GROUND AND AIRBORNE ELECTROMAGNETIC METHODS

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1. SUMMARY

Electromagnetic (EM) methods are used to map variations in electrical properties. The main physical property involved in these methods is inductive electrical conductivity, which is a measure of how easily electrical current can pass through a material. Conductivity is a complex function of several variables including the conductivity of solid materials, conductivity of pore fluids, porosity, arrangement of pores and degree of saturation. Case studies are continuing to improve our understanding of the relationship between the conductivity of geological units and the processes such as weathering and groundwater movement that influence the principal controls on bulk conductivity.

For many years, variations in the conductivity of regolith were seen as a source of geological noise for EM surveys that were focussed on conductive base metal mineralisation. Applications that call for mapping regolith conductivity variations as an adjunct to discrete conductor detection or as an end in themselves are now well established.

A range of simple-to-operate, compact instruments are available to map average conductivity to depths of less than a metre to several metres. These instruments are used extensively in salinity and shallow groundwater applications. The addition of data logging and satellite navigation functionality to the EM system permits large volumes of well located data to be acquired relatively quickly.

The most significant advances have been to EM systems that image conductivity as a function depth. Improvements in acquisition systems and data processing (eg. bandwidth of recorded information, signal to noise ratio and methods to convert recorded information into subsurface conductivity) have combined to enhance the quality of the information about the subsurface and to simplify interpretation.

2. DESCRIPTION

Introduction

Subsurface materials exhibit a very large range of electrical conductivity values (Figure 1). Fresh rock is generally a poor conductor of electricity, but layers of graphite and certain metallic minerals containing iron, copper or nickel are very good conductors. These latter substances conduct electricity by allowing the migration of electrons and are hence termed “electronic conductors”.

Highly conductive minerals are quite rare in the majority of geological settings. The electrical properties of most rocks are governed to a large degree by the amount of water filling the gaps between the mineral grains and amount of dissolved salt in this water. Pure water has a very low electrical conductivity while seawater contains high levels of dissolved salts (approximately 35ppt), mostly NaCl, and is a relatively good conductor of electrical current. Groundwater can vary in salt content from fresh through brackish (slightly salty) to saline (similar in salt content to seawater) through to hyper-saline (more salty than seawater). These materials conduct electricity through the migration of ions through the pore fluid and hence are termed “ionic conductors”.

In Papp, É. (Editor), 2002, *Geophysical and Remote Sensing Methods for Regolith Exploration*, CRCLEME Open File Report 144, pp 53-79.

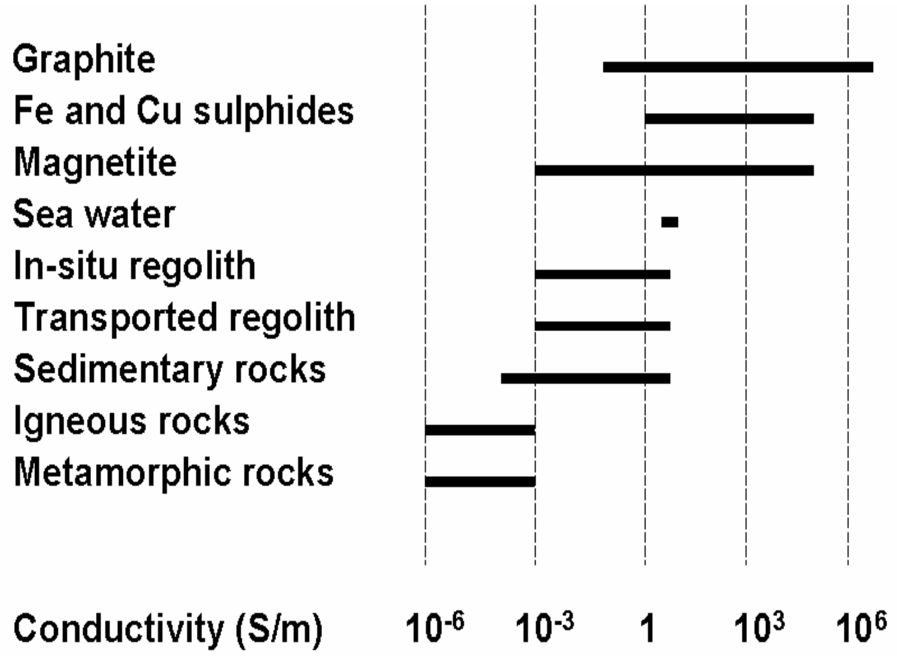

Figure 1. The range of conductivity values for various rocks and minerals.

EM subsurface investigation involves the transmission of electromagnetic energy, interaction of this energy with the ground, and reception of secondary, induced energy at a receiver (Figure 2). EM systems come in all shapes and sizes, but there will always be a source of electromagnetic energy (transmitter) and a receiver to detect the response of the ground. Currents induced in the ground are a function of conductivity. By processing and interpreting the received signals, it is possible to make deductions about the distribution of conductivity in the subsurface.

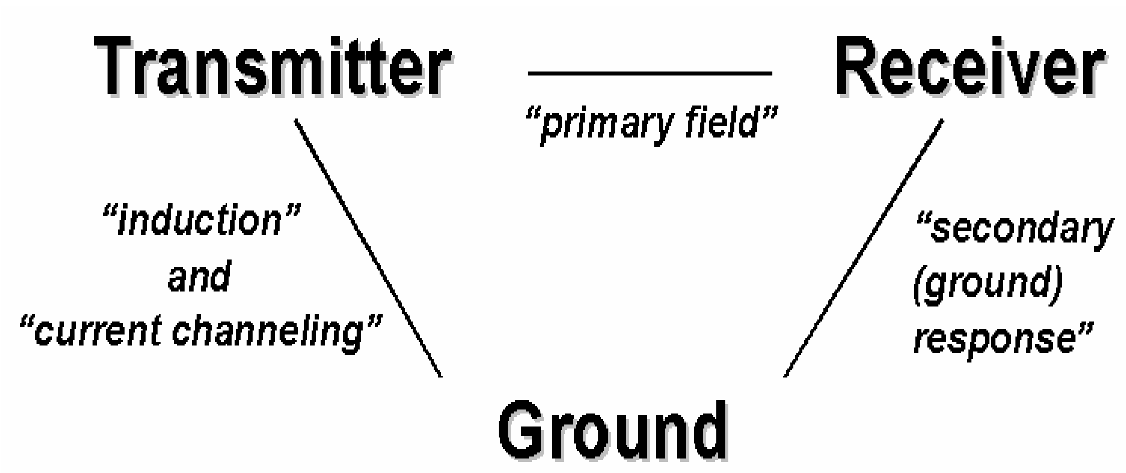

Figure 2. Interactions for an EM system.

Some electromagnetic methods take advantage of currents induced in the ground by natural electromagnetic waves. Lightning on a global scale is one of the strongest natural sources of electromagnetic energy used in this fashion. However, in the majority of cases, a man-made transmitter of electromagnetic waves is used, and the systems are described as "active" or "controlled source". A simple example of an electromagnetic instrument is a metal detector. This instrument is able to detect highly conductive metal objects buried at shallow depths. The same principles are used in EM mapping applications at vertical scales ranging from less than a metre to tens, hundreds or even thousands of metres.

The “active” nature of EM systems is in strong contrast to passive magnetic, gravity or gamma-ray spectrometric methods. Hardware limitations on signal to noise and bandwidth lead to proprietary configurations and added complexity in the processing and interpretation of EM data.

EM systems are classified in various ways by different authors according to the instrumentation, geometry of the transmitter-ground-receiver elements and the nature of the transmitted and recorded signal. A pure frequency domain (FD) EM system transmits a magnetic field signal at a single frequency with sinusoidal variation in amplitude. The recorded response can either be described by its total amplitude and phase with respect to the transmitter signal or by the amplitudes of components in-phase (“in-phase”) and 90° out of phase (“quadrature”) with respect to the transmitter signal. A pure time domain (TD) EM system transmits a magnetic field signal with a sharp step. The time decay of currents induced in the subsurface is sampled at a number of delay times (“windows”) following the step change in magnetic field. “Early” and “late” are qualifiers applied to windows in reference to the elapsed time following the change in the magnetic field. The window measurements contain information equivalent to that which would be obtained with a number of FD systems covering a range of frequencies. The equivalent range of frequencies is referred to as the “bandwidth” of the system. In practice, EM systems are often a combination of these two end members, and it is important to note both the bandwidth and signal to noise characteristics of the system being employed at each of these equivalent frequencies.

A single or multi-turn loop is generally used as the transmitter element of EM systems. A time varying current passing through the loop is used to create a time varying magnetic field. Wire coils are most commonly used as the receiver element of EM systems, but superconducting SQUID magnetometers have also been used. A voltage is induced in the receiver coils proportional to the time rate of change of the magnetic field directed along the axis of the coil. Two or three coils may be used to measure the response along perpendicular axes. The horizontal component of the response along the survey line is referred to as the X component. The horizontal component of the response perpendicular to the survey line is referred to as the Y component. The vertical component of the response is referred to as the Z component. An X component transmitter loop teamed with a trailing X component receiver coil is referred to as a horizontal “coaxial” configuration. A Z component transmitter loop teamed with a trailing Z component receiver coil is referred to as a vertical axis “coplanar” configuration.

The “scale” of an EM system is an indication of the largest dimension of the transmitter-ground-receiver geometry. For different systems, it may be the size of the transmitter loop, or the separation of the transmitter and receiver, or the terrain clearance of the transmitter or receiver. The “footprint” of an EM system is the area (but more strictly the volume) of the ground beneath the system that contributes the majority of the response (Liu and Becker, 1990). This is a complex function of the “scale” of the system, the transmitted power and frequency range, receiver sensitivity, and ground conductivity distribution. As a guide, the footprint is approximately a disk with a diameter which is a small multiple (eg. 2 to 3 times) the scale of the system.

The “skin depth” is the depth at which signal is reduced to 1/e (~37%) of the original amplitude. For a FD EM system:

$$\text{skindepth} = \sqrt{\frac{2}{\mu_0}} \cdot \sqrt{\frac{1}{\sigma \cdot 2 \cdot \pi \cdot f}} \approx 500 \cdot \sqrt{\frac{1}{\sigma \cdot f}}$$

where $\mu_0 = 4 \cdot \pi \cdot 1 \cdot e^{-7}$ H/m, σ is the conductivity of the subsurface in S/m and f is the frequency of the system in Hz. The equivalent concept for a TD EM system is the “diffusion depth” which is the depth at which the local electric field reaches a maximum,

$$\text{diffusion depth } = \sqrt{\frac{2}{\mu_0}} \cdot \sqrt{\frac{t}{\sigma}} \approx 1260 \cdot \sqrt{\frac{t}{\sigma}}$$

where $\mu_0 = 4 \cdot \pi \cdot 1 \cdot e^{-7}$ H/m, σ is the conductivity of the subsurface in S/m and t is the delay time in seconds of the measurement after a step change in the transmitted magnetic field. The concept of skin depth or diffusion depth is a convenient way to represent the relative penetration of electromagnetic energy at different frequencies or times (ie. signal) (Figure 3), but does not include allowance for noise (ie. signal to noise). “Depth of investigation” or “depth of detection” are more complex quantities which are derived by factoring in noise levels into “depth of penetration” calculations.

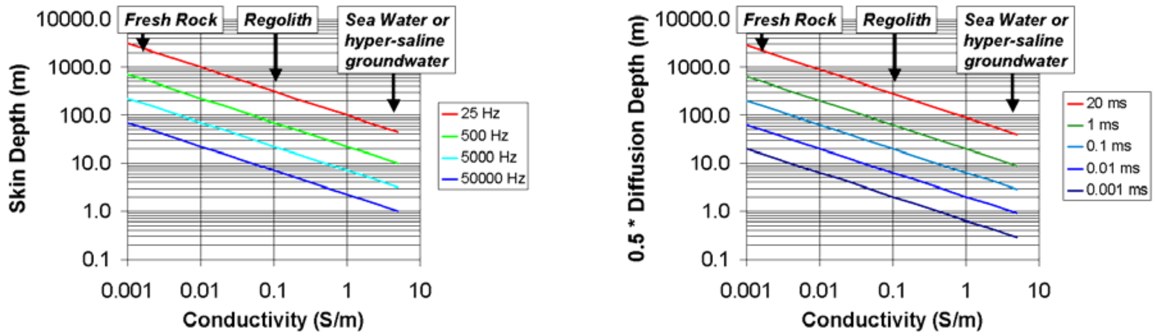

Figure 3. Skin depth and diffusion depth charts.

Since the depth of penetration is a function of frequency or delay time, measurements made at a number of frequencies or delay times can be used to determine the variation in conductivity with depth. The process of determining conductivity is akin to taking the difference between measurements at successive frequencies or delay times. An unfortunate consequence of this differencing procedure is that sensitivity to noise increases. Shallow vertical resolution is determined by high frequency / early time performance. The depth of penetration is determined by performance at low frequency / late time. Intermediate frequencies / times provide the detail between these extremes. Factors in the success of transformation of recorded response to conductivity include bandwidth, the distribution of intermediate measurement frequencies or times, noise levels, the system geometry (due to its effect on the sampling volume), knowledge of variations in system geometry at different measurement points, spatial sampling and spatial processing functions.

Transformation of measured response to conductivity can help to overcome the complexity present in the measured response due to the system’s hardware, software and geometry characteristics. Ideally, the final output of a detailed EM survey would be a 3-D conductivity distribution of the subsurface. This would be the optimum output for data integration and follow-up work.

Due to difficulties in computing the response for 3D conductivity distributions, practical conductivity transformations are restricted to those employing a “1D” approximation for each recorded location. Measurements taken at each location are treated in isolation from those acquired at other locations. The ground is assumed to show conductivity variations in only one direction (ie. along a vertical axis), and hence all conductivity layers are infinite in horizontal extent. A special case used with single frequency or single time delay measurements is a “halfspace” where the subsurface is considered to have uniform conductivity both vertically and horizontally. In reality, the 1D criteria will never be exactly satisfied, but the results can be useful provided the ground has a reasonable degree of horizontal uniformity over the footprint of the measurement. This is often the case in regolith and flat to shallow dipping sedimentary environments. Hence, conductivity is the primary form of output for some applications (eg. regolith mapping and mapping for salinity and groundwater). Tabular, steeply dipping targets do not satisfy a 1D assumption, and hence are misrepresented on conductivity sections that employ this assumption. This is one of the reasons why conductivity is a secondary form of output for discrete conductor applications.

3. FIELD PROCEDURES

Electromagnetic measurements can be made using ground-based instruments, but also using instruments mounted in specially adapted aircraft. The latter enables rapid systematic coverage over large areas for relatively low cost, without causing ground disturbance. In doing so, however, there is usually some trade-off in spatial resolution, near surface vertical resolution, and depth of penetration against the best possible ground-based data (see Smith, et al. (2001) for an example of a comparison of ground and airborne EM methods over the same target). Given knowledge of the likely conductivity variations in the survey area, simplifying assumptions can sometimes allow flexibility in the choice of EM method, allowing cheaper, less sophisticated options to be used to produce an adequate outcome.

Airborne EM

Typical airborne EM (AEM) systems include:

1. Time domain (TD) fixed wing airborne EM (AEM) systems, such as TEMPEST (Lane, et al., 2000) (Figure 4) and GEOTEM (Smith, et al., 1996);

2. Time domain (TD) helicopter systems, such as Hoistem (Boyd, 2001);

3. Frequency domain (FD) helicopter systems, such as DIGHEM (Huang and Fraser, 2001) (Figure 5) and Hummingbird (Valleau, 2000); and,

4. Frequency domain (FD) fixed wing EM systems, such as that operated by the Geological Survey of Finland (GTK) (Poikonene, at al., 1998).

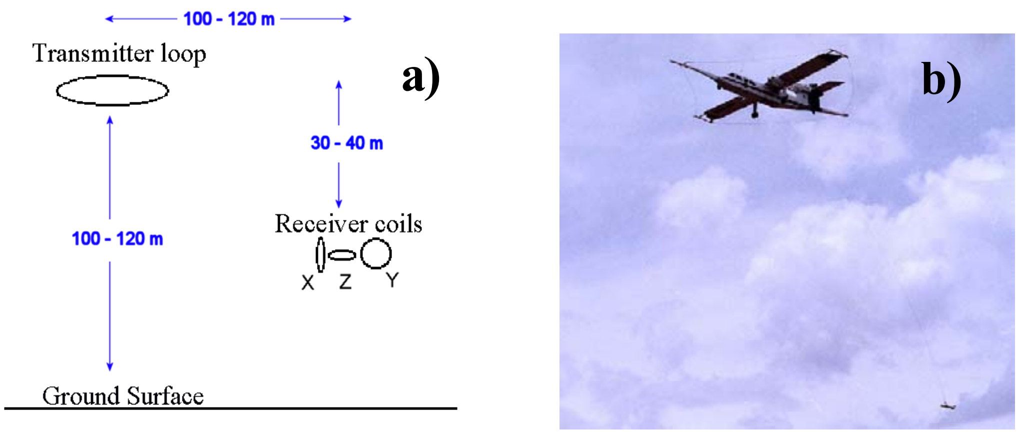

Figure 4. a) Transmitter loop and receiver coil configuration for the TEMPEST AEM system. b) TEMPEST AEM system on a Trislander aircraft in 1999. The transmitter loop is draped around the nose, tail and wingtips of the aircraft. The receiver coils are housed in a bird trailed behind the aircraft on a tow cable. The bird is visible in the lower right corner of the photograph. The tow cable is only partially extended in this photograph. Processed data typically consist of measurements at 15 delay times ranging in time from 0.013 to 20 milliseconds after a step change in the transmitted current.

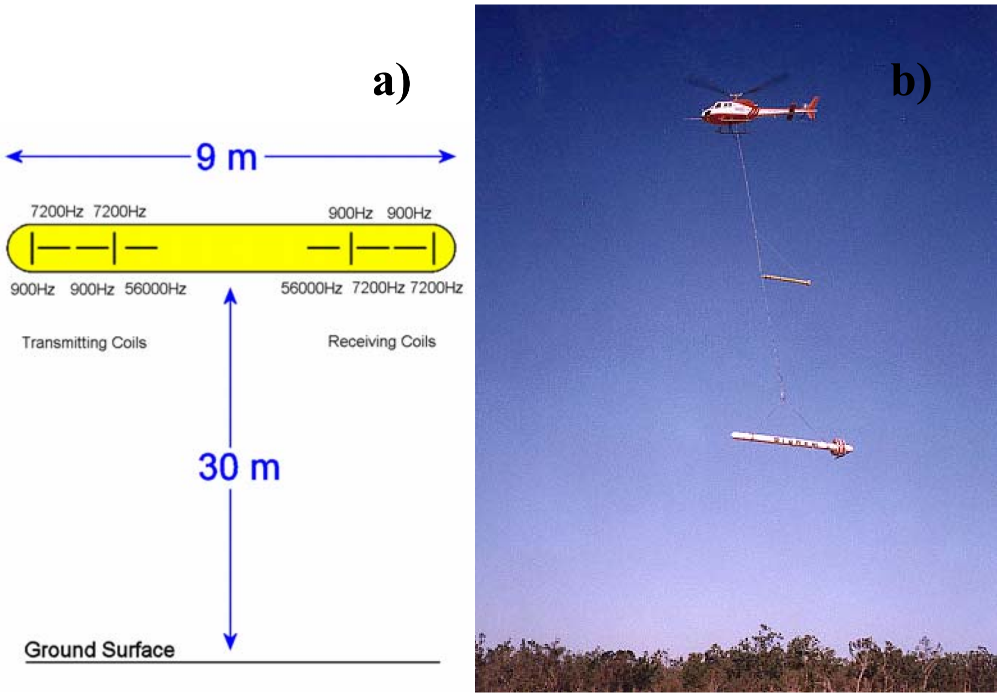

Figure 5. a) Arrangement of the 5 separate transmitter and receiver coil pairs for one of several possible configurations of the DIGHEM system. Each coil is shown as a black bar inside the bird shell. There are two horizontal dipole ("coaxial") coil pairs and three vertical dipole ("coplanar") coil pairs in this example. b) DIGHEM system preparing for operations. The small yellow bird halfway down the tow cable is a magnetometer bird. The EM bird is the larger bird at the end of the tow cable, 30 m below the helicopter.

Data are acquired at relatively close spacing along flight lines (3 to 15 m). The use of along line processing functions reduces the independence of the individual measurements. The selection of the spacing between lines is one of the major decisions to be made when planning a survey as it is a major influence on survey cost for a given system. The expected spatial variability of the subsurface conductivity needs to be considered. A rule of thumb is that the maximum line spacing should be approximately 0.5 times the across-line horizontal dimension of the smallest feature to be detected (after noting the effect of the system footprint). This ensures that features of this size will be sampled on at least 2 adjacent lines. For example, a line spacing of 200 m or less would be desirable for detecting the response of a nickel sulphide orebody with a strike length of 400 m. It is also worth bearing in mind that the grid cell size of plan view images will generally be about 0.25 to 0.2 times the line spacing.

Typical production rates are between 50 and 120 line km per hour of operation. Weather conditions and operational procedural requirements can restrict production to 20 to 30 hours per week.

AEM methods are generally combined with other geophysical methods, for example magnetics, acquisition of a digital elevation model (DEM) and/or gamma ray spectrometrics. The operation of the EM system, the type of magnetics system utilised, the terrain clearance of the magnetic sensor and the choice of line spacing can degrade the quality of the output of the magnetic system from that which could be obtained with a dedicated airborne magnetic system. However, the differences are not always significant. Similarly, weight restrictions, the terrain clearance of the gamma ray detector and the line spacing can degrade the quality of the output of the gamma ray spectrometric system from that which could be obtained with a dedicated airborne gamma ray spectrometric system.

The overall accuracy of a DEM derived from airborne geophysical measurements (Figure 6) depends on the altimeter and satellite navigation instruments used. A standard differential GPS receiver and radar altimeter would result in elevation values with a standard deviation of around 2 m in flat terrain. A carrier phase GPS receiver and scanning laser altimeter are capable of sub-decimeter accuracy in flat terrain (Stone and Simsky, 2001, Carter, et al., 2001).

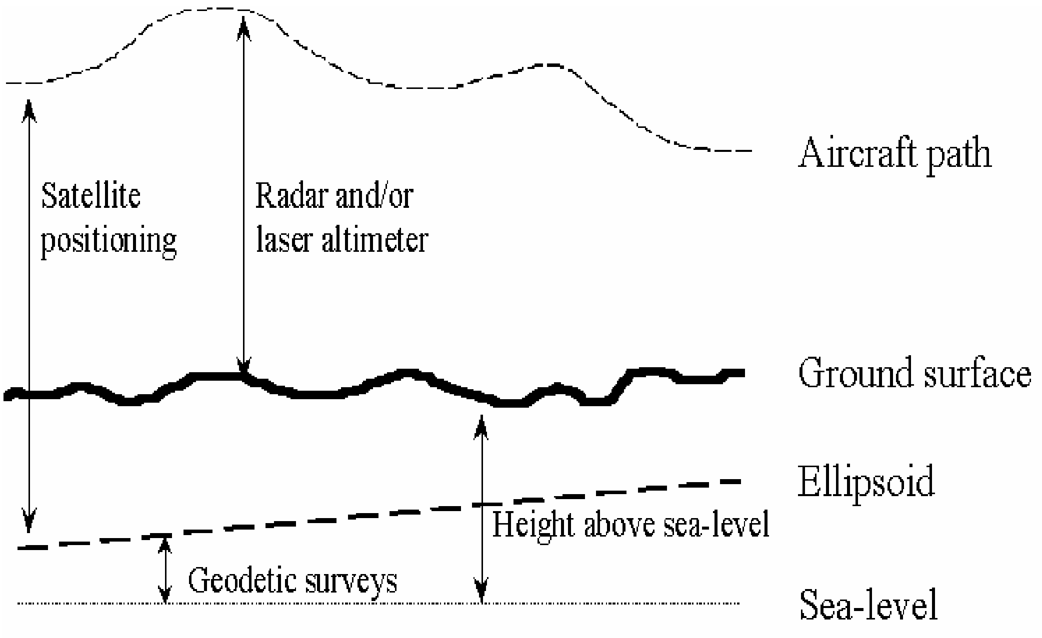

Figure 6. Method for deriving elevation (ie. the height above sea level) from airborne measurements. A GPS system on the aircraft measures the height of the aircraft above the ellipsoid. An altimeter measures the height of the aircraft above the ground ("terrain clearance"). The separation between the ellipsoid and sea level is known from geodetic surveys. Height above sea level is calculated as height above the ellipsoid plus the ellipsoid – sea level separation minus the terrain clearance.

Ground EM

Ground EM measurements are acquired at points along line traverses or at individual spot locations using either FD or TD instruments.

The most popular FD ground EM instruments are the Geonics suite of instruments (eg. EM31 (Figure 7), EM34 and EM38). These instruments take measurements using a single transmitter frequency and apply an approximate transformation to convert the output to apparent conductivity (ie. the halfspace conductivity that would produce the observed response). For further information on the theory of these instruments see McNeill (1980). Production with the smaller instruments that have the transmitter and receiver coils in a fixed assembly carried by an operator (eg. EM31 and EM38) can be several line km per hour of operation. Production with the larger EM34 system can be up to 1 km per hour depending on the transmitter and receiver coil separation and station spacing. Depth of penetration depends on the separation and orientation of the transmitter and receiver coils, ranging from 0.75 to 1.5 m for the EM38, 3 to 6 m for the EM31 and 10 to 60 m for the EM34. The addition of a data logger and GPS satellite navigation can substantially improve survey productivity and accuracy.

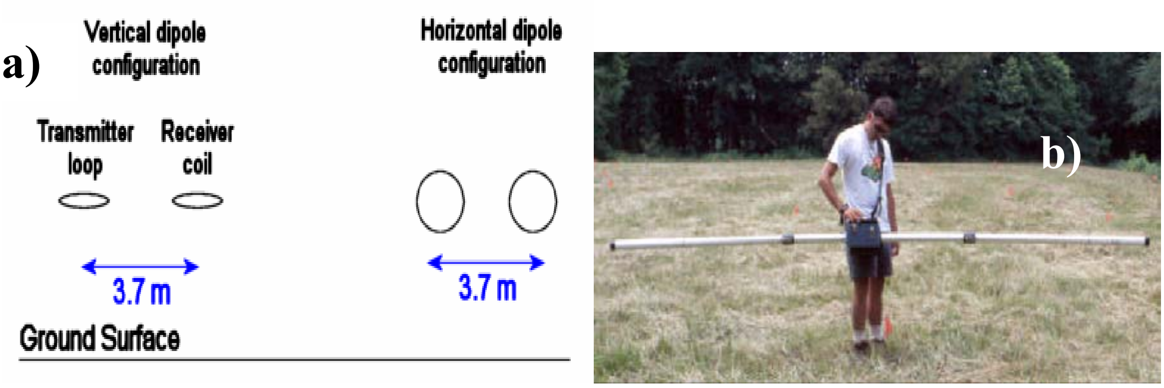

Figure 7. a) Transmitter loop and receiver coil configuration for the EM31 frequency domain ground EM instrument showing both vertical and horizontal dipole configurations. b) EM31 instrument in operation.

Time domain ground EM instruments use a square loop for the transmitter and either a small loop or a specifically designed coil for the receiver (Figure 8). A team of 2 or more people is generally required to lay out the wires for the transmitter loop at each station. Instruments are marketed under various trade names by several companies (eg. Zonge GDP, Zonge NanoTEM, PROTEM, SMARTem, SIROTEM). Output consists of the response amplitude for a range of delay times after the current in the transmitter loop is turned off. A repetitive waveform is utilised, and the response is averaged over a period of time to improve the signal to noise. This process can last from just a few seconds to several minutes. As a guide for ground TEM survey design, the loop side length needs to be between 0.25 and 1.00 times the required depth of investigation. Production depends on the nature of the terrain, vegetation cover, station spacing and size of the transmitter loops. Typically, production of 1 to 3 line km per day is achieved.

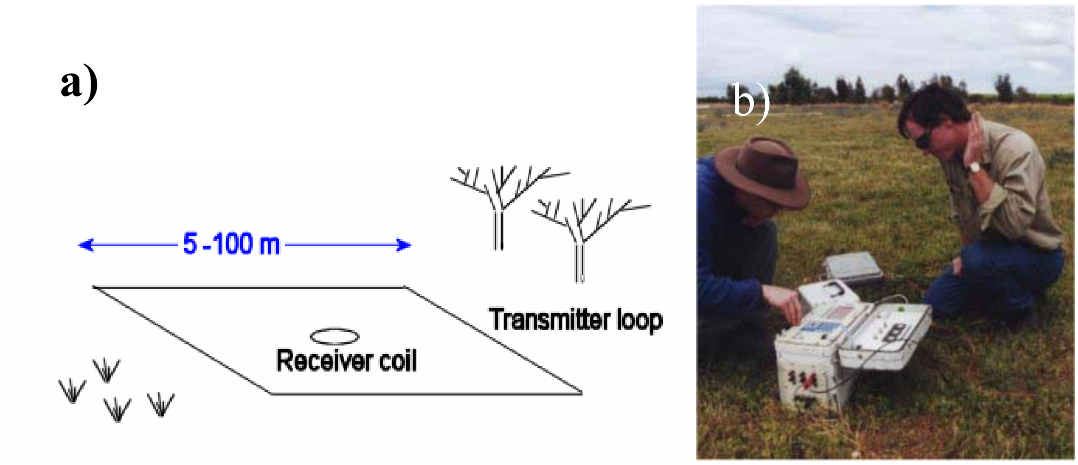

Figure 8. a). Transmitter loop and receiver coil configuration for typical in-loop time domain ground EM. b). Time-domain ground EM instruments (NanoTEM transmitter and GDP data recorder). (Photo courtesy: Mike Wall, University of Adelaide).

EM instruments are also used in borehole surveys to measure the conductivity of material within a short distance of the borehole wall. An example of a borehole conductivity logging tool is the Geonics EM39 instrument. Further information on the theory and practice of borehole conductivity logging can be found in McNeill (1986).

4. DATA PROCESSING AND PRESENTATION

Traditionally, data from EM surveys were viewed as line profiles of the measured response. This is still the principal mode of presentation when searching for the response of a discrete conductor. Contour maps and images are the basic presentation forms for displaying the spatial patterns in EM data. Increasing use of this style of presentation spurred an interest in AEM as a regolith and geological mapping tool, since an association between systematic variations in the conductivity and thickness of *in situ* regolith materials and bedrock type became apparent in many areas (Palacky, 1989).

Data Processing

Single frequency ground instruments (eg. EM31) produce output (eg. apparent conductivity) that can be readily viewed as along line profiles or images of the single parameter. Data reduction and processing for FD airborne EM surveys and TD ground and airborne EM systems is quite involved. The outputs for FD systems are levelled and filtered in-phase and quadrature amplitude together with levelled and filtered apparent conductivity for each measurement frequency. See Valleau (2000) and Huang and Fraser (1999) for further information on the processing of FD AEM data. The outputs for TD systems are levelled and filtered window response amplitudes for a series of delay times ("windows") (eg. the profiles at the top of Figure 9). See Duncan, et al. (1998), Strack (1992) and Lane, et al. (2000) for further information on the processing of TD ground and airborne EM data.

Simple Image Presentations

Data from frequency domain AEM surveys are typically presented as images of the apparent conductivity at different transmitter frequencies. The depth of penetration is greater at lower frequencies, but the actual depth of penetration at a particular frequency is a function of the subsurface conductivity. The more conductive the ground, the shallower the penetration (Figure 3). Images of apparent conductivity for a single frequency will thus represent some form of average conductivity from surface to different depths across the survey area depending on conductivity.

TD EM systems can have complex transmitter waveforms and response functions. Although generally true, later windows do not necessarily correspond with greater depth of penetration. Greater amplitude does not necessarily correspond with higher conductivity. Images of response amplitude or apparent conductivity represent time slices of response rather than slices at constant depth across the survey area. It is important to keep this in mind when working with images of window data.

For any airborne EM system, the geometry of the transmitter loop, receiver coil and ground elements are continually varying along each line. These variations have a significant effect on the measured ground response. Approximate corrections can be applied to the measured response for these geometry variations (Green, 1998a) provided the variations are known with sufficient accuracy. Application of these corrections reduces the number of variables affecting the response, thus simplifying interpretation and enhancing the effectiveness of subsequent processing should this processing not account for these geometry variations separately.

Methods of processing and displaying multi-spectral remote sensing data such as principal component analysis can be applied to multi-frequency or multi-time delay EM data (Green, 1998b). Computational demands are generally low, and large AEM surveys can be processed quite quickly. These methods are often applied to AEM data to obtain a quick overview of the spatial and "spectral" (time or frequency dimensions) patterns in the data. The disadvantage of these methods is that it remains difficult to relate the output to conductivity and depth, and hence difficult to integrate the products with other subsurface information.

Transformation to Con*d*uctivity

Through a combination of circumstances (eg. discrete high conductance base metal targets, resistive terrain, narrow bandwidth, poor signal to noise ratio), the early airborne and large ground EM systems were used solely for the detection of discrete conductors associated with base metal mineralisation. These were essentially binary systems where there was either an anomalous response or background response. As a result of improvements to EM systems, it has become possible to map more subtle contrasts in electrical properties, and it is increasingly worthwhile to pursue methods to convert the measured response to conductivity.

The measured response needs to be converted to conductivity to determine how conductivity is changing with depth and position. As previously discussed, all of the practical methods to convert response to conductivity assume that the subsurface conductivity is horizontally layered (ie. a 1D approximation). Iterative inversions determine a model of the subsurface conductivity structure that has a response that matches the observed response. These procedures are computationally intensive, particularly if a large number layers are used. Two classes of inversion are commonly used. "Smooth model" or "Occam" inversions (Farquharson and Oldenburg, 1993, Zhang and Oldenburg, 1999) use many layers but link the conductivity of each layer to that of adjacent layers and to a reference model through a model objective function. The layer thickness values are generally fixed, with only the layer conductivities being free to vary during the inversion process. In the other class, the layer thickness and conductivity parameters are independent of each other and both the layer thickness and conductivity values are generally allowed to vary (Sattel, 1998). The number of layers is far more restricted than is the case in "smooth model" inversions. Approximate transformation methods such as those used by "EMFlow" (Macnae, et al., 1998) employ various approximations and only a single iteration. This reduces the time taken to convert response to conductivity in comparison with inversion methods.

Presentation of Conductivity Data

Conductivity data can be displayed in a variety of ways. Although the 1D assumption means that each observation is treated in isolation and that the subsurface is perfectly horizontally layered, conductivity-depth values calculated for each observation can be stitched together into sections to provide a representation of the 2D variation of conductivity. This is sometimes referred to as a "parasection". Further, the conductivity depth profiles can be combined into a 3D gridded volume from which arbitrary sections, horizontal depth slices and isosurfaces can be derived (Lane and Pracilio, 2000).

Distillation of essentially continuous and gradational conductivity distributions into discrete conductive "units" or layers can be useful for summarising information from large surveys. This is particularly so when the application calls for mapping the conductivity, depth to top and thickness of a semi-continuous layer of transported or *in situ* regolith. Several (semi-)automated schemes exist for picking the layer boundaries, for example layered inversion (Sattel, 1998), conductive unit parameters (Lane, 2000) and inflection point analysis (Hunter and Macnae, 2001). Lawrie, et al. (2000) and Worrall, et al. (2001) contain examples comparing calculated layer boundaries with boundaries interpreted from lithological mapping.

5. INTERPRETATION

Interpretation of EM data can be thought of as a four-step process. First, the data are assessed in terms of quality. Next, the data are related to subsurface conductivity. Then the conductivity distribution is related to units of more direct significance to the application (eg. discrete massive sulphide bodies in base metal exploration applications, pore fluid salt concentration in soil salinity applications). Finally, the mapped EM response is fully integrated with all other information in the project area and recommendations for further action are determined.

The assessment during the first step establishes limits for how far the data can be pushed before noise features or other artifacts become significant. During the second step, the measured data are converted to a meaningful physical property distribution. The limitations of the data, model and the conversion algorithm are noted at this time so that a suitable appreciation of the fidelity of the output in relation to the true conductivity distribution can be established. The third step involves an analysis of the controls on conductivity so that conductivity can be related to something of more direct relevance to the application. The final integration step generally involves a broad range of inputs from the project team. On some occasions, the data integration exercise prompts another iteration through earlier steps with a different focus or different set of constraints.

An understanding of the controls on bulk electrical conductivity is required for interpretation. Sauer, et al. (1955) present a model of conduction for porous aggregates immersed in a conductive fluid that can in turn be related to conduction along three separate pathways - conduction through the solid material, conduction through the pore fluid and conduction across the interface between solid material and the pore fluid. Bulk conductivity is then a function of the conductivity of the solid material, conductivity of the pore fluid, the electrical properties of the solid/fluid boundary, porosity, arrangement of the pores and saturation.

Various empirical relationships have been developed between some or all of the components of this model and conductivity. In the context of sedimentary units within a petroleum exploration setting, Archie (1942) used the expression

$$\sigma_e = \frac{1}{a}\varphi^m s^n \sigma_w$$

where σ_e is the bulk effective conductivity, σ_w is the pore fluid conductivity, φ is the porosity, s is the saturation, and a, m and n are derived factors ($0.4<a<2$, $1.3<m<2.5$, $n\approx2$). The “formation factor” is defined as a/φ^m. This expression assumes that contributions related to conduction through the solid material and conduction across the solid/fluid boundary are not significant. These assumptions hold true when the pore fluid is moderately to highly conductive and clay minerals are low in abundance.

Expressions that describe the bulk conductivity of partially saturated materials containing clays and low salinity pore fluid are far more complex. When considering the bulk conductivity of fresh rock and low salinity groundwaters, a term related to the conductivity of the solid materials (σ_s) needs to be considered. Conduction can be electronic, in the case of sulphide minerals, or related to cation exchange for many clay minerals. This term dominates when considering many graphitic or metal sulphide lithologies.

Regolith materials are variably conductive, by virtue of differing physical and chemical properties. Bodies of regolith materials with the same parent material and subject to the same weathering processes can produce spatially coherent responses in electromagnetic data. Unfortunately, regolith materials do not have unique conductivity values. This is perhaps obvious since regolith conductivity is strongly influenced by saturation and pore fluid conductivity and these vary from one area to the next. Thus, it is not possible to consult a reference table of conductivity values for different regolith materials and use this information to unambiguously separate different classes of regolith material (eg. separate transported regolith from *in situ* regolith, *in situ* regolith derived from parent material A from that derived from parent material B, or regolith unit 1 from regolith unit 2). Some educated guesses based on previous experience in similar environments can be made when relating conductivity variations with geological units. However, strategic drillhole lithological logging, conductivity logging and detailed surface mapping are required to verify and quantify relationships.

6. APPLICATIONS WITH SELECTED EXAMPLES

Discrete Conductors

Massive sulphide deposits are localised bodies that generally have substantially elevated solid material conductivity. When conductive regolith is present, an understanding of the regolith is required to correctly interpret the EM response of a discrete conductor as the regolith response may mask or modify the response of the discrete conductor. The converse is also true in that the presence of a discrete conductor or basement conductor will influence the interpretation of regolith response. An appreciation of the response of discrete conductors can be obtained from examples in Dentith, et al. (1994). McIntosh, et al. (1999) present a case history of gravity, IP and TD ground EM for the Las Cruces massive sulphide deposit located beneath 120 m of conductive transported Tertiary sediments. Leggatt, et al. (2000) present examples of the airborne EM response of base metal deposits in Canada. Wolfgram and Golden (2001) present examples of the airborne EM response of several nickel sulphide deposits. Further examples are provided by Peters (1996, 2001).

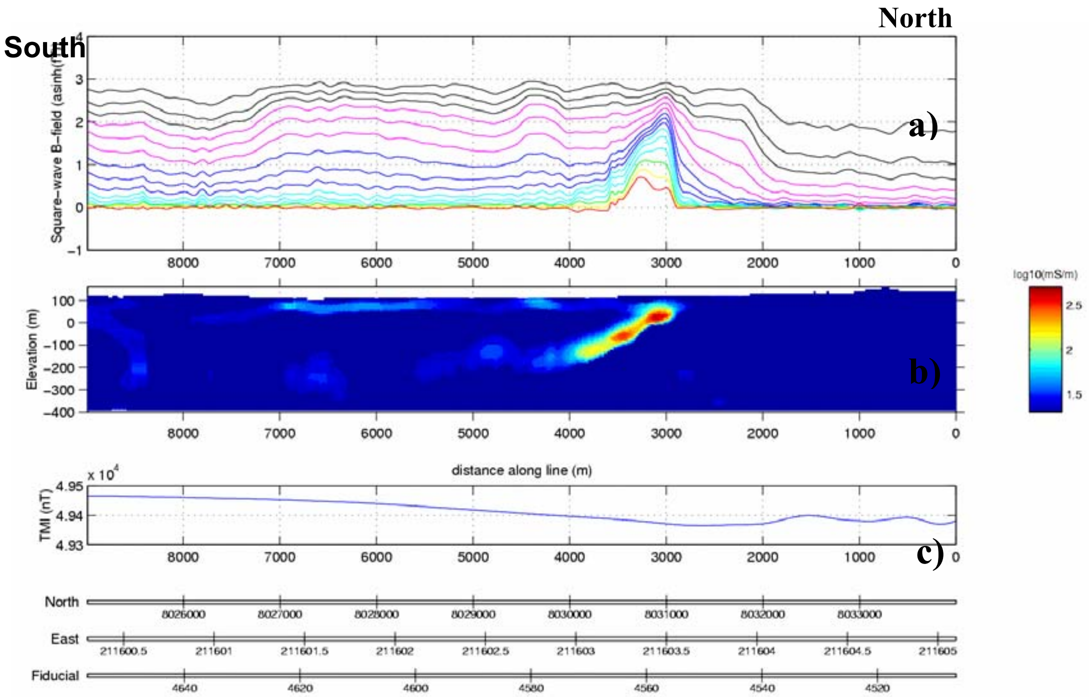

Figure 9. a). TEMPEST AEM Z-component square-wave B-field response profiles. b). conductivity section; and, c). total magnetic intensity profile for line 10281 (211600 mE) over the Walford East base metal prospect, Queensland (Lane, et al., 2000).

The example in Figure 9 illustrates the usefulness of applying a conductivity transformation in a situation where the input data are sufficiently broadband and accurate and where the 1D assumption in the transformation is reasonable (ie. dips are shallow or flat such that conductivity variations within the system footprint can be approximated by horizontal layers). The presence of a strong dipping conductor, corresponding to semi-massive to massive pyrite, is obvious in the profiles of response between 2900 and 4000 m distance along the line. The characteristics of a variably conductive regolith layer and extensions to basement conductors further to the south are not immediately obvious in the profiles yet are well imaged in the conductivity section. The sedimentary sequence in this location is essentially non-magnetic, enhancing the value of mapping regolith and basement conductors with AEM methods.

Kimberlites

Macnae (1995a, 1995b) discusses the application of geophysics to exploration for kimberlites and lamproites. In general, these diatremes are associated with discrete geophysical anomalies related to a physical property contrast between the intrusion and the host rock. Jenke and Cowan (1994) present examples of ground and airborne EM response for pipes in the Ellendale region of Western Australia. The majority of the pipes with a recognisable EM response show a localised enhancement in near-surface conductivity. This may be due to a combination of factors such as the increased depth of weathering of the kimberlitic material relative to the host, the presence of clays with elevated solid material conductivity or increased conductive pore fluid levels in the weathered kimberlite. Smith, et al. (1996) present examples of the airborne EM response of pipes in the Lac de Gras region of Canada. In this environment, the weathered kimberlitic material is more deeply scoured during glaciation leading to an association between kimberlites and small freshwater lakes containing conductive lake-bottom clays. An increase in near surface conductivity is thought to result from a combination of the conductive lake bottom sediments and saturated weathered kimberlite.

Groundwater

Potts (1990) presents examples from the Murray Basin in southeast Australia of the use of an EM34 instrument to define low conductivity zones associated with buried shoestring sands. These sands, in the depth range 0 to 20 m, have lower solid material conductivity and lower pore fluid conductivity relative to the surrounding clays. Bores are used to pump low salinity groundwater from the sands.

Gettings, et al. (1999) and Wynn, et al. (2000) describe the use of TD airborne EM to map aquifer features in the San Pedro Basin, USA. There was generally a good correlation between the uppermost conductor recognised in conductivity sections and water table depth. The increase in conductivity below the water table possibly reflects an increase in saturation by conductive groundwater (20-100 mS/m) below the water table. Paine, et al. (2000) and Rodriguez, et al. (2001) used TD airborne EM and conductivity logs for groundwater investigations in the Middle and Lower Rio Grande, USA. The conductivity of sediments in the Middle Rio Grande was found to be inversely proportional to grainsize, with implications for hydraulic permeability.

Fitterman and Deszcz-Pan (2001) used FD airborne EM, TD ground EM soundings and conductivity logs, to map characteristics of a shallow aquifer in the Everglades region of the USA. The extent of seawater intrusion was mapped by noting the transition when moving inland from high conductivity to low conductivity at shallow depth. The depth to the base of this shallow aquifer was mapped by picking the depth associated with a change in conductivity.

Salinity

Slavich and Petterson (1990) present examples of the use of an EM38 instrument to estimate soil pore fluid salinity in the 0 to 0.6 m depth range. Cook, et al. (1992) and Cook and Kilty (1992) present examples from Borrika (approximately 50 km east of Murray Bridge in South Australia) of ground and FD airborne EM methods used to map recharge. Shallow conductivity was inversely proportional to recharge rate. Areas of low recharge had higher saturation, higher pore fluid conductivity and hence higher conductivity than areas of high recharge.

Bennett, et al. (2000) provide a summary of the use of EM38, EM31, EM34 and EM39 instruments in southwestern Australia and conclude that most of the observed variation in conductivity can be correlated with various measures of salinity (electrical conductivity of the soil saturation extract, EC1:5, percentage by weight of chloride ions). Variations in saturation, porosity, arrangement of pores, conductivity of solid material (clay content) and temperature were minor contributors to the observed variations in conductivity.

Street (1992), George, et al. (1998), Lane and Pracilio (2000), Lawrie, et al. (2000), and Lane, et al. (2001) present examples of the application of airborne EM to hydrological investigations in areas of dryland salinity in Australia.

Paine, et al. (1997) present an example of using FD airborne EM for mapping near-surface conductivity plumes associated with leakage of brines from petroleum wells in Texas, USA.

Mapping

Palacky (1989) was instrumental in recognising the potential for mapping geological units in weathered terrains via the response of conductive *in situ* regolith. Attention was drawn to the local-scale influence of parent lithology, together with structure and alteration, over the *in situ* regolith clay mineralogy, clay content, porosity and in some instances, even groundwater conductivity. The local-scale consistency of these factors, and their impact on conductivity, enables units with the same parent lithology to be identified and mapped. Based on a number of studies, it was found that saprolite was generally the most conductive regolith horizon, and that saprolites developed over mafic and ultramafic parent lithologies were generally thicker and more conductive than those developed over felsic lithologies.

Two well documented examples of regolith mapping applications in the Yilgarn Province of Western Australia are the Lawlers study area (Emerson, et al., 2000, Bishop, et al., 2001, Emerson and Macnae, 2001, Macnae and Bishop, 2001, Munday, et al., 2001) and the Balgarri or Grant's Patch study area (Lane, 2000, Worrall, et al., 2001, Bell, et al., 2001, Meyers, et al., 2001). A comparison of the regolith section and conductivity sections derived from TD ground and airborne EM measurements for Grant's Patch is shown in Figure 10. The conductive interval correlates well with *in situ* saprolite. This result was confirmed with downhole conductivity measurements. The spatial patterns in near-surface conductivity, thickness and conductance were used in a complementary manner with information from aeromagnetic and gravity data to map bedrock geology as part of a gold exploration project (Meyers, et al., 2001).

Rutherford, et al. (2001) examined the regolith material from a number of drill holes at the Cawse lateritic Ni deposit, Western Australia. The regional watertable is located near the base of the regolith profile at a depth of 50 m or more. Hence, the degree of saturation is an important control on conductivity in the unsaturated zone at depths of less than 50 m. Soluble salt content is also an important control on the electrical conductivity. A coincidence of elevated conductivity and Ni enrichment was noted at hydromorphic barriers, but the relationship between conductivity and Ni grade was quite variable. Subdivision of the regolith into hydrostratigraphic units and identification of hydromorphic barriers enabled a better understanding of the spatial patterns in electrical conductivity to be obtained. Armed with this knowledge, airborne EM data could be used to locate impermeable barriers and faults that are the important controls on the development of Ni laterite mineralisation.

An airborne EM survey was flown over an area surrounding the Challenger gold deposit, central South Australia, for Geoscience Australia, Primary Industries and Resources South Australia and the Cooperative Research Centre for Landscape Evolution and Mineral Exploration. The deposit is hosted by granulite-facies granite gneiss (Bonwick, 1997). Topographic relief is subdued and the presence of a variable thickness (generally less than 50 m) of weathered and transported material makes it difficult to map subsurface features using surface mapping techniques. The patterns in an image of conductance of near-surface material (Figure 11) reflect very deep channels (200 m +) filled with conductive material (red), areas of thinner conductive transported cover generally less than 30 m thick (yellow and green areas with dendritic outline), areas of *in situ* conductive regolith (green and yellow linear and curvi-linear zones) and areas without conductive regolith (blue). The pair of N/S trending channels were interpreted to be up to 200 m deep (Figure 12) and filled with sediments carrying saline groundwater. A drill hole (Figure 11) into the eastern channel encountered 210 m of sediments and lignite before passing into gneissic basement material. The water resource encountered in basal sands of the channel is being evaluated for use in the proposed mine. The host gneissic material is not easily differentiated either visually or using magnetics. In areas where the conductivity of basement material is not obscured by transported material, basement is separated using EM data into ovoid and elongated resistive areas and surrounding mantles where conductive *in situ* regolith is developed over fresh rock. The sub-crop of the Challenger deposit is located in a zone of conductive regolith (Figure 11). The source of the variability in the nature of *in situ* regolith materials is unknown. The bedrock is uniformly resistive, however it is probable that weathering may have picked out subtle variations in bedrock composition and/or structure.

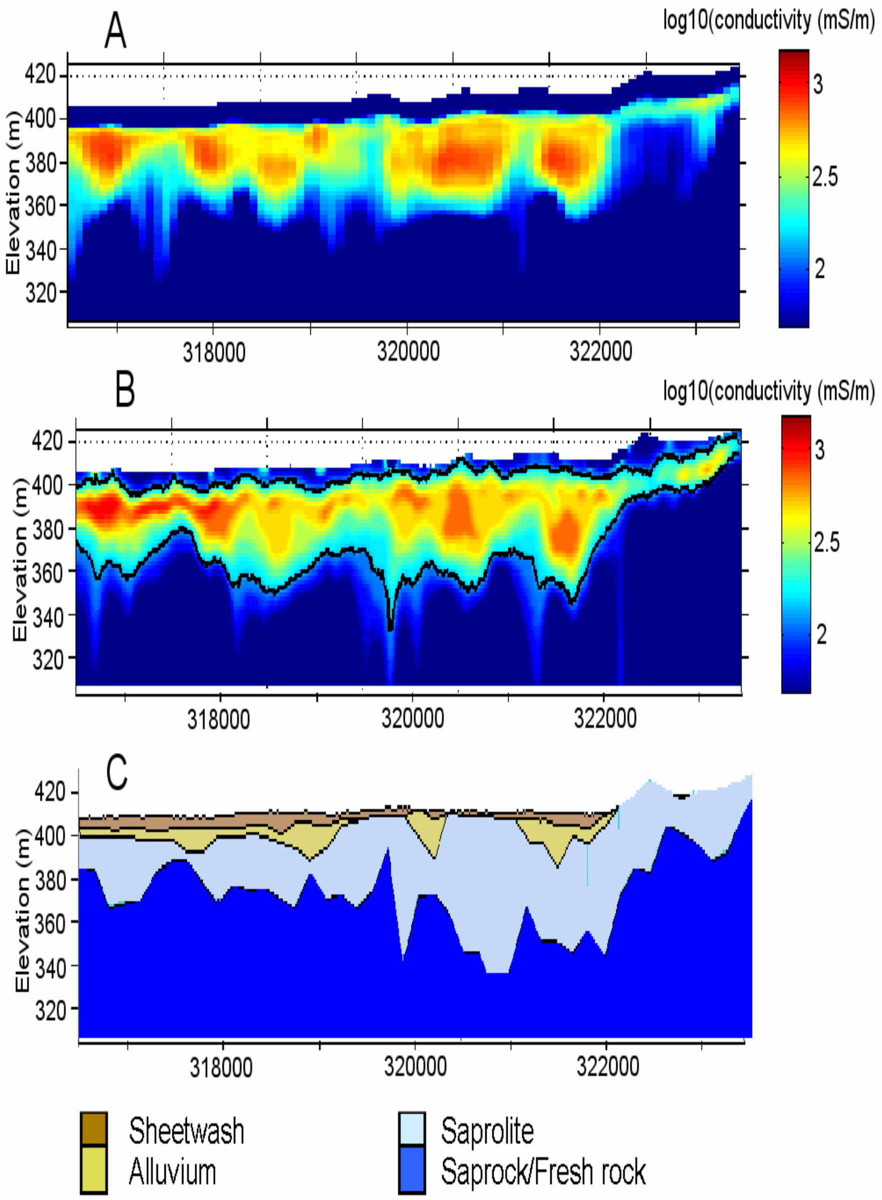

Figure 10. Conductivity sections for a) PROTEM ground EM and b) TEMPEST airborne EM data along line 6626720 mN at Grant's Patch, Western Australia. The upper and lower bounds of a 'conductive unit' with a minimum threshold of 100 mS/m are shown over the TEMPEST section. The regolith profile derived from drilling c) is also shown (Worrall, et al., 2001).

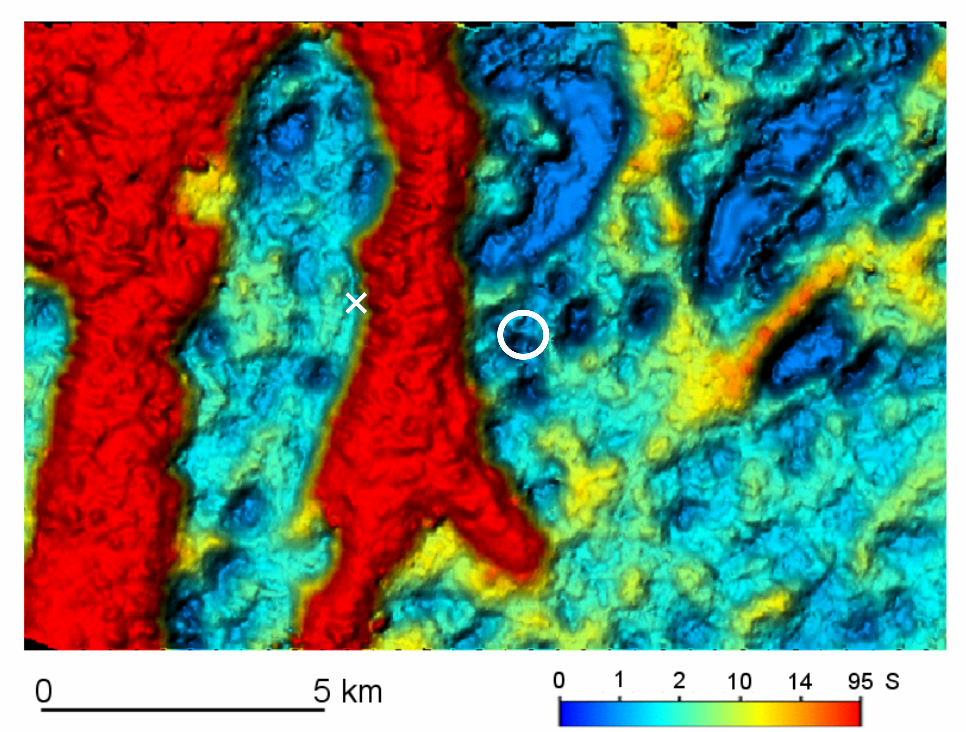

Figure 11. Image of conductance of the conductive unit defined by a variable conductivity with a minimum threshold of 30 mS/m, calculated from TEMPEST AEM data for the Challenger area, South Australia. The location of the Challenger deposit is shown with a white circle. The location of a borehole into one of the deep channels is shown with a white cross.

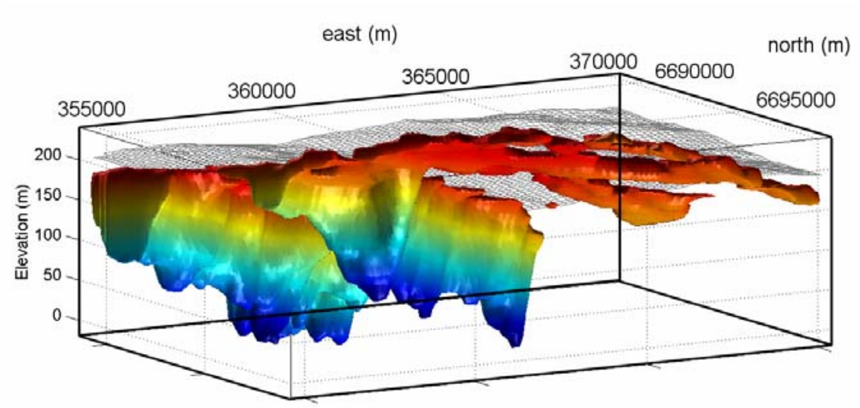

Figure 12. A conductivity isosurface from the Challenger area, South Australia, derived from TEMPEST AEM data. Elevation is in metres above sea level. The grey mesh representing the surface elevation shows very subdued topography. The isosurface, enclosing all material with conductivity greater than 200 mS/m, is coloured by elevation above sea level from blue (sea level) to red (200 m above sea level). The conductive material includes two deep channels of transported material in the west and thinner transported material and in situ regolith in the east. The viewpoint has an azimuth of 150° and an elevation of 10° below the horizontal (Skirrow, 2001).

Regolith stripping for gravity interpretation

In situ and transported regolith materials most commonly have a negative density contrast with underlying fresh bedrock. In areas where the thickness of regolith varies laterally, the gravity response of the regolith layer can substantially contribute to the local-scale gravity response. This will produce many false anomalies and mask the true anomaly of an underlying target (Braine and Macnae, 1999; Bell, et al., 2001) unless the regolith contribution to the gravity response can be independently determined and subtracted from the local gravity response.

EM methods can be used to map the depth to the base of the near-surface conductive layer (Figure 13). Under suitable conditions, this interface will relate to the transition from regolith to fresh rock. After selecting a representative density for the regolith material, the gravity response of the regolith layer is calculated and subtracted from the gravity data. The residual reflects the gravity variations due to fresh bedrock materials, departures from the assumption of lateral and vertical uniformity in regolith density and local differences between the interpreted base of the conductive layer and the actual regolith / fresh rock interface.

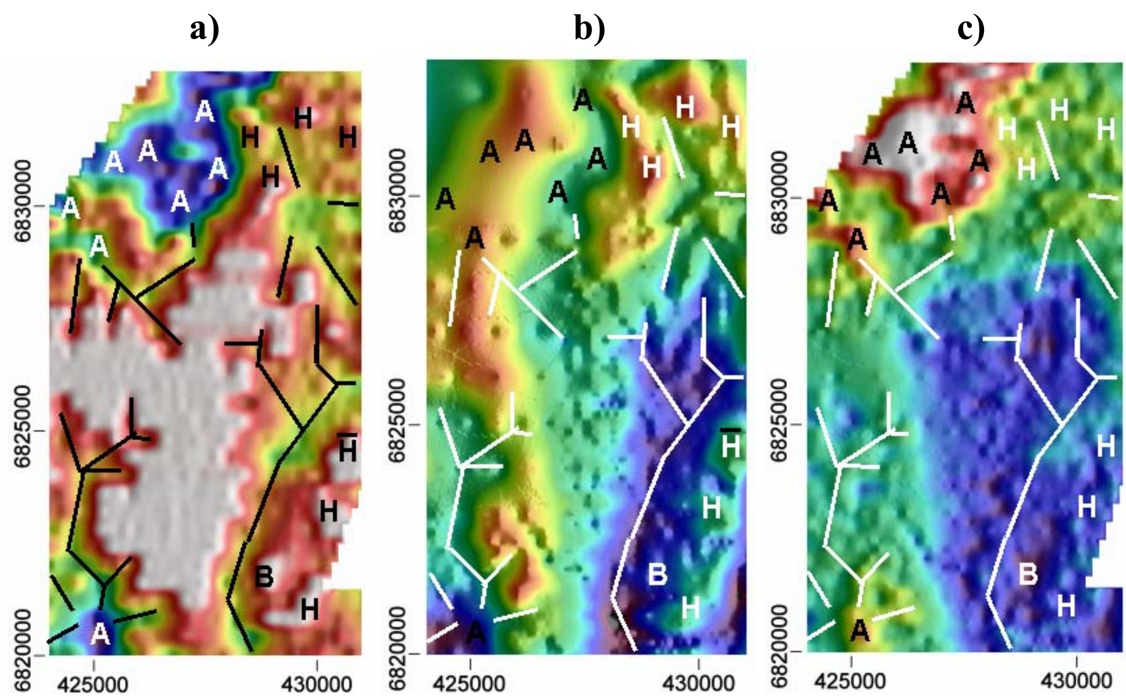

Figure 13. a) Depth to base of conductive regolith, based on manual interpretation of conductivity sections derived from TEMPEST AEM data. The linear colour scale ranges from less than 25 m (white-red) to 100 m (blue-purple). Locations labelled with "H" are local bedrock topographic highs with associated residual gravity highs. "B" is a local bedrock topographic high without an associated residual gravity high. Locations labelled with "A" are areas with thick regolith. Lines mark the axes of regolith troughs. b) Residual Bouguer gravity after removing a regional trend from the data. The linear colour scale ranges from –2 mgal (blue-purple) to 2 mgal (white-red). c) Residual Bouguer gravity adjusted for response of the regolith layer using a density contrast of –0.6 g/cm^3. The linear colour scale ranges from –1 mgal (blue-purple) to 6 mgal (white-red). Data provided by Metex Resources NL. Processing and interpretation by Southern Geoscience Consultants.

An example from the Laverton area in Western Australia is shown in Figure 13. Troughs in the interpreted regolith unit, the axes of which are marked with lines, correspond to local gravity lows in the Bouguer gravity. The absence of a correlation between these axes and bedrock gravity (Figure 13c) suggests that an appropriate density contrast has been used to remove the response of these regolith features. A series of local highs in the observed gravity in the NE and SE corners of the survey area (marked with "H" symbols) are interpreted to be directly attributed to bedrock topographic highs.

They do not appear to have any bedrock density contrast (Figure 13c). The interpreted bedrock topographic high, labelled as “B”, appears to be different in that it is not associated with a local gravity high. This could be a low-density bedrock feature or a patch of resistive regolith misinterpreted as a bedrock topographic high (eg. an area of silica-alteration). Areas of interpreted thick regolith (marked with “A” symbols) appear to be associated with high density bedrock units (eg. mafic volcanics or intrusions). An alternate possibility is that the Bouguer gravity has been overcompensated for the regolith gravity response in these areas (ie. the interpreted regolith thickness is too large and/or the magnitude of the assigned density contrast is too large).

7. PROBLEMS AND LIMITATIONS

Acquisition

Selection of the most appropriate acquisition system and parameters is a common problem with EM methods. A clear understanding of the survey objectives will certainly help guide the selection process. Some of the factors to consider in planning an EM survey are:

1. Survey objectives;
    - expected 3D conductivity variations
    - target size
    - required depth of investigation
    - resolution
    - area to be covered
    - coupling of the EM field with the target

2. Ground conditions;
    - results of previous electrical or EM surveys (these provide indications of the conductivity variations)
    - presence of substantial grounded metal objects (eg. pipelines, railway lines)
    - presence of interfering EM sources (eg. powerlines, electric fences)
    - topographic variations
    - altitude (AEM surveys)
    - vegetation (ground surveys)
    - location and access

3. Output requirements;
    - basic products, advanced products or complete planning, monitoring and interpretation service

4. Available technologies;
    - developments occur quite rapidly in the field of EM methods

5. Selection of contractor;
    - safety systems
    - experience
    - availability
    - support

6. Temporal conditions;
    - required time frame for the survey
    - weather conditions (dry, stable conditions preferable)
    - EM noise levels (ambient EM noise levels are lower in winter than in summer)

7. Financial constraints.

Broad advantages and disadvantages of different acquisition systems can be established but detailed comparison is difficult because it is not always possible to establish an appropriate common point of reference between the systems. For example, if systems have different measured quantities, how do you compare noise levels? How do you weight performance in diverse categories such as bandwidth, footprint, signal to noise, and cost? Improvements to methods of converting from measured response to 3D conductivity will greatly assist in providing a more logical common point of reference.

When embarking on a major survey, a small trial survey can assist to sort out teething problems and to confirm that appropriate survey parameters have been chosen. Factors to consider include:

1. Timing of the trial with respect to the main survey;

    - immediately beforehand (Are all relevant parties on site and empowered to make decisions on the spot?); or,
    - well in advance (more time to analyse and interpret the results, but increased mobilisation costs)?

2. Isolated traverses or a grid?

3. Ensuring coverage of representative ground conditions, noting the variability of the ground conditions in the project area and the nature of the target;

    - it is very frustrating to undertake a trial that is too small to indicate whether the chosen configuration will be effective over a larger survey area.

4. Survey an area with ground truth;

    - but be prepared to discover that not everything about the area was known or "true".

5. System tests to establish signal to noise levels;

    - repeat lines,
    - acquisition of data at high altitude (free of ground response).

Processing and Presentation

Simple presentations of measured response for a particular frequency or delay time are often difficult to interpret. These presentations reflect the contribution from the conductivity distribution to varying depths across a survey. Additionally, the measured response is strongly influenced by complex system characteristics. This results in a highly non-linear relationship between conductivity and response.

The most significant impediments to simplifying the interpretation of EM data are the restrictions placed on the conversion from measured response to 3D conductivity. A 1D assumption leaves significant residual artifacts near strong lateral contrasts in conductivity (Figures 14 and 15). Even in areas where a 1D assumption is a valid simplification, artifacts in predicted vertical conductivity distribution need to be considered in detailed quantitative applications (Hunter and Macnae, 2001) (Figure 16). Non-uniqueness in predicted vertical conductivity variation could also be a significant issue in some applications.

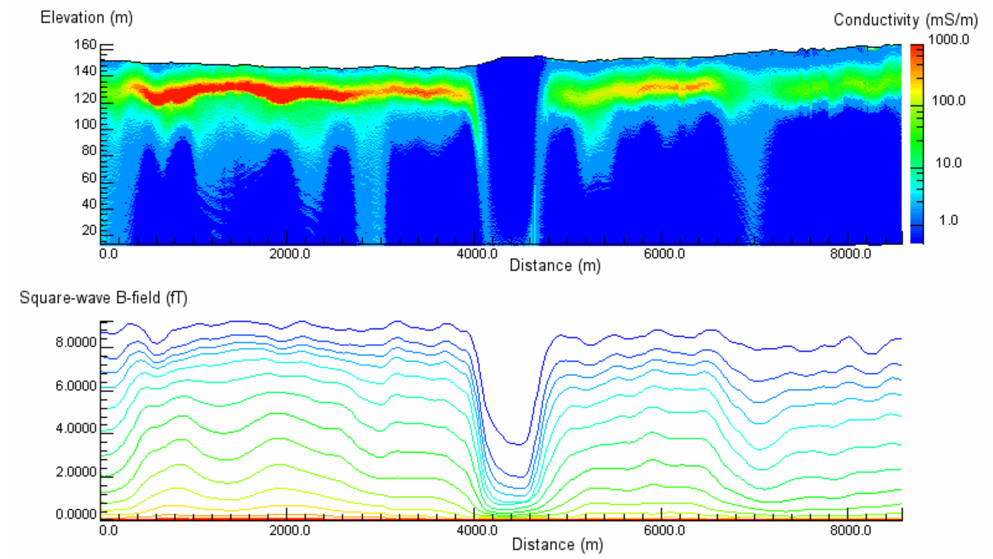

Figure 14. CDI conductivity section and TEMPEST Z component window response amplitudes for line 10390, Lake Harris, South Australia. The 1D assumption in CDI calculation results in "drooping moustache" edge artifacts at strong lateral contrasts in conductivity. Examples are evident at distances of 4000 and 4650 m along this line. Weakly elevated conductivity values extending from the conductive near-surface layer to depth at 0-200 m, 2700-3000 m and 7000 m are more subtle edge effects.

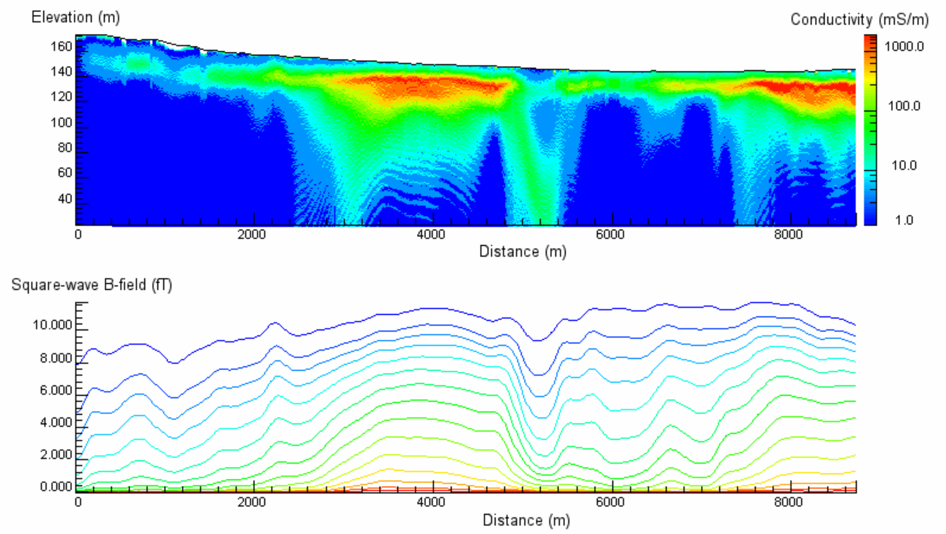

Figure 15. CDI conductivity section and TEMPEST X component window response amplitudes for line 20510, Lake Harris, South Australia. The 1D assumption in the CDI calculation results in edge artifacts at strong lateral contrasts in conductivity. A good example is evident at a distance of 5,000 m along this line. Features extending to depth around 3,000 and 7,500 m distance along line are more subtle edge effects. "Ribbing" or repeated steps present in low conductivity values at depth in the intervals 2,500-4,500 m and 7,400-8,800 m distance along line are artefacts of the conductivity transformation.

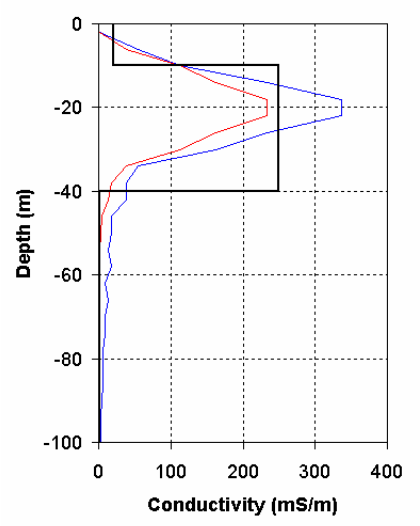

Figure 16. Example of 3 layer conductivity model (black) and EMFlow CDI conductivity soundings obtained after converting the forward model response of the 3 layer model to conductivity. The red sounding curve was obtained with halfspace basis functions whilst the blue curve was obtained with exponential basis functions. This example demonstrates some typical behaviour of the CDI algorithm used in EMFlow. Total anomalous conductance is reasonably well predicted whilst sharp conductivity boundaries are smoothed, and an overshoot is present below the top of the most significant near-surface conductive layer.

Despite the limitations noted above, it must be reiterated that in many regolith applications, conversion to conductivity is highly beneficial in reducing the complexity of the system response, in facilitating integration with other subsurface information, and in developing an appreciation of the 3D conductivity distribution.

Interpretation

Artifacts due to noise and assumptions made during data processing can be difficult to recognise. The residual imprint of the acquisition system characteristics (eg. bandwidth, footprint) and the processing that is applied to the data (eg. along line processing functions applied to AEM data) must be constantly borne in mind when interpreting the data. Relatively few detailed studies of the conductivity of regolith materials that could serve as a guide for interpretation have been published. Since, conductivity is a function of several parameters (eg. conductivity of solid material, arrangement of pores, saturation, conductivity of fluid, clay content), unravelling the relationship between conductivity and geological units is not always straightforward. In regolith applications, interpretation of EM information (ie. establishing the relationship between conductivity and geological units) is significantly aided by detailed surface mapping and judicious use of drilling. Used in this fashion, EM methods provide an objective basis for interpolating between relatively widely spaced boreholes and/or small areas of detailed surface mapping.

8. ACKNOWLEDGMENTS

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APPENDICES

Appendix 1 - Survey Costs

For surveys carried out by contract crews, costs are generally broken down into 3 categories; 1) mobilisation / de-mobilisation, 2) a daily (ground EM) or line km (airborne EM) rate; and, 3) standby. The rates depend on factors such as the system involved, product requirements, timing requirements, location, distance between base of operations and the survey area, size (ie. number of days or line km) and the line configuration (eg. length, separation). The survey organisations can generally provide a quotation fairly readily upon receipt of a survey proposal.

For airborne surveys, the line km rate can vary from over A$100 per line km for small areas to less than A$50 per line km for very substantial surveys (10's of thousands of line km). Rates for fixed wing and helicopter surveys are similar.

For TD ground EM surveys, the daily rate for a 3-person crew is typically A$1000 to A$2000. Production varies considerably depending on the terrain and the configuration. These costs are likely to amount to A$250 to A$1000 per line km.

Standby charges (for bad weather, client delays etc) are typically less than A$1000 per day for a ground EM crew and several thousand dollars for an airborne EM system.

Single-frequency ground EM instruments can be hired for less than a few hundred dollars per day. Production depends on access and sample interval, but can be 5 to 10 km per day. Some of these systems have been fitted to all-terrain vehicles and incorporate a GPS antenna for location. Productivity is higher, as are the costs.

Appendix 2 - Survey Organisations

Airborne Electromagnetic Systems

Fugro Airborne Surveys
65 Brockway Road, Floreat, WA 6014
Telephone: +61 8 9273 6400

UTS Geophysics
Valentine Road, Perth Airport
P O Box 126, Belmont, WA 6014
Telephone: +61 8 9479 4232

Ground Electromagnetic Systems

Fugro Ground Geophysics
65 Brockway Road, Floreat, WA 6014.
Telephone: +61 8 9273 6400

McSkimming Geophysics Pty. Ltd
30 Needham Court, Kiels Mountain, QLD 4559.
Telephone +61 7 5450 8100

Outer-Rim Exploration Services
PO Box 1754, Aitkenvale, QLD 4814.
Telephone +61 7 4725 3544

Solo Geophysics
3A McInnes St, Ridleyton, SA 5008.
Telephone +61 8 8346 0924

Zonge
98 Frederick St, Welland, SA 5007.
Telephone +61 8 8340 4308

Appendix 3 - Associations

Assistance with EM methods can be obtained through a number of professional geophysical organisations.

Australian Society of Exploration Geophysicists (ASEG) (http://www.aseg.org.au/)
Society of Exploration Geophysicists (SEG) (http://www.seg.org/)
The Environmental and Engineering Geophysical Society (EEGS) (http://www.eegs.org/)
Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) (http://www.sageep.com/).

Appendix 4 - General Texts and Further Reading

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