Surveys in Geophysics (2005) 26:653–669
DOI 10.1007/s10712-005-1760-0 

# MINING, ENVIRONMENTAL, PETROLEUM, AND ENGINEERING INDUSTRY APPLICATIONS OF ELECTROMAGNETIC TECHNIQUES IN GEOPHYSICS

S.N. SHEARD[1], T.J. RITCHIE[2], KAREN R. CHRISTOPHERSON[3] and E. BRAND[4]

[1]*Inco Ltd, 145 King St West, Suite 1500, Toronto, Ontario, M5H 4B7, Canada*
*E-mail: nsheard@inco.com*
[2]*Geophysical Resources and Services Pty Ltd, 1/17 Duncan St, West End, Queensland, 4101, Australia E-mail: chinookgeo@aol.com*
[3]*Chinook Geoconsulting, Inc., 26961 Hilltop Road, Evergreen, CO, 80439, USA*
*E-mail: chinookgeo@aol.com*
[4]*The G-tek Group, Unit 3, 10 Hudson Road, Albion, Queensland, 4010, Australia*
*E-mail: ebrand@g-tek.biz*

(Received 3 June 2005; accepted 21 April 2005)

**Abstract.** Electromagnetic (EM) techniques are extremely important as a direct detection geophysical tool utilized in the base metal industry. They were developed in countries such as Canada, whose thin conductive weathering overburden did not hamper the penetration of EM signals and enabled exploration to depths on the order of 300 m. As a result, EM techniques were used widely in North America and Scandinavia for many years before they became common in countries with a thick conductive overburden, such as Australia. The 1980s and 1990s have seen the use of EM methods move from anomaly finding to mapping, as well as the development of better, faster and more accurate computer modelling algorithms. A review of EM papers, for the years 1998 to 2002, showed that most dealt with EM techniques as mapping tools. Airborne, ground and marine EM techniques are still being developed, as are data processing and interpretation software. The advent of robust 2-D and 3-D computer modelling and inversion algorithms has led to the acceptance of EM methods as a mapping tool for many environmental and petroleum industry applications, a trend which is expected to increase.

**Keywords:** data processing, electromagnetics, environment, mapping, mining, petroleum

## 1. Introduction

Electromagnetic (EM) techniques are one of the most widely used exploration methods for sulphide prospecting in the base metal industry. However, today they are also used to help manage environmental issues, and aid petroleum exploration, and they have many engineering applications.

This paper outlines the historical development of the EM method, culminating in a literature study of geophysical papers published over a four-year period to 2002. The equipment used in airborne, ground and marine surveys is discussed, as is the current state of data processing and interpretation. The current applications of the EM method are also covered and comments are made on the possible future of EM techniques.

## 2. Development of the Subject

### 2.1. A brief history

The global development of EM techniques in the base metal industry was initially dependent on the type of surficial geologic environment. The ground EM technique, developed in Scandinavia, the USA and Canada in the first half of the twentieth century, owes its success in these countries to the lack of a conducting overburden. A thick overburden of weathered/oxidised rock is generally electrically conductive and thus impedes the EM signal. In Australia, a thick weathering overburden is common and its masking effect of the sub-weathered geology proved to be a major stumbling block for the EM method's adoption by industry.

The development of airborne EM (AEM) methods in Canada in 1948 heralded a new era of geophysical exploration. The initial results were encouraging, and in 1954 the first deposit discovery attributed to an airborne EM survey, the Heath Steele Zinc–Lead–Copper–Silver deposit in New Brunswick, Canada, was announced (Fountain, 1998). In Australia it was not until the 1970s that EM methods began to be used extensively, over known economic ore deposits, such as the Teutonic Bore in Western Australia (Fritz and Sheehan, 1984), despite the first successful surveys being conducted in 1928 at Leadville by the Imperial Geophysical Experimental Survey (Broughton Edge and Laby, 1931). The main reason for their popularity was the development and utilisation of time domain EM systems (TEM), which had potential to 'see' below the conductive overburden.

The 1980s saw the introduction of microprocessor-based equipment, and the movement from 1-D to simple 2-D interpretation. This led to a greater confidence in the results and ushered in the birth of EM methods as a mapping tool. However, the move from finding anomalies to mapping did not take hold in industry until the late 1990s, due to the large cost of both ground and airborne surveying.

The 1980s was also the decade when the use of borehole EM methods increased. Downhole EM (DHEM) extends the search radius from 10 to perhaps 100 m, and is particularly useful in areas where thick overburden, shallow uneconomic sulphides and peripheral mineralised horizons interfere with the surface EM response causing poor target definition. In particular, a SIROTEM DHEM survey at Hellyer, in Tasmania, illustrated how a non-intercept borehole can be used to indicate the presence of a conductive body and, as a result, to direct drilling (Eadie, 1987).

The 1990s witnessed the increased use of airborne EM technologies both in the base metal and environmental sector. The desire to build and fly a helicopter time domain system that could match and, hopefully, outperform the standard airborne systems at the time instigated a technological race. The 1990s also saw the widespread use of AEM to map geology through cover, often as an alternative to airborne magnetics surveying. Case histories were published; one particular example of EM as a mapping tool was shown by a QUESTEM survey at the Lady Loretta prospect, in the western part of the Mt. Isa Inlier, Queensland, Australia. This survey mapped faults, fold structures, and carbonaceous and pyritic shale horizons that hosted the mineralisation (Anderson et al., 1993) (see Figure 1).

The major advancements in EM processing were made in the late 1990s. Robust processing schemes, such as those described by Larsen et al. (1996) and Zerilli et al. (1997), greatly improved the abilities of magnetotellurics (MT) acquisition in noisy environments. Such processing schemes are now routinely applied.

There are several operating mines or major deposits whose detection can now be directly attributed to finding EM anomalies. Examples include the Ernest Henry copper–gold deposit in northwest Queensland, Australia (Webb and Rowston, 1995), and the Thompson Nickel Deposit in Canada (see Figure 2).

### 2.2. Literature survey

A review of papers published between 1998 and 2002, with references to EM methods has been undertaken. In this study, 112 papers were reviewed and the results tabulated. The subjects covered were sorted into the different categories presented in Table I.

Table I shows that there is an overwhelming number of papers on EM methods as a mapping tool, and that research into computer modelling algorithms continues aggressively.

## 3. Equipment

### 3.1. Airborne systems

Recently the airborne geophysical industry has undergone a significant shakedown with FUGRO Airborne Surveys dominating the market and controlling the majority of frequency and time domain systems currently in use. The two commercial time domain fixed wing systems are called

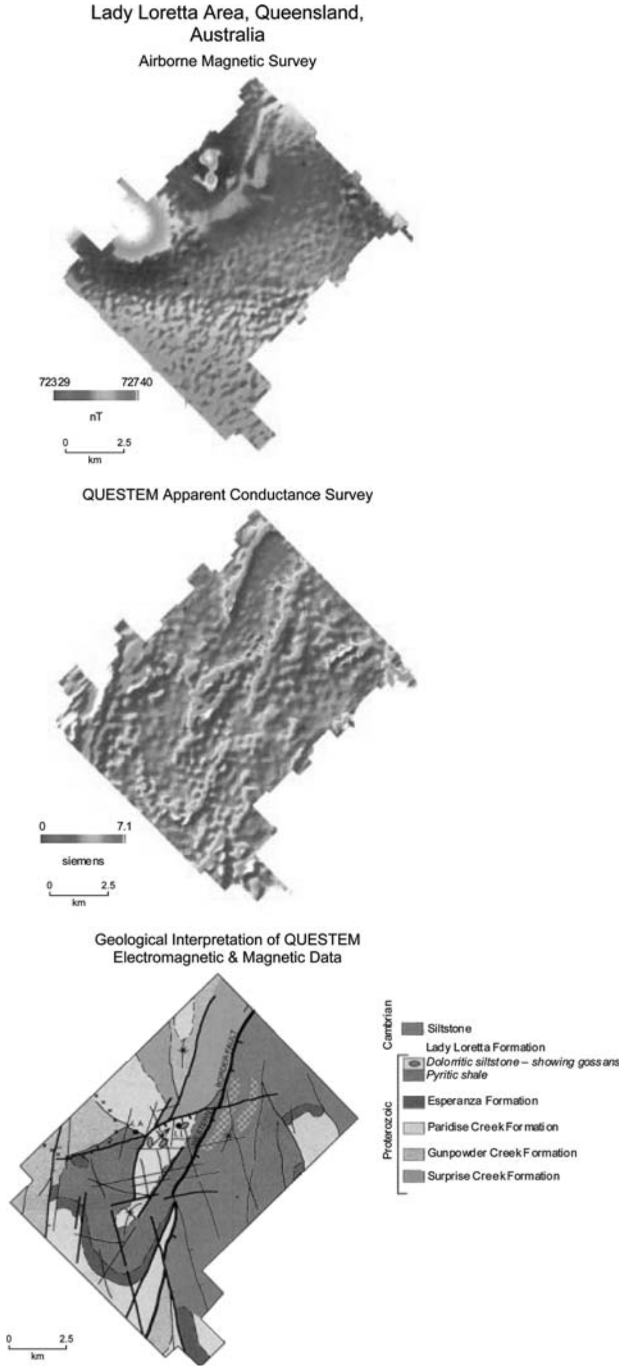


*Figure 1*. Airborne EM mapping in Queensland, Australia (after Anderson et al., 1993).

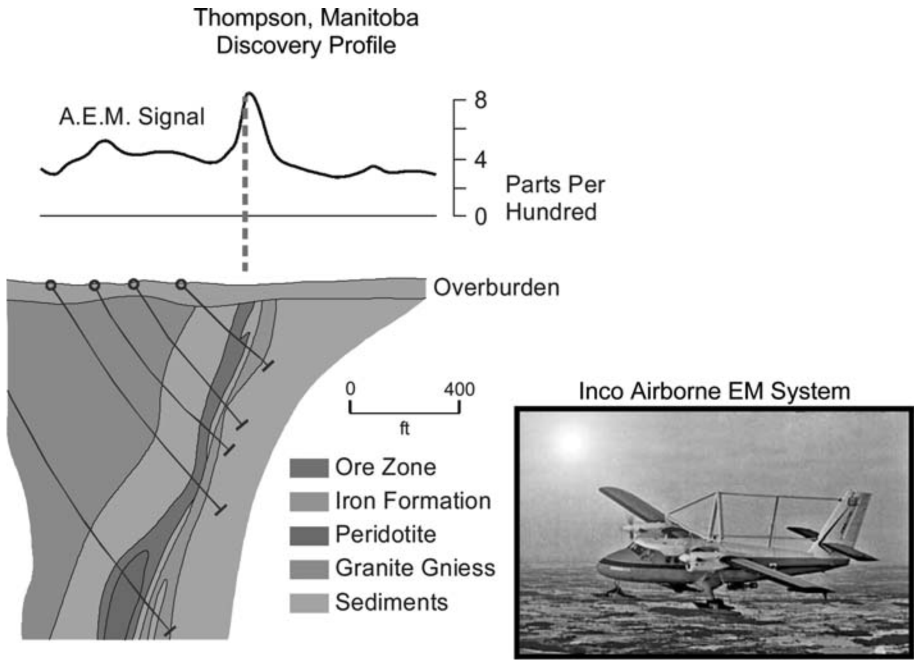


*Figure 2*. Inco's proprietary AEM system, and a profile over the Thompson Deposit in Canada.

TABLE I

Number of papers in different categories published between 1998 and 2002

| Broad EM category | Sub-category | Application | Number of articles |
|---|---|---|---|
| Mapping | Airborne EM | Geological | 7 |
| | | Environmental | 7 |
| | Ground EM | Geological | 5 |
| | | Environmental | 16 |
| | Marine EM | Geological | 1 |
| | | Environmental | 1 |
| | Magnetotellurics | | 4 |
| | Total | | 41 |
| Direct detection or discovery | | | 8 |
| Case histories | | | 11 |
| Equipment | | | 5 |
| Theoretical modelling and research and development | | | 42 |
| Oil, gas and coal | | | 1 |
| Ground penetrating radar | | | 4 |
| Total number of articles | | | 112 |

MEGATEM and TEMPEST, with SPECTREM being the only other system, owned and operated by Anglo American Inc. All three systems employ the same sensor ('bird') trailing the aircraft, and all systems use a 3-component receiver. The asymmetric geometry makes interpretation somewhat difficult. Other problems are caused by the varying height of the transmitter and receiver above the ground, and consequently above the underlying geology. Today's systems attempt to minimise this power loss by increasing the dipole moment of the transmitter, either by increasing the number of turns of the transmitter loop or increasing the transmitter current. All of these increase weight and thus cost.

The improved time-domain AEM system, MEGATEM (see Figure 3), operates at frequencies from 12.5 to 90 Hz. Both the magnetic field ($B$) and its time derivative, ($\mathrm{d}B/\mathrm{d}t$) are observed in three orthogonal directions (two horizontal axes and one vertical axis). The transmitter dipole moment (and, therefore, the transmitter power) claims to be the largest of any operating AEM system, with a transmitter loop area of 406 $\mathrm{m}^2$, with four or five turns of wire, and a dipole moment exceeding $10^6$ A $\mathrm{m}^2$.

The FUGRO website (http://www.fugroairborne.com/Services/airborne/EM/megatem/) claims that; "in 1999, Noranda Inc. undertook a complete evaluation of existing AEM technology in order to determine the most effective AEM system to re-evaluate the Abitibi Mining district in Quebec, Canada. This was achieved by systematically surveying, with each AEM system, a test grid that included three known deposits at different depths. The results indicated MEGATEM to be the most effective system and a MEGATEM survey was flown in late 1999 to re-evaluate the Matagami mining camp. As follow up of this survey, the Perseverance Deposit was discovered in March 2000."

Ironically, FUGRO Airborne Surveys is also the owner of the TEMPEST technology which, on the same website, claims: "the quality detail and accuracy of TEMPEST data reveals geological and structural information that cannot be matched by other airborne techniques." However, in another

Fugro's MEGATEM Airborne EM


*Figure 3.* Fugro's MEGATEM AEM System.

twist, Anglo American Inc. claims (on their website http://www.spectrem.co.za) that its system, SPECTREM, is "arguably the most advanced AEM system in existence."

Regarding helicopter systems, advances have been made largely in time domain EM where, for example, the GPX operated HOISTEM (http://www.gpx.com.au) is now being commercially offered. The GPX website states that: "Hoistem's power into the ground and small footprint compares with the best ground EM systems. It surpasses in penetration and definition all current airborne systems."

The tried and tested frequency domain systems such as Dighem, and now offered by Fugro, are still being employed and offer good service. The systems have been updated, increased power and signal quality using digital technology. The data quality for mapping exercises, such as near-surface structural mapping, is good. Since the systems are prone to drift, when employed for accurate quantitative work – such as interpreting the conductivity of ground water salinity over repeat surveys – they can exhibit problems. Therefore, the systems need to be stabilised if they are to be used in the future for accurate geotechnical work.

In Canada, McPhar Geophysics Pty. Ltd. is developing two new systems: the Hawk, a fixed wing multi-frequency (200 Hz–25 kHz) system, and a multi-waveform digital TDEM helicopter-borne system. Ontario Mineral Exploration Technologies (OMET) is also currently investigating modelling, interpretation methods and field trials of a prototype AFMAG (Audio Frequency electroMAGnetic) system with Geotech.

The Barringer Airborne MT system, DICON, has been under development for several years. Some test surveys have been flown and the first commercial survey should be completed soon. The system measures orthogonal components of both the electric ($E$) and magnetic ($H$) fields. Application for petroleum exploration will be aimed at mapping alteration effects due to hydrocarbon migration rather than for the mapping of structure or stratigraphy associated with oil/gas traps. The system can also be used to explore for other resources.

### 3.2. Ground systems

Ground electromagnetic surveys are undertaken in various ways using a variety of equipment. In base metal exploration EM surveys, where the transmitter loop is either fixed or moved with respect to the receiver, are still commonly used to prospect for good conductors. Generally, equipment capable of measuring multiple channels is employed. Examples include the Zonge Engineering GDP32 (http://www.zonge.com/grgdp322.htm), SMARTEM (http://www.emit.iinet.net.au), UTEM (http://www.sjgeop.bc.ca/sj_utem.html), the PROTEM (http://www.geonics.com/tdem.html), and the CRONE system (http://www.cronegeophysics.com). All of these systems are proven performers and all can operate in a downhole mode.

Apart from the traditional EM surveys, other methods have become more commonplace for mineral prospecting. These include controlled-source audio magnetotellurics (CSAMT) pioneered by Zonge, and continuous profiling MT, first described by Torres-Verdin and Bostick (1992). Both methods have the capability of deep penetration. Lately, MIMDAS (Sheard et al., 2002), the MIM propriety system, is also conducting such surveys, generally in conjunction with induced polarisation (IP) surveys.

### 3.3. Marine systems

Marine EM systems have become commercially viable in recent years. Three companies now offer marine controlled-source surveys, primarily for petroleum exploration. These companies (EMGS, OHM, AGO) acquire EM surveys as a complement to more traditional offshore seismic surveys by mapping resistivity contrasts associated with the presence of hydrocarbons.

AOA Geophysics, based in Houston, Texas, which markets seafloor MT and controlled source EM surveying, now operate their marine services via a subsidiary, AOA Geomarine Operations, AGO (now owned by Schlumberger). Their first marine MT (MMT) survey was initiated in 1995, offshore from southern Italy. Since then, marine MT data have been acquired in the Gulf of Mexico and offshore from West Africa. A major survey was carried out in 2001 on the North Atlantic Faeroes Shelf, between the Shetland Islands, the UK and the Faroes Islands (http://www.agoem.com) (see Figure 4).

*Figure 4*. Deployment of a marine EM sensor (courtesy of AOA Geophysics, Inc.).

## 4. Data Processing and Interpretation

Modern EM data can be subjected to a large number of processing and interpretation procedures that vary from the simple 1-D to complex 3-D. In all forms, forward and inversion modelling techniques are available. Recent years have seen great advances in the field of EM interpretation; there is a plethora of research and development institutions, both public and private, undertaking this work, notably the Universities of Utah and British Columbia, and the Commonwealth Science and Industrial Research Organization (CSIRO) in Australia.

Some of the new TEM systems are developing proprietary signal processing techniques in order to improve the signal-to-noise ratio and to realize more information from the data. Borrowing concepts from other fields such as seismic geophysics and electrical engineering, much improved data are obtained and these lead to better quality interpretations. Numerous robust-processing schemes and tensor decomposition algorithms have been developed and refined, aiding the improvement and understanding of MT data (Larsen et al., 1996; Zerilli et al., 1997).

The advent of laptop computer-based 3-D codes has offered better interpretation in complex areas, especially overthrust hydrocarbon plays and complex mineral areas. Several projects in recent years have benefited from applying 3-D modelling in conjunction with 2-D codes. Previously, interpretations based solely on 2-D interpretations could not adequately model the complex structure. A good example of this is given by Ravaut et al. (2002), where integration of 2-D and 3-D MT modelling with geologic constraints provided an interpretation of steeply-dipping beds in the Bolivian overthrust (see Figure 5).

## 5. Applications

### 5.1. Environmental applications

Electromagnetic surveying is an excellent mapping technique which allows full 3-D mapping. This is done by measuring signals at different frequencies or in a time sequence, thus permitting the conductivity at different depths to be computed. The accuracy and ease of computation depend on the source geology configuration. However, with reasonable assumptions, a conductivity depth image (CDI) can be constructed. If measurements are taken at close enough intervals, a 3-D image can be formed.

The best examples of the use of EM in mapping are generally derived from airborne systems, because of their more extensive coverage. EM mapping applications are still in their infancy for, despite the value of mapping often discussed in the minerals industry, their actual use is not as extensive as that

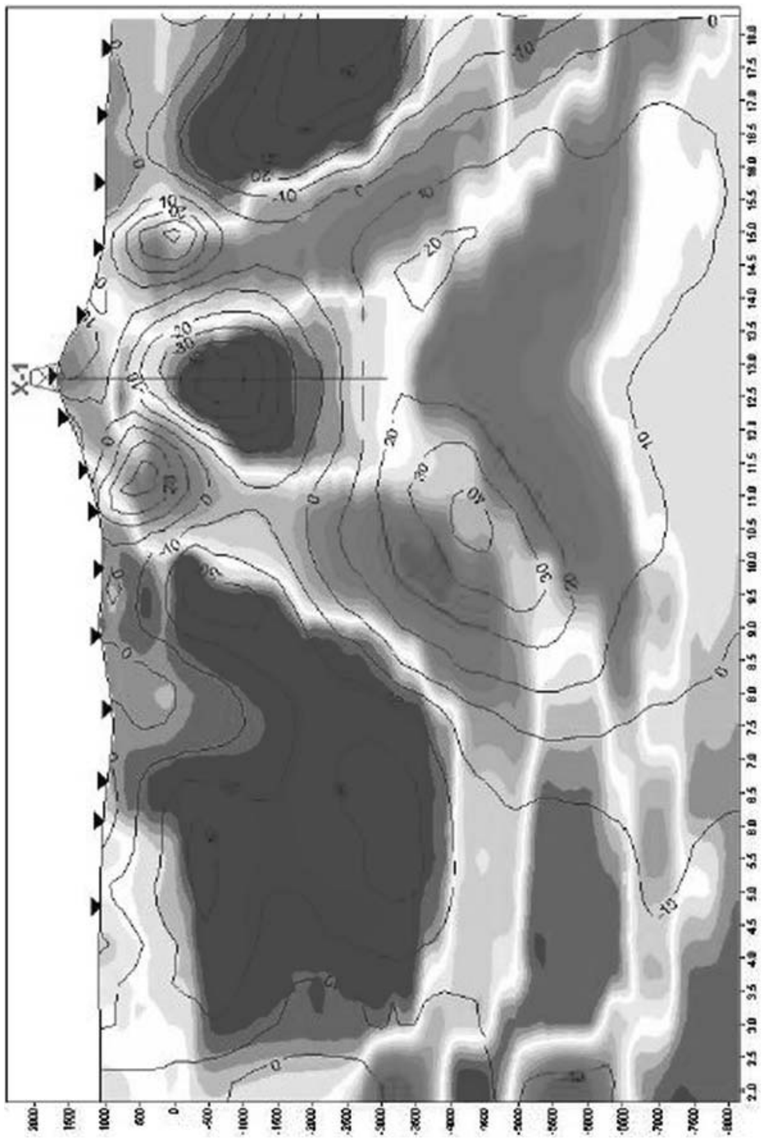


*Figure 5*. Example of a 3-D MT model showing steeply dipping beds in the Bolivian overthrust. Horizontal units are given in km, and vertical units in m; reds are more resistive and blues are more conductive. Contours are per cent change in resistivity between initial and final models (from Ravaut et al., 2002; courtesy Total).

of conventional mapping techniques, such as magnetic surveys. One reason for EM's restricted use as a mapping tool is the large expense of the surveys, which is typically several times that of magnetics surveys. Another is the perception that EM techniques can only be used as a direct detection tool. This means that government agencies will not undertake surveys which they perceive as providing certain companies with unfair advantages, particularly if anomalies are identified on tenements controlled by that company.

In environmental applications, EM methods are becoming an acceptable tool, e.g., the connection between the increased conductivity of contaminated waters, saline ground water, leakage from tailing dams or acid mine drainage has been well documented. Well-constrained airborne EM surveys have now become a very useful part of environmental mapping technology. An example shown by Rutley and Fallon (2000) was to identify any fluid migration trends the Ravenswood mine in Queensland, Australia. The 1999 survey used a helicopter-borne, frequency domain EM system, called Hummingbird. The results of the survey, carried out at 34133 Hz and shown in Figure 6, indicated that two major conductive trends existed. The first trend was fluid migration along a known fault, with ponding of the conductive fluid along the fault. The second identified trend was a strong pattern of migration away from the tailings dam. Having identified these fluid migration pathways, a more effective pump-back system for use during mining was installed.

As noted previously, ground systems are not often considered as regional mapping tools, chiefly due to their limited coverage. However, by collecting

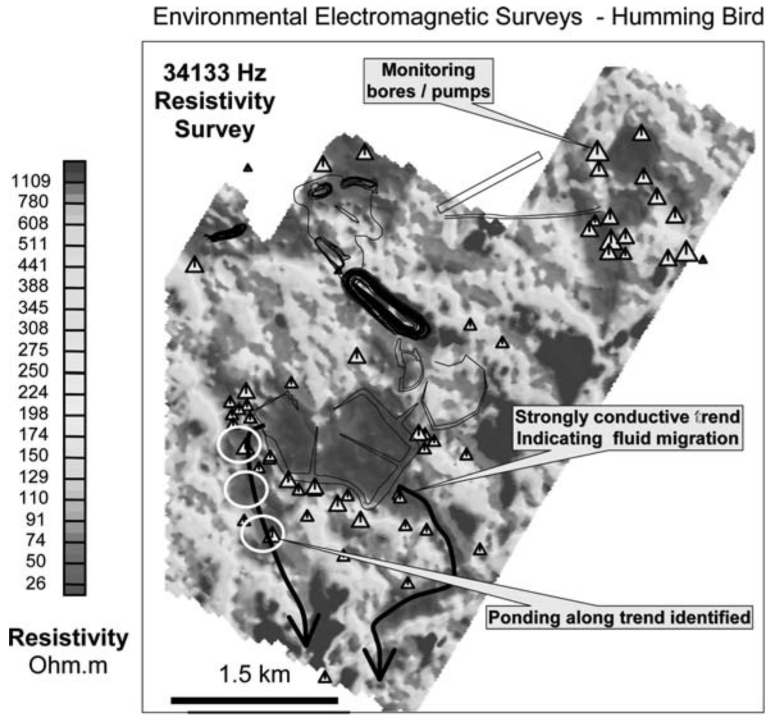


*Figure 6*. Environmental electromagnetic survey using the Hummingbird airborne system showing the surface resistivity in the area of the Ravenswood Mine, Queensland, Australia.

closely-spaced EM data in areas of interest, significant coverage can be obtained, thus enabling the use of ground EM as a mapping tool (e.g., Rutley et al., 2000). Rutley (personal communication, 2002) outlined the results of a recent, ground Zonge NanoTEM, in-loop, moving-loop, survey that was conducted at a Copper Refineries, Ltd. (CRL) site in Townsville, Queensland, Australia. The survey was carried out to map contaminant leakage from the site infrastructure. The NanoTEM system was utilised because of its fast turn off, enabling high resolution of shallow layers. Subsequent processing and inversion of the data enabled the cross-sectional mapping of conductive zones. Seven trends were identified by the survey, as shown in Figure 7. Spatially restricted, elevated conductivities were observed around the plant dam, with a major trend showing seepage at moderate depth around the plant infrastructure. As a direct result of this survey, CRL were


*Figure 7*. Conductivity depth sections at the Industrial Cooper Refineries, Ltd., plant near Townsville, Queensland, Australia.

able to identify areas of fluid migration, and adjust their environmental management plans accordingly.

EM methods are also seen increasingly as an appropriate method to search for groundwater, for irrigation, public supply, and other uses. Surveys have been conducted in Puerto Rico, Chile, Brazil, China, the US and other countries using Stratagem$^{TM}$ (a hybrid AMT/CSAMT), AMT, FEM and TEM. Although most of these surveys are proprietary, some examples of these applications have been published. Figure 8 shows results from an airborne EM survey for groundwater at the Arizona/Mexico border (Wynn, 2002); AMT was also used for groundwater studies in Texas (Pierce, 2002) and ground FEM in Brazil (Steensma and Kellett, 2000). The latter survey was followed up by airborne FEM.

### 5.2. Petroleum industry applications

MT now seems to be reasonably accepted by oil companies as a useful tool in the search for oil and gas. Although the incidence of land surveys has not increased significantly, the method is used for exploration primarily in seismically-difficult areas such as overthrust and high-velocity (carbonate, volcanic) cover and base-of-salt problems. In certain areas, MT is also applied for reconnaissance usually as a forerunner to more expensive seismic surveys.

Recent MT surveys for petroleum have been conducted in Albania, Bolivia, China, Germany, Greece, Holland, Italy, Iran, Japan, Libya,

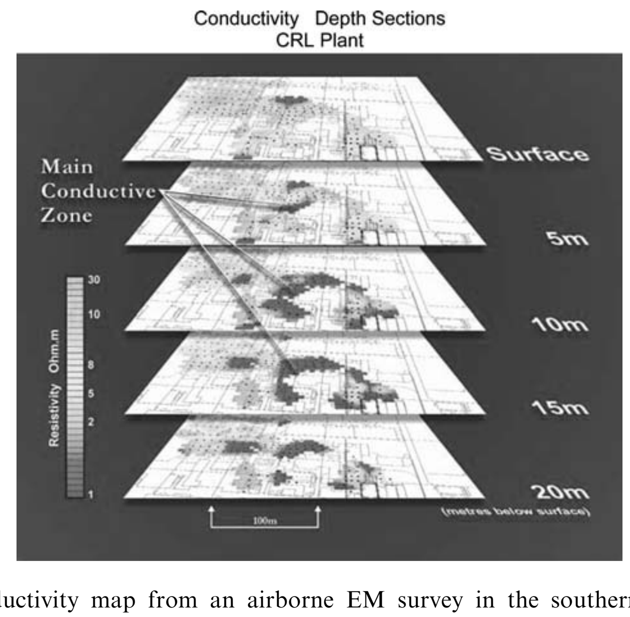


*Figure 8*. Conductivity map from an airborne EM survey in the southern USA; warmer colours represent higher conductivity, interpreted to be the aquifer (from Wynn, 2002).

Poland, Romania, and USA. China continues to be a major user of MT for petroleum exploration; a discovery based on MT, gravity and magnetics has been reported (Dou et al., 2001).

Several large surveys have been carried out in the USA in recent years. Additionally, more than 1000 MT stations of 1980s vintage have been re-interpreted for use in petroleum exploration in Washington, Wyoming, Oregon, California and other states. These studies are designed as precursors to new exploration, as clients realize the usefulness of MT for exploration in the increasingly important oil and gas plays of the western USA.

Marine MT, now commercially acquired in the North Sea, Gulf of Mexico, and offshore from Africa, is mainly applied for sub-salt and sub-basalt exploration (Hoversten et al., 2000; A. Orange, personal communication, 2003). Also, newer controlled-source marine EM systems are being used to discern the location of hydrocarbon vs. water in order to make decisions on drilling locations with better success.

Long Offset Transient EM (LOTEM) surveys are not widely used, but they are valuable for shallower oil plays. A better understanding has been gained of processes above oil and gas fields, such as resistivity changes caused by migration. Ziolkowski et al. (2002) describe using a LOTEM system to perform reservoir monitoring.

The new Montason LOTEM system had its first field survey in 2001. This system is designed to detect hydrocarbon reservoirs, indirectly and directly, but it can also be applied to other resources like minerals and ground water.

## 6. The Future

The base metal mining industry continues to use electromagnetic techniques as a front line tool for exploration. They are now used extensively to map below the Earth's surface, often as a supplement to magnetic mapping as they can provide better resolved depth information. This aspect is important in shallow environmental applications and is an area of continual growth.

While EM methods will continue to have their place in mining exploration, applications will expand for groundwater, hydrocarbons and geothermal exploration in the future. Therefore, as our need for resources grows, EM methods should continue to provide valuable tools for exploration.

There may also be applications of EM techniques in aiding seismic statics corrections. Some attempts have been made over the past two decades (den Boer et al., 2000), but there are difficulties with the integration of seismic and EM data. Sorely needed is a workstation, or platform cross-over, so that EM information can readily be utilized in seismic processing and interpretation.

Tests aimed at mapping water and $CO_2$ floods, and hydrocarbon reservoir monitoring, with TEM progressed for several years and some results have recently been published (Wright et al., 2001; Ziolkowski et al., 2002).

The largest advances in EM applications in the geophysical industry will most probably come from the implementation of 3-D inversion codes on laptops, thereby allowing interpreters and researchers to better understand and interpret the data conveniently. This should also lead to the increased acceptance of EM methods by industry as EM interpreters provide faster, better, and more accurate products.

## 7. Conclusions

The first EM systems developed had major limitations, which were manifested as an inability to "see" below conductive cover, and inadequate presentation techniques. Through the years, new breakthroughs were made, and today EM techniques have developed into robust, versatile methods that can be used in a majority of geological environments. The results can be presented in 1-D, 2-D or 3-D. Over the last four years, the use of EM as a mapping tool for mining and environmental applications has increased significantly, as has the use of EM methods in the petroleum industry. As a result, EM techniques are a leading tool in the mining and environmental industries. In the future it appears that they may play an increased supporting role in both on-shore and off-shore petroleum surveys.

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