Towed transient electromagnetic survey for groundwater investigation - challenges and solutions.

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SUMMARY

Towed transient electromagnetic survey (TEM) is conducted by towing loops of wire behind a vehicle, one transmitting and several receiving. The loop sizes must be large enough to transmit/receive moments well in excess of EM noise levels while loop inductances must be kept low in order to keep turn-off time and system response low enough to resolve shallow detail. Long systems with the towing vehicle well in front of two separate non-metallic loop support structures are practical. As such a system must fit through farm gates, between trees, and along road margins without undue traffic disruption, it must be capable of folding to legal road vehicle width. Processing involves most of the normal complications of airborne EM survey but with the additional complication that the system cannot be elevated high above the ground to isolate system response. Additional challenges are identification and removal/minimization of noise and metallic source anomalies: 1. created by movement of coils through the magnetic field of the earth, 2. created by buried telephony cables, and 3. from other sources such as power lines, buried metal pipes and fences. Much of Australia is reasonably navigable and not densely covered with infrastructure and it is in these parts of Australia where towed TEM systems, which can be deployed and manoeuvred flexibly, have a market for groundwater and other exploration.

Key words: Groundwater, TEM, electromagnetic, towed.

INTRODUCTION

Why conduct towed TEM?

An increase in demand for bulk water storage free from evaporation loss has led to increased interest in groundwater. Electrical conductivity (EC) is usually the most appropriate property to use for economical imaging of groundwater distribution and salinity. Recharge hotspots and groundwater flow pathways generally are reflected in EC imagery. Both galvanic and electro-magnetic imaging techniques readily resolve recharge pathways in areas with reasonably clayey soils due to the combined effect, on bulk electrical conductivity, of low clay content associated with recharge pathways and low salinity of surface water that is the source of the recharge. Such techniques may also readily identify seawater intrusion wedges and other subterranean salt stores that threaten irrigation and infrastructure.

Groundwater is a relatively low value and extensive geophysical target so viable survey solutions must cover a lot of ground, and depth range, at low cost. This is a challenge met by towed TEM systems.

What exactly is towed TEM?

Towed TEM is conducted by towing generally horizontal loops of wire behind a vehicle, one transmitting and one or several receiving. For groundwater investigation, the loop sizes generally are at least a few meters long. Loops may be one inside another, overlapping or separated by some distance. A transient 'pulse of current' is injected through the transmitter loop and turned off cleanly and rapidly. The ground is enveloped in the resulting magnetic field and tries to maintain this field after current is turned off by developing a 'smoke ring' of current within it. The 'smoke ring' dissipates and expands at a rate dependent on ground electrical conductivity (EC). The receiver loops at the surface detect and record change in the magnetic field of the 'smoke ring'. The process is repeated many times per second and stacked into records geo-located generally with DGPS or GPS. Figures 1 & 2 present two towed TEM systems.

Figure 1 The AgTEM2 (Groundwater Imaging 2010) survey platform during early trials. The platform is designed to quickly transform from road legal form to survey capable form. It is designed to resolve a large depth of investigation from 1m to 100m (and in the future potentially 100's of metres). Booms fold in and out via remote control. The Trailer, made of fibreglass, has a drawbar which extends to separate the closest transmitter loop edge from the towing vehicle by 5m raising its ground clearance to over 1m as it does so.

Figure 2 A Slingram TEM system designed for rougher terrain, easy setup and packup, and with ability to be driven through narrow gaps.

Comparison with alternative techniques for imaging groundwater

Electrical conductivity survey traditionally has been conducted using:

1. electrodes or wire loops manually arranged on the ground (conventional geo-electric and TEM techniques),
2. airborne electromagnetic systems, or
3. using small vehicle mounted frequency domain electromagnetic (FDEM) systems.

There have emerged niche markets for conduct of surveys using towed equipment capable of surveying deeper and/or with greater vertical detail than the small FDEM systems and/or with less setup costs than the airborne EM systems.

Due to loss of detail with respect to depth of EM methods, very deep groundwater investigations must still be relegated to techniques common with oil exploration and not discussed further in this paper.

EC is the most commonly imaged aquifer property but some techniques imaging other groundwater related properties include Electrokinetic Sounding (EKS) (Baird, 2001) and nuclear resonance imaging (NMR) (Hertrich et. al., 2002). This paper focuses on EC imaging techniques due to the lower productivity of NMR and the current experimental status of EKS.

EC imaging for groundwater investigation has been conducted from the air using electromagnetics (EM) (Brodie, et. al., 2004, Ley-Cooper et. al., 2007, Noteboom et. al., 2007), from the ground using EM (Sørensen, et. al., 2000) or capacitive geo-electric equipment (Ball, 2006) or from water using geo-electric or EM equipment (Allen, 2007, Ball, 2006, Barrett et. al., 2006, Telfer et. al., 2005).

On land, geo-electric equipment is difficult to tow unless used with capacitive electrodes (Ball, et. al., 2006) which bring their own limitations but electromagnetic devices can be readily towed. Frequency domain EM devices may be relatively small but need either large coil separation or precisely calibrated and stabilized electronics to image to greater depths. Transient electromagnetic devices resolve multiple depths using multiple time gates and numerous gates may be sampled without adding to instrument complexity or cost.

Historic towed TEM

Early adoption of towed TEM was conducted by the Aarhus hydrogeophysics group (HGG) in a precursor to the SkyTEM system, the PATEM system, which was used for groundwater investigation in Denmark (Sorensen, et. al., 2000). The system was abandoned in preference to their airborne TEM system, Skytem largely due to the dense network of fences that needed to be negotiated in typical Danish terrain. As Australian agriculture is less extensive, the fence problem is not prohibitive to us. Subsequent to and independently from the Aarhus HGG, Zonge Engineering also utilized towed TEM with their NanoTEM system on some occasions. (Telfer, et. al., 2005, Barrett et. al., 2006, plus earlier occasions in the USA). Allen conducted early trials with towed mats (Allen, 2007) as did Western Australian experimenters (Harris et. al., 2006).

AIRBORNE EM vs. TOWED DEVICES

Due to its greater survey speed, should airborne EM simply now replace towed TEM for groundwater investigation applications? I believe that both of these applications of EM have their niche which is defined by the criteria given below.

Airborne EM has merit as it can cover large areas in detail at relatively low cost. The cost, per linear kilometre, is not, however, necessarily lower than towed techniques, especially when interpretation issues are included in the cost. This is particularly the case for smaller projects and pilot studies that cannot justify the mobilization costs of airborne EM equipment. Towed techniques have three other significant advantages over airborne EM:

1. No measurement of, and compensation for, an air-layer is required leading to reduced interpretation complexity, one less source of error, and, in some cases at least, increased vertical resolution. Additionally, no depletion of transmission efficiency due to the air layer occurs when the system is towed rather than airborne.
2. Comparatively low hourly acquisition rates permit greater stacking rates per unit distance covered. For this reason, the moment of the system need not be anywhere near as large as the moment of an airborne system targeting the same depth.
3. Towed equipment has a much smaller near surface footprint. It is in the near surface that sources of cultural interference exist which can corrupt data. The operator of towed equipment can therefore get much closer to fences and other metallic objects without compromising data integrity. The more focused towed TEM at-surface footprint enables detailed survey in amongst sources of cultural interference where an airborne system may have the interference blended, inseparably through otherwise useful data. The towed system, can additionally, clearly sample and identify cultural interference by driving right to the sources so that much greater confidence can be placed in the process of separating out the unaffected parts of the dataset.
4. Towed TEM is conducted with close observation of the environment. It is recommended that, should geologically trained personnel operate the system, geological mapping, identification of other sources of anomalies and correlation of surface features with the data be conducted simultaneously with acquisition. Geological mapping, often now under-rated, often leads to clear explanation of otherwise ambiguous TEM data. In contrast, airborne TEM must be separately investigated by later on-the-ground investigation which, in some cases where there is complex surface outcrop, can take almost as much time as a towed TEM survey.
5. Interaction with those present on the site can have both positive and negative effects – usually, however, farmers are glad to discuss results being acquired when encountered and this can have a positive effect on public relations. Frequently, historic clues they provide, such as old drilling results, true locations of bores, and response of the site hydrology to various climatic events prove to be valuable to TEM data interpretation. Where there is

conflict, farmers can have control over where exactly survey may proceed whereas they may not with airborne surveys – this too may avert public relations crises.

6. No noisy low-flying aircraft that may scare animals which may then stampede are required, however, this is not generally a concern of consequence.

Airborne equipment has the following advantages:

1. It can readily negotiate terrain and vegetation that cannot be traversed by towed equipment. Groundwater exploration is often conducted across cleared farmland where the obstacles are typically land access issues, some crops and fences.
2. Acquisition is faster, and therefore large areas can be covered quickly and generally economically.
3. To date, large powerful airborne systems have been developed while power and dimensions of existing towed systems are smaller due to lack of investment.
4. Airborne techniques are affected differently to towed systems by phenomenon such as the super-paramagnetic effect (Lee, 1984) and induced polarization effects.
5. Negative impact on farmers resulting from driving across their land is avoided. Towed TEM can create negative impact with farmers due to potential for mistakes in identification of property boundaries, leaving of gates open accidentally, disruption of stock and farm personnel, pushing down of crops and having strangers on the land and around valuables. Pre-negotiation with farmers is necessary for both towed and airborne EM surveys.

It would seem that a towed system could be scaled down to survey with much more detail than an airborne system but there is a limit to this truth as scaling down of TEM systems is a difficult challenge.

CHALLENGES AND SOLUTIONS

Towed TEM perhaps has not been developed to much extent due to the many difficult challenges there are to its success and because those capable of creating solutions are in demand from airborne EM practitioners. It may seem that it is possible to just scale down and tow a conventional TEM system without any bother but it is not that simple. Listed here are numerous challenges, and their solutions, relevant to towed TEM:

1. The loop sizes must be large enough to transmit/receive moments well in excess of EM noise levels while inductance, which increases with the square of the number of loop turns, must be kept low in order to keep turn-off time and loop self responses low enough to resolve shallow detail. The problem is not pronounced when imaging highly conductive features such as UXOs or near- surface saline groundwater but is very problematic when imaging resistive features. Usually, only 1 to 8 turns are practical on transmitter loops due to the inductance problem. The receiver loops too must have limited turns if their self-response is to be manageable. Receiver coils typically used with conventional 100 x 100m TEM loops can be completely impractical on a towed TEM system due to the much greater primary field concentration at the receiver in such systems. The coil self response magnitude is proportional to the primary field strength. Such inductance problems may be minimized by operating in slingram mode (transmitter and receiver coils both are horizontal and are separated by some considerable distance) or by using bucking arrangements. Bucking arrangements require high dimensional stability and, in contrast to airborne systems, may be compromised by variation in system mutual inductance with the near-surface. Slingram mode, in turn, introduces a secondary challenge - it has compromised near-surface detection due to the sampling volume of the propagated current ring by the time it passes under the receiver coil. Since, depth of exploration is dependent not only on distribution of current flowing through the ground, but also on pickup sensitivity distribution of the receiver coil, it is still possible to get considerable near surface sensitivity from slingram systems providing that appropriate inversion software is used. When the receiver coil is placed out of the transmitter loop minimum depth of focus is compromised due to departure from near-zone electromagnetic behaviour (Spies, 1989). An additional, fast-response receiver coil placed centrally in the transmitter coil may help with near surface response but often is not practical due again to self response, considerably enhanced due to its situation in a high primary field area. Not all conductivity-depth transformations and inversions programs accommodate slingram data neverlone mutual slingram and in-loop data but EM1DInv (from Aarhus HGG) does.
2. Proximity of transmitter and receiver loop wires to metallic parts of the towing vehicle must be avoided to reduce the magnitude of system response or no shallow detail may be resolved. Over typical Australian ground (reasonably conductive) it has been found that vehicle influence drops beyond detection on many systems once the vehicle is around 6m from the closest loop edge. Over resistive ground, it is more problematic due to lower ground response to vehicle response magnitude ratio.
3. In practical systems, system response must be measured and removed as it is much greater at the receiver loop than with conventional large loop ground based TEM. Processing therefore involves all the normal complications of airborne EM survey but with the additional complication that the system cannot be elevated to high altitude to measure system response, instead a very resistive site must be used for this purpose. Transmitter signal may be continually measured as a means of measuring drift in system response.
4. The next challenge is that noise created by movement of coils through the magnetic field of the earth must be either measured and/or minimized. High frequency resonate movement must be minimized by designing supporting structure to reduce vibration while low frequency noise can be removed in processing. Larger receiver loops reduce the effect of coil movement considerably, particularly should they be flexible, resulting in lack of synchronization of movement noise from

different parts of the loop. An example of movement noise in a TEM decay is given in Figure 6. When the coil is on a mat, it generally does not suffer from movement at frequencies above the sampling frequency as there are no taut elastic components that can resonate. Noise lower than the sampling frequency can be removed in post-processing of appropriately stacked data using techniques common to airborne TEM survey (eg. Noteboom, 2007).

5. The equipment must be compact enough to be economically viable and robust enough to be towed through all sorts of terrain. Various designs involving towed mats, fibreglass, PVC and other plastic and wooden carts have been tried and the best of these have been chosen for commercial operation. Towed mats only are useful when small and heavy. Too light, per square metre, and the wind picks them up causing safety concerns among other issues. A 4 x 6m 2mm thick sheet weighs nearly 100kg and can be hurtled through the air when passed by large traffic.
6. Buried Telephony cables and other sources of noise must be avoided. It is suspected that inductive compensation for cable capacitance on telephony cables results in a resonating transient response when coupled with a TEM system. Telephony cables are avoided using a real time graphical display of transients measured - the driver will observe the response and replan course across ground. Similarly, response of fences, powerlines and other metal objects is tested by the driver watching the real time transient display, and then due avoidance measures are made by the driver. Later, the test responses and any other affected data is rejected in an interactive graphical data editing system. Much of Australia is reasonably navigable and not densely covered with infrastructure and it is in these parts of Australia where towed TEM systems have a market for groundwater and other exploration. Examples of types of noise, their effect on TEM decays and how the noise may be removed are given in Figure 6.

DEVELOPMENT OF EQUIPMENT FOR TOWED TERRESTRIAL SURVEY

Towed transient electromagnetic arrays have been applied by Sørensen, et al.(2000), and the author (Allen, 2007) however the full potential of the technique is far from being realised. Other options for fast towed TEM data acquisition have been described by Harris et. al. (2006) and Hatch et. al. (2007).

The challenges, (1) and 2), result in long, usually slingram, systems with the towing vehicle well in front of the non-metallic loop support structure. As such a system must fit through farm gates, between trees, and along road margins without undue traffic disruption, it must be capable of folding to legal road width (2.5m, or for oversize arrangements, 5 or 6m). My Monash Geoscope TerraTEM driven 2.5m structures presently are imaging to around 30m deep while 6m wide structures are imaging to around 80m deep without an external high power transmitter. It is anticipated that in future, deeper imaging will be practical with such systems and more focused shallow imaging will be facilitated by primary field bucking arrangements. 2.5m wide systems may be towed on plastic sheets while 6m wide structures are feasible using arrangements of folding plastic, wooden and/or fibreglass booms.

Key features of practical towed TEM devices are:

1. They must facilitate towing of sufficiently large area transmitter loops and one or more receiver loops upon largely non-metallic structure;
2. They must be robust enough to withstand field use including impacts with tree stumps hidden in long grass;
3. They must be capable of passing through farm gates and between other common obstructions without undue delay;
4. They should be designed in such a way that they can isolate and minimise effects of incomplete transmitter turn off, loop self and mutual inductance, super-paramagnetic near-surface minerals and chargeable near-surface minerals;
5. The transmitters need to be able to cleanly transmit high currents. Dual moment operation is beneficial; and
6. They must be readily road transportable and GPS equipped.

Figure 2 presents a platform with the transmitter and receiver loops placed on dragged sheets. The sheet is 2mm thick polyethylene which is heavy enough to prevent lifting by all but strong wind and rigid enough not to catch on stumps, barbed wire, and other obstacles. Practical size of the sheet is limited by the combination of the necessity of weight per unit area needed to prevent lifting by wind, and total weight which needs to be low enough to permit man-handling. The sheet is very useful for permitting precise layout of primary field nulling coils when using central loop receiver loops, and for spacing multi-turn transmitter loops so as to reduce self-capacitance and, to a lesser extent, self-inductance. It is difficult to increase the number of transmitter loop turns without compromising turn-off ramp integrity. This is a problem well understood by designers of airborne TEM systems.

PRESENTATION AND INTERPRETATION OF TOWED SURVEYS

Interpretation of three dimensional aquifer structure is improved when a three dimensional imaging solution is used. Figures 4 & 5 presents a profile image of EC, projected in 3D, along wth borehole graphics. It is suggested that this method of presentation permits improved quality control of the data because line-to-line relationships between features can be identified along with improved identification of relationships between the data and geographic features. As only the discrete layered inversion is presented, gridding interpolation artefacts are minimised and quality control is improved.

Figure 8 also presents most of the types of features that are resolved in electrical conductivity imagery. The interpretation process combines observations of EC value, elevation of resolved features relative to water tables, and whether features are closed off at depth or increase in size with depth (ie. Whether they are concave down or concave up). Sharpness of boundaries also is often relevant.

Once dense coverage is achieved, presentation solutions such as depth slices become more practical. A non-gridded depth slice is presented in figure 3. Dense ground coverage reduces 3D heterogeneity 'noise' that may otherwise be caused by undersampling. The dense sampling frequently is essential to interpretation of data in some sedimentary environments due to the small dimensions and non-linearity of relevant sedimentary features. This is particularly the case for palaeochannels. Multiple layers of palaeochannels may be resolved and viewed in a collection of depth slices.

TOWED TEM EXAMPLES

Examples of towed TEM data, inverted to give resistivity-depth transformed data, are given in Figures 3 to 5. Non-gridded data without interpretation is presented as this paper discusses the acquisition technique, not interpretation.

CONCLUSIONS

Electrical conductivity imaging, using towed devices, for groundwater investigation can be highly effective. Geological system complexity, typical of sedimentary environments can often be resolved. This is important for the precise management of groundwater, permits creation of meaningful groundwater models, and can open up the possibility of efficiently managing recharge. Multi-depth groundwater connection with surface water bodies can be studied using geo-electric equipment while multi-depth survey across dry ground may be effectively completed using transient electromagnetic equipment. Once developed to full potential, towed imaging solutions are appropriate techniques for many groundwater investigations.

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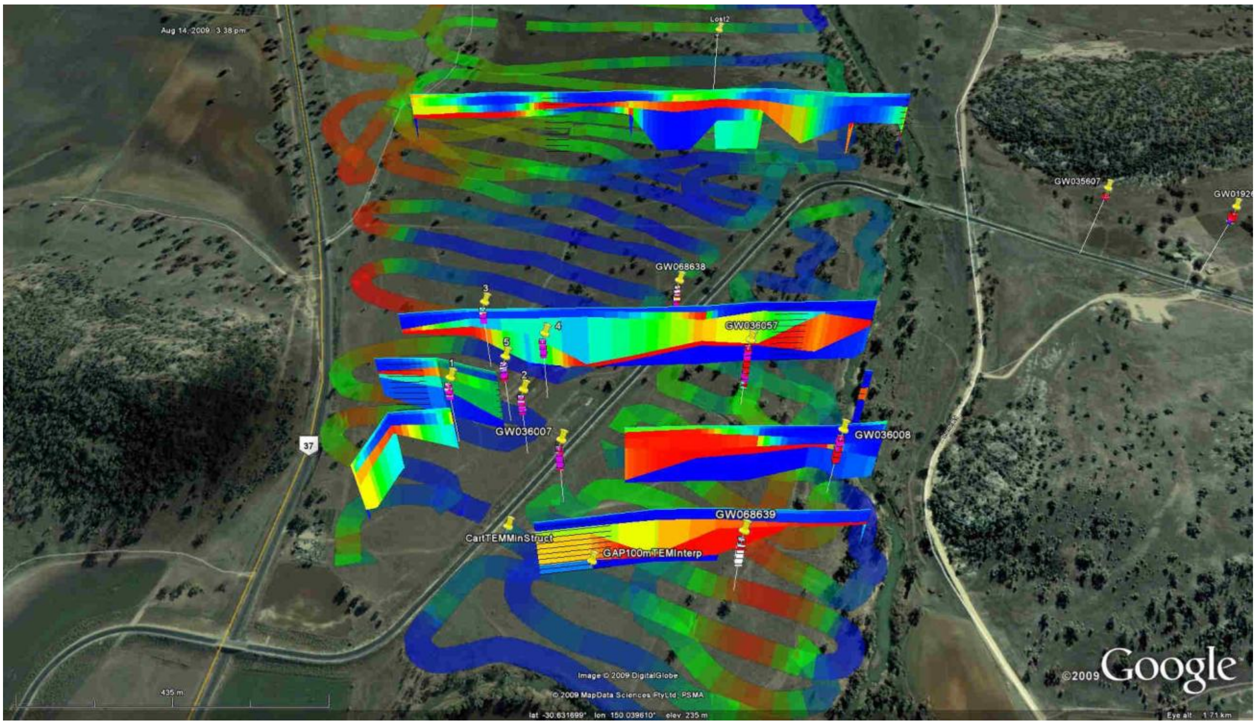

Figure 3 Comparison of 5 layer inversion of 100 x 100m loop TEM with the 42m layer of the towed TEM dataset. The 100 x 100m loop data is projected 100m above the ground. In the colour scale, red is most conductive while blue is most resistive.

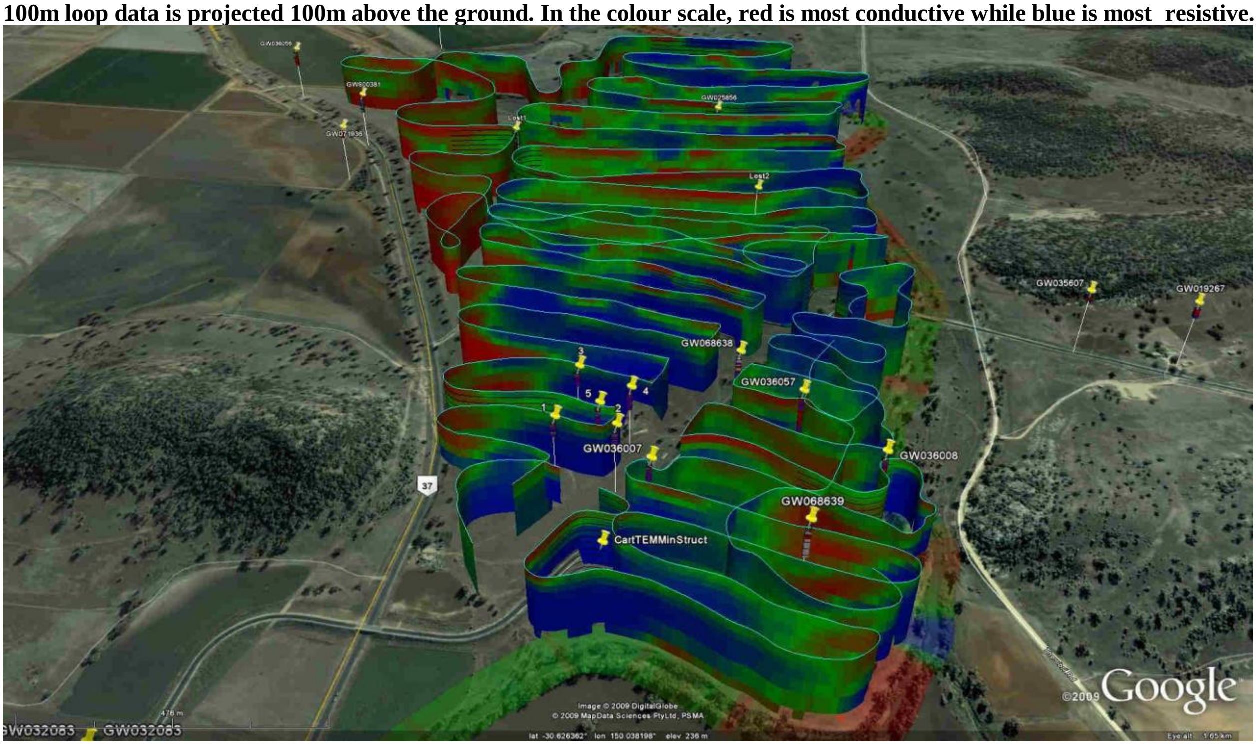

Figure 4 Towed TEM data inverted using EM1DInv, smoothness constraint and a 9 layer model. The 42m depth slice data from this dataset is presented in figure 3. The resistive features shown are generally lava flows at this site while, both beneath and above the flows exist unconsolidated permeable sediment and beneath this a mixture of resistive and conductive basement rocks. The towed TEM was instrumental, along with targeted drilling, in proving up the presence of the lava flows which effectively almost entirely block off the only subsurface drainage of a large groundwater aquifer. The survey is situated just north of Boggabri, NSW.

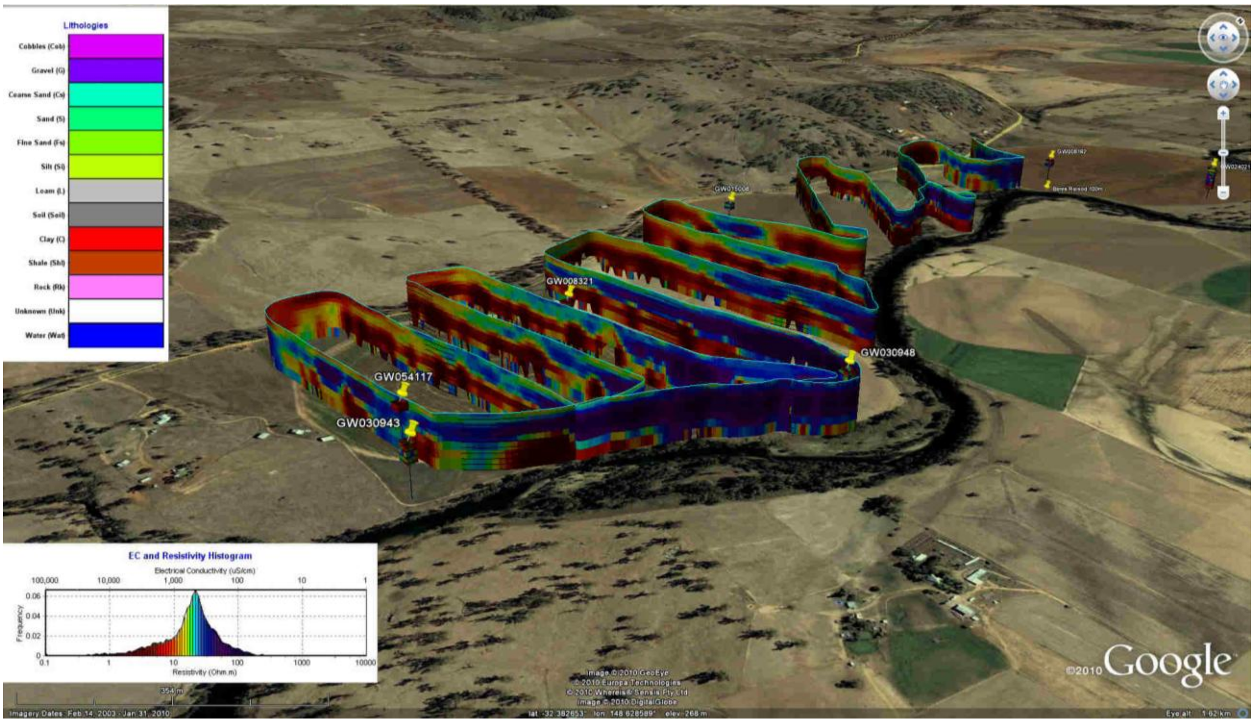

Figure 5 Towed TEM data inverted using EM1DInv, smoothness constraint and a 10 layer model. Resistive river alluvium of variable depth is observed overlying conductive shale. Displayed bore logs have facilitated this interpretation. This dataset was collected in half a day using AgTEM2 (see figure 1).

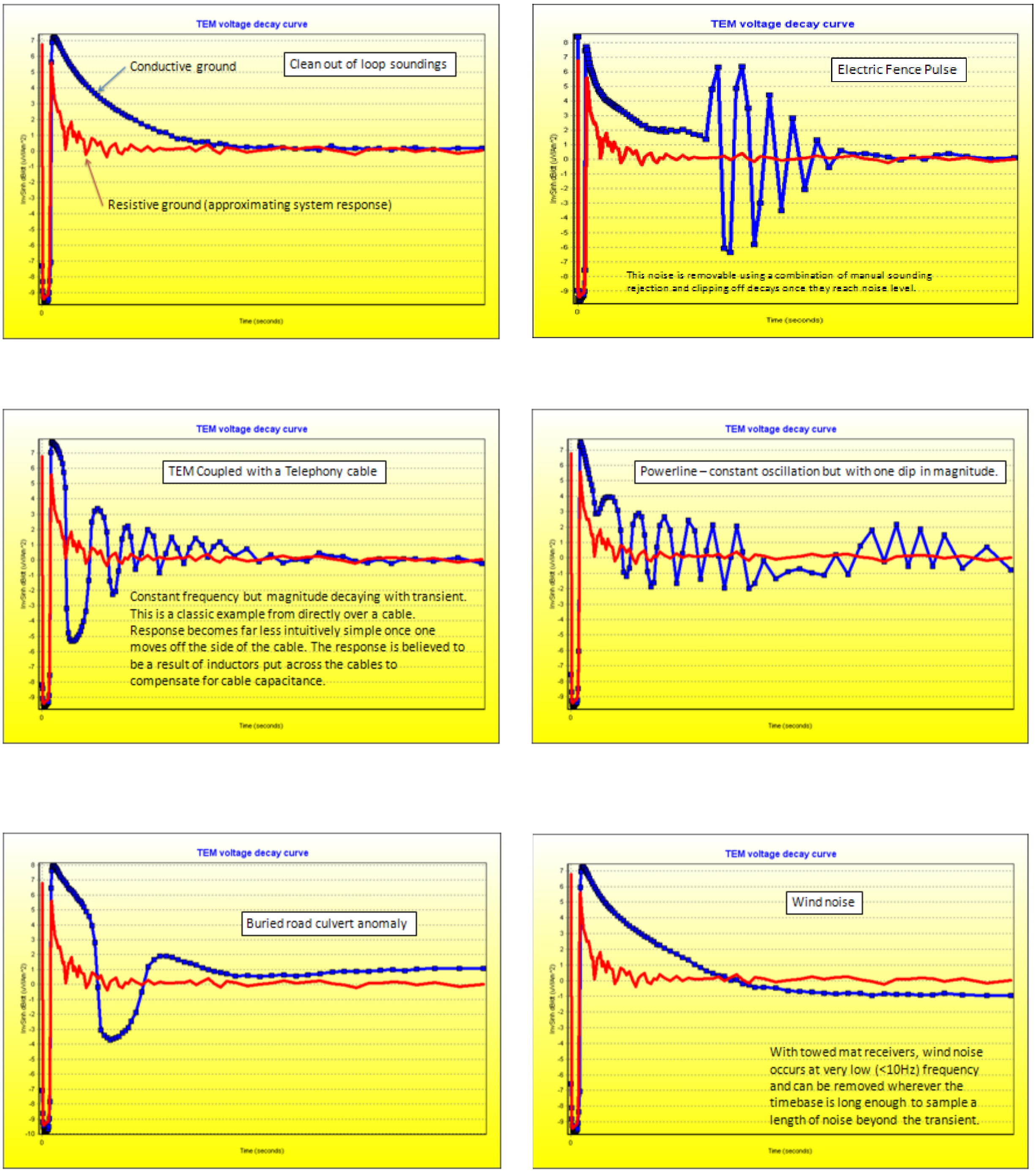

Figure 6 Various out of loop TEM decays presented on a linear time scale. (a) Conductive ground response compared to resistive ground response (approximately system response which is removed) (b) Electric fence noise (c) Telephony cable coupling (d) Powerline noise (e) buried metal anomaly and (f) wind noise.