ELECTRICAL AND
ELECTROMAGNETIC
METHODS
PAPER 63

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ELECTROMAGNETIC TRENDS — SPATIAL, TEMPORAL AND ECONOMIC

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ABSTRACT

Over the past decade, steady incremental advances have been made in the application and interpretation of EM data in geophysical exploration. With the dramatic gains in computer processing speed and storage capability, true multichannel and data streaming receivers are now becoming commercially available; however the lack of inexpensive and compact magnetic field or dB/dt sensors of sufficient sensitivity for EM measurements is the main obstacle to progress in data acquisition. Even with dramatic computing advances, routine applications of 3-D forward modelling (let alone inverse modelling) of EM data are scarce. Significant problems remain with the various published algorithms and much effort is still required before the range of acceptable accuracy of the available programs is established, and the programs are perceived by users to be robust, stable and easy to use. As a result, approximate processing algorithms continue to attract research and development.

INTRODUCTION

At the time of our last review paper 10 years ago (Macnae and Spies, 1988) the major advances in ground EM were the move to higher power sources, the widespread use of time-domain systems for sounding and exploration to depths of several hundred metres, and the development of approximate imaging tools to supplement the computer-intensive inversion codes being developed. We predicted continued improvements in acquisition, instrumentation and interpretation (predicated on increases in base-metal prices) as well as spin-offs from research into energy exploration, crustal sounding and other applications of EM.

How did these predictions fare? The 1990s saw fluctuating and generally low base metal prices, there was a period of consolidation in development in EM instrumentation and interpretation, and reduced mineral industry funded research and development. Anticipated spinoffs into energy exploration were hindered by low oil prices and restructuring of research laboratories in oil companies to focus more on decreasing costs rather than increasing reserves.

The major area of development we did not anticipate — the move to early-time, higher resolution TEM systems — was driven to a large extent by the environmental cleanup crisis in the U.S and post-communist Europe, and the need to better define and resolve small targets at shallow depths. Attempts were made to bridge the gap between ground-probing radar (GPR) with depths of investigation limited to a few meters, and inductive EM systems that could not resolve structure shallower than tens of meters.

The 1990s have been more a period of consolidation in the use and understanding of EM rather than a decade of major advances. A major event in EM was the publication of a two-volume text by the SEG (Nabighian 1991). Although a plethora of computer codes for 2-D and 3-D modelling and inversion had been developed in the 1980s, their use is not widespread due to difficulty of use, inadequate accuracy checks, and the continued evolution of programs attempting to take advantage of advances in computer hardware.

INSTRUMENTATION ADVANCES

The 1980s saw a move towards deeper penetration, higher power EM systems. During the 1990s, in contrast, major efforts in instrumentation have been invested in pursuing the shallower end of the depth scale, driven by an interest in non-invasive characterisation of the near surface for environmental and engineering applications, and a recognition that early-time TEM systems could compete with the new automated electrode arrays being developed for d.c. resistivity sounding.

A number of instrument manufacturers now offer TEM systems with turnoff times in the microsecond range for transmitter loops of the order of 10 m in size with several amps of current, and sampling at microsecond intervals. Some have three-component receivers. These early-time measurements are approaching the frequency regime where displacement currents affect the data, but for most applications traditional quasi-static assumptions appear to be adequate.

A number of specialised instruments are now manufactured to serve the shallow buried metal market, especially for UXO (unexploded ordnances). The Geonics EM61, for example, measures a combination of TEM field and vertical gradient to decrease sensitivity to the very near

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surface, while focussing on the 1 to 2 m depth range. Other shallow-probing TEM systems have been designed for dense and rapid coverage over large areas, for example a pulled-array TEM system used for groundwater studies is described by Sørensen *et al.* (1995).

A broadband frequency-domain EM system operating over the frequency range 31 kHz to 32 MHz has been developed at the University of Arizona for environmental geophysical surveys (Sternberg and Poulton, 1996). The system measures ellipticity to a very high accuracy (0.1%) with continuous automated calibration, and neural network 1-D interpretation on site.

A serious attempt to bridge the gap between wave-propagation GPR and inductive EM was made by the U.S. Geological Survey for the purposes of investigating the top 10 m for environmental applications, particularly the mapping of shallow subsurface waste materials on government facilities. Parallel research was conducted on both time and frequency-domain approaches. The VETEM (very early time EM) system was designed to measure over a time range of 10 to 1000 ns (Pellerin *et al.*, 1994), and the high-frequency sounder (Stewart *et al.*, 1990) over the frequency range 0.5 to 30 MHz. The frequency range of these systems makes them sensitive to both displacement currents and conduction currents, so that dielectic and conductivity properties affect the response. Research has not proceeded as quickly as anticipated due to difficulties with instrumentation, theory, and modelling in this nether world of electromagnetics. In addition, much laboratory and petrophysical work remains to be done on the highly dispersive electrical properties of soil materials at these frequencies.

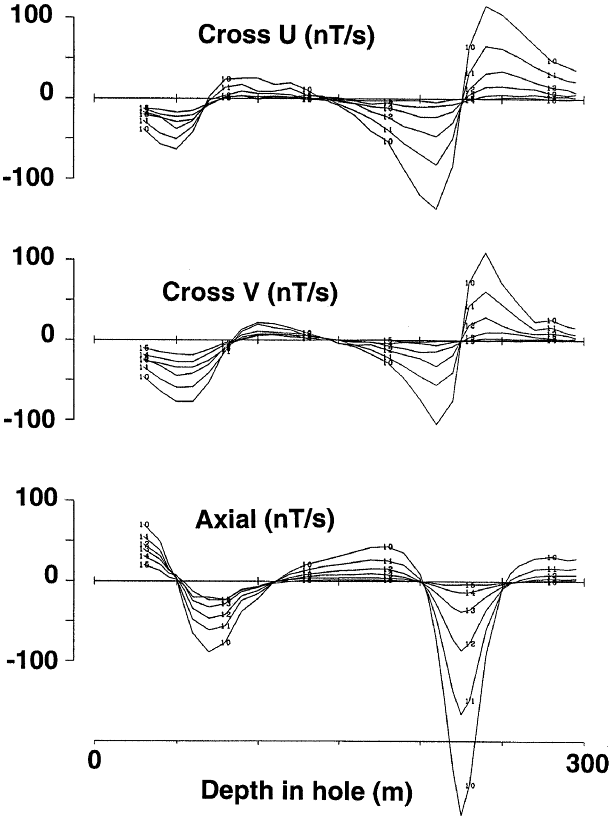

Figure 1: *3-component down hole EM data acquired using the Crone PEM system (Hughes and Ravenhurst, 1997).*

Axial component drill hole data was starting to find extensive use ten years ago (Dyck and Asten, 1988). Drill hole EM interpreters have long called for the oriented 3-component data needed to locate targets in 3-D, and technology for this has appeared over the last decade. The challenges lay in making sensitive and low-noise cross-hole detectors to fit small diameter mineral exploration drillholes, and in the techniques for probe orientation. At first separate axial and cross-hole component sensors were available, but full 3 component sensors are now being produced for most EM systems. Different manufacturers have taken different approaches to the orientation problem, for example the prevention of rotation through wheels designed to contact the drillhole walls or the use of miniature magnetic and gravity sensors for orientation. Figure 1 shows an example of Crone data collected in Australia, where Hughes and Ravenhurst (1997) were able to infer target direction from the polarity of the cross-components, and where the noise level in the cross-hole components is almost as low as is the axial component. A broader review of borehole electrical and electromagnetic geophysical techniques is given by Spies (1996).

The CSAMT (controlled source audiomagnetotelluric) technique has advanced steadily with improvements in low-noise sensors and acquisition systems, with wideband measurements from millihertz to tens of kilohertz now common. Often the controlled source is used only in the higher-frequency bands (above 10 Hz or so) and natural fields are used at lower frequencies, and several stand-alone MT/CSAMT systems are now commercially available.

Multichannel, laptop or PC driven systems such as the 32 channel Zonge system are now commercially available. The chief limitations lie in the cost and relatively large size of magnetic or *dB/dt* sensors of sufficient sensitivity to be useful for EM. Data processing hardware speed has advanced to the point that streaming receivers that will continuously dump data sampled with say 20 bits at 100 kHz are now feasible, and are being implemented as generic receivers in airborne EM systems. Such a generic streaming system is also available for ground data acquisition, with the Smartem system manufactured by Electromagnetic Imaging Technology providing 16 bits at 160 kHz in each of 8 channels. Techniques in adaptive and predictive noise cancellation have been developed (Spies 1998; Olsen and Hohn, 1992) to take advantage of time-series processing of EM data.

NEW TECHNIQUES

A number of new methods have emerged or been resurrected over the last decade. The surface NMR method was developed in the USSR for water detection, where it was called "hydroscope" (Trushkin *et al.*, 1995). Initial demonstration surveys in the USA in the early 1990s were plagued by poor signal levels, but the instrumentation is being improved by BRGM and IRIS Instruments, and shows considerable promise for hydrological investigations to depths of 100 m or so.

An interesting development was the combined use of a large loop source with an airborne receiver (the FLAIRTEM system, Elliott, 1995), which is a similar concept to the earlier TURAIR system from the late 1960s, to achieve reconnaissance deep coverage in rugged areas.

Smith and Klein (1996) presented compelling evidence for detection of IP effects with the airborne Geotem system. This however was in a special case where target polarisation was high in a very resistive area where normal inductive effects did not dominate the response.

The SAM (Sub Audio Magnetics) system developed by Cattach (1996) measures total field magnetometric resistivity, where a high sensitivity cesium magnetometer is used to detect alternating magnetic fields generated by a large grounded transmitter, superimposed on the earth's static magnetic field. This system has convincingly mapped electrical as well as magnetic structures in the ground. Transients (or phase-lag) seen in the system show evidence of both EM and IP effects.

MODELLING ADVANCES

Modelling codes have advanced steadily over the past decade, accelerated by impressive improvements in performance and dramatic lowering of cost of computer hardware. Major advances have taken place in the modelling of increasingly complex targets, with a realisation that full 3-D modelling is usually required where a layered-earth (or 1-D) model is inadequate.

One-dimensional modelling and inversion is now in routine use, with commercially-supported programs available on desk top PCs through such companies as Interpex Ltd. and Encom Technologies Ltd. The inversion programs are based on linearized assumptions and therefore do not cover the entire model space (Nekut and Spies, 1989), but are generally robust, reasonably fast (several minutes per sounding on a PC) and are readily automated to handle profile data which are exported as stitched 1-D profiles. Many of these programs output parameter statistics that give some indication of the equivalence or confidence intervals associated with the result.

A major conceptual advance was the maximally-smooth or maximally-flat Occam inversion of Constable *et al.* (1987), which fits a smoothly-varying depth profile to the data without need for a priori assumptions about the number of layers. The method is computationally intensive, though, and not as widely used as 1-D inversions to a few

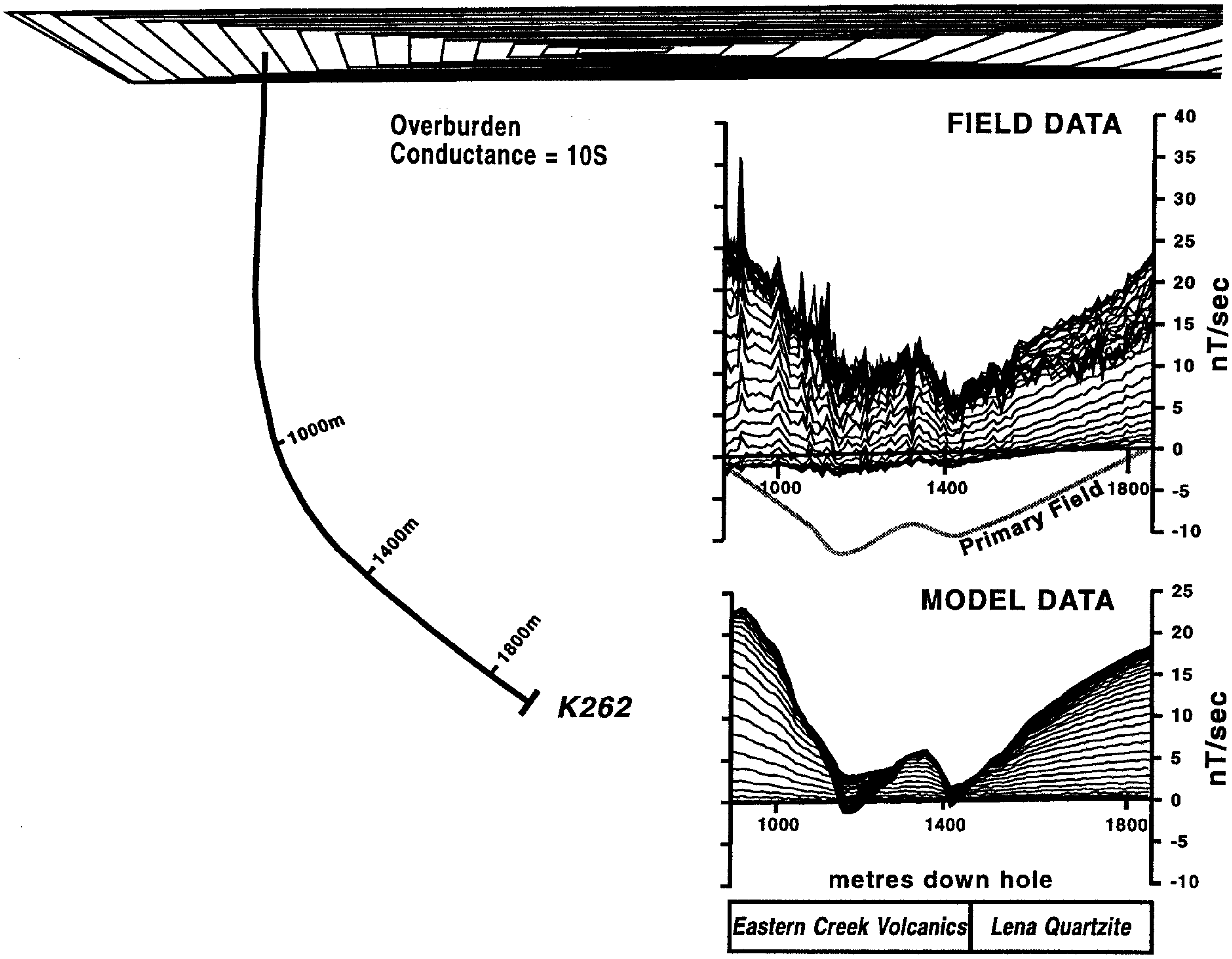

Figure 2: *False down hole EM anomalies caused by drill hole curvature explained by 3-D plate modelling (Jackson et al., 1997)*

(2 or 3) discrete layers. Further, if the geology is fault and contact bounded, the method may not produce an optimal image. However, the maximally smooth physical property image is a good tool to visualise the possible bounds on conductivity structure rather than get false confidence in an inverted depth or structure.

The recognition that magnetic susceptibility affects EM data in some environments has led to joint conductivity-susceptibility 1-D inversion (Zhang and Oldenburg, 1995; Sattel 1996).

Moving on to higher-dimensional modelling and inversion, 2-D models are usually assumed to be appropriate for far-field or magnetotelluric methods, and a variety of smooth 2-D MT inversion algorithms have been developed that minimise structure in some sense (Smith and Booker; 1988; deGroot-Hedlin and Constable, 1990).

To simulate the response of a 3-D EM source in a complex earth, it is necessary to move to 2.5-D (2-D body and 3-D source) or 3-D modelling. The 2-D assumption is recognised to be generally unsuitable for controlled-source EM methods because it cannot model both current channeling and induction effects. However, since it is nearly as difficult to formulate the 2.5-D problem as it is for 3-D, only a few examples have appeared (e.g., Leppin, 1989; Valla, 1992; Unsworth *et al.*, 1993; Torres-Verdin and Habashy, 1994; and Xie *et al.*, 1997).

3-D models of a target such as a sphere or rectangular plate in free space were in common use a decade ago, and still find application today. An example of representing a simple overburden with a rectangular loop model is given in Figure 2 (Jackson *et al.*, 1997) for the case of a conductive overburden and a curved drill hole. Even though the overall amplitude fit is poor, the two negative responses about 150 m wide seen in the field data can be modelled simply as a change in coupling of the overburden response to the axial component down the curved drill hole. Program MultiLoop (Macnae *et al.*, 1988) was developed to allow for the modelling of unconnected multiple conductors in free space, and has proven to be an extremely useful tool in drill hole data interpretation. Figure 3 (Jackson *et al.,* 1997) shows a very complex set of known and unknown conductors in the vicinity of the Mt. Isa mine. A multiple conductor model was used to fit the very complex drill hole profile, and infer the presence of two off-hole target conductors. The field data incidentally shows the advances in probe technology which allows probing to depths well in excess of 2 km.

Full 3-D EM modelling has advanced greatly since first introduced by Hohmann 25 years ago (Hohmann 1975). Increased computer power and memory has allowed the use of increased number of cells or nodes, which translates to increased model complexity, frequency range and accuracy. Many of these codes are designed to run on a high-end desktop workstation or PC. Key advances over the last decade were Newman *et al.* (1986) who extended Hohmann's integral equation solution to the time domain, and the development of finite-element and finite-difference solutions capable of handling much more complex models (e.g., Mackie *et al.*, 1993; Druskin and Knizhnerman; 1994; Newman and Alumbaugh, 1995; Smith 1996, a, b; Wang and Hohmann, 1993), with extensions to higher frequencies to include displacement currents (Alumbaugh *et al.*, 1996). An excellent summary of progress and challenges at the middle of the decade is presented by Raiche (1994). Increasingly, modelling codes

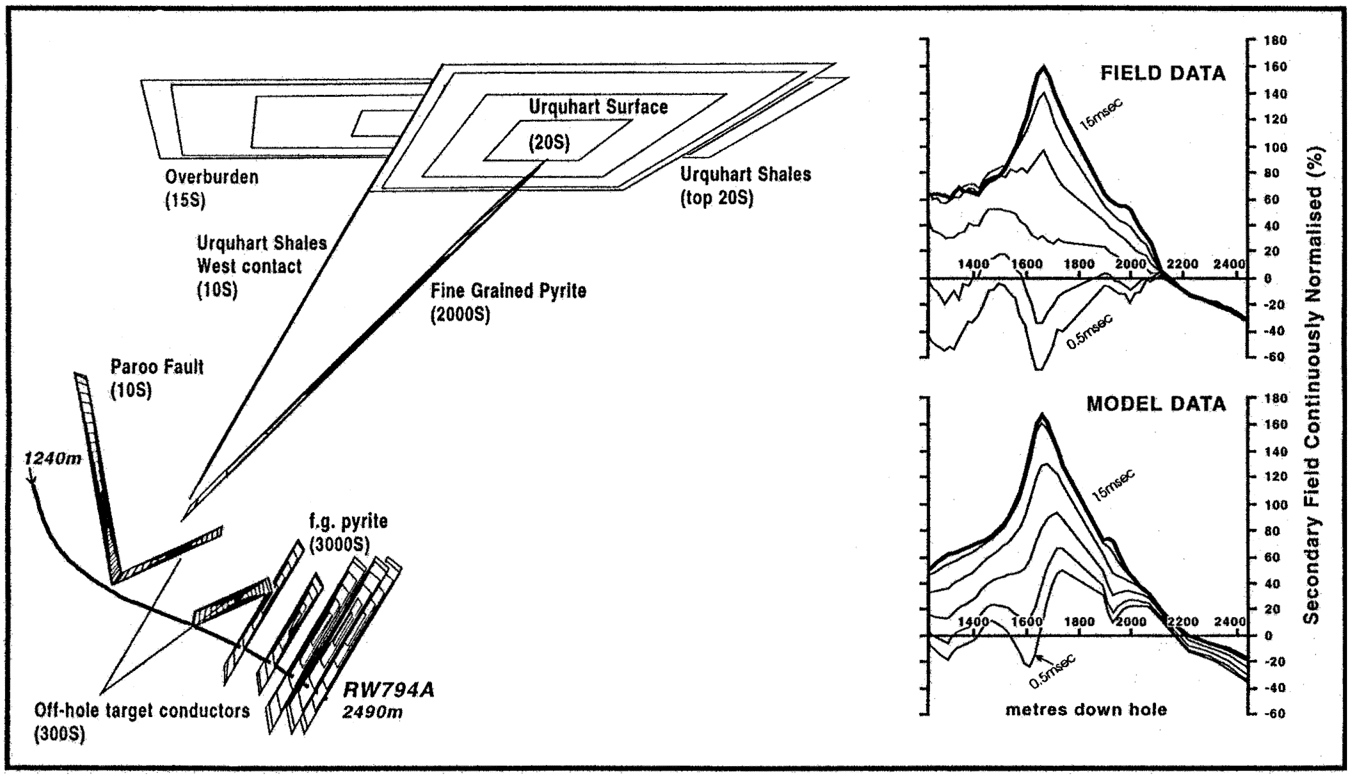

Figure 3: *The discovery of two off-hole conductors in a complex geological environment illustrates the effectiveness of simple multi-loop modelling (Jackson et al., 1997)*

are being taylored to suit specific equipment and field specifications, so that system response is automatically taken into account.

A major workshop on 3-D EM (Oristaglio and Spies, 1995) captured a snapshot of advances in the field, with 71 papers dealing with 3-D modelling, inversion, and practice. One of the papers at the workshop (Smith and Paine, 1995) compared results from a number of existing codes, and highlighted a problem continually faced by researchers in the field—verification of results. A realistic assessment of accuracy must still be seen as a major challenge in EM modelling for anything but layered earths. Comparative studies such as the COMMEMMI project and AMIRA P441 (*http://ntcrcserver.crcamet.mq.edu.au/crcamet.htm*) are an important step in this direction.

3-D INVERSION

Solutions to the full 3-D inverse problem in electromagnetics have proved an elusive goal. In addition to the need for an accurate forward modelling code, there is the need to calculate a large sensitivity matrix and solve a large system of equations. Various approaches to the latter issues are reviewed by Oldenburg (1994), and include generalized subspace methods, conjugate gradient methods, and approximate inverse mapping procedures.

It is possible, though, to extend the traditional approach to 3-D inversion by brute-force use of computer power. The standard inversion process is iterative, and at each iteration hundreds or thousands of individual forward solutions must be computed. Thus, to best tackle a full 3-D inversion problem requires a parallel processor computer in which hundreds or thousands of processors are operating on the problem simultaneously. For example, Newman and Alumbaugh (1997) describe how the forward modelling and inversion domains of the problem are broken up across a series of processors such that each processor is computing the results for a small section of the model. Because each processor is operating on this small subsection, and because hundreds of processors are operating simultaneously, the run time is decreased by a factor which is approximately equal to the number of processors employed.

An example of 3-D inversion from Alumbaugh and Newman (1997) is given in Figure 4. This example is for a crosswell data set in which a vertical magnetic dipole (VMD) transmitter is in the centre well (designated by the black pixels in the image) and VMD receivers are located in the four surrounding wells. The objective was to image an injected plume of salt water at 30 m depth (notice the area of high conductivity just to the north of the central well). The total number of source positions involved was 22, and the number of receivers was 44, which yields a total of 1012 data points collected at a frequency of 9.8 kHz. The forward modelling domain in this example is 46 by 46 by 54 cells which yields over 300,000 electric fields values to be solved for in each forward problem, and the inversion domain consists of 30 by 30 by 30 cells which yields 27,000 unknown electrical conductivities to estimate. Running on 576 processors of Sandia National Labs Intel Paragon took approximately 4.5 hours to finish the seven iterations needed to produce this image. The same problem would have taken over a week on a high end IBM workstation.

APPROXIMATE SOLUTIONS FOR 2.5-D AND 3-D

There has been increased effort in the development of approximate solutions for 3-D simulation. This has been partially driven by the need for more rapid forward modelling, but increasingly driven by the realisation that 3-D EM inversion will not be practical on desk-top computers for the forseeable future unless alternative avenues are pursued.

McNeill *et al.*, (1984) developed an approximate 3-D modelling scheme based on an estimation of the relative contributions of vortex (induction) and galvanic (current channelling. This was followed by Flores and Edwards (1992) who computed the approximate response of multiple conductors, Fernyhough (1985) and Liu and Asten (1993) for a plate beneath a conductive overburden.

More recently, a fundamental re-evaluation of the limitations of the Born approximation has led to practical rapid 3-D modelling schemes that are still quasi-linear and are valid over a much wider frequency range and conductivity contrast than previously considered feasible. These 3-D modelling schemes (Habashy *et al.*, 1993; Zhdanov and Fang, 1996), have also been extended to 2.5-D and 3-D inversion (Habashy and Torres-Verdin, 1994; Zhdanov, and Fang, 1995) and show considerable promise.

Considering the large amount of resources that have gone into EM modelling and inversion over the last few decades, it is unfortunate that very little has emerged into the public domain or is commercially offered via a software vendor for use by the explorationist. Most of the advances listed above remain in the realm of academic or research code, and access to the codes is generally restricted to academia or consortia sponsors. 1-D codes are reasonably well represented in the commercial realm, and several companies (Encom Technologies, Interpex Ltd, and Wight Systems Engineering) offer 2-D MT modelling and inversion. Limited commercial 3-D software is offered by Encom, Lamontagne Geophysics and Petros Eikon.

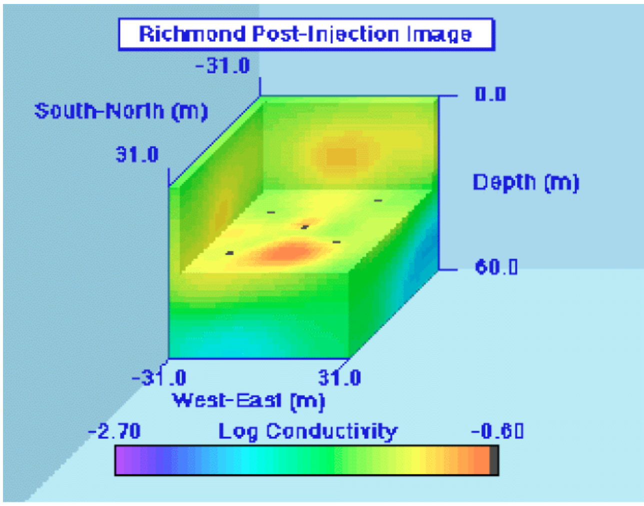

Figure 4: *3-D inversion of a synthetic crosswell single frequency EM data set computed on a massively parallel workstation. The computation took 4.5 hours on an 576-processor Intel Paragon (Alumbaugh and Newman, 1997).*

PROCESSING ADVANCES

A number of novel data acquisition and processing techniques have been developed to suppress the effects of near-surface inhomogeneities on EM methods that use electric field sources or sensors. The EMAP (electromagnetic array profiling) technique described by Torres-Verdin and Bostick (1992) has been adapted to detailed mapping for mineral exploration in a technique called continuous impedance profiling (Morrison and Nichols, 1996). Arrays of electric dipoles, contiguous in the profile direction and orthogonal to the measured magnetic field, are processed using the EMAP algorithm, which applies a depth-varying spatial filter to remove the distortion effects of near-surface conductors to produce a 1-D profile. Alternatively, the data may be modelled with a variety of the minumum-structure inversion or imaging schemes as described above. The technique has also been successfully applied in a closely-sampled areal (2-D) sense, but results are as yet unpublished.

Approximate depth imaging as described by Macnae and Lamontagne (1987), Fullagar and Reid (1992) and (Smith and Buselli, 1991) has led to several different and fast approximate 1-D imaging algorithms. In an airborne application one day of flying can be processed to stitched sections in about 4 hours on a desktop PC, compared to 15 days to perform a 3 layer inversion on a VAX cluster (Sattel, 1996). Christensen (1997) describes a practical method for rapid 2-D interpretation of TEM profiles based on an adaptive Born approach, that reduces artifacts often present in stitched 1-D profiles (Figure 5).

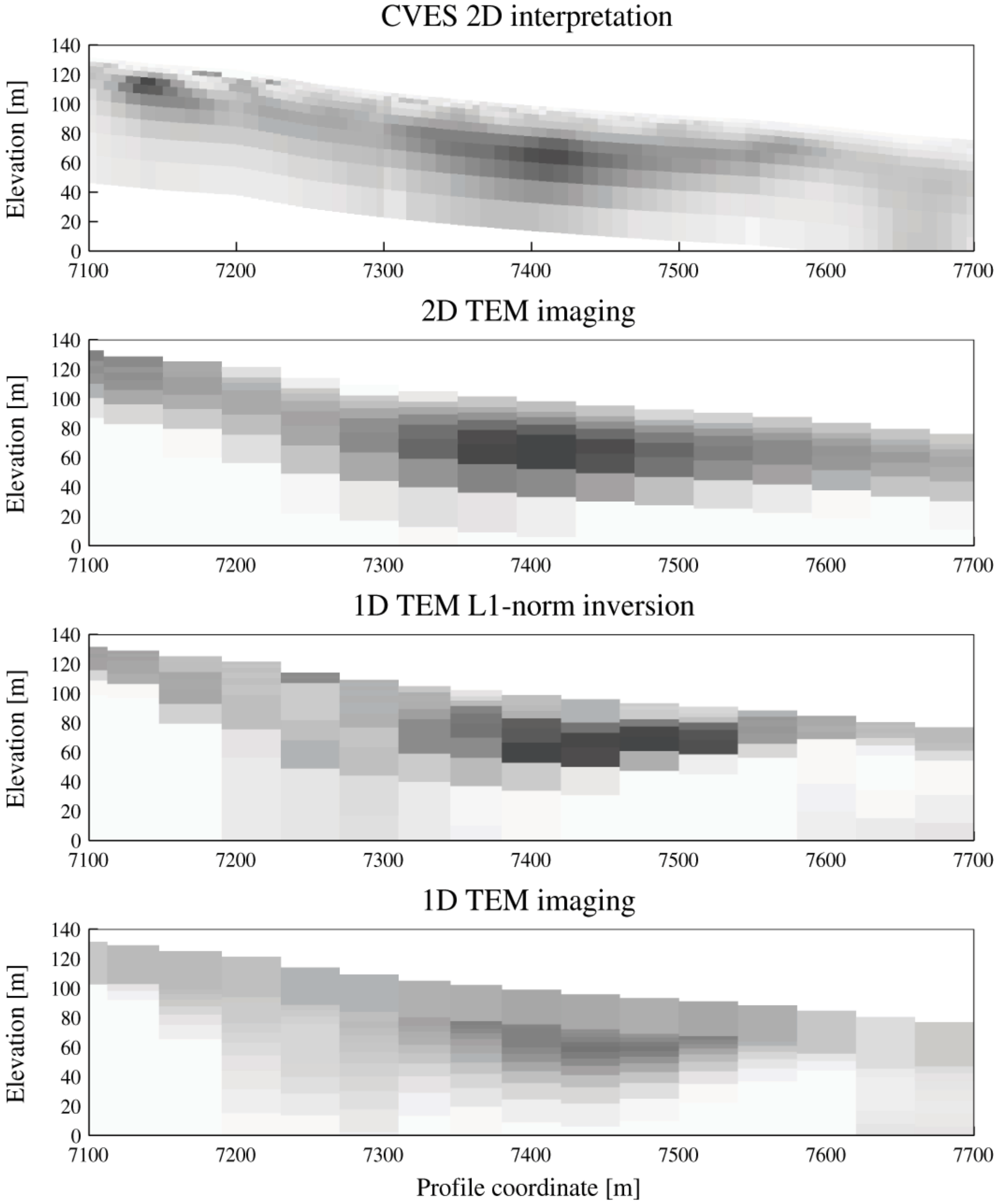

Figure 5: *Comparison of various TEM inversions (after Christensen, 1997).*

INTERPRETATION ADVANCES

There has been a recognition in the last decade that massive sulphide conductors (particularly if copper or nickel rich) may be extremely conductive, and economic sized bodies of well connected sulphides may have responses that do not decay in the normal time windows of a TEM system. An example is work by King (1997) where the new footwall discoveries in the Sudbury basin commonly have conductances in excess of 5000 S. If such a target is intersected (Macnae and Mutton, 1997), both on- and off-time measurements are affected strongly in its immediate vicinity. However to detect such a non-decaying response at any distance, measurements in the on-time of an EM system are required (Macnae and Mutton, 1997).

If the aim of a survey is to detect very poor conductors (whose rate of decay is so rapid that the response is over before the first measurement window of an off-time EM system), work by Annan *et al.* (1996) has indicated that responses in the on-time are able to determine conductivity structure in an airborne survey case in the arctic where no good conductors were present. These field examples show that on-time data may detect conductors both off-scale resistive and off-scale conductive to normal off-time measurements. Further quantification of these effects is presented by Stolz and Macnae (1997).

CONCLUSIONS FOR THE DECADE AHEAD

Based upon experience, we are not as confident in our predictions as we were a decade ago. However, with the effort going into 3-D and other EM modelling, the presence of comparative studies such as the AMIRA P441 (*http://ntcrcserver.crcamet.mq.edu.au/crcamet.htm*) and the COMMEMMI projects, we believe that 3-D forward modelling of proven accuracy will be possible on fast desktop computers. Approximate modelling is likely to become more stable and widely applied. The major obstacle to the development of true multichannel EM systems that have high bandwidth and the throughput needed to make measurements from many receivers over time delays from sub-microsoconds to seconds is the lack of sensitive, small and inexpensive magnetic field (or its time derivative) sensors. Unless this problem is solved, true multichannel EM systems are unlikely to emerge in the next few years.

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