in Melbourne, Australia, has been on calibrating AEM systems to give more precise results (Macnae and Springall 2011; Davis and Macnae 2008a, b; Davis et al. 2009). This precision is primarily driven by the requirement to map small or subtle changes seen in environmental (salinity) mapping, but the improvements might also help to explore for minerals. One interesting outcome was the novel saw-tooth nature of the Versatile Time domain ElectroMagnetic (VTEM) current waveform that was identified in the paper by Davis and Macnae (2008b).

If the motion of an EM bird relative to the fixed-wing aircraft could be monitored, then it would be possible to accurately predict the primary field and identify good conductors. Smiarowski et al. (2010a), based primarily at the University of Toronto, attempted to predict the relative bird position from parameters such as the height, attitude and speed of the aircraft. The method was not accurate enough to detect extremely good conductors, but it was able to detect conductors with time constants that were seven times greater than the largest time constants that could be identified using standard methods.

The proliferation of AEM systems in the early years of the millennium generated a requirement to compare AEM systems. Macnae (2008) showed that helicopter systems have responses that are larger than fixed-wing systems when a conductor is shallow, but fixed-wing systems with larger dipole moments can have a larger response from deeper bodies.

2.3 EM Data Interpretation Methods

Other work at RMIT University involves an alternative to conductivity-depth images. Hennessy and Macnae (2010) proposed a square-root transformation of coincident-dipole data that makes the EM data more like potential field data and therefore allows Euler deconvolution techniques to be applied to the data. The square-root operator has two solutions, one positive and one negative, so Hennessy and Macnae had to design a procedure to select an appropriate sign on either side of where the system is null-coupled to the target. Challenges for this method are (a) handling filtering effects, (b) nonzero backgrounds and (c) dealing with thick conductors that do not have a specific location where the EM system is null-coupled to the target. The method was tested on field data and showed some limitations, so further work was proposed.

2.4 Methods for Levelling and Processing EM Data

Improved methods for data processing involve new concepts and theoretical analyses, and this type of work can be done in academia without significant capital expenditures. Empirical methods for levelling data are described by Beiki et al. (2010). Other empirical methods for levelling data have been proposed by an independent consultant (Huang 2008), and Siemon (2009), a representative of the German Institute for Geosciences and Natural Resources. It would be interesting to use a common data set to compare these methods with each other and with the standard microlevelling methods (Minty 1991; Ferraccioli et al. 1998).

Theoretical work at the Colorado School of Mines on using equivalent source techniques in potential field data has been extended to electromagnetic data as a way of reducing the noise (MacLennan and Li 2011). The authors suggested that the cleaned data could be used in time-lapse experiments (which are of little interest in mineral exploration), but the method could also be used to look for deep sources provided that there are multiple receiver stations for each transmitter location.

2.5 EM Data Acquisition Experiments

A number of interesting data acquisition projects have been undertaken at universities. In one, Dennis and Cull (2012) used data collected on multiple axes radiating from a transmitter loop to map the anisotropy. In another project, Sternberg (2010), from the University of Arizona, measured changes in the Earth's magnetic field over 366 days. This data set is very useful in designing surveys either for controlled source EM surveys, where this variability is a source of noise, or for natural source AMT surveys, where it is signal. The temporal variability is most relevant for areas in or close to Arizona; extrapolating the conclusions to other locations should be done with caution, as the nature of the variation in the Earth's magnetic field will be different in other locations and hemispheres.

2.6 EM System Development

Very few controlled source EM systems are being developed at Universities. The GRounded Electrical-source Airborne Transient EM (GREATEM) system, which uses a grounded source and a heliborne receiver, has been in development at Hokkaido University in Japan over a 10-year period (Mogi et al. 2009). This system has not yet been applied to mineral exploration work.

2.7 Case Studies Relevant to Mineral Exploration

There are a limited number of case histories involving EM methods published by academics. Mohanty et al. (2011), based at the Indian Institute of Technology, showed how geophysics could be used to explore for chromite. Their study used magnetic, gravity, Very Low Frequency (VLF)-EM and resistivity methods. In this area of India, the VLF-EM was concluded to be of some use, but less use than the gravity and resistivity data.

Shirzaditabar et al. (2011) collected magnetics, helicopter EM and ground resistivity data over a porphyry deposit and used the latter to generate 3D resistivity sections.

Another study interpreted Induced Polarization (IP) effects in EM data at the El Arco porphyry copper deposit (Flores and Peralta-Ortega 2009). Inverting for the chargeability and relaxation time of the polarization, it was observed that the locations where the chargeability was high were in good agreement with the locations of high sulphide volume and veinlet (rather than disseminated) mineralization. Further studies are required to determine whether this methodology could be used more generally for mineral exploration. Theoretical studies in IP effects in electromagnetic data (e.g., Kamenetsky 2011) are thus important.

Some of the techniques introduced to automatically classify areas for the purpose of geological mapping (Paasche and Eberle 2009; Leite and de Souza Filho 2009) do not use electromagnetic data, but including this information should improve the results as there will be addition information available for analysis.

A multi-institution collaboration involving the Université du Québec en Abitibi-Témiscamingue and École Polytechnique de Montréal generated a case study comparing three vintages of airborne EM (AEM) systems over the Aldermac ore body in western Quebec (Cheng et al. 2009). The authors showed that the recent MEGATEM system gave a signal ten times larger than older INPUT airborne EM systems and that the MEGATEM could identify the body when it was 200 m deep below complex and chargeable overburden (Cheng et al. 2009). Other projects from this collaboration investigated ways of removing spheric noise from the MEGATEM data using wavelet processing (Bouchedda et al. 2010), methods for detecting and interpreting anomalies in the electromagnetic data (Claprood et al. 2008) and a case history illustrating how electromagnetic methods can map mine tailings (Smith et al. 2008).

In addition to exploring for mineral deposits, electromagnetic methods can also be used to characterize the waste from the mining process (Poisson et al. 2009) and to characterize the sites that will be used for mine waste in the future (Ramalho et al. 2009).

3 Refereed Work Emanating from Government

Governments are primarily interested in stimulating mineral exploration work in their jurisdictions, so the published work reflects this emphasis. The Finnish government has recently completed the AEM coverage of the whole country using a system built specifically by the Finnish Geological Survey. Leväniemi et al. (2009) describe a recent upgrade to the Finnish AEM system and introduce some of the processing done to the data. In a recent example, Airo and Mertanen (2008) use data from this system to support their study of a greenstone belt that hosts gold mineralization.

The Finnish system has also been used by the British to survey all of Northern Ireland and the Isle of Wight (Beamish and Young 2009). Part of the justification for the Northern Island work was to promote mineral exploration, although the examples given were primarily environmental and near-surface deposits (gravel and peat). Following the release of the survey data, the area of land licensed for mineral exploration increased from 15 to 70%. The same data set was used by Beamish (2012) to showcase the application of horizontal and vertical derivatives applied to conductivity data. In reality, the vertical derivative of conductivity is infinite at the Earth's surface and zero above the surface of the earth. However, Beamish calculates the vertical derivative using methods developed for potential field data which assumes the derivatives are continuous and differentiable at and above the Earth's surface, and he argues that these derivatives bring out high-frequency information and the tilt derivative of the conductivity normalizes the images to show strong and subtle features simultaneously.

The Commonwealth Scientific and Industrial Research Organization (CSIRO) of the Australian government has been involved in the development of software for EM modelling and inversion under the sponsorship of a number of companies and institutions through AMIRA (Raiche 2008). This software code is now in the public domain. The CSIRO has also reported on the development of a Superconducting QUantum Interference Device (SQUID) sensor that can be used for ground-based EM systems (Leslie et al. 2008).

Another arm of the Australian Government, Geoscience Australia (GA), is interested in acquiring large EM surveys to stimulate mineral exploration (Stolz 2012) and reported on an AEM survey in Western Australia where an unconformity of relevance to uranium exploration was evident (Costelloe et al. 2010; Hutchinson et al. 2010). A similar survey flown in the Northern Territory of Australia (Costelloe and Brodie 2011) used a helicopter Time domain EM (TEM) system, and the authors claim that conductive features were detected to 1,500 m depth. Validating this claim would require a careful sensitivity analysis. A third survey, the largest undertaken by GA, covering 95,000 km^2 of South Australia, was primarily intended for uranium exploration, but also mapped geology below cover in areas where there are gold and coal deposits (Roach 2012).

The Swedish government has been routinely collecting tensor VLF-EM data as a conductivity mapping tool on their regional geophysical surveys (Pedersen et al. 2009). The VLF method works well in Sweden due to the strong signals coming from multiple directions and the lack of interference from topography and conductive overburden. In an example published by Persson et al. (2011) the current density image derived from the VLF-EM identified a metasedimentary structure containing pyrrhotite and graphite. The ground geophysical methods used to follow up these anomalies were resistivity and radiomagnetotellurics. One of the quantities introduced by the Swedes for displaying the VLF-EM data is the "peaker" (Pedersen et al. 2009). This quantity has since been used for displaying airborne AFMAG data, as will be discussed below in the section presenting unrefereed results. Other display methods developed for VLF-EM, such as apparent resistivity images, resistivity depth sections (Pedersen et al. 2009) and current density images (Persson et al. 2011), could also be used for AFMAG.

Another case history of radiomagnetotelluric and controlled source tensor MT methods being used to map hydrothermal copper deposits to a depth of 40 m is presented by Bastani et al. (2009).

In China, government groups seem to undertake a primary exploration role similar to what that which the mining companies would undertake in the western world, so there are a number of published case histories on mineral exploration work (Chen et al. 2010; Xue et al. 2012).

4 Refereed Work Undertaken Primarily by the Service Companies

There is a limited amount of work published in the refereed literature by representatives of service companies. These are primarily on system developments and case histories.

4.1 System Developments

A brief description of the HeliGEOTEM system and some case histories to showcase the system were published by Smith et al. (2009). The paper covers data acquisition, processing, data display and modelling and includes a comparison with other airborne EM systems. As the HeliGEOTEM was one of the few systems able to acquire multicomponent data, the authors emphasized this aspect. The HeliGEOTEM system is no longer available, being replaced by the HELITEM system.

A description of the SkyTEM helicopter TEM system was published by Reid (2010) and includes one example of data over the Flying Doctor Pd-Zn-Ag deposit in Broken Hill, Australia. The conductivity-depth transforms of the z-component data show two deep features on either side of the subvertical conductor. According to Reid, these types of artefacts occur when the dips are greater than 30°; however, he argues that conductivity-depth transforms are still useful in understanding the geoelectric structure of the surrounding area.

Yin and Hodges (2009) proposed a closed loop of wire for testing the transmitter and receiver systems of a helicopter time-domain system. This is a lot simpler than flying over a conductive body at a well-documented test site (which is usually far away).

Kowalczyk (2008) describes an innovative system for collecting controlled source EM data on the sea floor for massive sulphide (black smoker) exploration. These systems must acquire data in very rough and rugged terrain, and the electric field measurements commonly used in marine controlled source electromagnetics (mCSEM) would not be feasible. Hence, a system using a magnetic field source and sensor was deployed.

One interesting paper published by Vallée et al. (2010) describes the development of a processing procedure that uses the signal from powerlines to infer the geoelectric structure. This signal is normally considered noise, but Vallée et al. show that it can be used to map large structures similar to those mapped by VLF-EM or AFMAG. The method worked well in the published case, but not so well when it was tested at the Reid-Mahaffy test site (not published), so its utility is dependent on the geology of the area and the location and orientation of the powerlines.

4.2 EM Applications/Case Histories

Other work published in the refereed literature by service companies appears when both the contracting companies and the mining companies want to demonstrate how EM technology can solve exploration problems.

One problem is understanding whether airborne electromagnetic systems are able to identify subtle alteration haloes; in the Athabasca Basin, these haloes are usually mapped with more expensive ground resistivity methods (Nimeck and Koch 2008). Several EM systems were tested to see whether they were able to map alteration at two sites. In one case (Millennium), the high-frequency TEMPEST system was able to identify a subtle conductivity anomaly in the top 300 m, but not able to see deeper than this; the MEGATEM system was not really able to see the alteration in the top 500 m, as the response was dominated by the highly conductive graphitic body in the basement below 520 m depth (Smith et al. 2010). However, at the other site (Midwest), the alteration was between two conductive features, lake sediment at surface and a highly conductive graphitic structure at about 200 m depth, so the subtle alteration could not be confidently identified (Smith et al. 2011).

4.3 EM Data Processing or Data Presentation

A conductivity-depth imaging scheme developed for electromagnetic data was described by Combrinck (2008). The method was tested on synthetic data, and it was concluded that the method worked well where the ground was horizontally layered. Images over a vertical conductor showed strong artefacts on either side of the conductor and a relatively resistive zone at the conductor location. Another conductivity-depth imaging scheme, based on a pseudo-layer half-space model, was described by Huang and Rudd (2008).

5 Refereed Work Undertaken Primarily by Mining Companies

The work published by personnel in mining companies primarily consists of case histories or examples where new data processing techniques have been applied to data.

5.1 Case Histories

A comparison of ground and airborne electromagnetic data for identifying kimberlites in Botswana is presented by Cunion (2009). He concluded that the two data sets were comparable, but the airborne data could cover a larger area with greater sample density for similar cost.

There are a number of mining case histories in *The Leading Edge*, a journal of the Society of Exploration Geophysicists, that showcase electromagnetic methods. Nimeck and Koch (2008) show how EM methods can be used to explore for uranium in combination with magnetics, resistivity and downhole logging. Geophysical methods used in the discovery of the Cinco de Mayo carbonate replacement deposit were described in some detail by Robertson and Megaw (2009), and airborne and ground EM methods were an important part of the exploration program.

The discovery of the Maria deposit in Mexico (Visser and Lajoie 2012) is a good example of how geophysics can be successful if the explorers are doggedly persistent *and* lucky. In this example, EM was extremely important in the discovery. Just to underline the difficulty in getting these case histories published, the latter case history was published 30 years after the deposit was discovered.

An article written by McIntosh (2009) summarizes the impact of geophysics in Rio Tinto's exploration programs; interesting examples include an MT survey for lithium exploration and a ground EM survey that was used by the mining engineers to plan the extraction process. McIntosh also outlines the Rio Tinto perspective on the business of mineral exploration.

5.2 Data Processing and Display

A technique developed by the CSIRO called self-organizing maps is capable of dividing maps up into different zones. Essentially the method looks for distinct classes of physical property distributions that it can subdivide into distinct classes that are representative of geology in some way. The method was implemented by BHP Billiton, and Rajagopalan et al. (2008) give an example of this technique applied to a number of geophysical data sets including helicopter EM data and concluded that it was successful in identifying kimberlite pipes.

6 Work in Other Fields with Possible Impact to Mining

6.1 Hydrogeology

There has been considerable work in the application of airborne EM to hydrogeology. Examples of methods for one-dimensional inversion modelling are provided by Viezzoli et al. (2008), Auken et al. (2009), Brodie and Sambridge (2009), Vallée and Smith (2009a, b), Christensen and Tølbøll (2009), Siemon et al. (2009) and Guillemoteau et al. (2011). These techniques could be applied for mineral exploration work, where the geology is flat-lying: for example, to map laterite deposits and large palaeochannels or to look for unconformity deposits in sedimentary basins.

Work to reduce the noise in hydrological investigations (Reninger et al. 2011) and to better calibrate the systems used for agricultural monitoring (Minsley et al. 2012) might also provide benefits that flow through to mineral exploration.

6.2 Unexploded Ordnance

The US military have funded EM system developments that are primarily for unexploded ordnance (UXO) detection and discrimination.

Zhang et al. (2010) describe fluxgate induction sensors that can measure the Earth's magnetic field and the electromagnetic fields. They concluded that these sensors show promise and suggested they might be suitable for combining into arrays to reduce the noise levels. If this is the case, then they might be of use in mineral exploration. Another system described by Sternberg et al. (2008) uses a transmitter that is rotated to reduce the noise and drift. These UXO systems could be scaled up for use in mineral exploration if they are successful.

Doll et al. (2010) describe an airborne system that was developed for UXO detection but has been tested for mineral (diamond) exploration. The results show significantly better resolution than a standard mineral exploration survey collected on the ground.

Finally, a general finite element approach developed for UXO identification (Mukherjee and Everett 2011) could also be used in mineral exploration.

7 Journals Publishing EM Methods Applied to Mineral Exploration

In the period 2008–2012, there were a total of 52 papers published in the referred literature that relate to mining exploration and electromagnetic induction methods. Table 1 summarized the different types of organizations that published papers, how many papers they published and the journal they published in. *Geophysics* is the journal with the most articles related to mining, followed by *Journal of Applied Geophysics* and then *Exploration Geophysics*. The organizations most strongly represented are academic institutions and government organizations, while service providers and mining companies have made a smaller contribution.

8 Unrefereed Literature

There are significant advances in systems, processing, interpretation and case histories that have taken place that are not published in the refereed literature. The major exploration

Table 1 Articles in refereed journals relating to EM induction methods for mining 2008–2012

	Geophysics	Geophysical Prospecting	Exploration Geophysics	Journal of Applied Geophysics	Other
Academia	15	2	6	9	3
Government	1	2	1	3	1
Service Companies	3	1	2	1	1
Mining Companies			1		
Total	19	5	10	13	5

geophysics societies (SEG, ASEG, SAGA, SBGf and EAGE) all convene meetings, and "extended" or "expanded" abstracts from these meetings are readily accessible to their members and the public. Abstracts are also available from two independent workshops on electromagnetic methods: one on airborne methods held in Helsinki, Finland (AEM 2008), and another in Hyderabad, India (AEM 2011). There was also a workshop on natural-fields EM methods held prior to the ASEG in 2012. In total, there are about 300 extended abstracts related to EM and mining available in these sources. The following sections discuss some of the more important extended abstracts, and they are included in the reference list.

8.1 Work on System Development

8.1.1 Controlled Source Systems

A number of extended abstracts introduce airborne EM systems. The AeroTEM helicopter system is described by Rudd and Walker (2009) and Rudd (2011). This system was offered by Aeroquest, one of the first companies to introduce a helicopter time-domain EM system. This company managed to last 4 years after the global financial crisis before being purchased by their competitor, Geotech, in May 2012. The Russian four-frequency EM-4H system, which can be installed on fixed or rotary wing aircraft, is described by Volkovitskiy et al. (2008). The HELITEM system is briefly introduced by Mulè et al. (2012a), and one line over the IR2 conductor at Forrestania is presented. The helicopter SkyTEM system is described briefly by Sorensen et al. (2011), and a calibration procedure for SkyTEM system is presented by Davis et al. (2010a).

A brief description of the helicopter VTEM system, showing how the dipole moment has increased in the years since the system was first introduced, is given by Prikhodko et al. (2010). Documentation of the reduction in noise levels of the VTEM system is provided by Combrinck (2010). Both authors claim that the depth of exploration of VTEM has improved with time: Prikhodko et al. show this with sections over Caber that show deeper material as the dipole moment increases, and Combrinck uses synthetic modelling to show how the system can see deeper bodies. A deconvolution approach for removing additive noise that corrupts the early-time VTEM response is presented by Macnae and Baron-Hay (2010). The pendulum motion of the VTEM loop is quantified by Smiarowski et al. (2010b), who found that the vertical motions have a range of about 5 m. They showed that this variation had an effect on synthetic data, but did not quantify the impact that this had on the parameters that characterize a conductor (depth, dip, conductance, etc.).

Except for the Russian system, all these systems are helicopter time-domain systems. A table documenting the specifications of nine time-domain helicopter TEM systems as of 2009 is given by Sattel (2009).

A description of the fixed-wing MEGATEM system is presented by Smith and Lemieux (2009), and they also gave a number of case history examples to demonstrate the capability of the system.

Stettler (2009) describes a novel experiment that uses a time-domain EM system with a circular transmitter of diameter of 10 m suspended around a spherical helium balloon with a 5 m diameter. The balloon was walked through the survey area in Yemen by three people and achieved a depth of penetration of about 100 m. A picture of the system in Yemen is shown in Fig. 1. It might be fairly easy to scale this system up to achieve a greater depth of penetration.

In a pragmatic vein, two mining company employees (Wallace and Bourne 2010) describe a number of pre-survey flight checks that can be done to ensure that an airborne EM system is working and to check the noise levels. They also suggest setting tolerances for the survey height and aircraft speed to ensure good data.

8.1.2 Sensor Technology

There has been a lot of recent interest in using B-field or SQUID sensors for ground electromagnetic systems. Webb and Corscadden (2009) describe the use of a low-temperature SQUID sensor to explore for conductive features below 400–500-m-thick conductive overburden. Woods (2010) compares SQUID and induction coil data and argues that the SQUID data is better and hence the station spacing and transmitter loop size (and hence the survey cost) can be reduced. A comparison of low-temperature SQUID and induction coils data is discussed by Smit and LeRoux (2009) who conclude that the SQUID sensor can see the conductor at more than 600 m depth, while the induction coil cannot see the conductor but can only be used to infer the geoelectric structure of the overlying sandstone. An attempt to deploy a SQUID sensor on an airborne EM system is described by LeRoux et al. (2009) who conclude that the task is difficult, but that the authors have learnt a number of lessons that could be valuable for future work on this or similar projects. Work on using a ground loop to calibrate the above airborne system is described by du Plooy and Bell (2009).

Alternatives to the SQUID sensors are closed induction coils where the sensor measures the current induced by the changing field. Macnae (2012a) presented some preliminary tests of such a sensor and suggested that the noise levels are less than the ambient noise due to spherics and so could be used to collect EM data at least as good as the data collected using SQUIDs.

8.1.3 Systems for Detecting Highly Conductive Bodies

The problem of detecting conductive bodies with airborne EM systems is difficult, as these conductors have responses which decay slowly. Hence, the dB/dt response, which is normally measured, is small. Measuring the B-field is advantageous as the response is normally larger. The exception is for extremely conductive bodies (e.g., copper and nickel ore) where even the B-field response in the off-time goes to zero (Smith 2001). The only nonzero response is in the on-time, and this response is identical in shape to the primary waveform, so it is termed the “time-domain in-phase response”. This in-phase component is difficult to distinguish from system geometry changes. The results from an experimental

Fig. 1 Balloon-mounted airborne system. The transmitter is a 10-m-diameter wire loop suspended around a 5-diameter helium balloon. There is a second 2-m helium balloon added for additional buoyancy. Figure courtesy of Edgar Stettler and Thani Dubai Mining LLC

survey that used two helicopters, one carrying a VTEM transmitter and the other an AFMAG receiver, are described by Smiarowski et al. (2010c). Multiple GPS receivers were used to monitor the system geometry changes and predict the changes in the primary waveform so that these could be subtracted to leave the residual in-phase response of the extremely conductive bodies. They concluded that the system could detect extremely conductive bodies when the transmitter is about 400 m away from the receiver. However, nobody has decided to deploy such a system, presumably because it is perceived to be too expensive. Another way of attacking this problem is suggested by Lee (2010) who proposes a system that measures the EM gradients. The assumption seems to be that the gradients are used to estimate the system geometry and the in-phase primary response from the system can be predicted so that the in-phase response of the conductor in the ground can be detected.

8.1.4 Natural-Field Systems

The ZTEM (Z tipper EM) system (Lo and Zang 2008) is a modern version of an airborne audio frequency magnetic (AFMAG) system that measures the z-component on a sensor carried below a helicopter and calculates the tipper using the horizontal components measured at a base station. In the last 4 years, there have been a large number of case histories, comparisons with other systems and modelling studies that use ZTEM data. These will be described in the sections below.

The latest descriptions of various natural source EM systems can be found in a volume edited by Richard Lane (Lane 2012) that contains the extended abstracts of a natural-field workshop held prior to the ASEG in 2012. A company called EMPulse describes their transient AMT method, while Geophysical Resources and Services describes the MIMDAS system that is capable of MT data acquisition. Geotech offers three natural-field systems: the ZTEM, FW-ZTEM and AirMt system. Quantec offers three MT systems (Titan 24, Spartan MT and Orion 3D). The ORION is an MT system that acquires MT data on a 3D grid. There are also MT systems offered by Phoenix, Zonge and Metronix. Some of these system descriptions are brief, but others contain quite detailed information. A good comparison of two Geotech AFMAG systems (ZTEM and AirMt, the Airborne Magnetic tensor) systems is contained in Legault et al. (2012a). The ZTEM measures the well-known tipper from MT studies, but the latter measures three components of the magnetic field at the survey location and a base station. The tensor that relates these two vector quantities can be used to derive a complex scalar quantity called the amplification parameter, which is claimed to be independent of rotation of the survey sensor.

In a very interesting paper at the natural-field workshop, Macnae (2012b) gives an overview of four types of natural-field techniques (of which MT is just one) and then points to the fact that information about the source (its location, time and strength) is freely available and using this information would allow highly conductive bodies to be detected in addition to reducing static shift and distortion effects while improving the signal-to-noise ratio. Another innovation introduced by Macnae (2010) is a sensor to measure the electric field without any contact with the ground. This sensor was used to generate a TE mode AMT section along a 1-km traverse line.

A new distributed array receiver system called ZEN is described by Urquhart and Schultz (2011). The system is primarily designed for MT, but it seems it could also be used with a transmitter and therefore used for controlled source EM, which would make the system of greater interest to the mineral exploration community.

8.2 Work Describing Application of EM (Case Histories)

8.2.1 EM Discoveries of Conductive Ore Bodies

In mineral exploration, EM methods play varying roles in helping to discover mineral deposits. A case history where fixed-loop EM played a primary role in discovering the Jaguar deposit is presented by Cantwell et al. (2009). In another case, downhole EM contributed to the discovery of the Moran deposit (Johnson et al. 2010). The discovery of a number of manganese prospects near Kumarina, Western Australia, is documented by Kita et al. (2012); three examples where airborne EM methods have been used to discover prospects are given by Combrinck et al. (2009a); a case when airborne data discovered a prospect and borehole EM data are being used to guide drilling is described by Selfe (2009a); a case where EM played an important role in a discovery is discussed by Witherly

(2009a), and a case where EM played a secondary role in mapping an alteration halo associated with a porphyry deposit is presented by Howe and Kroll (2010). The importance of airborne EM in the past and future discovery of ore deposits in the Abitibi greenstone belt of Quebec, Canada, is discussed by Witherly and Allard (2010). A final example, from the Indian workshop describes the discovery of a lead–zinc deposit with the INPUT airborne system in the late 1960s (Gupta et al. 2011).

8.2.2 Other Cases When EM Data have been Acquired to Assist Mineral Exploration

In order for EM methods to be successful, it is important to measure the anomalous response over known ore deposits so that similar anomalies can be recognized elsewhere. Witherly (2009b) describes three surveys over previously known nickel deposits that document how the response character varies depending on the environment. Another example, the Cristalino Cu–Au deposit in the Carajas area of Brazil, shows that this deposit has a strong response at late time that can be seen even when the overburden is both thick and conductive (de Almeida et al. 2011). Botha and Yeslem (2009) show that magnetic and VTEM electromagnetic data can be used to identify magnetite deposits. The SkyTEM system has been used for mineral exploration in Greenland (Christensen et al. 2009).

Some people have argued that helicopter time-domain systems generate data that can be drilled directly without ground follow-up. However, Thompson and McKinnon-Matthews (2009) argue that acquiring ground data will ensure that better targets (more conductive and possibly deeper bodies) will be drilled. On the other hand, Selfe (2009b) argues that in cases where there is a lot of human infrastructure the ground data can be strongly contaminated, whereas the airborne data provide results that can at least be interpreted.

A case history presented by Pittard and Bourne (2009) described the use of borehole petrophysics to characterize the geophysical or petrophysical signature of ore, and the authors argue that this can be used to give mineral explorationists the confidence to fly airborne EM surveys.

8.2.3 EM for Geological Mapping to Assist Mineral Exploration

In some cases electromagnetic methods cannot be used to discover ore bodies directly, but the ore deposits may be associated with some type of geological structures which can sometimes be detected or mapped electromagnetically.

Wijns (2009), Tsiboah and Grant (2009), Meyer et al. (2010) and Chaturvedi et al. (2010, 2012a, b) give insight into how EM can play an important role in outlining the geology to assist in the mineral exploration process. Combrinck et al. (2009b) give an example of geological and structural mapping of a covered area in Namibia, and Finn et al. (2010) describe how regional AEM can be used to assist in mapping overburden thickness that can then be used to guide subsequent exploration programs. Espinosa-Corriols and Kowalczyk (2008) document the collection of a number of geophysical data sets in the Quesnel porphyry belt and conclude that the airborne VTEM survey is useful for mapping the overburden thickness. A fixed-wing frequency-domain survey of the Isle of Wight was used to show that the measured conductivity could be diagnostic of the lithologies on the geological map (Beamish 2011). On the volcanic island of Mayotte (off the east coast of Africa), Foged et al. (2011) concluded that it would be challenging to convert a resistivity value to lithology.

In the Athabasca Basin uranium deposits are known to be associated with large magnetic structures, highly conductive graphitic conductors and weakly conductive alteration (Nimeck and Koch 2008, Smith et al. 2010). Several airborne surveys over uranium deposits in the Athabasca Basin are presented by Witherly (2009c). In other locations, uranium is found in palaeochannels, which can also be mapped with airborne EM (Walker and Kroll 2010). A paper by Ramesh Babu et al. (2011) described a case history where layered earth inversions are used for uranium exploration in India.

An interesting case history presented at AEM2008 described a collection of physical property data and showed how it can be used use for mapping shales associated with sulphides (Airo and Hyvönen 2008).

A comparison of four types of geophysical methods for mapping kimberlites was undertaken by Verma et al. (2011). He concluded that the more expensive and logistically difficult the method, the better the results.

The concept of self-organizing maps was extended to three dimensions by Fraser et al. (2012), using data derived from 3D inverse modelling of electromagnetic, magnetics and gravity gradiometry data all collected with the MEGATEM system and inverted by TechnoImaging.

8.2.4 EM Surveys for Economic Development or Stimulus

The role of airborne surveys in stimulating mineral exploration in African countries (Uganda, Senegal, Nigeria, Mali and Namibia) is outlined by Reford et al. (2009), Reford et al. (2010), Konate and Reid (2010) and Hutchins and Negonga (2010). In most of these programs, electromagnetic surveys play a follow-up role and cover a smaller area that the larger magnetic and gamma-ray surveys. A large geophysical survey in British Columbia covered the Quesnel terrane, which is rich in copper and gold porphyry deposits. The magnetic and gravity data from this survey were inverted using the UBC 3D inversion programs, and the EM data were inverted with a one-dimensional layered earth model (Phillips et al. 2010).

8.2.5 Case Histories Using Natural-Field EM Methods

A case history where the ZTEM system has picked up a response coinciding with a graphitic conductor that is more than 800 m deep and more than 8 km in length has been presented by Lo et al. (2009). Mapping this conductor is important for uranium exploration, and it would be interesting to attempt 3D inversion modelling on this example. Other case histories containing primarily ZTEM data have been presented by Izarra et al. (2011), Legault et al. (2009a, b, 2011, 2012b), and Witherly and Sattel (2012).

Other MT surveys that investigate the deep crustal structure close to mineral exploration areas are presented by Evans et al. (2012), de los Ángeles García Juanatey et al. (2011) and Jones et al. (2009).

Transient AMT data (Goldak and Kosteniuk 2012) were collected and interpreted using 2.5 D inversion at Pasfield Lake, Saskatchewan (Goldak et al. 2010). These data and those provided by Witherly et al. (2010) are used to conclude that the Pasfield anomaly might be caused by a meteorite impact and thus be a site for uranium mineralization, a direct analogy to the uranium mineralization that is seen near the Carswell meteorite impact structure. A subsequent study (Hautot et al. 2011) showed that 3D inversion gave a resistivity structure that was more consistent with the potential field data than the 2.5 D inversion.

Finally, Ingerov et al. (2009) claim that magneto variation profiling (MVP) data were used to discover a kimberlite pipe in Russia.

8.2.6 Case Histories That Compare Airborne EM Systems

An interesting comparison of two airborne EM systems (VTEM and Hoistem) over the Nepean Mine conductor was presented by Combrinck et al. (2008), who conclude that the Hoistem system was only able to collect signal to delay times of 5 ms, whereas the VTEM was able to see the response from a bedrock conductor between 5 and 10 ms. HeliGEOTEM data over the same location are presented by Smith et al. (2009) and show an anomalous response to delay times of 14 ms. Mulè et al. (2012b) present HELITEM and GEOTEM over the NC2 conductor at Nepean Mine, but they do not draw any specific conclusions from the two data sets.

A comparison of four airborne systems (Resolve, VTEM, AeroTEM IV and Gemini) over the WD 16 conductor north of Sudbury is presented by Witherly (2009d). This target has a high conductance and the frequency-domain Resolve system gave the highest estimate of conductance. The time-domain systems gave lower estimates of conductance, but the values increased as the base frequency decreased. Using a B-field sensor rather than a dB/dt sensor also increased the estimate of conductance. The time-domain systems were considered to penetrate to greater depth than the Resolve system.

8.2.7 Case Histories That Compare Airborne and Ground Systems

A comparison of MEGATEM, GEOTEM, VTEM and Geonics and Zonge ground EM systems was undertaken by Davis and Groom (2009). They found it was possible to get a consistent earth model that explained all data as long as care was taken in ensuring that the finite bandwidth of the systems was taken into account and the correct waveform, receiver coil transfer function and window positions were used.

8.2.8 Comparisons Between Controlled Source Systems and ZTEM

Following the introduction of the natural-field ZTEM system in 2008, there has been an interest in testing this system over known deposits and comparing the capability of the system with the existing controlled source systems. Kaminski et al. (2010) presented a comparison of VTEM and ZTEM data over a kimberlite covered by conductive lake sediments. The authors argue that the VTEM can only see the conductive overburden, whereas the ZTEM can see the difference between the bedrock and the kimberlite. In this case, the ZTEM data were inverted with a 2D algorithm. Two years later, 3D inversion results for both the ZTEM and VTEM were presented by Kaminski and Oldenburg (2012), and they concluded that 3D inversions gave a stronger conductivity contrast. Another comparison of VTEM and ZTEM at Forrestania showed that VTEM was able to see the IR2 bedrock conductor, while the ZTEM anomalies were subtle and overpowered by the response of larger structures (Sattel et al. 2010a). The same authors also presented a similar comparison of VTEM and ZTEM over the Mt Milligan porphyry deposit (Sattel et al. 2010b) and found that the VTEM data showed finer spatial resolution, but there was some additional information in the ZTEM.

The very large Pebble porphyry deposit in Alaska was investigated with three geophysical methods: IP data outlined the chargeable mineralized zones close to the surface, but did not detect the eastern part of the deposit which is covered by up to 300 m of volcano-sedimentary rocks; SPECTREM airborne EM data were (just) able to detect the eastern part, while the ZTEM results can be interpreted to depth with greater confidence (Paré and Legault 2010).

In one of his three examples, Witherly (2009c) compares MEGATEM and ZTEM and concluded that both were able to detect a large conductive zone at 800 m depth.

From these comparisons, it would seem that the ZTEM is successfully able to detect large structures, in some cases to greater depth than controlled source airborne EM systems. However, the ability of ZTEM to detect the small IR2 conductor at Forrestania is not as good as the VTEM controlled source airborne system.

8.2.9 Comparison Between AMT and Controlled Source EM with a SQUID Sensor

AMT data are commonly thought to provide depth of penetration better than most controlled source EM systems. Figure 2 taken from Webb and Corscadden (2009) compares the conductivity-depth section derived from AMT data with a section derived from controlled source EM data using a SQUID sensor. The area has a conductive overburden layer 400 m thick with a resistivity of 2 Ohm m. Note that the horizontal scales are different. The AMT section, plotted down to 1,200 m total depth, shows a slight perturbation close to the centre of the section, which Pretorius (2009) states is due to a faulty remote reference station. The section derived from the controlled source SQUID data shows a strong clearly anomalous feature below the overburden between 400 and 1,200 m depth. Pretorius argues that the SQUID sensor was able to collect clean data to late time and hence image this structure. Theoretical modelling to support this conclusion has not been published.

8.2.10 Comparison Between MT and IP/Resistivity

Gharibi et al. (2012) presented a case history over the Golden Arrow property, Sunrise, Nevada, USA, which showcases the MT data with 3D ground resistivity and IP data. From the results presented, it is difficult to make detailed comparisons.

8.2.11 Unusual Effects in EM Data

An important effect known to impact on coincident-loop ground EM data is the superparamagnetic (SPM) effect (Buselli 1982). In coincident-loop data, this manifests itself as a small very slow decay ($\sim$1/time) that becomes evident at late time and it is significantly reduced by offsetting the transmitter and receiver loops by a few metres. However, with the introduction of large-loop helicopter systems, Mutton and Mortimer (2009) argue that SPM effects are once again becoming evident. They feel that users of these systems should be aware that the effect could be evident in the data and suggest that they design their acquisition programs to avoid the SPM effects (by flying higher) or designing the ground follow-up to first characterize the SPM. Later, Mutton (2012) suggests that the receiver must be more than 120 or 150 m from the transmitter loop to avoid SPM. He also suggests that a portable magnetic viscosity meter called the MVM1 can be used to identify SPM effects in the soils. SPM effects can often be recognized by their spatial patterns, which look like drainage channels (present or palaeochannels). Another way of recognizing SPM in airborne data comes from an empirical observation that SPM effects are much greater

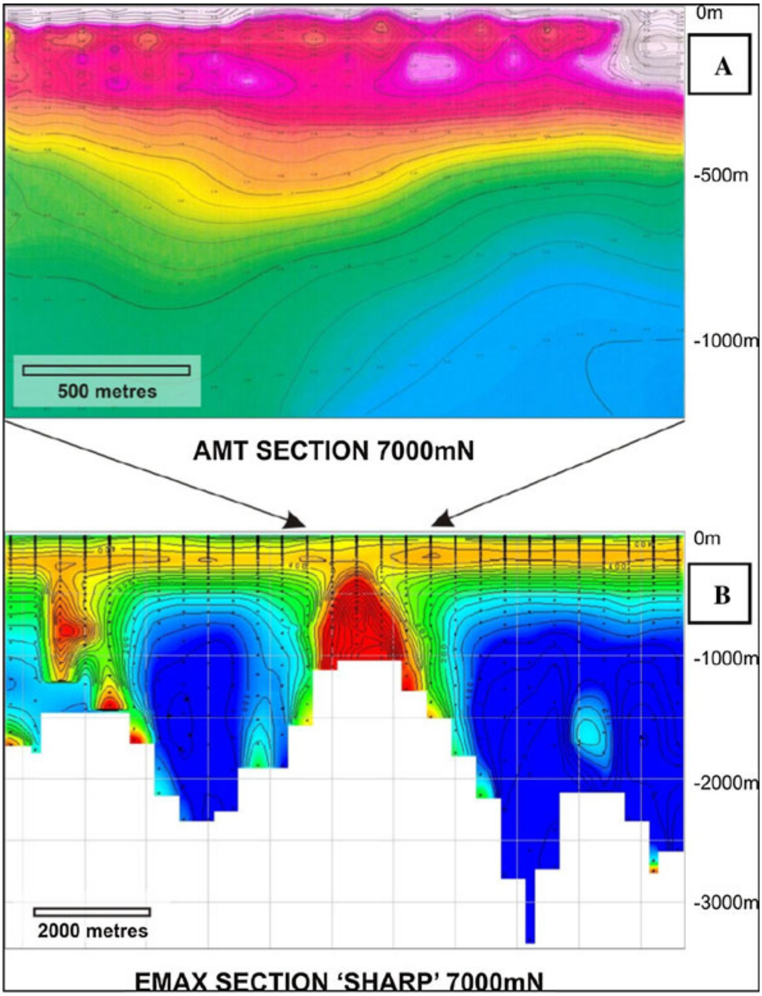

Fig. 2 A comparison of an AMT conductivity-depth section (top) with a section derived from controlled source EM data using a SQUID sensor (bottom). Note that the horizontal and vertical scales on both plots are different. The controlled source SQUID section is plotted to a total depth of 3,000 m and shows a strong bedrock conductor between 400 and 1,200 m depth. The overburden is 2 Ohm m and 400 m thick. Figure courtesy of Mike Webb and Anglo American, taken from Webb and Corscadden (2009)

when the aircraft is closer to the ground. Thus, slow decays that correlate with locations where the altimeter reading is small are possible locations for SPM effects.

Interestingly, in the figures presented by Mutton and Mortimer (2009), there are also induced polarization effects evident. IP effects have also been discussed in a number of other expanded abstracts: Beran and Oldenburg (2008) present a way of estimating the induced polarization parameters of a two-layer earth, and Walker (2008) documents three different types of induced polarization responses observed in AeroTEM data. Walker concludes that more work is required to extract information of exploration significance from data that show IP effects.

8.3 Work on Modelling and Inversion

8.3.1 Conductivity-Depth Imaging or One-Dimensional Schemes

Improved methods for conductivity-depth imaging schemes continue to be an area for active research. New or improved methods for airborne data are described by Fullagar and Pears (2010), Davis et al. (2010b) and Macnae et al. (2010). Christiansen and Auken (2009) suggest using the EMMA or EM1DINV program, which is freely available for ground or airborne systems. All these programs are most suitable when the environment is close to a layered model.

8.3.2 Inversion of Natural-Field EM Data

Holtham and Oldenburg (2012a) describe procedures they have proposed for inverting ZTEM data. An example of a 3D inversion of ZTEM and MT data is in Holtham and Oldenburg (2010b), and a ZTEM inversion for a large and complicated synthetic model is described by Holtham and Oldenburg (2012b). Kowalczyk and Van Kooten (2012) also describe procedures for 3D inversion of ZTEM data, and they illustrate this with an example where ZTEM is being used to map the Silver Queen molybdenum porphyry deposit. Titan MT data over Silver Queen are presented in Retallick and Hearst (2012) and Bournas et al. (2012), and the latter authors claim that the ground MT data are better at resolving the structures than the airborne data. Quantec Geoscience has derived a 3D model from 2D inversions of the MT data over Silver Queen. Both the ZTEM and MT inversions are presented in this review paper courtesy of New Nadina Explorations Ltd. Figure 3 shows a small part of the ZTEM inversion in the left column, and the right column is the MT inversion results. Each row represents the data at five different depth horizons from about 100 m below surface (top) to 1,300 m below surface (bottom). The MT data are acquired on the ground over many hours, and reliable electric and magnetic field data can be obtained for frequencies between 0.01 and 10,000 Hz. On the other hand, the ZTEM data were collected high in the air in just a few minutes with only the vertical magnetic field being measured at frequencies between 30 and 720 Hz. Given that the MT data have electric field measurements, horizontal magnetic field measurements, greater spatial sampling, broader frequency range and the lower sensor height, it is not surprising that the MT results show finer resolution with more features. On a broad scale, both data sets have a conductive feature in the triangle in the south-east corner of the survey area. However, the response associated with the Silver Queen body has been imaged differently in the two data sets. The dashed outline on all images is the outline of an anomaly seen on the Titan IP inversions. The ZTEM shows something conductive at this location in the 100 and 500 m depth slices, but a resistor in the 200 m depth slice; there is a hint of something in the 1,000 m slice and very little in the 1,300 m depth slice. The MT data show greater coherence, with there being no strong conductor until a depth of 500 m, but this conductive feature persists to 1,300 m depth. The MT data therefore appear to image the conductive zone associated with the deposit more coherently.

Interestingly, another example presented in Retallick and Hearst (2012) shows that an MT survey has mapped a deep conductor on a property explored by Golden Valley Mines. Vallée and Smith (2009b) also presented data released by Golden Valley Mines, which was also deep, but in their case, the conductor was large and detected with GEOTEM, an airborne fixed-wing time-domain EM system.

An example of ZTEM data presented as the “peaker” (Pedersen et al. 2009) is presented by Sattel and Witherly (2012) for a test site at Forestania, Western Australia. These authors

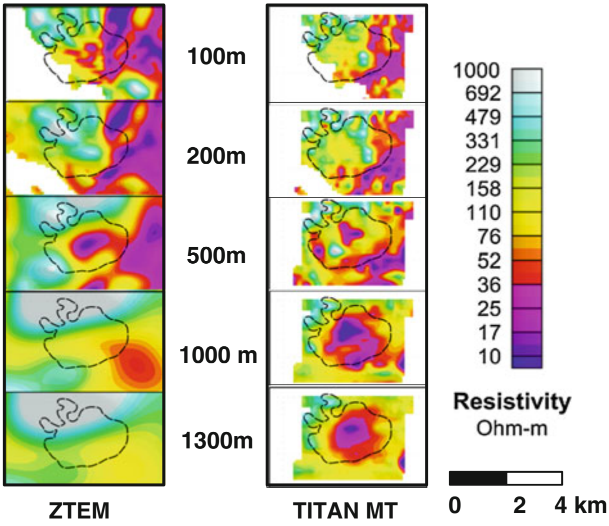

Fig. 3 A comparison of ZTEM data (left) and Titan MT (right) at five different depths below surface (100, 200, 500, 1,000 and 1,300 m). The ZTEM image is a section of a larger survey. The dashed line on the images is a chargeable zone identified in an IP survey. The resistivity colour bar and scale bar are to the left; north is to the top. Data shown courtesy of New Nadina Explorations Ltd

also tested 2D and 3D inversion methods on this data, and the 3D inversions appeared to give the better results. However, the small sulphide bodies were not imaged definitively, apparently being overwhelmed by the response of larger regional structures.

VTEM data, ZTEM data and ZTEM 2D inversions over the Forestania test site are presented by Legault et al. (2010) along with an extensive discussion of the test site. The ZTEM has mapped out a number of large features and the intrusive bodies that host the mineralization, but these authors concede that ZTEM does not seem to have detected the conductors directly. As a bonus, the same paper also contains a discussion of ZTEM and VTEM data over the Eagle's Nest deposit in northern Ontario.

Inversion of ZTEM and AirMt data over the Nebo-Babel Ni-Cu-PGE deposit in Western Australia has been undertaken by Legault et al. (2012a), and it was concluded that the 3D inversions did a better job than the 2D inversions.

A comparison of ZTEM 3D inversions and 3D inversion of SPECTREM fixed-wing time-domain EM data over the Alaskan Pebble deposit is presented by Pare et al. (2012) and Zhdanov et al. (2012). The two methods show similar features, except the ZTEM images features more than twice as deep as the SPECTREM, including an untested feature at depth. In neither case do the EM systems see the mineralization; they both appear to be mapping major structures and alteration.

The Mt Milligan ZTEM data discussed above were inverted using a 3D model by Holtham and Oldenburg (2010c) who imaged the resistive stock in the correct location with a dip that is consistent with the geological information. The VTEM data at Mt Milligan were inverted to find a 3D model by Oldenburg et al. (2010). It is not possible to compare the two data sets, as the ZTEM abstract shows data from Sects. 9350 N and 9500 N, while the inversion sections for the VTEM abstract has no northing indicated.

8.3.3 Inversions of Controlled Source EM Data

Three-dimensional inversion for the AFMAG and MT methods is simpler than moving source inversion as you do not have to deal with multiple source locations. However, the moving or multiple-source problem (the primary problem in mineral exploration) is a much larger problem to solve. Cox et al. (2010) tackle this problem by removing the impact of cells far from the sources by using a “moving footprint approach”. The 3D inversion method of Cox et al. has been tested in a number of areas. The early tests on data from the Reid-Mahaffy test site show inconsistent results, with the DIGHEM sections for line 50 showing three conductors, but the MEGATEM sections showed as many as five conductive features. This might be because each conductor has two lobes in the MEGATEM z-component response and each lobe on the profile was interpreted as a conductor. Also, the inversion section for the challenging target on line 150 was not presented. However, Glenn Wilson, formerly of Technoimaging, has kindly supplied Fig. 4, which shows more recent results of MEGATEM inversion at Reid-Mahaffy. This figure has three panels: the first, panel (a), is the measured z-component response in window 11; panel (b) is the predicted response for the same window from the inverted 3D model; and panel (c) is the resistivity model at a depth of 175 m below surface. Each of the positive–negative–positive anomaly profiles in the z-component data has been imaged as a single conductive feature, and the complex zone on the left between 5402000 N and 5403000 N has been correctly imaged as three conductive zones. The challenging deeper conductor between 5403000 N and 5404000 N (centre and right) is seen on adjacent lines as a single conductor.

Another recent test of the Cox et al. (2010) algorithm is in an area where there is a complicated shear zone and the inversion results have been compared with conductivity-depth images (Combrinck 2011, Combrinck et al. 2012). A horizontal section displaying the 3D inversion results are more consistent with the conductivity structure interpreted using vertical plates than maps produced from the Conductivity-Depth Imaging (CDI) section.

Another approach to solve the multisource problem is to use direct solvers (Oldenburg et al. 2008). These authors demonstrated this concept on a synthetic survey, solving for just nine source positions. However, for large airborne surveys where there might be ten thousand survey positions, this approach has to be modified in some way. Yang and Oldenburg’s (2012) modification is discussed above in the refereed section.

A final approach to making the problem more tractable is to simplify the forward problem. One way of doing this is to convert the data to the resistive-limit or moment of the impulse response, which linearizes the inversion problem. Schaa and Fullagar (2010) attempted this approach and found that a whole survey could be inverted to give geologically reasonable results in just 3 min cpu time.

8.3.4 High Contrast Inversion

Inverting to find the conductivity structure when there is a highly conductive body in a highly resistive background is an important problem in mineral exploration. Oldenborger and Oldenburg (2008) gallantly tackled this problem using synthetic data, but concluded that more work was necessary. Ansari and Farquharson (2011) have commenced a study to look at the relative importance of inductive and galvanic current flow for MT data. Extending this study to controlled source data is important, as it is expected that the inductive term will have an even greater impact.

The Multiloop III program was specifically written for modelling the inductive current flow. It does this by assuming that the background has zero conductivity (so there is no galvanic current) and the only current is an inductive current flowing entirely within a thin conductor. The Multiloop III program is also able to account for interaction between multiple conductive bodies. Walker and Lamontagne (2008) used Multiloop III program to show three things: that many vertical conductors can have a response that looks like a

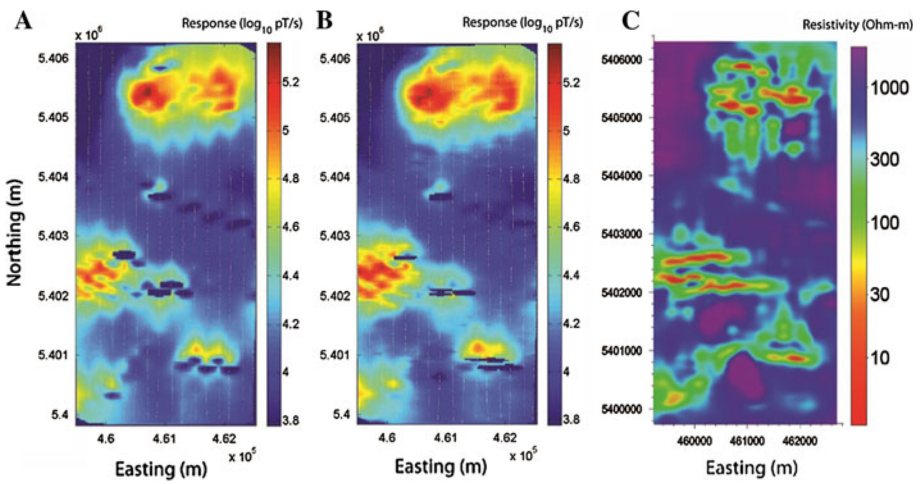

Fig. 4 Panel (a) shows the observed data from channel 11 of the vertical component of the MEGATEM dB/dt data. Panel (b) shows the predicted data from the same channel. Both data have been corrected for the lagging applied to the MEGATEM data to remove effects of alternating flight lines. Panel (c) shows a horizontal cross section of resistivity at a depth of 175 m recovered from the 3D inversion. Figure courtesy of Glenn Wilson of TechnoImaging

horizontal conductor; that multiple conductors would give the wrong location if interpreted as a single conductor; and that the amplitude of the response of a conductor is affected by surrounding weaker conductors. The ability of the Multiloop program to model curved conductive surfaces was illustrated by Walker and Terblanche (2010), when they modelled the Gamsberg deposit.

8.3.5 Parametric Inversion

Arnetts (2012) has been working with the Loki 3D EM forward modelling developed at the CSIRO. He linked the forward problem with a parametric inversion and tested it on synthetic data, concluding from this example that using parametric inversion required that the initial guess be close to the correct answer.

8.3.6 Inductive Source Resistivity Modelling

The inductive source resistivity method has enjoyed a resurgence in the last few years. Lamontagne Geophysics has collected a number of surveys (in the Athabasca Basin and the Falconbridge footwall area). A forward modelling study of ISR data, undertaken by Yang and Oldenburg (2010), showed that the method was sensitive to zones between the transmitter and receiver and that deep resistive zones could be detected. The ability to extract IP data from the decay of the ISR data was investigated using synthetic inversion and resistivity modelling undertaken by Marchant et al. (2012).

8.3.7 Frequency-Domain to Time-Domain Conversion

Controlled source EM data are largely acquired in the time domain, so one important aspect of most controlled source modelling is converting the data from the frequency to the time domain. Generally, this is done using the fast Fourier transform, digital filters or the Gaver–Stehfest algorithm. The former two methods require a large number of frequencies to work, while the later requires great accuracy. An alternate approach is to fit a set of basis functions to the data in the frequency domain that have known analytic transforms to the time domain. This is typically done with functions that decay as exponents in the time domain. Tehrani and Slob (2010) working with marine CSEM data propose a set of basis functions that have power law and error function decays in the time domain. It would be interesting to see this method tested on mineral exploration data.

8.3.8 Other Analytic Work in Modelling Electromagnetic Data

Very little analytic work is currently being done in electromagnetic modelling. One exception is a theoretical development where Sampaio (2011) derived approximate solutions for a 2D problem: the EM response of a fault. Faults are of interest to mineral explorers, as deposits sometimes occur close to faults. However, in mineral exploration, the EM source is generally finite, so the 3D problem is of greater interest and Sampaio acknowledges that this is a challenge.

9 Meetings at Which EM Methods Applied to Mineral Exploration are Presented

As mentioned above, about 300 talks or posters have been presented on EM techniques in the period covered by this review. Of these, I have classified 128 by the industry sector that employs the authors in a similar manner to Table 1. The results are summarized below in Table 2.

In this table, the contribution from academia and government is comparable to the number of papers in Table 1; however, the contributions from the service companies and mining companies have increased substantially. Of particular note is the large number of contributions, particularly from the service companies and mining companies at the ASEG meetings. Hence, if one is interested in learning about mining geophysics and EM methods, and/or in reaching an audience interested in mining geophysics and EM, then this is the meeting to attend and present one's results.

10 Conclusions

There have been a broad range of improvements in EM methods applied to mineral exploration: data acquisition system development, system calibration, geometry

Table 2 Classification of important talks or posters relating to EM induction methods for mining from 2008 to 2012

	SEG events	EAGE events	ASEG events	Workshops with no affiliation	Other (SAGA, SBGf)
Academia	10	6	11	1	3
Government	3	1	11	5	
Service Companies	11	1	17	4	3
Mining Companies	6	1	24	3	7
Total	30	9	63	13	13

monitoring, modelling, inversion and application case histories. In the last 5 years, we have moved from one-dimensional inversion to methods that allow us to see the three-dimensional variations in the conductivity. As computing power increases and the algorithms are made more efficient, we will start to see 3D inversions done more routinely. There has been considerable development work on natural-field EM systems and corresponding effort in modelling and inverting the data from these systems. One case history shows that the ZTEM method is not able to see a compact highly conductive body, but in many examples ZTEM and other natural-field techniques are able to see large structures. This means that large porphyry deposits may be detected with EM systems such as ZTEM. This technological development seems to be consistent with the greater emphasis that the exploration industry has been placing on looking for large porphyry-type systems in the last few years (Au, Cu and Mo deposits).

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