A time and place for everything: an overview of AEM interpretation methods

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SUMMARY

Airborne EM surveys have become increasingly popular in the mineral exploration industry for both direct and indirect detection of mineralization. Various AEM systems and platforms are available in the market today as well as different software packages for the interpretation of data. The software implement different approaches to interpreting EM data such as decay constant evaluation, plate modelling, conductivity depth imaging and 1D to 3D inversions.

In this paper the applicability of the different interpretation options to achieve survey goals is discussed. Special attention is given to the importance of correctly describing system and survey parameters as well as appropriate application of the interpretation software. Different solutions are obtained using different approaches and discriminating between accurate and inaccurate models remains the responsibility of the interpreter. A solid foundation in EM theory combined with geological control is required to produce meaningful results, even with the most sophisticated software available.

Key words: EM, Plate Modelling, CDI, Inversion, Decay Constant

INTRODUCTION

Airborne electromagnetic (AEM) surveys have become increasingly popular in the mineral exploration industry for both direct and indirect detection of mineralization. Direct targets consist of mineralization such as massive sulphides. Indirect targeting includes mapping of carbonaceous units associated with uranium mineralization, massive sulphides associated with gold mineralization or delineation of structural features such as shear zones and thrust faults. AEM surveys for regional geological mapping and groundwater management are also performed with increasing frequency. In the broadest sense the objective of all these surveys is to map subsurface conductivity. However, the more specific goals, such as mapping laterally extensive, shallow, contaminated aquifers or finding small massive sulphides under conductive cover determine the most suitable survey and system parameters as well as interpretation approaches. AEM system comparisons are not uncommon in literature (Macnae, 2007; Allard, 2007; Sattel, 2009) and new work remains relevant as regular improvements are demanded in a highly competitive market.

As with all geophysical data, some insight can be gained by simply viewing the measurements itself and correlating it to geological features, but in order to extract the maximum value from a data set a number of processing and interpretation technique are utilized. All of these aim to convert measurements of an electromagnetic field (normally in terms of voltages) to a conductivity distribution that is representative of the earth model. The predicament facing the interpretation geophysicist is that the different tools available for interpretation very often do not produce the same results. Even worse, a single method can produce a wide range of results with only a small variation in input parameters.

There are two main reasons for these discrepancies:

1) Assumptions made in the interpretation procedure regarding the geological model are not valid, e.g. modelling steeply dipping conductors with an algorithm designed for a layered earth.
2) The AEM system and/or survey parameters are not described accurately.

Examples from field and synthetic data illustrating these points are presented for decay constant, plate modelling, conductivity depth imaging (CDI) and inversion applications. When non-unique models are obtained, a critical evaluation based on EM theory and geological control is recommended to ensure meaningful results.

SOFTWARE CATEGORIES

The main categories of interpretation software and approaches are described here, but not each specific software package available today. Although reference to commercial products is made for the sake of practicality, this analysis will focus on the type of information that interpreters can choose to work with, and is not intended to promote or demote specific products within their respective categories.

Table 1: Summary of the main categories and examples of software referred to in this paper.

Main Category	Software example	Interpretation approach
Advanced processing	Decay constant calculation *(TGC in-house)*	Extract conductivity information in 2D; no depth information
Plate Modelling	Maxwell *(EMIT)* EM Anomaly Picks *(Geotech Ltd in-house)*	Conductivity and depth solutions in 3D for plate- or prism-like models
CDI	EMFlow *(Pitney Bowes)*	Fast transform to provide a conductivity depth model in 1D
1D inversions	Airbeo *(CSIRO/AMIRA's P223 suite)*	Slower, (arguably) more accurate method to model 1D earth
3D inversion	Large scale 3D AEM inversion *(TechnoImaging)*	Integral equation block model solution for any type of earth model

Each of the interpretation approaches performs well if applied to the type of earth model it was designed for; and sometimes even to other situations, provided the interpreter understands how deviations from the appropriate type of model will affect the results. Specific application of these approaches (except 1D inversion) to a West African gold exploration project is discussed in a later section to illustrate the typical results that can be expected.

CONSIDERATIONS FOR SPECIFYING AEM SYSTEM PARAMETERS

The solutions obtained from any software are highly dependent on the parameters used to describe the system. The most basic description comprises the transmitter waveform and geometry, the receiver geometry, units of measurement and location (GPS and radar) parameters. If the software allows for the inclusion of information on analogue and digital filtering, this should also be included. System parameter descriptions remain a headache for the interpreter as specifications vary for each system in the market and also between different models of the same type of system. Information (when) provided by contractors are not always in the same units or format as required for software input and manual conversions are often required.

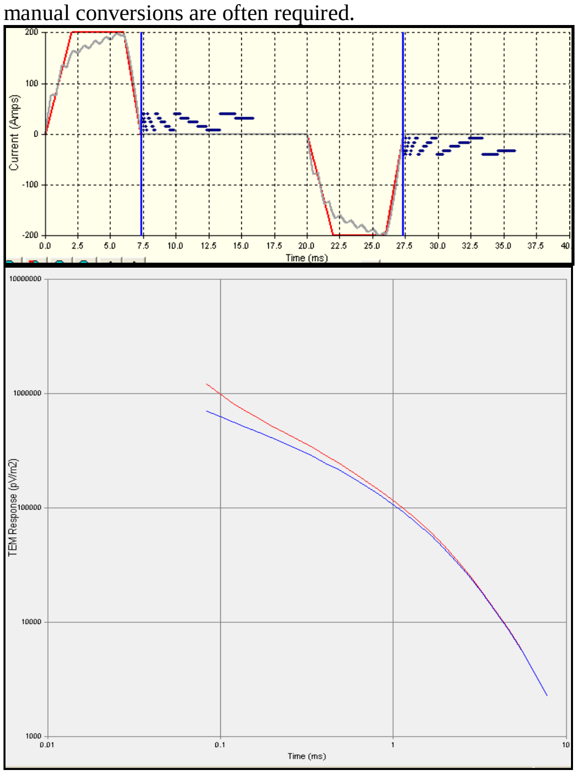

Figure 1. *Measured (grey) and approximated (red) VTEM waveform in the top panel. The bottom panel shows the difference in a forward modelled decay curve due to the two waveform descriptions.*

Approximations that speed up run-time, such as describing an airborne loop as only a magnetic dipole and reducing a 1000+ point waveform to 4 points, are popular. It is critical to evaluate the effects of any approximations made on specific systems and geological environments before applying it to a data set. This is illustrated in Figure 1; the effect of simplifying a system waveform is seen on the early part of a decay curve.

APPLYING EM THEORY TO UNDERSTAND DECAY CONSTANT DISCREPANCIES

Decay constant (τ) calculation is described as an advanced processing technique as it contributes conductivity information, though no depth information. The theory and application for calculating τ is straightforward at first glance. However, when applied to field data, discrepancies with the simplified theory are immediately evident. A study based on 20 synthetic test models and six different ways to calculate τ was undertaken (Combrinck, 2011). System waveform, B versus dB/dt data and the effects of a conductive host rock were analysed. Results indicated that finite host rock conductivity severely influences on τ calculations for AEM data. The most accurate results are obtained by using time gates where the decay curve most closely represents a single exponential decay and not necessarily the latest times as is true for conductors in an infinitely resistive environment. Application to field data requires selective filtering to reduce the effect of noise.

APPLYING GEOLOGICAL CONTROL TO MAP MULTIPLE STEEPLY DIPPING CONDUCTORS

The early Proterozoic Birimian greenstone belts of West Africa consist of steeply dipping metasedimentary and metavolcanic units. These can be traced for hundreds of kilometres along strike, trend north to northeast, are typically 20 to 60 km wide, and are separated by wider basins of mainly marine clastic sediments. Thin but laterally extensive chemical sediments, consisting of cherts, fine-grained manganese-rich and graphitic sediments, often mark the transitional zones. The margins commonly exhibit faulting on local and regional scales, and these structures are fundamentally important to the development of gold deposits for which the region is well-known (Griffis et al., 2002).

Within the Birimian greenstone belts, extensive fault networks are generally defined by zones of graphitic mylonite as well as quartz and carbonate veining (Allibone et al., 2002). These graphitic zones (Figure 2) manifest themselves as sub-vertical conductors. Delineating these steeply dipping conductors and their inferred thrust faults play a critical role in gold exploration, even though there is not a direct relation between graphite and gold mineralization. Due to the dense vegetation and limited outcrops, AEM surveys have been routinely flown in the region for geological mapping.

Figure 2. *Typical sub-vertical carbonaceous units associated with shear zones and possible mineralization in the Birimian greenstone belts of West Africa.*

The area described here is almost entirely underlain by Birimian metasediments with localized volcaniclastic components. All investigations to date indicate that the gold is associated with broad quartz stockwork systems, most often hosted in thinly bedded metasediments, including numerous graphitic bands. A series of mainly NE-SW trending mineralized shear systems were proposed as the most promising target features by the project geologist (Griffis, R. J., pers. comm.), and mapping these was one of the main objectives of the subsequent AEM survey and interpretation. Delineation of individual thrust faults, and specifically identifying dilational jogs, bends and localized regions of decreased conductivity (possibly indicating silicification associated with gold mineralization) were additional requirements. A comprehensive interpretation was performed on the VTEM data using standard AEM interpretation workflows (Combrinck, M. and Botha, W., pers. comms.),

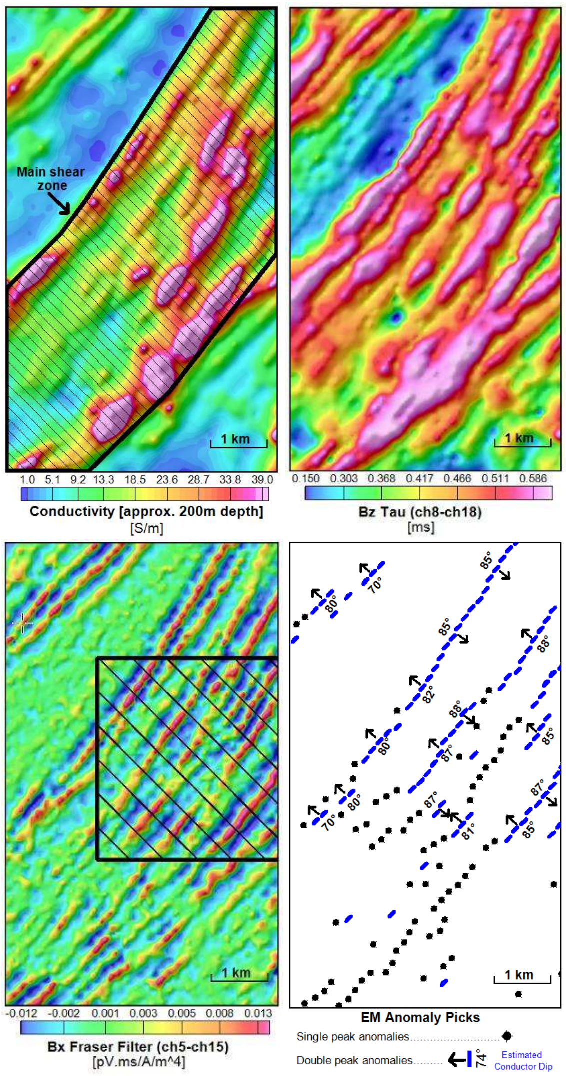

Figure 3. *EMFlow conductivities at depth 200 m (top left), decay constants (tau) calculated from B_z (top right), stacked Fraser filtered B_x data (bottom left) and EM anomaly pick symbols (bottom right). The hashed polygon (top left) indicates the interpreted extent of the main shear zone system that is comprised of multiple sub-vertical thrust faults and the hashed rectangle (bottom left) outlines the data used in the subsequent 3D inversion.*

including EMFlow CDI's, decay constant analysis, semi-automated EM anomaly picking, and Fraser filtering of the inline component data. Only those results relevant to sub-vertical conductor delineation have been included here. As shown in Figure 3, the 3.5 km broad north-east trending shear system was identified from all of the aforementioned interpretation products.

However, due to the sub-vertical nature of these conductors, their close proximity to each other, and the presence of conductive overburden up to 50 m thick, none of the aforementioned methods provided results that could confidently be assigned as potential drill targets. The maxima of the Fraser filtered inline component data proved the most useful for mapping the centre, top positions of conductors in plan view, and dips could be inferred from the EM anomaly picks. The limitations of such an interpretation were that the positions mapped from the inline component data assumed vertical dips only, and dips and depths–to-top inferred from the EM anomaly picks were accurate only for flat topography and no overburden effects. Hence, there remained ambiguity in the assignment of potential drill targets.

Plate modelling did not fall within the scope of the original interpretation, but was subsequently applied to three discrete anomalies for additional comparison. EMIT's *Maxwell* plate modelling was used. Two parallel plates were used to simulate the VTEM response from the broad conductive zones. These results confirm the sub-vertical nature and locations of the conductors. However, accurate modelling required the use of multiple plates, as well as simulation of the conductive overburden that dramatically increased the runtime and lead to nonunique results.

TechnoImaging's large-scale 3D AEM inversion (Cox et al., 2010) was applied to a subset of the VTEM data (Figure 3) that contained the shear zone. The 3D earth model was discretised to 12.5 m across strike, 25 m along strike, and the vertical cell size increased with depth. Both inline and vertical B data were jointly inverted. The upper panel in Figure 4 shows a plan view of the 3D conductivity model at 200 m depth below the surface. Note how the conductors, recovered from the 3D VTEM inversion, closely match those positions and continuity inferred from the Fraser-filtered inline component contours (black). For comparison, the lower panel in Figure 4 shows a similar comparison of the Fraser-filtered inline component contours with EMFlow CDI-derived conductivities at the same 200 m depth. As expected, the CDI-derived conductivities are mapped adjacent to their true positions; an artefact typical of all 1D methods. Moreover, the conductivities derived from 3D inversion are representative of the actual rocks, whereas the CDIs underestimate the conductivity.

Viewed in section, the lower panel in Figure 5 demonstrates how the 3D AEM inversion accurately delineated sub-vertical conductor geometries, and how well these correspond with those instances where the Maxwell plate models were fitted (Figure 5). For comparison, the upper panel of Figure 6 demonstrates how the EMFlow CDI-derived conductivities are displaced relative to the actual conductor location, depth and dip.

Knowledge of the geological model in this area played a major role in analysing the different results, understanding the discrepancies and coming up with realistic conductivity models.

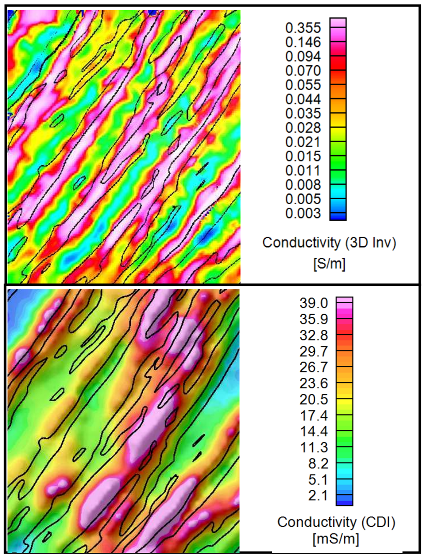

Figure 4. *(Upper panel) Horizontal cross section of conductivity at 200 m depth recovered from 3D inversion with contours of the Fraser filtered inline components superimposed. (lower panel) Horizontal cross section of conductivity at 200 m depth recovered from EMFlow CDI with contours of the Fraser filtered inline components superimposed.*

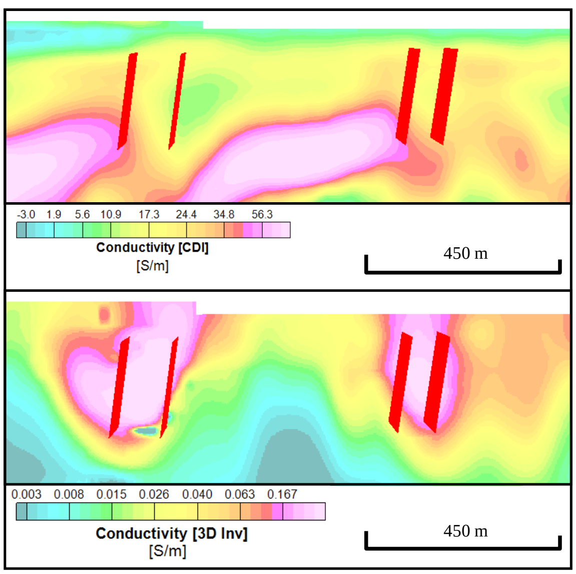

Figure 5. *A 1.2 km vertical cross section through two sub-vertical conductors extracted from (upper panel) the EMFlow CDI-derived conductivity model, and (lower panel) the 3D AEM inversion model. Maxwell plate models are superimposed in red. Note that two plates were required to simulate the VTEM responses for each conductor.*

CONCLUSIONS

It is crucial to understand the approximations and intended uses of software when interpreting EM data. Correct system specifications are non-negotiable! When faced with discrepancies in the models obtained using different interpretation approaches priority should be given to the methods most closely resembling the geological environment. Despite our best efforts, geological complexities cannot always be matched with a suitable technology. However, discrepancies arising in these instances can be anticipated through theoretical analyses or empirical experiments and aid the interpreter in presenting a realistic earth conductivity model.

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