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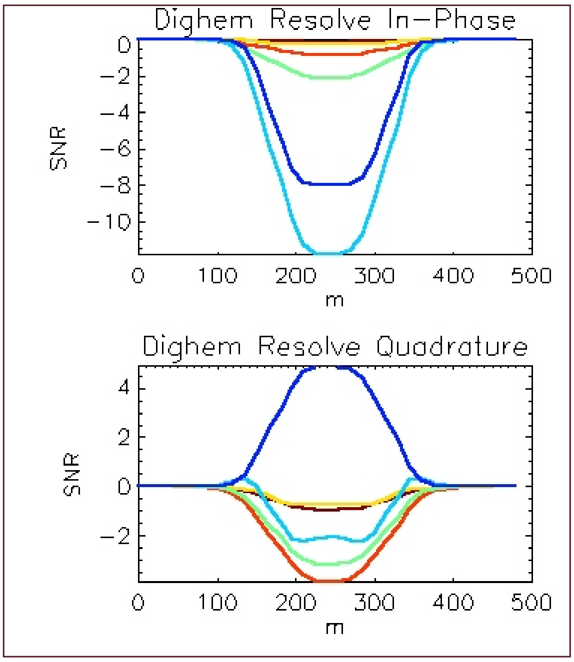
FORWARD MODELLING AIRBORNE ELECTROMAGNETIC DATA FOR THE RIVERLAND, SOUTH AUSTRALIA



A. Green and T. Munday

CRC LEME OPEN FILE REPORT 171

September 2004

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Report prepared for the South Australia Salinity Mapping and Management Support Project.
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PREFACE

The report is a CRCLEME contribution to the South Australian Salinity Mapping and Monitoring Project (SA-SMMSP) being conducted under the auspices of the National Action Plan for Salinity and Water Quality. It summarises some scoping work undertaken ahead of the call for tenders that concerned the acquisition of airborne geophysical data, and represented an effort to be more considered in their application to natural resource management issues.

Following discussion with South Australian colleagues, concerning issues of relevance to salinity management in the Riverland region of South Australia, we established a scoping study to determine whether the Blanchetown Clay might be a resolvable target for current airborne electromagnetic systems, and if so what system might be most appropriate for its detection. Of particular interest was whether recent advances in EM system technology, improvements in their noise characteristics and data processing and display would enable the reliable mapping of these clay units including their thickness. For modelling purposes, a representative geological model was defined for the Blanchetown Clay along with a corresponding schematic geo-electric model.

This report captures the outcomes of a set of milestone reports submitted to the SA Technical Advisory Committee as part of early scoping studies conducted by CRCLEME on behalf of the SA-SMMSP.

This work indicated that high resolution frequency domain helicopter EM data rather than fixed-wing time domain EM systems were most suited to the detection of the clay at a resolution appropriate for planning purposes

T.J. Munday
Riverland SA-SMMSP Sub-Project Leader

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ABSTRACT

Central to the South Australian Salinity Mapping and Management Support Project (SA-SMMSP) planning process was an acceptance that only the most appropriate geophysical system/s were to be employed within National Action Plan priority regions of South Australia. As part of a project scoping activity in the Riverland region, we sought to determine whether airborne geophysics could realistically be used to map variations associated with the Blanchetown Clay, an important sedimentary unit, which has significant implications from a groundwater recharge perspective. Previous study had suggested that the clay could be mapped with an airborne electromagnetic (AEM) system. As part of the scoping activity we were also concerned to define which AEM system would be best suited for this, and what survey parameters might be chosen to map variability associated with the clay.

This was achieved by defining a representative regolith-geological model for the Blanchetown Clay, including information on the nature, geometry and spatial variability of this unit. We also acquired borehole geophysical logs and ground EM data to help define the electrical properties of representative regolith/sedimentary materials. From this we constructed a geo-electrical model which formed the basis for the forward modelling of expected airborne EM response for particular airborne EM systems given a set of varying ground conditions. The AEM systems examined here included both time and frequency domain systems. Specifically, model responses were determined for the Hummingbird, DIGHEM^{V} and RESOLVE helicopter frequency domain (FDEM) systems, and the TEMPEST and HOISTEM time domain (TDEM) systems.

Modelling was conducted using MARCOAIR which computes the electromagnetic response of 3D prisms contained in a multi-layered host. Relatively complex models can be constructed using combinations of prisms. A series of 1D models were run in this study to determine the expected response of several airborne EM systems when targeting a conductive near surface unit. AEM system geometry and noise characteristics were considered. These forward modelling studies and results suggest that:

1. Frequency domain EM (FDEM) systems outperform the time domain EM (TDEM) systems for the problems/targets faced in the Riverland area, being more sensitive to variations associated with the slightly conductive, near-surface Blanchetown Clay.

2. Modelled responses for the RESOLVE FDEM system suggest that, of all the systems examined, it is the best suited to mapping near surface conductivity variations.

3. TDEM and FDEM systems appear to be similar in performance with respect to detecting changes in the quality of the groundwater system.

4. Our ability to separate the effects of spatial variation in both the clay and groundwater layers is moderately good with both TDEM and FDEM systems.

Survey design and in particular line spacing, would be determined by the size of holes in the that need to be detected. Our recommendation is that the line spacing be chosen so that at least two lines intersect the smallest hole that is of interest. In the modelling the smallest hole was taken as being 150m, and a line spacing of 150m was deemed appropriate.

1. INTRODUCTION

1.1. Background

The National Action Plan for Salinity and Water Quality (NAP) recognises the potential for airborne geophysical technologies to deliver relevant soils, regolith, geological and salt store information at the farm and/or catchment scales for natural resource management. However, it also recognises that airborne geophysics can only contribute to improve regional and catchment salinity plans when the information provided is linked with hydrologic and hydrogeological information and modelling. This philosophy underpins the NAP's South Australian Salinity Mapping and Management Support Project (SA-SMMSP).

The SA-SMMSP developed a strategy for the application of geophysics from an understanding of regional variations in landscape, hydrogeology, land use and the requirements of particular communities. The blanket acquisition of geophysical data over particular catchments was not entertained. At the outset of the project, recognition was given to benefits of acquisition by particular systems at particular scales, given cognisance of the target and the resource needs of the decision makers. In this regard, the SA-SMMSP represents a significant departure from previous studies seeking to apply airborne geophysics in land management. It also reflects the thinking promoted earlier on the relevance of geophysics in land management (George and Green, 2000). This report describes one component of the strategy we adopted for the Riverland area (Lower Murray NAP Region).

Central to the SMMSP planning process was an acceptance that only the most appropriate geophysical system/s were to be employed in each of the five strategically important catchments/areas within National Action Plan priority regions of South Australia. In this report we focus specifically on results from the forward modelling of airborne electromagnetic (AEM) system response to determine whether airborne geophysics could realistically be used to map variations associated with the Blanchetown Clay, an important sedimentary unit, which has significant implications from a groundwater recharge perspective (Cook *et al.*, 2001).

It has been suggested that through an improved understanding of the spatial distribution and thickness of the Blanchetown Clay, targeted recharge reduction options can be better defined for the Riverland region of the River Murray, with consequent effects for river salinity. 30% of the salt load of the Murray at Morgan is sourced from the reach of the River Murray between Renmark, Loxton and Kingston. As a consequence, this region is a priority area for intervention under the NAP. Besides providing options for revegetation in areas of dryland agriculture, this knowledge could also assist in the zoning of irrigation development, helping determine where irrigation could be located to improve irrigation efficiency and the effectiveness of drainage works in irrigation areas. Presently, information on the spatial variability of the Blanchetown Clay does not exist at the resolution required for planning controls, despite efforts to compile it from bore logs. A question posed for the SA-SMMSP was whether airborne geophysics had the potential to map the clay layer at the required resolution and accuracy, at a fraction of the cost of drilling.

1.2 Aims and scope

The purpose of this study was:

1. *to ascertain whether commercially available AEM systems could be used to effectively map the presence or absence of a near surface conductor associated with a clay rich sedimentary unit known as the Blanchetown Clay.*

2. *to determine which AEM system would be best suited for this, and what survey parameters might be defined map variability associated with the clay.*

These goals were achieved through:

(i) Defining a representative regolith-geological model for the Blanchetown Clay, including information on the nature, geometry and spatial variability of this unit.
(ii) Acquisition of borehole geophysical logs and ground EM data to help define the electrical properties of representative regolith/sedimentary materials.
(iii) Definition of a geo-electrical model
(iv) Forward modelling of expected airborne EM response for particular airborne EM systems given a set of varying ground conditions.

The AEM systems examined here included both time and frequency domain systems. Specifically, model responses were determined for the Hummingbird (Valleau 2000), DIGHEM^{V} (Huang and Fraser 2001) and RESOLVE helicopter frequency domain (FDEM) systems, and the TEMPEST and HOISTEM time domain (TDEM) systems. TEMPEST has a fixed-wing configuration (Lane et al, 2002), and HOISTEM is a helicopter mounted time domain system (Boyd, 2001).

A staged approach was taken in this modelling study. Initially, the modelled response from the Fugro DIGHEM^{V} FDEM and TEMPEST fixed-wing TEM systems was examined and compared. Previous work by Cook and Kilty (1992), in the Mallee of South Australia, had suggested that DIGHEM could be used help map a near surface clay unit with implications for recharge modelling. In this instance we were interested in determining whether TEMPEST, with it's broad bandwidth, stable performance and good signal:noise characteristics would provide an alternative mapping option to DIGHEM. With the availability of further information concerning AEM system geometry and noise characteristics, an additional set of forward models were run to define the potential of several other AEM systems for mapping the presence or absence of the Blanchetown Clay.

The intended outcome of this work was a more informed process in defining specifications for Tender documents covering the proposed survey work in the Riverland area. The geo-electrical model developed here was used in the Tender process, with potential contractors asked to demonstrate whether their nominated systems could detect the desired target, namely the Blanchetown Clay. The results described here also provided an independent basis for evaluating tender submissions.

2 TARGET DEFINITION

2.1 Introduction

In this section we examine the nature, variability and distribution of the target - the Blanchetown Clay. We also define its petrophysical characteristics as a precursor to developing a geo-electrical model for forward modelling purposes. An appreciation of compositional variations along with the depositional setting for this sedimentary unit are important in helping constrain its geometry for modelling and provide an understanding of how the observed geophysical response might vary across the region. The latter issue is the focus for studies currently being undertaken as part of the SA-SMMSP.

2.2 Study site location

The Riverland region, a focus for this scoping study, is located in the western Murray Basin in South Australia, between Renmark, Loxton and Kingston on Murray (Figure 1). This region is important in that it is known to contribute significantly to the salinity of the Murray River,

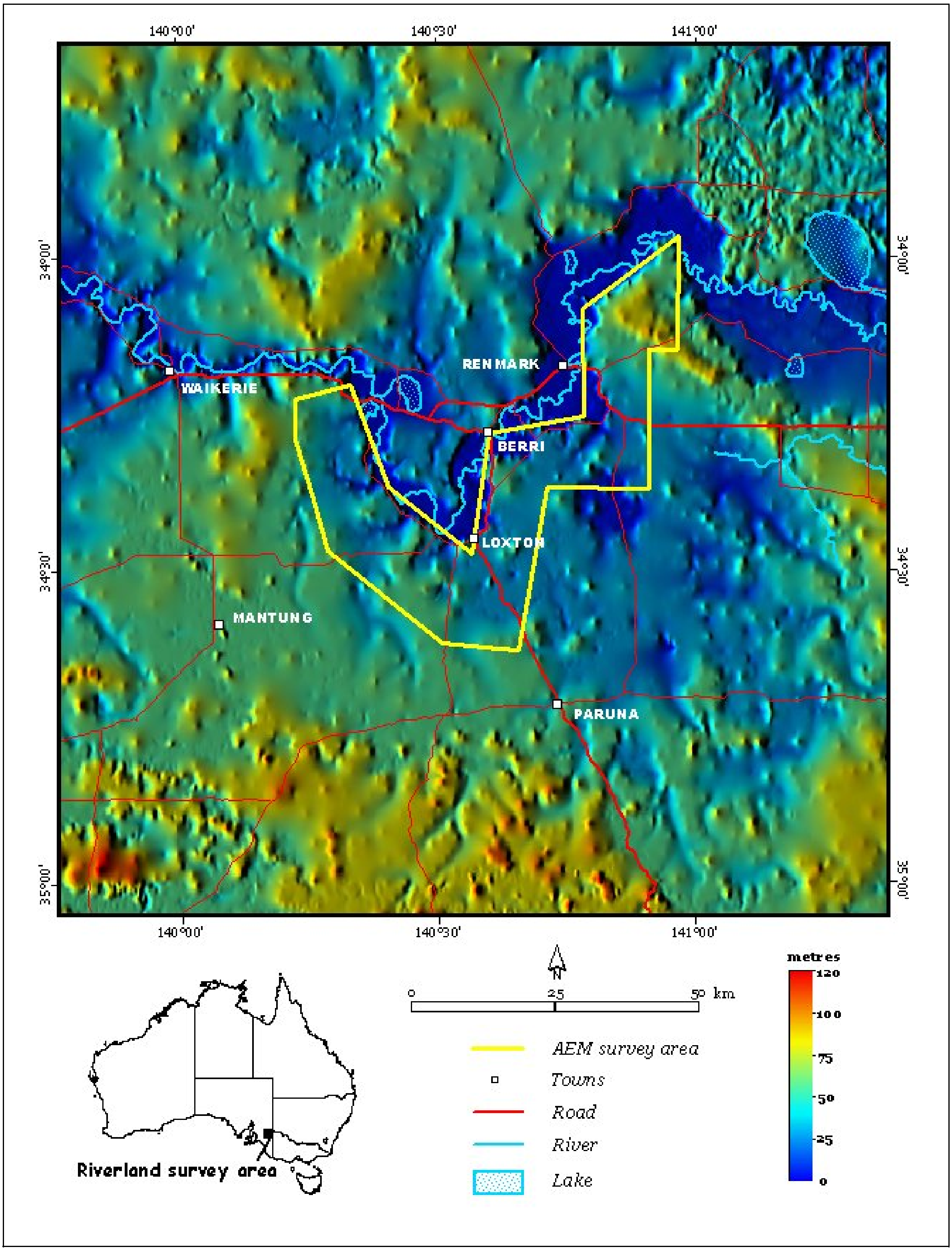

Figure 1: Location of the Riverland AEM survey area. AEM survey area (yellow polygon) is draped on a sun-shaded (illumination direction from the west) pseudocoloured DEM for the region.

much of it attributed to natural causes, namely a saline groundwater system. Recent increases in recharge from irrigation and dryland agriculture has seen a dramatic rise in the salt load in this reach of the river (Cook *et al.*, 2001). Whilst improved irrigation practice and interception schemes have helped reduce the salt input into the river, pressure for further development and the scale of the problem require additional strategies to minimise reliance on relatively high cost salt interception schemes and their "off-site" penalty (Glen Walker *pers comm* 2001). Low recharge agricultural practices are one option, requiring improved understanding of soil and regolith characteristics. In the Riverland region, the presence of the Blanchetown Clay is known to significantly inhibit recharge but information on the spatial distribution and variability (including thickness) of these materials is limited to scattered drillholes and outcrop.

The region selected for detailed study as part of the SA-SMMSP is swath paralleling the southern bank of the river, having a width varying between 15 and 20km (Figure 1).

2.3 The Blanchetown Clay

2.3.1 Composition

The Blanchetown Clay is described as a greenish-grey to red-brown or variegated, silty to sandy clay interbedded with thin beds of quartz sand, and locally some micrite lenses (Brown & Stephenson, 1987). The unit was deposited in a mega lake, Lake Bungunnia, in the Lower Murray between the Late Pliocene (2.4 Ma) and the Pleistocene (0.7 Ma) (Stephenson 1986), although more recent palaeomagnetic studies suggest lake sedimentation may have begun as early as 3Ma and continued to at least 300ka. The Blanchetown Clay is overlain by younger aeolian and fluvio-lacustrine sediments and the Bungunnia limestone (in the western part of the Murray Basin). In places the clay outcrops at the surface. The unit is underlain by the Loxton Parilla Sands. Mineralogical analyses of the Blanchetown Clay indicate that the dominant clay minerals present are illite and kaolinite (White, 2000, Tan *et al*., 2004), and that the composition does not vary significantly across the study area.

A study of particle size variations associated with the Blanchetown Clay suggests that the unit trends from a sandy-clay to a silty-clay from east to west. This may have significance in respect of its petrophysical, particularly electrical properties and should be borne in mind when considering the potential of airborne geophysical data to map spatial variations in the unit.

2.3.2 Extent and thickness of the Blanchetown Clay unit

An interpretation of available borehole data, along with local outcrop, indicates that the Blanchetown Clay is irregularly distributed throughout the area. A map of clay thickness derived from an interpretation of available borehole data attests to that variability (Figure 2). Clay thickness varies, in part as a function of the local topography at the time of deposition. Locally the clay may attain thicknesses of 20m, but more commonly is only a few metres thick (Stephenson 1986). The unit is generally thicker in the east. The overlying sediments are commonly up to 5m thick, exceeding some 20m where larger dunes are present.

The present day topography can be regarded as a reasonable approximation of the landscape 1-2Ma ago (ie. at the time the unit was deposited). Borehole data suggest that the 60m AHD contour is a good approximation for the maximum extent of Lake Bungunnia and therefore the upper limit expected for the elevation of the Blanchetown Clay unit (Stephenson 1986).

2.3.3 Geometry and topography

As mentioned above, the geometry of the unit is partly a product of topography at time of deposition and partly due to post-depositional erosion (Brown & Stephenson, 1987, and White, 2000). In western Victoria and in eastern South Australia, the Blanchetown Clay occurs in swales between topographically high beach strand ridges of the Loxton-Parilla group of sediments (Colwell 1977. Both the lower and upper surfaces of the unit are irregular as a consequence. An interpretation of borehole logs over the region confirms this (Steve Barnett *pers comm,* 2002).

2.4 Petrophysical characteristics of the Blanchetown Clay

Previous studies had suggested that the Blanchetown Clay is characterized by particular petrophysical properties, most notably elevated electrical conductivities relative to sedimentary units above and below (Cook et al. 1992, Cook and Kilty, 1992, Hatch et al., 2002). Inductive conductivity borehole logs collected as part of this scoping study confirmed this.

Boreholes 7029-617 and 6928-518 (Figure 3) intersect the Blanchetown Clay near surface (top 20m), and where present, the unit is characterised by a relative increase in apparent conductivity (shown as the black trace) and natural gamma (shown as the red trace), relative to the overlying and underlying sedimentary/regolith units. Borehole 7028-625 shows an elevated conductivity near surface which may also be related to the presence of clay. Holes 6929-323 and 7028-429 don't intersect the Clay. For these holes, the elevated conductivity noted at 32m and 18m below the ground surface respectively, is related to the presence of a conductive, saline groundwater. The conductive groundwater is also intersected in the first three holes, occurring at approximately 41m (hole 7029-617), 32m (hole 6928-518) and 26m (hole 7028-625) below the land surface. The conductivities are considerably greater than those associated with the Blanchetown Clay units.

No attempt was made here to determine the causes of the conductivity associated with the Blanchetown Clay, although Cook and Kilty (1992) attribute the response to textural changes in the materials (ie. more or less clay) rather than accumulations of salt, water or some other factor. However, more recent study suggests that the water content is also an important driver of the observed electrical conductivity (Tan *et al.*, 2004).

Average conductivities for the Blanchetown Clay were calculated as being between 20 and 200mS/m. This contrasts with average responses for the underlying sand units of between 20 and 50mS/m. The groundwater conductivities vary, ranging between 50 and 8000mS/m.

3 FORWARD MODELLING

3.1 Simplified geological and geo-electrical model of the Blanchetown Clay

To aid the forward modeling of an AEM system response, we constructed a set of simplified geological and corresponding geo-electrical models of the target environment. A simplified geological section for the Blanchetown Clay and related sedimentary units is depicted in Figure 4a. A corresponding geo-electric model is shown in Figure 4b.

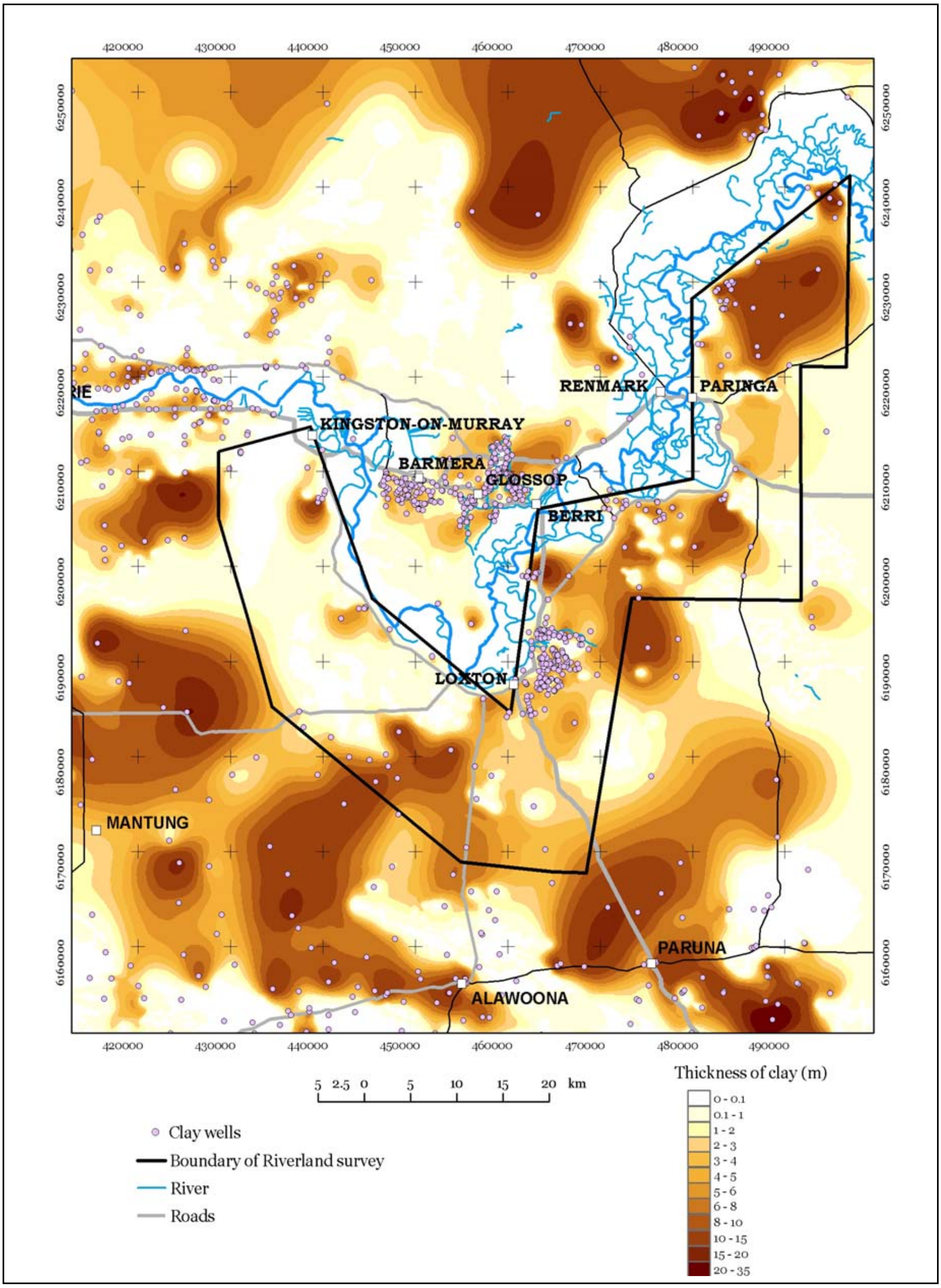

Figure 2: Thickness of the Blanchetown Clay in the Riverland region as defined from an interpretation of borehole data (Source: Barnett, 2002). Boreholes used in the area shown as purple dots.

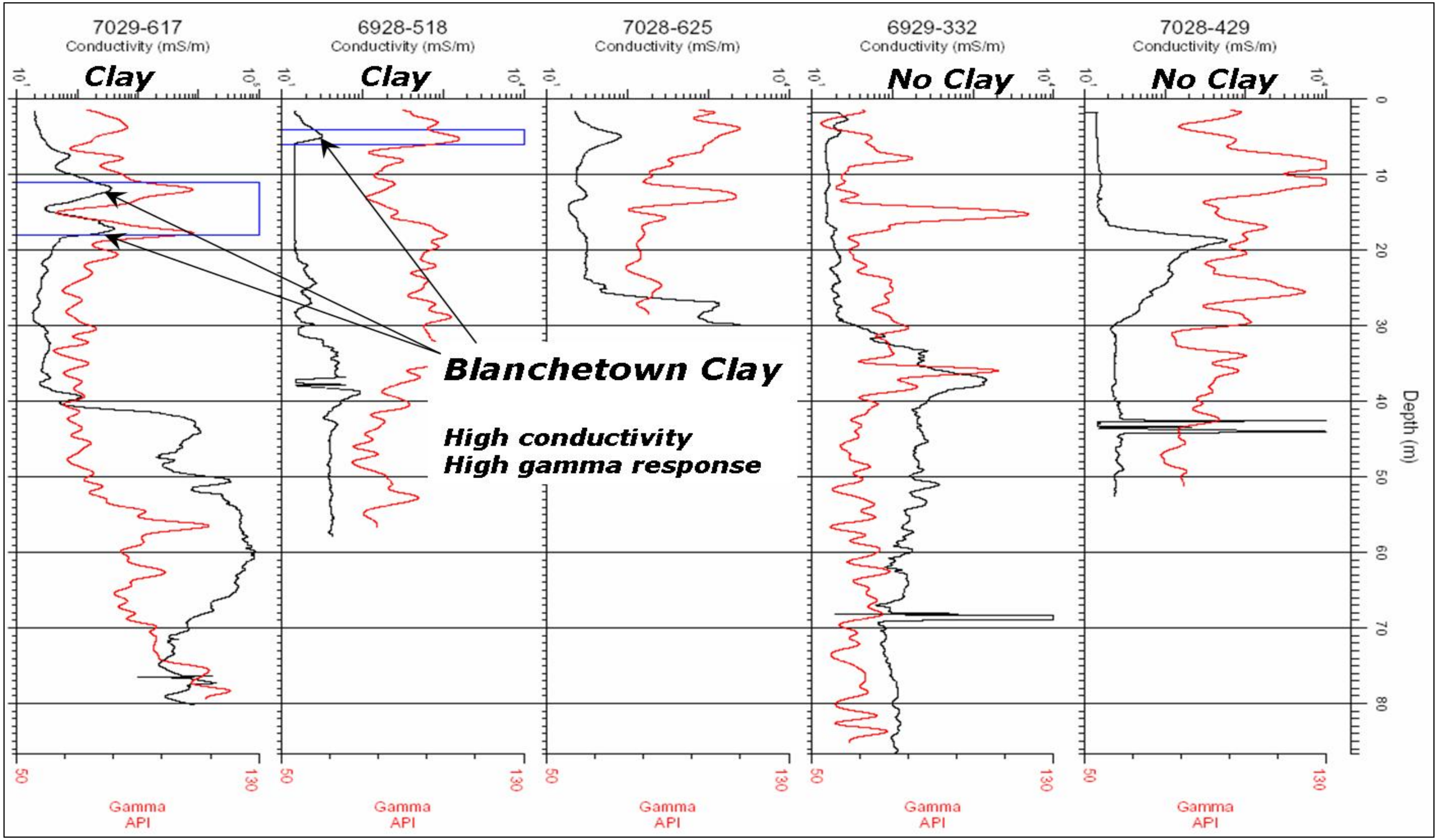

Figure 3: Borehole geophysical logs for five bores in the Riverland region, South Australia. Inductive conductivity logs are shown as a black trace, and natural gamma logs as a red trace. Known intervals of Blanchetown Clay are marked by blue rectangles.

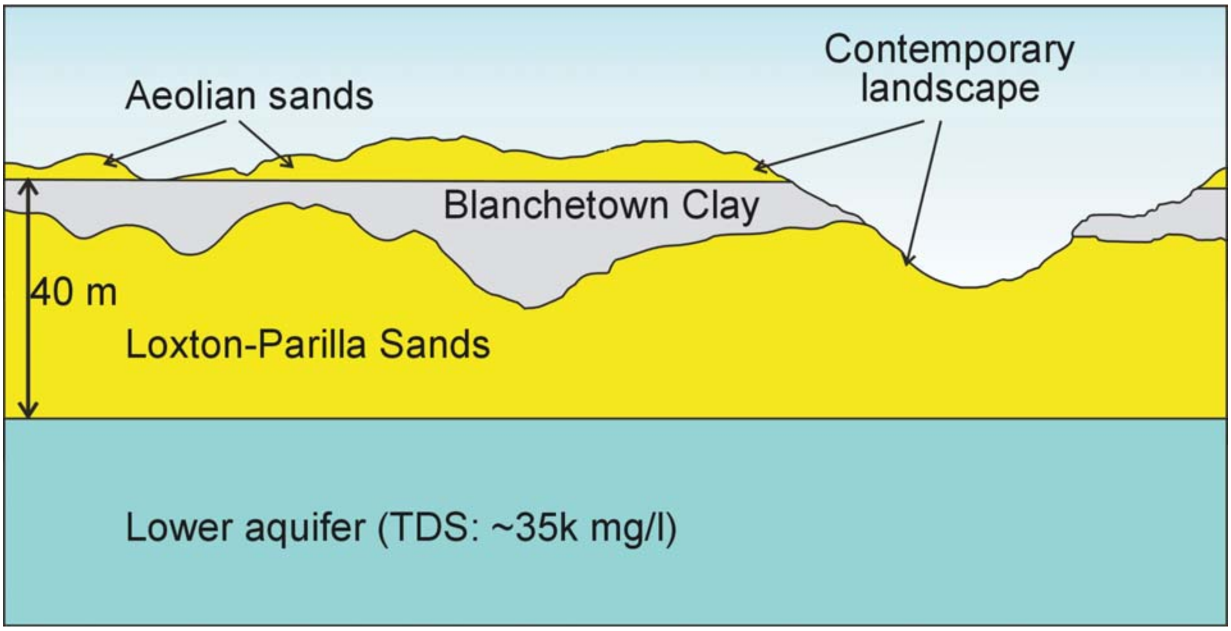

Figure 4a: Schematic geological section detailing the stratigraphic relationships between the Blanchetown clay and overlying and underlying sand units found in the Riverland area.

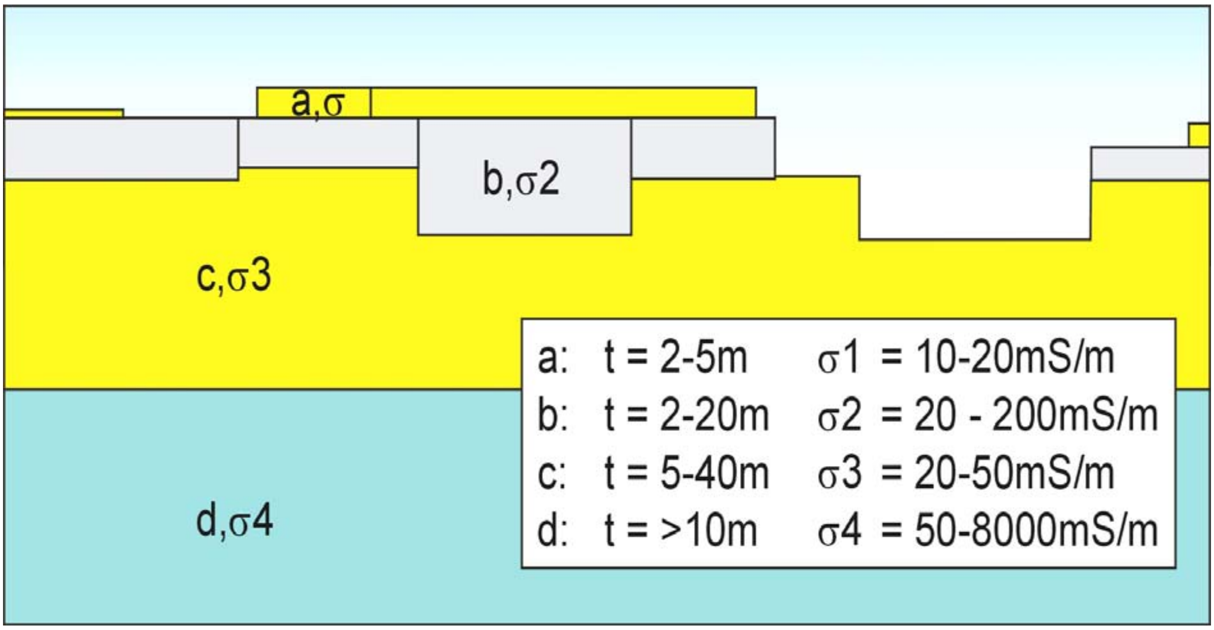

Figure 4 b: Geo-electrical model based on the geological model shown in Figure 4a.

Given that one of our principal concerns was to determine whether the clay was present or absent in the landscape, we simplified the model even further with a view to determining whether AEM systems could detect the presence of a "hole" in the equivalent of the Blanchetown Clay unit. The resulting geological model was represented as that shown in Figure 5. This model was designed to test whether an AEM system could detect small changes in clay conductivity/thickness assuming constant groundwater conductivity. This simpler section was used for all the forward modelling studies described here, although the more complex geo-electrical model shown in Figure 4b was subsequently used as a basis for the Tender submissions.

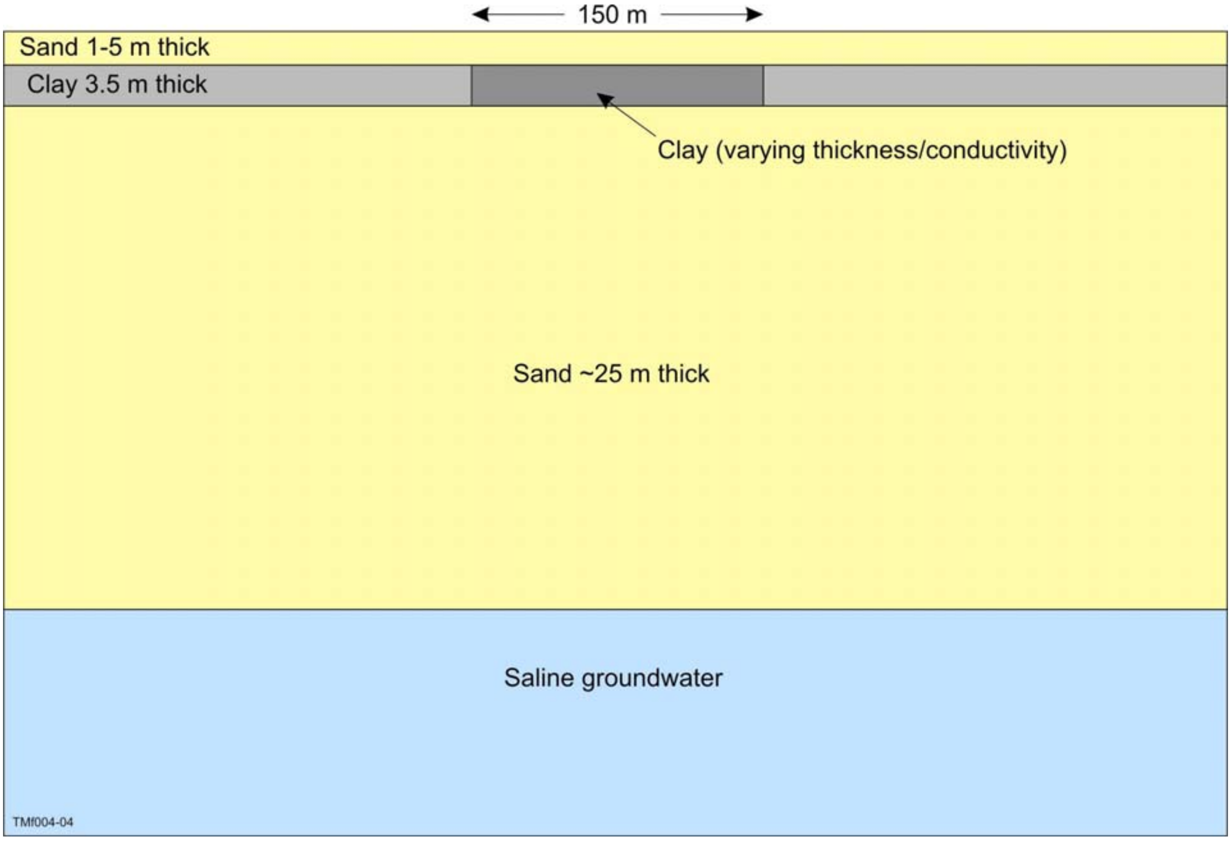

Figure 5: 1D geological model, assuming spatially varying clay. In this model it is assumed that the top of the groundwater has known elevation, the top of the clay (where it exists) has known elevation (although in reality this surface is also known to vary locally). For the purposes of modelling, the clay layer has a variable central portion, referred to as the "hole", which is 150m wide. Either side of the hole, the clay is of uniform thickness.

3.2 Forward modelling

Modelling was conducted using MARCOAIR developed by Art Raiche of the CSIRO Exploration and Mining EM Modelling Group (Raiche, 2001). MARCOAIR computes the electromagnetic response of 3D prisms contained in a multi-layered host. Relatively complex models can be constructed using combinations of prisms such as that shown in Figure 4b. A series of 1D models were run in this study to determine the expected response of several airborne EM systems when targeting a conductive near surface unit as proposed above.

Several assumptions were made in the modelling, namely that

1. *The top of the groundwater has known elevation.*
2. *The top of the clay (where it exists) has known elevation.*
3. *The sand has known, constant conductivity*
4. *The materials are isotropically conductive.*
5. *There are no dielectric effects to consider.*

Assuming a 1-dimensional model, then only four variables need be considered. They are:

1. *Groundwater*
2. *Conductivity*
3. *Clay conductivity*
4. *Clay thickness and the thickness of the sand cover over the clay.*

One additional point worthy of note, was that in the forward modelling we were not concerned about mapping thick clays very accurately, but rather we do care about knowing were it thins out.

If valid, these assumptions would simplify the inversion and interpretation of the AEM data. It would also mean that there would be a better chance of using a limited number of frequencies such as offered by the FDEM systems (eg. DIGHEM) as compared with the number offered by the TDEM systems (eg. TEMPEST).

4 RESULTS

4.1 Fixed-Wing Time Domain vs Helicopter Frequency Domain EM Systems

As mentioned earlier, our initial concern was to determine whether there was a choice between TEMPEST and one of a number of frequency domain electromagnetic (FDEM) systems for mapping the clay. Although available FDEM systems have important differences, in comparison with TEMPEST, they are much the same and, as result, the initial modelling was only concerned with a comparison between TEMPEST and an established FEDM system, namely DIGHEM^{V}.

In the following case studies, a conductive groundwater and a variable clay layer have been assumed. Whatever the assumptions made, the problem of a spatially varying clay and groundwater layer remain. To keep the initial models simple, the effects of one or other changing were examined. The complications resulting from both changing at the same time were then considered. While several models have been run, only those that illustrate the critical issues are shown here.

***Case 1: Spatially varying clay with constant groundwater conductivity*.**
In this example, the conductivity of the clay layer in the "hole" is reduced by making the factor ‘f’ less than one (ie. 0 < f < 1). By varying the conductivity of the “hole” in the clay layer by this factor allowed us to determine the efficacy of an AEM system in detecting small changes in the clay conductivity. In the real world, these changes, if observed, could reflect a change in thickness, texture (i.e. change in amount of clay, silt or sand), and/or conductivity. The detection limits are defined as being that value of (1-f), where the amplitude of the peak of the stripped anomaly in the most sensitive channel is three times the system noise level.

Stripped X component responses for the TEMPEST system (see Figure 7) were compared with those for the DIGHEM^{V} system (see Figure 8) for the model shown in Figure 6. Here, the the clay “hole” is assigned an f=0.75, giving a clay unit with a conductance of 0.26S compared with the adjacent clay unit having a conductance of 0.35S. The model was run with two values for the thickness of the sand cover, namely 1 and 5m. The plots on the left are for a cover 5m thick and those on the right for a cover of 1m. All plots have been normalized by an estimate for three times the noise level. Therefore they can be viewed as plots of signal-to-noise ratio. Numbers greater than one constitute "detection". The DIGHEM^{V} noise standard deviation was taken as 1 ppm in all channels, while TEMPEST noise levels were taken from the high altitude data acquired in a survey flown in southern Queensland. These were taken as being most representative of the noise envelope for the TEMPEST system configuration at the time of this study. The *“noise level”* was assumed to be three times the standard deviation of available noise measurements. In the normalization procedure described above, the stripped DIGHEM ppm result was divided by 9 and the TEMPEST data was divided by nine times the high altitude standard deviations derived from the Southern Queensland data.

Only those DIGHEM channels where the maximum SNR is greater than one have been plotted. In phase responses are shown in red, with the modelled quadrature responses shown

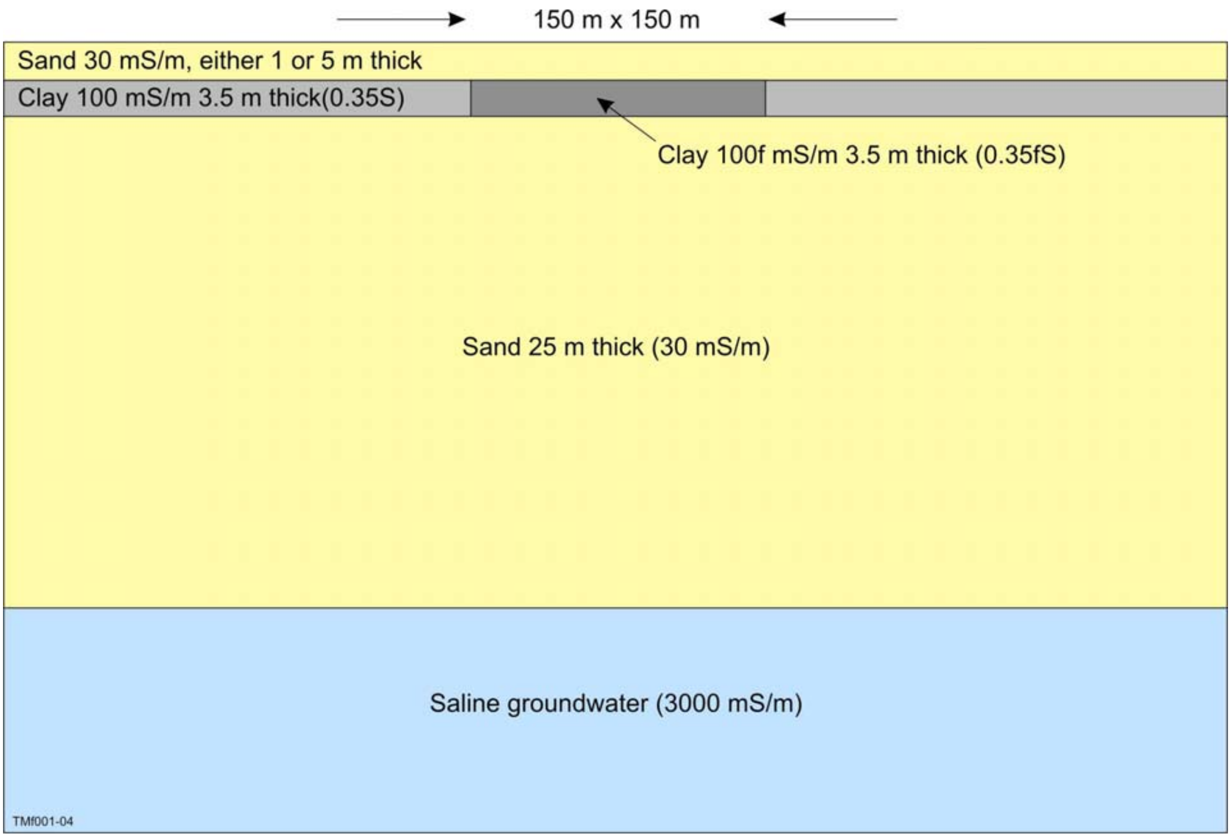

Figure 6: 1D geo-electric section assuming a spatially varying clay conductivity. In this model the clay "hole" in the centre of the section has a conductivity of 100f mS/m (with f = 0.75). The adjacent clay units have a conductivity of 100 mS/m. In this model it is assumed that the top of the groundwater has known elevation, the top of the clay (where it exists) has known elevation (although in reality this surface is also known to vary locally), and the sand has constant conductivity.

in blue (Figure 8). Results suggest that the target, defined in Figure 6, approaches the limits of detectability with the 5500Hz vertical co-planar frequency, but that higher frequencies perform well by comparison. The positive quadrature response in the 56 kHz channel is not a modelling error, the same thing happens with 1-D models. It occurs because increasing the resistivity shifts the total frequency response to the higher frequency. The quadrature response is bell shaped and 56 kHz is on the high-frequency side of the maximum of the bell. Consequently, shifting the frequency response to the right results in an increased quadrature response.

In this example, only the modeled responses for the TEMPEST X component have been plotted (Figure 7). Those for the Z component have a different shape but virtually the same amplitude range and are therefore no better for assessing detectability of gaps in the clay layer. The forward modelling suggests that for this model (f = 0.75) TEMPEST just detects the "hole" while DIGHEM is almost a factor of 10 better. High frequency/early time information is clearly important for this problem and care would have to be taken to distinguish variations in the sand cover from those in the clay layer.

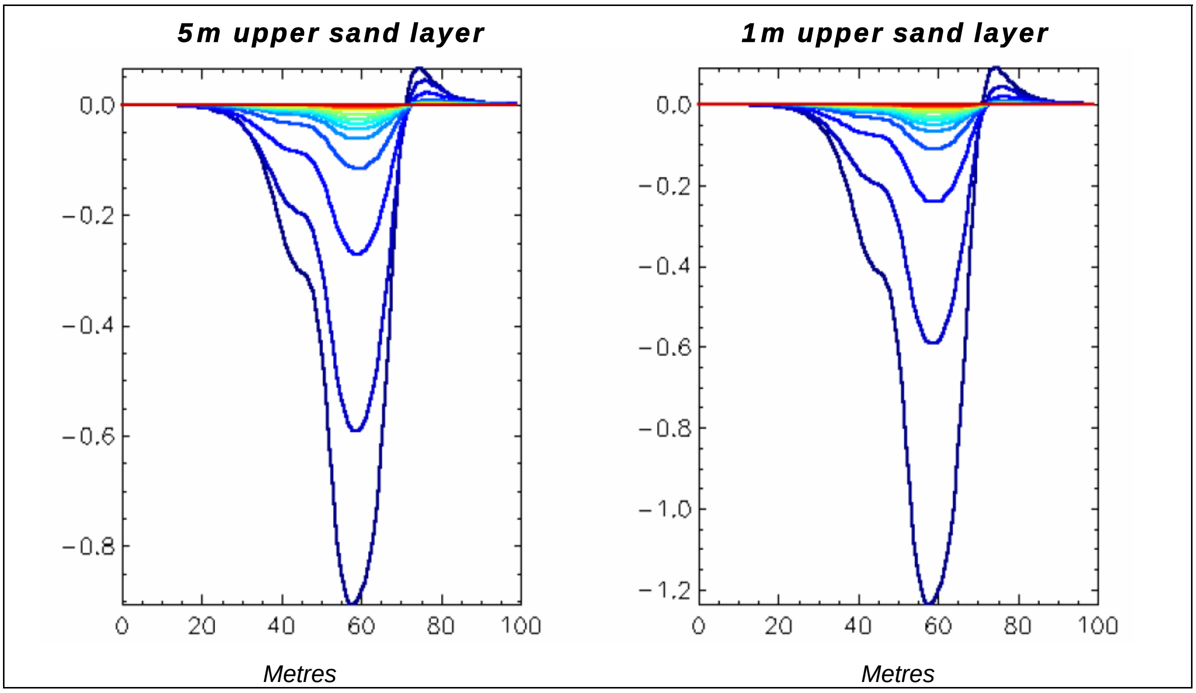

Figure 7: Stripped TEMPEST X component modeled response for the model shown in Figure 6. Early time responses are plotted in blue, with later times in yellows and reds.

The effects of any along-line smoothing performed by the contractor were not allowed for in this study, although this type of processing is performed on both TEMPEST and DIGHEM^{V} data. For small targets such as examined here, the likely effect of such processing would be to degrade the performance of TEMPEST somewhat more than that of DIGHEM^{V}. DIGHEM^{V} should have fewer problems resolving this target, because of its lower altitude (30m) and airspeed (33 m/s). Reasonable smoothing is unlikely to degrade this systems' capability to detect holes in a clay layer when compared with TEMPEST.

Given that a target with the parameters defined in Figure 6 is at the limit of TEMPEST's capability, smoothing is likely to lead to a more significant degradation in detectability. Our analysis has neglected to consider the error associated with drift in HEM data. Drift usually causes very low spatial frequency changes along line. The modeling used here is for stripped data which provides a natural filter for such effects. Nevertheless it is clear that DIGHEM would be superior to TEMPEST whatever the complications.

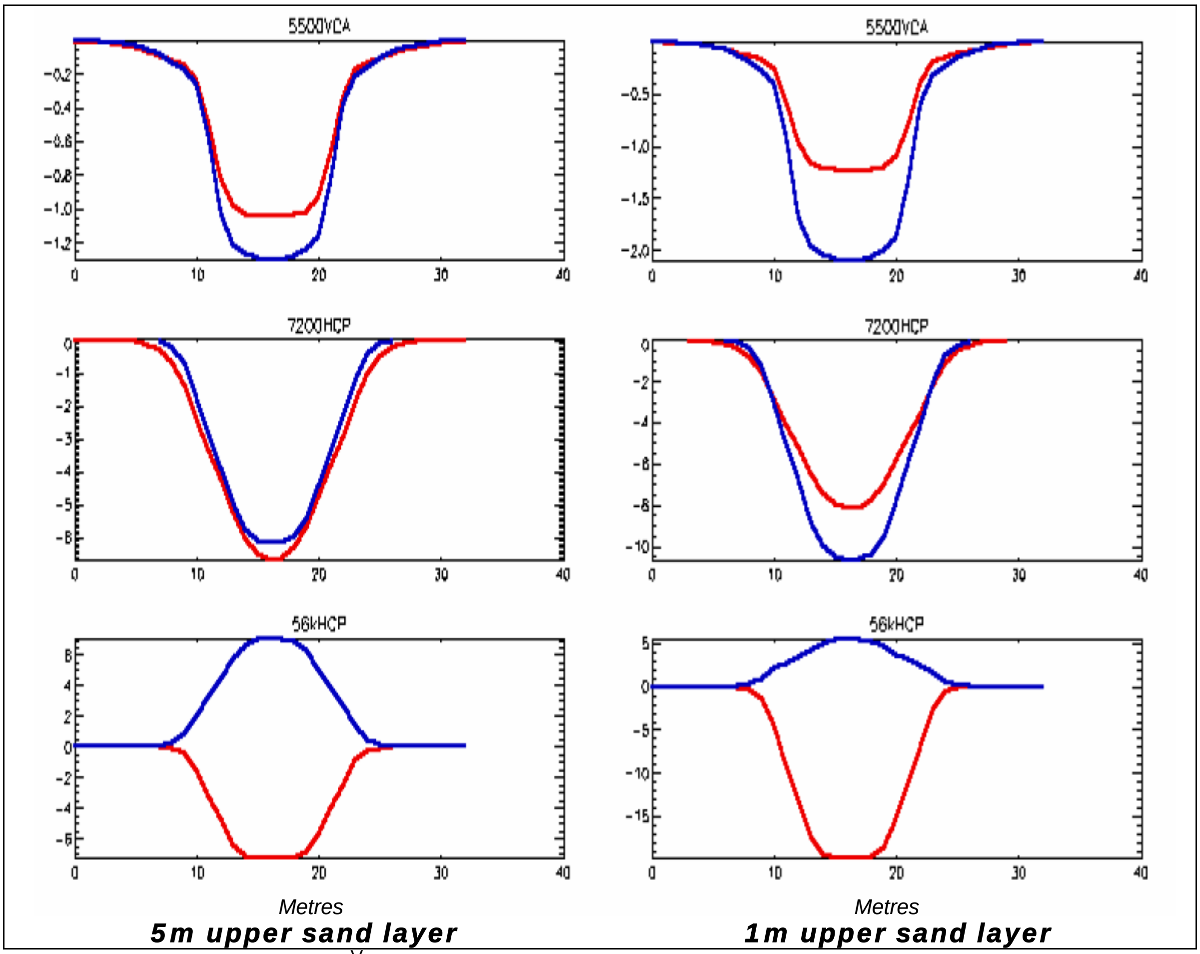

Figure 8: Stripped DIGHEM^V in-phase (red) and quadrature (blue) responses for the model shown in Figure 6. Modelled responses for 5500Hz (top), 7200Hz (middle) & 56kHz (bottom) are shown for upper sand layer of 5m (left column) and 1m (right column).

Case 2: Spatially uniform clay with varying groundwater conductivity.

In this case study, the low frequency or late time responses are expected to be significant.

Setting f = 0.75 to vary the conductivity of groundwater gives the results shown in Figures 10. The stripped responses for TEMPEST are shown on the right and those for two frequencies (400Hz Horizontal co-planar and 900Hz vertical co-axial) of DIGHEM^V. Both systems appear to have about the same ability to detect a change in the groundwater conductivity. However, in this case, only the lowest frequency (400 Hz – top right in Figure 10) DIGHEM channel will be useful. It is worth noting that TEMPEST also has some positive early-time responses that potentially could be mistaken as a response from variations in a clay layer.

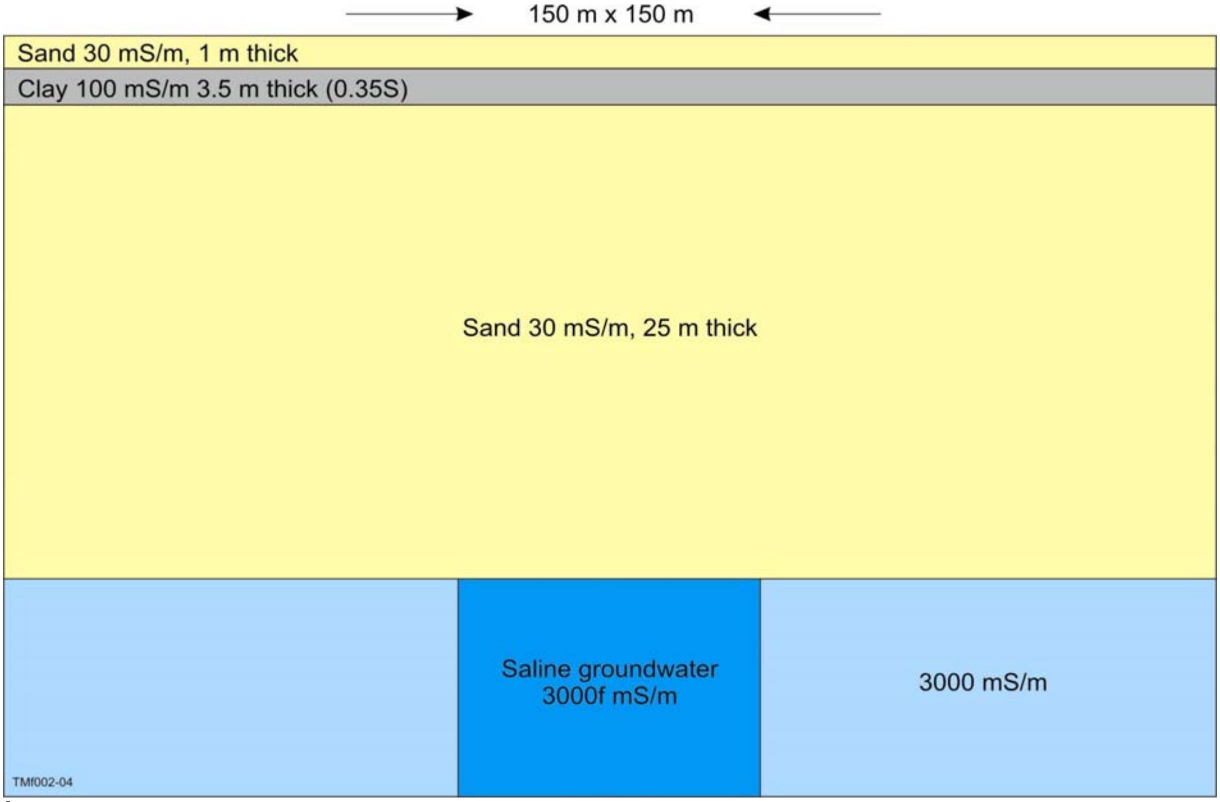

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Figure 9: 1D geo-electric model assuming a spatially varying groundwater conductivity (with f =0.75) and uniform clay conductivity (100mS/m). In this model it is assumed that the top of the groundwater has known elevation, the top of the clay (where it exists) has known elevation (although in reality this surface is also known to vary locally), and the sand has constant conductivity.

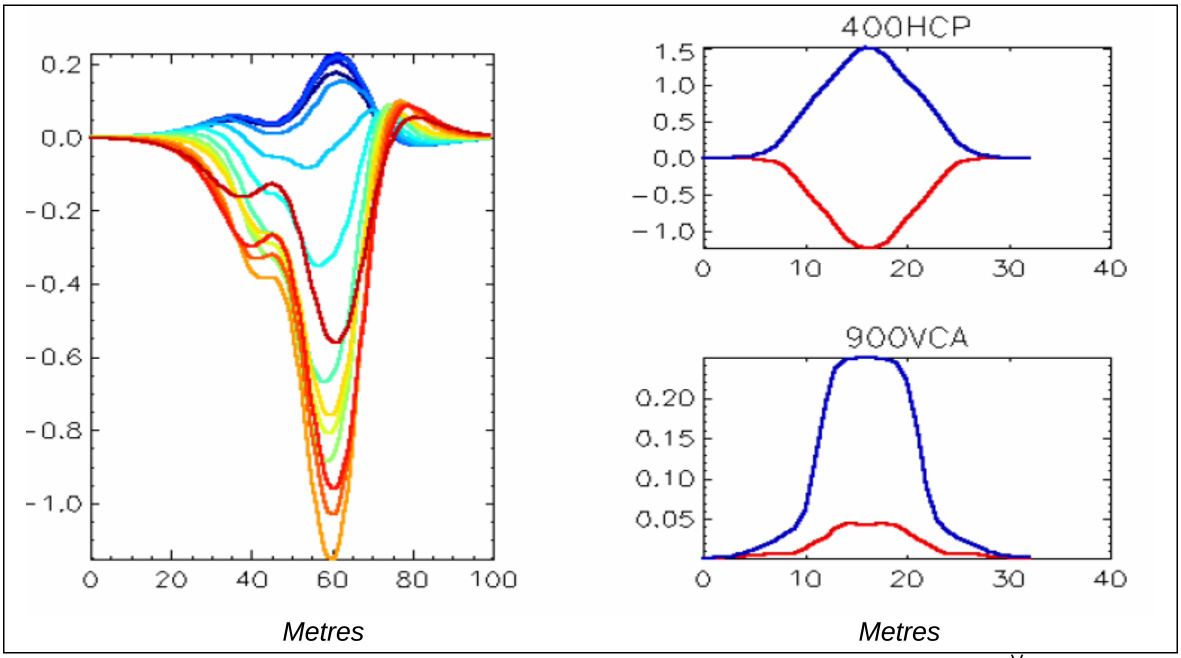


Figure 10: Stripped responses for TEMPEST X Component (left) and DIGHEM^{V} low frequency channels (right) for case 2 target (Figure 9).

Case 3: Spatially varying clay with varying groundwater conductivity.

In this case study, there are two layers with a varying conductivity. They are the clay unit (f1) and the groundwater (f2) (See Figure 11). The stripped responses for the model shown in

Figure 11 are shown in Figure 12 (TEMPEST) and Figure 13 ($DIGHEM^V$). The $DIGHEM^V$ responses when f1 = f2 =0.75 are plotted on the left with those when f1= 0.75 and f2 = 1.33 plotted on the right. The only change in the modeled responses occurs at the lower frequencies with a reversal of the 400 Hz pattern when the groundwater becomes more conductive. The higher frequency $DIGHEM^V$ channels appear to be dominated by variation in the conductivity of the clay.

TEMPEST appears to have the same ability to separate variations due to changes in the clay layer from those due to changes in the groundwater. However, TEMPEST is less sensitive to the clay variation.

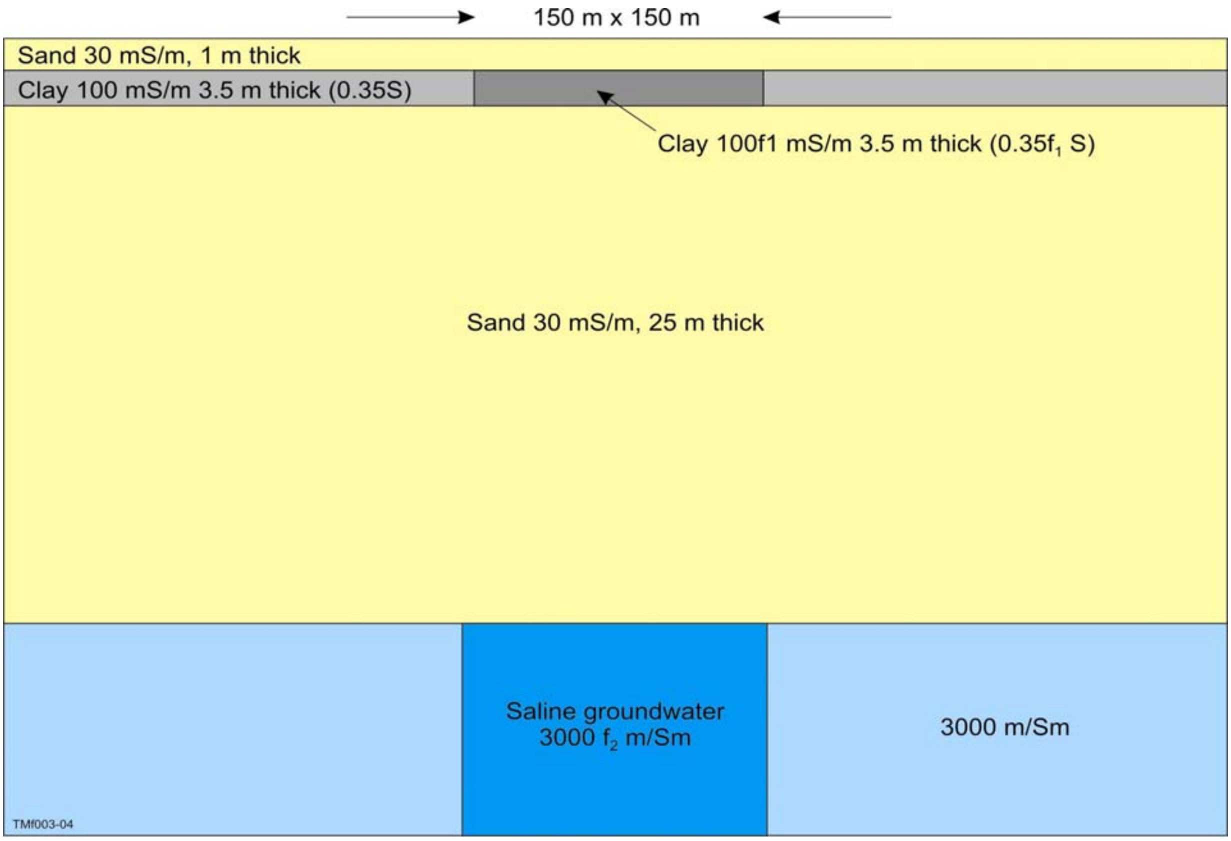


Figure 11: 1D geo-electric model assuming a spatially varying clay (with f1=0.75) and groundwater conductivity (with f2= 0.75 and 1.33). In this model it is assumed that the top of the groundwater has known elevation, the top of the clay (where it exists) has known elevation (although in reality this surface is also known to vary locally), and the sand has constant conductivity.

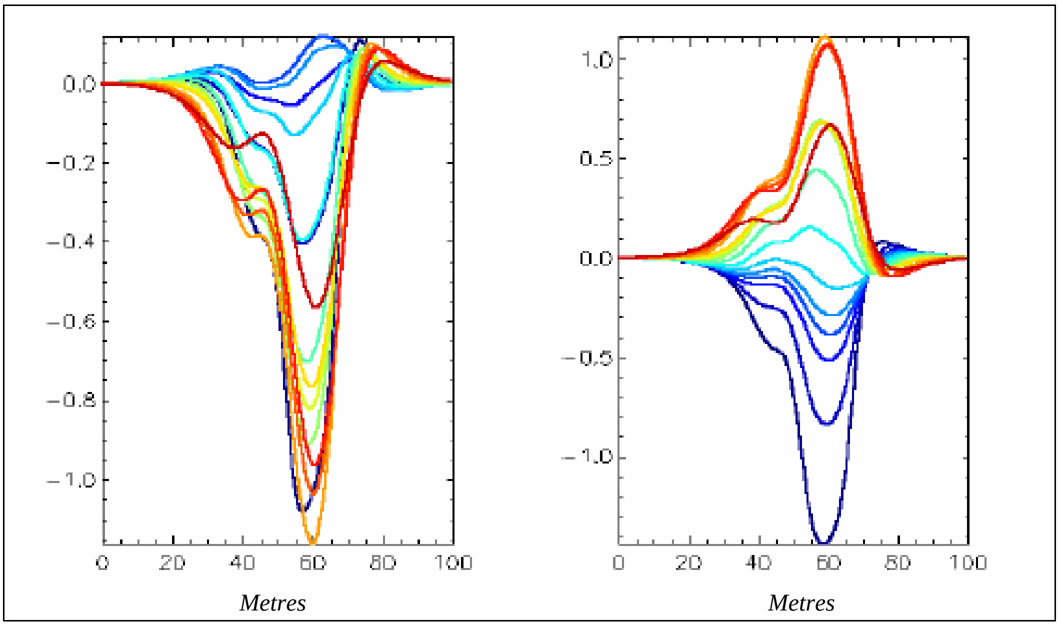


Figure 12: Stripped TEMPEST responses when f1 = f2 =0.75 are plotted on the left with those when f1= 0.75 and f2 = 1.33 plotted on the right.

4.2 Summary of DIGHEM^V vs TEMPEST Forward Modelling Results

Results from a comparison of the DIGHEM^V frequency domain helicopter EM system and the TEMPEST fixed-wing time domain EM system suggest that the former is best suited to mapping variability associated with a near-surface clay unit such as the Blanchetown Clay, confirming the earlier findings of Cook and Kilty (1992). This is attributed to its sensitivity to the near-surface conductivity variations. Both TEMPEST and DIGHEM^V would appear to be similar in performance with respect to detecting changes in the composition of the saline groundwater. The modelling also suggests that our ability to separate the effects of spatial variation in both the clay and groundwater layers is moderately good with both systems.

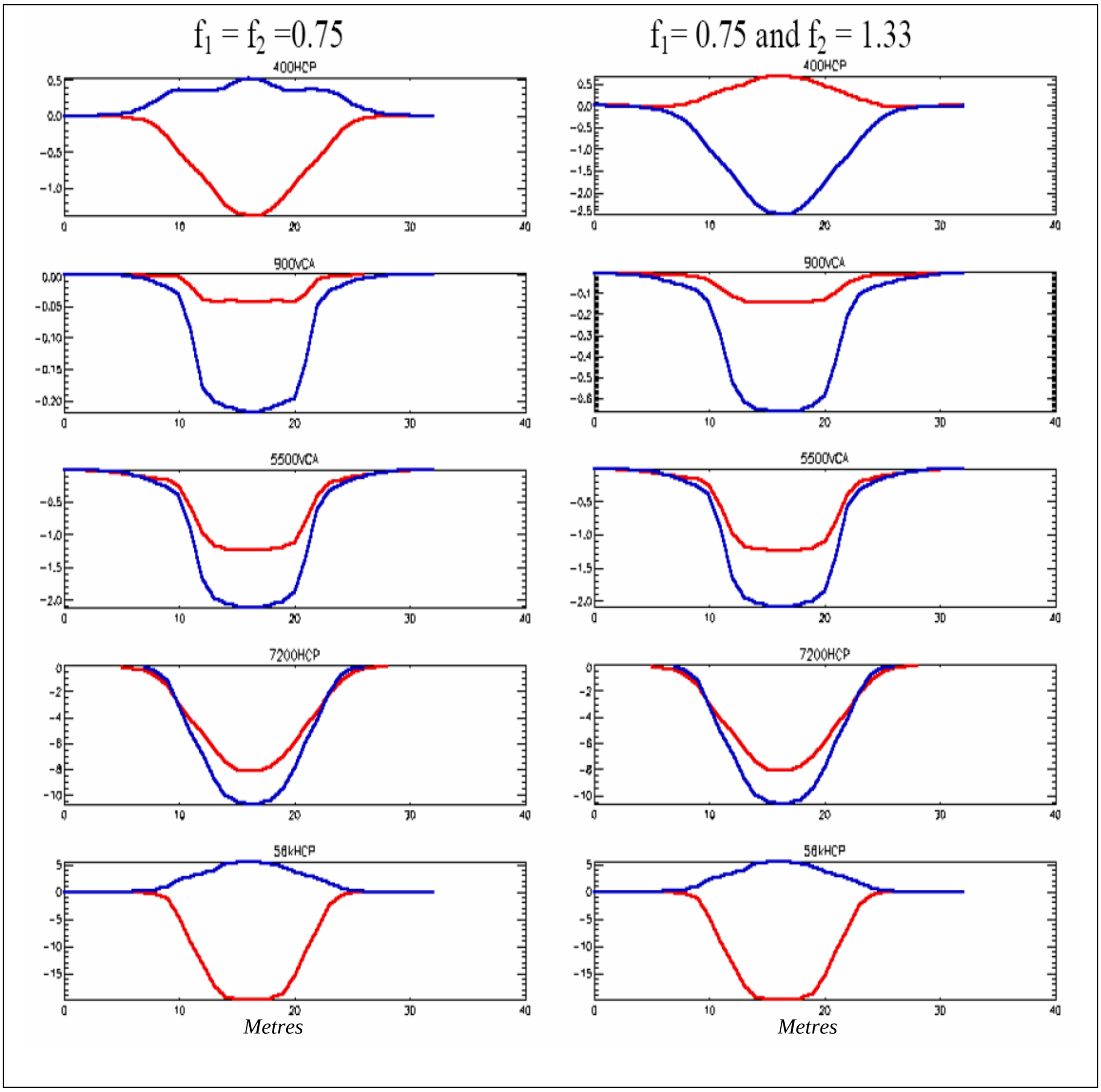


Figure 13: Stripped DIGHEM^{V} in-phase (red) and quadrature (blue) responses for the model shown in Figure 11. Modelled responses are for 400Hz, 900Hz, 5500Hz, 7200Hz and 56kHZ are plotted from top to bottom respectively. DIGHEM^{V} responses when f1 = f2 =0.75 are plotted on the left with those when f1= 0.75 and f2 = 1.33 plotted on the right.

4.3 Revised AEM modelling

Subsequent to the modelling undertaken above, further information concerning AEM system geometry and noise characteristics became available. This allowed an additional forward modelling study to define the potential of several other commercially available AEM systems for mapping near surface clay units. For this work, the model shown in Figure 5 was used, where the conductivity of the clay "hole" was modulated by factor 'f' with f = 0.75. 1m of sand was defined as the uppermost layer.

4.3.1 System Characteristics

Four AEM systems examined were HUMMINGBIRD, DIGHEM Resolve, TEMPEST and HOISTEM. For the first three, the system geometries and frequencies and noise levels were as defined by Ross Brodie (Geoscience Australia, pers comm 15/4/02) and subsequently revised as noted below.

The modelled TEMPEST geometry had the bird at (-118,0,-42) relative to the aircraft which was flying at 105m. The details for the frequency domain systems are shown in the following tables. The revised noise levels are based on the results of studies of repeat line data for various HEM systems (Ross Brodie, Geoscience Australia, pers comm 15/4/02, and Green and Lane 2002).

RESOLVE			Noise Standard Deviations	
Frequency (Hz)	Orientation	Coil Separation	Tendered	Revised
400	HCP	7.9	3.5	9
1600	HCP	7.9	3.5	8
3300	VCX	8.99	3.5	17
6400	HCP	7.9	7	28
25000	HCP	7.9	14	16
100000	HCP	7.9	17.5	16

HUMMINGBIRD			Noise Standard Deviations	
Frequency (Hz)	Orientation	Coil Separation	Tendered	Revised
880	HCP	6.01	3.5	10
980	VCX	6.01	3.5	3
6606	HCP	6.26	7	22
7001	VCX	6.26	14	5
34144	HCP	4.93	17.5	8

Table 1: Helicopter FDEM system geometry, frequencies and noise levels.

In order to get a useful comparison of signal-to-noise performance it is necessary that we establish a common definition of noise. In the following discussions noise will be measured in terms of its standard deviation, with noise quoted as peak-to-peak, and the standard deviation is assumed to be 1/2√2 (0.35) of the peak-to-peak values. The motivation behind this assumption is described in Appendix 1. this represents a change from from previous discussions (see Section 4.1) where either the standard deviation or three times the standard deviation was used.

In the case of HOISTEM time domain EM system, estimates for the noise in survey mode were not available, except for some high altitude, Tx-on, measurements. Based on previous experience with the TEMPEST system, these high altitude values were multiplied by five to get an estimate of the noise in survey mode. It should be stressed that, of all the systems described here, this HOISTEM noise estimate is the least reliable.

The (multiplicative) rescaling factors used are given in Table 2.

EM System	Noise Measurements	Rescaling factor
Hummingbird	Peak-to-peak (ppm)	0.35
RESOLVE	Peak-to-peak (ppm)	0.35
TEMPEST	Std.Devs. of repeat lines (fT)	1.0
HOISTEM	High altitude Std. Devs.(µV)	5.0

Table 2: Multiplicative rescaling factors used to account for noise

Based on Richard Lane's note (*Analysis of TEMPEST Repeat Lines,* 5th April 2002) and a subsequent revision (Ross Brodie e-mail 15/4/02), the standard deviation of the TEMPEST noise for the ith channel was calculated as:

$$\sigma_i = 0.082(15 - i)/14 + 0.008 \text{ fT.}$$

The raw HOISTEM channel standard deviations come from recent data from Graham Boyd (e-mail 12/04/02), with these analysis is based on a discussion by Green (2002) They are :

> 727, 386, 272, 305, 228, 257, 229, 232, 257, 217, 245, 217, 46, 35, 25, 16, 13, 11, 11, 9, 11, 9, 10, 8, 8, 7, 8 µV.

These new values are plotted in Figure 14 with the older values discussed in Green (2002). The improvement is substantial.

4.3.2 Model Results - Revised Noise levels

Results of the MARCOAIR calculations for four EM systems are plotted in Figures 15 and 16 No special consideration was given to dielectric effects in this modelling. The vertical axis, in all cases, is the ratio of the model calculation divided by the noise in the appropriate channel.

These results differ from those described previously because of changed definition of noise. As a consequence, the absolute magnitudes cannot be compared with results from the earlier modelling.

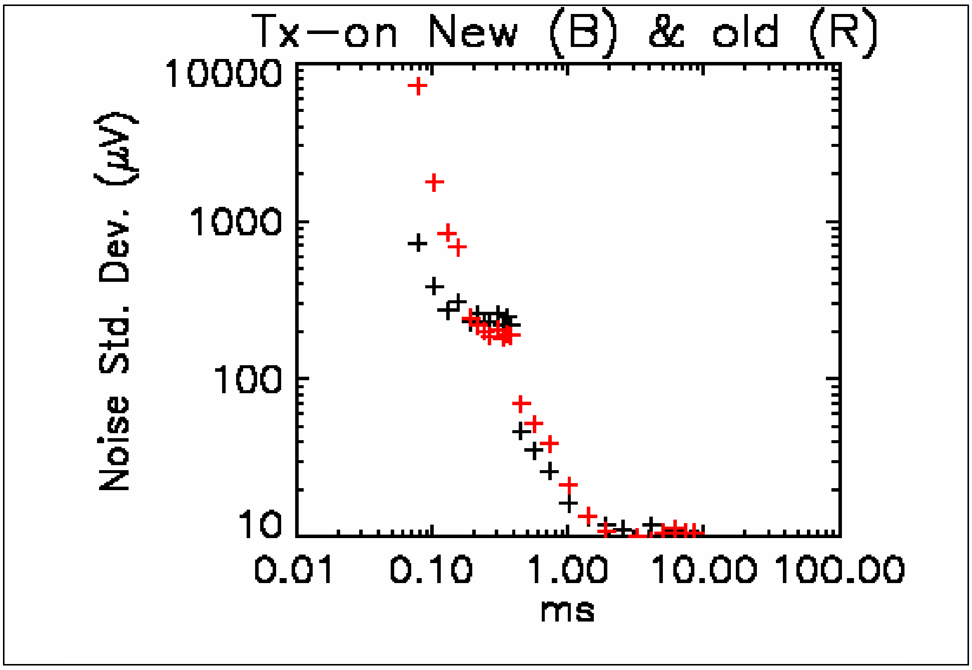
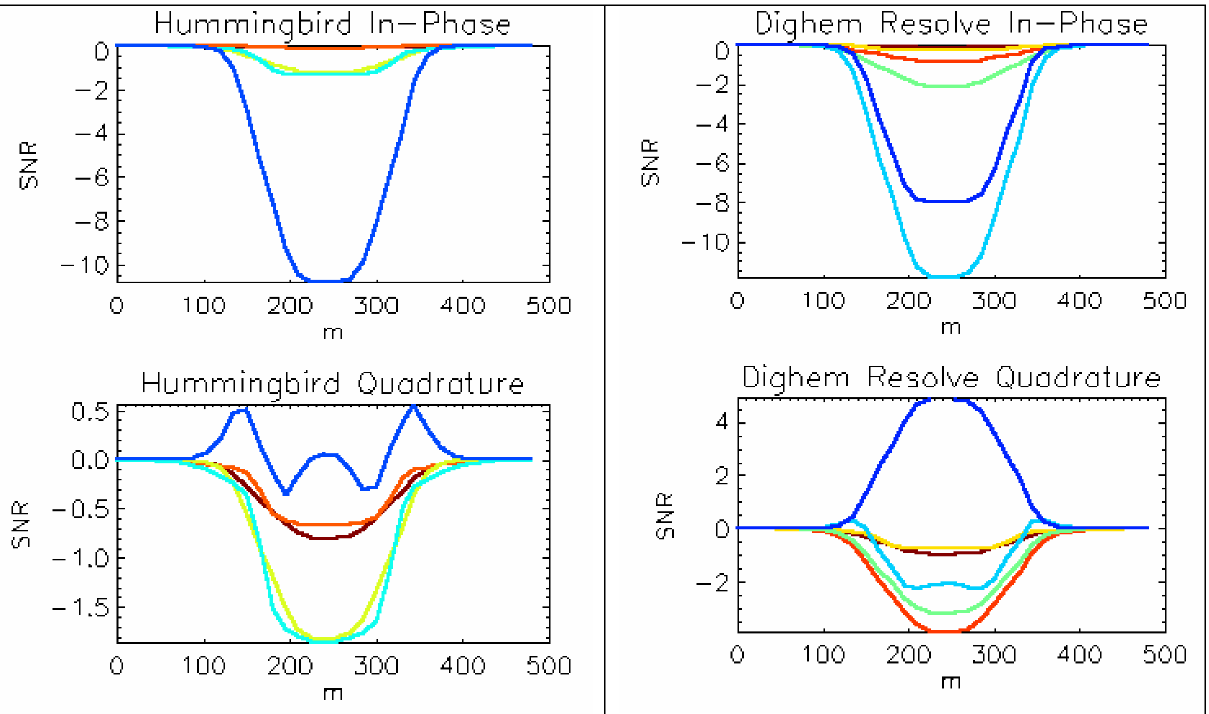


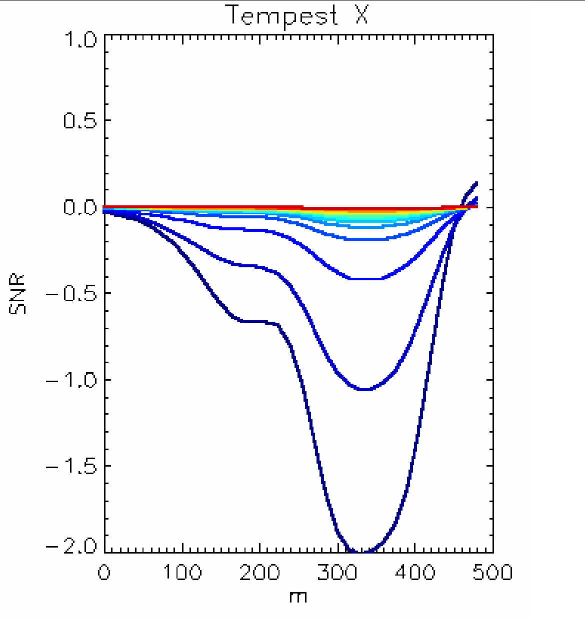
Figure 14: HOISTEM channel noise standard deviations for the HOISTEM helicopter Time domain EM system.



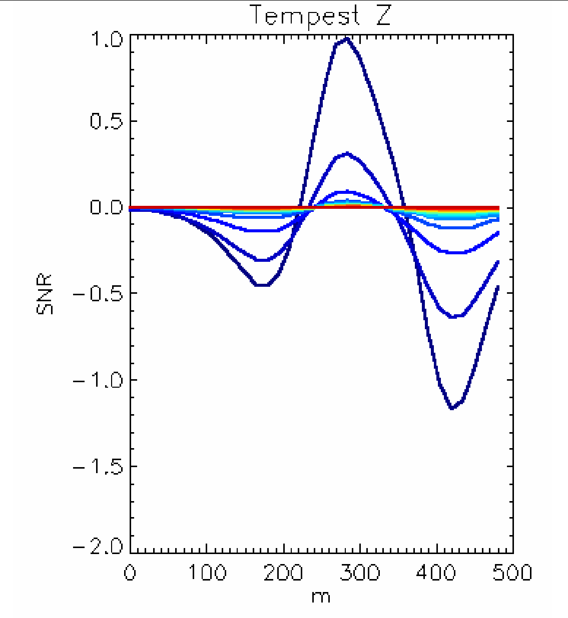
HUMMINGBIRD	RESOLVE
880 Hz HCP (red), 980 Hz VCA (brown), 6606 Hz HCP (yellow), 7001 Hz VCA (green), 34144 Hz HCP (blue)	400 HCP (red), 1600 HCP (brown), 3300 VCA (yellow), 6400 HCP (green), 25000 HCP (light blue), 100000 HCP (dark blue)

Figure 15: Stripped responses from the HUMMINGBIRD and RESOLVE helicopter Frequency Domain EM systems. Higher frequency data are plotted in blue, with lower frequencies in yellows and reds.

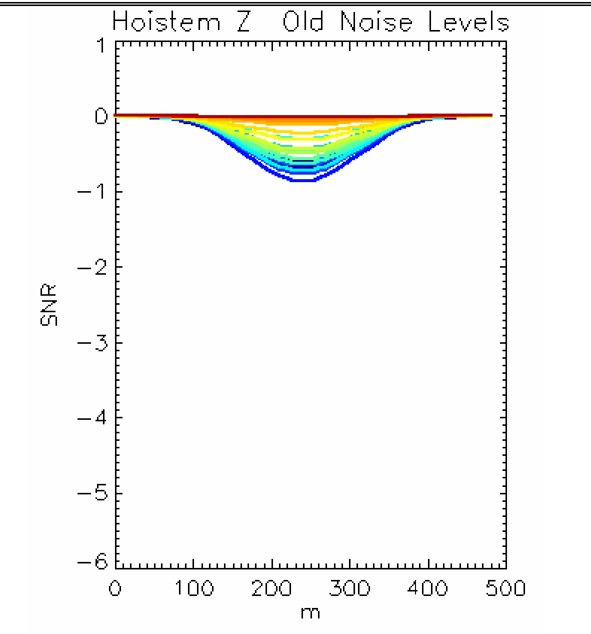
The stripped responses from the HUMMINGBIRD and RESOLVE FDEM systems suggest that both would detect variations in a near-surface clay layer. However, the RESOLVE system has the better performance across a larger range of frequencies. Results from modelling the responses of the two time domain EM systems are plotted in Figure 16. Results from modelling with the revised early time noise values for HOISTEM indicate that it would substantially outperform TEMPEST. However, neither of the TDEM systems perform as well as the Frequency Domain systems. The RESOLVE system outperforms all systems with respect to the target described in Figure 5.



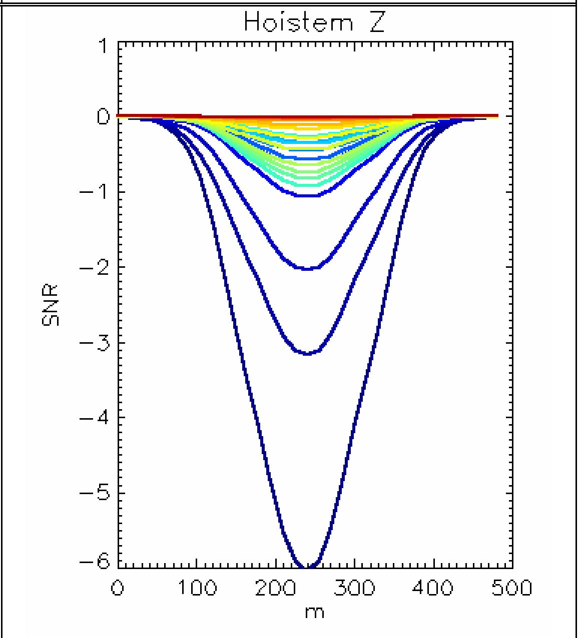
TEMPEST X component data



TEMPEST Z component data



HOISTEM Z component data – Old noise levels



HOISTEM Z component data – New noise levels

Figure 16: Stripped responses from the HOISTEM and TEMPEST Time Domain EM systems. X and Z component data for the TEMPEST system are shown on the top left and right respectively. Results from revised modelling of HOISTEM Z component data indicate a significant improvement in the detectability of near surface conductivity variations with the early time channels. Higher frequency data are plotted in blue, with lower frequencies in yellows and reds.

4.3.3 An Overall Measure of System Performance

The modelled HOISTEM and TEMPEST responses plotted in Figure 16, indicate that HOISTEM has many more channels at early time capable of detecting near surface conductivity variations compared with TEMPEST. This raises the question, as to whether, from the perspective of mapping “clay holes”, it is better to have a lot of channels of moderate performance compared with a fewer number with an excellent performance.

This problem was considered by examining the length of the normalized response vector. Thus:

$$r_j = \left(\sum_{i=1}^{N} \frac{R_{i,j}^2}{\sigma_i^2} \right)^{1/2}$$

Where $R_{i,j}$ is the modelled response in the ith channel at the jth station on the profile. If we accept for the moment that it is useful to quantify the discrimination capability of various AEM systems, then we can plot the modelled response (R) as shown in Figure 17 below. Figure 18 is a plot of the probability of detecting a "clay hole" in the presence of noise given that we accept a 1% chance of a false alarm (i.e. detecting a "hole" when it's not there). This probability assumes the application of a matched filter with the known "hole" characteristics.

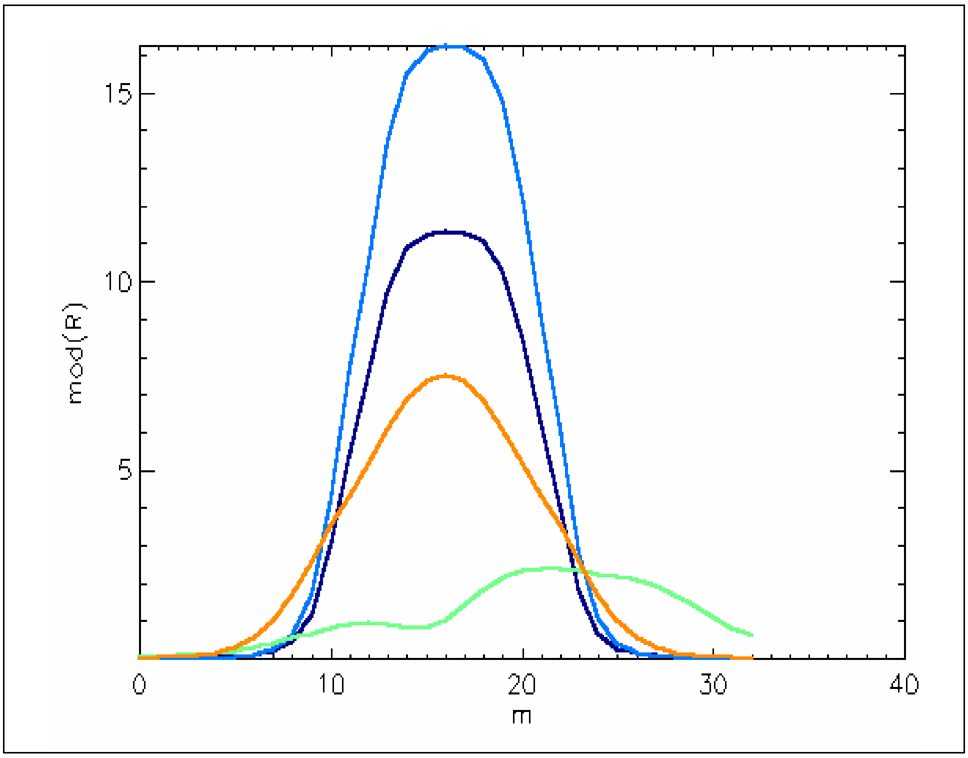


Figure 17: Modelled response (R). Light blue curve - RESOLVE system, Dark blue curve – Hummingbird, Orange curve – HOISTEM; Green curve – TEMPEST.

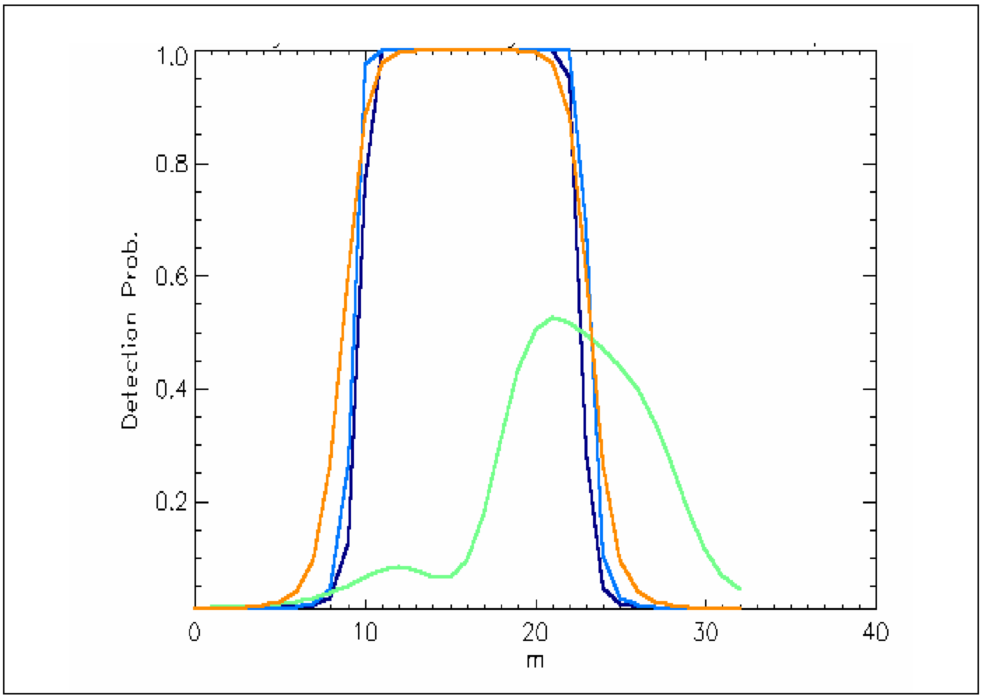


Figure 18:: Probability plot for four different EM systems, indicating the likelihood of detecting a hole of the dimensions indicated in Figure 5. Light blue curve - RESOLVE system, Dark blue curve – Hummingbird, Orange curve – HOISTEM; Green curve – TEMPEST.

5 CONCLUSIONS

These forward modelling studies and results suggest that:

5. Frequency domain EM (FDEM) systems outperform the time domain EM (TDEM) systems for the problems/targets faced in the Riverland area, being more sensitive to variations associated with the slightly conductive, near-surface Blanchetown Clay.

6. Modelled responses for the RESOLVE FDEM system suggest that, of all the systems examined, it is the best suited to mapping near surface conductivity variations.

7. TDEM and FDEM systems appear to be similar in performance with respect to detecting changes in the quality of the groundwater system.

8. Our ability to separate the effects of spatial variation in both the clay and groundwater layers is moderately good with both TDEM and FDEM systems.

9. If the RESOLVE system were to be used, survey design and in particular line spacing, would be determined by the size of the "holes" that need to be detected. Our recommendation is that the line spacing be chosen so that at least two lines intersect the smallest hole that is of interest. In the modelling the smallest hole was taken as being 150m, and a line spacing of 150m was deemed appropriate. However, given this situation the expected response from a line not over the centre of the hole remains undetermined. Nevertheless, when the line does not pass over the centre of the "hole", the modelling suggests we would still have a reasonable chance of detecting a 150 m "hole" even though it was exactly between the flight lines.

10. ACKNOWLEDGEMENTS

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APPENDICES

Appendix 1 - Noise Estimates for AEM data

The following figure shows a plot of two signals. The black plot represents gaussian white noise with a mean of zero and standard deviation of one. Peak-to-peak values are of the order of 6. The red plot is a sinusoid with amplitude of 1 (peak-to-peak of 2); it has a standard deviation of $1/\sqrt{2}$.

In much of the repeat line data we have seen from AEM systems the characteristics of the noise are much more like a sinusoid than the white noise distribution. So, until more information is available, We suggest that in order to convert noise quoted as peak-to-peak values to standard deviations we multiply by 0.35 ($1/2\sqrt{2}$)