Mapping Groundwater and Soil Moisture using multi-depth Electrical Conductivity data from towed TEM carts

David Allen*
Groundwater Imaging Pty Ltd
82 St Georges Tce, Dubbo, NSW, 2830, Australia
David@GroundwaterImaging.com.au

SUMMARY

Groundwater presence and salinity both correlate with electrical conductivity, a property readily mapped over a swath of depths by various geophysical instruments. Thus, it would seem then that exploration for groundwater could be a simple matter, however, for most groundwater investigations the level of detail of geological complexity demands detailed acquisition and multi-dataset interpretation.

Towed or airborne electromagnetic survey permits multi-layer map coverage of a site as is necessary for revealing geological detail that would make little sense when viewed as individual transects. Further, because electrical conductivity responds to so many natural variables related to groundwater, multi-disciplinary information must be included in the interpretation. In many cases, the footprint of an airborne system will be too large to sufficiently resolve complexity of geology and cultural interference to successfully site bores. In other cases the mobilization cost of an airborne system will, on its own, exceed the exploration budget. In these cases, towed electromagnetic devices including $AgTEM_4$™ cart have a niche.

Exploration depth and resolution of practical towed devices is very limited by their practical size constraints so great care must be taken in other design aspects including effective, robust primary field nulling and maximizing of transmitter loop – receiver loop separation.

Case studies of groundwater exploration demonstrate these geological interpretation and physical design challenges and limitations.

Key words: electromagnetic, groundwater, towed, slingram, resistivity.

INTRODUCTION

Ground moisture presence and salinity are the dominant variables affecting geophysical parameters electrical resistivity (or its inverse – electrical conductivity commonly abbreviated as EC) (Daily et. al. 2005), dielectric permittivity (Galagedaraa et. Al. 2005) and nuclear magnetic resonance (Sucre, 2011) all of which can be sensed within the near surface using geophysical devices traversing the surface. Much can be mapped in tremendous detail yet exploration remains a challenge, both pragmatically, due to the perceived low value of water and lack of water managers' experience with, and confidence in, geophysics, and technically, due to complexity of the earth being studied.

Consider the case of fresh groundwater in gravel overlying weathered saline basement rock. This is easy to identify using electrical resistivity. But what if, within the basement there is unweathered granite, and then on top there are lava and pyroclastic flows present in old river channels within the flood plain. Further, what if the water table is at considerable depth such that many features must be penetrated by signal even before target aquifers are sensed. Without prior knowledge of possible existence of these additional features geophysical data interpretation becomes much more difficult. Further, clients typically have not prepared themselves for the cost of mapping such complicated conceptual models that they have often failed to envisage. In this example, cost effective application of very detailed geophysics, along with well thought through geological interpretation is necessary for groundwater exploration. Similarly, for pollution plume delineation and monitoring, it may be easy to map a saline plume within a homogenous host but may be more difficult to image if the natural salinity in faults within that host ground is very high, thereby masking part of the response that we are looking for from the pollution plumes. Devices capable of collecting all the necessary detail at appropriate depths easily are needed, along with drill hole and other information, should groundwater exploration be effectively completed within typical budget constraints.

HISTORY OF TEM USING TOWED CARTS

Towed sled and cart TEM (Transient ElectroMagnetic) systems have been used for tens of years but have not realised a large market due to slow speed of acquisition and/or cumbersome logistics. Two designer groups, Aarhus Hydrogeophysics Group and Zonge have made significant efforts leading to limited commercial use (Sorensen, 1997, Barrett 2005, MacInnes 2001). Aarhus have favoured a Slingram approach in their design called PATEM (with a transmitter loop in one sled followed by a receiver loop in a second sled). Used in Denmark, their system was limited by access across numerous small land parcels typical of Denmark and has been succeeded by the SkyTEM airborne TEM system. Both PATEM, and its successor, SkyTEM, use transmitter and receiver loops with multiple turns attached to separate circuits to facilitate low moment – shallow response, and high moment – deep response acquisition. Zonge have adopted an in-loop approach with a single turn receiver loop within a single turn transmitter loop all mounted on a towed platform. With no primary field bucking, their systems have limited depth of investigation. Various groups have made towed TEM systems for unexploded ordinance detection (Geometrics 2011) but these are of a small scale and are not more widely applicable.

AgTEM$_4^{™}$ CART DESIGN

A towed cart TEM system - AgTEM$_4^{™}$ cart was developed to image the groundwater related earth parameter electrical conductivity. While maintaining practical ability to pass through farm gates and over rough terrain, it has been designed to fold out to create a transmitter loop 6m wide with good geometric stability around an overlapping, null-coupled receiver loop in a separate plane within the cart core. A towing vehicle separation of 5m is maintained. Such a system is suitable for shallower exploration while, to see deeper, a second slingram receiver loop may be added (i.e. a second receiving loop is set up, separated by considerable distance horizontally from the transmitter loop). Although additional receiver loops may be towed by, or mounted via framework to the towing vehicle, to see deeper, the receiver loop/loops must be separated further, either by static placement of rows of receiver loops on the ground or by use of a separate vehicle to carry the receiver antennae. Both of these solutions demand precision location/orientation and time synchronization technology and strongly benefit from 3D EM modelling and inversion. With the receiver loop/loops movement separated from that of the transmitter loop, variable configuration surveying becomes possible such that very comprehensive, detailed, deep 3D surveys become feasible.

Options for appropriate distribution of towed cart loops are discussed in detail in Allen (2013). The remainder of the design of the AgTEM$_4^{™}$ cart is shown in Figure 1. The system is presently driven by a Monex Geoscope TerraTEM system. The transmitter is able to reliably transmit around 12 Amps into the AgTEM system, with a turnoff time of 16 uS in a two turn transmitter loop ($65m^2$) . The receiver loop is 10 turn with area of $20m^2$. I anticipate that the system will be improved with delivery of a 50 Amp TerraTEM 24 capable of continuous acquisition in the near future.

EM loops are susceptible to noise generated by movement through the earth's magnetic field. Loop padding, air bag suspension and large diameter wheels absorb high frequency vibrations and transform movement noise to frequencies low enough to reject in processing. Ride quality is further enhanced by maintaining the same wheel separation as that of the towing vehicle so that the cart tows along the towing vehicle tracks.

Elastic cords hold the loop firmly in shape except when the front booms are deflected by tree impacts or to pass through gates. After deflection, the booms spring back into their firmly fixed positions required for primary field nulling.

Figure 1: AgTEM$_4^{™}$ cart with an additional receiver loop forward of the towing vehicle.

CASE STUDIES – GROUNDWATER EXPLORATION USING Towed TEM

In the following case studies, results are discussed from surveys performed on several farms. These surveys were conducted using line spacing of between 10m and 50m, generally in irregular grids taking advantage of orientation of cultivation and logical paths around obstacles. In many locations, separation from cultural features such as fences had to be considered. This was done by surveying up to the features, observing their response and then moving far enough away that the observed cultural response was no longer visible in the data. Various examples of such real time data observation, including wind noise, fence anomaly detection, telephony (buried insulated conductor) cable detection, powerline anomaly detection, electric fence spike detection, and buried road culvert response are given in Allen (2012). Using this system data have been collected over a number of different target types, which demonstrate typical complexities and how they may be explored using electrical conductivity imaging (See Figure 2).

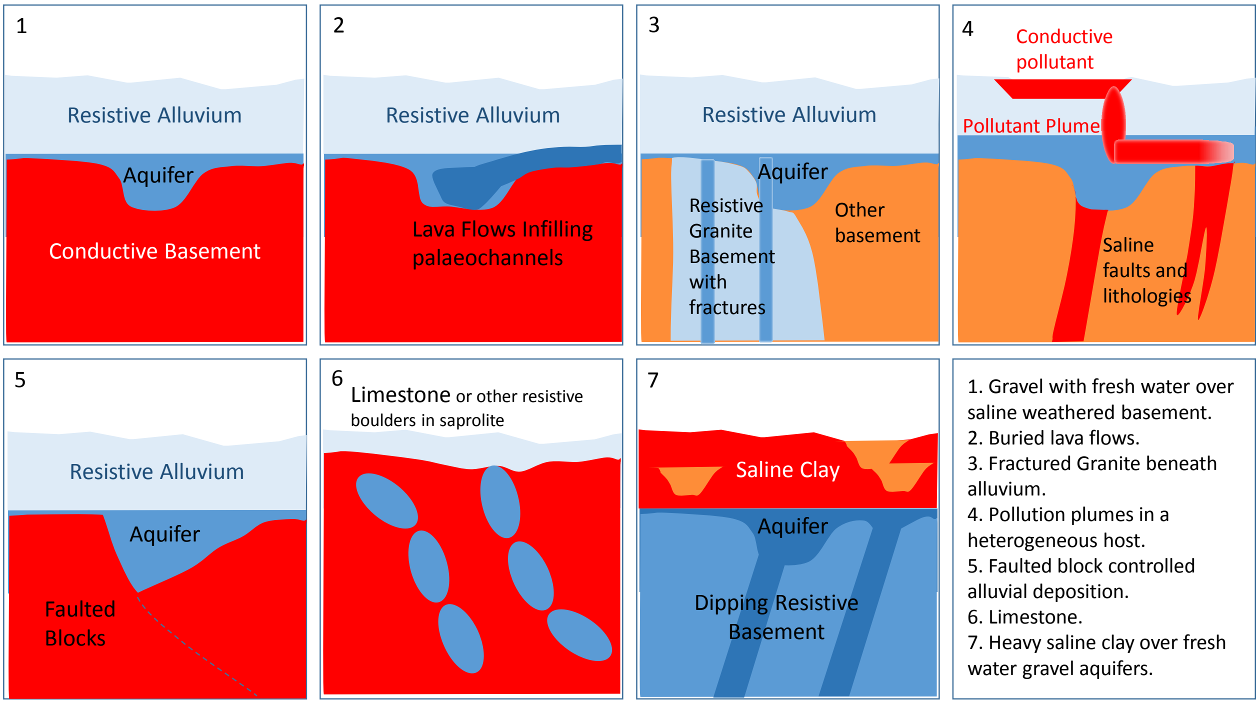

Figure 2 Conceptual models of typical TEM targets. Notice that in many cases the target is far from ideal in terms of resolvability using TEM yet, with sufficient consideration of survey design these problems can be resolved.

1. Gravel with fresh water over saline basement.

This is a common situation in Australia where much of the older, folded, indurated rock is highly weathered. An example was presented in Allen (2012 – reproduced here in Figure 3), with resistive fresh water in gravel overlying an undulating conductive weathered basement – the ideal scenario for electromagnetic exploration. A deep, gravel-filled channel was detected 70m deep incised into high conductivity, weathered basement. This scenario is relatively easy to image and interpret.

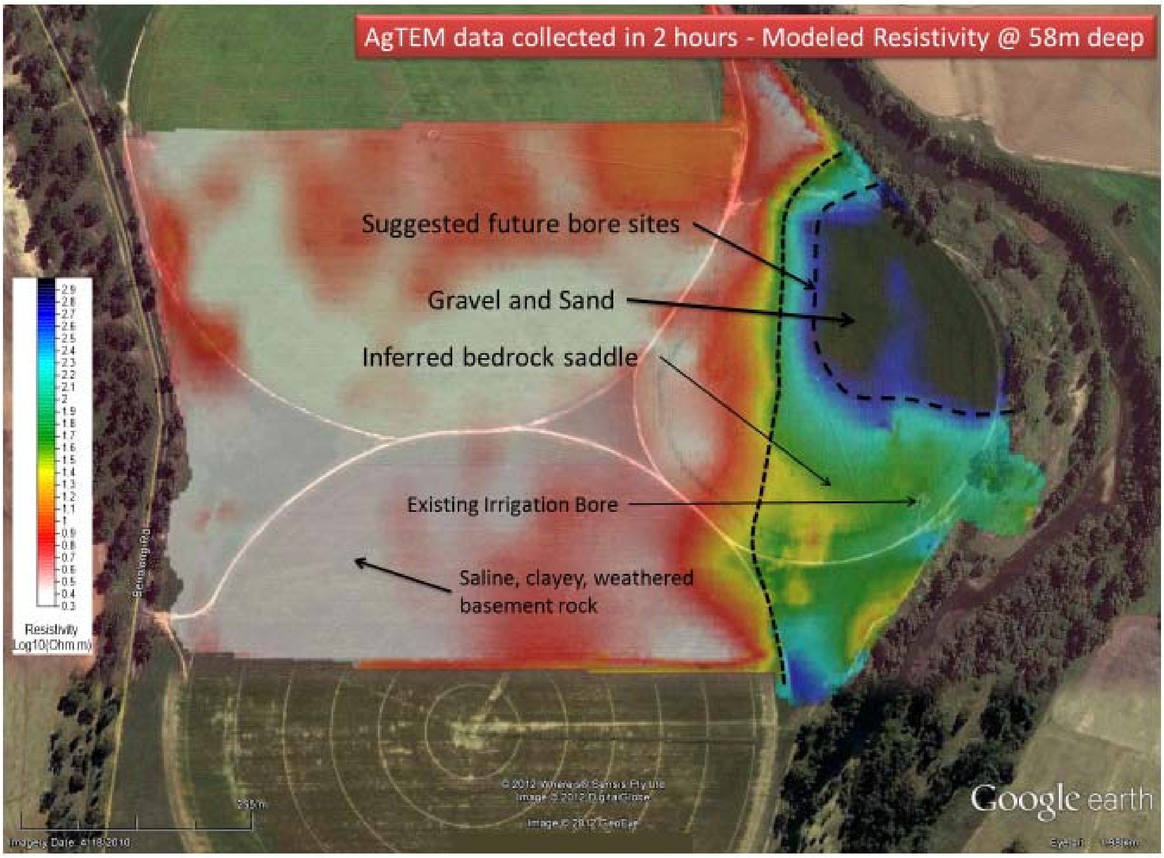

Figure 3 TEM response of gravel with fresh water overlying saline weathered basement.

2. Buried lava flows.

Lava flows within alluvial sediment generally are relatively resistive but pyroclastic layers within can be highly porous and weathered, therefore conductive both hydraulically and electrically. There are groundwater flow complications associated with such flows which typically have blocked and filled prior river channels, damming and redirecting those rivers. A lava flow typically appears as a sinuous resistive feature resembling a palaeochannel in some cases. Typically, one drill hole intersecting the flow is then needed to identify the whole flow as being of pyroclastic origin or a palaeochannel. Groundwater exploration in this environment may target permeable brecciated, or pyroclastic zones within flows or may look for sands and gravels beyond or crosscutting the flow. Resistivity contrasts may be subtle as shown in Figure 4.

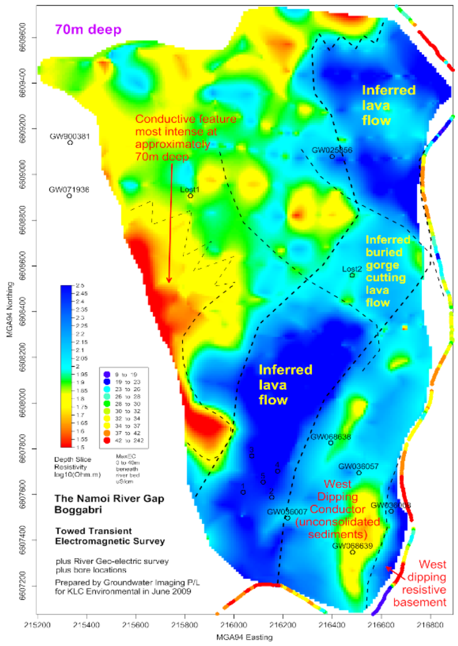

Figure 4 A lava flow in a palaeochannel subsequently cut by another palaeochannel and covered with sediment. Without both drill-hole data and detailed TEM data this complex conceptual model would never have been realized.

3. Fractured Granite beneath alluvium

Granite is resistive and does not form significant salt and clay when weathered so the weathered granite may be of similar resistivity to that of fresh water in gravel and sand. For this reason the gravel/sand and weathered granite may be indistinguishable based on comparisons of electrical conductivity alone. In this situation, however, detailed surveying distinguishes alluvial and fractured rock geometric features. Where fast flowing water has eroded through granite leaving steep buried terrain the interpretation is more difficult as a buried fracture zone may both underlie and resemble gravel filling a buried gorge. Nevertheless, a detailed survey in this type of environment (see Figure 5) reduces the number of drilling targets needed to get a full detailed understanding of the site.

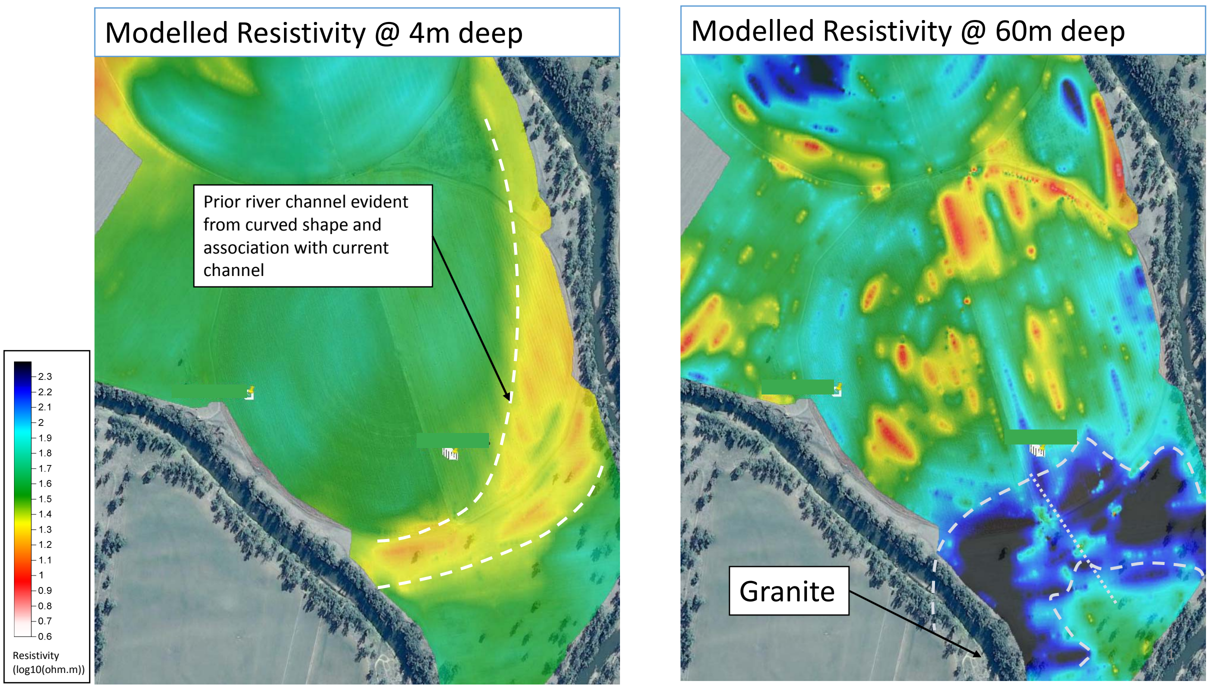

Figure 5: Towed TEM survey of alluvium over buried granite and other folded rock. Alluvial features are evident in shallow data above the water table. To find a good bore location, deeper data affected by granite and folded rock potentially cross cut by buried gorges filled with gravel must be interpreted. At this depth, data noise and inversion instability is also beginning to appear and can be disregarded by ignoring any trends that are not evident across multiple survey lines. In this case interpretation requires the assistance of some drill holes –the best bore site may not be targeted in the first hole.

4. Pollution plumes in a heterogeneous host

It is usually simple to image a saline pollution plume within a homogeneous non-saline host but such a situation is not common and is more likely found only when oversimplified conceptual modelling is considered. It is more common for the host to also have saline sediments or natural fluids in fractures (see Figure 2). With sufficiently high data density it is possible to define plume shapes radiating from a source overprinting the background saline features. In this situation, detail is very important. Without sufficient data resolution it is possible to mistakenly attributing natural saline features as pollution from man-made sources. Pollution sources are typically also in areas where cultural features such as metal pipes and fences that affect electromagnetic data. Detailed acquisition identifies and isolates the effect of such features on data so they can be excluded. To correctly interpret natural lineaments and other features around plumes it is critical to survey well beyond the plumes.

5. Faulted block controlled alluvial deposition

It is common for faulting to have occurred during alluvial deposition and this can alter and control deposition yet leave little evidence at the surface. Detailed electrical conductivity surveys reveal the difference between straight sets of faulted block edges and meandering alluvial features partially controlled at depth by the faulting. This type of interpretation can very quickly eliminate large areas from prospective groundwater exploration.

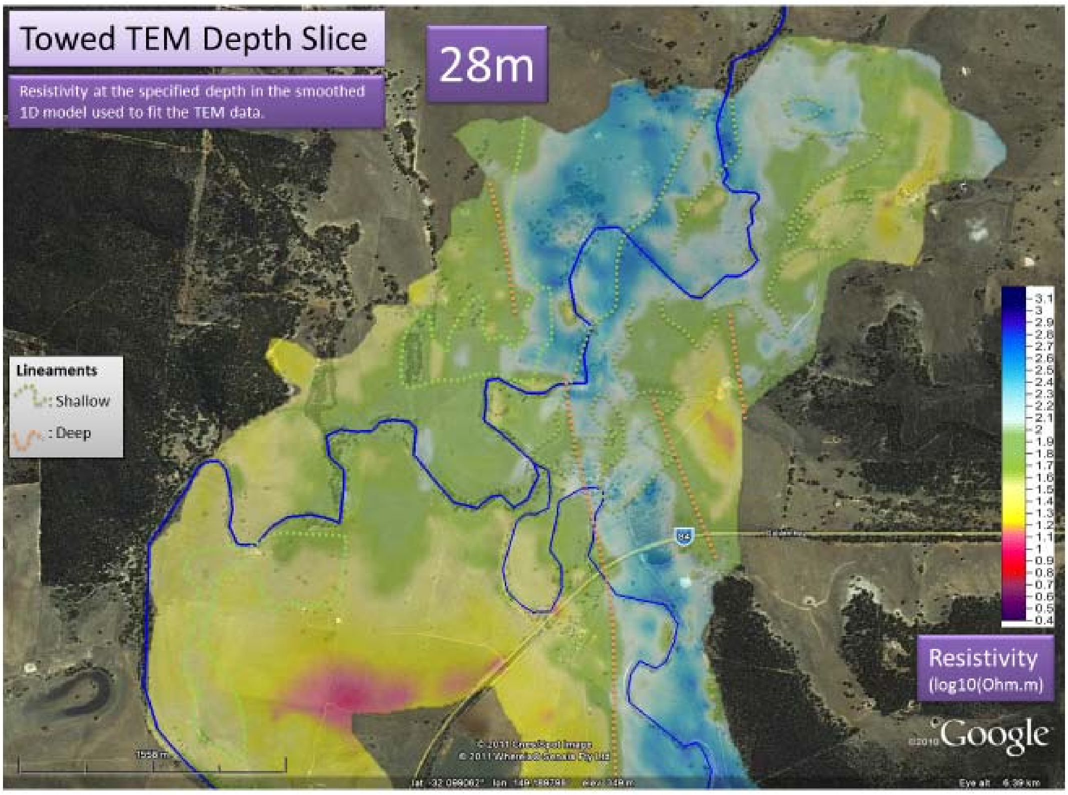

Figure 6 TEM data dominated by tilted and faulted rock where surface geomorphology reveals only meandering channels (green dotted lines superimposed from a shallower resistivity map). Note the straight approximately north-south lineaments (orange dotted lines interpreted from this and deeper resistivity maps).

6. Differentiating hard rock from weathered rock

Limestone is an extremely resistive rock that weathers to an electrically conductive clay that retains ground moisture. This means that electromagnetic surveying over limestone can tell a lot about limestone boulder distribution by imaging the conductive clay surrounding resistive limestone boulders. Many igneous rocks also weather to conductive saprolite containing boulders (Figure 7). In this example the rock is to be mined as dimension stone. The approximate locations and depths of the most competent boulders have become evident. Similarly, such surveying is useful for blast pattern design optimization and excavation planning in any quarry or road cutting where resistivity contrasts exist.

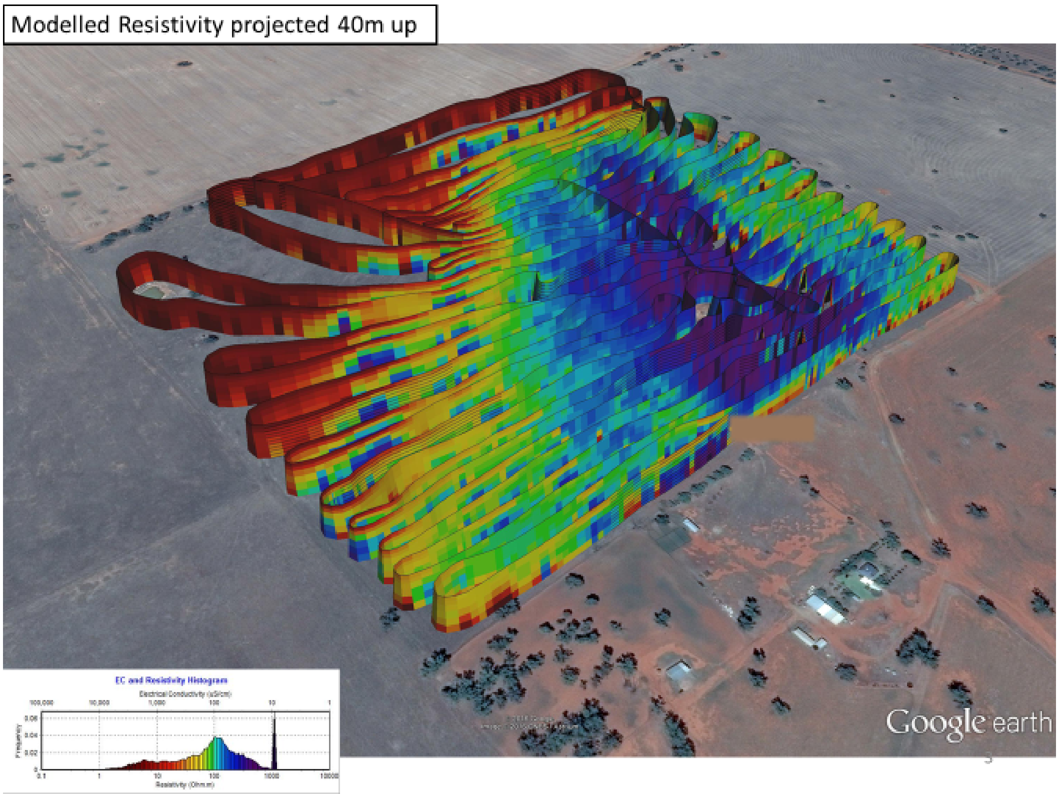

Figure 7 An example of hard rock (Monzodiorite) definition using mine-scale TEM survey (20m spaced lines).

7. Heavy saline clay over fresh water sand and gravel aquifers

A surficial layer of clayey and/or saline sediment may strongly impair depth of investigation and resolution of electromagnetic imaging systems but, with sufficient power, imaging beneath such sediment is possible. If deeper aquifers are sufficiently thick then it will be possible to image with sufficient loop moment and transmitter receiver loop separation. Figure 8 is a successful example of imaging through saline clay soil with the AgTEM cart alone (without a slingram loop).

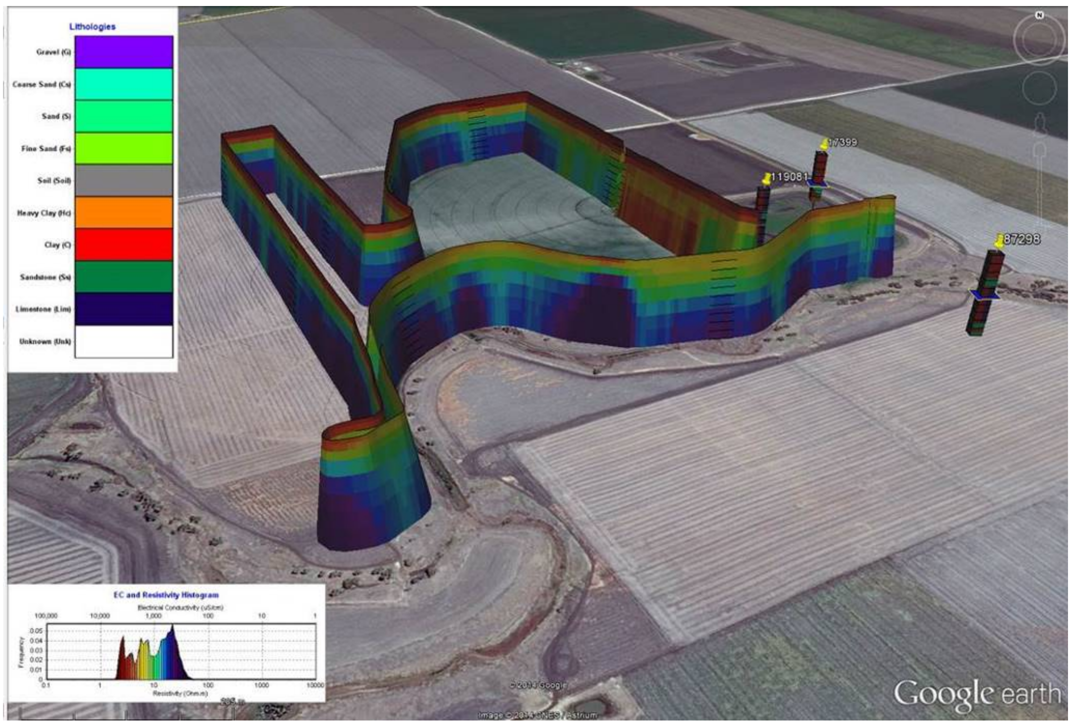

Figure 8 Imaging through saline clayey soil (Condamine Alluvium) to infer sands and accessible fresher water beneath (Purple deep features). Modelled resistivity here is projected 50m up.

COMPARISON OF OVERLAPPING LOOP DATA WITH SLINGRAM DATA USING AgTEM$_4$™ CART

When a survey needs to be collected to depths of 30m or less, the AgTEM$_4$™ Cart may be used without the need for extra receiving loops and this makes setup and pack up easier and driving among obstacles quicker. When a survey requires information to greater depths it is often necessary to use an additional slingram receiver loop suspended off the front of the towing vehicle. Although the standard receiver loop in the AgTEM cart is designed to null couple with the transmitter loop, this receiver loop is directly over the area of ground highly affected by the transmitter loop. This means that a comparatively high proportion of the signal received by this receiver loop is from shallow induced current (even at late times).

Further, fast turnoff of the transmitter pulse in the present TerraTEM is achieved by using a high clamping voltage (In the TerraTEM 24 clamping voltage is selectable). As per the principles of all solid state switching equipment, after the back EMF drops to the clamping voltage, the transmitter waveform decays relatively slowly and exponentially and this part of the waveform induces current in the ground directly beneath the transmitter loop well out to late times. The smaller the cart is made and the sharper the initial turnoff is made, the more problematic this overprint of shallow effects onto late time data becomes so that it is hard to distinguish response resulting from deep conductors from response affected by shallow heterogeneities. The Aarhus PATEM system reduced this effect by collecting both "high moment" and "low moment" data sets, i.e. sampling with high current through multiple loop turns and slow turn-off then low current through few loop turns and fast turnoff then combining the two results in processing (Sorensen, 1997).

In most TEM systems, damping resistors built into both the transmitting and receiving loops remove resonance from the turnoff but can do nothing to remove the late time, exponentially decaying, part of the primary field waveform (i.e. the part beyond where back EMF in the transmitter drops below the clamping voltage of the solid state switching circuitry). These effects can be partially removed by modelling the waveform and using it in interpretation but this is only a partial solution.

Another problem is that ground effects other than resistivity affect the response, especially where high currents are induced directly beneath the transmitter loop. These include induced polarization and super-paramagnetic effect both of which create long time constant responses from highly induced near surface material (Buselli, 1982, Cole & Cole, 1941, Kratzer et.al. 2012 & 2013). The combination of these effects cannot be entirely separated from that of deeper ground features on the receiver loop within the cart. The slingram loop, placed further away, however, is further from the ground directly affected by the transmitter loop where high currents are induced while it samples equally well the response from currents circling in deeper ground. With greatly diminished proportion of signal coming from the near-surface, it is therefore able to image deeply using standard inversion software.

Figure 9 shows an extreme case of contrast between 1D modelled in-cart receiver loop data and slingram loop data at a resistive site revealing how different the two resulting modelled datasets can be. In this case, a fixed system response is subtracted from each decay before inversion (in contrast to the more effective and sensible method of modelling the full-waveform in the 1D inversion). If the transmitter waveform could be accurately measured, it could be modelled to improve the in-loop data in particular. Note that it is expected that there will be slight differences in response between the two systems as the slingram setup couples slightly differently with the ground than the "normal" setup.

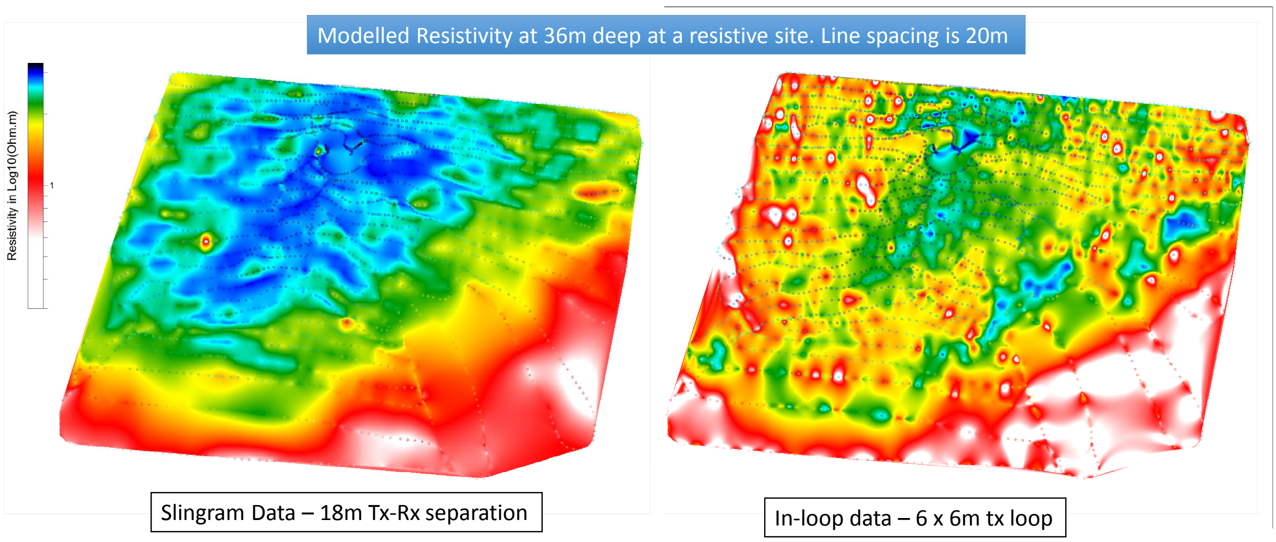

Figure 9 Comparison of inloop and slingram modelled data. Even though both datasets are modelled response at 36m deep, the slingram data seems to depict broad deep features while the in-loop data seems to be dominated by isolated features. This is the same data set shown in Figure 7.

CONCLUSIONS

Groundwater exploration would be relatively easy were it not for the complexity of typical geology hosting groundwater. Not only is there complexity of how the rocks and sediments were deposited but also with how groundwater has interacted with and weathered them over time. Deciphering of that complexity requires detailed geophysics integrated with other sources of information.

Geophysics is not a 'silver bullet'. Geophysics must be applied in sufficient detail to allow geological complexities to be revealed and interpreted in the midst of cultural interference. Once applied in sufficient detail, groundwater occurrence, quality and accessibility may be very comprehensively interpreted.

Airborne EM is good at providing a solution at around the detail level of 1:100,000 scale mapping or coarser while towed cart EM may provide greater detail, even amongst fences and other cultural interference. Towed cart EM can be conducted competitively on small task-focused jobs with smaller mobilization overheads than airborne EM. Towed cart EM struggles to deliver detailed deep data (50m deep or greater) without compromising versatility and cost although reasonably versatile solutions may explore 100m deep.

ACKNOWLEDGMENTS

I thank the many farmers for whom I have collected data over the years. I am not able to identify many of you, so as to maintain the confidentiality of the data collected over your land.

Michael Hatch is thanked for very comprehensive revision of this paper.

REFERENCES

This paper sources its information almost entirely from field observations so there are few references. Data is available subject to permission from individual farmers who own that data – it can generally be obtained with permission upon demmand should confidentiality and anonymity be maintained so as not to affect farm value.

Allen, D., 2012, Towed transient electromagnetic survey for groundwater investigation – challenges and solutions. Extended Abstract – Proceedings of the 22nd International Geophysical Conference and Exhibition of ASEG, 26-29 February 2012 – Brisbane, Australia.

Allen, D., 2013, Towed transient electromagnetic survey using various loop configurations. Extended Abstract - Proceedings of the 23rd International Geophysical Conference and Exhibition of ASEG, 11-14 August 2013 – Melbourne, Australia.

Barrett, B., Heinson, G., Hatch, M., Telfer, A., 2005. A water-borne transient electromagnetic (TEM) system for river sediment salt-load detection, *Journal of Applied Geophysics*, **58**(1), 29-44.

Buselli, G., 1982, The effect of near-surface superparamagnetic material on electromagnetic measurements: *Geophysics,* **47**, 1315-1324. Doi:10.1190/1.1441392

Cole, K., and Cole, R., 1941, Dispersion and absorption in dielectrics I. Alternating current characteristics: *The Journal of Chemical Physics,* **9**, 341-351. Doi:10.1063/1.1750906

Daily, W., Ramirez, A., Binley, A., and LaBrecque, D., 2005, Electrical resistance tomography theory and practice, in: DK Butler (ed), *Near-Surface Geophysics, Investigations in Geophysics*, **13**, Society of Exploration Geophysicists, Tulsa, 2005, pp. 525-550.

Galagedaraa, L.W., Parkinb, G.W., Redmanc, J.D., von Bertoldib, P., Endresd, A.L., 2005, Field studies of the GPR ground wave method for estimating soil water content during irrigation and drainage, **Journal of Hydrology, 301**, Issues 1–4, 20 January, Pages 182–197, doi:10.1016/j.jhydrol.2004.06.031

Geometrics, 2011, Metalmapper manual. http://www.geometrics.com/files/metalmapper_manual_beta1.pdf

Kratzer, T., and Macnae, J.C., 2012, Induced Polarization in airborne EM: *Geophysics,* **77**, E317-E327. Doi:10.1190/geo2011-0492.1

KRatzer, T., Macnae, J.C., and Mutton, P., 2013, Detection and Correction of SPM effects in airbourne EM surveys: *Exploration Geophysics* doi:10.1071/EG12048

MacInnes, S., Snyder, S., Zonge, K., Durham, J., Dickerson, J., 2001, Fast TEM for UXO mapping at Gambell, Saint Lawrence Island, Alaska. Presented at UXO -Countermine Forum, Session 30, Location and Mapping, New Orleans, Louisiana, April 9-12 http://zonge.com/fast-tem-for-uxo-mapping-at-gambell-saint-lawrence-island-alaska/

Sorensen, K.I, 1997, The Pulled Array Transient Electromagnetic Method. Proceedings of EEGS, p135, www.earthdoc.org/publication/download/?publication=16279

Sucre aus Baruta, O.S., 2011, A Low-Field NMR Tool for Soil Moisture. Von der Fakult¨at f¨ur Mathematik, Informatik und Naturwissenschaften der RWTH Aachen University zur Erlangung des akademischen Grades eines Doktors der Naturwissenschaften genehmigte Dissertation vorgelegt von M. Sc. darwin.bth.rwth-aachen.de/opus3/volltexte/2011/3667/pdf/3667.pdf