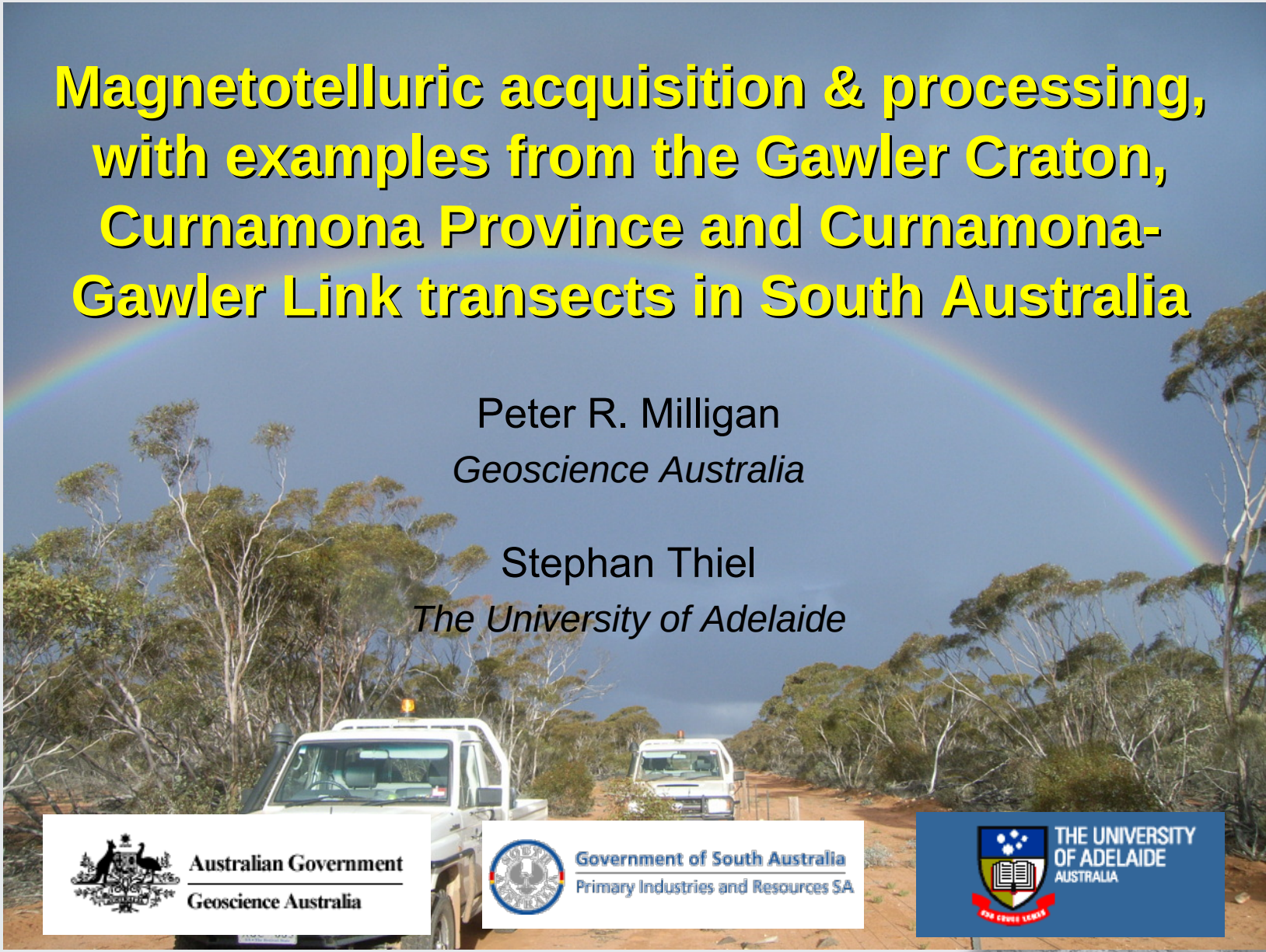
Magnetotelluric acquisition & processing, with examples from the Gawler Craton, Curnamona Province and Curnamona-Gawler Link transects in South Australia

Peter R. Milligan
Geoscience Australia

Stephan Thiel
The University of Adelaide



Australian Government
Geoscience Australia

Government of South Australia
Primary Industries and Resources SA

THE UNIVERSITY OF ADELAIDE
AUSTRALIA

Acknowledgements

Graham Heinson, Goran Boren, Jonathon Ross, Hamish Adam — *The University of Adelaide*

Jenny Maher, Jingming Duan, Tanya Fomin, Steven Curnow — *Geoscience Australia*

Tania Dhu, Emily Craven — *Primary Industries and Resources South Australia*

Ted Lilley — *Australian National University*

- Australian Government Onshore Energy Security Program for funding
- AuScope (NCRIS) for access to Magnetotelluric equipment
- Seismic Acquisition & Processing Project of Geoscience Australia
- Geodynamic Framework Project of Geoscience Australia
- School of Earth & Environmental Sciences, University of Adelaide
- Primary Industries & Resources South Australia (PIRSA) Minerals
- Quantec Geoscience (via Terrex Seismic)

Contents

1. Introduction
2. MT Theory
3. Field data acquisition
4. Processing
5. Analysis
6. Modelling
7. Conclusions

1. Introduction

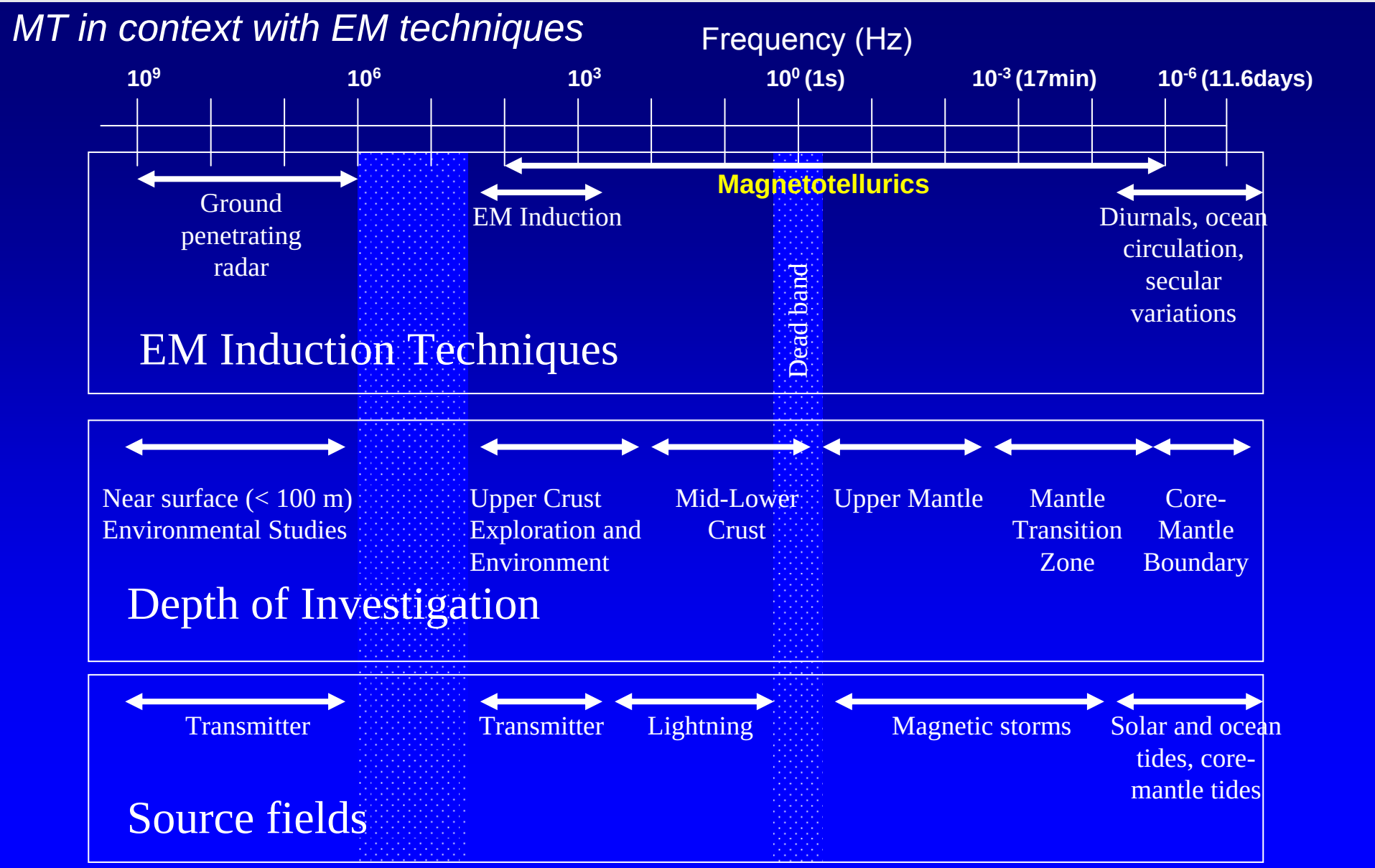
The Magnetotelluric Method (MT) records time variations of Earth's magnetic and electric fields over a wide frequency range at arrays of ground sites to measure Earth electrical resistivity (conductivity) structure with depth (near-surface to core/mantle boundary)

- Magnetic field variations are the source signals
- Electric field variations are the response signals
- Ratio of Electric to Magnetic provides resistivity measurement

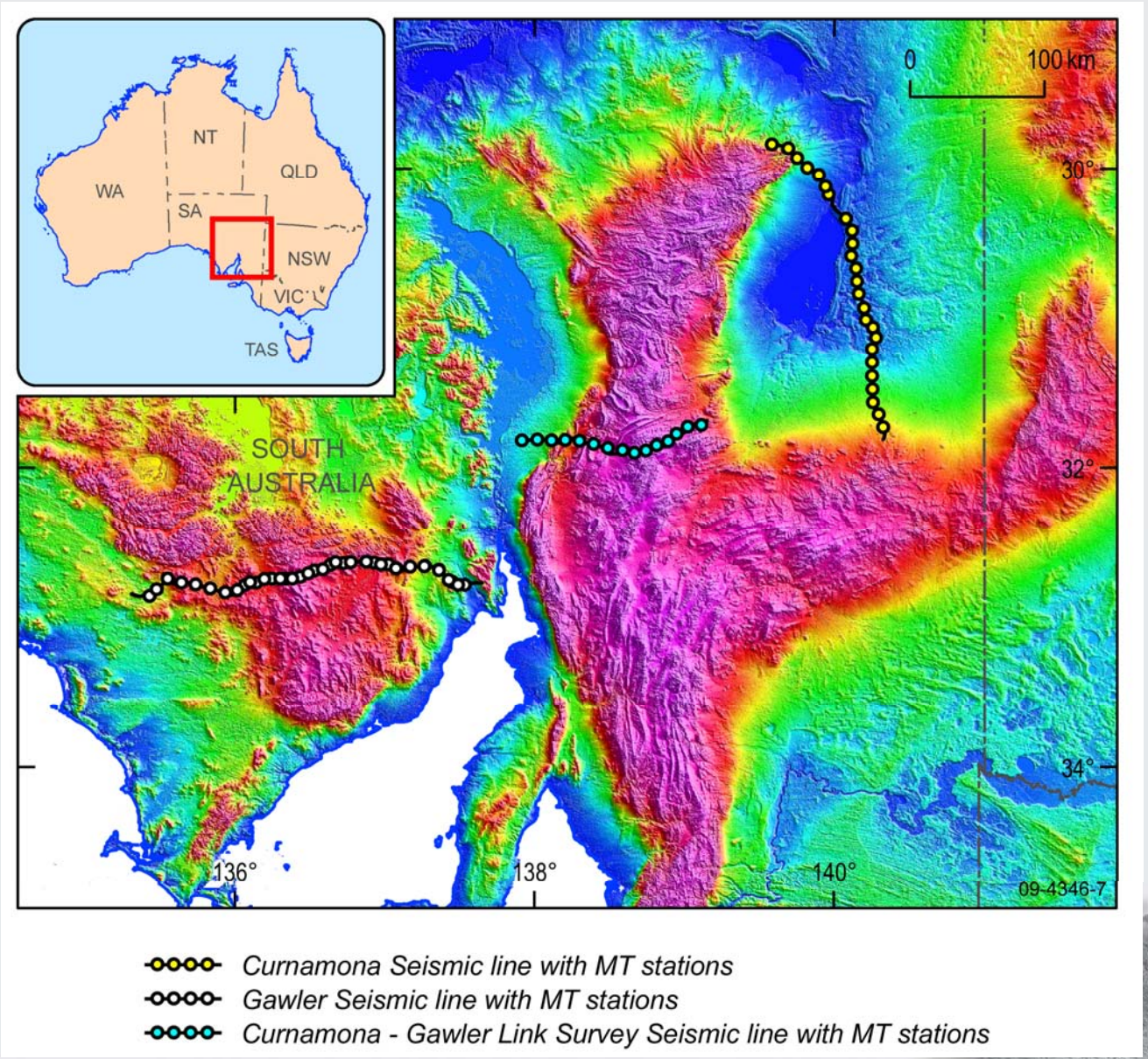
- Complimentary Earth physical property measurement to deep seismic imaging
- Excellent at mapping sedimentary basins

Three collaborative projects along seismic transects in South Australia

1. Introduction



1. Introduction



1. Introduction

GA collaborative SA projects

Survey specifications

Gawler — AuScope (University of Adelaide):

Long-period (LP) (3-component Fluxgate, sampling at 10 Hz, bandwidth .1 to .0001 Hz)

Broadband (BB) (2-component Lemi induction coils, sampling at 250 Hz, bandwidth 100 to .001 Hz)

12 Long-period sites (20 km spacing) & 24 Broadband sites (10 km spacing) in 2008

16 Broadband sites in 2009, with some repeat and some infill to 5 km

50 m dipole separation

Curnamona-Gawler Link — AuScope (PIRSA):

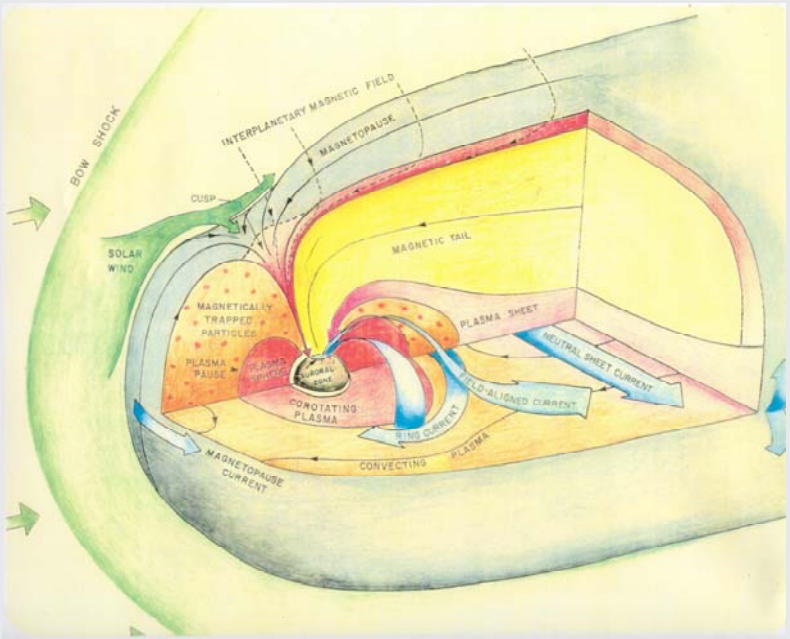
15 LP & BB sites, 10 km spacing, 50 m dipole separation in 2009

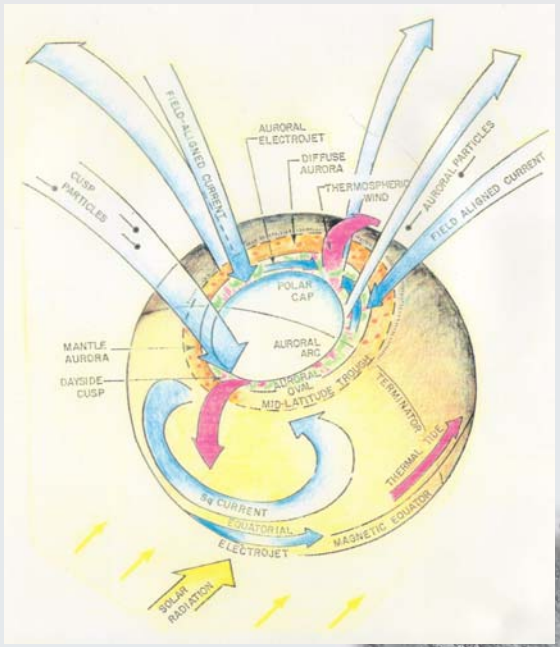
Curnamona — Quantec Geoscience (through Terrex Seismic) (Geoscience Australia): Quantec REF-TEK system

3-component BB, 25 BB sites, 10 km spacing, 100 m dipole separation, bandwidth 250 to .001 Hz, in 2008 - 2009

2. MT Theory

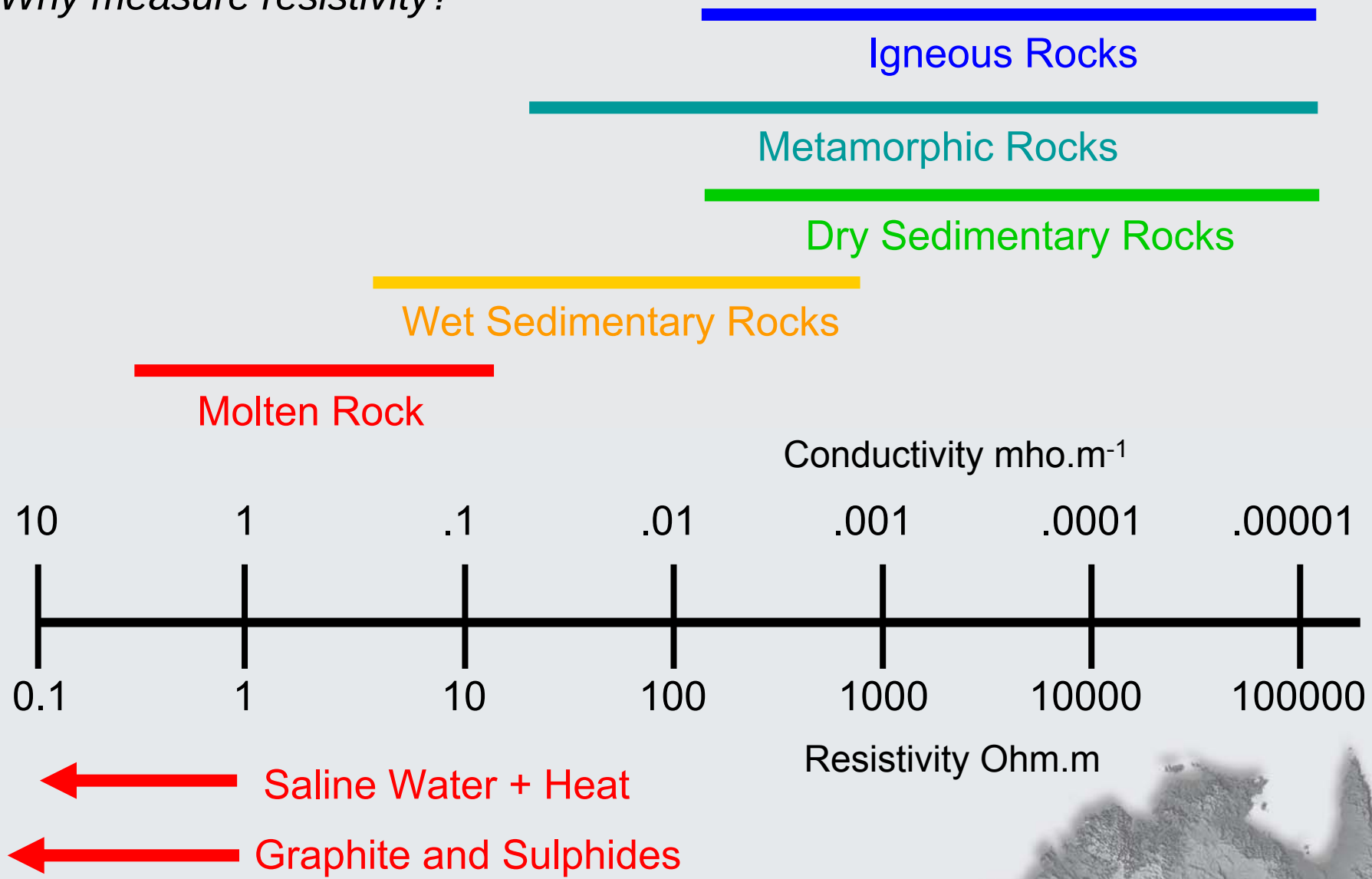
- Passive surface measurement of the Earth's natural electric (E) and magnetic (H) fields
- Assume planar horizontal magnetic source field (reasonable assumption in mid-latitudes, far from external source regions)
- This is a diffusive process, the physics based on Maxwell's equations of electromagnetic induction
- Measure time changes of E and H at arrays of sites
- Frequency range 10 KHz to .0001 Hz (0.0001 s to 10000 s)
- Ratio of E / H used to derive resistivity structure of sub-surface





2. MT Theory

Why measure resistivity?

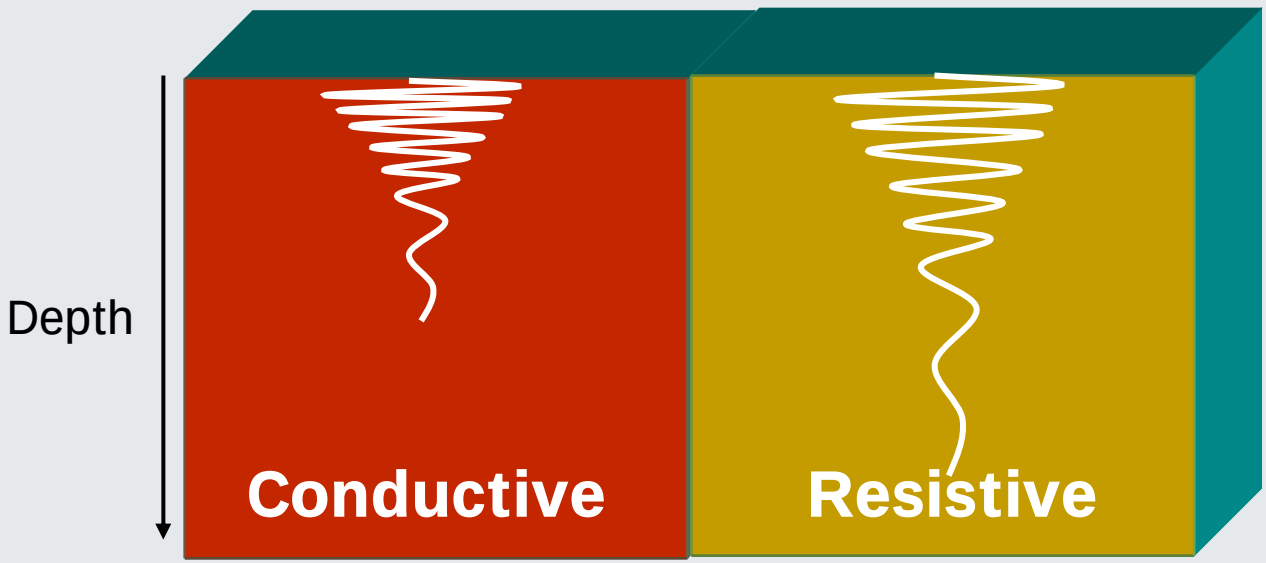


2. MT Theory

Depth of Investigation – Skin Depth

3 concepts:

1. Low frequencies penetrate deeper than high frequencies
2. High frequencies image the near-surface
3. Signals penetrate further in resistive material



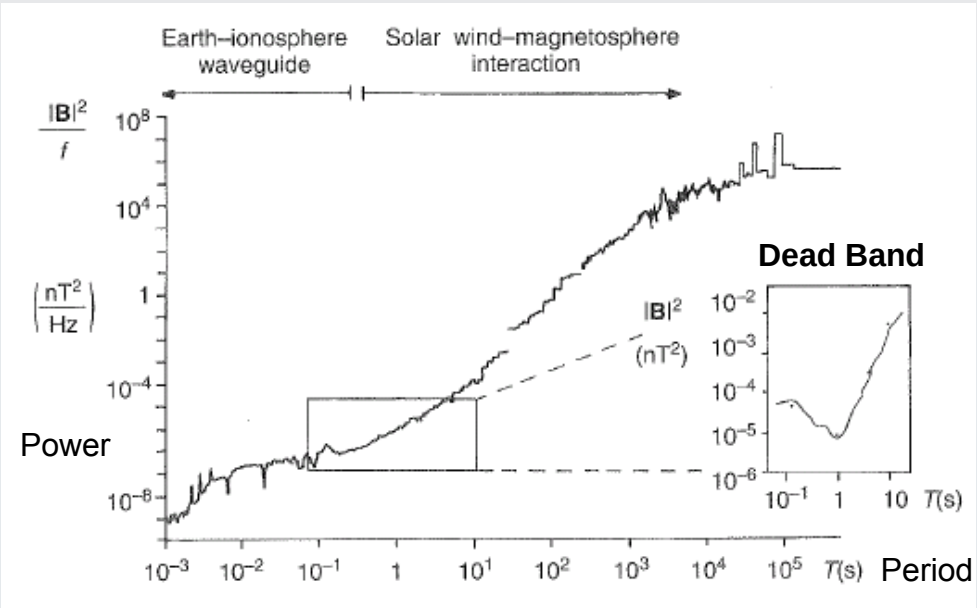
2. MT Theory

Source fields

High frequencies >1 Hz from Spherics, generated by world-wide thunderstorms

Low frequencies <1 Hz from Earth's magnetic field variations

- solar wind interactions
- variations with periods from seconds, minutes, hours, days to yearly cycles (eg. micropulsations, bays, storms)



Dead Band

10^{1} to 10^{-1} Hz

0.1 to 10 s

Little energy

Skin depths 1.5 to 15 km, upper-middle crust

2. MT Theory

Impedance tensor

Measure two orthogonal components of electric field and two orthogonal components of magnetic field (usually north, x and east, y).

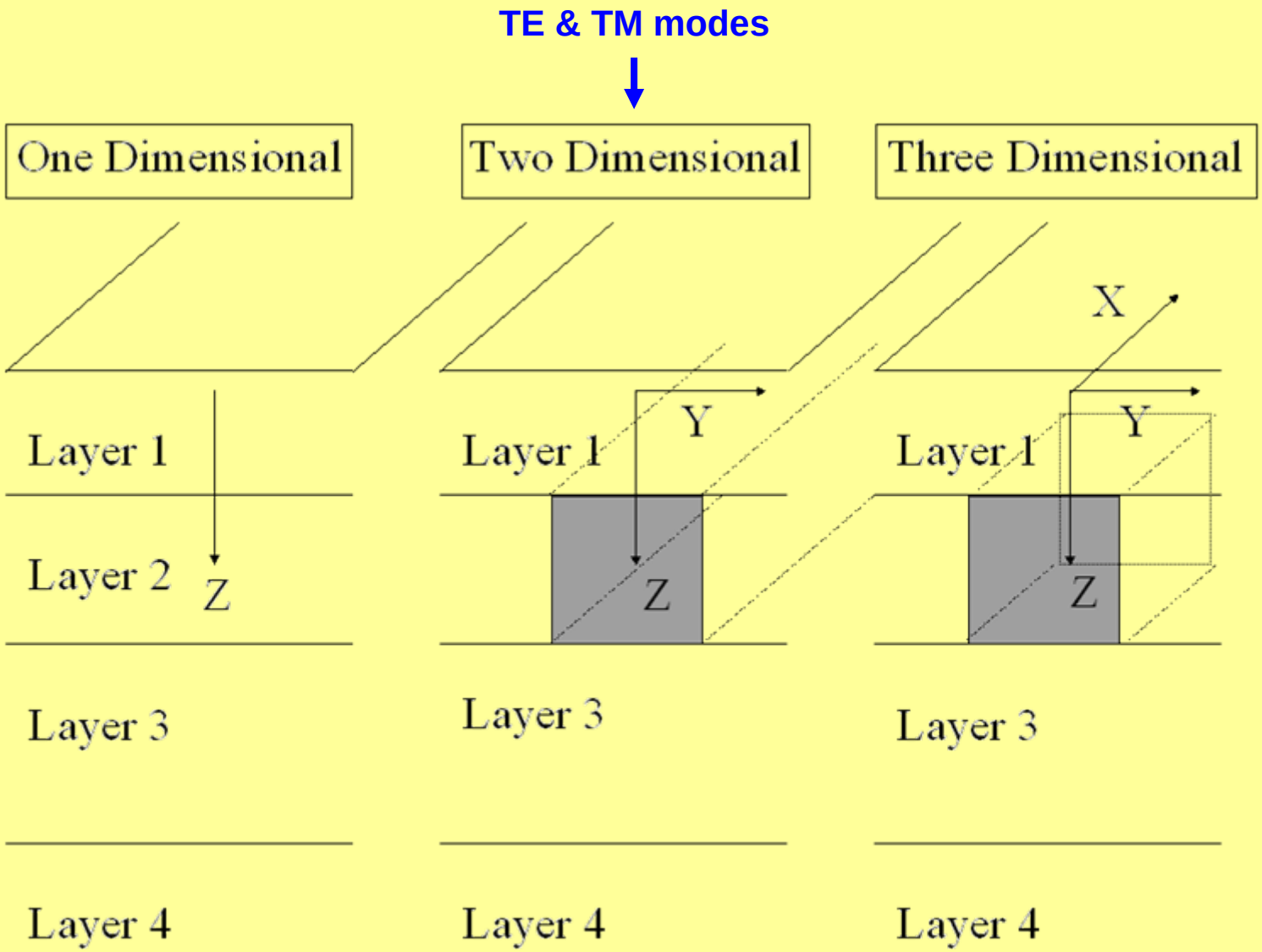
Apparent resistivity is determined from their ratios.

The magnetotelluric impedance tensor is defined as:

$$\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix} = \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

The impedance tensor transfer function values Z are complex values of frequency.

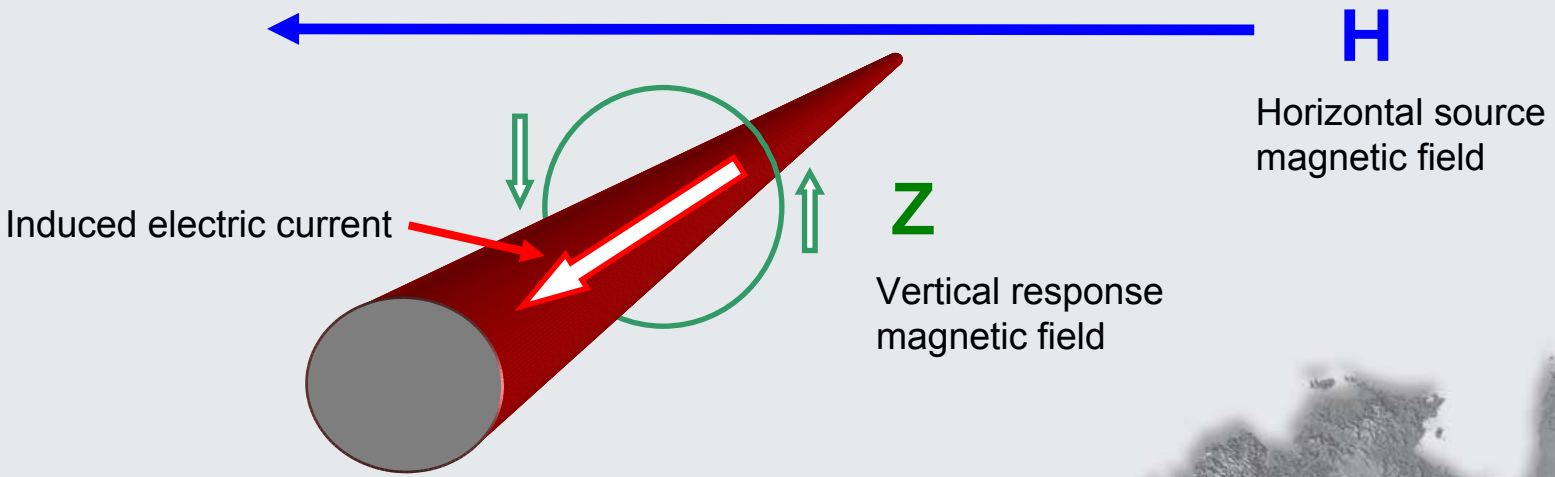
2. MT Theory


TE & TM modes
One Dimensional
Two Dimensional
Three Dimensional
Layer 1
Layer 2
Z
Layer 3
Layer 4
Layer 1
Y
Z
Layer 3
Layer 4
X
Layer 1
Y
Z
Layer 3
Layer 4

2. MT Theory

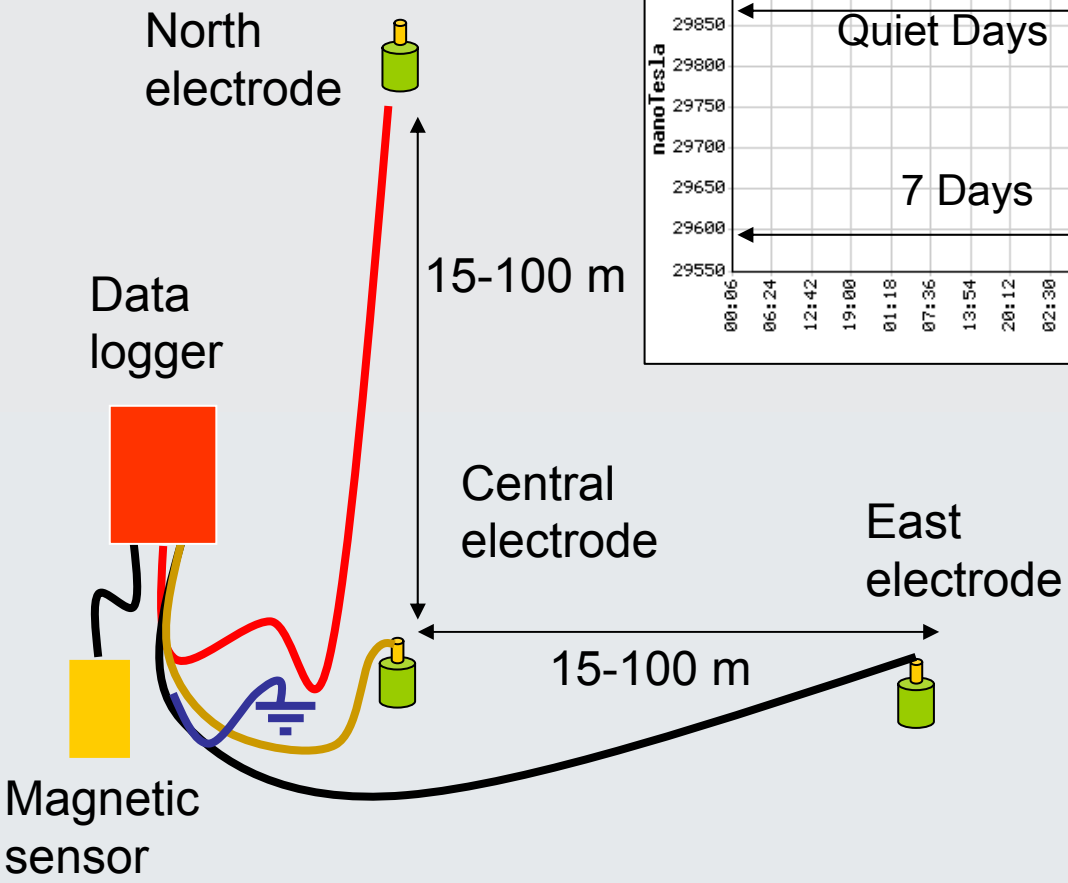
Geomagnetic Depth Sounding – Parkinson Arrows

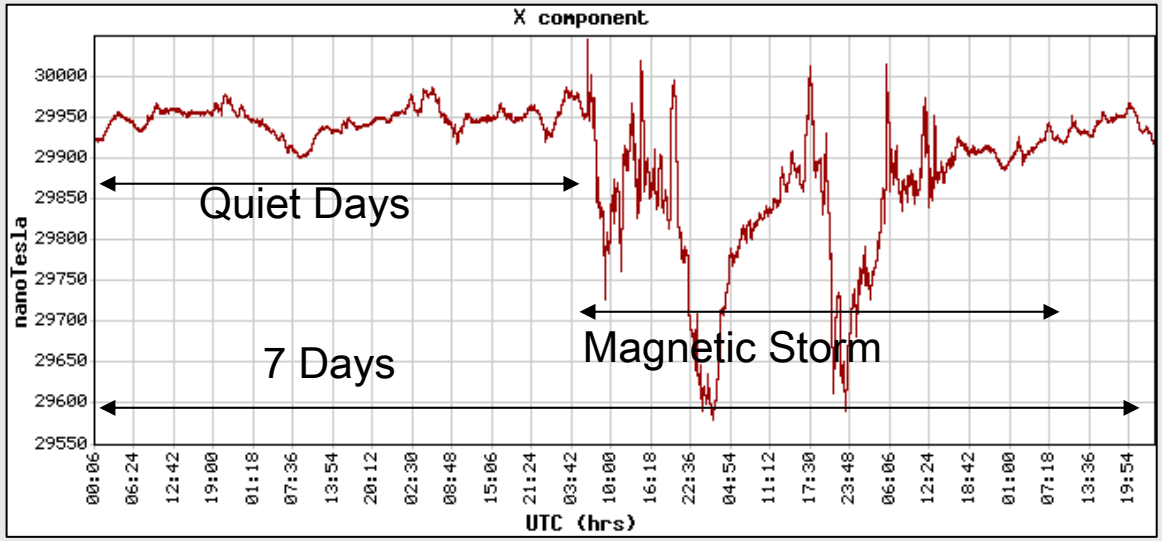
- Geomagnetic depth sounding relates vertical magnetic field variations to horizontal magnetic field variations
- Ratios of Z to H are complex functions of period
- Ratio is always zero for a 1D Earth, so ratio senses 2D & 3D structure
- Parkinson Arrows "point" to subsurface electric currents – provide lateral information



3. Field data acquisition

Equipment layout





3. Field data acquisition

Induction coils for broadband acquisition - AuScope

3. Field data acquisition

Fluxgate sensors for long-period acquisition - AuScope

3. Field data acquisition

Copper/copper sulphate electrodes - AuScope

3. Field data acquisition

Data acquisition systems

AuScope Earth Data Logger system (Gawler & Curnamona-Gawler Link transects)

Quantec REF-TEK system (Curnamona transect)

3. Field data acquisition

Field locations

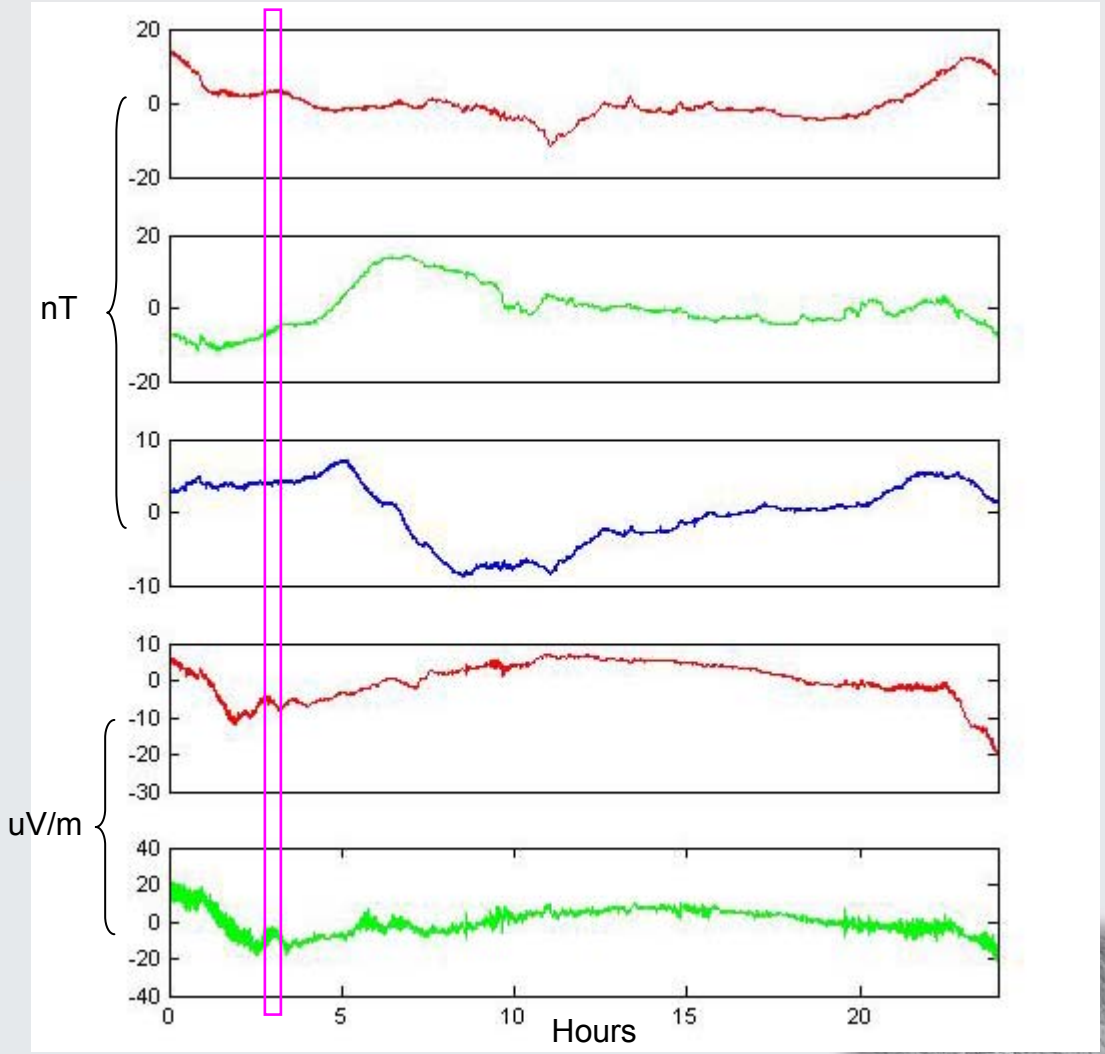
Gawler transect ⬆

Curnamona-Gawler Link transect ⬇

3. Field data acquisition

Example time-series as recorded in the field

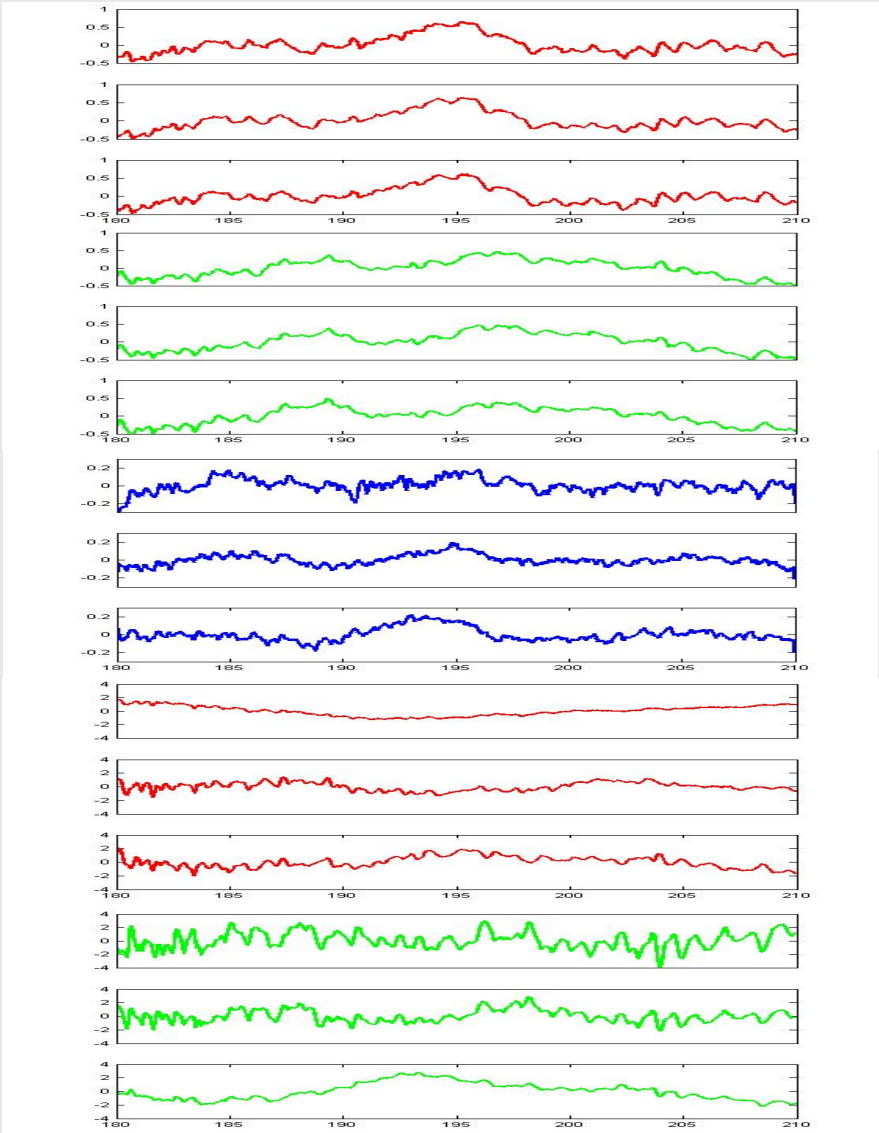
Gawler transect 21 August 2008



3. Field data acquisition

Example time-series as recorded in the field

Gawler transect 21 August 2008



Record width 30 minutes

4. Processing

Processing steps

- Read data
- Calibrate
- Rotate to geographic coords
- Edit
- Calculate spectra & impedance tensor components
- Store in EDI files
- Calculate apparent resistivity (δ) & phase (θ) from impedance tensor
- Display δ and θ graphically and as pseudosections
- Display Parkinson arrows

4. Processing

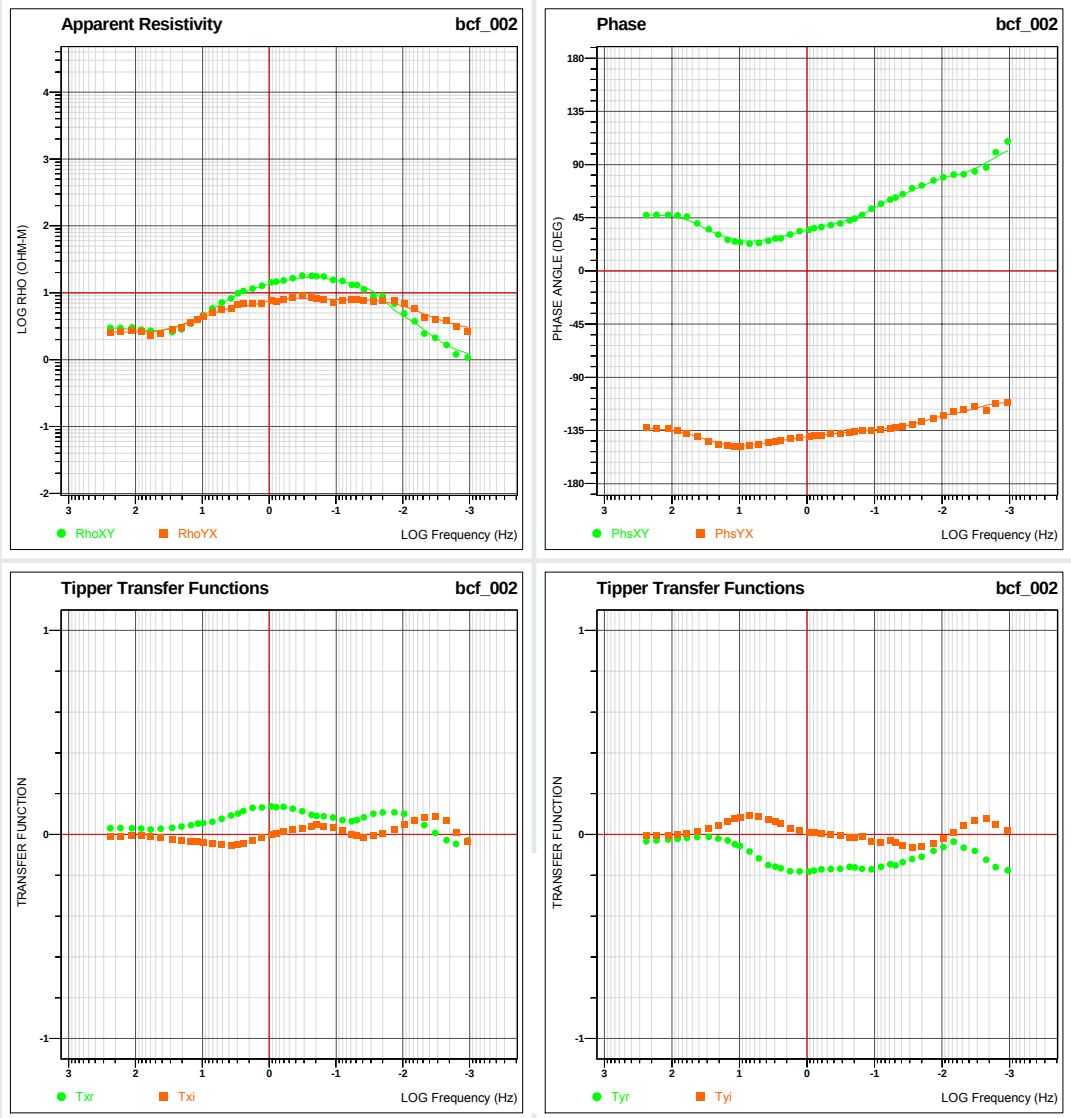
Calculation of impedance tensor values (AuScope processing)

- Time series data are converted to the frequency domain
- Program BIRRP5 of Alan Chave is publicly available for non-commercial use (*Bounded Influence Remote Reference Processing*)
- Remote referencing with other sites (or observatory data) to remove uncorrelated noise
- For each frequency, the impedance equation is solved for Z with noise in E and B

$$\begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \end{pmatrix} = \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

4. Processing

Calculation of Apparent Resistivity & Phase from tensor elements

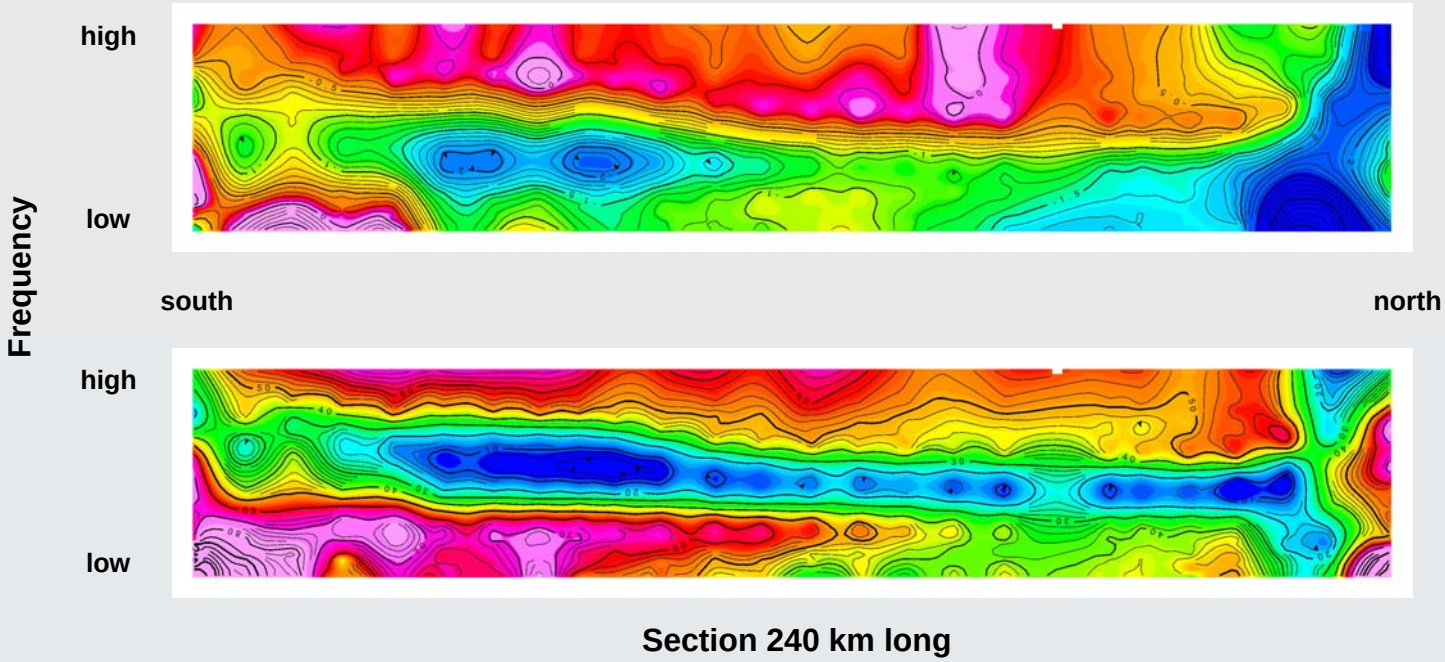


Curnamona transect example (Quantec Geoscience)

4. Processing

Curnamona transect example

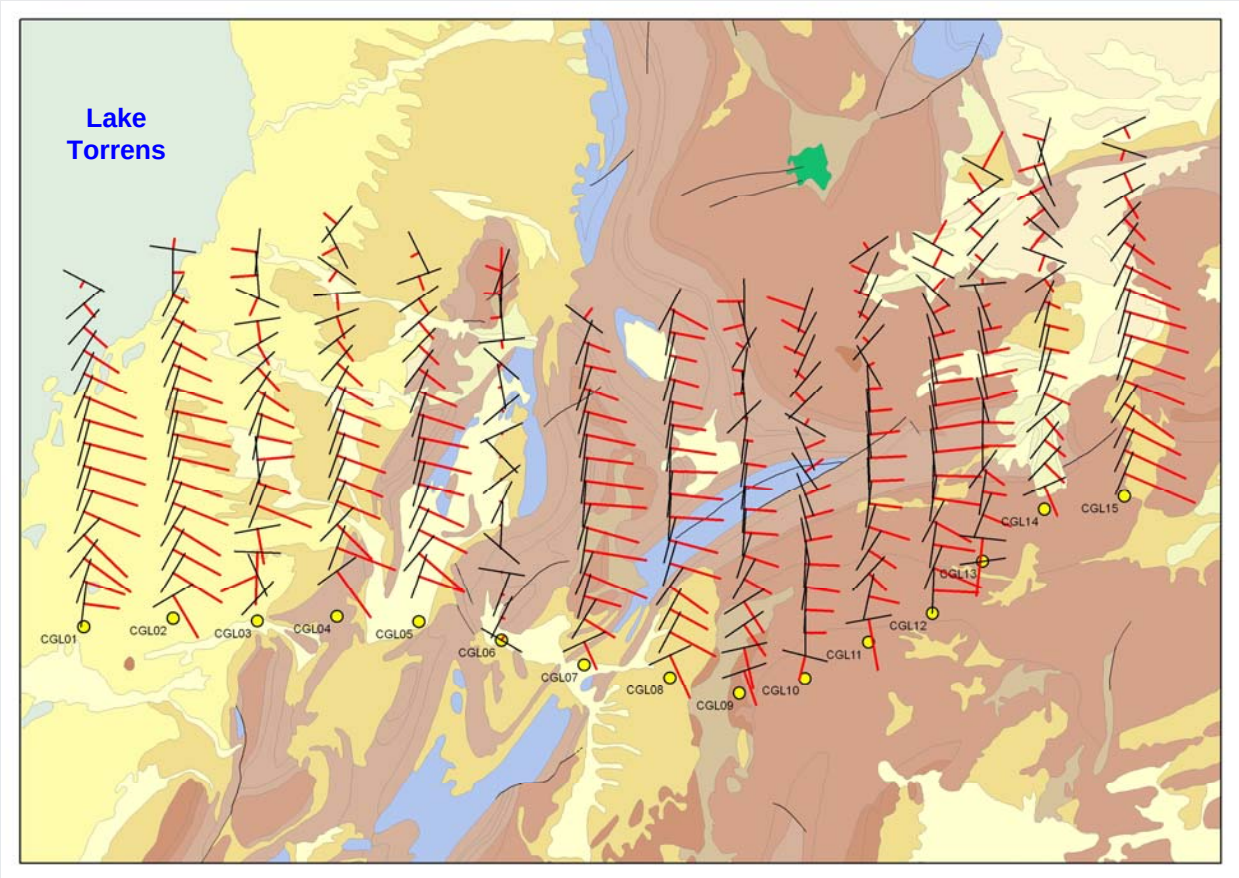
Pseudosections of apparent resistivity & phase



4. Processing

Parkinson arrows

Curnamona-Gawler Link transect example

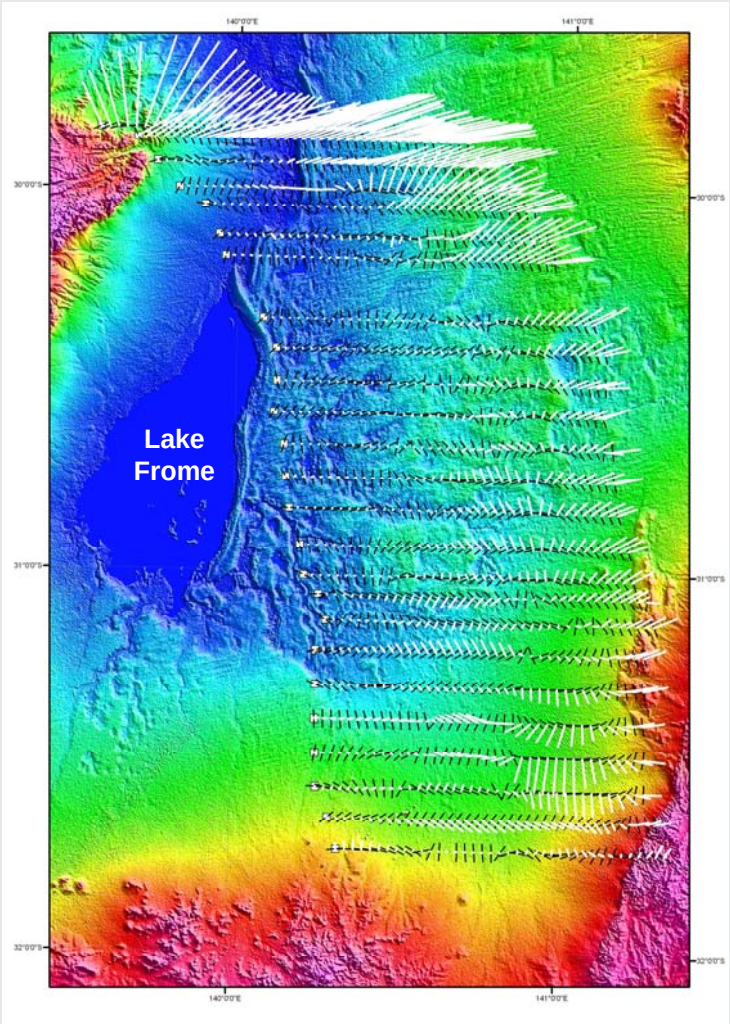


Long-period in-phase arrows (red) and strike symbols (black). Arrows point mainly east to southeast, indicating a current system in that direction (perhaps the Flinders Conductivity Anomaly).

4. Processing

Parkinson arrows

Curnamona transect example



In-phase arrows (white) and strike symbols (black). Arrows point mainly northeast to east, indicating a current system in that direction (perhaps the Flinders Conductivity Anomaly).

5. Analysis

Analysis of MT tensor

The impedance tensor is the Earth filter, relating E response to H source

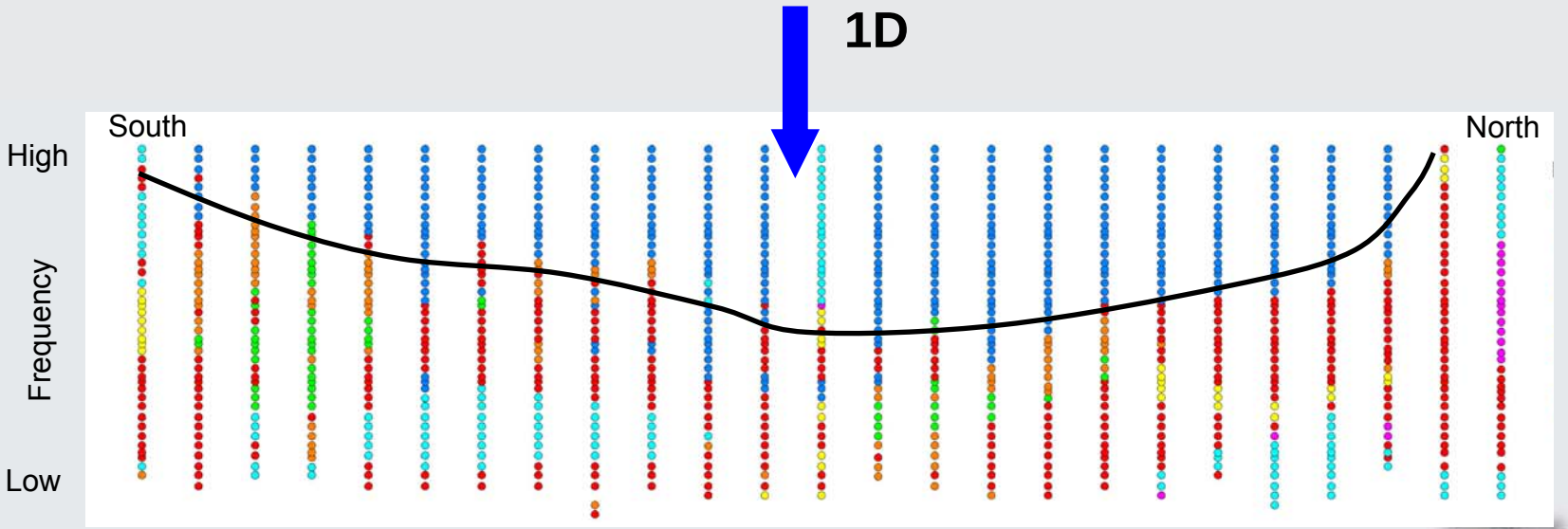
However, there are complicating factors:

- Dimensionality of Earth (1D, 2D state of art, 3D in infancy)
- Strike direction (from impedance tensor and phase tensor if 2D)
- Static shift
- Electric field distortion (eg. current channelling)
- Magnetic field distortion (eg. uniform source field assumption not true)
- Noise (from various sources, both natural & cultural)

5. Analysis

Analysis of impedance tensor for dimensionality and strike

- Rotational invariants of the impedance tensor can be analyzed for dimensionality & strike
- If a well-defined 2D strike can be determined, then the tensor can be rotated so that the TE mode is parallel to strike, and the TM mode perpendicular to strike.
- A phase tensor can be defined & presented as an ellipse – less subject to distortions

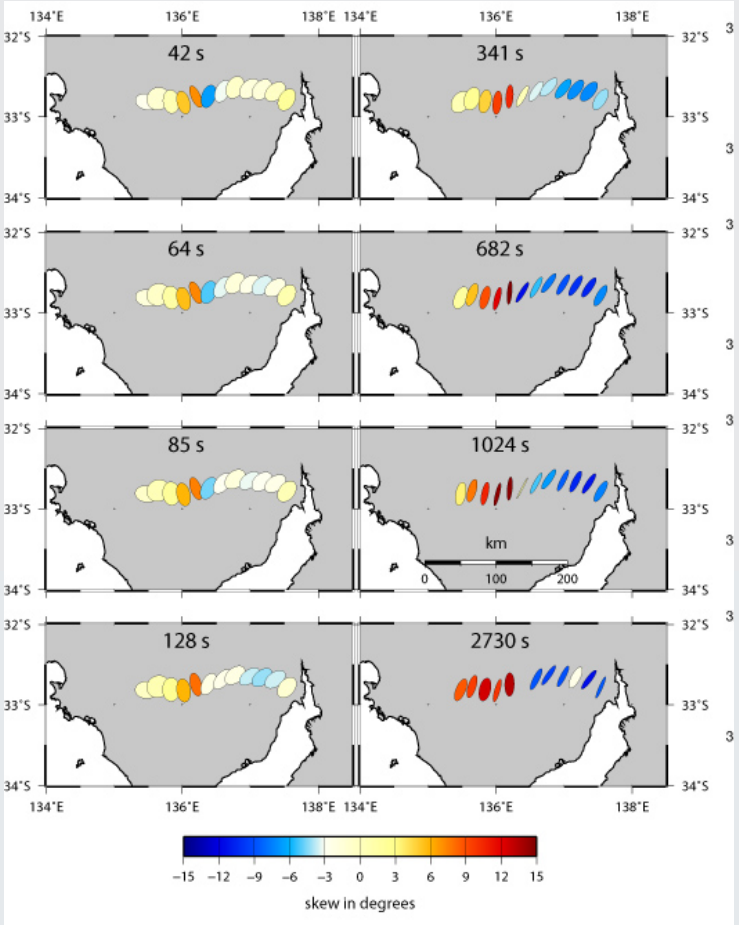


Dimensionality example of Curnamona traverse data using WALDIM program

Phase tensor ellipses

5. Analysis

Gawler transect, 12 long-period responses

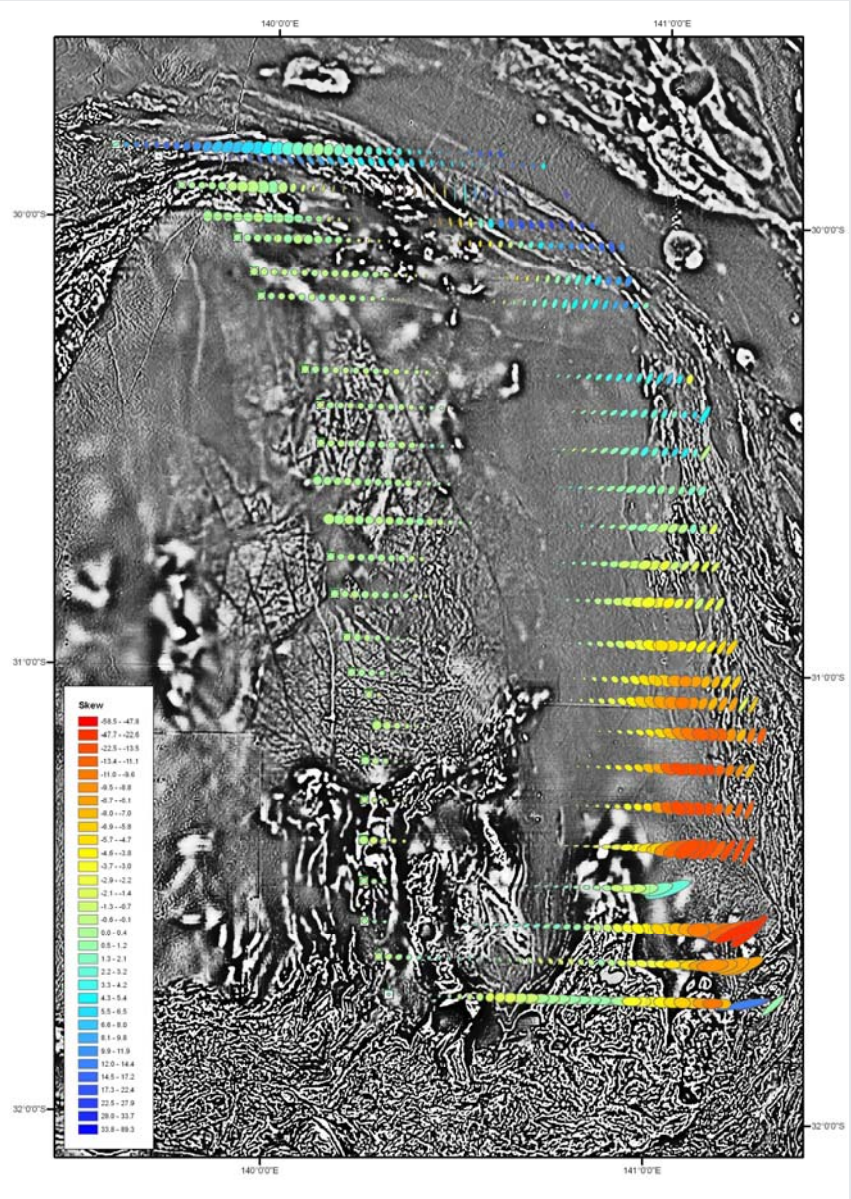


For periods up to a few 100 s, there is a clear distinction between the western and eastern sites with varying major current flow as depicted by the major orientation of the ellipses. Skew values indicate mostly 2D for periods up to 300 s with increasing complexity for longer periods.

5. Analysis

Phase tensor ellipses

Curnamona Traverse, 25 BB sites



Ellipses coloured by skew

6. Modelling

Modelling – a complex subject

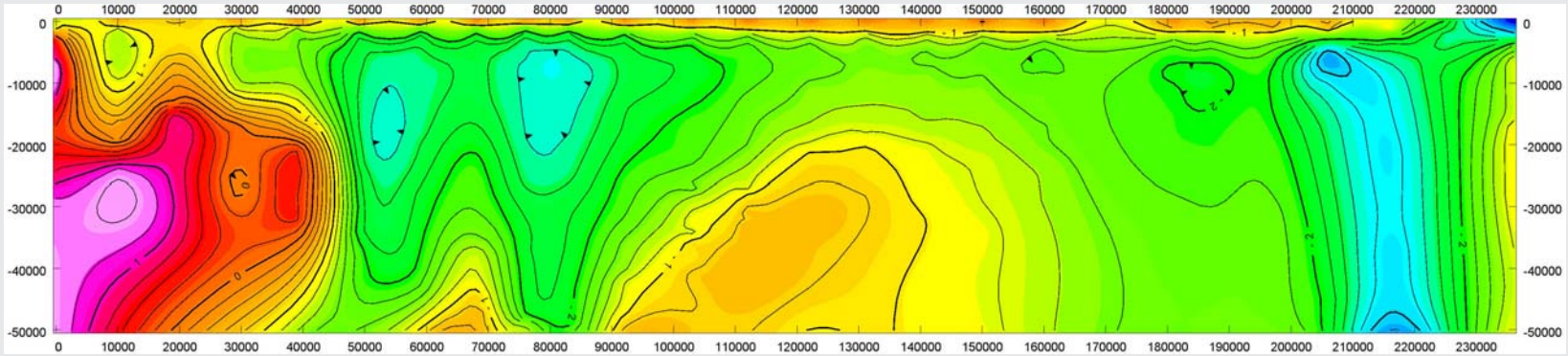
- **1D** – forward & inverse are easy and straightforward, but most data not 1D. Good when structures relatively wide compared with depth, such as aquifers & sedimentary basins.
- **2D** – forward & inverse codes well-developed, this is “state of the art”. Resolution best for conductive structures. Can model TE, TM & Hz modes separately or jointly.
- **3D** – still mainly in the research phase, codes not generally available, but much of the Earth is 3D!

- Models can be unconstrained, or constrained by known features, and degree of smoothness controlled
- The more known rock property information the better
- Future challenge is joint inversions with seismics, magnetics & gravity, and constraints of structures & properties

6. Modelling

1D modelling – Bostick transform of Curnamona traverse data

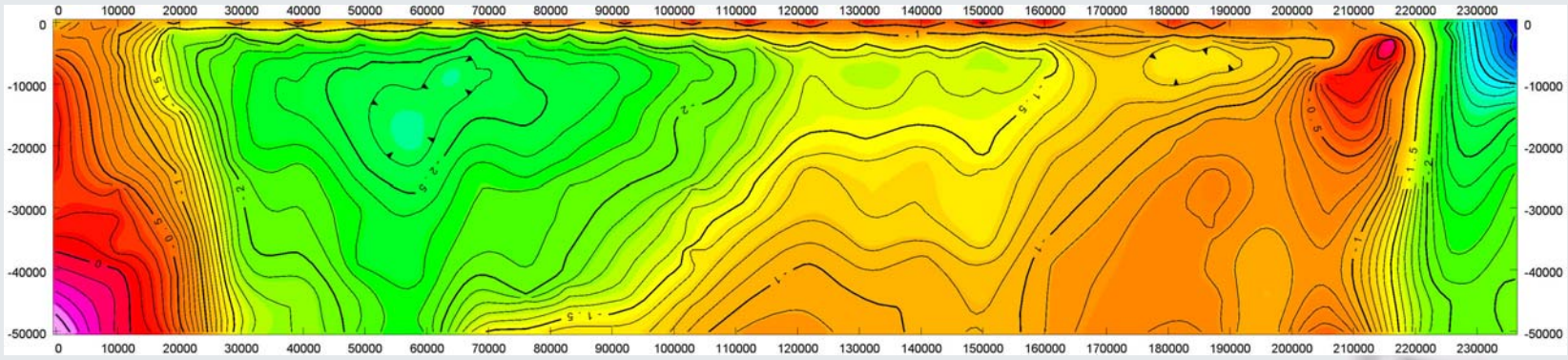
TE mode



South

North

TM mode

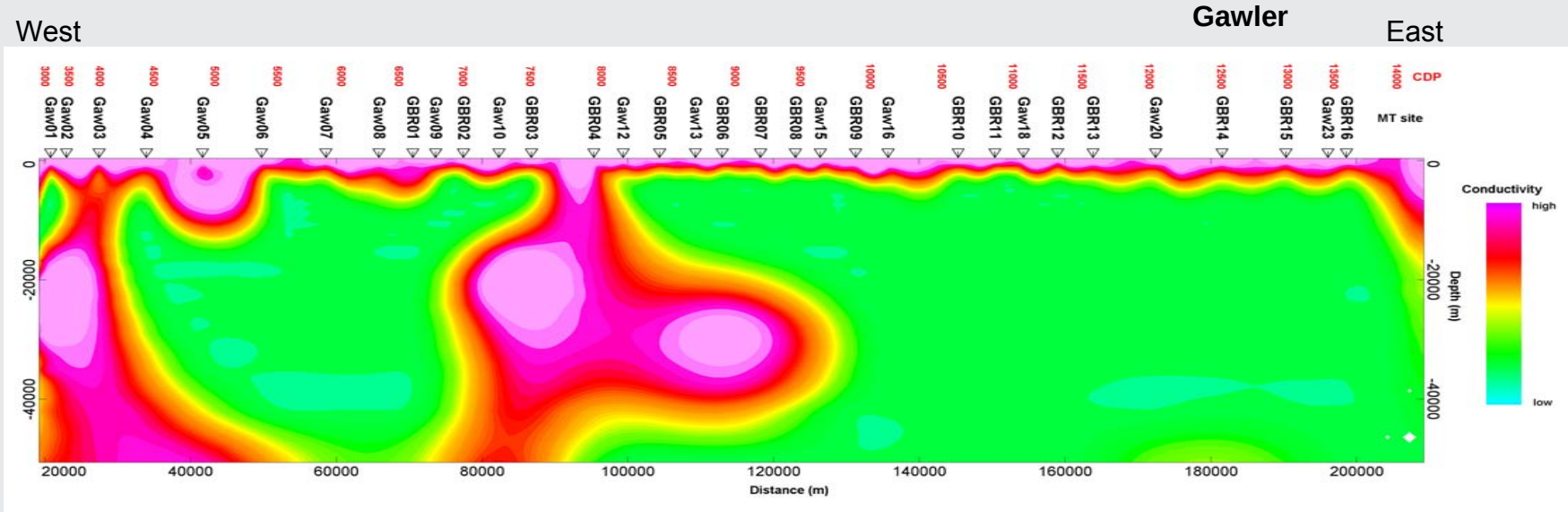


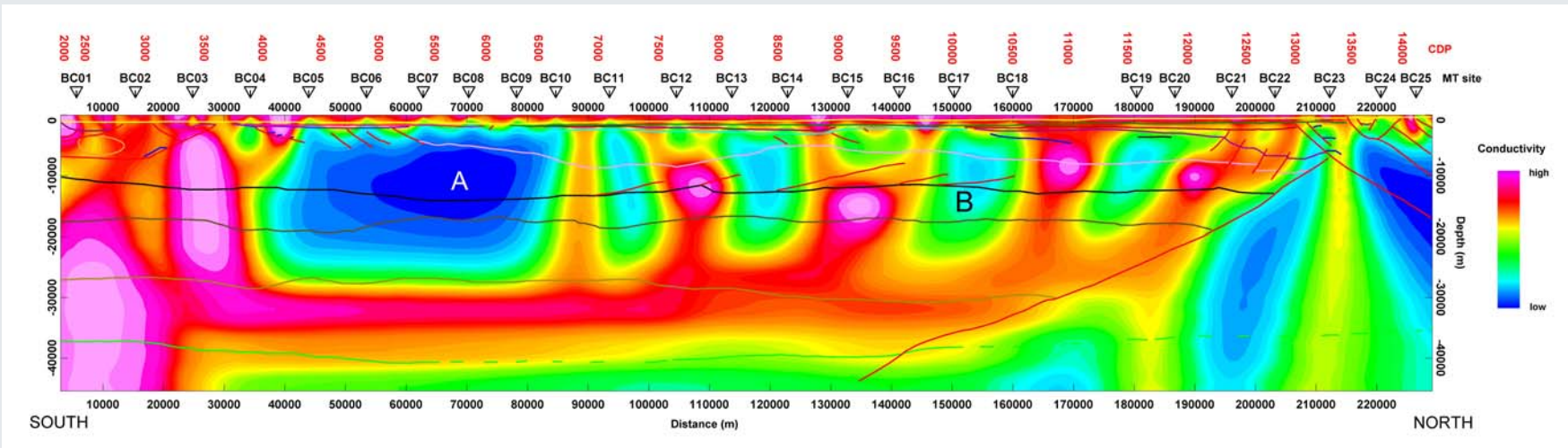
Show major features of data – low accuracy

6. Modelling

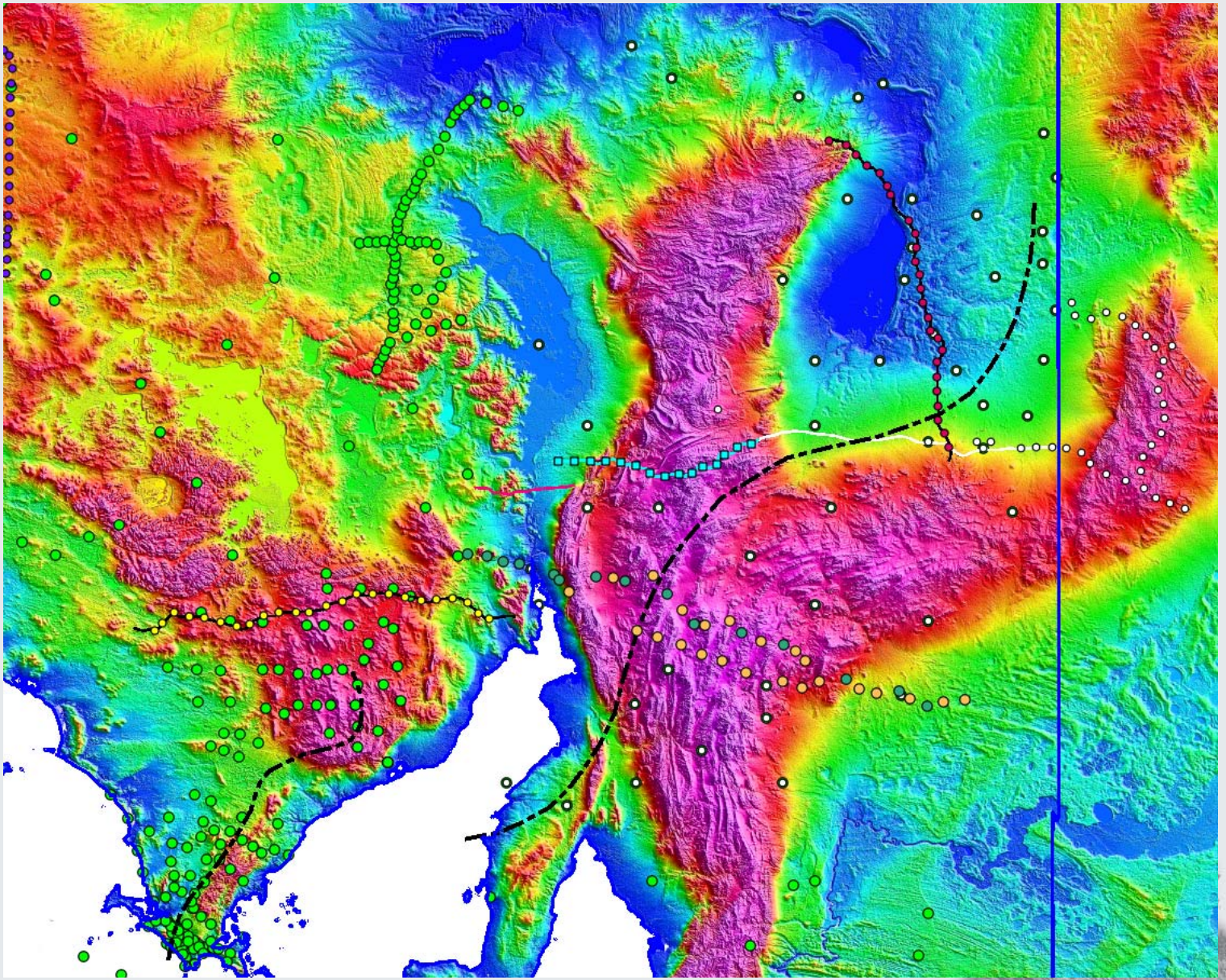
2D modelling

Using the Rodie, Mackie finite difference NLCG method as implemented in WinGLink software





7. Conclusions

- MT data acquired along 3 seismic transects in SA in collaboration with U of A and PIRSA
- Earth conductivity is complimentary to information from the seismic method, and the MT method has been briefly described
- Examples of display & analysis of data
- Analysis confirms major features of Earth conductivity, useful prior to inverse modelling
- Top of section sediments are well imaged by MT
- Curnamona data show correlations with interpreted seismic structures, but also reveal other resistive and conductive regions which show no obvious correlations with the seismic data. Also show a response to the Flinders Conductivity Anomaly.
- Gawler data show a distinct conductive anomaly in the crust in mid-section (perhaps the extension north of the Eyre Peninsula Conductivity Anomaly), and a deeper conductive region in the west
- Processing and modelling of all three sets of data are on-going – results presented here are preliminary

7. Conclusions