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Metalliferous mining geophysics — State of the art after a decade in the new millennium

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ABSTRACT

Mining exploration was very active during the first decade of the twenty-first century because there were numerous advances in the science and technology that geophysicists were using for mineral exploration. Development came from different sources: instrumentation improvements, new numerical algorithms, and cross-fertilization with the seismic industry. In gravity, gradiometry kept its promise and is on the cusp of becoming a key technology for mining exploration. In potential-field methods in general, numerous techniques have been developed for automatic interpretation, and 3D inversion schemes came into frequent use. These inversions will have even greater use when geologic constraints can be applied easily. In airborne electromagnetic (EM) methods, the development of time-domain helicopter EM systems changed the industry. In parallel, improvements in EM modeling and interpretation occurred; in particular, the strengths and weaknesses of the various algorithms became better understood. Simpler imaging schemes came into standard use, whereas layered inversion seldom is used in the mining industry today. Improvements in ground EM methods were associated with the development of SQUID technology and distributed-acquisition systems; the latter also impacted ground induced-polarization (IP) methods. Developments in borehole geophysics for mining and exploration were numerous. Borehole logging to measure physical properties received significant interest. Perhaps one reason for that interest was the desire to develop links between geophysical and geologic results, which also is a topic of great importance to mining geologists and geophysicists.

INTRODUCTION

At the end of the last millennium, mining exploration experienced an economic rise starting in about 1993 and ending in 1999. Then in the first decade of the new millennium, exploration rose steadily for six years and peaked in 2007, after which it entered a strong decline at the end of 2008 and reached a nadir in 2009. The exploration economy gradually began to recover at the beginning of 2010. During the first decade of the twenty-first century, exploration and mining geophysics research and development were concentrated mainly in academia, the service industry, and in government institutions. In Australia, the Commonwealth Scientific and Industrial Research Organization (CSIRO), which had been a strong actor in mining geophysics research and development, sharply reduced its activity in the decade 2000 through 2010 (Raiche, 2008).

The airborne EM industry experienced a consolidation in the number of businesses and systems available at the start of the decade 2000 through 2010, but new players stepped in and introduced new systems. Gravity methods continued to take advantage of the revolution in global positioning system (GPS) technology and became popular in the air. Ground geophysical systems took advantage of the revolution in microprocessor technology, with more data being acquired and stored and more sensors being deployed. Magnetic methods did not undergo a significant advance in acquisition hardware or software, but data modeling, data interpretation, and integration among data sets improved. A tremendous advance took place in the application of time-domain helicopter EM methods for mining exploration in various environments, with many new systems being introduced. Modeling tools using EM also were improved. Progress was made in the application of seismic methods for mining

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activities. In parallel, there were developments in the integration of geophysical data with geology.

GRAVITY METHODS

Review papers summarizing research in gravity leading up to and at the start of the new millennium include Hansen (2001), Nabighian and Asten (2002), and Nabighian et al. (2005). An "Airborne gravity 2004 workshop" was held in Sydney, Australia, and the papers presented there are available on the following Web link: http://www.ga.gov.au/image_cache/GA4758.pdf. Dransfield (2007) gave a good history of gravity gradiometry and presented its various applications to mineral exploration. In a later paper, Dransfield (2010) reviewed the progress from 2005 to 2010 in airborne gradiometry: Noise levels were nearly halved and routine incorporation of regional gravity data led to gravity data sets that contain a broad range of wavelengths. The Falcon technology developed by BHP Billiton successfully discovered several mineral deposits (Dransfield, 2007), one of the first of which was the Santo Domingo Sur deposit in Chile (Figure 1a). The gravity-gradient high shown in Figure 1b corresponds to the mineralization mapped by drilling. The BHP Billiton technology was transferred to Fugro Airborne Surveys in 2008 and now can be used for mineral exploration. In parallel, other commercial airborne gravity gradiometry systems were developed by Bell Geospace (Hammond and Murphy, 2003) and Arkex (Lumley et al., 2004). These latter systems measure multiple gradients, which can be combined to reduce the total noise level (Murphy et al., 2006). Another approach was the development of airborne vector gravimetry by Sander Geophysics Ltd. (Annecchione et al., 2006). Li and Jekeli (2008) developed and tested a vector gravimetry system installed on a ground vehicle by combining GPS data with an inertial navigation system.

In gravity processing, several groups developed methods for generating terrain corrections. Garcia-Abdeslem and Martin-Atienza (2001) developed a method to compute the terrain corrections for a gravity survey using a digital elevation model. This method is based on a forward-model solution for computing the gravity effect resulting from a rectangular prism of uniform mass density that is flat at its base but has a nonflat top. In gravity gradiometry, Kass and Li (2008) developed an efficient terrain-correction algorithm and examined the spatial extent and resolution of terrain models required for performing accurate terrain corrections. Dransfield and Zeng (2009) proposed a method for selecting an optimal survey flight over a known terrain, given a desired terrain-correction error. Dransfield (2009) proposed using sparsely sampled regional gravimetry data to provide the long-wavelength information, thereby conforming the derived gravity to the regional gravity.

In signal processing, Lyrio et al. (2004) proposed an automatic, data-adaptive 1D wavelet-filtering technique specially designed to process gravity gradiometry data. Pajot et al. (2008) developed a method to reduce noise when the gravity-gradient tensor and gravity data are both measured in the same area. The algorithm is based on a least-squares simultaneous inversion of observations and physical constraints, inferred from the gravity-gradient tensor definition and its mathematical properties. Not only does the method use measured values of the tensor components, it also uses simultaneously measured gravity data in the same survey area.

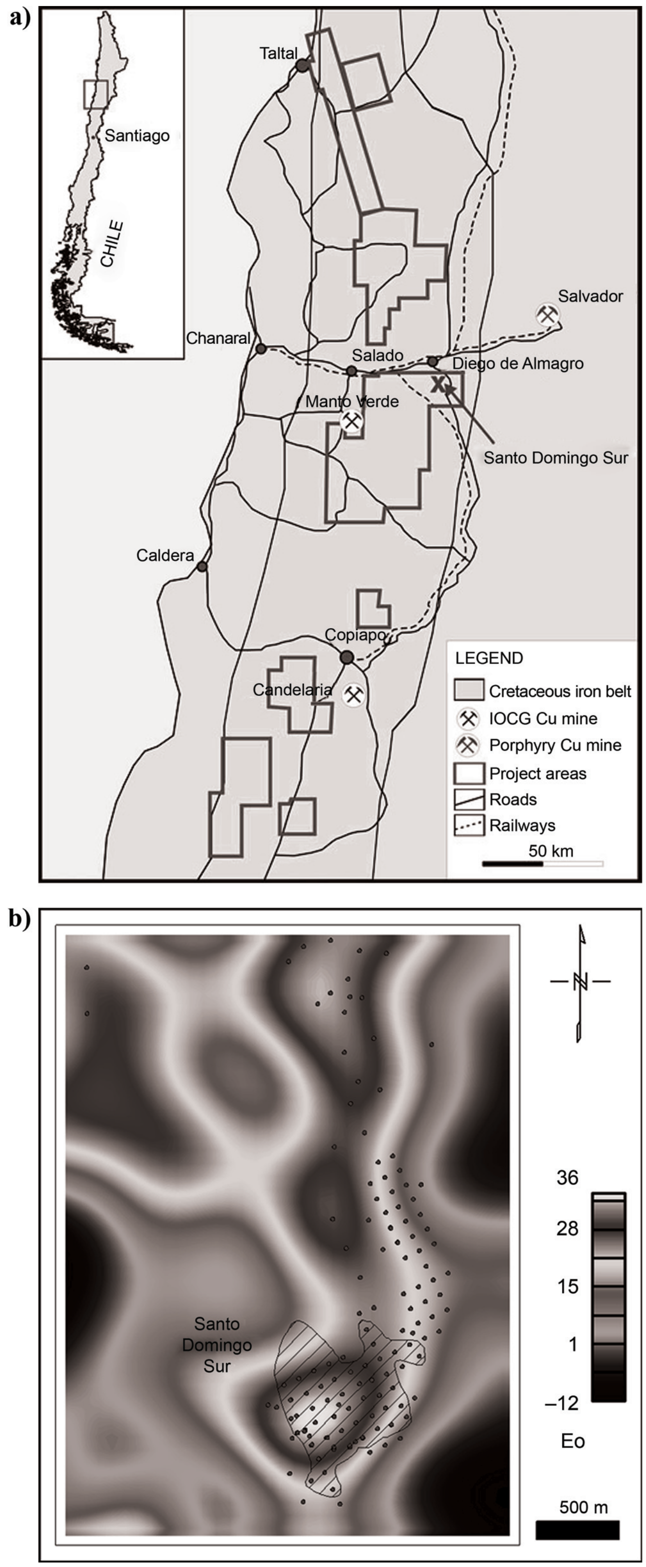

Figure 1. (a) Map of the Far West Candelaria copper project areas in northern Chile, showing the existing copper-gold mines such as Manto Verde and Candelaria. The location of the Santo Domingo Sur deposit is indicated by a cross. Detailed gravity gradient signature of the Santo Domingo Sur deposit. "Eo" is Eötvos. From Dransfield (2007). Used by permission.

Advances occurred in gravity interpretation. From the residual gravity anomaly, Abdelrahman et al. (2001a) used three least-squares approaches to determine successively the depth, shape, and amplitude coefficient related to the radius and density contrast of a buried structure. The same year, also from residual gravity data, Abdelrahman et al. (2001b) determined simultaneously the shape and depth of a buried structure using filters of successive window lengths. Later, Abdelrahman et al. (2003) used two different least-squares approaches to determine the depth and amplitude coefficient of a buried faulted thin slab. Zhdanov et al. (2004) interpreted tensor gravity data, based on regularized focusing inversion. Mikhailov et al. (2007) proposed an interpretation method that is especially designed to benefit from the simultaneous use of all components of the gradiometry tensor components and the normal gravity field.

Several gravity inversion methods used constraints in different ways. Silva and Barbosa (2006) estimated the location and geometry of several density anomalies, using user input to define the assumed outline of the gravity sources. The results from 3D Euler deconvolution were used as a priori information by Rim et al. (2007) when inverting gravity data. In other work, Dias et al. (2009) estimated a 3D density-contrast distribution producing strongly interfering gravity anomalies.

When solving the forward problem, Zhou (2009) calculated the gravity anomaly using the vector-potential line-integral method. The model is a rectangular prism with a density contrast. Caratori Tontini et al. (2009) showed how 3D fast Fourier transform (FFT) can be used for rapid computation of 3D forward models of a potential field. This potentially can lead to fast 3D inversion schemes. Other developments applicable to both gravity interpretation and magnetics interpretation are covered in the next section.

MAGNETIC METHODS

Nabighian et al. (2005) presented the most significant developments of the magnetic exploration method for mineral exploration from its beginning to 2005. Here we carry that forward by focusing on the 2005–2010 period, and we also add some developments that could not be covered in Nabighian's review because of space constraints.

Survey technology

Aeromagnetic surveys are used routinely for mineral exploration, mostly to help in mapping geology. Instrumentation remained essentially the same over the decade 2000 through 2010, with the vast majority of surveys flown using differential dual-frequency GPS, which results in an accuracy of about 3 m. Efforts were made by Vallée et al. (2005) and Vallée et al. (2007) to quantify and understand better the impact of geomagnetic noise on aeromagnetic surveys. Measuring the transverse magnetic gradient provides information that improves the quality of the gridded data, and the technique now is used often because the increase in cost is marginal (O'Connell et al., 2005). Cowan and Cooper (2003) advocated the use of tight-drape surveys that can be done using either crop-dusting airplanes or helicopters. This is not always practical for cost or safety considerations. Surveys also can be flown using a preplanned flight surface (Sander, 1998) to minimize the height difference between flight lines and tie-lines at their intersections and therefore to improve the leveling of the magnetic data. All surveys flown for the Geological Survey of Canada now use that technique because it allows better magnetic-data leveling, especially in rugged areas.

Dransfield et al. (2003) showed how airborne vector magnetics can be used to map remanently magnetized banded iron formations. They computed the vector components of the total magnetic field, using information from the three fluxgate magnetometers employed for compensation, along with the data regarding the orientation of the aircraft obtained from a gyroscopic platform. In the data set they examined, the platform was installed on the aircraft as part of an airborne gravity gradiometry survey. That type of platform is not installed on most aeromagnetic survey aircraft, so the technique is not used commonly. However, it does show that this methodology could help with interpretation problems when magnetic remanence is present.

Stolz et al. (2006) discussed the development of a magnetic full-tensor SQUID system for airborne geophysical applications, and Rompel (2009) presented examples of the use of this instrument. Such a system allows better 3D modeling of magnetic bodies and improves the detection of weak magnetic features. The U. S. Geological Survey developed a prototype (Bracken and Brown, 2006) magnetic tensor system designed to be used for unexploded ordnance (UXO) detection. That system uses an array of highly accurate triaxial fluxgate magnetometers to measure the magnetic tensor. This and other developments in the use of magnetic sensors for UXO might have an application in mining geophysics in the future.

Data processing

Various techniques were developed to enhance aeromagnetic data to improve qualitative interpretation. First and second vertical derivatives have a physical meaning and still are used commonly, but many of the techniques developed recently are strictly image-processing tools designed to help the interpreter detect subtle patterns in aeromagnetic data. Cooper and Cowan (2007) used horizontal orthogonal-gradient ratios to enhance linear features, and Cooper and Cowan (2008) used statistical techniques to outline better the edges of potential-field data. This subject is closely related to edge-detection techniques in which the goal is to locate abrupt changes in susceptibility that may be related to lithologic contacts. Pilkington and Keating (2009) compared several edge-detection methods and showed that many provide equivalent information.

Leveling is an essential step in the production of an aeromagnetic map, but little was published on this subject between 2000 and 2010. Mauring et al. (2002) and Mauring and Kihle (2006) proposed use of a moving differential median filter to level magnetic data. The technique is most useful when one is processing old surveys that have few tie-lines.

Aeromagnetic data must be interpolated on a regular grid for further processing and integration into geographic information system (GIS) databases. Because the data are sampled much more densely along flight lines than across them, it follows that the interpolated grid suffers from aliasing in the direction perpendicular to the line orientation. The sampling rate of magnetometers typically is 10 Hz, or approximately 8 m when a fixed-wing platform is used, whereas line spacing can be anywhere between 50 m and 400 m depending on the survey objectives. Survey height typically varies between 60 m and 150 m. Billings et al. (2002) used continuous global surfaces to interpolate magnetic and gravity data. For magnetic data they used a thin-plate spline, and their results compare well with standard minimum-curvature gridding. Smith and O'Connell (2005) used a constrained anisotropic diffusion filter to enhance the trends between adjacent flight lines.

Interpretation of aeromagnetic data is much more complex when manmade cultural noise is present, especially when surveys are flown over populated areas. Hassan and Pierce (2005) developed a semi-automated technique for removing cultural noise from aeromagnetic profiles prior to gridding. Salem et al. (2010) proposed an equivalent-source technique to remove cultural noise. They used the analytic signal calculated along a profile to identify shallow sources and then removed corresponding magnetic data from the profile. The missing data then were calculated from an equivalent source, a horizontal cylinder oriented perpendicularly to the line direction.

Interpretation

Interpretation can be either qualitative or quantitative. Qualitative interpretation of magnetic data is used for geologic mapping and is based on the use of various enhancement techniques. Quantitative techniques generally fall into two categories: the automated, simple model techniques, which are based on the assumption of homogeneous functions, and inversion techniques.

Techniques based on the properties of homogeneous functions

The theory of homogeneous functions has been used extensively to develop new and faster interpretation techniques. The best known is certainly Euler deconvolution, which has been the source of many new developments since its introduction by Thompson (1982) for profile data and by Reid et al. (1990) for gridded data. The structural index is really the degree of homogeneity of the field; in other words, the fall-off with distance. Its selection is critical because it influences the interpreted depths. Thurston (2010) pointed out that for a potential field to obey the Euler equation, the degree of homogeneity must be an integer. Thurston (2010) continued that many real sources behave as if they had a fractional degree of homogeneity, and he showed that in one case (a thick dyke) useful results nevertheless can be obtained.

Various techniques have been proposed to determine the best structural index automatically. Mushayandebvu et al. (2001) introduced an additional relation that represents the transformation of homogeneous functions under rotation, and the combined use of both relations yields a better solution of the Euler equation. For 2D sources, it then is possible to estimate dip and susceptibility. In further work, Mushayandebvu et al. (2004) showed how the eigenvalues of the equations used for Euler deconvolutions can be used to determine automatically whether a source is 2D and 3D.

Nabighian and Hansen (2001) unified Euler and Werner deconvolution in three dimensions via the generalized Hilbert transform. Pilkington and Keating (2006) showed that the local wavenumber is simply the vertical derivative of the analytic signal scaled by the amplitude of the analytic signal. Salem et al. (2008) obtained a linear system of equations similar to Euler deconvolution from the horizontal and vertical derivatives of the tilt angle (Miller and Singh, 1994). In addition to estimating the location of the source, the method allows one to determine the structural index, or the homogeneity degree, without any a priori information. The use of second-order derivatives of the field can make the method sensitive to noise, and the authors suggested upward continuation of the field to counteract the effect of noise. However, it should be noted that modern surveys have a very low level of noise.

Phillips et al. (2007) proposed use of the curvature of the magnetic field as an interpretation tool. The eigenvalues and eigenvectors of the curvature matrix within a small data window are used to estimate the location and strike of the source of an anomaly. Its depth and structural index are estimated from the total gradient or the local wavenumber.

Interpretation techniques were developed that are based on upward continuation of the magnetic field at a series of increasing heights, combined with application of high-pass filters. The advantage of these techniques is that upward continuation reduces the noise level, thereby improving the signal-to-noise ratio (S/N) for deep targets. The disadvantage is that upward continuation works best for isolated anomalies because anomalies near each other merge as the continuation height increases. Sailhac et al. (2000) used a continuous wavelet transform to interpret magnetic data from a profile. Their technique is equivalent to computing the analytic signal at a series of increasing heights. They then interpreted for the depth of the source and for its degree of homogeneity. Once these are determined, the dip and the susceptibility of the source can be calculated. Using a similar approach, Vallée et al. (2004) estimated the source and the depth. They did this on the basis of the analytic signal and the analytic signal of the first vertical derivative of the magnetic field upward continued to a series of increasing heights. Fedi (2007) determined depths and structural indices from a field that has been scaled to specific power laws of the continuation heights; he then estimated depths by using the extreme points of the scaled field. Subsequently, Fedi et al. (2009) proposed the use of a geometric method combined with a reduced Euler deconvolution to interpret for the depth and degree of homogeneity of the source. In this technique, the magnetic field is upward continued at a series of heights, and ridges are obtained from the first horizontal and first vertical derivative of the magnetic field continued to a series of heights. This technique is closely related to the continuous wavelet transform. Keating (2009) used the local wavenumber upward continued to a series of increasing heights to solve directly for the degree of homogeneity and the depth of a source. His technique also allows one to determine whether the source is homogeneous.

Stavrev and Reid (2007) used a similarity transform to estimate the degree of homogeneity for sources of complicated shapes. Gerovska et al. (2010) developed a technique called MaGSoundDST, which is based on the differential similarity transform, to interpret magnetic and gravity data in three dimensions. Salem et al. (2007) used the tilt angle to interpret magnetic data. Although their technique is restricted to contacts, it also can be used to interpret large magnetic sources.

Inversion

The objective of 3D inversion is to obtain a 3D model of the subsurface whose magnetic response reproduces the observed magnetic field. The subsurface is represented by a large number of prismatic cells of uniform magnetic susceptibilities. The problem is underdetermined because there are more parameters to be estimated than there are observations, and computing time generally is high. Techniques such as depth weighting are used to constrain the model. Portniaguine and Zhdanov (1999) introduced focusing stabilizers that make it possible to recover models with sharper boundaries and contrasts. Figure 2 demonstrates the advantage of focusing regularization for 3D inversion of full tensor magnetic gradiometry data from Tallawang, Australia (Schmidt et al., 2004). As can be seen, the smooth inversion underestimates and smooths the susceptibility distribution, compared with the focusing inversion. Li and Oldenburg (2003) used a fast wavelet transform to speed up the inversion and a logarithmic barrier method to obtain positive susceptibilities. Fullagar and Pears (2007) proposed using an adaptive 3D mesh to discretize the subsurface, thereby allowing the inclusion of geometric and physical property constraints. Lelièvre and Oldenburg (2009a) showed that including physical properties and structural information in an inversion results in more realistic models. Pilkington (2009) proposed use of a sparseness constraint, which leads to simpler and better-resolved models. Use of a data-space method combined with the conjugate-gradient solver results in a very fast inversion algorithm.

All these techniques assume perfect induction and do not take magnetic remanence effects into account. Lelièvre and Oldenburg (2009b) solved the remanence problem by inverting for the three components of the magnetization vector; they also allowed for the inclusion of geologic information. Li et al. (2010) proposed two techniques to deal with remanence. In the first, they estimate the magnetization direction and then incorporate that information into a 3D inversion. The second technique is to invert the amplitude of the magnetic anomaly vector, which depends only weakly on magnetization direction.

AIRBORNE EM METHODS

Many developments in airborne EM (AEM) methods occurred during the first decade of the present millennium. Several of those developments were for UXO detection, bathymetry, groundwater exploration, and salinity mapping. Because this paper concentrates on metalliferous mining geophysics, we will not discuss those airborne EM developments further except to say that they created an opportunity whereby methods developed for other applications could be applied to mineral exploration. As an example, the spatially constrained inversion techniques developed for mapping hydrogeology (Auken et al., 2008; Viezzoli et al., 2009; Brodie and Sambridge; 2009; Vallée and Smith, 2009b) could be used for cases in which the mineral deposits are in quasilayered environments (e.g., nickel laterites and manganese deposits). As another example, the EM induction spectroscopy method, developed initially for use in UXO detection, was proposed subsequently for use in mineral exploration (Huang and Won, 2002). Because there is a significant effort in

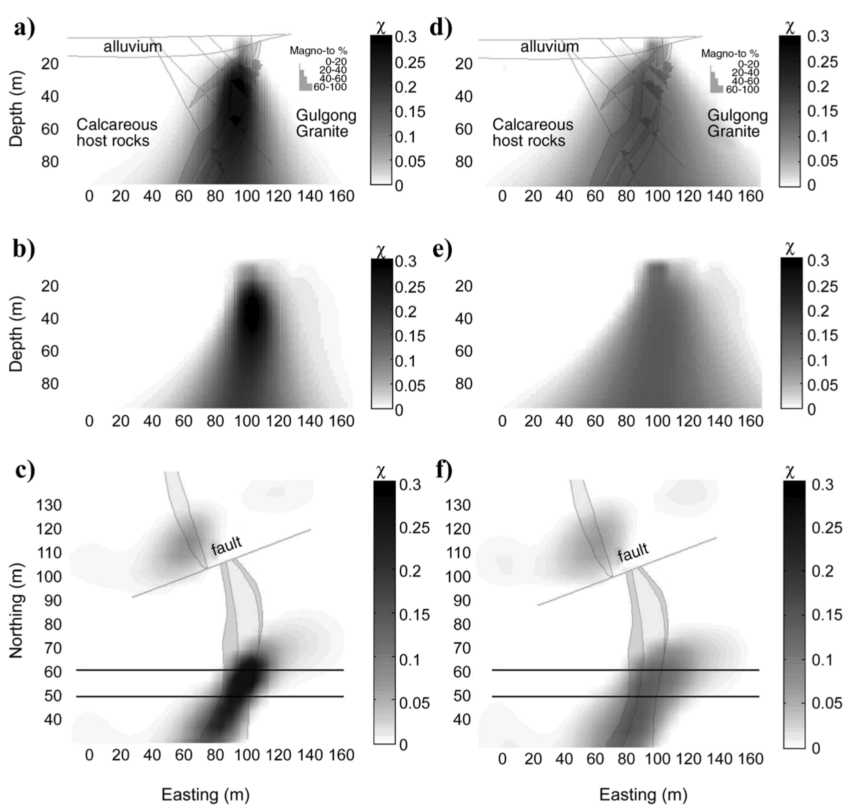

Figure 2. 3D inversion of GETMAG full-tensor magnetic-gradiometry data with minimum support (focusing) regularization, for vertical cross sections along measurement profiles (a) 50 m N, and (b) 60 m N; and for (c) a horizontal cross section at 25 m depth. For comparison, results are also shown for 3D inversion with minimum-norm (smooth) regularization, for vertical cross-sections along profiles (d) 50 m north and (e) 60 m north; and for (f) a horizontal cross section at 25-m depth. Superimposed on the susceptibility models is geology of the Tallawang magnetite skarn, from Schmidt et al. (2004). Used by permission.

hardware development for detection of unexploded ordnance, perhaps some of the small-scale systems developed (e.g., Beard et al., 2004) could be scaled up for mineral exploration if there is a perceived benefit.

Near-surface developments of airborne EM will not be discussed in this paper. Interested readers are referred to the review by Auken et al. (2006).

Development of new systems

Corporate developments at the end of the twentieth century included the purchase of several airborne geophysics firms by Fugro NV. That consolidation of the industry resulted in some analog frequency-domain helicopter EM systems previously marketed by High-Sense Geophysics, Sial Geosciences, and Aerodat being replaced by a single system, the DIGHEM, which had been upgraded to digital acquisition. The QUESTEM system, a time-domain system developed by World Geoscience, was withdrawn from the market. Fugro did enhance the systems that were not discontinued. The dipole moment of the MEGATEM system was doubled (Smith et al., 2003), the GEOTEM system was upgraded to a higher dipole moment at low frequencies, the TEMPEST system was improved by incorporating the three-component receiver sensor used by the GEOTEM system, and the RESOLVE system was introduced as a commercial version of a helicopter frequency-domain system built for the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover, Germany (Sengpiel and Siemon, 2000). The latest version of RESOLVE has a highest frequency of 140 kHz and includes a capacity for internal, in-flight calibration.

Systems operated by other organizations also were improved. A proprietary time-domain system called SPECTREM, operated by Anglo American plc, was upgraded to provide 50% more transmitter power and a greater ability to reject sferic noise (Leggatt et al., 2000). The fixed-wing frequency-domain system developed in Finland by the Finnish government (Leväniemi et al., 2009) was used overseas, in collaboration with the British government, for a major survey covering all of Northern Ireland (Beamish and Young, 2009).

Figure 3. The HeliGEOTEM system acquiring data in the Dominican Republic. From Smith et al. (2009). Used by permission.

The most significant development of the decade was the introduction of helicopter time-domain electromagnetic systems. The pioneering work on commercial systems was done by Aeroquest, THEM Geophysics, and Geotech (Allard, 2007). The corresponding systems were the AeroTEM system (Balch et al., 2003), the THEM system (Allard, 2007), and a system that eventually was called the VTEM system (Witherly et al., 2004b). In a short amount of time, some of these systems, or their descendants, developed very quickly, with reduced noise levels and higher dipole moments (Witherly and Irvine, 2006). Soon they were being compared to fixed-wing time-domain systems (Macnae, 2008). A system called SkyTEM, developed in Denmark (Sørensen and Auken, 2004), is intended primarily for mapping hydrogeology but has been used also in mineral exploration. The SkyTEM introduced a novel feature: being able to excite the earth at multiple base frequencies (e.g., at 25 Hz and 222 Hz). This is achieved by having two separate transmitters, one of which transmits a relatively small signal at a base frequency of 222 Hz for a fraction of a second and then switches off, and the other of which transmits at 25 Hz for about a second. The NEWTEM time-domain helicopter system (Eaton et al., 2002; Eaton et al., 2004) is a proprietary system operated by Newmont Mining Corporation. A similar system, called HoisTEM (Vrbancich and Fullagar, 2004; Allard, 2007), was developed by Normandy-Poseidon in a loose collaboration with Newmont. The system was available commercially for a brief time, but it was replaced by two similar systems: RepTEM and XTEM. Sattel (2009) provides some details on the RepTEM system, and information about the XTEM system can be found on the GPX Surveys Web site.

One difficulty with helicopter time-domain systems is that the receiver is near the transmitter. This proximity makes it difficult to take measurements during the transmitter pulse or at early delay times after the pulse. Various systems have addressed that issue in different ways. The AeroTEM system is rigid, which means that a bucking coil can be used to create a zone around the transmitter, where the primary field is very small. An alternative approach is used by the SkyTEM system, in which a receiver loop is placed above and slightly behind the transmitter loop. Here, the primary field is mainly horizontal, and the horizontal coil (vertical dipole) that is used as the receiver is essentially null-coupled. With the HeliGEOTEM and HELITEM systems (Fountain et al., 2005; Smith et al., 2009), the receiver is moved a significant distance up the tow cable, as shown in Figure 3, where the primary field will be smaller. In a recent development, the VTEM system introduced a nonrigid bucking coil. Another way to null-couple the receiver from the strong primary field was proposed by Miles et al. (2010).

Other non-time-domain helicopter systems also were developed. An airborne AFMAG system, called Z-TEM, has been deployed by Geotech. It measures the z-component (vertical component) of the natural fields, using an airborne receiver, and it measures the horizontal components at a remote ground station. These horizontal components are assumed to be the same at the helicopter, so that a tipper can be derived and used for interpretation. Some modeling and Z-TEM results were presented by Lo and Zang (2008). In Sweden, there were further developments on an airborne very-low-frequency (VLF) system. The concept of a tensor VLF technique was developed at Uppsala University and deployed by the Geological Survey of

Sweden. Methods for processing and displaying this type of data were developed (Becken and Pedersen, 2003; Pedersen and Becken, 2005), and Pedersen et al. (2009) presented two case histories that use such a system.

Semiairborne systems developed and documented in the years 2000 through 2010 include the GREATEM system (Mogi et al., 2009) and the TerraAir system (Smith et al., 2001). A novel use of unstacked full waveform (stream) data was proposed by Vallée et al. (2010). The EM data from the transmitter and the 60-Hz powerlines are separated in the frequency domain, and the latter are used to derive maps that show geologic structures in the survey area. Experience from a survey near Chibougamau, Canada, indicates that the field from the powerline can illuminate large structures not seen on the normal fixed-wing EM data.

Other developments in systems

In the early part of the decade, much work came to light regarding the measurement of the B-field response rather than the dB/dt response. Lee et al. (2001) and Lee et al. (2002) concluded that the performance of the SQUID sensor is comparable to that of induction-coil sensors, but they suggested that the SQUIDs would perform better at base frequencies below 20 Hz. Smith and Annan (2000) showed that the advantages of B-field acquisition can be obtained by integrating the on- and off-time response of an induction coil (dB/dt) sensor.

Several advantages arise if we know the accurate position and orientation of the transmitter and receiver. Knowing these geometric parameters can result in better estimates of subsurface conductivity and the depth to conductive features (because the response measured is dependent on geometry). Approximate methods for estimating the receiver position were described by Smith (2001c) and Vrbancich and Smith (2005). In bathymetric studies, knowing the system geometry is important, so considerable effort (Kratzer and Vrbancich, 2007) was put into monitoring the geometry with GPS and inertial measurement units (IMU). If this is straightforward and provides a significant benefit, it could be adopted for use in the airborne EM systems used in the mineral exploration industry. If the position is being used to estimate the in-phase response of highly conductive (nickel) bodies, extremely accurate estimates are required (Smith, 2001a; Hefford et al., 2006).

Similar work on monitoring system geometry was undertaken for frequency-domain systems. In that case, accurate bird orientation (roll, pitch, and yaw) results in better estimates of the conductivity structure of the subsurface. Davis et al. (2009) devised methods for measuring and predicting those orientations. In another study, Yin and Fraser (2004) showed that by using the changes in dipole geometry, it is possible to correct 95% of the errors that are generated by changes in the attitude of a frequency-domain helicopter EM system. More accurate results were obtained by Fitterman and Yin (2004) for the full induction solution.

Accurate measurements of system geometry are not required for measuring the in-phase response with the frequency-domain systems because such systems are rigid. Efforts to improve the calibration of helicopter frequency-domain systems were shown to result in better data being derived from AEM systems (Ley-Cooper and Macnae, 2007; Macnae et al., 2008). A procedure involving a ground loop was devised by Davis and Macnae (2008a, b) to improve understanding of the time-domain waveform shape and of timing and altimeter geometry errors; that procedure also results in derivation of better fidelity information from the data. One advantage of this work is that the precise nature of most of the time-domain system waveforms becomes apparent (Davis and Macnae, 2008a). All contractors now are trying harder to make high-quality waveform information available. When comparing ground EM and airborne EM, other workers (Davis and Groom, 2009) also noted the importance of system parameters such as waveform shape, window position, and receiver response functions.

An idea that has some currency is to convert a real waveform to an idealized waveform such as an impulse or a step. This is the procedure used in processing data from the Spectrem system (Leggatt et al., 2000) and the TEMPEST data (Lane et al., 2000). Sattel et al. (2004) extended this concept to the half-sine waveform and cited some advantages. Huang and Cogbill (2006) proposed an acquisition procedure for ensuring that AEM systems are giving repeatable data and for quantifying the system noise. The method involves flying a repeat line regularly and analyzing the repeatability of the estimated apparent resistivity at each frequency. This work is done using a frequency-domain system, but a similar procedure could be used for time-domain systems.

Sattel and Macnae (2001) investigated the measurement of gradient data. They argued that the greater spatial resolution of the gradient measurement could resolve closely spaced features and, depending on the noise levels, might be able to resolve shallow features.

Data-processing improvements

Several groups worked on improving the methods for converting helicopter frequency-domain data to a half-space apparent resistivity. Beard (2000) discussed the relative merits of look-up tables and inversion methods to estimate resistivity. Huang and Fraser (2000) advocated the use of look-up tables to estimate magnetic permeability and then resistivity. Huang and Fraser (2001) then extended their method to estimate resistivity, permeability, and permittivity. In 2002, they suggested that quad-quad algorithms give the best estimate of resistivity in permeable areas (Huang and Fraser, 2002b). The same year, they also suggested using high-frequency data to estimate dielectric permittivity and then using that permittivity to estimate the resistivity at other frequencies (Huang and Fraser, 2002a). Completing a sweep of five papers, Huang and Fraser (2003) suggested solving for the permeability and resistivity of a layered earth using singular value decomposition (SVD) inversion techniques. The next year, Hodges (2004) advocated the use of inversion methods to estimate conductivity, permeability, and permittivity. Methods for converting time-domain data to conductance and conductivity were described by Smith (2001b) and Smith et al. (2005).

A detailed study of how electrical permittivity can influence the frequency-domain helicopter EM response, particularly at high frequencies, was presented by Yin and Hodges (2005b). They showed that the free-space permittivity of air (and rock) has little impact on the frequency-domain EM response, but that the influence on the response can be substantial when the earth is dielectrically polarizable. Another theoretical study by Yin (2001) showed that electrical anisotropy also can have a significant impact on the EM response.

A good intuition for the physics of EM induction can be obtained from visualizing currents flowing in the ground. Yin and Hodges (2005a) presented a talk that included animations of the flow patterns of currents in several isotropic and anisotropic earths, demonstrating that the “smoke ring” description (Nabighian, 1979) describes frequency EM field propagation as well. An alternate method for creating maps of frequency-domain data was proposed by Sattel and Witherly (2008), who suggested converting the frequency-domain data to a decay constant. In the area that they examined, it is necessary to take magnetic permeability effects into account. Along similar lines, Hodges and Yin (2004) proposed that frequency-domain data could be converted to time-domain data via an earth model. This would allow many of the tools used in time-domain interpretation to be used on frequency-domain data.

Methods of approximate conversion (imaging) of AEM data to conductivity as a function of depth, assuming a 1D layered model, are now standard, and a wide variety of new techniques were introduced in the decade 2000 through 2010 (Sengpiel and Siemon, 2000; Siemon, 2001; Zhdanov et al., 2001; Zhdanov et al., 2002; Sattel, 2005; Combrinck, 2008; Huang and Rudd, 2008). Improvements to methods developed in previous decades also were proposed (Macnae, 2004). Davis et al. (2006) found that filtering the data to remove bird motion improves the quality of conductivity estimates. A method for estimating the depth to an interface visible on an image section was proposed and assessed by Macnae et al. (2003). Sattel (2004) studied the strengths and weaknesses of these methods for some AEM systems for the case of a 3D body. One of the weaknesses of these layered tools is that they yield artifacts when the geology is not layered. To reduce such artifacts, Wolfgram et al. (2003) proposed an extension of the 1D imaging tools. They introduced the idea of a 2D imaging algorithm, and the results they presented are promising.

Tools for 1D (layered-earth) inversion of AEM data developed significantly during the decade. Farquharson et al. (2003) described a method for determining conductivity and magnetic permeability from frequency-domain data. An approach that uses a simulated annealing (SA) algorithm was found by Yin and Hodges (2007) to be less dependent on the starting model. However, it also requires more computer time and experimentation with the SA parameters.

For time-domain data, Vallée and Smith (2009a) proposed an inversion method that smooths the vertical structure. Siemon et al. (2009) extended to frequency-domain data a laterally constrained inversion technique that was developed originally for time-domain data (Auken et al., 2008). That concept of lateral constraints was generalized to other flight lines by Viezzoli et al. (2008) in a technique termed spatially constrained inversion (SCI). Sengpiel and Siemon (2000) compared a 1D imaging tool and a parametric layered-earth inversion, and they discussed the circumstances under which either tool might be most appropriate and when a combination of both tools could be useful. Their standard approach was to use the imaging results as a guide to the first guess (or initial model) for a layered inversion.

A method for combining profile data from alternate flight directions was proposed by Smith and Chouteau (2006) to increase the S/N and reduce the “herringbone” artifacts that are a consequence of the asymmetry of fixed-wing AEM systems. Sykes and Das (2000) used a radon transform to remove herringbone artifacts from gridded data.

Leveling of frequency-domain helicopter EM data is always problematic. Alternate methods for leveling this type of data were suggested by Beiki et al. (2010) and Siemon (2009). The latter paper includes a good review of the standard methods for leveling data. A comprehensive description of the tools used for the general processing of frequency-domain HEM data was provided by Valleau (2000). Finally, Auken et al. (2009) described the general procedures used to process SkyTEM data.

Data interpretation and classification

A topic of interest to geophysicists is the volume of earth that is sensitive to an AEM system; that quantity is sometimes called the footprint. Beamish (2003) showed that the size of the footprint depends most strongly on the orientation and the height of the transmitter. A horizontal dipole has a footprint comparable to the height, whereas a vertical dipole has a footprint more than 1.5 times the height. Subsequent work by Reid and Vrbancich (2004) showed that the footprint depends also on the receiver orientation, and they looked at the case of fixed-wing towed-bird systems. Their work assumed that all current flow is at the inductive limit. Reid et al. (2006) removed this assumption in their analysis.

Several tools were developed to assist workers in interpreting airborne EM data. One procedure, described by Sattel and Reid (2006), estimates an appropriate layered earth and then inverts for a number of embedded electric and magnetic dipoles. Interesting results were obtained on data collected at the Bull Creek prospect in New South Wales, Australia, and the Harmony deposit in Western Australia. An alternate tool for rapidly estimating the depth, dip, conductance, and dimensions of a plate from AEM data was proposed by Claprood et al. (2008); it is an extension of the method proposed by Malo-Lalande et al. (2005) for ground EM data. Smith and Salem (2007) developed a tool for both interpreting the source of AEM anomalies and displaying the results in a pseudosection format. Chung and Keating (2002) used a statistical analysis of AEM and magnetic data to predict the statistical likelihood of a mineral deposit occurring. Another approach is to look at all the physical properties derived from the geophysical data and use these properties to classify the rocks in the subsurface using the concept of “self-organizing maps.” Rajagopalan et al. (2008) showed how that approach helped to identify new kimberlite targets in the Slave Craton of Canada. The importance of integrating the results from many geophysical methods (including airborne EM) and displaying the results as 3D images was emphasized by Witherly (2008). He also gave several illustrative examples.

2D and 3D modeling and inversion improvements

A significant body of work exists on EM modeling and inversion, but in this section, we restrict our discussion of the improvements to those that relate specifically to airborne EM. One group concentrating on AEM inversion methods was the group at the CSIRO in Australia (Raiche et al., 2000). Table 1 lists all the programs developed at the CSIRO. One program developed there specifically for airborne EM modeling is ArjunAir, which assumes a 2D geology and a 3D source. Annetts et al. (2000) used this program to show that the fixed-wing response of a vertical contact can mimic the response of a buried conductive body, especially when flying from a resistive quarter-space to a conductive quarter-space. They suggested that using multiple components and multiple flight directions can help one to determine when there really is a buried conductor. Raiche (2001) used the CSIRO program MarcoAir to show that for poorly conductive kimberlites, frequency-domain systems give stronger anomalies. The CSIRO program ArjunAir can invert AEM data to find a 2D structure, and this is practical for both time-domain and frequency-domain data. A published example presents the response measured over the Voisey's Bay ore body in Labrador, Newfoundland, Canada (Wilson et al., 2006), and the results are impressive. The same data were also inverted using a spectral Lanczos decomposition method by Tartaras et al. (2001) and Chernyavskiy and Zhdanov (2002), all members of the Consortium for Electromagnetic Modeling and Inversion (CEMI) at the University of Utah. Other airborne EM modeling and inversion work done at the University of Utah includes rigorous 3D inversions of frequency-domain AEM data (Cox and Zhdanov, 2006) and inversions in which the inverted data are restricted to a window that lies within the footprint of the AEM system (Cox and Zhdanov, 2007; Cox et al., 2010). Comparisons of layered-earth inversion and 3D conductivity imaging using the moving-footprint technique are shown in Figure 4. Even on a 1D section, the 3D inversion provides a better image of the conductivity structure. The group at the University of British Columbia (UBC) also made great strides in modeling and inversion and achieved practical inversion of airborne data (Oldenburg et al., 2005; Holtham and Oldenburg, 2008; Oldenburg et al., 2008; Holtham and Oldenburg, 2010).

In conductive environments, current-channeling effects are very important and have been modeled by Reid and Macnae (2000, 2002). In such cases, the model assumes that currents are at the low-frequency limit or resistive limit. Another rapid-modeling technique for AEM data is to use surface currents to model the inductive limit (King and Macnae, 2001). The concept of time-domain moments introduced by Smith and Lee (2002a) is a generalization of the inductive limit and the resistive limit (zero-order and first-order moments). The moments provide a means of rapidly calculating the response of layered grounds (Smith and Lee, 2002b; Lee et al., 2003) and spheres. The sphere model also can model platelike bodies by constraining the currents so that they flow in a specific direction (Smith and Lee, 2001). The sphere model was used in modeling the response of more complicated structures (Hyde, 2002) and potentially could be used for 3D inversion of AEM data (Schaa and Fullagar, 2009). The EMQ program is a commercially available package for modeling AEM moment data using a model of a sphere (Smith et al., 2003). Other commercially available packages for airborne EM modeling AEM data are Maxwell (www.electromag.com.au), EMIGMA (www.petroseikon.com), two of the UBC layered-earth inversion codes (EM1DFM and EM1DTM), and the Multiloop III program (Walker and Lamontagne, 2006, 2008).

Table 1. List of P223–EM modeling software available from the AMIRA Web site.

Program	Model description	Inversion	Topography
Airbeo	Layered earth	Yes	Flat earth
Beowulf	Layered earth	Yes	Flat earth
LeroiAir	Thin plates in layered host	Yes	Flat earth
Leroi	Thin plates in layered host	Yes	Flat earth
ArjunAir	2D mesh 3D source	Yes	Full domain
Arjuna	2D mesh 3D source	No	Full domain
SamAir	Compact 3D in uniform host	Yes	Limited
Samaya	Compact 3D in uniform host	Virtual	Limited
LokiAir	3D full domain	Yes	Full domain
Loki	3D full domain	Virtual	Full domain
MarcoAir	Prisms in layered host	No	Flat earth
Marco	Prisms in layered host	No	Flat earth

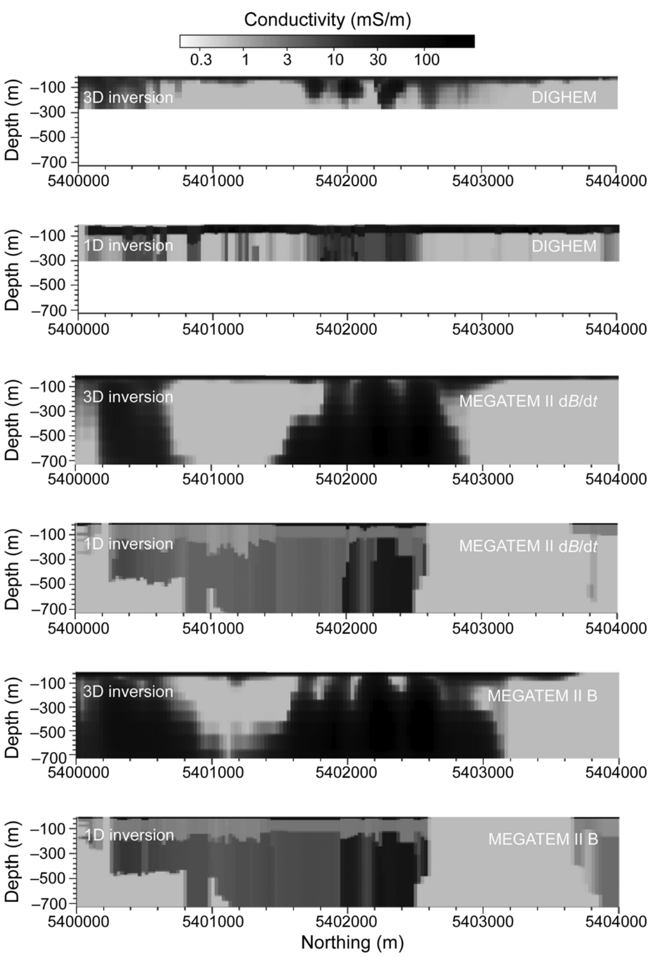

Figure 4. Vertical cross sections through 3D conductivity models along Reid-Mahaffy line L50, obtained from 3D inversion and 1D inversion for DIGHEM, MEGATEM II d*B*/d*t*, and MEGATEM II data. Courtesy of TechnoImaging.

Other developments

The decade 2000 through 2010 included interest in better understanding the effects of magnetic permeability on the airborne EM response. In one study, Sattel (2000) showed that incorporating large magnetic permeability into the numerical model does not have a significant effect on the calculated transient electromagnetic response.

Work also continued on understanding how IP effects manifest themselves in time-domain electromagnetic (TEM) data. Beran and Oldenburg (2008) solved an inverse problem but were unable to determine which layer is polarizable. In a ground study, Flores and Peralta-Ortega (2009) showed that porphyry deposits can be outlined with IP parameters derived from TEM data. Thus, it is possible that this could be achieved also with airborne data in some cases. Examples occur in the literature when airborne IP effects were observed in AEM data. In one paper, airborne IP effects are shown to outline a tailings dump (Smith et al., 2008). In another paper, Walker (2008) gave three examples of IP effects in helicopter TEM data over a tailings dump, a kimberlite, and a more extensive geologic feature. Finally, analytic solutions for the time-domain AEM response over a conductive half-space were derived by Smith and Lee (2001).

Case histories

Airborne EM systems continued to be used for their traditional role — the search for conductive massive sulfide deposits. The discovery of the Perseverance deposit (Québec, Canada) by an airborne time-domain EM system was described by Smith et al. (2003), and other examples were given in Smith et al. (2009). In an example from the South Ashanti Greenstone belt in Ghana (Asiamah, 2004), airborne EM and magnetic data did a "remarkable" job in resolving the geology in an area where there is a paucity of rock exposure. The geophysical data were judged to have contributed significantly to exploration efforts (Asiamah, 2004). In areas with conductive cover, Peters and Buck (2000) showed that identification of nickel deposits is not always straightforward with airborne EM data. Similarly poor results are obtained for the polymetallic Trilogy deposit in Western Australia (Sampson and Bourne, 2001). One way of addressing this problem of identifying nickel deposits that have conductive cover is to improve our understanding of the nature and response of that conductive cover. With this objective, Bishop et al. (2001), Macnae et al. (2001), Munday et al. (2001), Meyers et al. (2001), and Worrall et al. (2001) characterized the regolith in two areas in Western Australia. The Harmony deposit (Western Australia) and the Kabanga deposit (Tanzania) both show strong AEM anomalies (Wolfgram and Golden, 2001). Furthermore, model studies published by these authors showed that the Harmony deposit could be identified if it were buried as deep as 250 m below the surface. In a more resistive area of western Tasmania, AEM was not successful. In that case, the lack of success was attributed to the presence of nonconductive sulfides and proximal conductive shales (Basford and Hughes, 2000).

In the search for uranium, airborne EM surveys traditionally have been a valuable tool. In the Northern Territory of Australia, airborne data were used to identify the conductive unconformity surface with which uranium is associated (Beckitt, 2003). In Canada, AEM historically was used to search for conductive graphite with which uranium is associated (Smith and Koch, 2006), but more recently it also was used to look for alteration of the sedimentary section (Smith et al., 2010). McConachy et al. (2006) argued that airborne time-domain EM surveys can be effective also when uranium occurs in roll-front deposits.

Helicopter TEM was used successfully to explore for manganese deposits under thin cover in Western Australia (Hashemi and Meyers, 2004) and at Groote Eylandt in the Northern Territory of Australia (Irvine and Berents, 2000). However, in an area of very conductive cover, helicopter TEM was not as good at resolving deep structure as was the subaudio magnetic (SAM) method (Stolz, 2005). A large helicopter TEM survey in British Columbia, Canada, was used to map the geology associated with Cu/Au porphyries and to map the overburden thickness (Espinosa-Corriols and Kowalczyk, 2008).

In exploration for kimberlites, aeromagnetics is often the primary data set. Cunion (2009) argued that in the Kalahari of Botswana, in the secondary follow-up phase, airborne TEM was just as effective and more efficient than ground EM was. However, in the Slave Province of the North Territories of Canada, helicopter EM is often the primary tool because the magnetic maps are so active that it is often difficult to identify the magnetic signature of kimberlite. Jansen and Witherly (2004) presented a case history of the Tli Kwi Cho kimberlites, which were discovered with the DIGHEM system, and those authors also have published aeromagnetic and ground EM data from the same area. In addition, time-domain helicopter systems were tested at Tli Kwi Cho. One of the kimberlites manifested a normal positive response, but another displayed a negative response. Such a mixed response is typical of northern areas (Smith and Klein, 1996). On the other hand, Munday et al. (2004) suggested that in areas of highly conductive regolith, AEM cannot identify kimberlites — it can identify only changes in the conductivity/thickness of the regolith, which may or may not be related to any kimberlitic rock.

A large project undertaken during the first decade of the millennium was a collaboration involving two universities in Canada (Université du Québec en Abitibi-Témiscamingue and École Polytechnique), a mining company (Noranda, now part of Xstrata), and a geophysical contracting company (Fugro Airborne Surveys). One outcome of the project was several case histories over the Iso deposit (Cheng et al., 2006a, b), the Gallen deposit (Cheng et al., 2007) and the Aldermac deposit (Cheng et al., 2009), all in Québec, Canada. Additional work described above that was part of the same project includes that by Claprood et al. (2008) and other work involving wavelets (Bouchedda et al., 2010). These test sites, and locations such as the Reid-Mahaffy test site in Ontario, Canada (Witherly et al., 2004a), have been important locations for comparing airborne EM systems. In the case in which a test site is not readily available, Yin and Hodges (2009) suggested using a wire loop laid out on the ground as a test conductor.

Legault (2009a, b) presented two case histories of ZTEM, a heliborne AFMAG system. In one case, an anomalous response was associated with a graphitic conductor at least 500 m deep; in the second case the system was able to map large conductive structures associated with a copper-nickel deposit. Reed et al.

(2006) presented a case history that uses AEM, magnetic, and gravity data for platinum-group element exploration. They concluded that geophysics furthered the understanding of the geology of the environment but was not able to detect the deposit directly. Finally, a case history that presents the use of multiple methods, including AEM, describes the Cinco de Mayo carbonate replacement silver deposit in Chihuahua, Mexico (Robertson and Megaw, 2009).

Case histories for mine-environment problems

Ground geophysics commonly is used for characterizing waste dumps from mine sites (e.g., Poisson et al., 2009; Ramalho et al., 2009). Rutley and Fallon (2000) described the use of AEM to map the location at which contaminated groundwater was seeping from a tailings dump. One case described by these authors was an active mine, and they argued that the AEM data can be used to site boreholes to monitor the groundwater. At the Aldermac abandoned mine site, the IP effects measured with an airborne survey did an excellent job of mapping the tailings dump (Smith et al., 2008). In a coal mining area in Pennsylvania, frequency-domain helicopter EM was used to map zones of greater acid-mine drainage (Love et al., 2005).

GROUND EM METHODS

McMonnies and Gerrie (2007) and Williams et al. (2007) identified the major advances in ground geophysics during the millennium's first decade as SQUID technology, which is covered in this section, and array systems, which are covered in the ground IP section. Le Roux and Macnae (2007) described SQUID developments conducted by the Institut für Physikalische Hochtechnologie in Jena, Germany. That organization developed a low-temperature SQUID (LTS) ground transient electromagnetic system that is used currently in mining exploration. A factor of 5 to 10 advantage in S/N over other geophysical B-field sensors is achieved, and LTS can detect conductive targets with time constants of seconds. Discovery International Geophysics uses a SQUID successfully in TEM deep exploration (Woods, 2010). A high-temperature SQUID (HTS) was developed at the CSIRO (Osmond et al., 2002) and is being used by Crone Geophysics (Leslie et al., 2008). Malo-Lalande (2007) described a fixed-loop configuration that generates a strong horizontal primary field that is ideal for investigating steeply dipping and deeply buried base-metal targets.

EM MODELING AND INVERSION

During the decade 2000 through 2010, marine controlled-source electromagnetics (CSEM) was the focus of various groups working in EM modeling and inversion. However, efforts continued for developments in EM modeling and inversion that would be applicable to mining exploration. Major developments are summarized by Oldenburg and Pratt (2007).

3D EM methods

The Third International Symposium on Three-Dimensional Electromagnetics (3DEM-3) was held in Adelaide, Australia, in 2003. A special issue of *Preview* (Macnae, 2006) contained selected papers from this meeting. A CD containing fully refereed selected papers has been prepared and is available by writing to the Australian Society of Exploration Geophysicists (ASEG); for more details, see the Web site http://www.publish.csiro.au/?act=view_file&file_id=EG06222.pdf. The Fourth International Symposium on Three-Dimensional Electromagnetics (3DEM-4) was held in 2007 in Freiberg, Germany. The proceedings for that symposium are available online at http://www.geophysik.tu-freiberg.de/3dem4/3dem-4-revisited.htm.

Modeling

Sykes (2000) evaluated the accuracy of Hankel transforms for estimating the response of a vertical dipole source located on the surface of a half-space. For surface electromagnetic fields, analytic Bessel function expressions produce faster and more accurate results than digital filters produce. Badea et al. (2001) developed a program using a 3D finite-element approach for CSEM. The solution is based on a weak formulation of the governing Maxwell equations using Coulomb-gauged EM potentials. Johnson et al. (2001) presented an approach using a finite-difference time-domain method for high-resolution full-wave analysis of cross-borehole EM surveys of buried nickel sulfide deposits. The method is validated against analytic methods for simple cases, but it is a valuable tool for analysis of complicated geologic structures such as faulted or layered regions. Qian et al. (2002) revisited the plate conductor model to improve convergence and numerical accuracy in close proximity to the plate. Farquharson et al. (2006) compared the results obtained by an electrical-field integral equation and physical scale modeling of a cube in free space and in a conductive environment. Börner et al. (2008) developed an efficient numerical method for simulating transient electromagnetic fields that result from controlled sources in three dimensions. Börner (2009) reviewed modeling electromagnetic methods and after his discussion of advances in finite-difference and finite-element methods, he presented recent developments in 3D modeling techniques that may have a tremendous impact on the development of inversion strategies.

Inversion

Kaikkonen and Sharma (2001) analyzed the performances of linearized (local) and global nonlinear joint 2D inversions of very-low-frequency (VLF) and VLF-resistivity EM measurements. Zhdanov et al. (2002) developed a technique of fast TDEM inversion based on a thin-sheet conductance approximation called S-inversion. Farquharson et al. (2003) developed an algorithm that simultaneously inverts susceptibility-affected data for 1D conductivity and susceptibility models. Haber et al. (2004) developed a general formulation for inverting frequency-domain or time-domain electromagnetic data using an all-at-once approach, solving the forward problem and the inverse problem simultaneously in one iterative process. Schultz and Ruppel (2005) developed robust and convergent regularized, least-squares inversion algorithms for application in conductive terrains. Zhdanov and Tolstaya (2006) presented a new method for resolution analysis that is based on evaluating the spatial distribution of the upper bounds of the model variations, and they introduced a new characteristic of geophysical inversion — resolution density — as an inverse of those upper bounds. Pujol (2007) presented in a unified way the Levenberg-Marquardt damped least-squares method, which often is used in geophysical inversion. Song and Kim (2008) developed an inversion algorithm for loop-loop EM data, based on the localized nonlinear or extended Born approximation to the solution of the forward model. Oldenborger and Oldenburg (2008) reported preliminary results on 3D inversion with high contrasts in conductivity. Oldenburg et al. (2008) presented a practical formulation for forward modeling and inverting time-domain data that arise from multiple transmitters. Farquharson (2008) modified the typical minimum-structure inversion algorithm to generate blocky, piecewise-constant earth models, using l1-type measurements of the model structure.

P233 project

A major contribution in EM modeling and inversion during the decade was the release into the public domain of AMIRA P233 software (http://www.amirainternational.com/WEB/site.asp?section=news&page=projectpages/p223). The P233 consortium, led by Art Raiche, began in 1980 by developing EM software that used various approaches and was for different configurations. Table 1 lists the programs available on the Web site, and Raiche (2008) described them in more detail. The models for both forward modeling and inversion modeling include a general 3D finite-element full-domain model (Loki class), a 3D compact finite-element model embedded in a uniform host (Samaya class), 2.5D full-domain finite elements (Arjuna class), multiple 3D plates embedded in a multilayered host (Leroi class), 3D prisms in a layered host (Marco class), and a 1D layered earth (Airbeo and Beowulf). The programs can be used for any frequency or time-domain airborne, ground, or downhole EM system. All are based on complex resistivity, with options for including the Cole-Cole parameters for modeling induced-polarization effects.

INDUCED-POLARIZATION METHODS

Kingman et al. (2007) described a recent development in distributed acquisition in electrical geophysics. Distributed acquisition uses a large number of small-channel-capacity receivers deployed close to the sensor outputs. Each of those sensors and the associated receivers acquire data simultaneously. Although the ability to gather data sets with far greater source-sensor multiplicity is the most important advantage of a distributed-acquisition design, this approach also has several other important advantages, including greater depth of investigation, better productivity by reducing the cost per cubic kilometer evaluated, improved noise-reduction options, and seamless collection of multiple data types such as induced polarization, resistivity, magnetotellurics, and grounded-line EM coupling. In some cases these types of data can be acquired simultaneously. In other cases, the IP data are collected during the day and the MT data at night. For interpretation of IP data, 2D inversion has become a standard practice in mineral exploration (Nimeck and Koch, 2008). To explain IP effects in heterogeneous material, Zhdanov (2008) proposed a new theory, called the effective-medium theory of induced polarization (GEMTIP). The GEMTIP model allows one to find the effective conductivity of a medium with inclusions that have arbitrary shape and electrical properties. Application to a simple medium model shows that the GEMTIP model is closely related to the Cole-Cole model (Cole and Cole, 1941) and Wait's model (Wait, 1982).

SEISMIC METHODS FOR MINERALS

In the new millennium, the application of seismic methods to mineral exploration continued to develop, following publication of a book written by Eaton et al. (2003). In particular, efforts were made to select processing techniques properly, in accordance with the exploration target.

Li and Eaton (2005) presented seismic-reflection profiles conducted over the Tuwu porphyry-copper deposit in Xinjiang, China. The results show that seismic methods may be useful as an aid for mapping the flank of shallow, moderately dipping porphyry copper orebodies and associated strata. Hajnal et al. (2007) presented 2D and 3D seismic surveys acquired in the Athabasca Basin, Canada. Those surveys outline the 3D subsurface settings of known uranium deposits. Urosevic et al. (2007) reported on the processing and analysis of numerous seismic-reflection data acquired mainly across the Yilgarn craton, Australia. Novel seismic data-processing and imaging techniques were introduced successfully and improved image quality, and in combination with borehole log information they have enabled the expansion of the mining activities and the generation of several new exploration programs.

Malehmir and Bellefleur (2009) imaged massive sulfide deposits by reprocessing three-dimensional seismic-reflection data. They selected a processing approach that was based on a prestack dip moveout (DMO) and a poststack migration sequence, carefully focusing on the processing steps that are critical for data acquired in crystalline environments. They showed how the DMO approach enabled them to image the diagnostic diffraction signature of the deep massive-sulfide zone at Halfmile, New Brunswick, Canada, and helped improve understanding of the associated geologic structure. This is illustrated in Figure 5, in which the original processing and the new approach are displayed.

GAMMA-RAY SPECTROMETRY

Following an explosion of publications in the previous decade on noise-adjusted singular-value decomposition (NASVD) and maximum-noise-fraction (MNF) noise-reduction methods, there were few developments in gamma-ray spectrometry during the first decade of the millennium. Ramos et al. (2007) presented a methodology for reducing gamma-ray survey noise, based on manifold learning followed by nonlinear regression.

BOREHOLE GEOPHYSICS IN EXPLORATION AND MINING

The twenty-first century's first decade had many advances in borehole geophysics. Charbucinski et al. (2000) described a spectrometric gamma-gamma probe that was developed for orebody delineation of zinc-lead ore. Spitzer and Chouteau (2003) interpreted the results of a resistivity and IP borehole survey at Casa Berardi gold mine in northwestern Québec. Crosshole pole-pole and single-hole pole-dipole configurations were used to delineate the geometry of the body associated with the Casa Berardi fault system. Because the spatial data sampling was insufficient for 3D inversion, the interpretation was done using 3D DC and IP forward modeling. Bolin and Moon (2003) examined the potential of imaging spectroscopy to estimate sulfide percentage in drilling core material from the Stillwater Complex, Montana. Bellefleur et al. (2004) described the application of downhole seismic imaging of the Halfmile Lake deposit, New Brunswick, Canada. The massive sulfide lenses, which have significantly higher elastic impedances than do the host rocks, produce strong scattering. Elders and Asten (2004) analyzed noise of borehole magnetometric resistivity (MMR) and EM surveys. Mudge (2004) surveyed radial resistivity/IP using a downhole current electrode. Godber and Bishop (2007) detected low-resistivity targets using advances in downhole magnetometric resistivity (DHMMR). Lamontagne (2007) reviewed advances in borehole EM, which has become a standard technique in mining exploration. Qian et al. (2007) presented results of cross-borehole electric tomography. Seigel et al. (2007) and Seigel et al. (2009) developed a borehole gravity meter for borehole applications. Butler et al. (2007) reviewed the advances in seismoelectric data acquisition on the surface and in boreholes, most of which are attributed to improvements in instrumentation. Sun et al. (2007) estimated velocity dispersion using vibrator VSP data.

INTEGRATING GEOLOGY AND GEOPHYSICS

Another cross-fertilization between petroleum geophysics and mining geophysics during the decade occurred in the integration of geology and geophysics. The concept of the common-earth model, applied to orebody delineation, was introduced in the mining industry by McGaughey and Vallée (1999): Advanced visualization techniques allow simultaneous viewing of the three-dimensional physical-property model, the geologic information, and the geophysical results. Geophysical results may be simulated from a forward model, or the output from a numerical inversion in the form of an updated physical-property distribution can be compared with a geologic model.

The approach that Li and Oldenburg (2000) followed is to develop a new model objective function that allows incorporation of strike direction and dip angle into geophysical inversions. Alternatively, Fullagar et al. (2000) developed a modeling and inversion methodology to expedite joint geologic and geophysical interpretation of gravity data. The key features of their approach are the enforcement of drilling constraints (pierce points) and the imposition of density bounds on geologic formations and basement. As Roy and Clowes (2000) showed, different methods can be combined to construct a geologic model. They modeled the Guichon Creek batholith (GCB), British Columbia, Canada, from 2D seismic combined by 3D gravity and magnetic inversion. Integrated interpretation of geophysical results and geologic observations indicates that the GCB is a funnel-shaped feature in which mineralization is located above the stem of the batholith. More specifically, Bosch et al. (2006) jointly inverted gravity and magnetic data following a Monte Carlo method that provides an estimation for a 3D model of the structure and the physical properties of the medium. This method combines the gravity data and magnetic data with prior information about the mass-density and magnetic-susceptibility statistics, and statistical constraints on the model-interface positions. As McGaughey (2007) showed, successful integration of geologic and geophysical data for exploration targeting requires geologic and geophysical modeling technology and the knowledge necessary to put it into practice. Bellefleur et al. (2007) illustrated how seismic reflections can improve the understanding of subsurface geology of the Noranda central camp, Québec, Canada. Seismic data provide additional control in areas lacking boreholes and can extend geologic information at depth, as shown in Figure 6.

Mining discoveries also can occur from combining geology and geophysics. Martin et al. (2007) described a mining discovery that arose from the construction of a 3D common-earth model of the Noranda camp. This model involves importing multidisciplinary data sets and the propagation of the data throughout the model. A series of well-defined visual and quantitative queries based on conceptual ore-deposit models was developed to highlight prospective target areas. The discovery of the West Ansil deposit in Québec, Canada is credited to the use of this model. On another continent, Malehmir et al. (2009) presented a 3D geologic model of the Kriskineberg mining area, Sweden; that model was based on constrained 3D gravity inversion and seismic profiles. That 3D geologic model supports many previous interpretations but also reveals new features of the regional geology that are important for future targeting of base-metal and gold deposits.

Lelièvre et al. (2009) expanded the types of geologic information that can be incorporated into minimum-structure-type deterministic inversions involving minimization of an objective function. They also presented an iterative cooperative inversion strategy for combining multiple types of geophysical data and thereby recovering geologically realistic models.

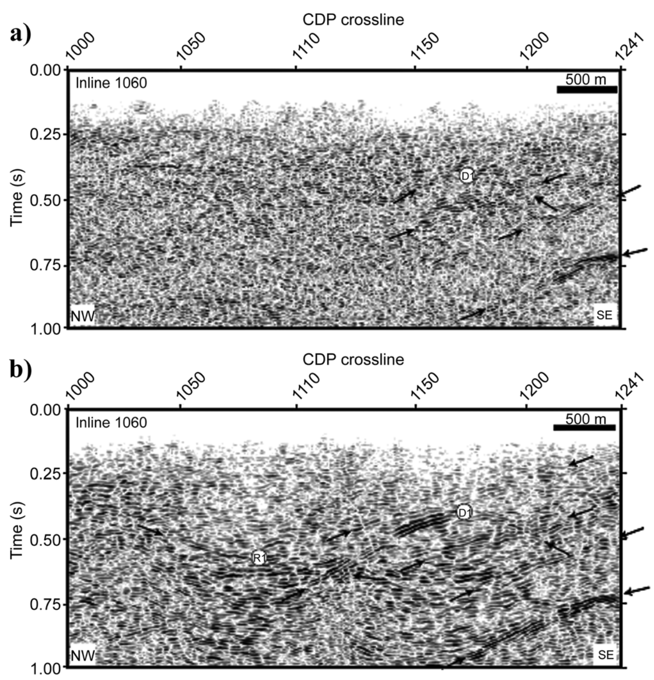

Figure 5. An unmigrated seismic section from inline 1060 of Halfmile Lake 3D seismic data, with (a) only NMO corrections applied and (b) NMO and DMO corrections applied. This figure demonstrates improvements in the continuity of several steeply dipping reflections in the southeastern side of the section and allowing imaging of reflections R1 and D1 originating for the deep volcanogenic massive sulfide deposit. From Malehmir and Bellefleur (2009). Used by permission.

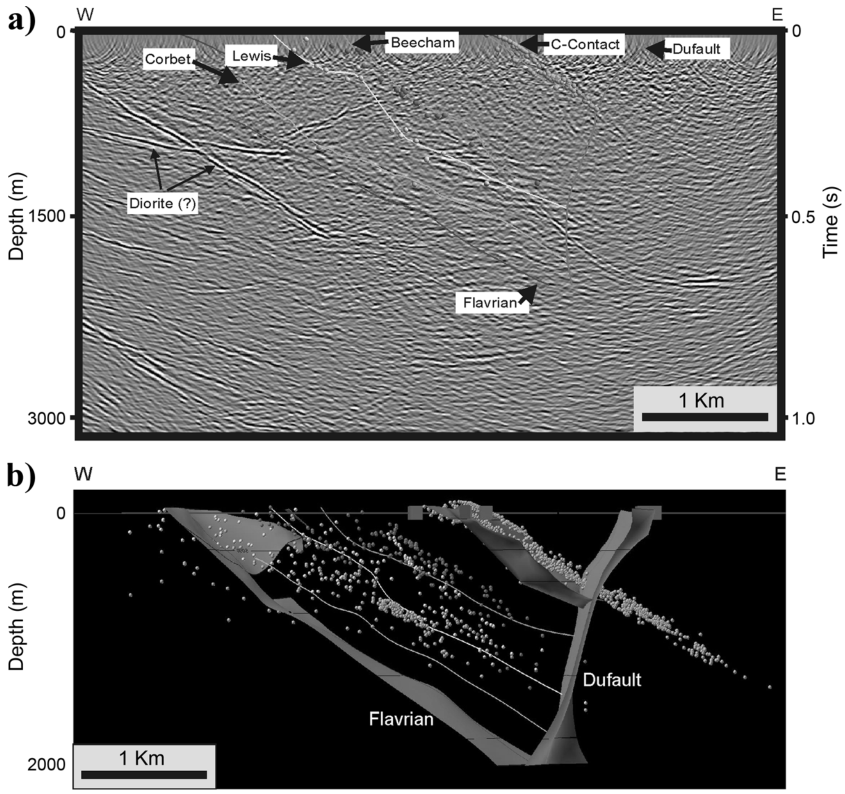

Figure 6. (a) Migrated data for the Amulet-001 seismic profile. Intersections with major lithologic contacts from the 3D geologic model also are shown. (b) The control points used to define the lithologic contacts (3D surfaces) are shown in a perspective view in (b). The depth axis in (a) assumes a constant velocity of 6 km/s. There is no vertical exaggeration in (a) and scale on the perspective view in (b) is approximate. From Bellefleur et al. (2007). Used by permission.

CONCLUSIONS

During the period from 2000 through 2010, a decade in which mineral industry exploration activity was highly variable, numerous scientific and technological developments occurred. In our opinion, six developments stand out as having changed the face of exploration geophysics:

1) the commercialization of helicopter time-domain EM,
2) the commercialization of airborne gravity gradient,
3) the development of new tools for EM modeling and inversion,
4) the development of many tools for magnetic interpretation including 3D inversion coming into routine use.
5) numerous developments in mining borehole geophysics, from downhole seismic to gravity, and
6) the growing application of geophysical and geologic integration in constrained common-earth-type models.

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