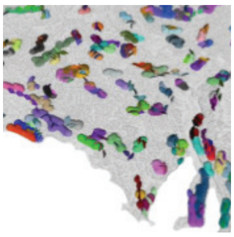
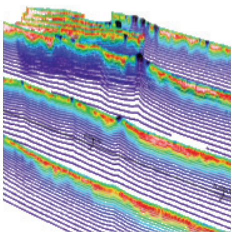
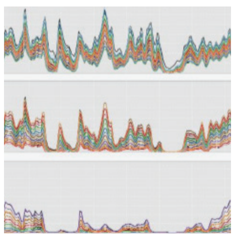
Forward and inverse modelling of airborne electromagnetic data and 3D fault generation of regional gravity data

Rod Paterson, Desmond FitzGerald,
Sara Jakica and Laszlo Katona







Report Book
2017/00020

SOUTH AUSTRALIA

Government of South Australia
Department of the Premier and Cabinet

Forward and inverse modelling of airborne electromagnetic data and 3D fault generation of regional gravity data

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April 2017

Report Book 2017/00020

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Forward and inverse modelling of airborne electromagnetic data and 3D fault generation of regional gravity data

Rod Paterson, Desmond FitzGerald, Sara Jakica and Laszlo Katona

ABSTRACT

1D/2.5D forward and inverse modelling was performed on AEM TEMPEST surveys conducted in Cariewerloo, Tarcoola and Frome and a VTEM survey in Northern Eyre Peninsula (Paris). Tarcoola and Paris data responded well to 2.5D inversions, with the Paris TEMPEST data displaying reasonable consistency between the measured X & Z components, allowing the inversion to resolve more complex 2D structure and extend the predicted geology deeper in section. This supports the notion that reprocessing older AEM data can extract benefit at little extra cost. TEMPEST data from Cariewerloo and Frome are relatively noisy, leading to the conclusion that original QC testing did not identify noise issues in the X and Z components. A workaround, re-scaling the Z component of the Frome data yielded acceptable results.

Reprocessing of the South Australian subset of the national gravity map, via anisotropic clustering and 3D Fault network generation was also performed. Full Tensor Analysis and an extended 3D worming method were used for geological dip determination from full tensor gravity gradiometry (FTG). Dips were determined automatically on 98 candidate faults, however the reprocessing of State-wide gravity data, derived from the national grid demonstrates that the full tensor analysis requires a higher standard industry quality data and that merged national database products are not sufficient to provide quality FTG products.

INTRODUCTION

In 2016, the Geological Survey of South Australia (GSSA) engaged the services of GeoIntrepid Geophysical Software Technology and Consulting Specialists (GeoIntrepid) to apply new data processing techniques to Airborne Electromagnetic (AEM) and Gravity datasets in South Australia. The work performed comes at a time of increasing interest in AEM data for minerals and water resource exploration and the ability to extract new information from currently held data is of profound importance to the state. Among a number of new processing techniques currently available, two that resonate with the current activities of the GSSA are the inverse modelling of AEM data, which models deeper geology than previous inversions using the same data, and the ability to process regional gravity data to extract structural information that can drive geological interpretation and feed into regional modelling programs.

For the AEM reprocessing work, area selection was based on two criteria, namely areas have existing open-file Airborne EM survey data and are geographically contained within current GSSA project regions. The regions selected for AEM forward and inverse modelling were:

- Frome Embayment Survey & Cariewerloo Traverses, 2010 TEMPEST (Uranium systems projects in the Frome Embayment and Eastern Gawler Province project regions)
- Northern Eyre Peninsula (Paris), 2014 VTEM (Southern Gawler Ranges project region)
- Tarcoola, 1999 TEMPEST (Western Craton Margins project region)

Reprocessing and modelling of AEM tests the techniques ability to resolve more complex geological structures, image deeper and image beneath shallow conductive bodies.

For the anisotropic clustering and fault network generation of regional gravity data, the objective was to extend worming methods to capture geological dips of regional scale bodies, a process that benefits from conversion of the source ground based gravity survey data to full tensor gradiometry.

All processing and results are provided in the GeoIntrepid report (Appendix 1). All data generated from the work is available via a download associated with this report (Appendix 2).

DISCUSSION

A detailed discussion of the process and results can be found in Appendix 1. Subsequent to the comments in the report regarding the quality of the Quinyambie (Frome) data, further processing and 2.5D inversions run since the GeoIntrepid Consulting Services Final Report have resulted in a set of acceptable deliverables for the Frome Tempest Survey, 2010. These results were obtained by applying a workaround of up-scaling the Z component by 15 percent, to balance the X and Z signals with each other. A further project may explore the option of reprocessing the raw streamed Tempest data for the Frome and Cariewerloo lines which have now been provided to the Geological Survey of South Australia, for the purpose of internal research and development.

APPENDIX 1. GEOINTREPID CONSULTING SERVICES FINAL REPORT ON 1D/2.5D FORWARD AND INVERSE MODELLING FOR AEM AND REPROCESSING OF STATE-WIDE GRAVITY DATA

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Final Report

Stage 1
1D/2.5D Forward and Inverse Modelling for AEM in the Following Areas: Cariewerloo, Gawler South Paris, Quinyambie, Western Craton Margins

And

Stage 2
Reprocessing of State-Wide Gravity Data

Prepared for:

Attn: Dr. Steve Hill

Department of State Development- South Australia
101 Grenfell Street, Adelaide
Adelaide SA 5001

Report Number:
21 September 2016

Prepared by:
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STAGE 1: 1D/2.5D FORWARD AND INVERSE MODELLING

EXECUTIVE SUMMARY

Intrepid Geophysics (IG) was contracted by Department of State Development – South Australia (DSD–SA) to:

Perform full 1D/2.5D forward and inverse modelling for airborne EM, with a new optimised GSVD solver and using a geological reference model where appropriate. The code will support all common commercial airborne EM systems. The modelling to take place in the following areas in accordance with the line details set out in Table 2.

- Cariewerloo: 4 lines - total length 600 km (Figure 1)
- Gawler South Paris: 10 lines - total length 172 km (Figure 2)
- Quinyambie (full 2.5km): 45 lines - total length 4257km (Figure 3)
- Western Craton Margins – Fowler: 10 lines - total length 538km (Figure 4)

Early on we found that we were unable to invert the delivered Tempest data for Quinyambie and achieve the quality of results we felt were possible. We found that the data was noisy particularly over Lake Frome and joint X and Z component inversions were problematic as a result of both correlated and uncorrelated noise in the 2 components. This made it difficult to cleanly image the deeper Eyre formation. The contractor delivered CDI's appeared to be smoothed so as to suppress this noise.

This leads to the conclusion that the QC processes undertaken by Geoscience Australia were not capable of identifying problems of this nature during acceptance testing. We would recommend a process of improving acceptance testing methods through consultation with the contractors. Typical issues are inaccurate transmitter-receiver geometry due to GPS dropouts during acquisition, drift in the scaling of the X component and processing problems caused by very high surface conductivities. One of the deliverables from follow up work on this dataset could be a map showing where current QC processes failed to find these issues.

We requested access to the original survey data in streamed IO format. DSD-SA agreed and a process to deliver that data to Intrepid is ongoing. Inverting the Tempest, Quinyambie data to the standards required is now outside of the scope of this project, and a proposal to revisit this work will follow as part of the Lake Frome ground water geochemical transport (Uranium exploration) 3D geology study.

There are some problems with TEMPEST noise on parts of the Cariewerloo lines (part of same 2010 acquisition as Quinyambie) where the joint inversion also struggles to fit both the X and Z components. Other areas have mostly responded well to 2.5D inversions, displaying reasonable consistency between the measured X & Z components (TEMPEST). This allows the inversion to resolve more complex 2D structure and extend the predicted geology deeper in section. This does support the notion that going back and reprocessing older AEM data can have a big benefit, for little extra cost.

Area	Summary		Line Kms
Cariewerloo		Total	600.55
Paris		Total	172.05
Quinyambie	Full 2.5km	Total	4257.42
Fowler		Total	537.75
	Grand	Total	5567.78

Table 1. 2.5D Inversion Area Summary

Area	Flight	Line	Distance	StartFID	EndFID	StartX	EndX	StartY	EndY	Date
Cariewerloo	0	4000202	175.06	4197	6938	124449	133171	6403824	6578637	2010
	0	7000101	111.01	2695	4457	151969	44027	6515193	6489496	2010
	0	7000201	174.28	6611	9367	121662	124427	6578068	6403828	2010
	0	7000301	140.21	11190	13519	50696	189377	6458039	6437425	2010
Cariewerloo		Total	600.55							

Gawler										
South	2	1000	19.41	30312	39038	615111	595709	6392572	6392741	2014
Paris	2	1010	38.59	12886	26410	582871	621456	6385096	6385116	2014
	1	1020	40.51	83588	98020	584283	624783	6376173	6376164	2014
	1	1030	22.56	101436	111621	623081	600530	6368443	6368596	2014
	1	1040	6.19	69000	71720	593725	587785	6390838	6389090	2014
	1	1041	6.22	72414	74520	587756	593725	6389103	6390843	2014
	1	1050	10.35	63433	67015	588161	598083	6387963	6390887	2014
	1	1060	12.67	57495	62836	600810	588653	6390568	6387016	2014
	1	1070	12.68	52108	56897	588934	601093	6385845	6389448	2014
	1	9000	2.86	44676	45542	571708	574570	6370067	6370065	2014
Gawler South	Paris	Total	172.05							

	0	10010	27.768	5319	5763	301875	286124	6590818	6613683	1999
	0	10020	48.791	4527	5313	273999	301158	6613518	6572992	1999
	0	10030	70.763	3394	4521	293348	254307	6556133	6615140	1999
	0	10040	89.011	1922	3389	235818	283505	6613994	6538850	1999
	0	10050	101.594	280	1917	273019	219230	6522500	6608669	1999
	0	10060	26.695	5769	6199	286022	301173	6614167	6592193	1999
	0	10070	27.064	6205	6637	301137	285767	6591554	6613826	1999
	0	10080	48.285	6643	7404	274485	301350	6613146	6573033	1999
	0	10090	48.592	7410	8202	301077	274067	6572674	6613057	1999
	0	10100	49.19	8207	8971	273556	300915	6612918	6572049	1999
West Gawler	Fowler	Total	537.75							

Area	Flight	Line	Distance	StartFID	EndFID	StartX	EndX	StartY	EndY	Date
Lake Frome	72	3006501	164.40	5989	8650	499953	335564	6603532	6603533	2010
Quinyambie	73	3006301	131.96	5229	7396	499942	367993	6608478	6608527	2010
Big Block	73	3006401	132.42	4454	6741	367540	499953	6606030	6606036	2010
2.5km Lines	74	3006101	131.05	4745	6929	499947	368910	6613527	6613527	2010
where flown	74	3006201	131.14	4162	6272	368819	499951	6611031	6611035	2010
	75	3005901	121.79	5304	7487	476577	354807	6618531	6618523	2010
	75	3006001	137.49	4275	6423	362473	499953	6616038	6616031	2010
	76	3005701	134.50	6006	8495	476570	342089	6623521	6623525	2010
	76	3005801	129.44	5575	7480	347077	476511	6621029	6621033	2010
	77	3005501	131.44	6097	8348	476563	345138	6628525	6628526	2010
	77	3005601	132.89	5241	7509	343621	476509	6626036	6626022	2010
	78	3005301	128.36	5924	8097	476543	348200	6633527	6633539	2010
	78	3005401	129.84	5284	7391	346676	476505	6631026	6631032	2010
	79	3005101	125.26	5660	7746	476534	351285	6638531	6638528	2010
	79	3005201	126.79	4976	7081	349729	476512	6636018	6636034	2010
	80	3004901	122.49	5934	7912	476522	354046	6643534	6643530	2010
	80	3005001	123.69	5169	7402	352830	476513	6641036	6641032	2010
	81	3004701	126.28	5790	7800	476487	350223	6648529	6648532	2010
	81	3004801	124.30	4990	7221	352234	476503	6645899	6646037	2010
	82	3004501	125.83	4735	6782	476472	350650	6653523	6653536	2010
	82	3004601	126.76	4019	6159	349732	476489	6651042	6651032	2010
	85	3004302	124.08	5296	7278	476471	352397	6658531	6658531	2010
	85	3004402	124.95	4736	6652	351527	476471	6656041	6656031	2010
	86	3004102	122.35	5264	7179	476455	354119	6663521	6663532	2010
	86	3004202	123.22	4784	6681	353250	476463	6661009	6661032	2010
	87	3004001	117.24	5169	6945	359212	476440	6666019	6666036	2010
	87	5003101	23.54	8525	8864	499976	476436	6641032	6641031	2010
	87	5003201	23.52	8009	8377	476440	499963	6636031	6636033	2010
	87	5003301	23.52	7467	7810	499965	476444	6631035	6631037	2010
	87	5003401	23.52	6878	7243	476438	499954	6626037	6626042	2010
	87	5003501	23.50	6350	6693	499945	476442	6621028	6621034	2010
	88	3003301	83.80	8627	10122	458209	374415	6678534	6678531	2010
	88	3003601	89.73	6913	8398	372576	462294	6676042	6676030	2010
	88	3003701	95.64	6703	8419	466366	370741	6673529	6673546	2010
	88	3003801	101.55	3144	4780	368893	470438	6671039	6671031	2010
	89	3003201	77.90	3137	4405	376259	454152	6681027	6681028	2010
	89	3003901	110.02	10553	12340	474568	364559	6668492	6668527	2010
	89	5002501	29.64	7993	8461	499953	470319	6671024	6671036	2010
	89	5002601	23.61	7459	7841	476356	499959	6666039	6666040	2010
	89	5002701	23.59	6875	7235	499959	476375	6661041	6661033	2010
	89	5002801	23.59	6336	6730	476384	499975	6656032	6656035	2010
	89	5002901	23.58	5788	6147	499979	476401	6651039	6651035	2010
	89	5003001	23.57	5228	5626	476417	499981	6646027	6646034	2010
	90	5002301	45.89	5752	6484	499952	454068	6681002	6681035	2010
	90	5002401	37.76	4945	5594	462193	499947	6676034	6676037	2010
Lake Frome	Quinyambie	Total	4257.42							

Table 2. Line Details of AEM Surveys for regions: Cariewerloo, Gawler South Paris, Quinyambie and Western Craton Margins

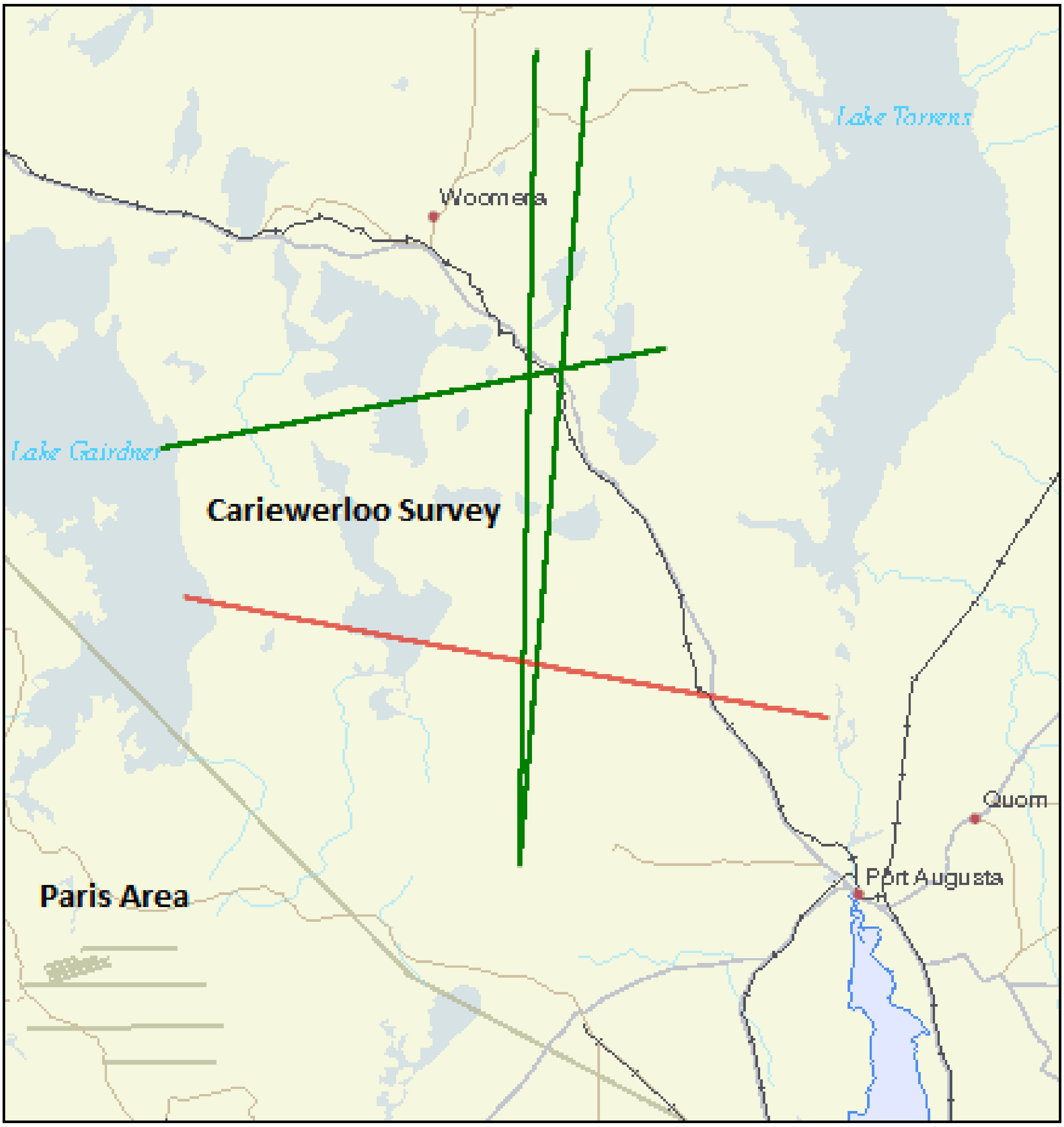

Figure 1. Cariewerloo AEM Survey

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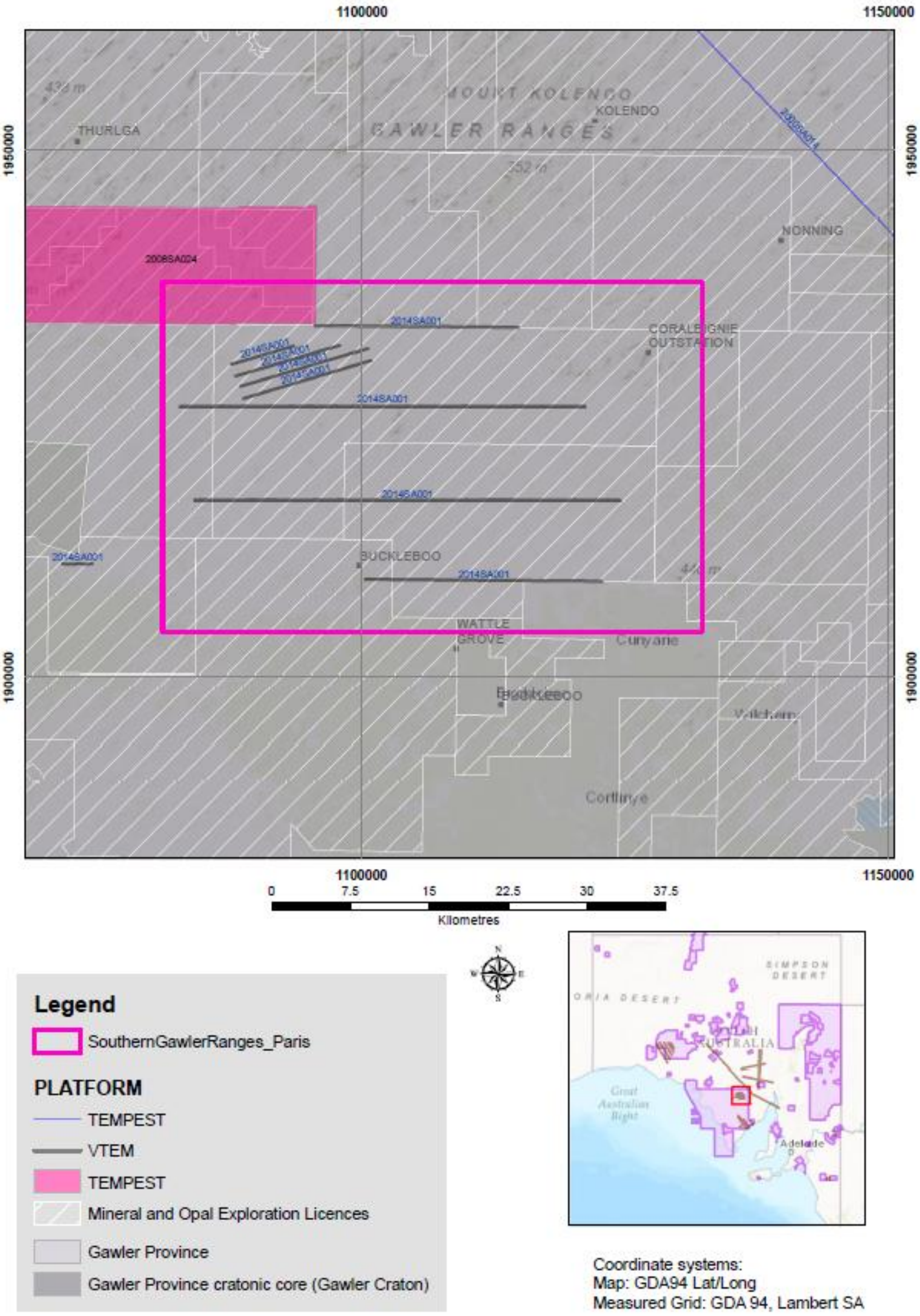

Figure 2. Southern Gawler Ranges – Paris, AEM Survey (excludes Tempest in the north-east corner, overlapping)

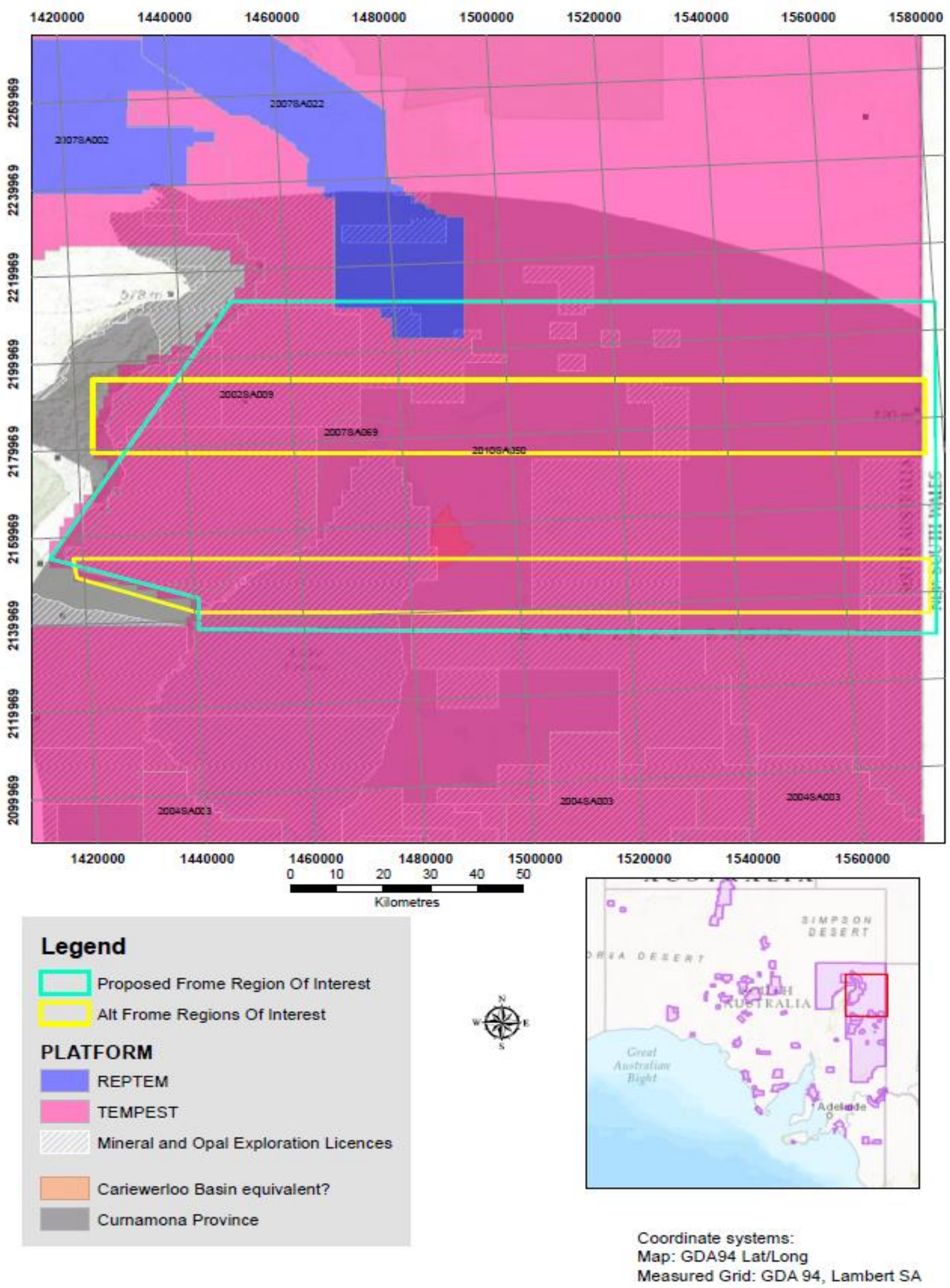

Figure 3. Frome region AEM Survey, Quinyambie (Full 2.5km) 45 lines – 4257 km (excludes blue REPTEM area in the north, overlapping)

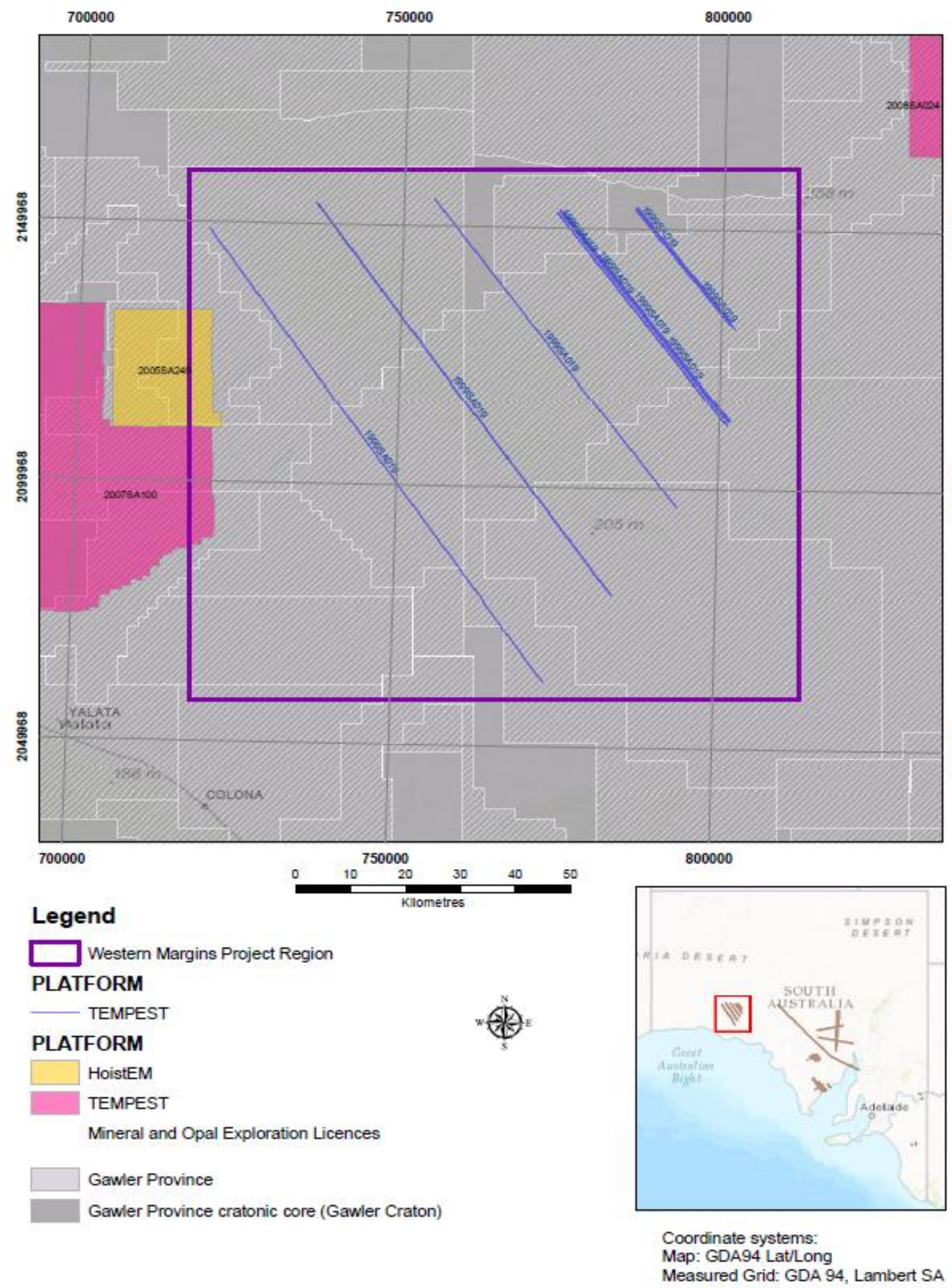

Figure 4. Western Craton Margins (Fowler) – 538 km (all lines)

BACKGROUND

Department of State Development- South Australia will supply:

1. Final located AEM data and an acquisition report detailing the AEM system characteristics and processing details for each of the four areas as delivered to DSD -

SA by the survey contractor. This data is mostly available from the SARIG open file data delivery system.

GENERAL SCOPE OF GEOINTREPID WORK

Intrepid Geophysics will supply to Department of State Development- South Australia:

1. An explanation of how the system response will be modelled.
2. The results of 2.5D inversions of the supplied survey data in ASCII files with the mesh definition and conductivities of the inversion models.
3. A new optimised solver will be applied where appropriate.
4. ASCII files with the input data and forward responses of the final inversion models at the original fiducials, along with the ancillary information, x, y, line, fid, etc.
5. This report detailing the inversion mesh discretization and the constraints used for all four surveys: Cariewerloo, Gawler South Paris, Quinyambie and Western Craton.
6. The 2.5D inversions will be carried out with the topography taken into account.
7. The 2.5D inversions will invert the TEM X and Z components jointly where available.
8. All stage 1 items shall be delivered by 30th September 2016.

WORKFLOW SUMMARY

INVERSIONS

The Client requested 2.5D Inversions be carried out in the four areas listed below (Figs 1-4):

- Cariewerloo - 4 lines - total length of 600 km (Figure 1)
- Gawler South Paris - 10 lines – total length 172 km (Figure 2)
- Quinyambie (full 2.5km) - 45 lines- total length 4257km (Figure 3)
- Western Craton Margins - Fowler- 10 lines-total length 538km (Figure 4)

The AEM systems used on the 4 Survey areas are:

- Cariewerloo – TEMPEST
- Gawler South Paris – VTEM
- Quinyambie – TEMPEST
- Western Craton Margins – Fowler - TEMPEST

DATA PREPARATION AND SETUP - By Survey Area

1. Where delivered as ASEG GDF ASCII data, the located AEM survey data is imported by Intrepid into a Geosoft gdb with the AEM channels stored in standard array channels. Otherwise the contractor's database (VTEM) can be used directly.
2. A GeoModeller project is created covering the extents of each survey area.
3. A DTM derived from the survey and augmented by 1sec SRTM data where necessary is loaded into the project.
4. A system file is created for the AEM system used on each survey. This requires knowledge of the transmitter frequency and waveform, measurement times and the system geometry. This information is usually derived from the contractor's survey acquisition report.

5. The AEM database is loaded into the project via the Geophysics EM wizard. This triggers the creation of 2D sections for each database flight line.
6. The user selects the database channels required by the inversion process.
7. An estimate of system noise is made by analysis of a low signal area of measured late time survey data imported into GeoModeller. This noise estimate is then saved to a configuration file for use in the inversion process

2.5D INVERSION SYSTEM SETUP DETAILS

The system parameters are loaded into the AEM module as shown in the following figures.

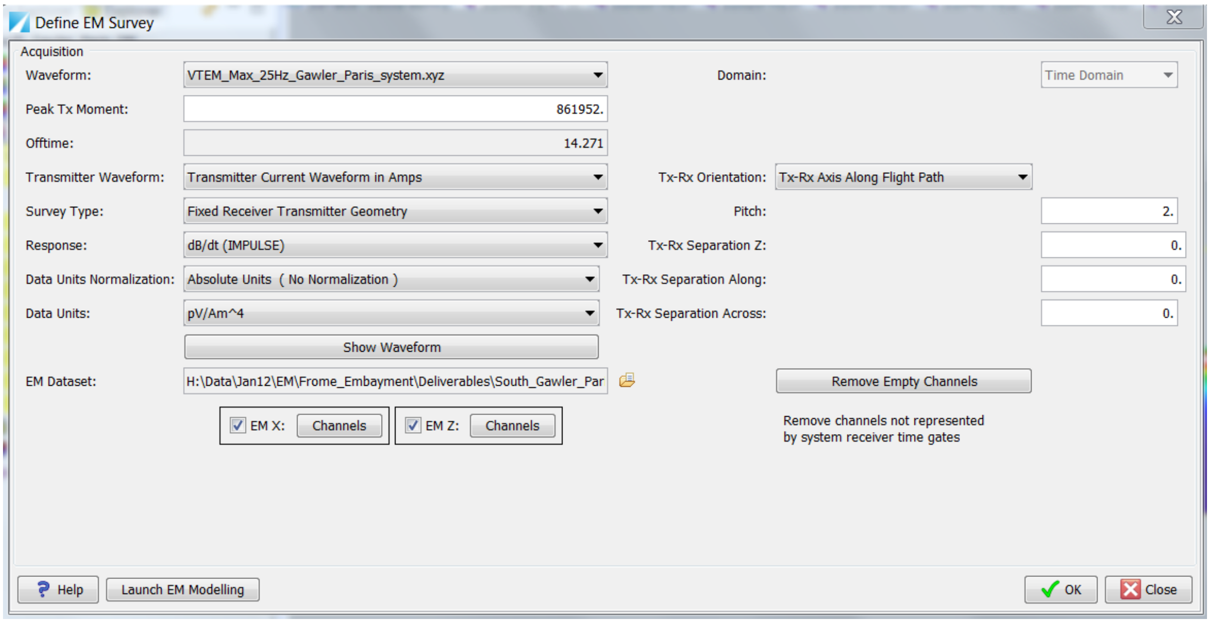

Figure 5. South Gawler Paris – VTEM Max System Setup

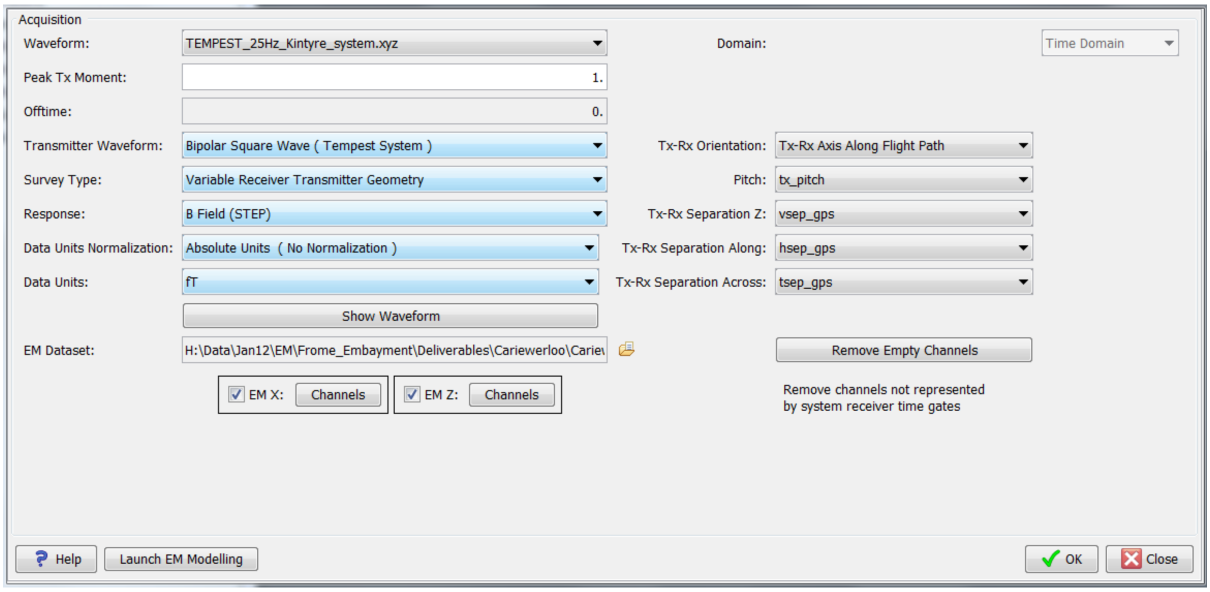

Figure 6. Cariewerlooo/Quinyambie – TEMPEST – Variable Tx-Rx Geometry

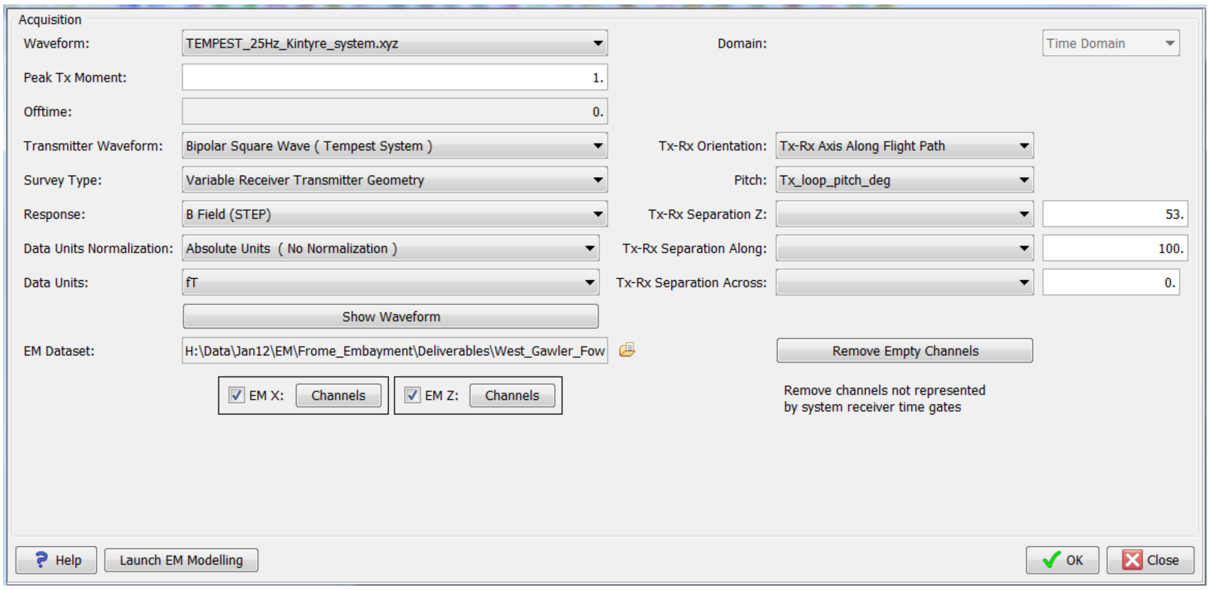

Figure 7. Fowler – TEMPEST – Variable Geometry (Tx Pitch only)

SYSTEM SETUP

Step 1: Load Waveform

Step 2: Enter Peak Transmitter (Tx) Moment

Step 3: Load the survey database (Geosoft .gdb or Intrepid ..DIR).

Step 4: Select Survey Type

Fixed or Variable Receiver Transmitter Geometry

Note: Most airborne systems use a Fixed Receiver Transmitter Geometry. However the inversion process can correct for variations in system geometry if measurements are recorded during flight i.e. TEMPEST, SKYTEM

Choosing **Variable Rx-Tx Geometry** triggers a change in the interface allowing database variables to be selected for variable parameters or fixed values otherwise:

- **Transmitter Loop Pitch**: ***AngleX***

  Pitch is positive up in the flight direction!

- **Tx-Rx Separation Z** – positive down: ***"Fixed value"***

  when Rx is below Tx the value is positive!

- **Tx-Rx Separation along** - positive behind: ***"Fixed value"***

  when Rx is behind Tx (i.e. trailing bird) the value is positive!

- **Tx-Rx Separation across** - positive to port (left): ***"Fixed value"***

  when Rx is to the left (port side) of Tx the value is positive!

Note: Currently the software does not allow different locations for the X and Z Receiver coils

Step 5: Select System Response:

B Field [Step] - TEMPEST
dB/dt [Impulse] - VTEM

Step 6: Choose the Data Normalisation method
Absolute Units (No Normalisation);

Most modern systems use Absolute Units; normalised units were common in some of the earlier systems such as GEOTEM and are also used by SPECTREM

Step 7: Choose the Data Units used by your System

TEMPEST BField in fT
VTEM dB/dt in pV/Am^4

Data units are usually defined in the delivered database metadata.
The units drop down is sensitive to whether normalisation has been applied.

Step 8: Click the Launch EM Modelling button to open the main modelling dialog.

This opens the modelling and visualisation panel for the AEM Observed data.

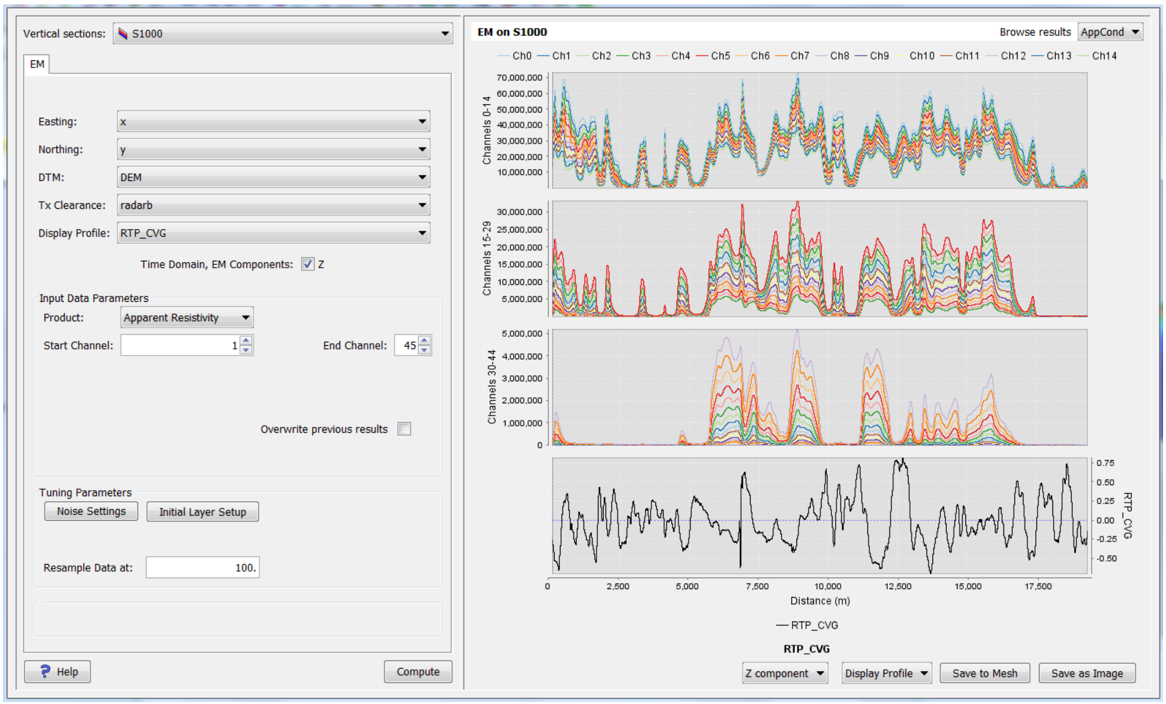

Figure 8. South Gawler Paris – VTEM Max

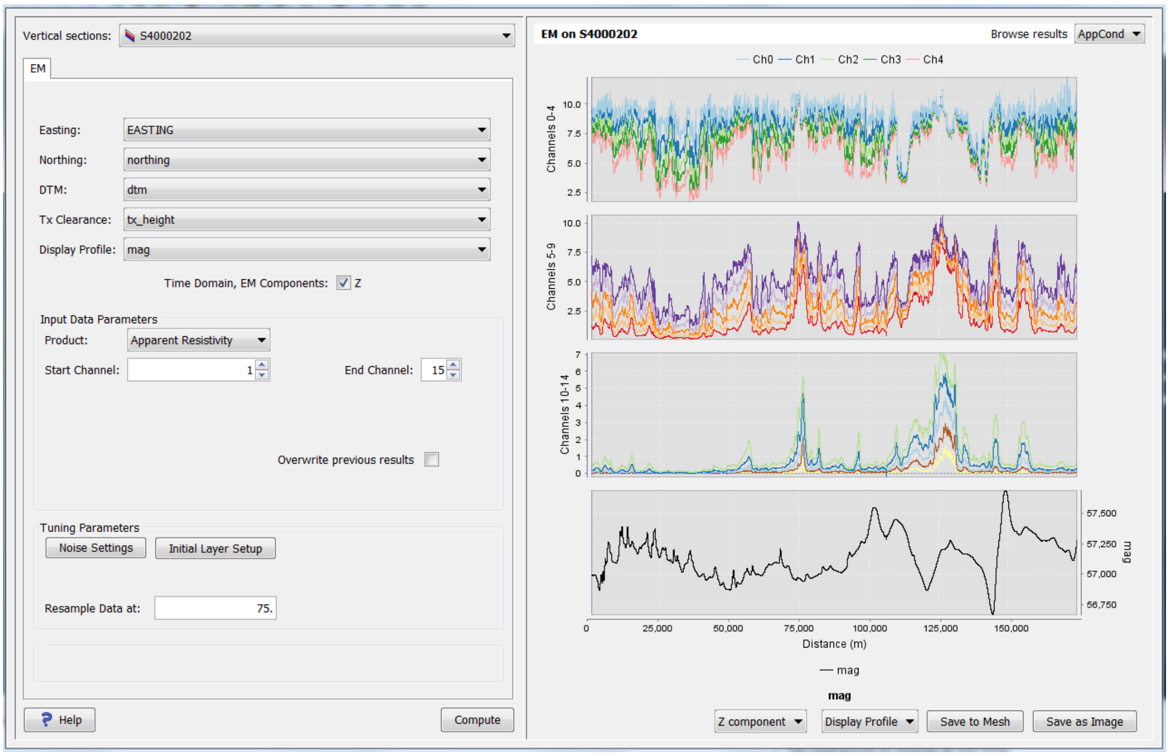

Figure 9. Cariewerloo – TEMPEST

Figure 10. Fowler- TEMPEST

Step 9: Select the required supporting channels:

Easting, Northing, DTM and Transmitter (Tx) Clearance and optionally select any other channel to assist interpretation as shown in the above dialogs.

This completes the general set up of the geometry and field selection prior to the commencement of modelling

NOISE ESTIMATION

See 7. Data Preparation and Setup

APPARENT RESISTIVITY

An Apparent Resistivity calculation may be done prior to inversion to obtain an estimate of background resistivity values. This is then used to select a suitable half space resistivity for the 2.5D inversion starting model.

2D INVERSION SET UP

2D Resistivity Inversion is chosen from the Product Dropdown; the dialog panel changes adaptively to provide the base 2D Inversion options as shown below.

Figure 11. South Gawler Paris – VTEM Max

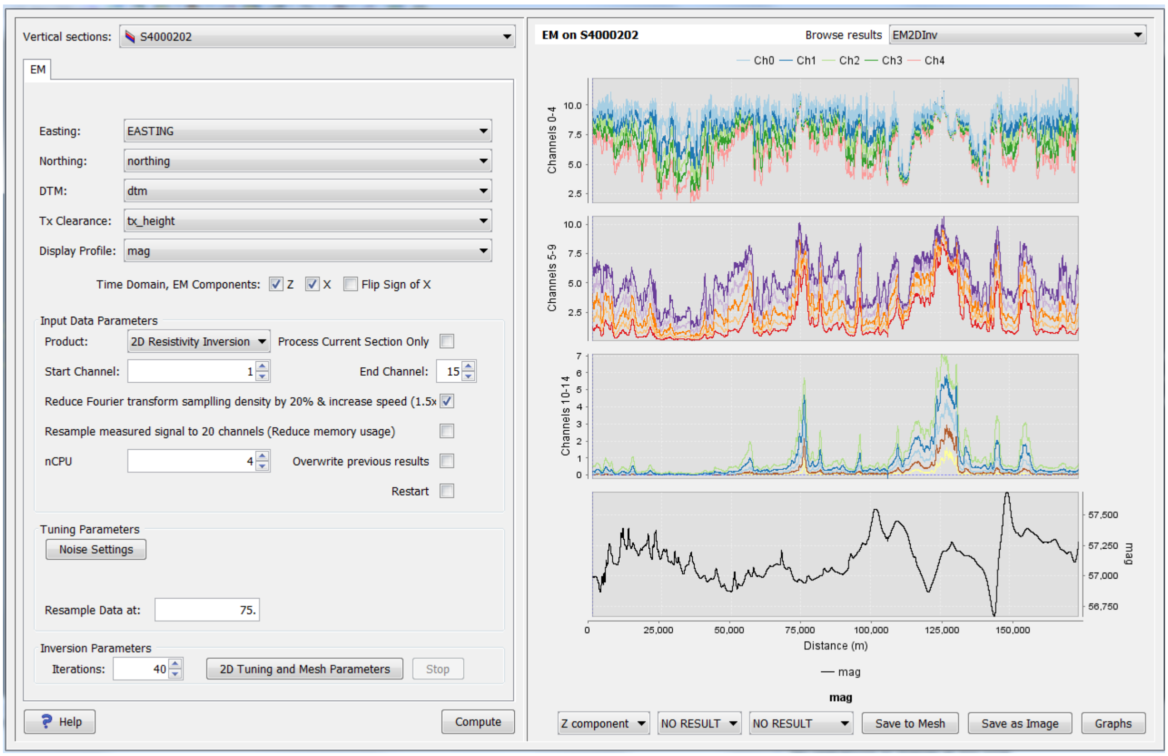

Figure 12. Cariewerloo – TEMPEST

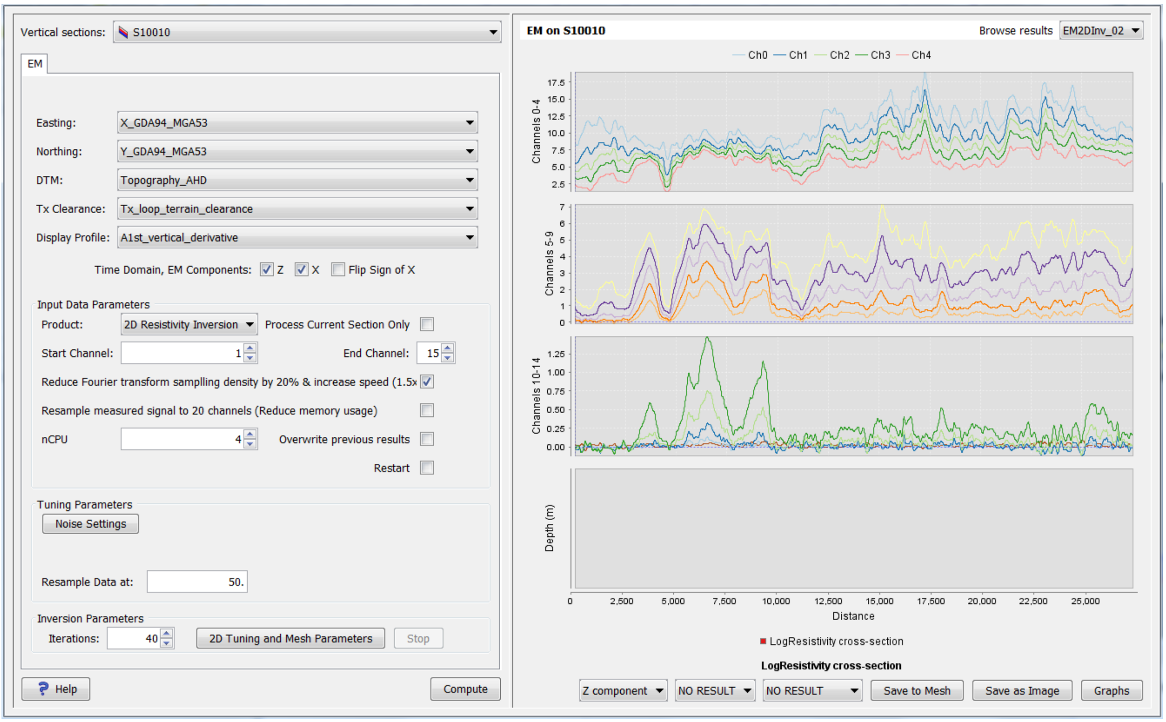

Figure 13. Fowler – TEMPEST

The available options and selections are described below:

Step 1: Component Selection

The component selection automatically defaults to **X** and **Z** when two components have been loaded from the survey database (i.e. the TEMPEST case).

Some systems (SkyTEM, HeliTEM) use an opposite sign convention for the **X** component and hence the **Flip Sign of X** toggle.

We choose to run joint **X, Z** component inversions for the ***TEMPEST*** surveys and a **Z** component only inversion for the ***VTEM*** survey.

Step 2: Channel Selection
We want to use all the available channels so accept the default settings
Accept the default Start and End Channels

Step 3: Choose the number of threads for inversion.
We choose 6 as the maximum for a high end 4 core/8 thread desktop to achieve maximum productivity

Step 4: Noise Settings:
This option is as discussed previously and there are no additional requirements for 2D inversion

Step 5: Resample Data at:
Length in metres of an average smoothing filter applied to the input data. Reduces the number of samples used in the inversion. Keep to the minimum required to preserve wavelengths of interest. Has a significant impact on inversion speed and memory requirements.

Note: The value chosen should be an interval less than or equal to the 2D inversion finite element mesh dX

We resample the observed data at 75m for Cariewerloo, 100m for Quinyambie and Paris and 50m for Fowler.

Step 6: Number of Iterations:

Set to the maximum required to obtain the desired misfit. Misfit convergence options defined under 2D Tuning and Mesh Parameters (see Table 3 below) control the iteration at which the inversion will stop i.e. it may not run for the full number of iterations.

Note: The inversion can be restarted from the last iteration if it appears that full convergence was not achieved.

We choose a maximum of 40 iterations.

2D INVERSION MESH AND TUNING SET UP

The 2D Resistivity Inversion mesh and tuning parameters dialog is selected by clicking the ***2D Tuning and Mesh Parameters*** button in the EM Modelling dialog.

The figures below show the 2D inversion mesh and tuning settings for the four survey areas

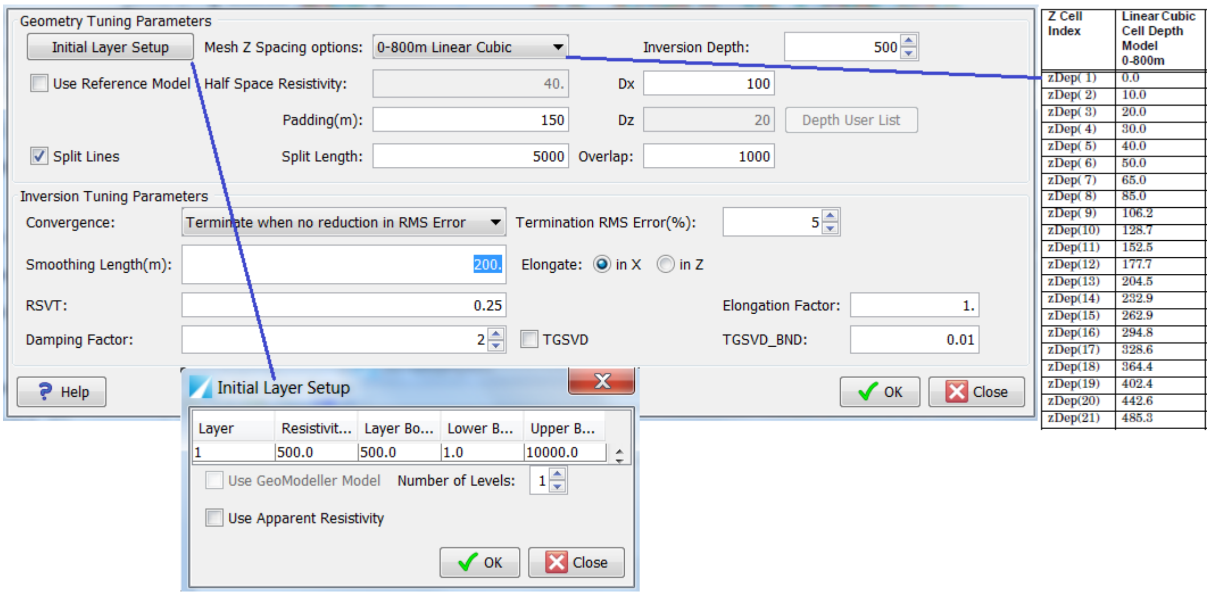

Figure 14. South Gawler Paris – VTEM Max

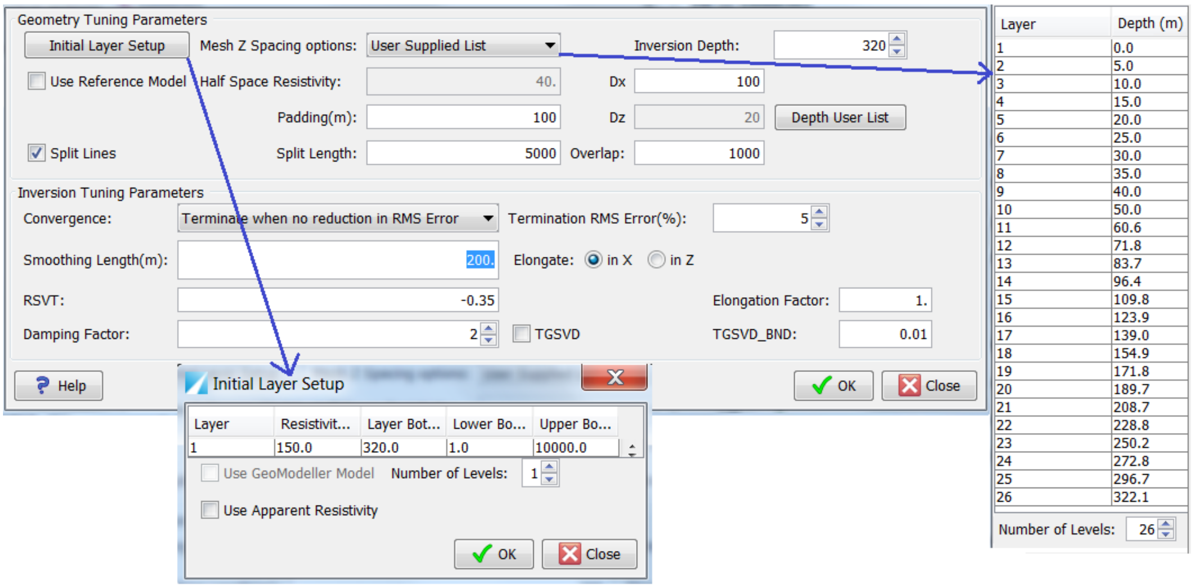

Figure 15. Cariewerloo - TEMPEST

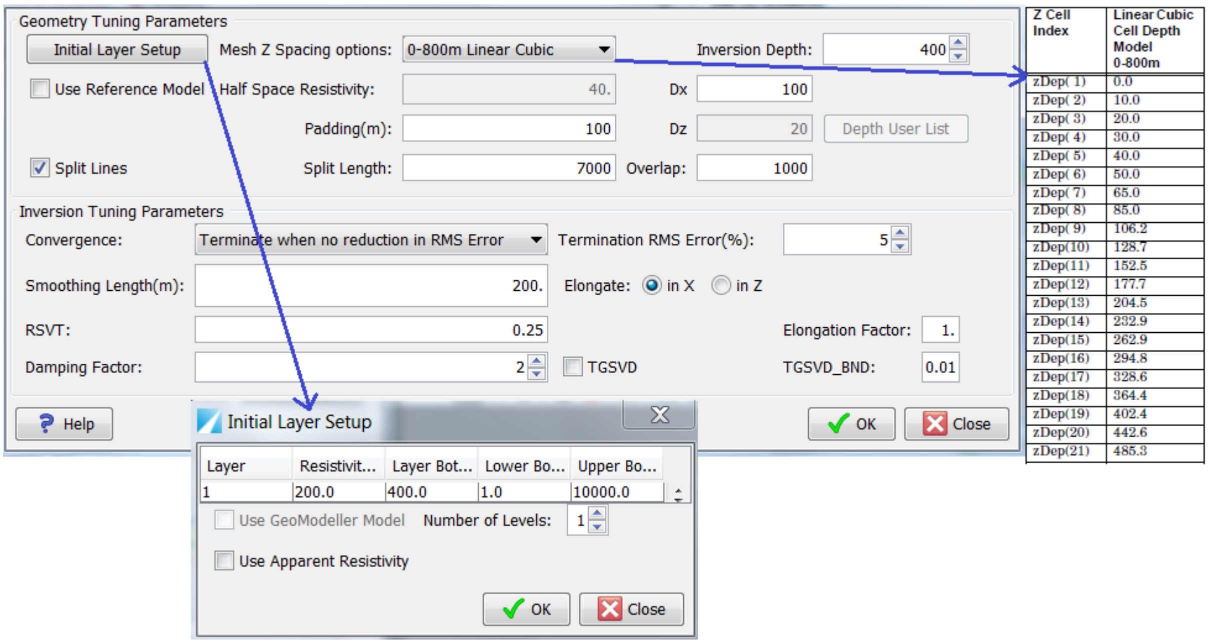

Figure 16. Fowler – TEMPEST

The tuning parameters and mesh constraints are described in the table below:

Geom/Tuning Parameters	**Cariewerloo Quinyambie Tempest**	**Fowler Tempest**	***Paris VTEM max***	**Description**
Inversion Depth	**320**	**400**	**500**	Constrains depth of the inversion.
Padding (m)	**100**	**100**	**100**	The padding distance; data points inside the mesh and within padding distance of the edge of the mesh are not used.
Dx (m)	**100**	**100**	**100**	The mesh X cell dimension (horizontal)
Dz (m)	**User Defined List**	**Lin. Cubic**	**Lin. Cubic**	A constant mesh Z cell dimension; Only used with the User Defined method.
Use Reference Model	**No**	**No**	**No**	If **Use GeoModeller Model** is ticked in the **Initial Layer Setup** dialog then: If ON AND a GeoModeller model exists then use the model mesh as the ***reference*** model. If OFF AND a GeoModeller model exists then use the model mesh as the ***starting*** model. ELSE use the **Initial Layer** resistivity as the starting model half space resistivity.
Half Space Resistivity	**150**	**200**	**500**	If Reference Model is Yes then specify the starting model half space resistivity in ohm metres. Otherwise we use the Initial Layer Setup resistivity for the starting model
RSVT, RSVT0	**-0.35, 0.02**	**0.25, 0.01**	**0.25, 0.01**	Initial Relative Singular Value Truncation, Minimum value. Dampens changes in non-sensitive cell conductivities for each data point during the initial stages of the solution. Percent expressed as a fraction. This value is set higher in 2D inversion i.e. 0.15
Smoothing Length	**200**	**200**	**200**	Over what distance (m) is the model expected to be smooth. Minimum is 2 cell widths in X.
Elongate in X or Z	**X**	**X**	**X**	Toggle required direction. Tries to force the model to be smoother in one direction compared to the other as long as data supports the notion.
Elongation Factor	**1**	**1**	**1**	The amount of stretching, the ratio of X to Z or Z to X depending on which Elongation option is chosen
Damping Mode	**2**	**2**	**2**	Defines the damping factor used to limit the change in insensitive or unimportant parameters; can be set to 1 or 2; 1 is less dampening and 2 is more.
TGSVD	**0**	**0**	**0**	Truncated singular value decomposition; truncates use of parameters associated with singular values less than the specified percentage of the largest singular value of the GSVD solution. In this case some parameters will not be used at all i.e. those that are two deep or two far away from the source.
TGSVD_BND	**0.01**	**0.01**	**0.01**	A fraction (percentage) defining the threshold at which we ignore singular values as described above
Convergence	**1**	**1**	**1**	1. Stops when no further reduction in RMS error. 2. Terminate at specified % RMS error.

Table 3. Tuning Parameters and Mesh Constraints

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2D INVERSION RESULTS

An overview of the 2.5D inversion results are shown below for each of the inverted areas. The results are shown in two forms.
Inverted profiles over observed profiles for each measurement time with early, mid and late times grouped together in two sets of 3 panels ordered from top to bottom with Z component channels followed by X component channels (where latter are available/inverted i.e. TEMPEST).
The inverted profiles are displayed in black and the observed profiles in cycled colours.
Below the profiles we show 2 panels illustrating the impact of noise thresholding on the X and Z components.
The final base panel shows the log conductivity section.

- Evolution by iteration RMS Misfit and Model Norm graphs for at least 3x5km parts of the inversion (start, middle, end).

- A GeoModeller section or stack of sections with a gridded log conductivity (mS/m) backdrop rendered using a linear stretch colour lookup with default stretch limits of 0 to 3 log mS/m. Labelled spatial vertical and horizontal scales are provided.
AND/OR
- An alternative display is one of the ungridded 3D point mesh on 2D sections or in 3D with a suitable point size rendered in the same fashion as the above.

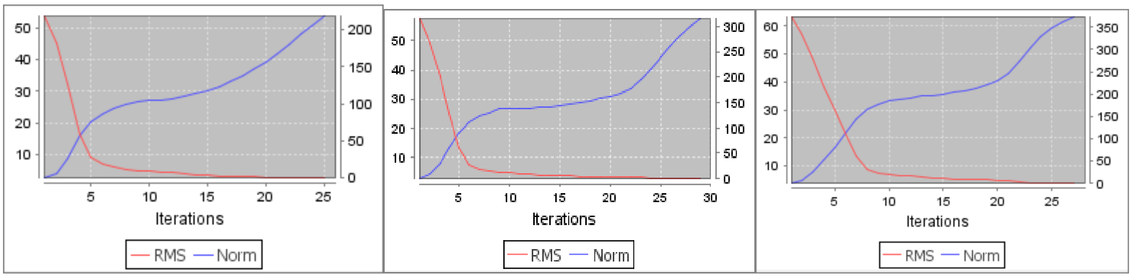

Figure 17. Cariewerloo – TEMPEST: 2.5D XZ Inversion

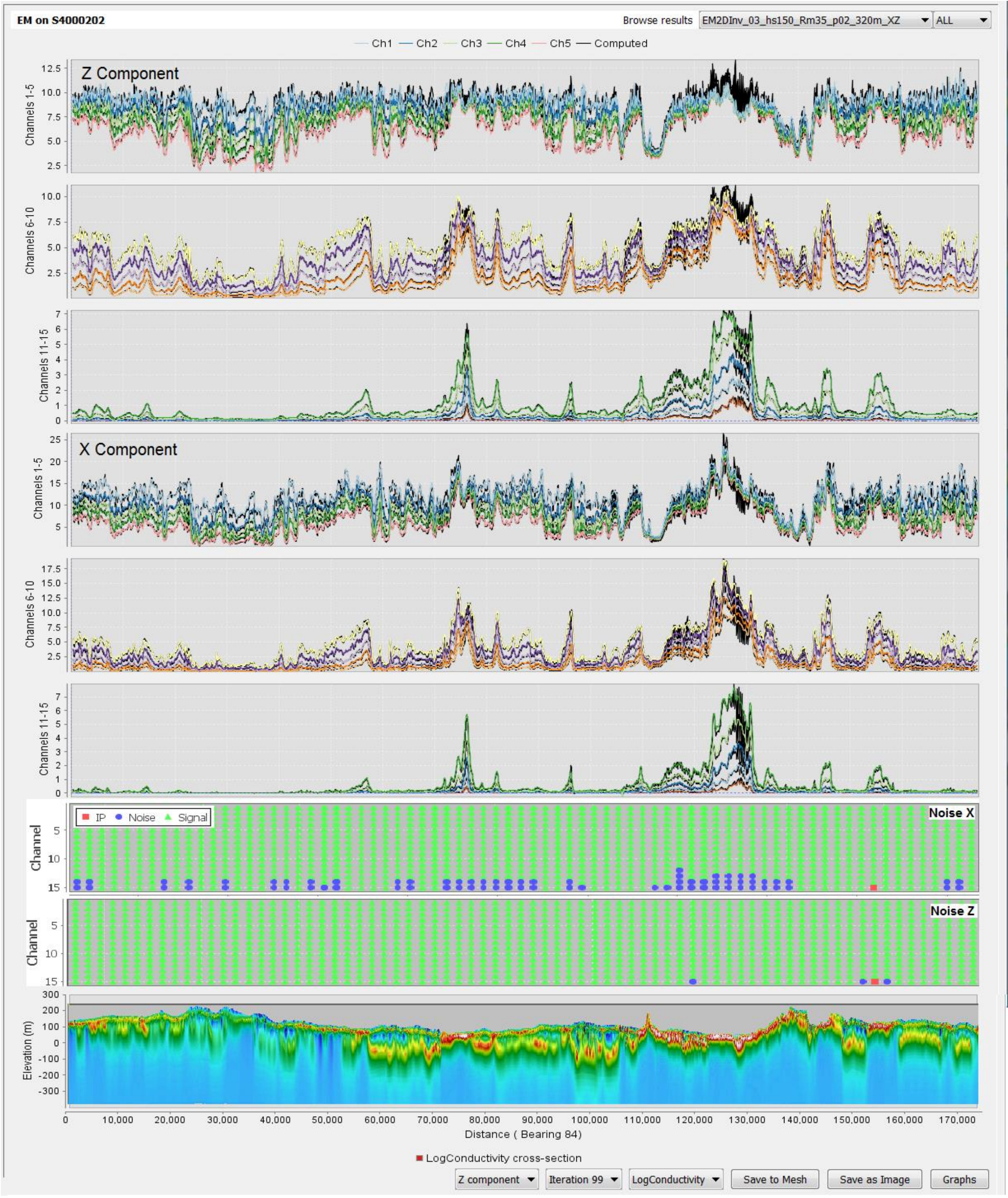

Figure 18. Cariewerloo – TEMPEST: 2.5D XZ Inversion Profiles, Noise Removal, Conductivity Section

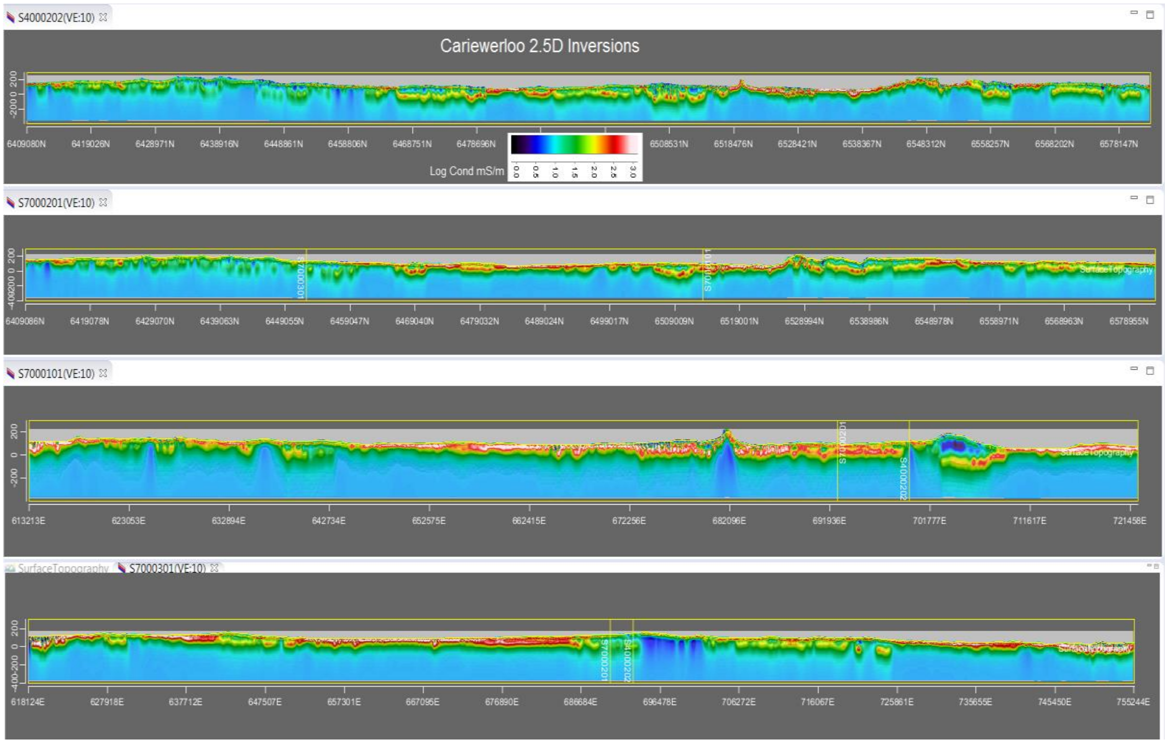

Figure 19. Cariewerloo – TEMPEST: 2.5D XZ Inversion Stacked Sections – All Lines

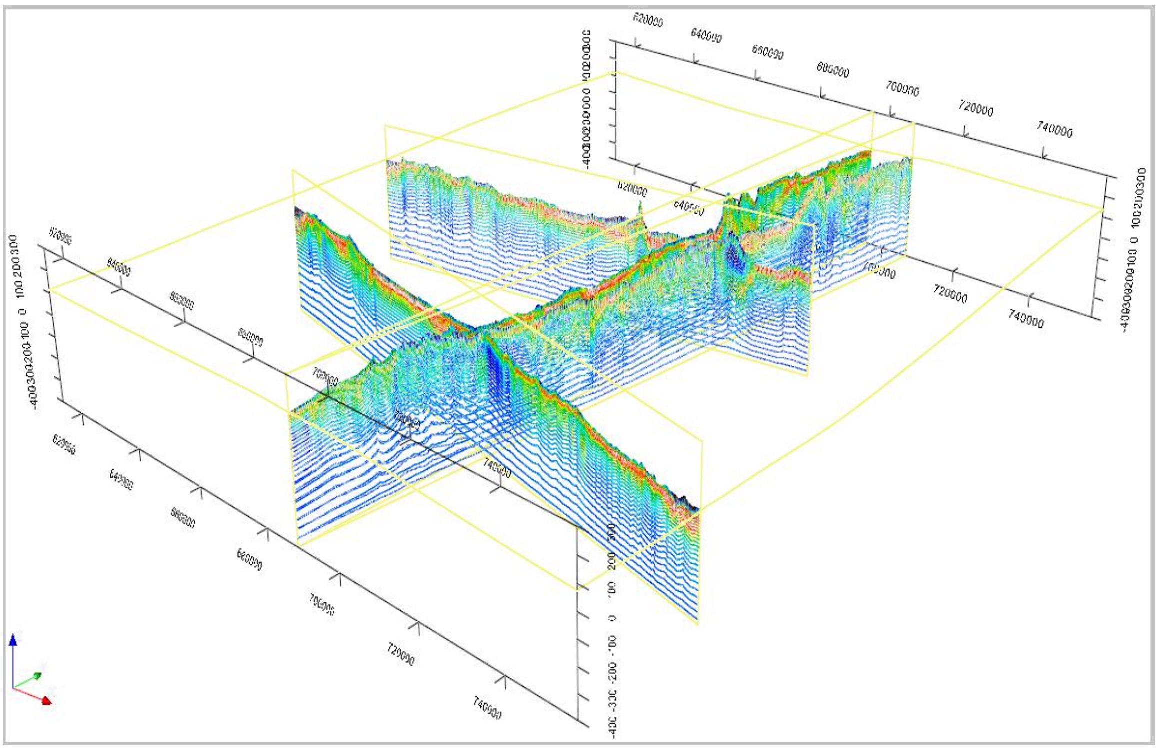

Figure 20. Cariewerloo – TEMPEST: 2.5D XZ Inversion 3D View

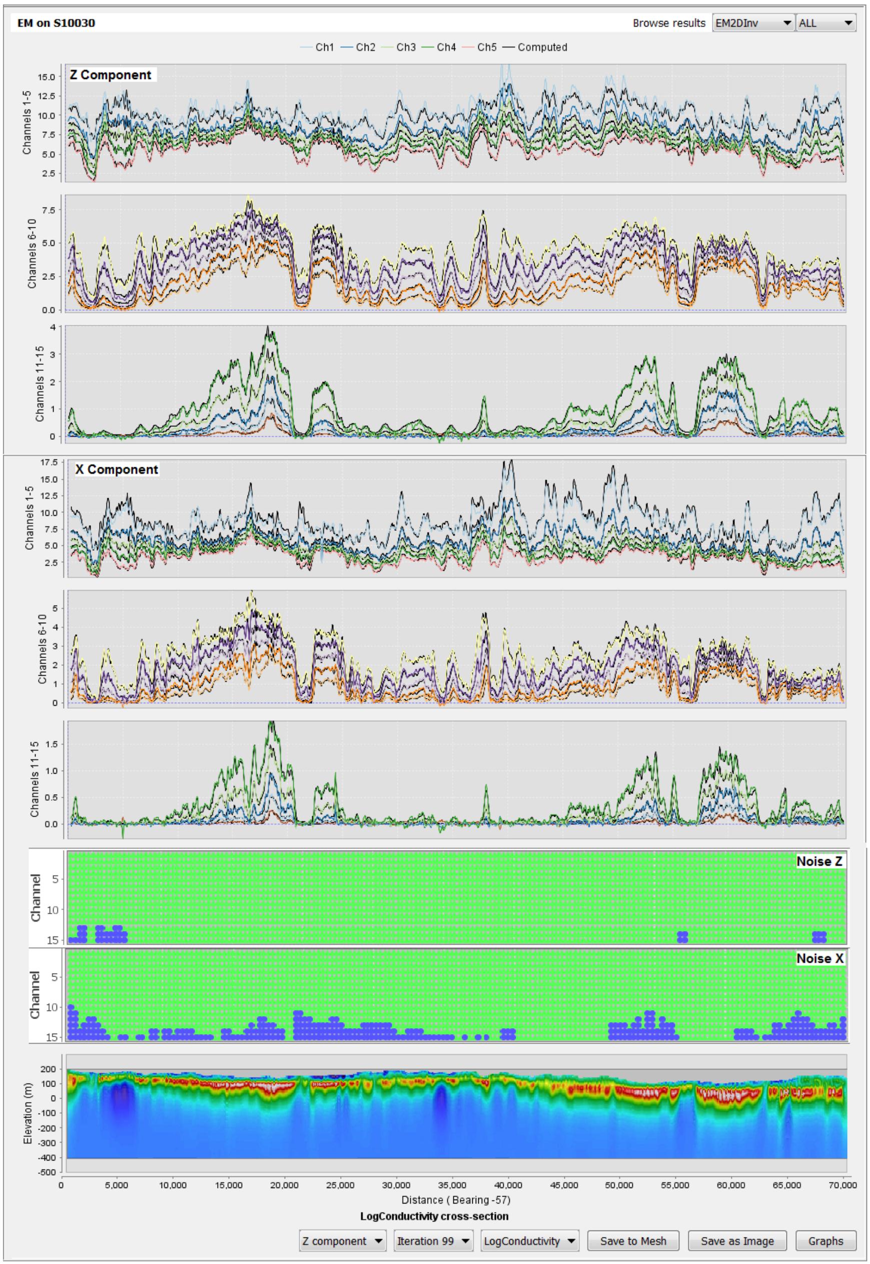

Figure 21. Fowler – TEMPEST: 2.5D XZ Inversion Profiles, Noise Removal, Conductivity Section

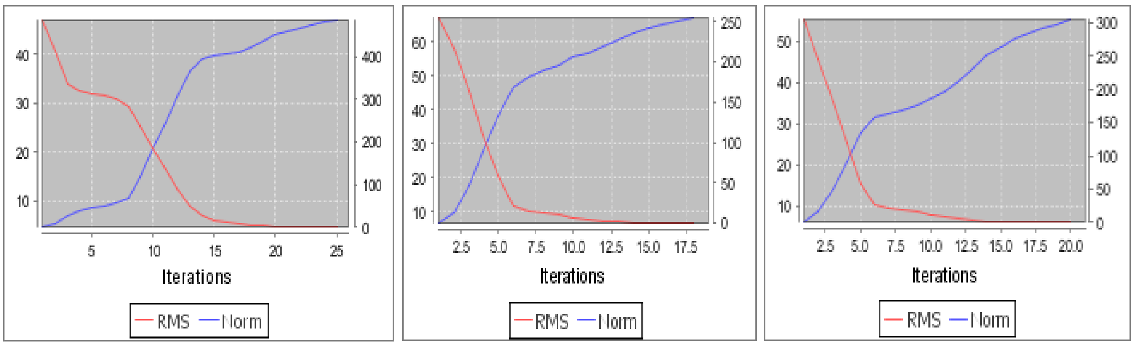

Figure 22. Fowler – TEMPEST: 2.5D XZ Inversion

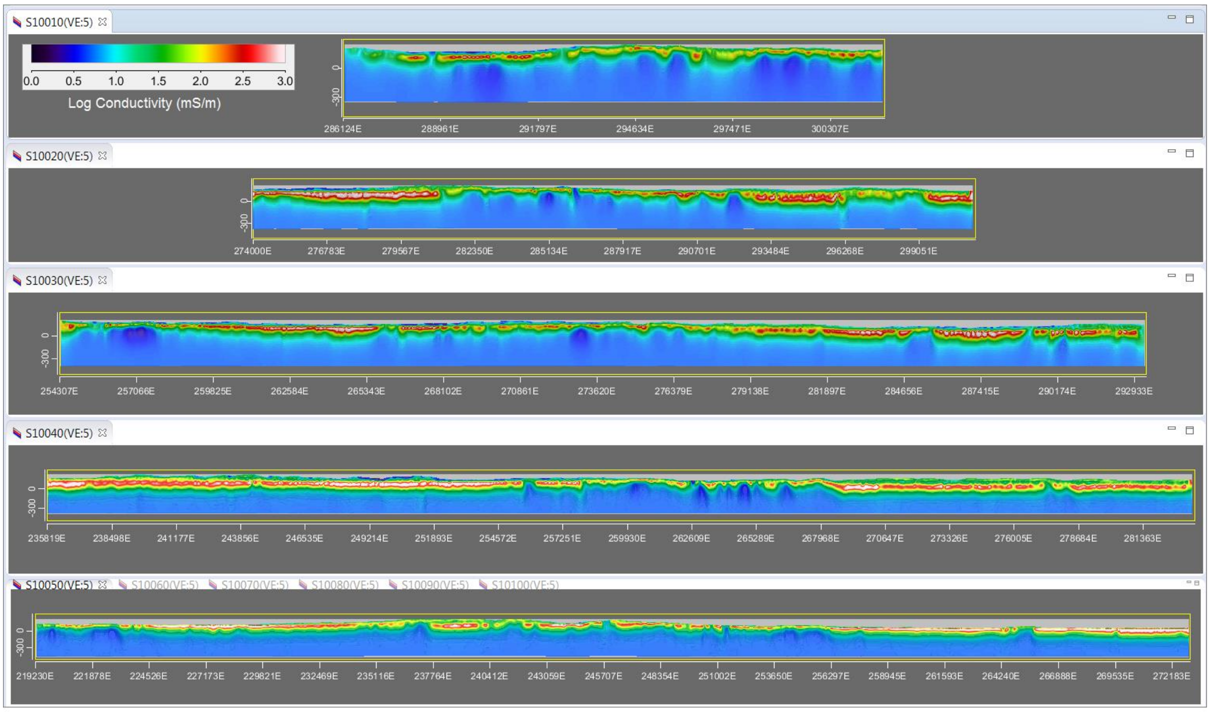

Figure 23. Fowler – TEMPEST: 2.5D XZ Inversion Stacked Sections – All Lines

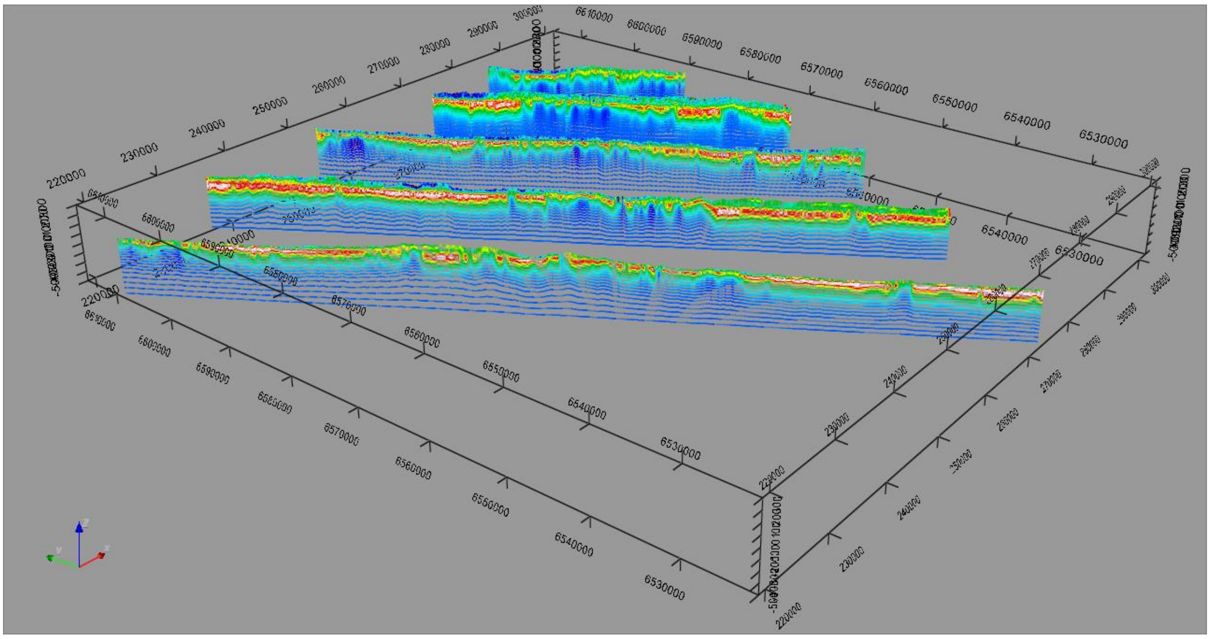

Figure 24. Fowler – TEMPEST: 2.5D XZ Inversion 3D View

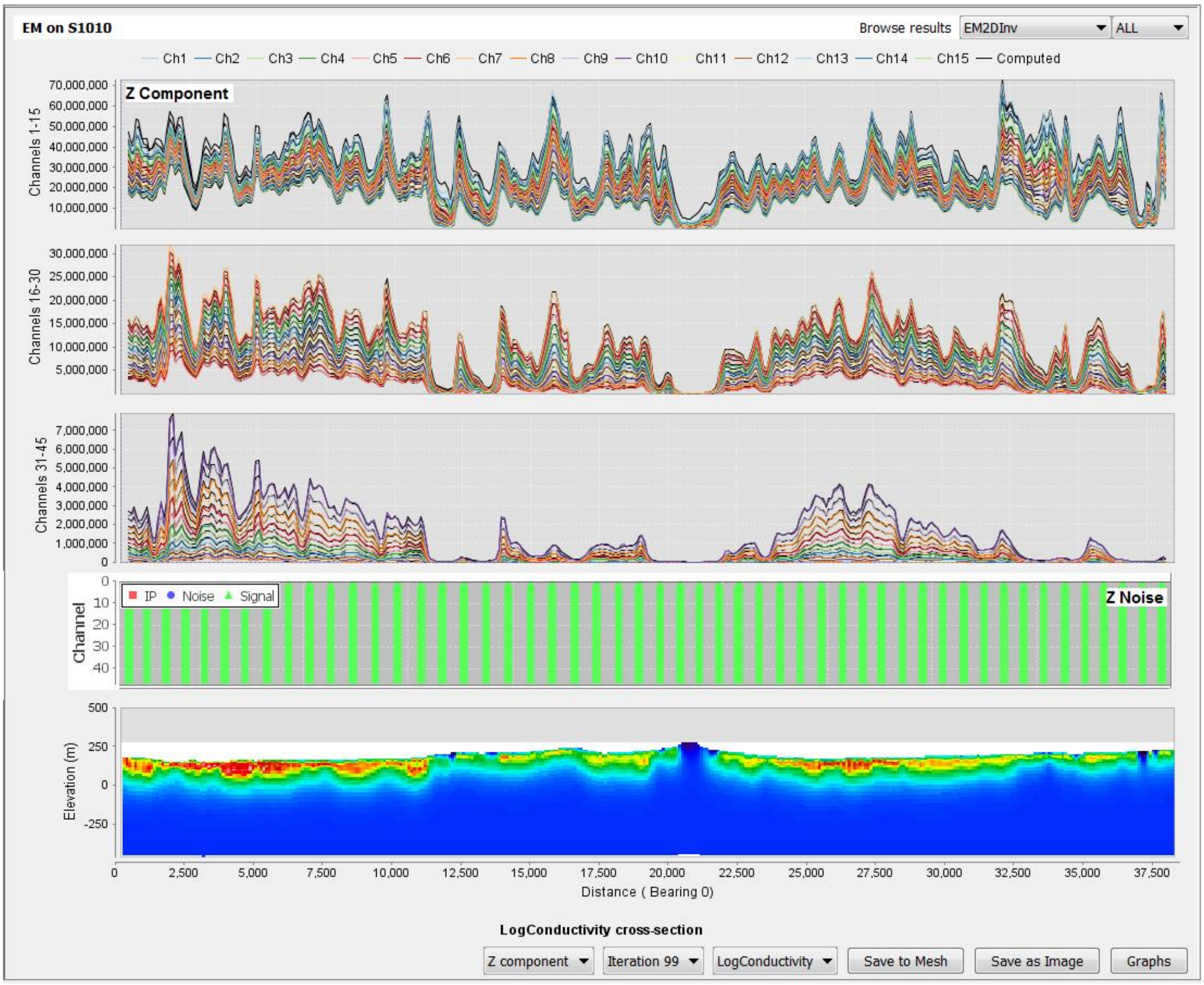

Figure 25. South Gawler Paris – VTEM Max Z Inversion Profiles, Noise Removal, Conductivity Section

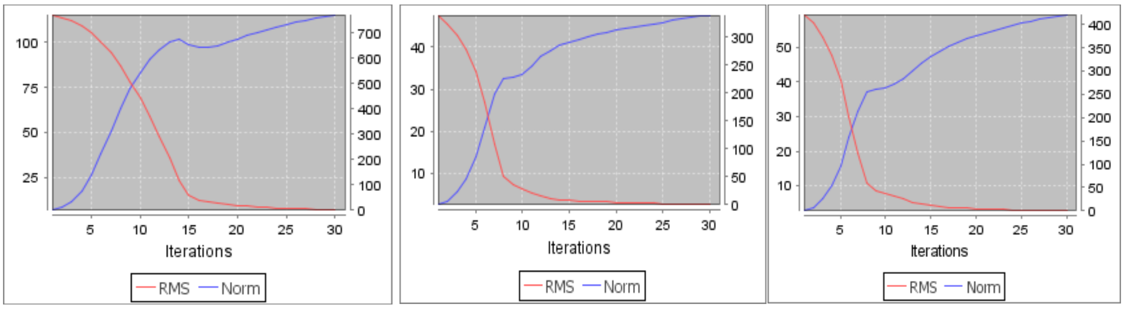

Figure 26. South Gawler Paris – VTEM: 2.5D Z Inversion

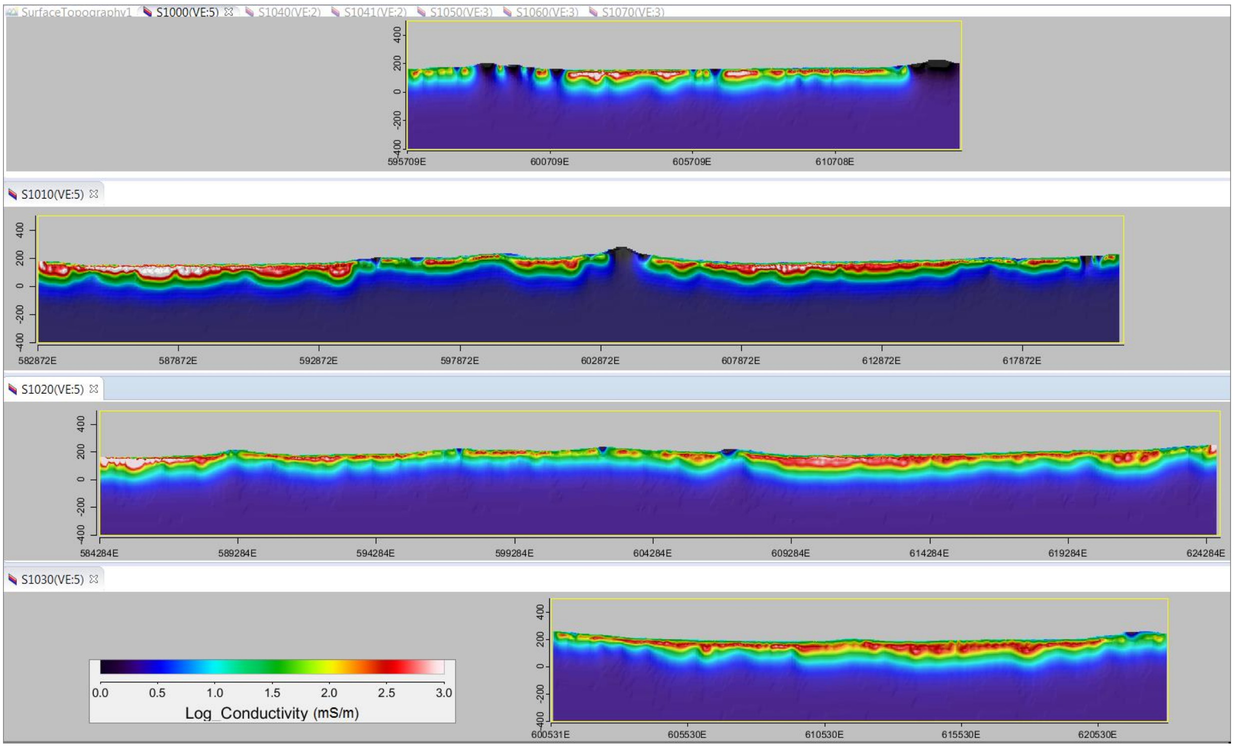

Figure 27. South Gawler Paris: 2.5D Z Component Inversion Stacked Sections

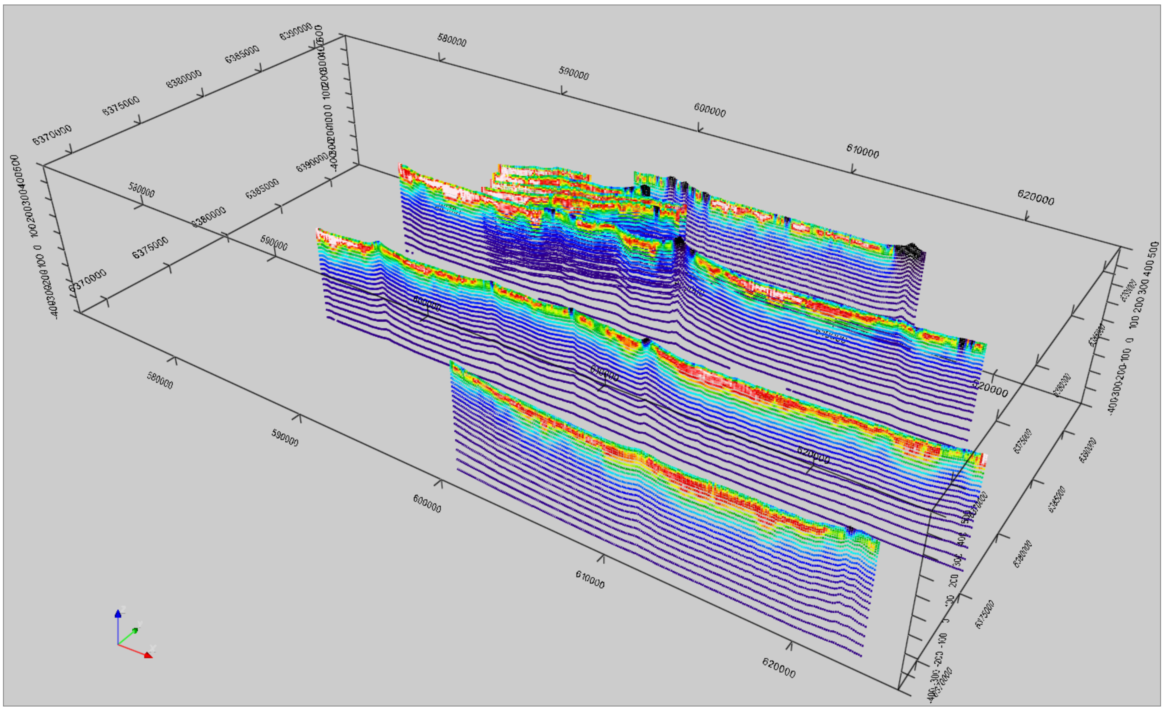

Figure 28. South Gawler Paris – VTEM Max: 2.5D Z Inversion 3D View

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2D INVERSION RESULTS SUMMARY

Cariewerloo, Paris and Fowler
The 2.5D inversion results from all areas are mostly dominated by relatively shallow conductive cover or regolith. The exception is Cariewerloo which shows some deeper more complex geological structure as both conductive and resistive features within and below the shallower conductive cover or regolith.

The Tempest data from both Cariewerloo (2010) and Fowler (1999) is relatively noisy compared to the more recent VTEMmax survey at Paris (2014).

There are some problems with TEMPEST noise on parts of some Cariewerloo lines where the joint inversion struggles to fit both the X and Z components. An example of this occurs on Cariewerloo line 7000301 over 5kms at the start and 5kms at the end of the line.

As a result of this noise and poor misfits for the joint X, Z inversion it was decided to run a Z only inversion on all four Cariewerloo lines. This improved the inversion quality and misfits on parts of these lines where the joint inversion was very poor.

An example is shown below:

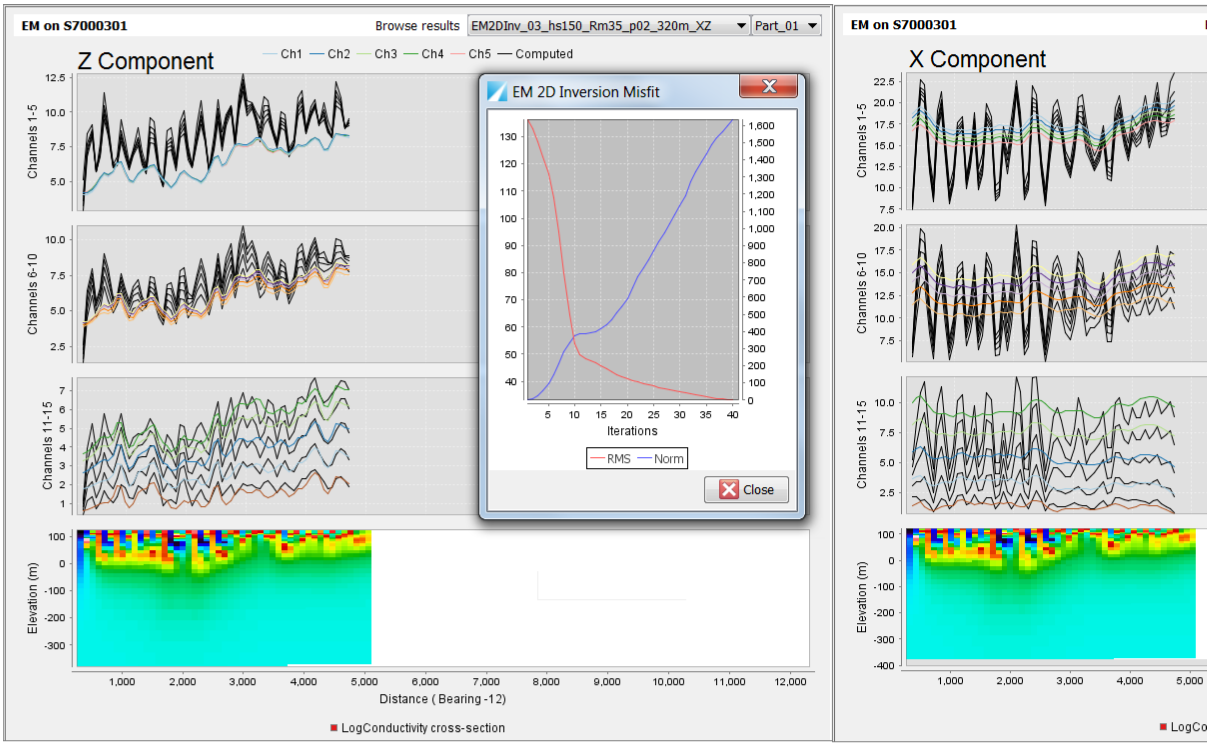

Figure 29. Cariewerloo - Line 7000301 0 to 5kms – XZ Inversion

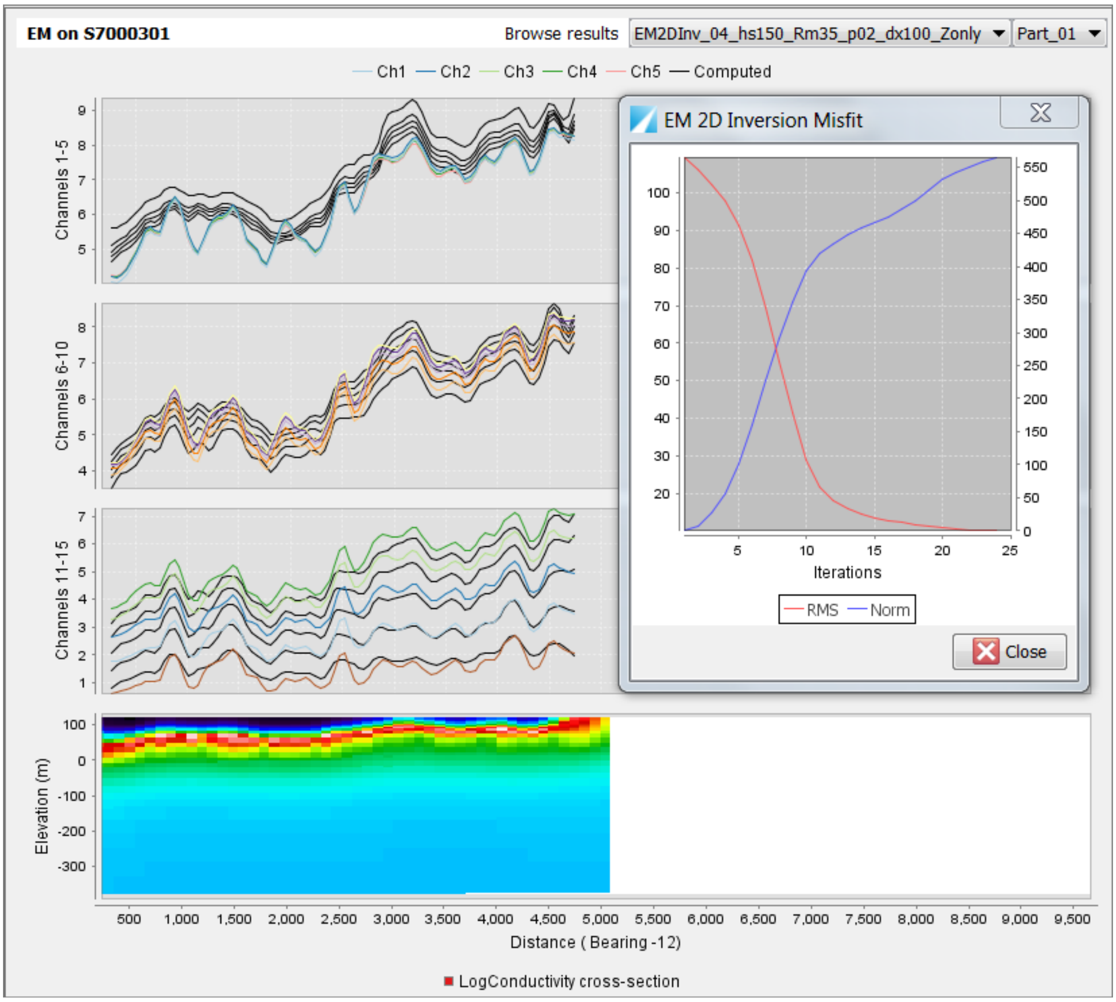

Figure 30. Cariewerloo - Line 7000301 0 to 5kms – Z Inversion

Both X, Z and Z only inversions completed for these lines have been delivered to the Client.

Quinyambie

The inversion of Quinyambie data demonstrated that the currently available data are not of sufficient quality to provide the standard of deliverable which Intrepid believes to be acceptable.

Access to the original survey data in streamed IO format was requested and CGG approval is still in progress.

Inverting the Quinyambie area to the standards required is outside of the scope of this project, and a proposal to revisit this work will follow as part of the Lake Frome ground water geochemical transport 3D geology study.

2D INVERSION DELIVERABLES

The 2.5D inversion results are delivered as follows:

I. **Located Data**

Cariewerloo - TEMPEST

a. A line based ASCII CSV data file containing the observed and predicted profile data for the inverted component channels (X, Z) on the original subsampled fiducials. The ASCII data file is accompanied by a DDF in ASEG GDF format to facilitate import to other compatible software.
The data are delivered in standard db/dT units of fT/sec
AND

b. A line based ASCII CSV data file containing the observed and inversion predicted profile data for the inverted component channels (Z) on the original subsampled fiducials. The ASCII data file is accompanied by a DDF in ASEG GDF format to facilitate import to other compatible software.
The data are delivered in standard db/dT units of fT/sec

c. A 3D ASCII CSV point mesh file containing inversion resistivity and conductivity results (numeric and log base 10 values) in units of ohm metres and milli-Siemens/m (mS/m) located on the original finite element X, Y, Z mesh points. The 3D point mesh also contains the original survey line identifier.

Formats of the 3 deliverables are shown in the tables below.

- Line based ASCII CSV data file containing the observed and inversion predicted profile data for the inverted component channels (X, Z) on the original subsampled fiducials.

TYPE(LINE)
DELIMITER(",")
SKIPRECORDS(1)
LINE INTEGER*4
Iteration INTEGER*4 NOSAVE ALIAS(LineNumber)
Fid REAL*8 ALIAS(Fiducial)
East REAL*8 IsX PROJ(MGA52,GDA94)
North REAL*8 IsY PROJ(MGA52,GDA94)
Ter REAL*8
Alt REAL*8
Pitch REAL*8
MAG REAL*8 NOSAVE
EM_X01 REAL*8
EM_X02 REAL*8
EM_X03 REAL*8
EM_X04 REAL*8
EM_X05 REAL*8
EM_X06 REAL*8
EM_X07 REAL*8
EM_X08 REAL*8
EM_X09 REAL*8
EM_X10 REAL*8
EM_X11 REAL*8
EM_X12 REAL*8
EM_X13 REAL*8
EM_X14 REAL*8

EM_X15 REAL*8
EM_Z01 REAL*8
EM_Z02 REAL*8
EM_Z03 REAL*8
EM_Z04 REAL*8
EM_Z05 REAL*8
EM_Z06 REAL*8
EM_Z07 REAL*8
EM_Z08 REAL*8
EM_Z09 REAL*8
EM_Z10 REAL*8
EM_Z11 REAL*8
EM_Z12 REAL*8
EM_Z13 REAL*8
EM_Z14 REAL*8
EM_Z15 REAL*8
GROUP BY LINE

- Line based ASCII CSV data file containing the observed and inversion predicted profile data for the inverted component channels (X, Z) on the original subsampled fiducials.

TYPE(LINE)
DELIMITER(",")
SKIPRECORDS(1)
LINE INTEGER*4
Iteration INTEGER*4 NOSAVE ALIAS(LineNumber)
Fid REAL*8 ALIAS(Fiducial)
East REAL*8 IsX PROJ(MGA52,GDA94)
North REAL*8 IsY PROJ(MGA52,GDA94)
Ter REAL*8
Alt REAL*8
Pitch REAL*8
MAG REAL*8 NOSAVE
EM_Z01 REAL*8
EM_Z02 REAL*8
EM_Z03 REAL*8
EM_Z04 REAL*8
EM_Z05 REAL*8
EM_Z06 REAL*8
EM_Z07 REAL*8
EM_Z08 REAL*8
EM_Z09 REAL*8
EM_Z10 REAL*8
EM_Z11 REAL*8
EM_Z12 REAL*8
EM_Z13 REAL*8
EM_Z14 REAL*8
EM_Z15 REAL*8
GROUP BY LINE

- 3D ASCII CSV point mesh file containing the inverted resistivity and conductivity results on the original finite element mesh points in units of ohm metres and milli-Siemens/m (mS/m).

TYPE(POINT)
DELIMITER(",")
SKIPRECORDS(1)
LINE INTEGER*4
Location REAL*8 NOSAVE
RL REAL*8
East REAL*8 IsX PROJ(MGA52,GDA94)

North REAL*8 IsY PROJ(MGA52,GDA94)
Resistivity_ohmm REAL*8
Log_Resistivity REAL*8
Conductivity_mS_m REAL*8
Log_Conductivity REAL*8

South Gawler Paris - VTEM

a. A line based ASCII CSV data file containing the observed and inversion predicted profile data for the inverted component channels (X, Z) on the original subsampled fiducials. The ASCII data file is accompanied by a DDF in ASEG GDF format to facilitate import to other compatible software.
The data are delivered in standard db/dT units of pT/sec

b. A 3D ASCII CSV point mesh file containing the inverted resistivity and conductivity results on the original finite element mesh points in units of ohm metres and milli-Siemens/m (mS/m). Log base 10 values are delivered for each also. The 3D point mesh also contains the original survey line identifier.

Formats of the 2 deliverables are shown in the tables below.

- Line based ASCII CSV data file containing the observed and inversion predicted profile data for the inverted component channels (Low and High moment Z) on the original subsampled fiducials.

TYPE(LINE)
DELIMITER(",")
SKIPRECORDS(1)
LINE INTEGER*4
Iteration INTEGER*4 NOSAVE ALIAS(LineNumber)
Fid REAL*8 ALIAS(Fiducial)
East REAL*8 IsX PROJ(MGA52,GDA94)
North REAL*8 IsY PROJ(MGA52,GDA94)
Ter REAL*8
Alt REAL*8
Pitch REAL*8
MAG REAL*8 NOSAVE
EM1_Z01 REAL*8
EM1_Z02 REAL*8
EM1_Z03 REAL*8
EM1_Z04 REAL*8
EM1_Z05 REAL*8
EM1_Z06 REAL*8
EM1_Z07 REAL*8
EM1_Z08 REAL*8
EM1_Z09 REAL*8
EM1_Z10 REAL*8
EM1_Z11 REAL*8
EM1_Z12 REAL*8
EM1_Z13 REAL*8
EM1_Z14 REAL*8
EM1_Z15 REAL*8
EM1_Z16 REAL*8
EM1_Z17 REAL*8
EM1_Z18 REAL*8
EM2_Z01 REAL*8
EM2_Z02 REAL*8
EM2_Z03 REAL*8
EM2_Z04 REAL*8

EM2_Z05 REAL*8
EM2_Z06 REAL*8
EM2_Z07 REAL*8
EM2_Z08 REAL*8
EM2_Z09 REAL*8
EM2_Z10 REAL*8
EM2_Z11 REAL*8
EM2_Z12 REAL*8
EM2_Z13 REAL*8
EM2_Z14 REAL*8
EM2_Z15 REAL*8
EM2_Z16 REAL*8
EM2_Z17 REAL*8
EM2_Z18 REAL*8
EM2_Z19 REAL*8
EM2_Z20 REAL*8
EM2_Z21 REAL*8
EM2_Z22 REAL*8
EM2_Z23 REAL*8
GROUP BY LINE

- 3D ASCII CSV point mesh file containing the inverted resistivity and conductivity results on the original finite element mesh points in units of ohm metres and milli-Siemens/m (mS/m).

TYPE(POINT)
DELIMITER(",")
SKIPRECORDS(1)
LINE INTEGER*4
Location REAL*8 NOSAVE
RL REAL*8
East REAL*8 IsX PROJ(MGA52,GDA94)
North REAL*8 IsY PROJ(MGA52,GDA94)
Resistivity_ohmm REAL*8
Log_Resistivity REAL*8
Conductivity_mS_m REAL*8
Log_Conductivity REAL*8

II. **2D Grids**

For all areas 2D section grids of Log Conductivity were prepared for each line at a resolution of 20x4 metres for X/Y, Z. The choice of X or Y is made on the basis of the dominant Line direction. The grids are supplied in both ERMapper (.ers) and Geotiff format. The Geotiff images have been prepared using a colour lookup table and linear stretch of Log Conductivity values of 0 to 3 mS/m.
The chosen registration allows them the geotiff images to be easily registered on the 2D section which is straight line fit between the start and end of line.

Note: The 2D inversion requires the adoption of a planar finite element mesh. The Inversion section points have not been reprojected back to the original observation points.

III. **GeoModeller Projects**

A GeoModeller project is provided for each of the inverted areas and contains the full inversion results as delivered allowing visualisation in the manner shown in the figures presented as part of the inversion overview in the 2D Inversion Results section above.

The 2D Inversion results for each section have been imported into the GeoModeller mesh grid environment as 3D point sets and as section backdrops for viewing and interpretation in both the 2D and 3D viewers.

Some training is recommended for getting the best value from the data in the software environment.

STAGE 2: STATE-WIDE GRAVITY DATA

EXECUTIVE SUMMARY

Intrepid Geophysics (IG) was contracted by Department of State Development – South Australia (DSD–SA) to:

Reprocess State-Wide gravity data via anisotropic clustering and 3D Fault network generation.

The DSD's state-wide gravity data is being reworked, and was not available for this study. Instead, the newly published GA version was used. The State-wide gravity data was extracted to demonstrate a leading edge full tensor technique for mapping 2D elongated geological features. This is the promised 3D anisotropic clustering, leading to zonal maps of common elongated geology, and targeted structural tilt/strike and dip determinations, directly from the FTG signal. We are left to conclude that as a result of this analysis, standard industry quality measured gradient data are required and that merged national land observation database products are not sufficient to provide quality products. A question related to the information content that can be gleaned from this GA gravity dataset remains as the underlying survey is not a FTG survey. Once the DSD's state-wide gravity data is finalised (at less than 400-meter cell spacing) a follow-on service should be agreed to perform an updated higher resolution full tensor analysis and 3D worm analysis on the DSD state wide data and a real full tensor gravity survey (several available). The 800m GA gridded data just does not carry the signal content required for this technique. An outcome from this study might well be that the case for acquiring measured gravity gradients can finally be stated more clearly in Australia. The move to 3D geology mapping requires more information content in the observations. The comparison of these two gravity data types demonstrates that gravity data acquisition type is a significant factor if more meaningful results wish to be attained. SA does have at least 5 Falcon surveys already, so some sort of a start has been made.

BACKGROUND

Department of State Development- South Australia will supply:

1. No data provided as the aim was to use new South Australian Gravity Grid that is not available yet. Hence, we used the newly distributed Geoscience Australia Gravity data.

GENERAL SCOPE OF GEOINTREPID WORK

Intrepid Geophysics will supply to Department of State Development- South Australia:

STATE-WIDE GRAVITY DATA

2. Reprocessed State-Wide Gravity Data, using the national gravity database onshore complete bouguer anomaly grid July 2016. To maintain data quality and synergies with the processing workflow the data was converted to Lambert Conformal Conic projection maintaining the original 800 meter data resolution. The file format was maintained as the supplied ERS format and was maintained during the workflow.
3. Anisotropic clustering- earthquake clustering to thin the event clouds to best fit 3D fault planes using the anisotropic tensor clustering algorithm.
4. 3D Fault Network Generation from Gravity- extension to wormE. This is multi-scale, and comes with a wide ranging set of new clustering options and dip/strike. Every fault feature has its own report. Aim will be to restrict to a State-wide exercise as a start.
5. All Stage 2 items shall be delivered by 30th September 2016.

WORKFLOW SUMMARY

STATE-WIDE GRAVITY DATA

Two workflows were used in this part of the work - Full Tensor Analysis and an extended 3D worming method. As the full tensor method is largely unknown in Australia, a recap of the method, as demonstrated in Nevada, USA, is supplied by way of a starting point. In that way, what might be expected to work can be demonstrated, and then, if things do not go well, a comment can be drawn on what was still missing.
The 3D extensions to worming are also not well known. These have been developed over nearly 5 years. There are 2 references in conferences papers, and also a case study on the Darling fault in WA, that cover the development and testing.
In both cases, the aim is to move classical potential field geophysics practise forward into the 21st century and come up with more appropriate 3D interpretation methods and make these more routinely available. DSD/GSSA already has access to these methods via the Intrepid beta program, V3.4.

DIP DETERMINATION

Intrepid Geophysics has developed two distinct dip determination methods:

1. Adaptation of the method of McGrath from 1991. In this case the aim was to find a fault escarpment, observe the profile of gravity data at right angles to it and from that derive the dip. Intrepid have modernised and automated this algorithm.
2. Intrepid have invented a dip determination method for full tensor gravity gradiometry as reported at the SEG 2014 workshop. In this case an isotropic clustering is used to map zones of influence of elongated 2D body. At the centre of this cluster and at right angles to the indicated strike, a profile of tensor data in the local coordinate system is used to find the dip by inversion of fitting a an ellipsoid between the tXZ and tZZ components along the profile.

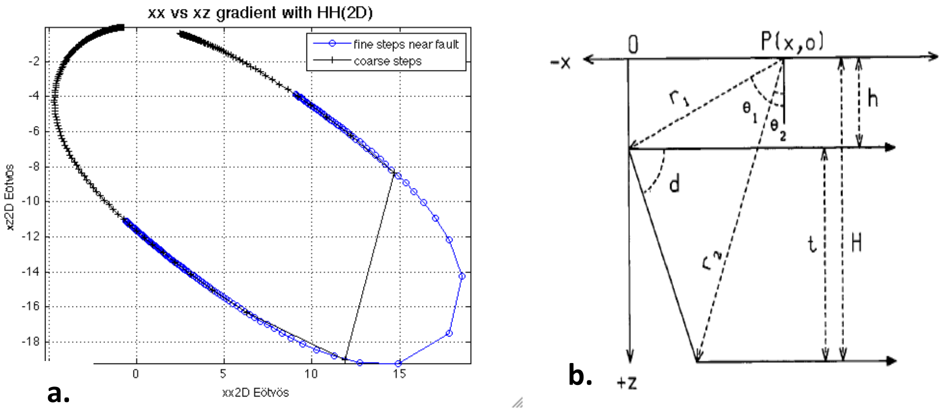

Figure 31. a. An Ellipsoid method for dip. b. McGrath method for dip

FULL TENSOR ANALYSIS

Technology to produce integrated, consistent representations of the gravity field includes levelling, gridding and worming. From this we can use emerging 3D interpretation methods that extract 2D features - 3D fault surfaces such as horst blocks and structural tilts (structural regionals).

An industry case example from Crescent Valley, Nevada Tensor Gridding as follows;

Full Tensor Gravity Gradiometry Survey plus Shuttle Radar Topographic Mission digital terrain model;
The FTG survey includes 91 lines and 22609 tensor samples. The deep blue is an area of Crescent Valley, Nevada (approx. 10km x 15km).

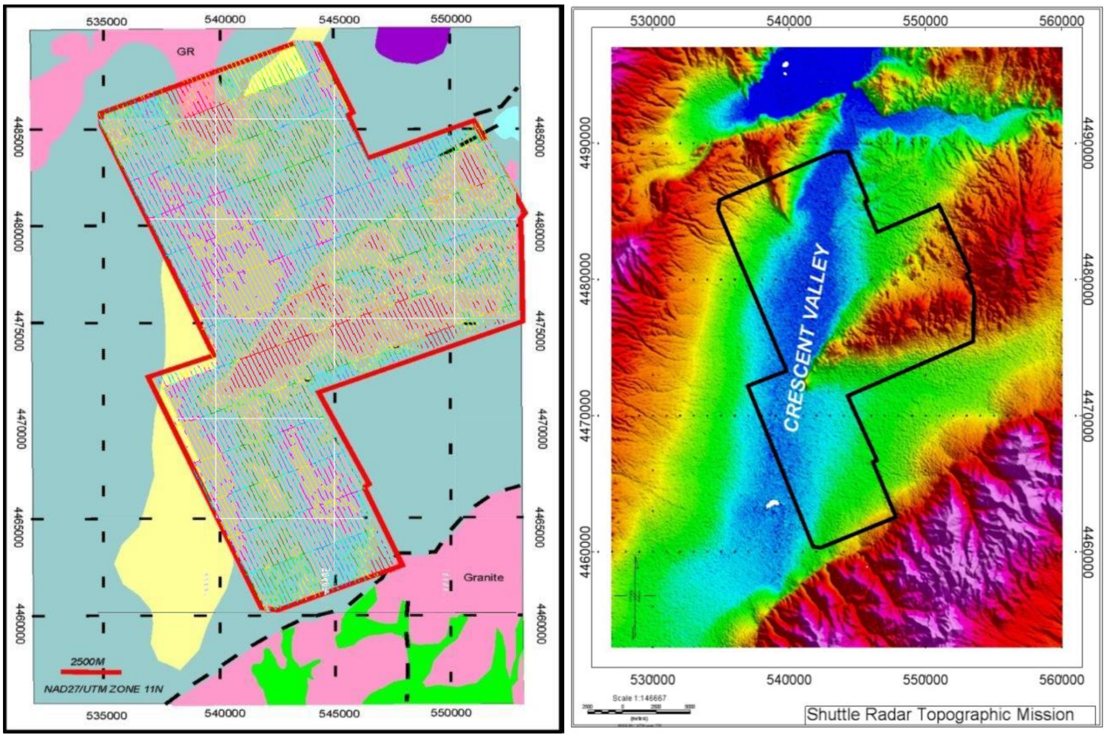

Figure 32. Full Tensor Gravity Gradiometry (left) and Shuttle Radar Topographic Mission Digital Terrain Model (right).

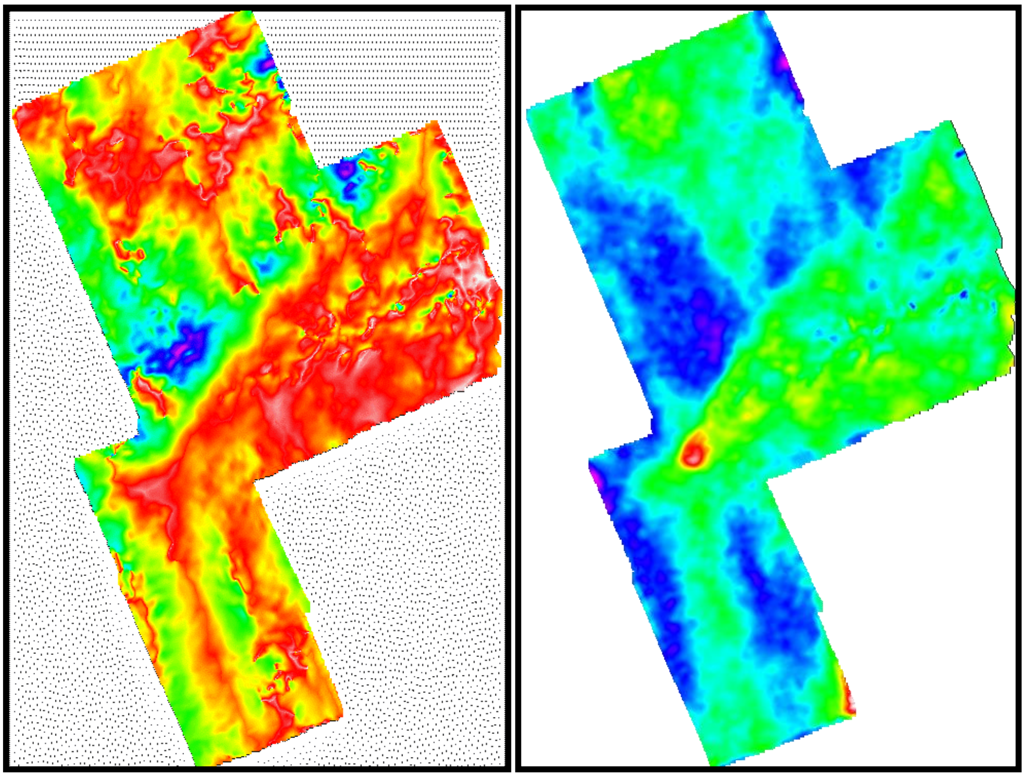

Figure 33. Phase enhancement derived from rotating each tensor to solve the Eigen system (left). The TZZ is shown as a comparison (right).

Field gradient tensor;

$$\mathbf{G} = \begin{pmatrix} g_{xx} & g_{xy} & g_{xz} \\ g_{yx} & g_{yy} & g_{yz} \\ g_{zx} & g_{zy} & g_{zz} \end{pmatrix} = \begin{pmatrix} g_{xx} & g_{xy} & g_{xz} \\ & g_{yy} & g_{yz} \\ & & \end{pmatrix}$$

Figure 34. Field gradient tensor; G is symmetric, trace (G)=0, equals 5 independent qualities.

Properties of the gradient tensor can be understood from a classic principal component analysis problem where the tensor is represented by an ellipse and is simply described by Eigenvalues and Eigenaxes. Eigenaxes are rotated by angle α with respect to reference system (i.e. observer).

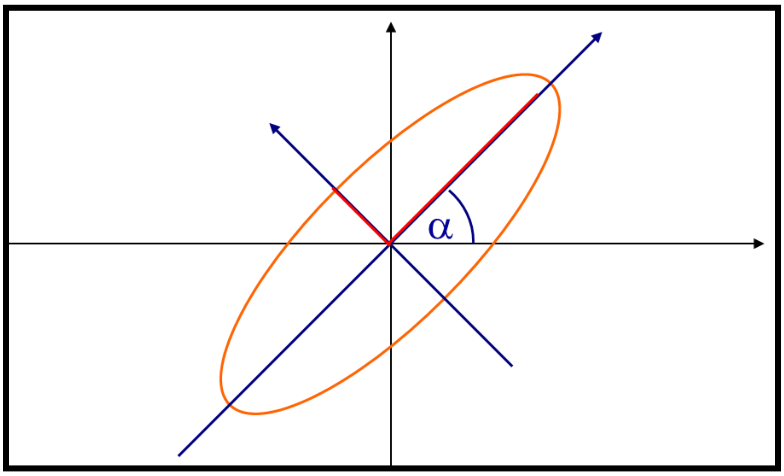

Figure 35. The tensor is represented by an ellipse.

Tensor components; A coordinate system can be found in which the tensor has only diagonal components. Separation of concerns between a structure geology target and the orientation of viewer relative to target. Hence if gyy equals zero, we have a 2D geological structure e.g. fault or contact.

$$\begin{pmatrix} g'_{xx} & & \\ & 0 & \\ & & g'_{zz} \end{pmatrix}$$

So the goal is to define 2D body zones. This is where traditional thinking related to data quality is challenged and a clear distinction between true FTG data and manufactured FTG from traditional acquisition.

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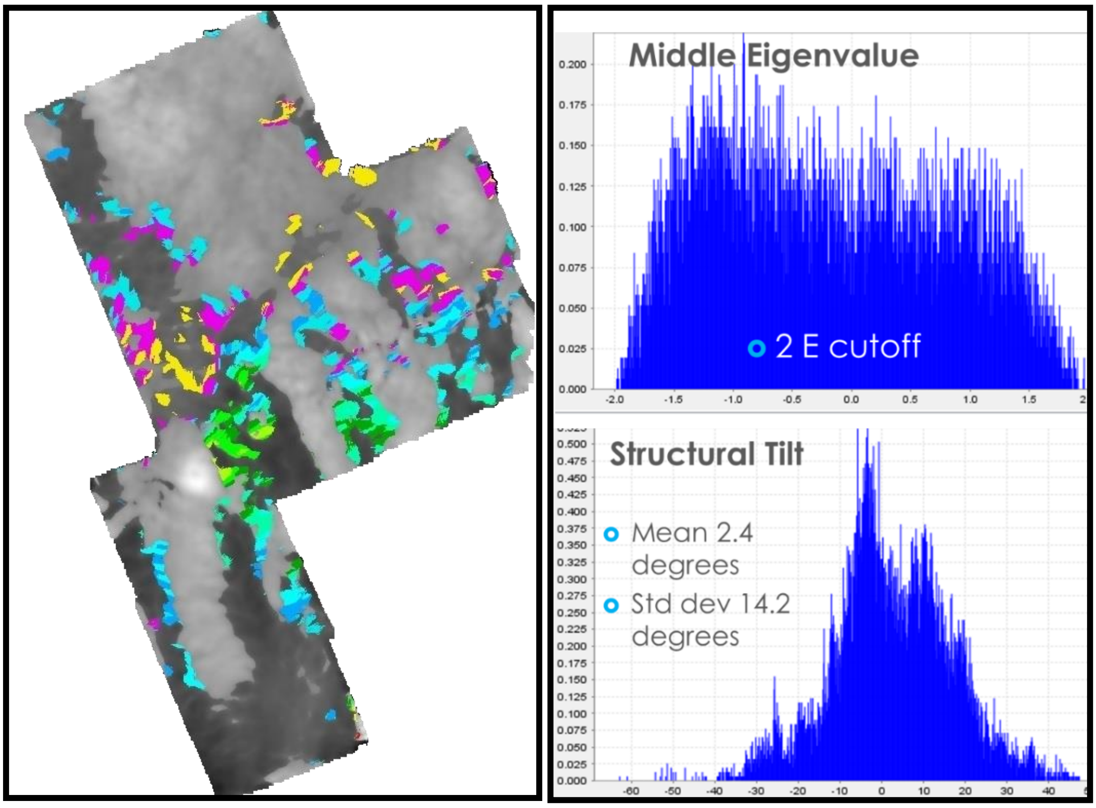

Figure 36. 2D body identification and related statistics of a typical FTG survey.

If the data quality is good, the final step of spatial clustering of the data can be completed.

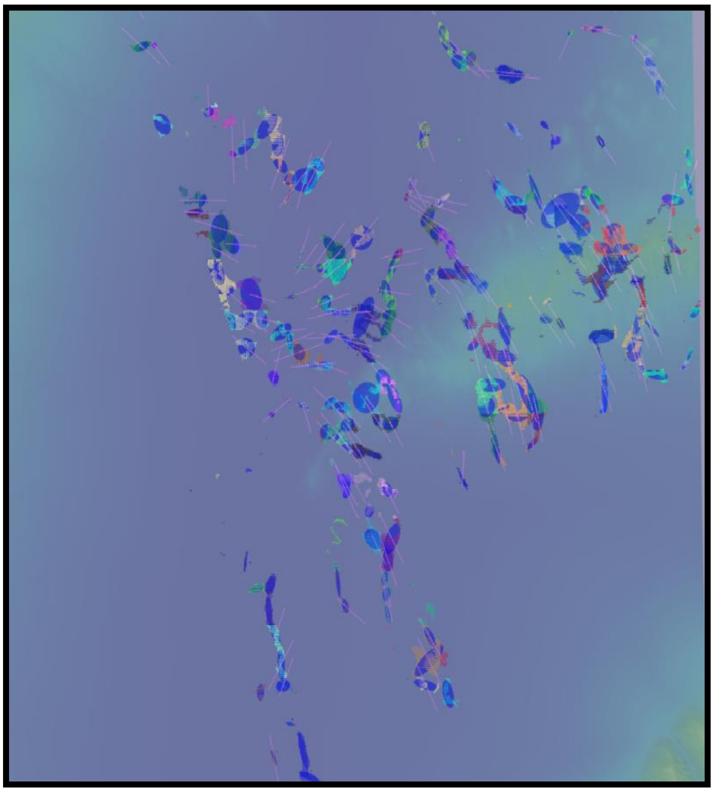

Figure 37. Spatial clustering of the FTG results.

3D WORMS

To generate 3D worms Intrepid can cluster the 2D related worms at each continuation level, starting from the highest upwards continuation level and then search the next lower level for proximal worms with similar strike. To complete this task, the data must support a feature at multiple level and have a minimum length. The number of levels of upward continuation with multi-scale edge picking can be specified during the workflow. During this analysis semi-parallel profiles at an interval along a fault is tested repeated along with the stability of the location, the dip and the tilt estimation along a worm.

X	Y	Depth	dip	strike	tilt
542620.2	4475958	1058.8	73.6	44.2	-5.8
542578.2	4475992	1011.2	72.5	43.3	-4.7
542559.6	4475994	923.2	87.7	41	-3.3
542583.2	4475966	1012.5	76.5	39.8	-4.2
542598.7	4475953	1047.2	77.5	39.8	-4.8
542597.5	4475952	1048.8	77.1	39.5	-4.7
542764.1	4475808	1487.1	-34	25.2	-9.7
542731	4475824	1308.5	-31.3	24.9	-7.9
542641.2	4475847	1089.9	-10.6	18.3	-2.5
542609.5	4475856	993	-8.5	18	-1.2

Table 4. Table showing the results from the workflow. First 6 results are quite acceptable. Last 4 estimates are less reliable- near the edge of the 2D zone.

To then create surfaces, the following is completed.

- Merge and chop short limbs, to match a longer worm at lower levels – allow 2 or more branches at shallower levels
- Estimate the shallowest contact depths.
  - This forms the near surface “contacts”
- Estimate dip one or more times for each feature
- Classify feature as linear/curvy
- Estimate the box that limits the extent of each feature

3D surfaces calculation and render

- Create new feature in the dataset
- Assign the contact data
- Assign the dips as an observation of a foliation, and its direction
- Limit the fault extent with the bounding box
- Calculate geometry using implicit function and sampling algorithm eg marching cube
- Export geometry, with a report on fault network formation parameters

REPROCESSING RESULTS AND CONCLUSIONS

It is not satisfactory to have a geologist spend months interpreting data without detailed records of all assumptions. Consequently, this significant documentation requirement is rarely completed. In addition, many software have limited documentation and are hence contain black-box workflows seen within Leapfrog, Petrel, and Gocad. Geomodeller can provide the exact workflow to reproduce the model result, even from a different user, with different experiences. Accountability of the modelling workflow is an absolute necessity when it defines the future baseline of environmental impacts of resource exploration and development.

Further accountability is defined by the available of a geomodeller modelling API and transparent project files or non binary files, in contrast to Leapfrog or Gocad. Transparency of the processes within the software, XML/ASCII files and a parametric workflow are fundamental in completing meaningful science.

Data: South Australia Grid Description

This Australian national gravity database onshore complete bouguer anomaly grid July 2016 product is derived from observations stored in the Australian National Gravity Database (ANGD) as at February 2016 as well as data from the 2013 New South Wales Riverina gravity survey. Out of the approximately 1.8 million gravity observations 1,371,998 gravity stations in the ANGD together with 19,558 stations from the Riverina survey were used to generate this grid. The grid shows complete Bouguer anomalies over onshore continental Australia. The data used in this grid has been acquired by the Commonwealth, State and Territory governments, the mining and exploration industry, universities and research organisations from the 1940s to the present day.

Continental Australia has a base coverage of 11 kilometres, with South Australia, Tasmania and part of New South Wales covered with gravity stations at a spacing of 7 kilometres. Victoria has station coverage of approximately 1.5 kilometres. Federal, State and Territory government initiatives have systematically infilled at a station spacing of 2 to 4 kilometres to improve coverage in areas of scientific or economic interest. Other areas of detailed coverage have been surveyed by private companies for exploration purposes. Only open file data held in the ANGD at February 2016 were used in the creation of the grid. The 2013 Riverina survey was added to the gridding process as this survey was not in the ANGD at the time.

The 2009 Bathymetry and Topography grid of Australia (Whiteway, 2009) and the 3 second Shuttle Radar Topography Mission (SRTM) Smoothed Digital Elevation Model (DEM-S) (Gallant et al., 2011) were used as the elevation models to calculate the Bullard C terrain corrections. These terrain corrections have been calculated using software from Intrepid Geophysics(1). The Intrepid algorithm utilises concentric rings subdivided into cells (Direen, 2001). The SRTM was used for the onshore terrain correction using five rings with a starting cell size of 90 metres resulting in a final radius of 92.2 kilometres. Four rings were used for the offshore terrain correction with a starting cell size of 250 m and a final radius of 64.0 km. The densities of materials used in the terrain corrections were 2670 kg/m^3 for land, 2200 kg/m^3 for marine sediments and 1027 kg/m^3 for sea water. The offshore and onshore terrain corrections were combined and applied to the spherical cap Bouguer anomalies used in the Bouguer Gravity Anomaly Grid of Onshore Australia 2016 to produce the complete Bouguer anomaly values shown in this grid.

The parameters of the geodetic grid are:

Grid spacing : 0.008333 degree (approximately 800 m)
Projection : Rectangular in latitude and longitude
Datum : GDA94
Scaling : Nil. Values are in decimal units (μms^{-2})
Null value : -99999.00
Data accuracy : 5 μms^{-2}, maximum error 100 μms^{-2} onshore
Data precision : 1 μms^{-2}

WORKFLOW SUMMARY: FULL TENSOR ANALYSIS

1. Input the national gravity database onshore complete bouguer anomaly grid July 2016.
2. Pre FFT grid conditioning including the conversion from mGal to Eotvos.
3. Application of the Filter “Tensor Query.”
4. Post grid restoration.
5. Output grid datasets For Tz to (Txx, Tyy, Tzz, Txy, Tyz, and Tzx).
6. Grid calculation using Tensor parts for all components.
7. Grid convolution;
   a. Purpose: Solve Principal Components of Full Tensor Only retain those solutions where a 2D body is indicated (Falcon not supported)
   b. Convolve a 3*5 window over the tensor gravity gradients grid, In each window, solve the 15 Principal components. If a minimum number are shown to have Gyy near 0.0, capture a points dataset of solved EigenSystem. This indicates areas of isolated elongated geology.
   c. The tyy noise floor of 2 EOTVOS units.
   d. Minimum local anomaly of 10 EOTVOS units.
   e. Minimum number of samples 10 in a convolution window that indicate a 2D body.

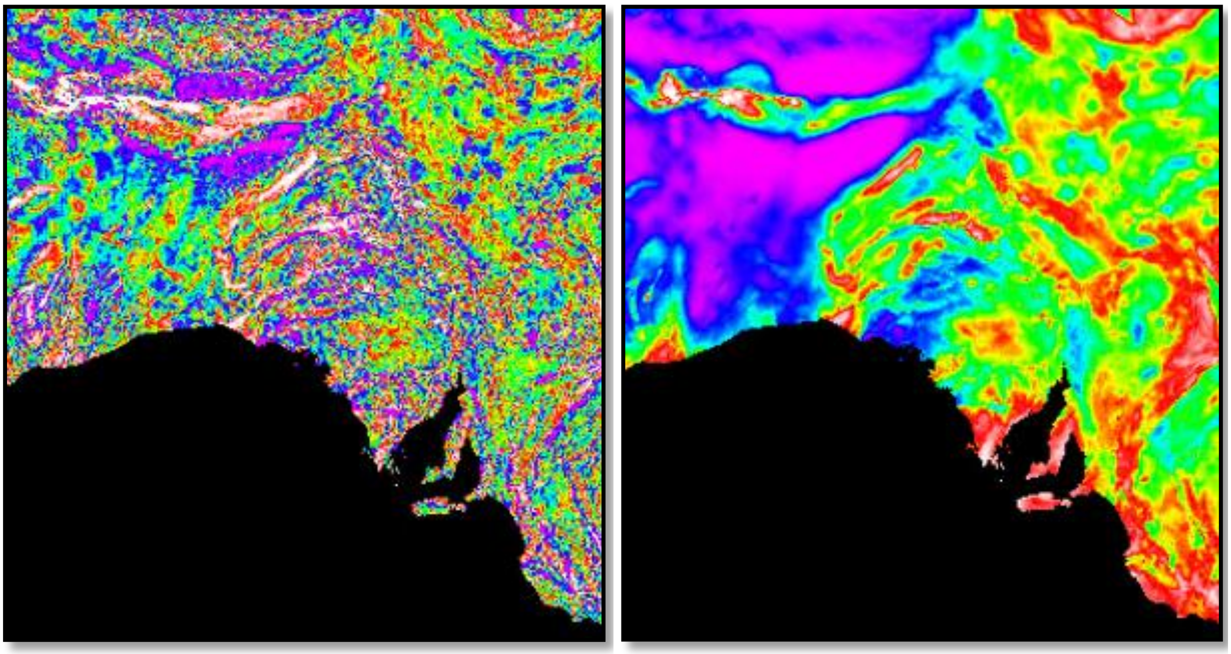

Figure 38. Input gravity data (left). The TZZ is shown as a comparison (right).

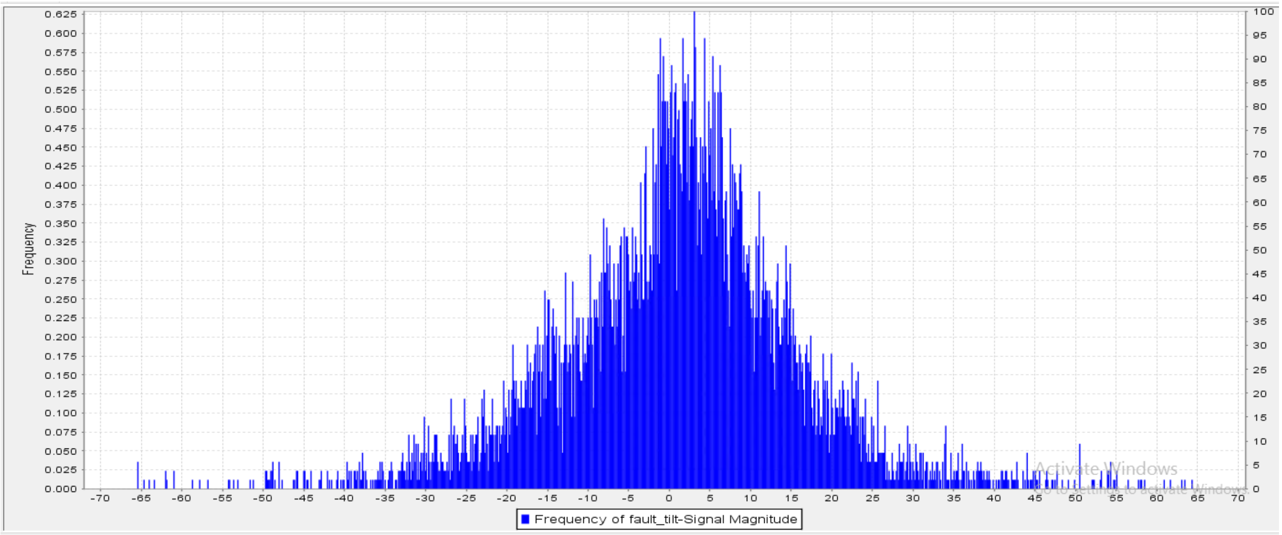

Figure 39. Regional tilt histogram, for the 2D body indicated sub-distribution.

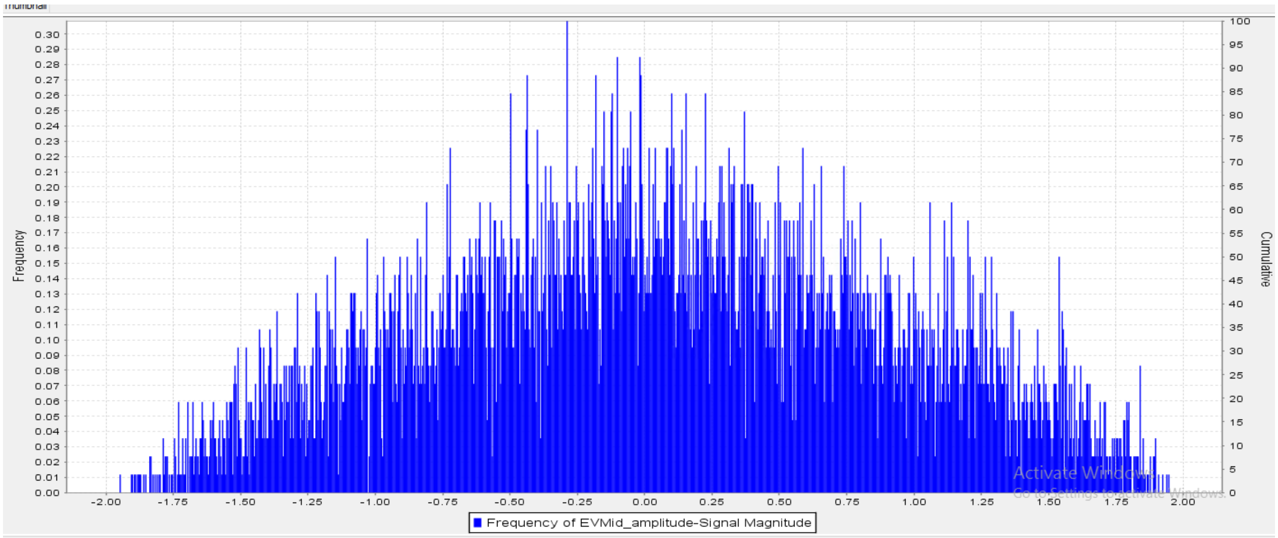

Figure 40. Two Eigen Value cut-off distribution for SA, picking out those zones where a 2D elongated body is indicated.

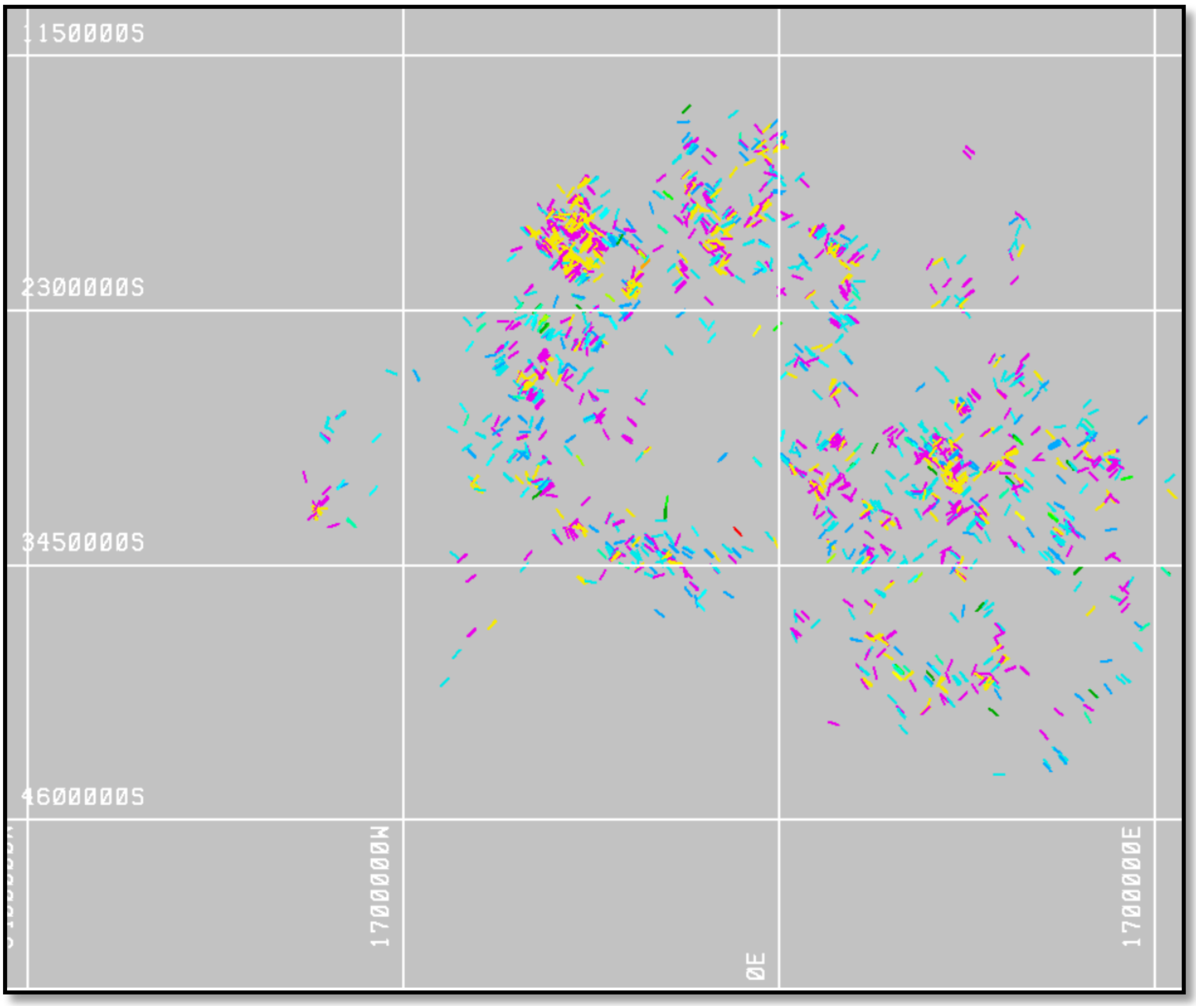

Figure 41.Image of the full tensor analysis for the whole of Australia. Clearly there is not enough real data that fore fills the minimum local anomaly of 10 EOTVOS units,

particularly for SA. Interestingly, there are dominant NE-SW, NW-SE biases in the strikes of the indicated 2D elongated bodies.

DATA QUALITY AND INFORMATION CONTENT

With all cases of integrated geophysics and geology a key consideration is how many rotational degrees of freedom are measured within the data. Due consideration of noise to data issues and do the results reflect geological surface orientations such as faults, bedding, and contacts, intrusions.

Significant care must be taken to manage the historical data and clearly separate and isolate gradiometers from aircraft motions. The reason for this is that angular motion is greatly attenuated across all frequencies by using a nested gimbal arrangement with active rotational isolation and pointing. The hardware used for optimized outcomes should include stabilize and point gradiometer instruments tuned to the desired survey frame. The latter maintains the inner gimbal frame alignment with ENU or NED survey frame (essentially an integrated INS/GPS navigation solution using the platform inertial sensors).

With quality FTG data (not traditional vertical gravity data) the following results should be attained.

1. Full gravity gradient tensors tell us more about near surface geology
    a. Strike of uncluttered faults/contacts
    b. Average tilt of a cluster of observations
2. Profile sampling, across the 2D feature
    a. Dip estimate using least squares ellipse fitting
    b. Works if well positioned (cluster method 25% of time)
    c. Hit and mostly miss, (worms method 12% of time)
3. Benefits are explicit 3D surfaces, unambiguous, with audit trail, independent of seismic.
4. Mainly applicable in top kilometre

EXTENDED 3D WORMING METHOD

The now standard 2D worming technology is first applied to the complete Bouguer dataset.

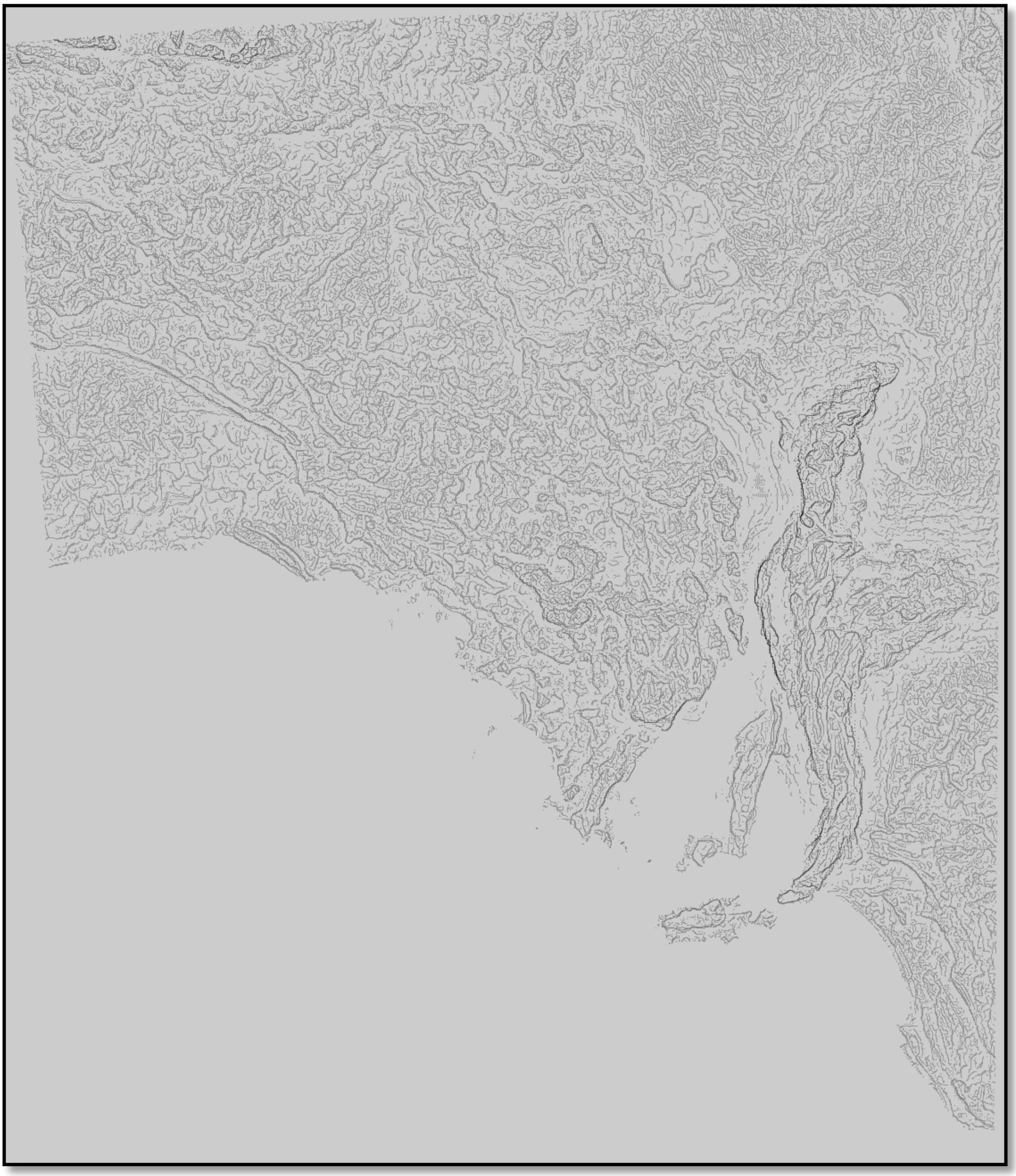

Figure 42. Image of SA 2D worms, with the darker shades indicating the strength and significance of the fault/contact signal, as measured by gravity.

The extensions into 3D are extensive (see FitzGerald, D., Milligan, P., ASEG 2013).

With the current shift to 3D geology modelling, issues arise to improve/generalise the worming technology to produce 3D contacts that can be interpreted, particularly the sub-set that indicates a primary fault network.

The new method allows the gathering of related worms to rapidly compute a consistent 3D fault network by linking the dominant 30 km deep features back to the surface.

These can be more readily understood, if described by workflow steps-.

- Cluster into a new data structure the 2D related worms at each continuation level
- Start from highest upwards continuation level.
- Search next lower level for proximal worms with similar strike.
- Require multiple levels of support in the original worm upward levels
- Merge and chop short limbs, to match a longer worm at lower levels – allow 2 or more at shallower levels
- Estimate the shallowest contact depths.
- Estimate dip at multiple points of indicated strong worm feature (McGrath method)
- Thin the interface feature points by a factor of 5
- Estimate the box that limits the extents
- Export an ASCII CSV file, with a report on fault network formation parameters
- Import into GeoModeller
- Create new faults in the project
- Assign the contact data
- Assign the dip as an observation of a foliation
- Limit the fault extent with the bounding box
- Calculate the 3D limited fault shapes
- Or
- Within the WormE tool, there is provision for some the 3D visualization
- Calculate the limited faults as implicit surfaces
- Export to VTK, *.vtp shapes
-

BRINGING THE RESULTS INTO 3D GEOLOGY CONTEXT

The tool of choice for us is Geomodeller, as it has an inherent ability to manage structural geology pseudo field observations and turn these into limited fault 3D surfaces, with extensive properties and characteristics. This is done via the co-kriging implicit surface/volume technology first developed by Jean Paul Chiles, of Geostatistics fame.

After the import steps, the 98 faults/contacts identified so far (well over 200 successful fault dip determinations, a very good outcome), using the GA gravity dataset, are ready for critical examination and discussions.

The first step is to verify the registration of the interface and foliation data with the original "worms". This is shown successfully in Figure 43. An apparent lack of solutions from the 2 prominent Musgrave faults is a concern, as these features are very obvious in the starting datasets.
The bounding faults from Spencer gulf seem more prominent than in the initial worms as well.

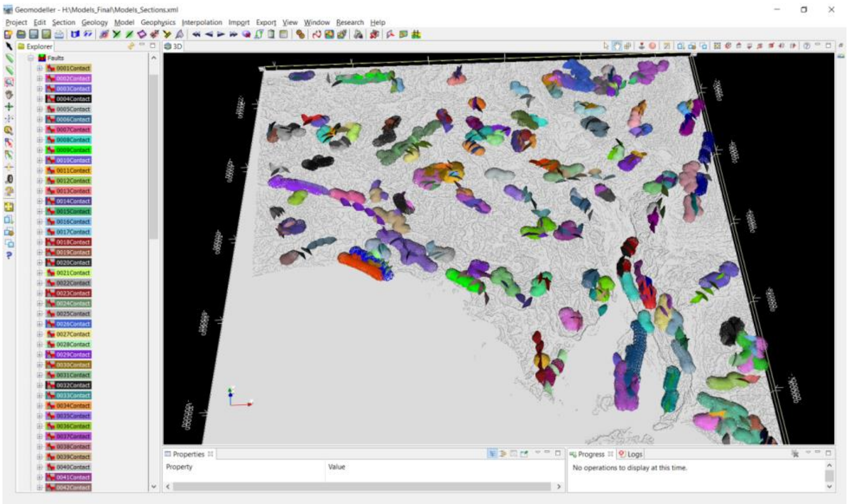

Figure 43. Image of SA 3D worms, showing where dips have been determined. On the left hand side in the explorer tree view, 98 candidate fault contacts are already automatically defined.

FURTHER INTERPRETATION & CALIBRATION

The work to this point fulfils the initial contracted requirements, but we have continued some way into the task of independent support from seismic and other sources, for the gravity derived 3D fault network.

The seismic line locations are available for some of the state, in the Lake Frome area, and while none of the faults there rank as strongly as elsewhere, we have started the process of creating sections along the seismic lines with a view to more detailed checking and calibration. It was always envisaged, that the velocity models used to depth convert the seismic data, might themselves benefit from information gleaned from gravity, as this is now pretty standard in high end oil reservoir/prospect work flows.

Another task is the one of merging independently determined parts of what might be seen as the same primary structure. This is done manually in the 3D environment.

There is no point doing this until there is sufficient confidence in the set of solutions for the primary fault network, if one is wanting to do a full regional study. The Musgraves seem to be a bit under represented still in the processing to date – perhaps another round of tuning can bring out more results in that part of the state, especially as there are at least 2 very prominent boundary faults indicated in the primary "worm" result.

STATE-WIDE GRAVITY DATA DELIVERABLES

The following data products have been supplied:

- The reprojected and subset Complete Bouguer input grid, sourced from GA
- The 2D elongated Intrepid points database, with the results from the Eigensystem analysis. ~ 8000 points
- The standard set of Intrepid wormE outputs, including the points, worms and linears, in both ASCII and Intrepid database form.
- The extended outputs from the 3D strike/dip determinations for the primary faults indicated in the worming analysis. These outputs are 3 ASCII csv files, with

clear systematic columns, indicating bunches of foliation determinations , interface points and approximate discrete or limited fault extents.
- A 3D geomodeller project with the alternate method of determining 3D strikes dips and discrete parts of the SA fault network. This is built in a Lambert Conic projection with the fault network populated via a standard import workflow prior to further interpretation.
- An FTG grid for SA derived from the GA dataset. This should be of interest as it opens the way to more novel interpretation methods in an easily accessible manner using the now standard methods available within Intrepid.

The reprocessing of State-wide gravity data, derived from the GA grid demonstrates that the full tensor analysis requires a higher standard industry quality data and that merged national database products are not sufficient to provide quality products. This result will become more meaningful when compared to the second phase of this work focused on DSD gravity products. Several observations have been made.
- Approximately 8,000 Eigenvalue solution points were generated as part of this workflow.
- These points contain estimates of tilt, strike and dip of local features.
- These points would not cluster up to the necessary standard to enable a satisfactory set of dip determinations.
- A grid /data resolution of less than 800 meters is required to generate viable clusters if the survey is not an FTG survey. A DSD resolution of approximately 400 metres may yield better results.
- Several histograms show unusual distributions that would not be seen in a real FTG survey.
- The Intrepid software is capable of completing this analysis for large datasets. In this case the whole of Australia was included.
- Phase two of this work will require DSD gravity data delivery and preferably an open file true FTG survey.
- Manufactured/calculated FTG pseudo-surveys have real limitations with regards to the quality of the results. Low quality input means a limited result.

REFERENCES

FitzGerald, D., and P. Milligan, 2013, Defining a deep fault network for Australia, using 3D "worming": 83rd SEG Annual meeting, Expanded Abstracts.

FitzGerald, D., and H. Holstein, 2014, Structural geology observations derived from full tensor gravity gradiometry over rift systems*:* 84th SEG Annual meeting, Expanded Abstracts.

McGrath, P. H., 1991, Dip and depth extent of density boundaries using horizontal derivatives of upward continued gravity data: Geophysics, v. 56, no. 10, 1533-1542.

APPENDIX 2. DATA DOWNLOAD URL

http://dsd-gdp.s3.amazonaws.com/GDP00070.zip