Chapter 3

3 CONVENTIONAL INTERPRETATION TECHNIQUES

"The definition of insanity is doing the same thing over and over and expecting different results."

(Benjamin Franklin, 1706-1790)

3.1 Introduction

The ultimate goal of doing any geophysical survey is to deliver a map or model indicating the subsurface distribution of physical properties, i.e. conductivity in the case of TEM and to interpret this data in terms of geology. When geological information are added to the geophysical model it is possible to link lithology or structures to distinct geophysical units of different conductivities and this serves as a very useful tool in constructing a final geological model.

This study is concerned mainly with the conversion of TEM data to a reliable subsurface conductivity distribution. Traditionally there are two separate classes of exploration targets for TEM surveys and based on these classes different survey geometries and interpretational procedures are followed. In modern day geophysics these two classes of surveys increasingly overlap but it is still important to understand the different approaches that were followed in the past as most of the interpretation techniques being used today were developed for very specific target conditions.

The first type of target is considered to be a confined conductor(s) in a resistive host rock. The theoretical assumptions made in this case are basically that the host rock has no influence on the electromagnetic propagation of fields and conductors are considered to be suspended in free space for all mathematical purposes. TEM surveys to detect this type of target are designed to emphasize lateral variations in conductivity and are called profiling surveys. The geophysical model derived from interpreting a survey like this would contain the location, conductivity and geometrical parameters of one or more finite conductors (two- or three-dimensional). These conductors would be simplified geometrical shapes such as spheres, ellipsoids, plates or prisms approximating true geological units. Typical geological targets are massive sulphides or linear structures like weathered faults or shear zones.

The second type of target is considered to be a half space or layered earth. The theoretical assumptions made in this case are that there are no finite conductors present and that the subsurface layers are perfectly horizontal. Mathematically this means that all processing reduces to one dimension. TEM surveys designed for this type of target emphasize vertical variations in conductivity and are called sounding surveys. Fairly realistic models of the subsurface are obtained by stitching together a number of sounding models to produce a conductivity depth section and effectively resolving geological features in two dimensions and not only one. Practical applications would include determining depth to bedrock or mapping saltwater intrusions into aquifers.

In reality a combination of these two approaches are necessary to obtain a complete subsurface conductivity distribution and it is towards this goal that most TEM research is currently focused. The most important factor when dealing with the huge amounts of data gathered in this instance is to automate as much of the processing and interpretation as possible in order to keep survey time and costs competitive in the exploration industry. At the same time it is important to resolve less conspicuous anomalies and map them more accurately as the tradition of "bump-hunting" is not profitable in modern day exploration. In the rest of this chapter the different techniques used in TEM interpretation will be discussed with reference to the optimum targets for interpretation as well as the potential for automation of these techniques.

3.2 Profiles versus soundings

Profiling and sounding can refer to different survey geometries or just to the way data is viewed, processed and interpreted. The same data set (or parts of it) can therefore be treated as either sounding- or profile data or both. The most relevant view or interpretation strategy is dependent on the primary target or goal of the survey as described in 3.1. Interpreting data in profile format involves looking at measured values as a function of distance, removing a half space response if required, and interpreting anomaly shapes associated with two- or three-dimensional conductors either through forward modelling, inversion or curve matching. This is very similar to modelling potential field data, but with some important differences.

There are as many profiles to consider as there were time channels measured (varying anywhere from 7 to 100) and often it is not possible to obtain a good fit for a specific conductor on all of these channels simultaneously. This can be ascribed to the fact that modelling software still approximates complex geological units in terms of simplified geometries as well as mathematical simplifications sometimes needed to solve a problem (see 2.3). Since TEM is an active source method (as opposed to magnetics and gravity) the transmitter current waveform, geometry and position all determine the actual shape and amplitude of anomalies. Different systems also measure different components of the magnetic field or its time derivative, again resulting in different anomaly shapes and amplitudes. Even if all the above factors are accounted for, the TEM method allows only for modelling of time varying current distributions unlike gravity, for example, where the measured field is a direct and unique consequence of the subsurface density distribution.

Interpretation of data in sounding format implies that a model is constructed with variation in depth only, and such a model always takes the form of a number of layer thicknesses and corresponding conductivities. Data are presented either as emf(t), $\partial \mathbf{B}/\partial t$, B(t) or more commonly, apparent resistivity as a function of time. As with profiling data, a model is determined through forward modelling, inversion or curve matching. Due to the one-dimensional nature of this interpretation, inversion can be applied successfully provided that the number of layers is known, a good starting model is used and the geology conforms fairly closely to the one-dimensional assumption made in these algorithms.

3.3 Forward Modelling and Inversion

Forward modelling is a process whereby a geophysicist tries to match field data with calculated values from a specified model by changing the model parameters until there is a close correlation between the field and calculated data. Inversion is a mathematical approach also described as optimization, minimization or solution of a system of non-linear equations. Most of the various inversion approaches (an exception is Occam's inversion) reduce to the guessing of an initial model (initial parameters), forward calculating the response of this model, determining the difference (error) between the calculated and measured response and adjusting the initial parameters in a way that would minimize this difference. A number of forward modelling and inversion algorithms have been published ranging from a single current filament approximation (Barnett, 1984) through to the most general case of complete three-dimensional models (Newman et. al., 1986; Newman and Hohmann, 1988; Xiong, 1992; Wang and Hohmann, 1993).

3.4 Limitations on automation of inversion techniques

Forward modelling as defined in 3.3 cannot be automated as it includes the active involvement of a geophysicist at every guess of a new model. In fact, inversion is the process whereby "guessing of models" is taken over by an algorithm or computer. Although mathematically sound, in practice there are a number of problems which often inhibits the successful implementation and automation of inversion procedures.

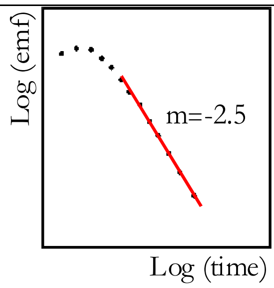
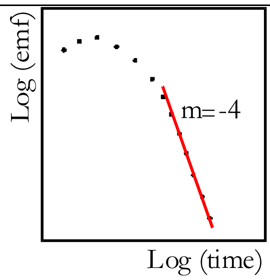
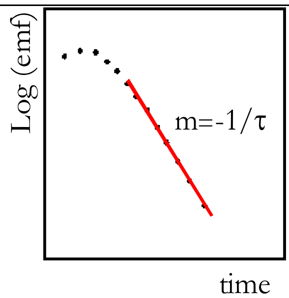
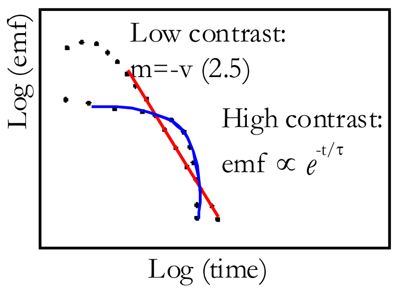
- A priori knowledge of the geology under investigation is needed; i.e. should inversion be run for a layered earth (with how many layers) or should it be done for multiple plates (and how many plates)?
- Even if the general structure is known, the initial model should be close to the real model to obtain mathematical convergence.
- In the case of convergence, it can be difficult to decide whether convergence was to the desired global minimum or just a local minimum which adds yet another unknown to the interpretation process.
- Equivalence
- Validity of assumptions; e.g. late time behaviour of models are compared with time channels exhibiting early or intermediate time behaviour.
- There have to be more data than free parameters which would become a problem when trying to implement a totally general three-dimensional cube as model (this would of course be the ultimate solution).
- The most limiting factor however, is the need for a very fast forward modelling algorithm. TEM algorithms are still very time-consuming for all but the simplest cases of layered earths and multiple plates.

Practical experience in the interpretation of TEM data with inversion software has shown that extensive forward modelling was needed before inversions could be run successfully and that the 3-10% statistical reduction in error did not always mean that a more geologically plausible model was achieved. In fact, correlation with geological data such as borehole and structural information proved invaluable to distinguish between mathematical equivalent models and more often than not mathematical accuracy had to be sacrificed to obtain geological feasibility in a model. This is especially true in a geologically complex area. The best of both worlds would naturally be the application of constrained inversion, where mathematical solutions are found subject to geological truths such as dip, strike, conductivity ranges and limits on dimensions of bodies. However, this information is very rarely available in the exploration industry before TEM interpretations have to be done. Consequently, it is very difficult at this point in time to see inversion as a fully automated procedure for interpretation of TEM data, although it could possibly be involved as a final stage of processing after initial models have been found through alternative routes.

3.5 Decay curve analysis

Decay curve analysis is an extremely useful tool with its major strength probably being simplicity. The TEM method is based on current distribution changes with time, and decay curve analysis is the simplest way of analysing the time-varying fields associated with this phenomenon. In Chapter 2 the specific equations describing the decay behaviour for general models were given with specific reference to the late time. A summary of these late time approximations is given in Table 3.1. Decay curve analysis is a tool that helps the interpreter to distinguish between the two basic classes and subsequent interpretation strategies as mentioned in 3.1. Plotting all data, station by station, on both log-log and log-linear graphs and analysing the slopes of any data forming straight lines in the late time yields very good information on the geological structure in two dimensions. It allows the interpreter to immediately divide the survey area up into regions containing the four models shown in Table 3.1, with the only complication that a conductor in conductive host rock and with very low contrast may be grouped with half space occurrences at this point. However, what is more likely to happen from experience in Case History 1, Chapter 5, is to find stations showing both isolated conductor and half space behaviour but at different time channels. Similar behaviour was also described at the Elura massive sulphide deposit which is situated under a conductive overburden, Australia, by Spies (1980). Decay curve analysis as described here doesn't give any information on depth of conductors, although the decay constant (τ) found from inverse slope of model 3 (and sometimes model 4) graphs is related to the dimensions and conductivity of the causative conductor McNeill (1980), allowing a further division to be made between targets worth further investigating or not. In instances where the subsurface geo-electrical structure is too complex to be approximated by either of the models in Table 3.1, neither of the described characteristics will be found on the decay curve and stations like this will form a class of their own and require some special attention in later stages of interpretation. One of these more complex decay curves involves a sign change in the vertical component of the $\partial \mathbf{B}/\partial t$ measurements inside the transmitter loop. It is impossible to see this behaviour in a conductive half space or layered earth environment and it therefore implies either an IP effect or extensive lateral variations (including two- or three-dimensional conductors) in the subsurface.

Table 3-1 Summary of late time approximations and behaviour for four general models.

Model	Late time behaviour	Decay plot properties
1. Conductive half space	$\frac{\partial H_z}{\partial t} \propto t^{-5/2}$ (Power law)	
2. Thin, conductive layer	$\frac{\partial H_z}{\partial t} \propto t^{-4}$ (Power law)	
3. Confined conductor in resistive host rock.	$\frac{\partial H_z}{\partial t} \propto e^{-t/\tau}$ (Exponential)	
4. Conductor in conductive host rock.	High contrast: $\frac{\partial H_z}{\partial t} \propto e^{-t/\tau}$ (Exponential) Low contrast: $\frac{\partial H_z}{\partial t} \propto t^{-v}$ (Power law)	

Decay curve analysis as described here, although not yielding the complete solution, can be applied without any user input and therefore has the potential to be fully automated. It is also very fast compared to inversion and can be applied to data in real time.

3.6 Transforms (Depth imaging)

Spies and Frischknecht (1991) describe depth imaging techniques as low cost (i.e. fast and automated) alternatives to modelling and inversion to provide an approximate image of the resistivity section directly from observed data. Originally developed as a "processing" step they now appear very useful for interpretation. Today there are a number of different imaging schemes or transforms (Macnae and Lamontagne, 1987; Nekut, 1987; James, 1988; Eaton and Hohmann, 1989; Smith et. al., 1994; Wolfgram et al., 1998; Tartaras et al., 2000), all based on simplifying some of the governing equations to such an extent that a direct solution for the depth and conductivity parameters can be found either analytically or through curve matching. Although not as accurate as full modelling or inversion the advantages of these schemes are computational speed and no need for initial models or other interactive user input. These methods can therefore be considered as completely automated.

3.6.1 Conductivity Depth Images (CDI's)

This technique has been developed by Macnae and Lamontagne (1987) for step-response sounding data and is routinely used in processing airborne TEM data. At each delay time the variation of the step-response as a function of geometry is transformed to an equivalent reference depth h, which can be related to the depth of electromagnetic field diffusion. The behaviour of h as a function of delay time is nearly independent of the source-receiver geometry. The slowness $\partial t/\partial h$ divided by the magnetic permeability is almost exactly proportional to the cumulative conductance measured from the surface down to a depth h. Thus an apparent conductivity (termed the "imaged conductivity") can be estimated at depth by $\partial^2 t/\mu_0 \partial h^2$. The result is a conductivity-depth section that can be generated automatically with no prior input needed from the operator. This method is based on the receding image theory of a plane (or S-layer).

3.6.2 Stationary current images (SCI) (SCI - trademark of Geoterrex-Dighem Pty Limited)

This method highlights the edges of conductors, gives an indication of dip and allows a qualitative estimate of the conductance of localized conductors (Wolfgram et al., 1998). The SCI emphasizes structural features because it is optimised for lateral contrasts in electrical conductivity. It is an empirically developed method only applied to GEOTEM®

system data and only results applied to synthetic data are available in literature (GEOTEM is a registered trademark of Geoterrex).

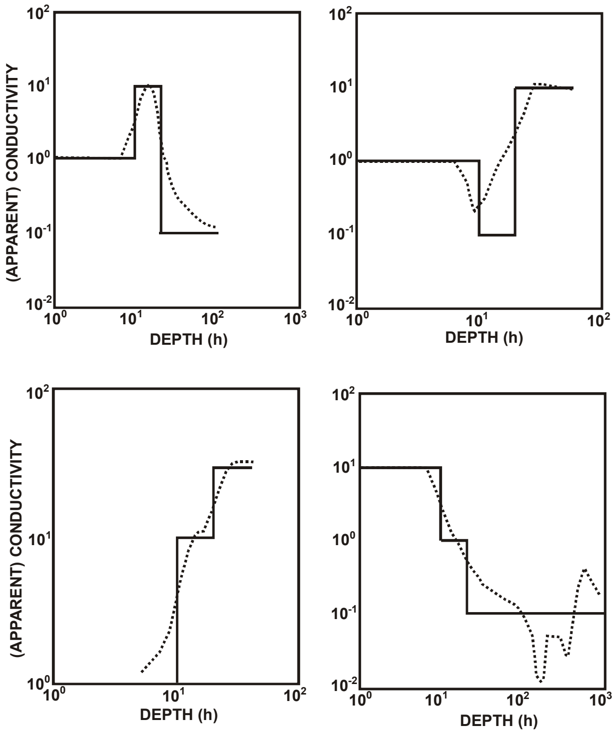


Figure 3-1 Comparison of apparent conductivity (calculated by differentiating the fitted slowness with respect to reference depth curve) with the actual conductivity for four three-layer models (after Macnae and Lamontagne, 1987).

3.6.3 S-layer differential transform

The S-layer differential transform was originally developed by Sidorov and Tikshaev (1969) and extended to an inversion technique by Tartaras et al., (2000). It is based on the late-time $\partial B_z/\partial t$ approximation of the S-layer model. The derivative of this equation ($\partial^2 B_z/\partial t^2$) is calculated and from these two equations the variables S (cumulative conductance) and d (depth) can be solved for at every time channel. Taking the partial derivative of S to d ($\partial S/\partial d$) gives the conductivity of a thin layer at depth d. The actual calculations are remarkably simple and when working in a conductive, layered region this method gives good results. The main criticism against the method (Tartaras et al., 2000) is the fact that it contains two numerical differentiations which are numerically unstable operators and therefore is extremely sensitive to noise. It is further based on the one-dimensional and late-time assumptions. Although, for the central-loop sounding geometry it can be shown (Tartaras et. al., 2000) that measured data almost always satisfy the late-time prerequisite.

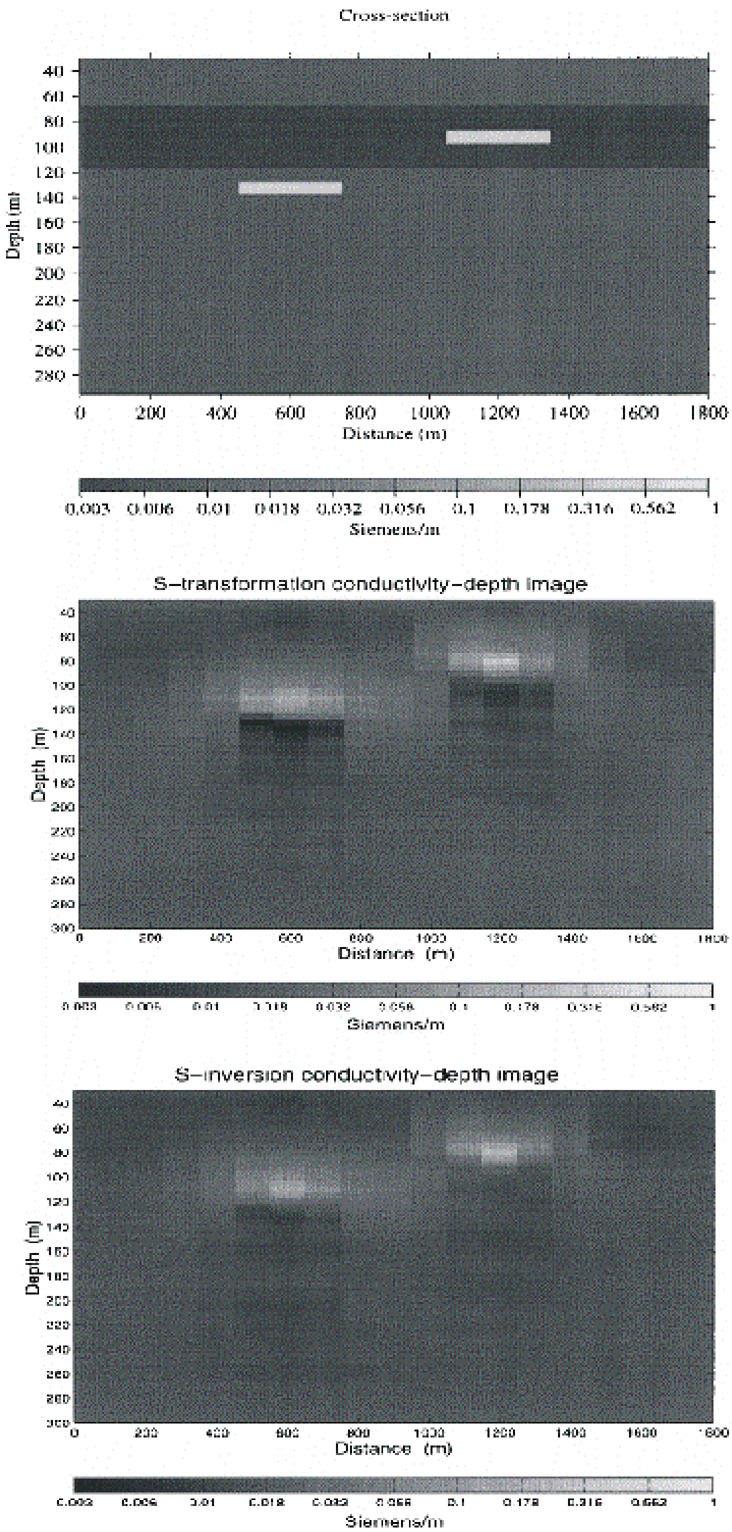


Figure 3-2 **Cross-section of the model (top); Conductivity-depth image obtained by differential S-transformation (centre); Conductivity-depth image obtained by regularized S-inversion (bottom). (After Tartaras et. al., 2000)**

3.7 Combining Strategies

Interpreting geophysical data almost never comprises the straightforward application of a fixed procedure. As with putting together the different pieces of a puzzle, the more information you have and the more angles you can view it from, the better your chances are of success. TEM data and processing are no different. Especially in TEM data there are still so many approximations made in even the best processing and interpretation algorithms that not one of them can be considered completely accurate. Automatically implementing and combining decay curve analysis with an improved imaging algorithm to isolate conductors will be discussed in the next chapter.