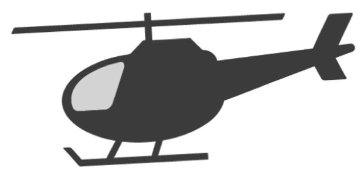
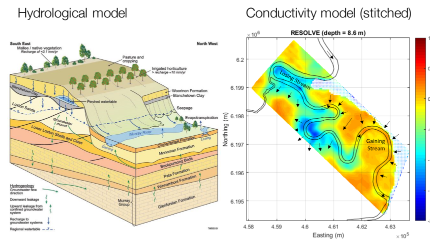
Field examples

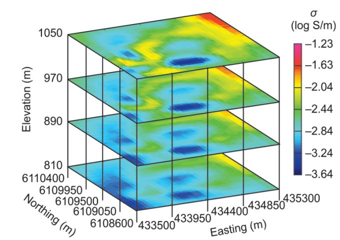


1D or 3D?

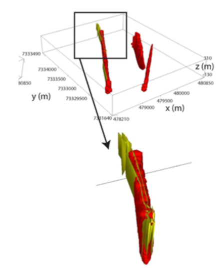
- Bookpurnong (moderately 1D)



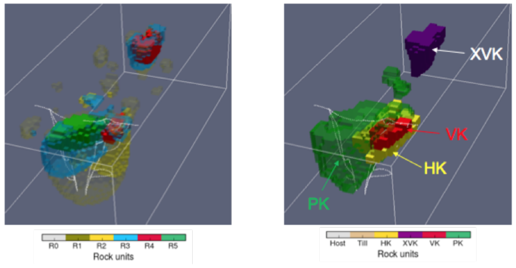
- Mt. Milligan (compact resistor)



- West Plains
  (thin conductive intersecting structures)

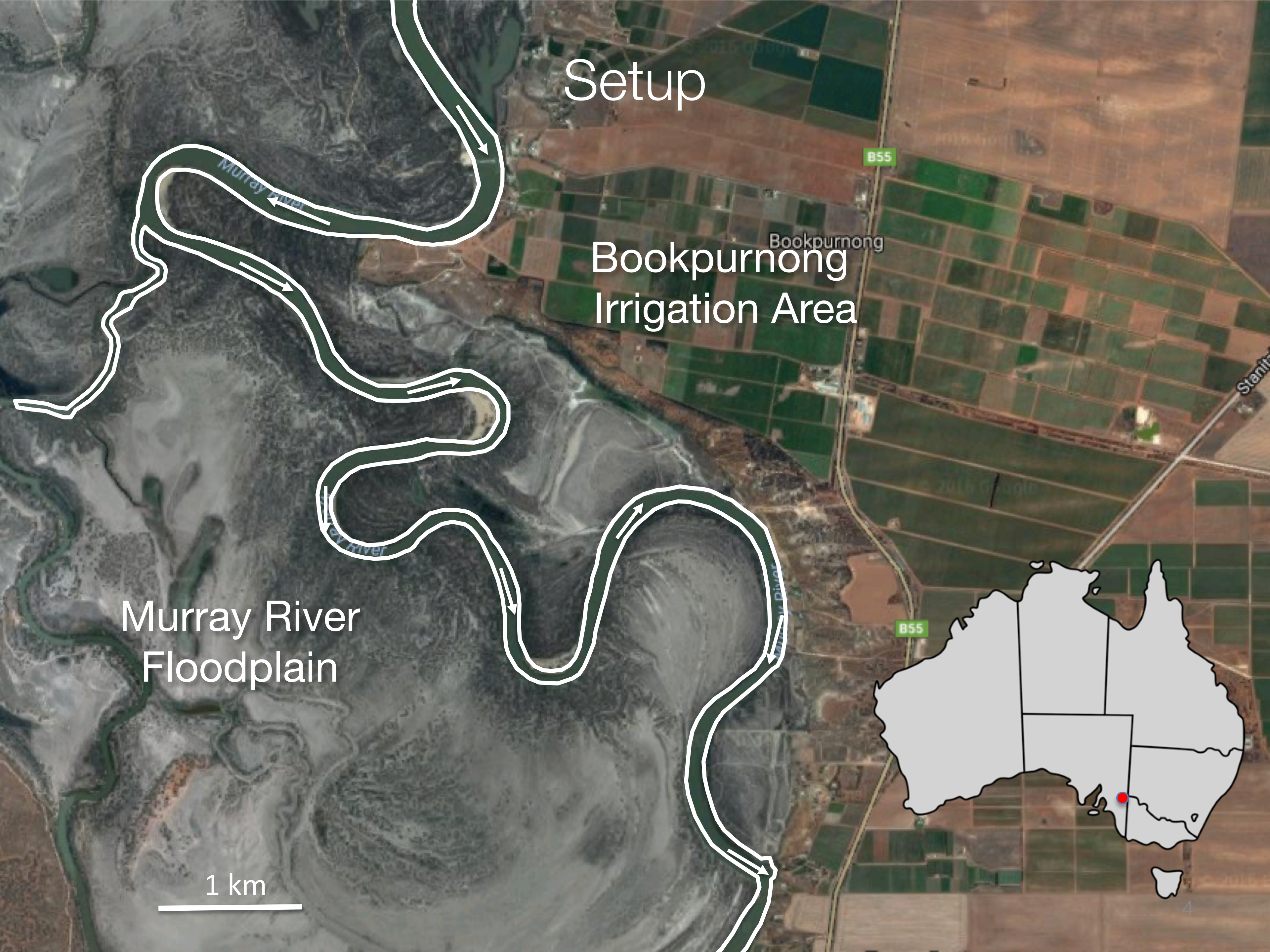


- TKC (compact conductor and IP)



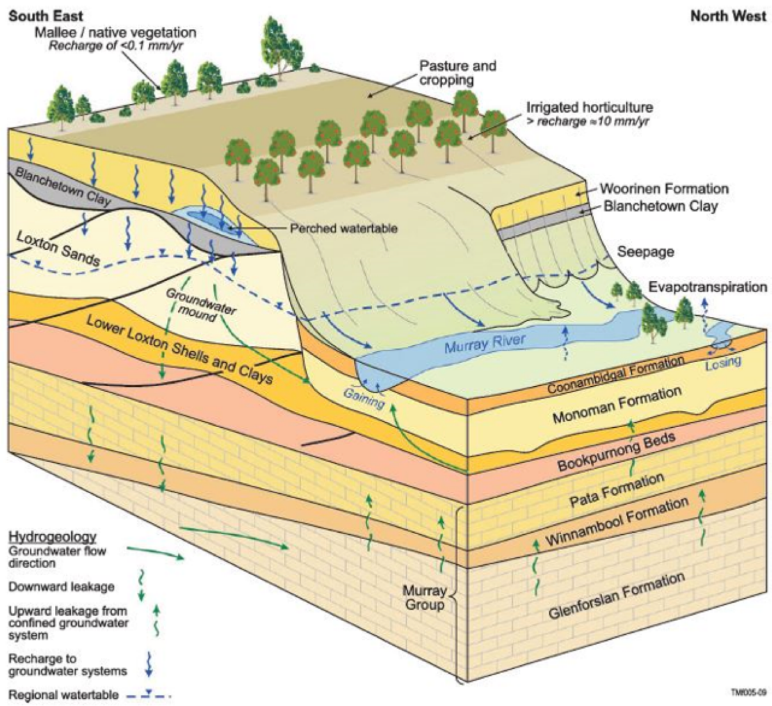
Bookpurnong

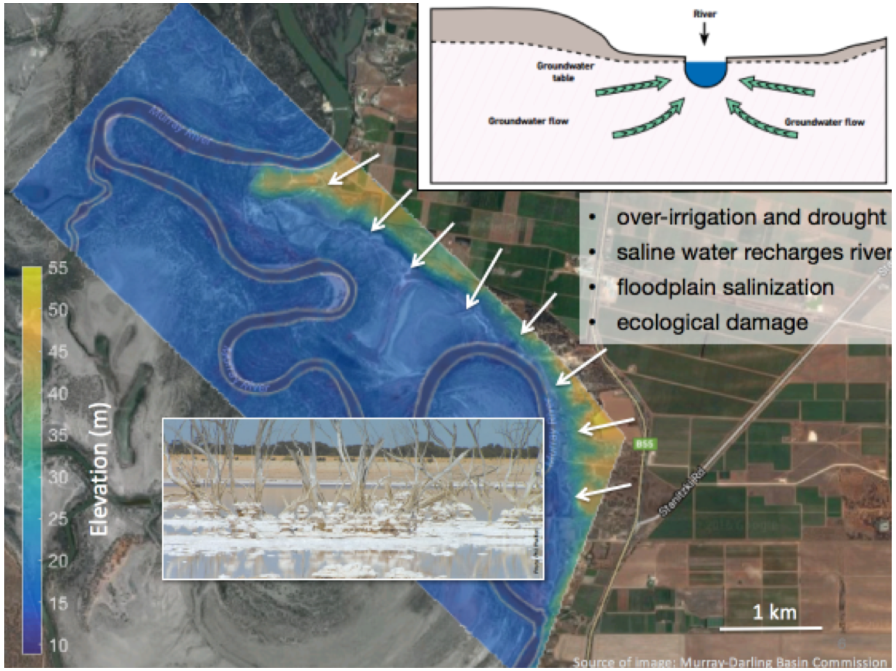
Viezzoli et al., 2009


Setup
Murray River
Bookpurnong
Bookpurnong
Irrigation Area
B55
B55
Murray River
Floodplain
1 km

Setup

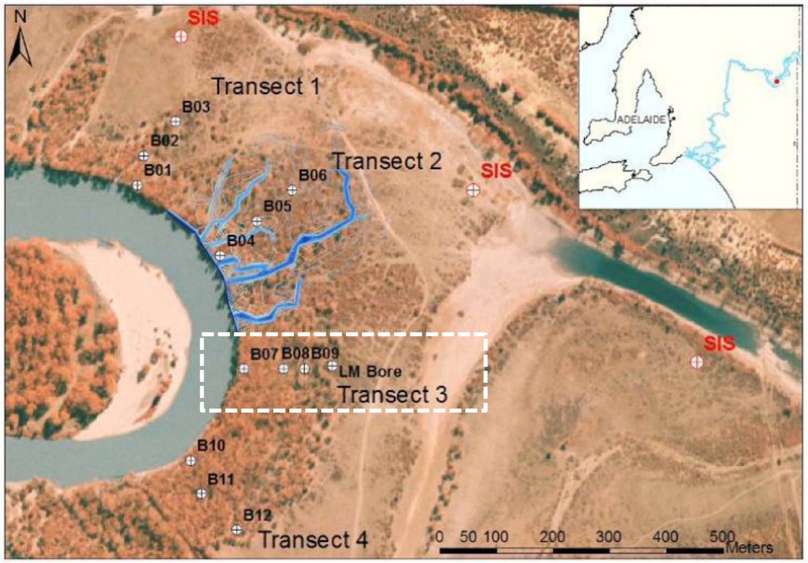
Hydrological model





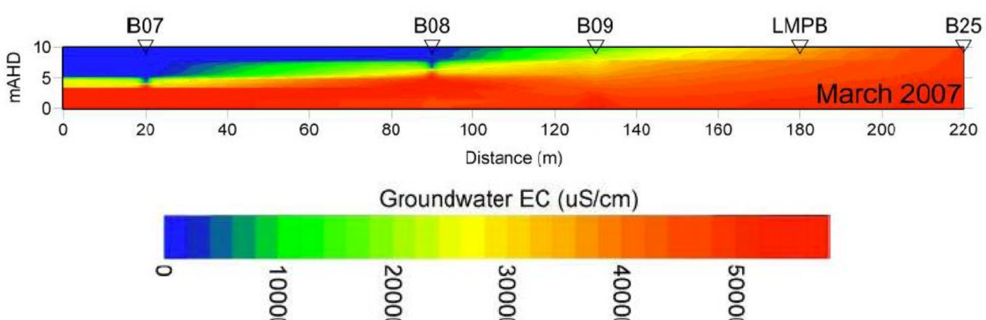
Properties

Location map for salinity measurements



Unit	Conductivity
Saline water	High, 3 - 5 S/m
Fresh water	Low, 0.01 S/m

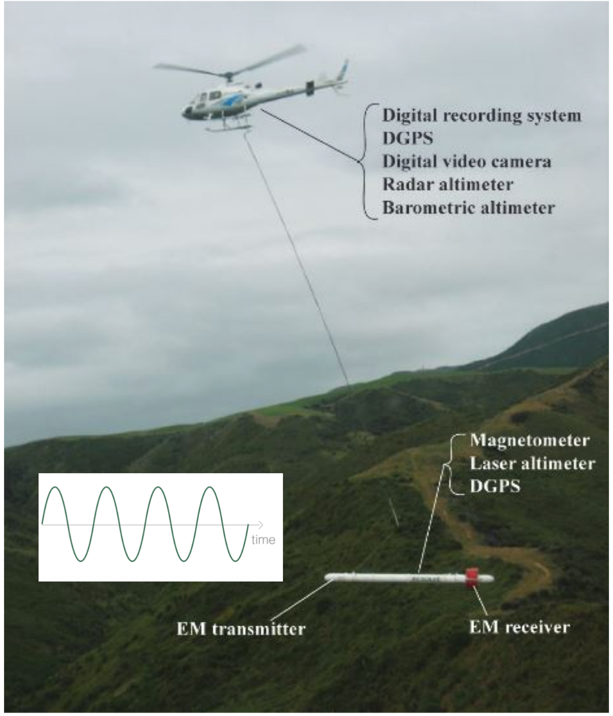
Conductivity from salinity measurements



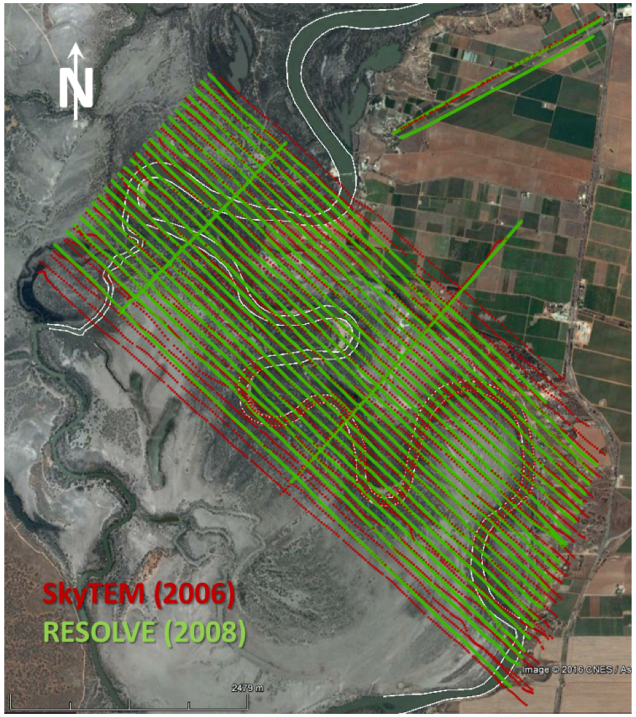
Holland et. al., 2008.

Survey

Resolve system (2008)



Flight lines

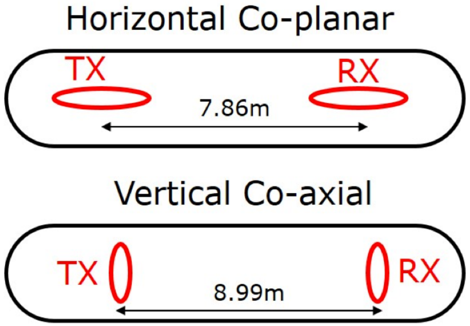


Horizontal Co-planar (HCP) frequencies:

- 382, 1822, 7970, 35920 and 130100 Hz

Vertical Co-axial (VCA) frequencies:

- 3258 Hz

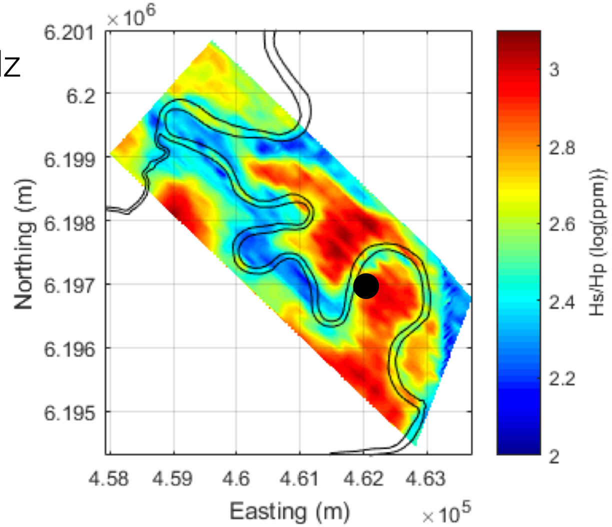


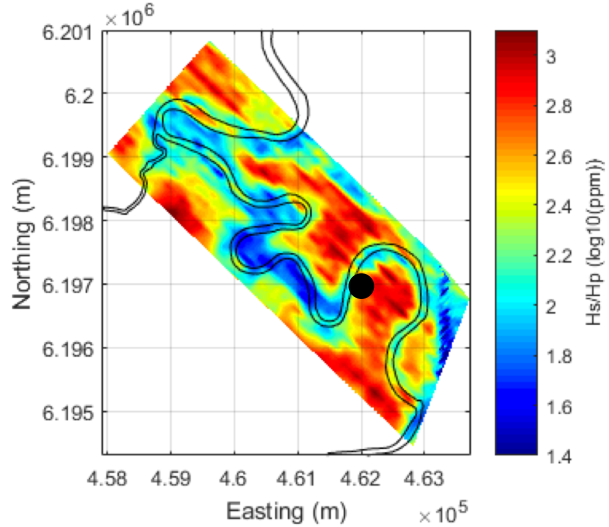
Horizontal Co-planar (HCP) data

In-Phase (Real)

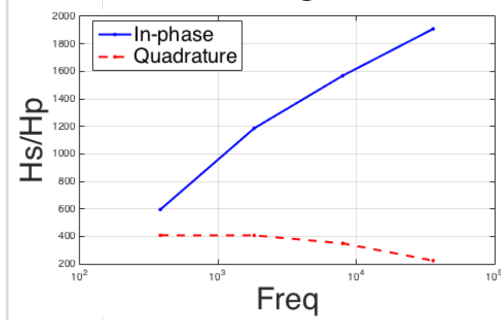
Quadrature (Imaginary)

382 Hz

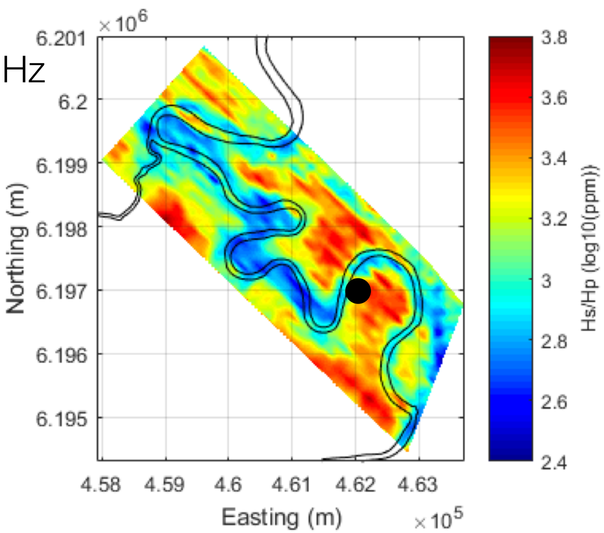


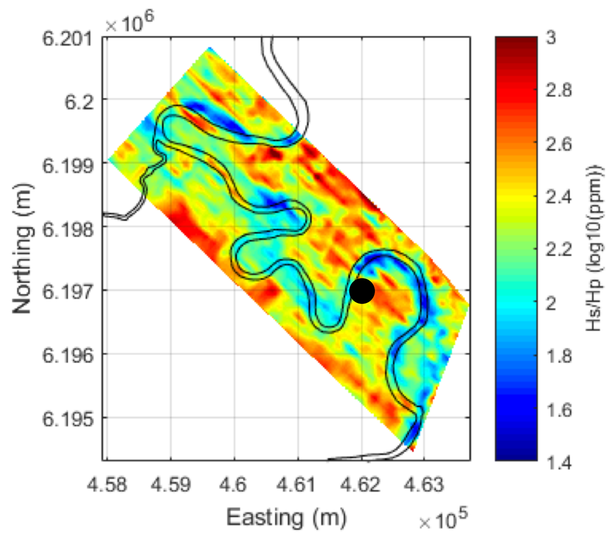


Sounding curve

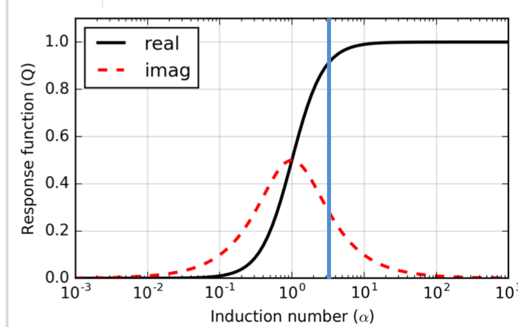


35920 Hz



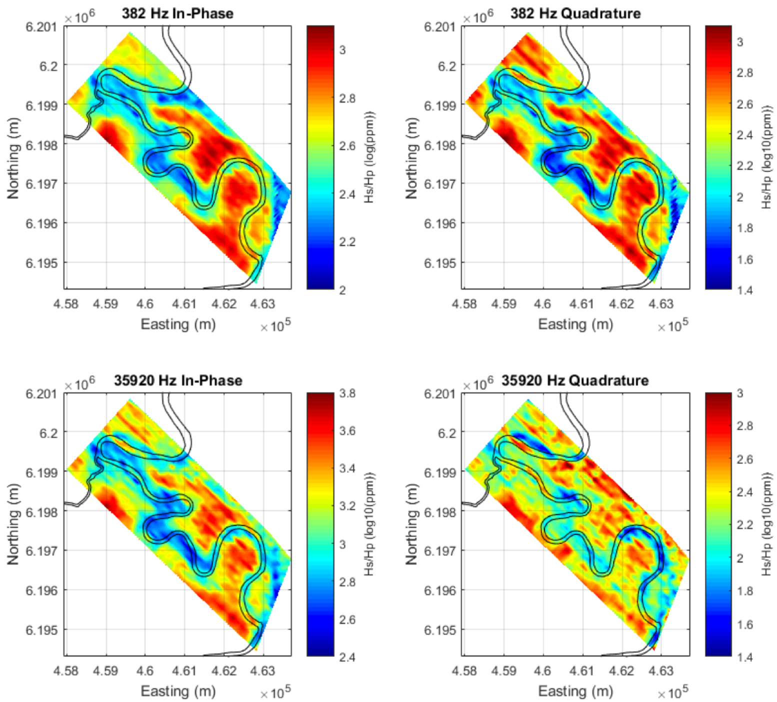


Response curve

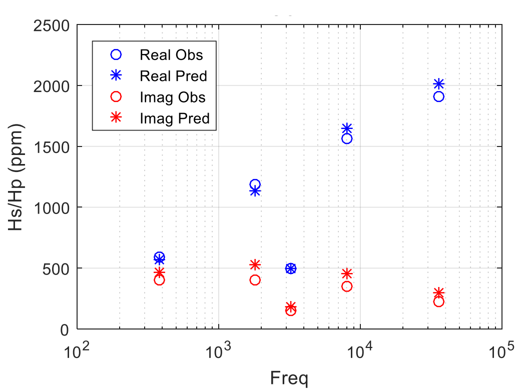


Processing: 1D inversion

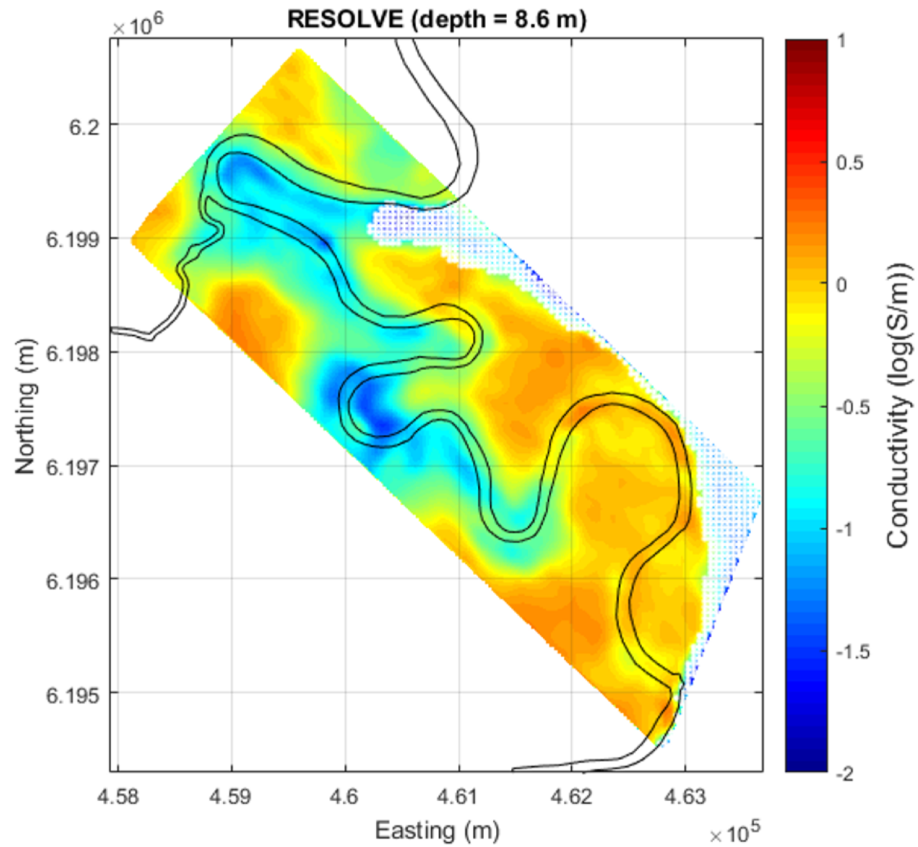
Data



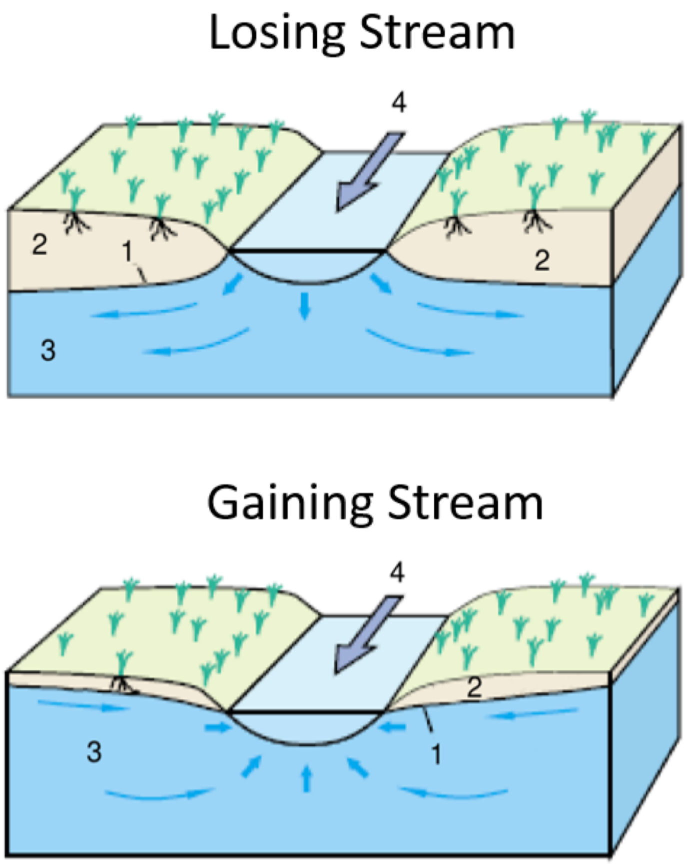
Data fit



Conductivity model (stitched)



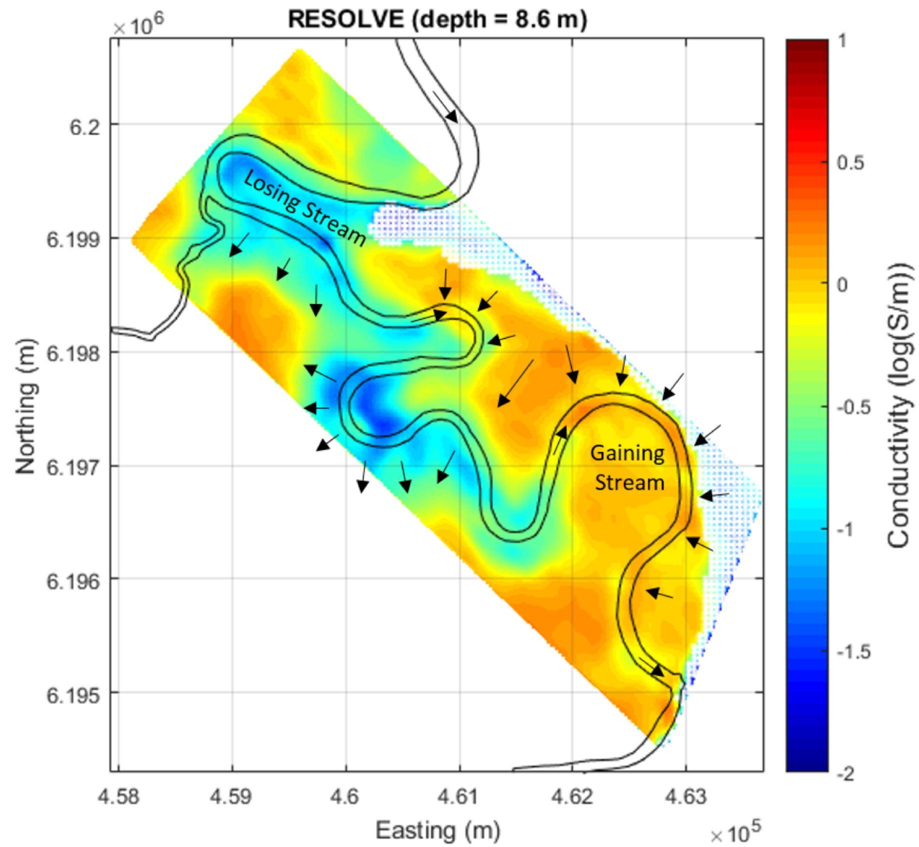
Interpretation



1 – Water table   2 – Unsaturated zone

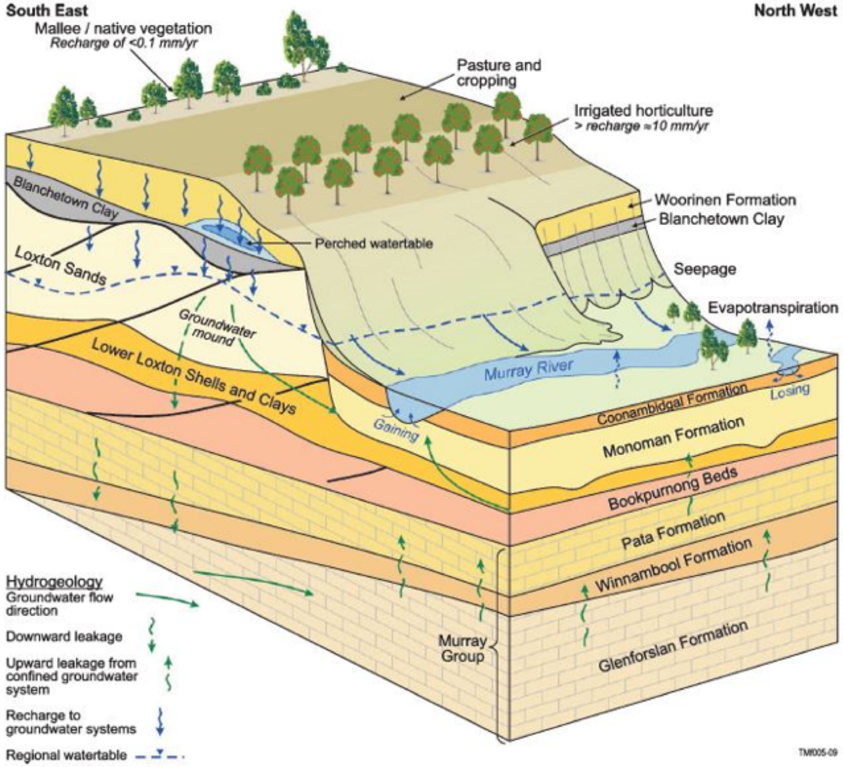
3 – Saturated zone   4 – Flow direction

Conductivity model (stitched)

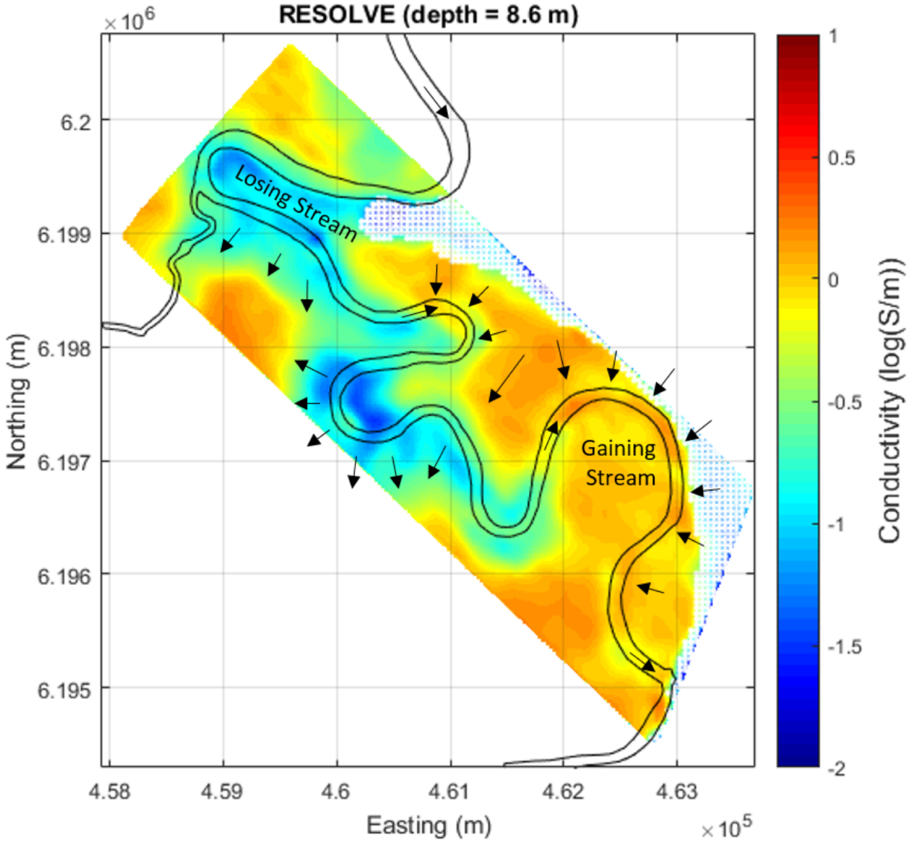


Synthesis

Hydrological model

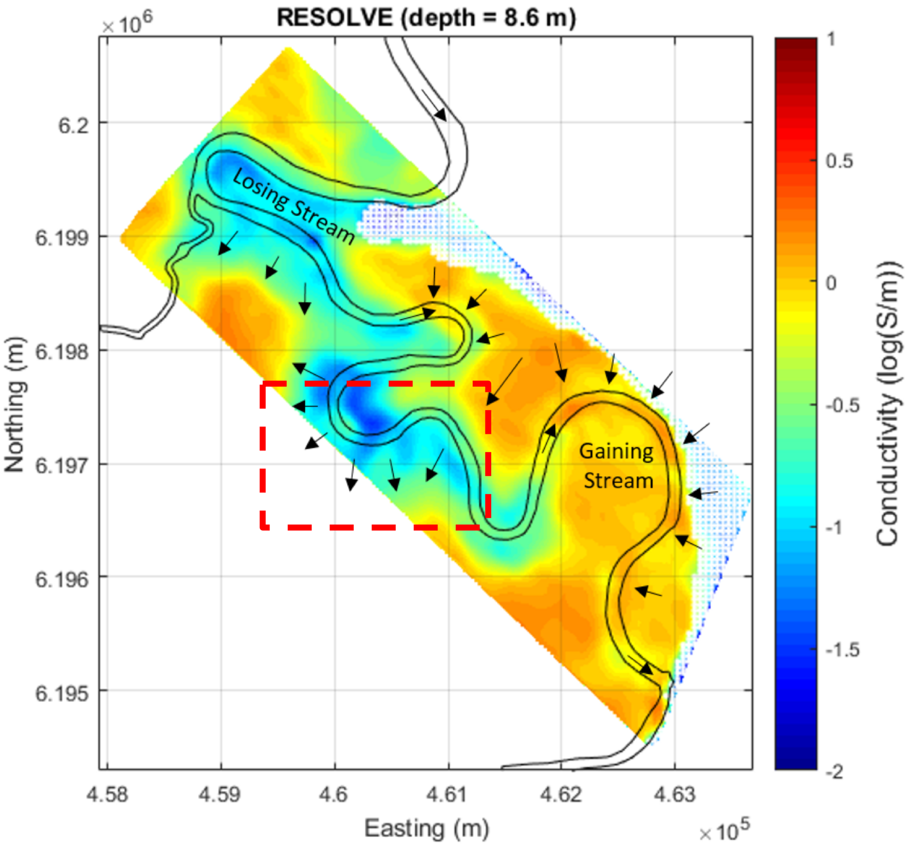


Conductivity model (stitched)



Need for 3D?

Conductivity model (stitched)

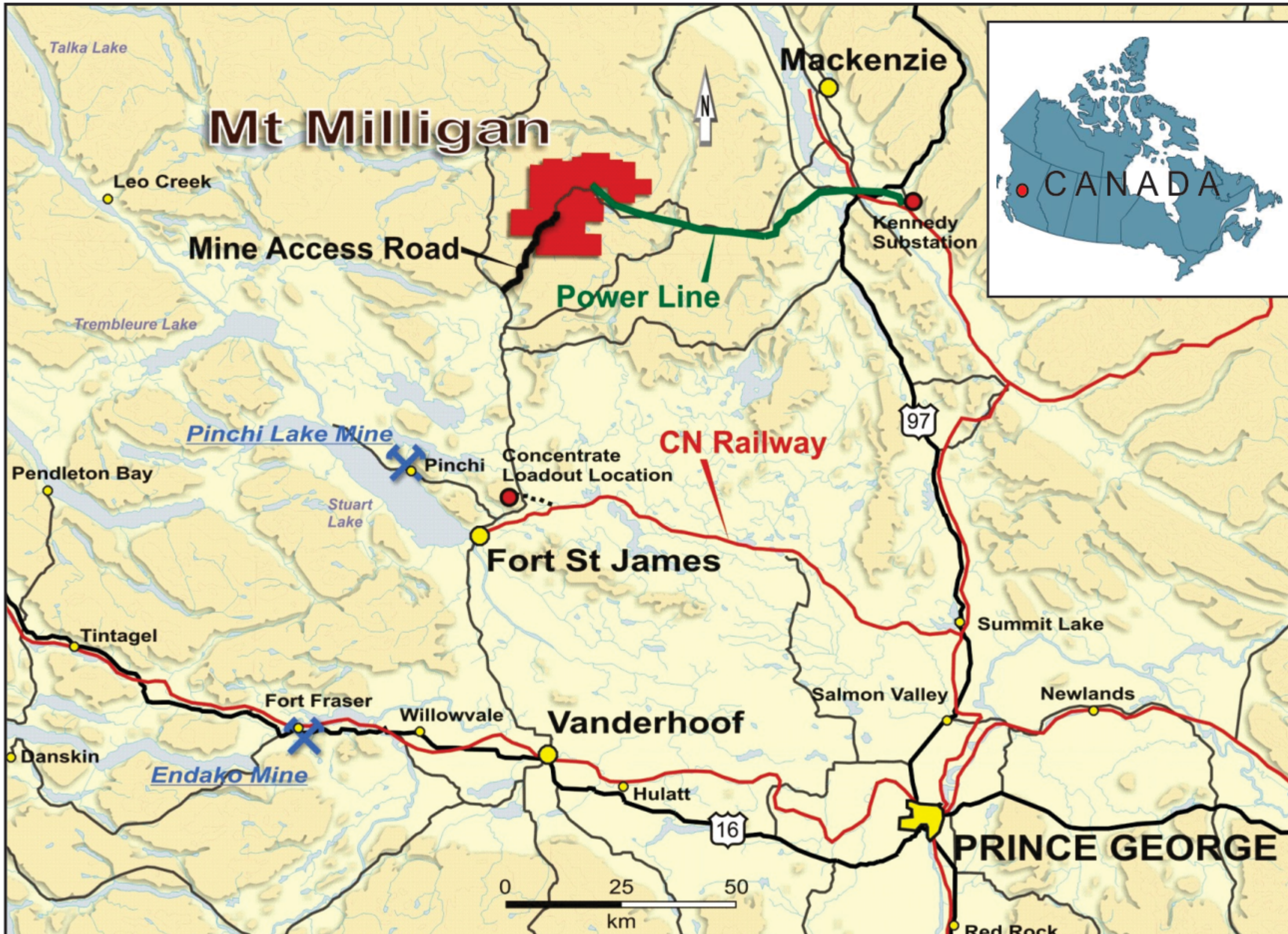


- Large scale features of flow reasonably defined with 1D
- 3D might be beneficial
  - regions of significant horizontal variation
  - time lapse

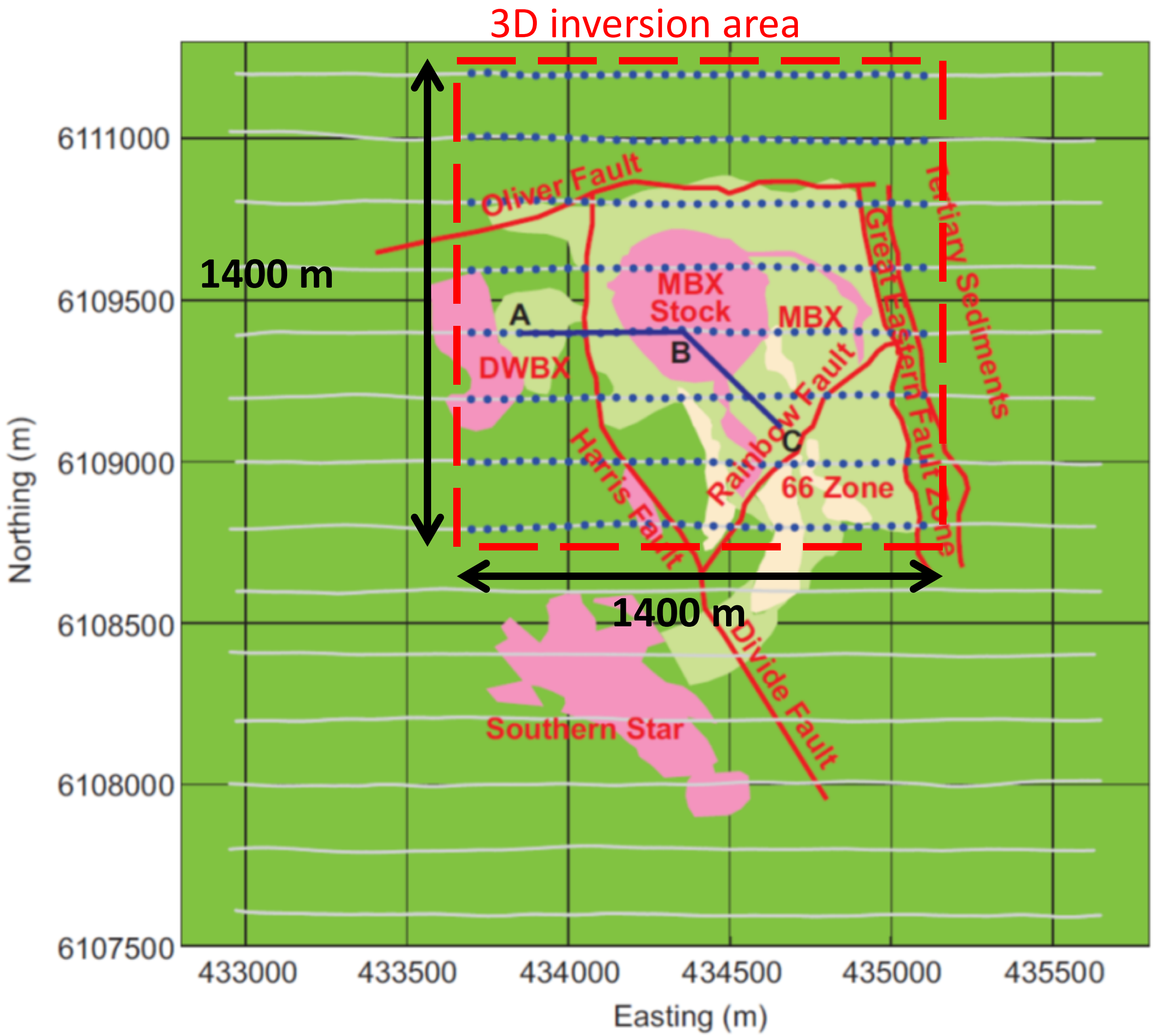
1D or 3D?

- Bookpurnong (moderately 1D)
- Mt. Milligan (compact resistor)
- West Plains (thin conductive intersecting structures)
- TKC (compact conductor and IP)

Mt. Milligan Cu-Au Porphyry Deposit



3D VTEM Inversion at Mt. Milligan



Data grid
8 x 29 = 232

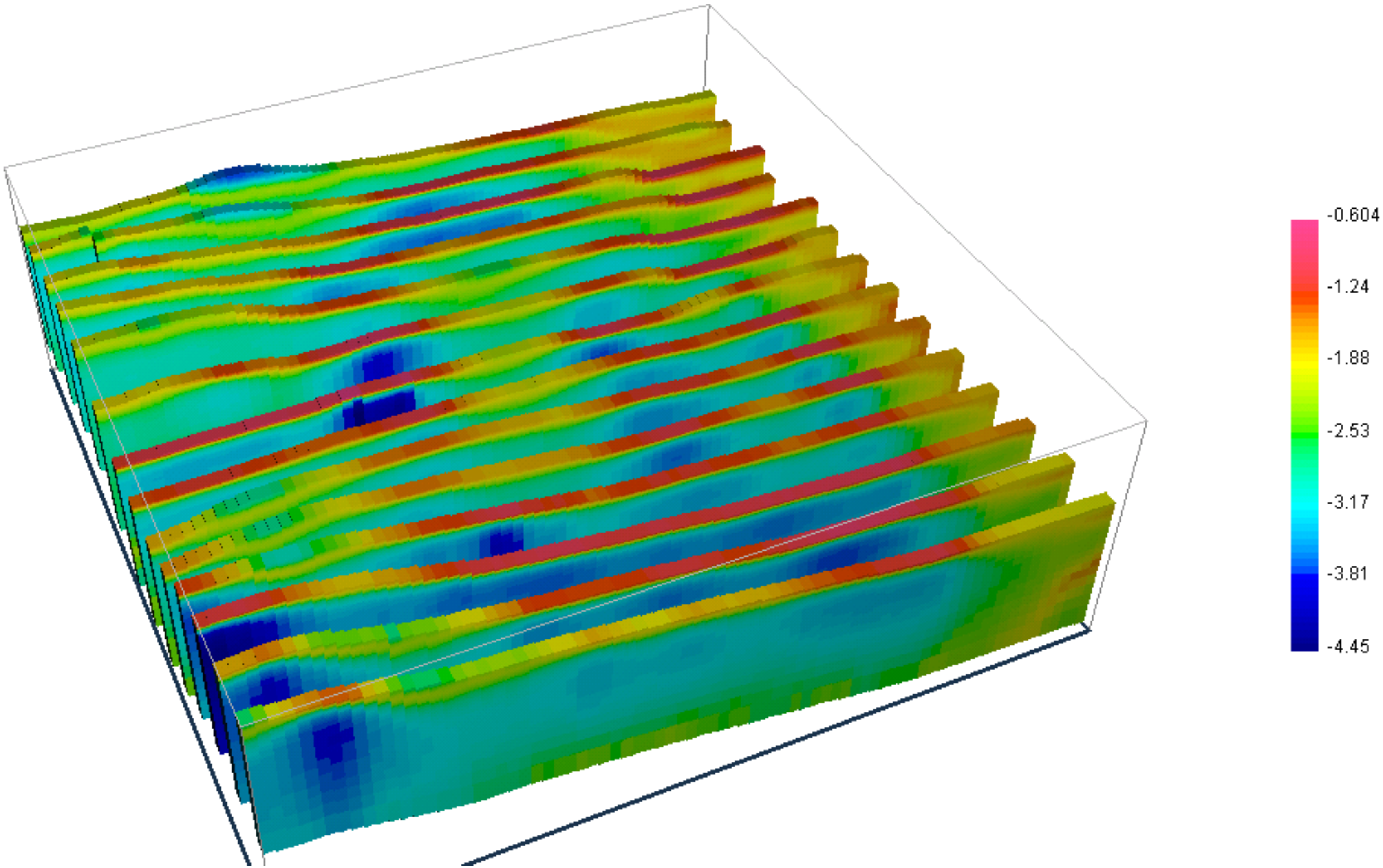
Line spacing 200m

Sounding spacing = 50m

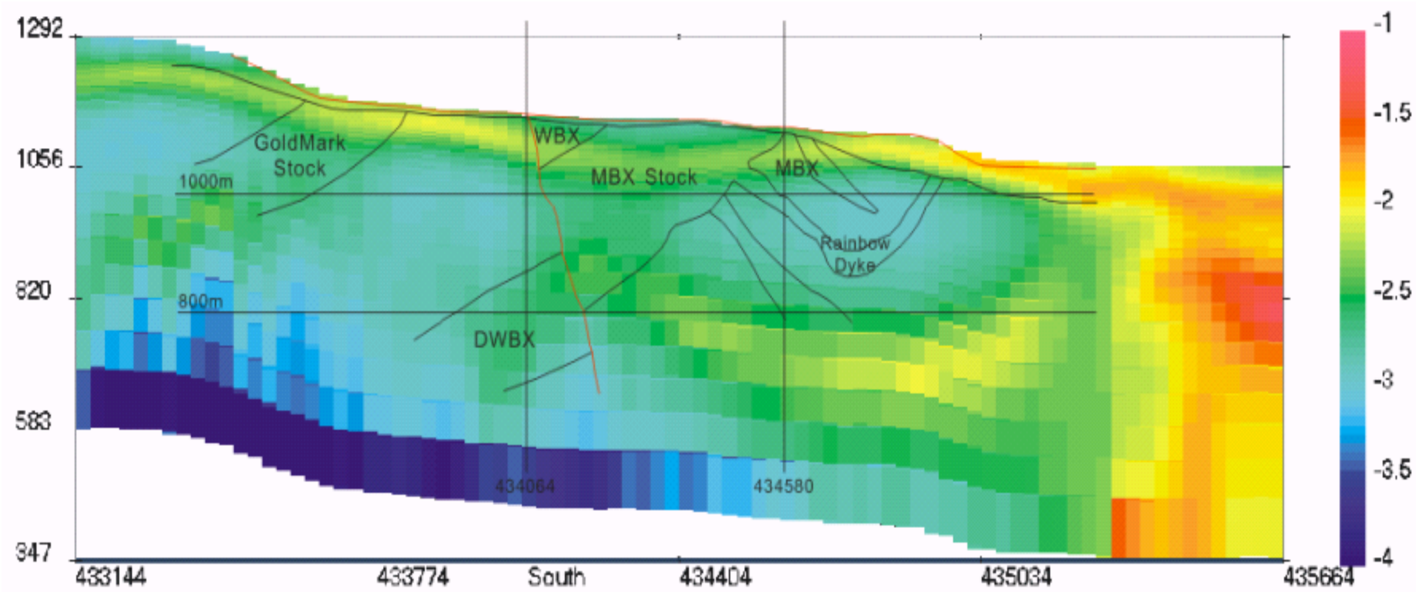
Flight height 20~90 m

Time channel
120 ~ 2745 μs

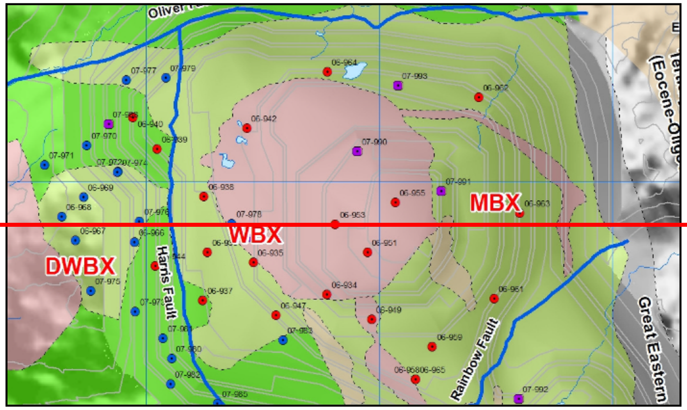
1D Inversion models at Mt. Milligan

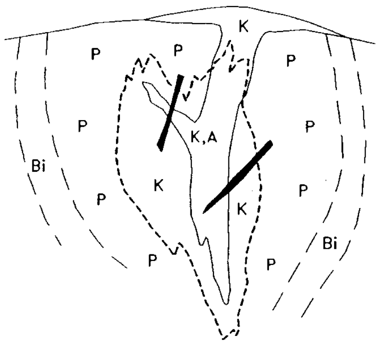


Un-interpretable features

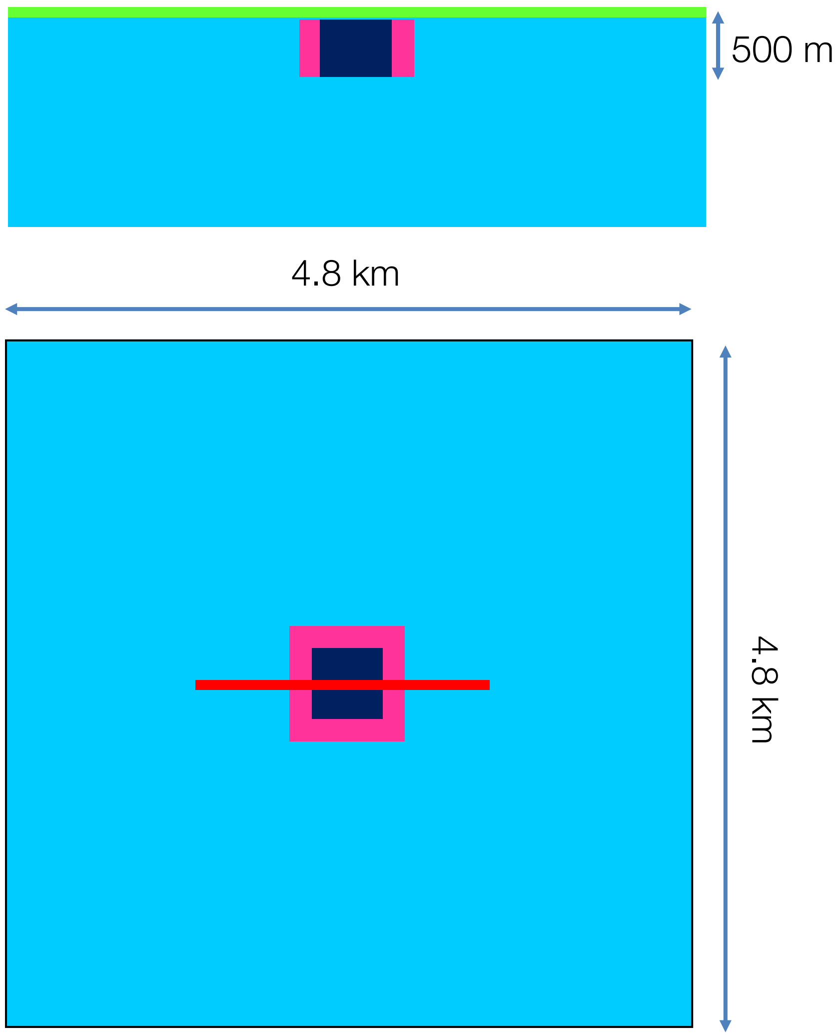


Geology Map

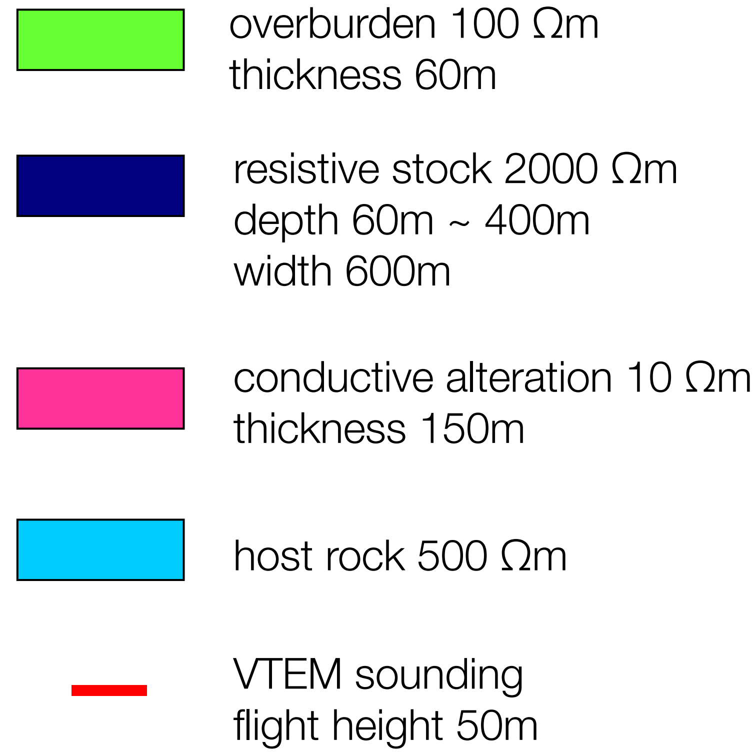




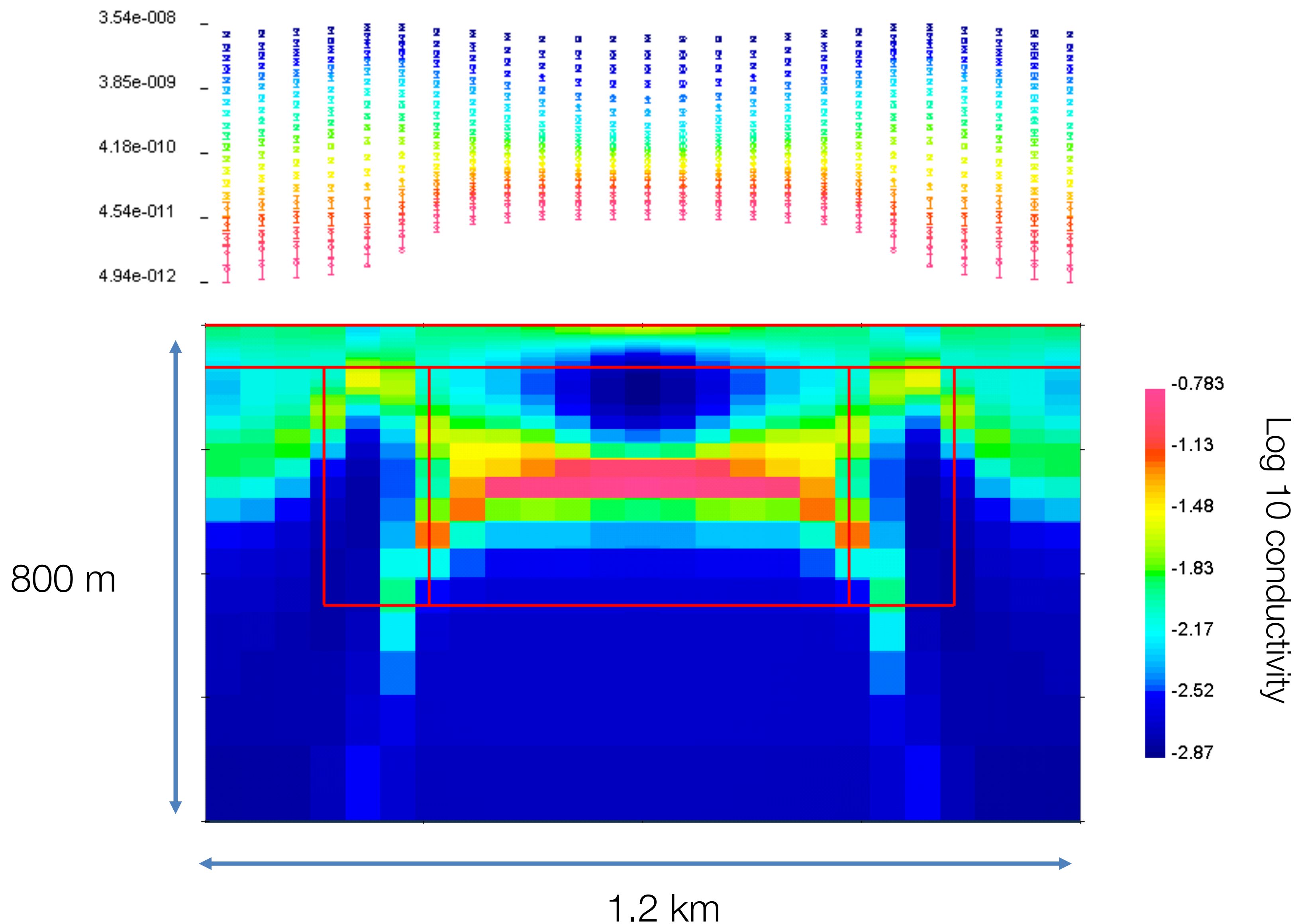
Synthetic Model of Mt. Milligan



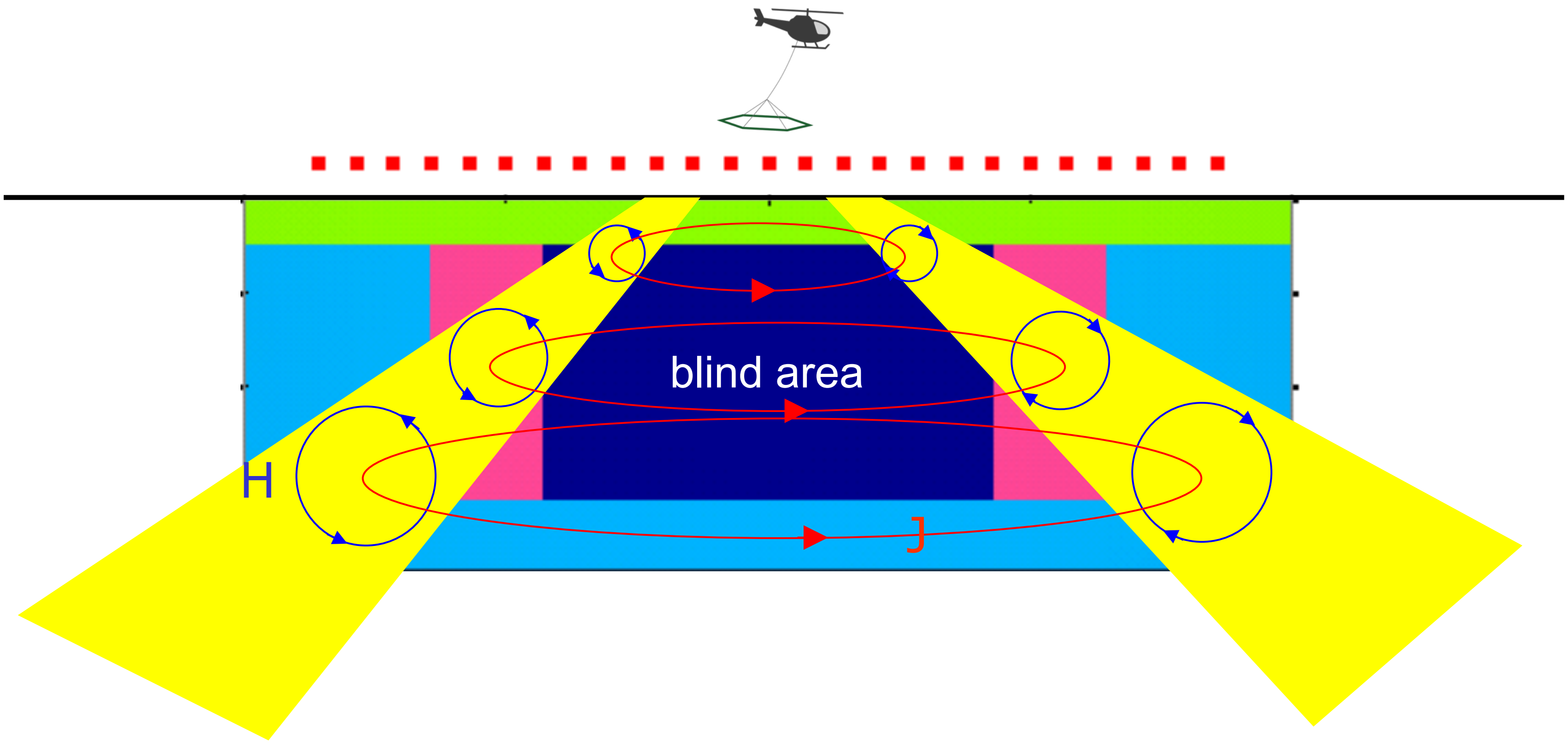
Resistive stock surrounded by conductive alteration halo



1D Inversion of 3D Synthetic Data

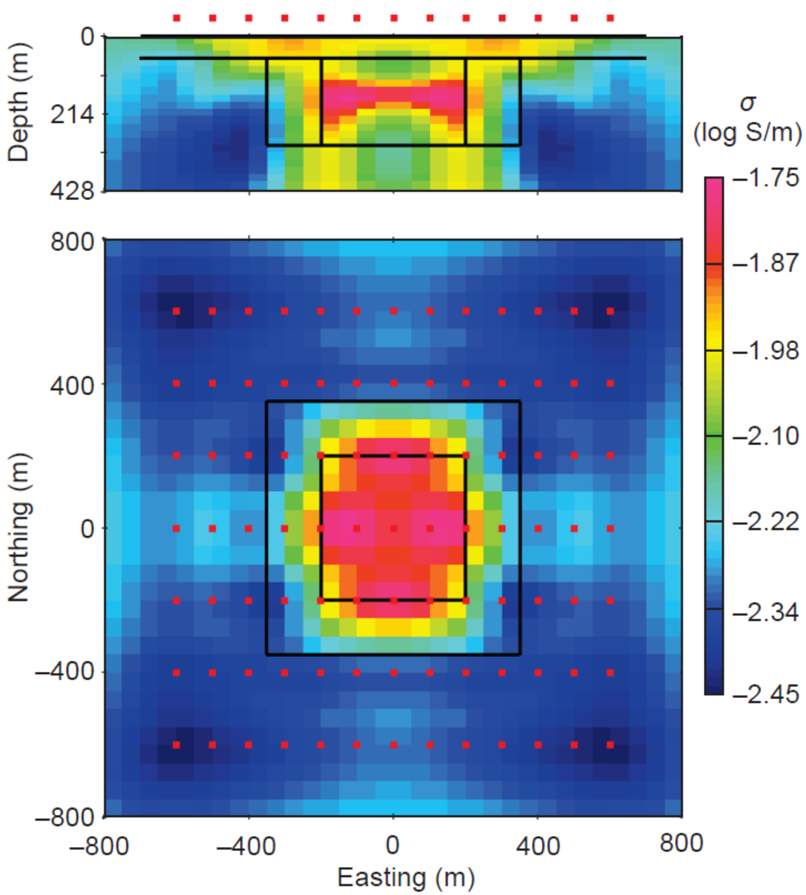


What is wrong with 1D inversion?

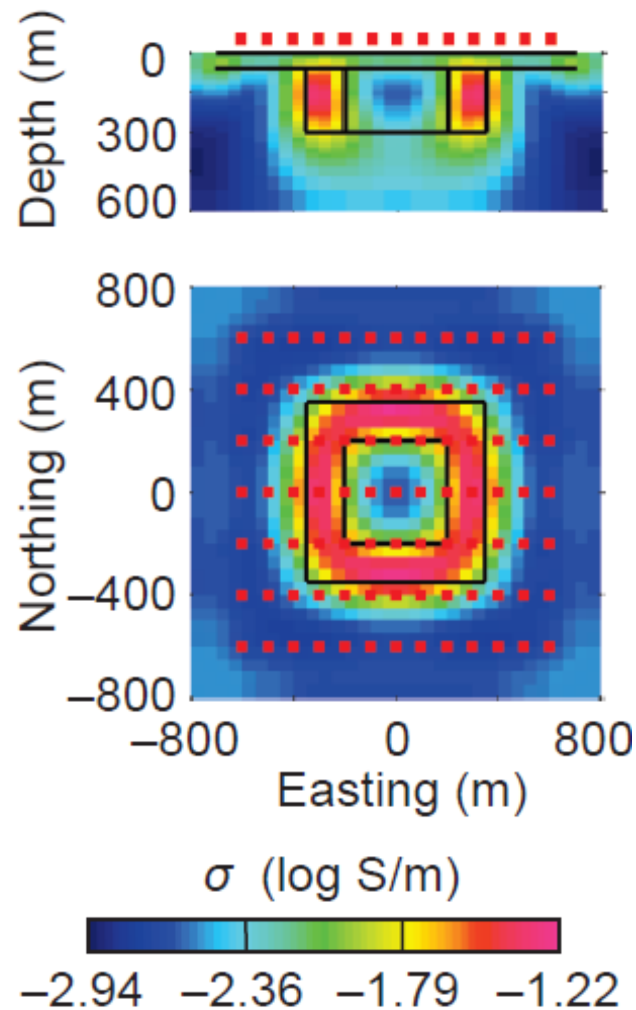


1D VS 3D: Mt. Milligan Synthetic Model

1D Inversion Model

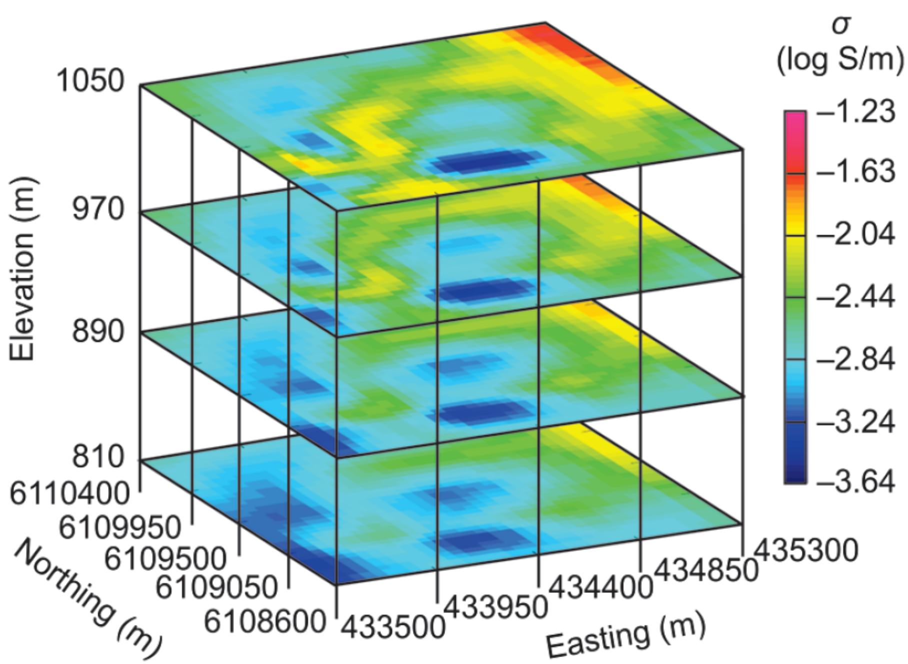


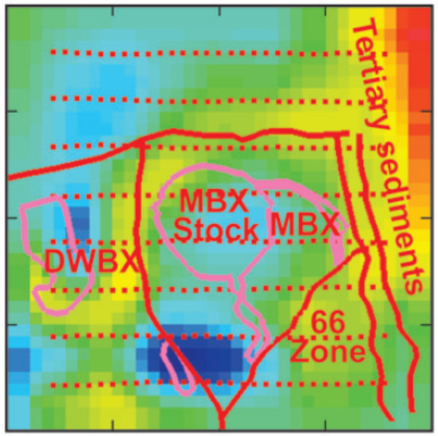
3D Inversion Model

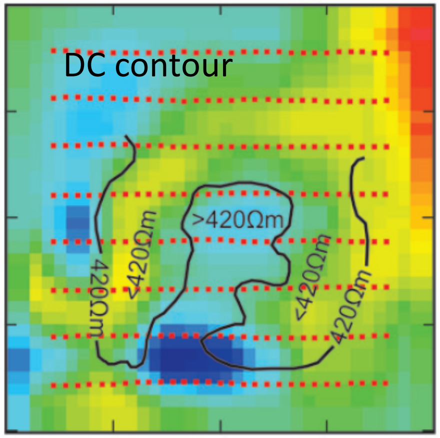


3D VTEM Inversion Model

- Resistive MBX stock
- Conductive sediments/faults/alteration
- Consistent with DC result

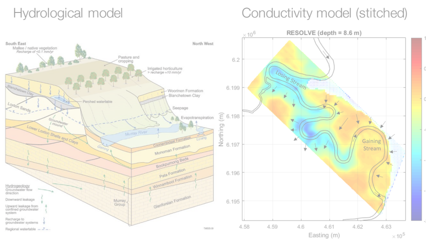




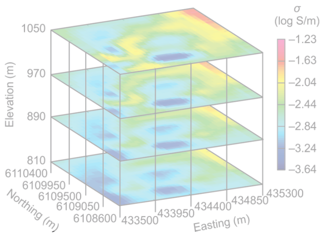


1D or 3D?

- Bookpurnong (moderately 1D)

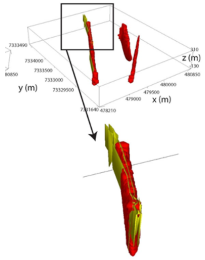


- Mt. Milligan (compact resistor)

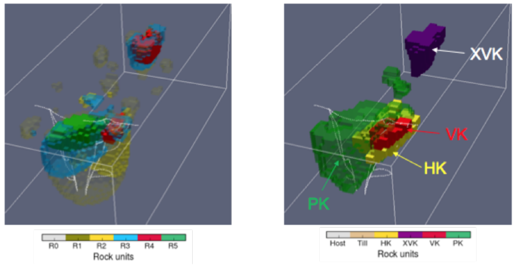


- West Plains

  (thin conductive intersecting structures)

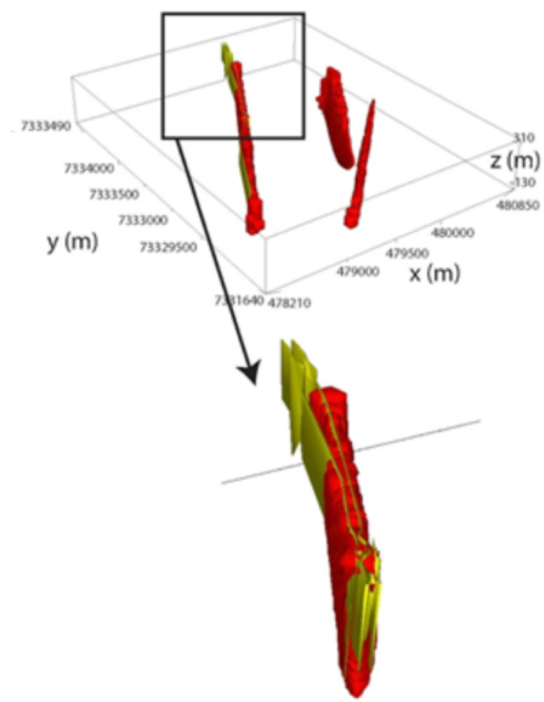


- TKC (compact conductor and IP)



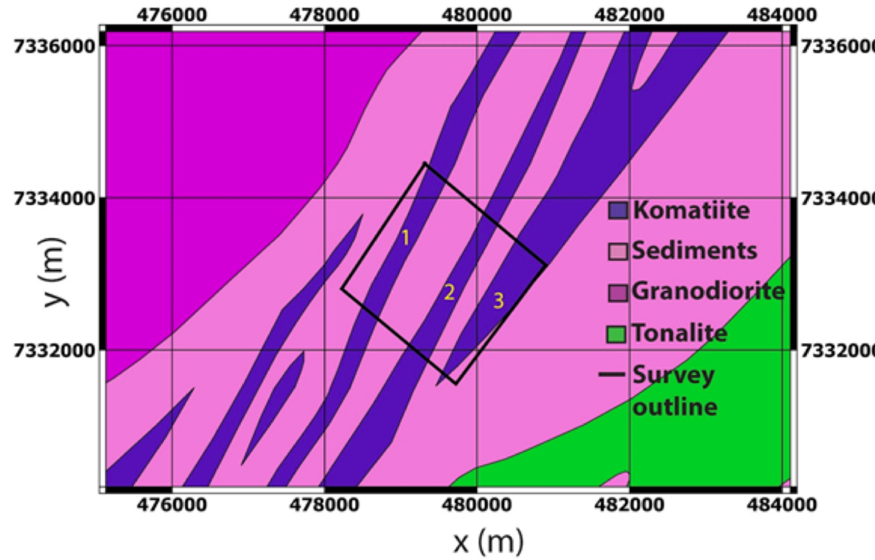
West Plains
Orogenic gold region

McMillan et al, 2014



Setup

Geology map

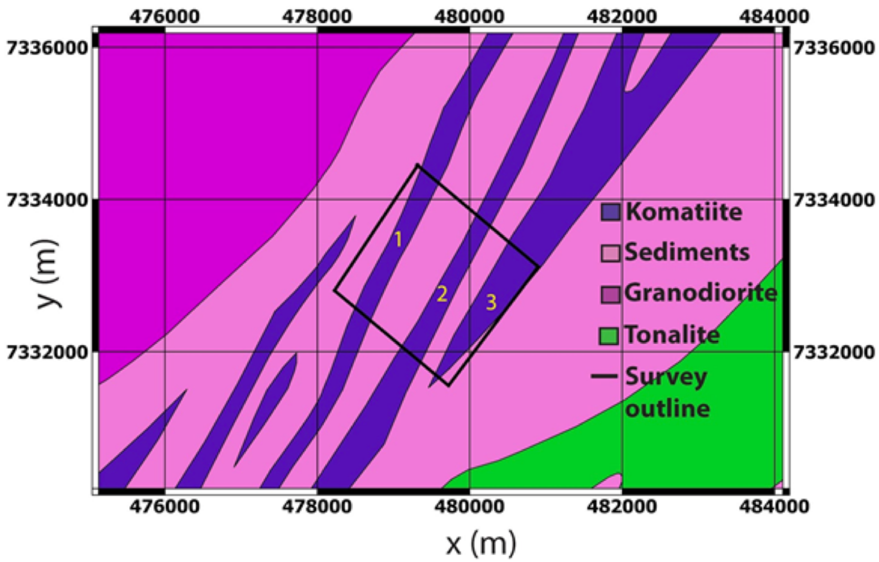


- Ultramafic komatiite units
  - steeply dipping
  - gold mineralization
- Area covered by thin layer of glacial material (outcrops scarce)
- Geology map from regional mag. survey
  - Low resolution; No dip information about the komatiite units

How do we image thin, dipping conductors in 3D?

Properties

Geology map



Dykes:

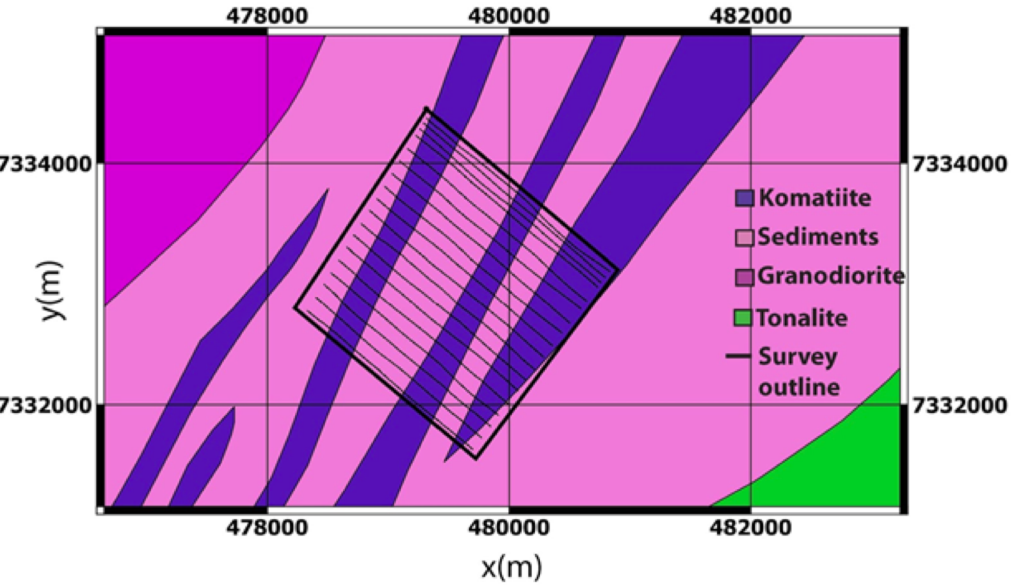
- thin
- highly conducting
- steeply dipping
- intersecting

Geology from magnetics

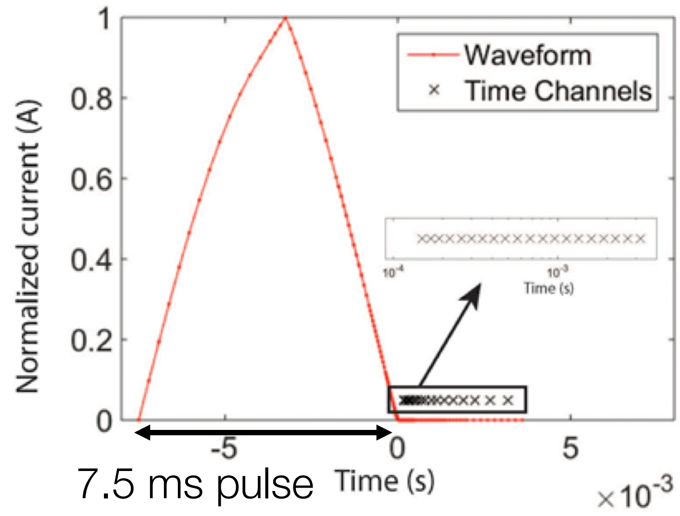
Units	Conductivity	Susceptibility
Komatiite	High	Moderate
Sediments	Moderate	Low
Granodiorite	Low	Low-Moderate
Tonalite	Low	Low-Moderate

Survey: VTEM

Survey lines



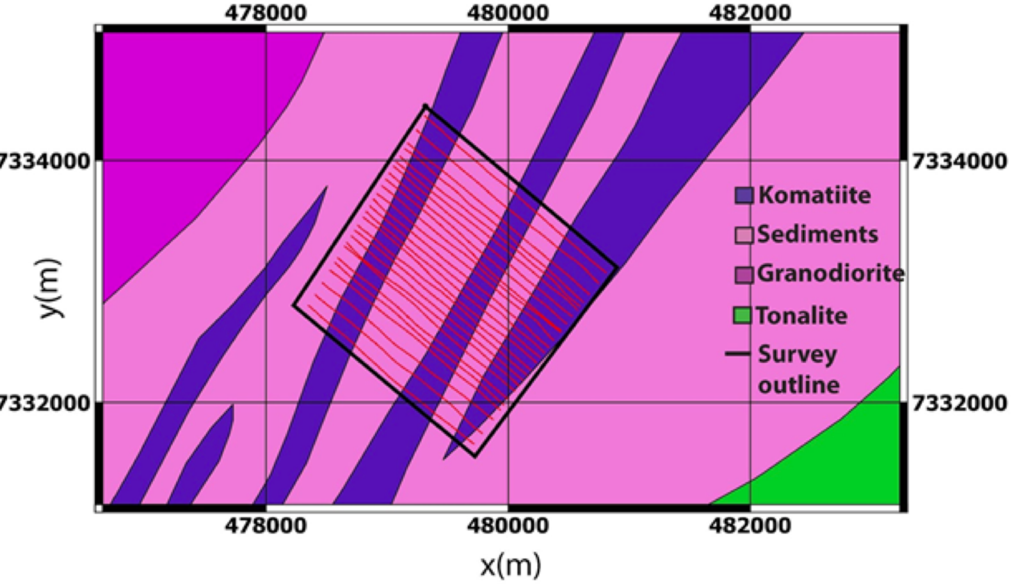
Current waveform



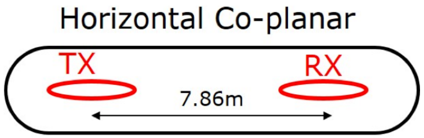
- VTEM (2003) system
  - Line spacing: 120 m; except several lines in the North part (60 m)
  - Line direction: 310 degree
  - Transmitter diameter: 18.5 m
  - Measured component: dBz/dt (26 time channels from 110-6340 μs)

Survey: RESOLVE

Survey lines



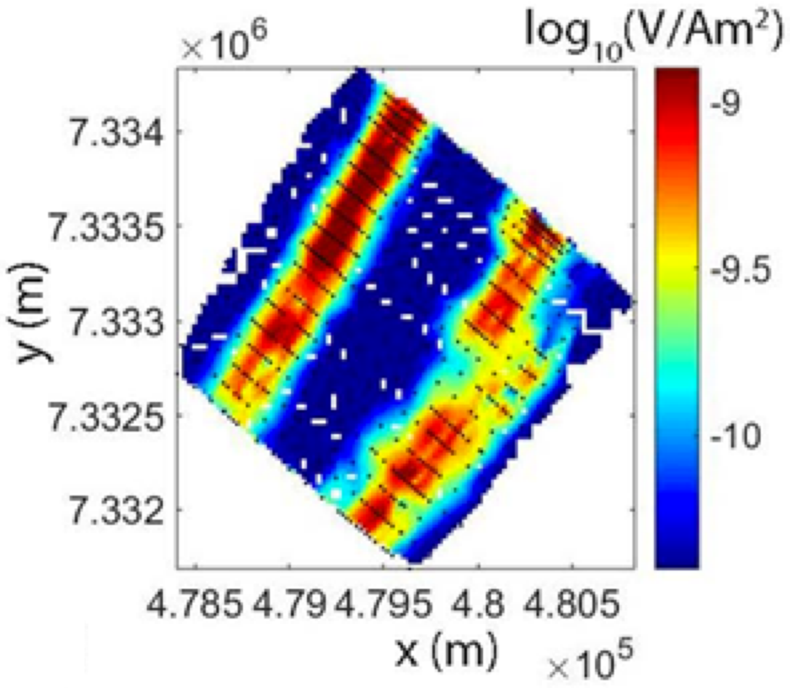
System



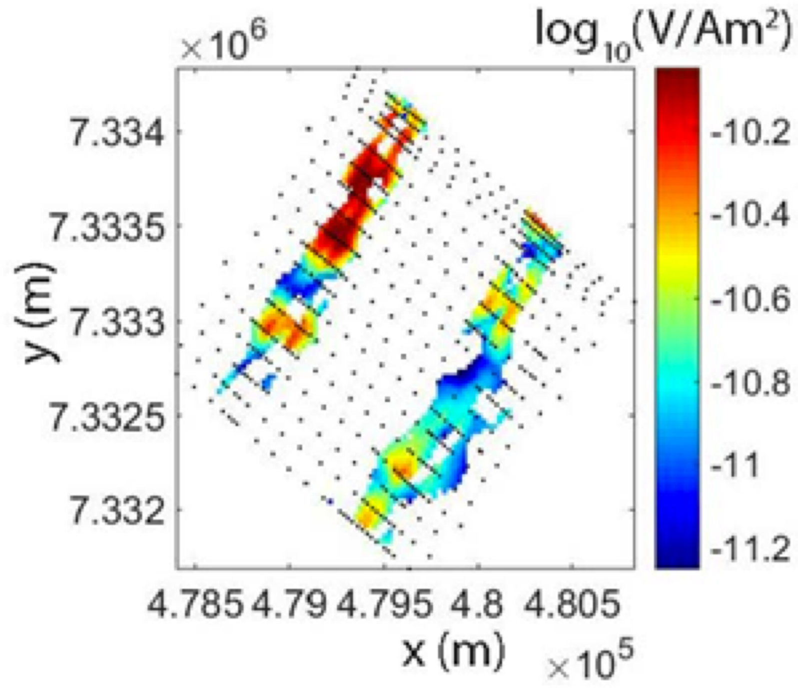
- RESOLVE (2005) system
  - Line spacing: 60 m
  - Line direction: 310 degree
  - Co-planar: 385-115,000 Hz (5 frequencies)

Data: VTEM

dBz/dt at 150 μs



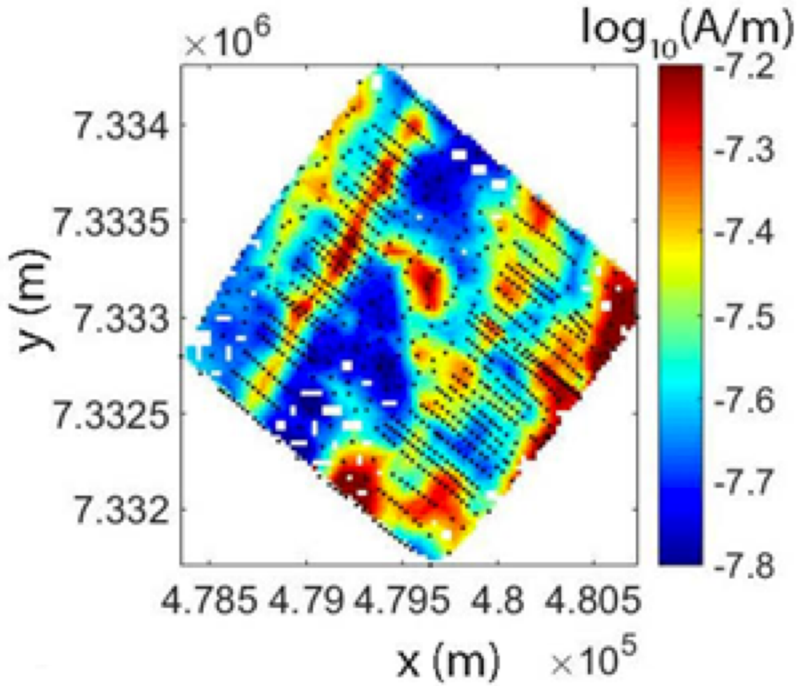
dBz/dt at 3180 μs



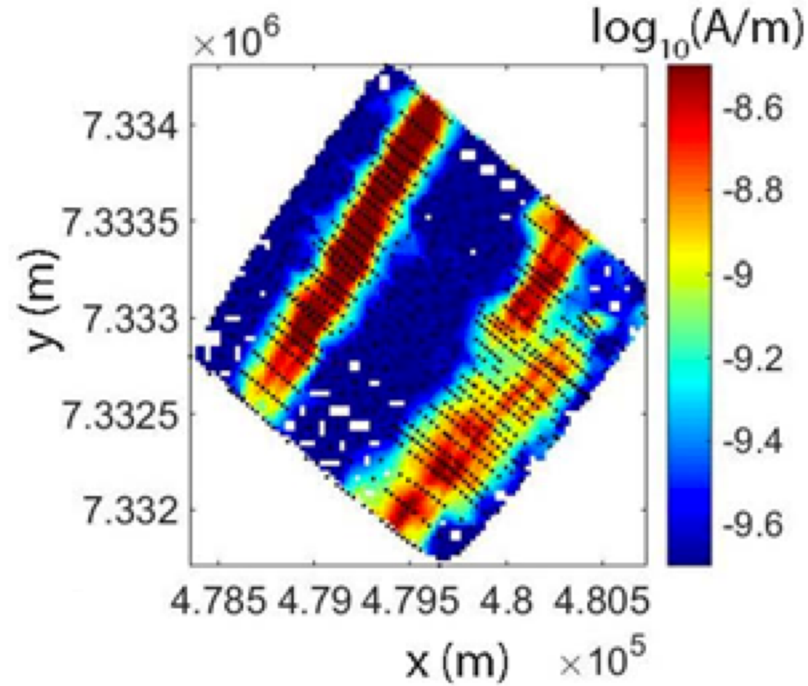
- At 150 μs: strong conductivity anomalies
- Noise level: 5×10^{-12} V/Am^2 (values below blanked-out)

Data: RESOLVE

Bz Imaginary at 115,000 Hz



Bz Imaginary at 385 Hz

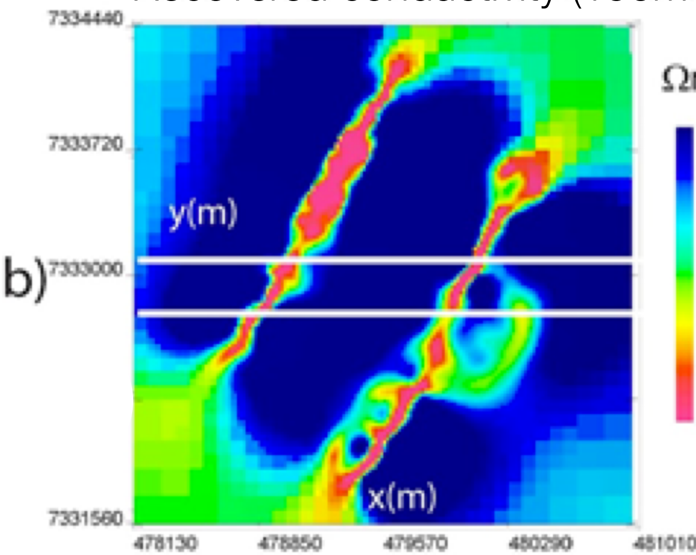


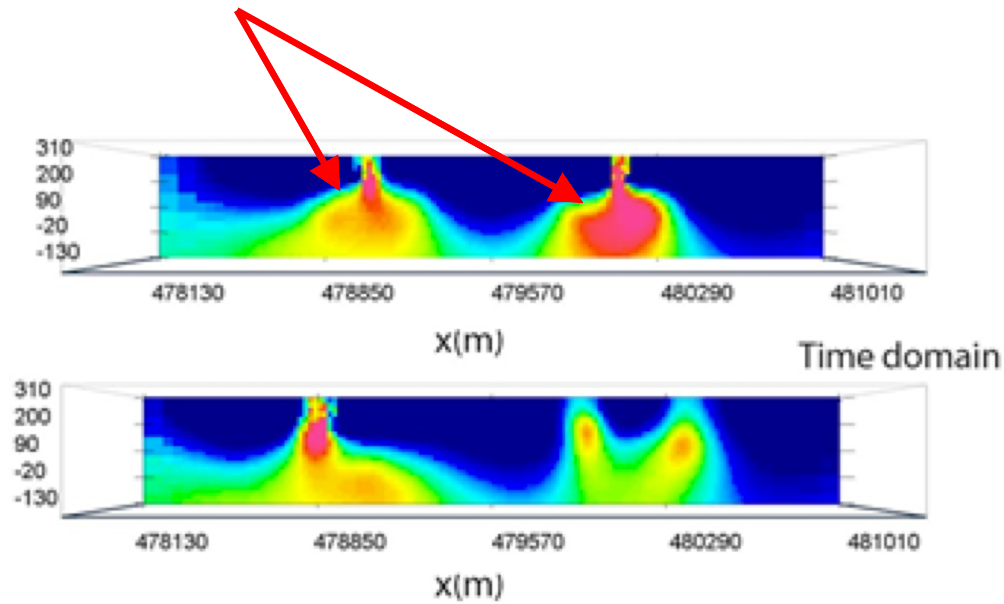
– 115,000 Hz data contains near-surface information
– 385 Hz data similar to the VTEM data at 150 μs

Processing: VTEM

- Voxel inversion
  - Starting model: 1000 Ωm
- Image conductors
- Smooth regularization blurs conductors at depth

Recovered conductivity (190m depth)

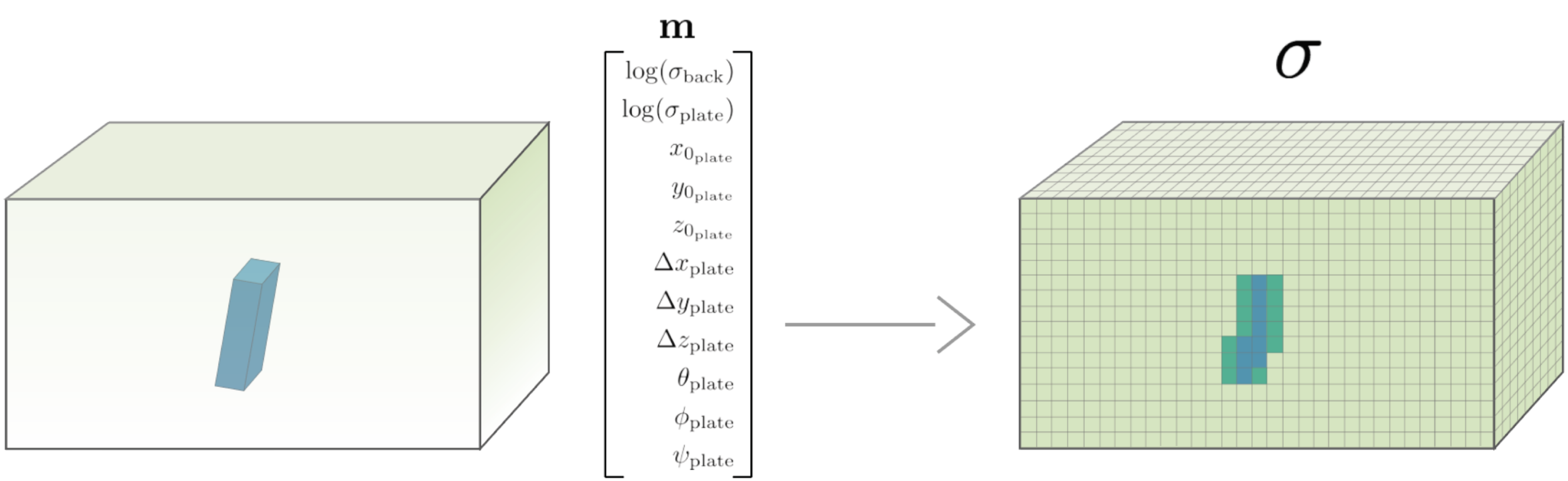




How do we image thin, dipping conductors in 3D?

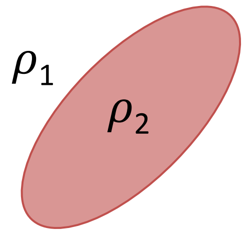
Parametric Inversion

- Mathematical description to be compatible with geology
- Find a representation using only a few parameters
- Thin dykes:
  - Plates (plate with parameters)
  - Ellipsoids (Gaussian ellipsoid with parameters)

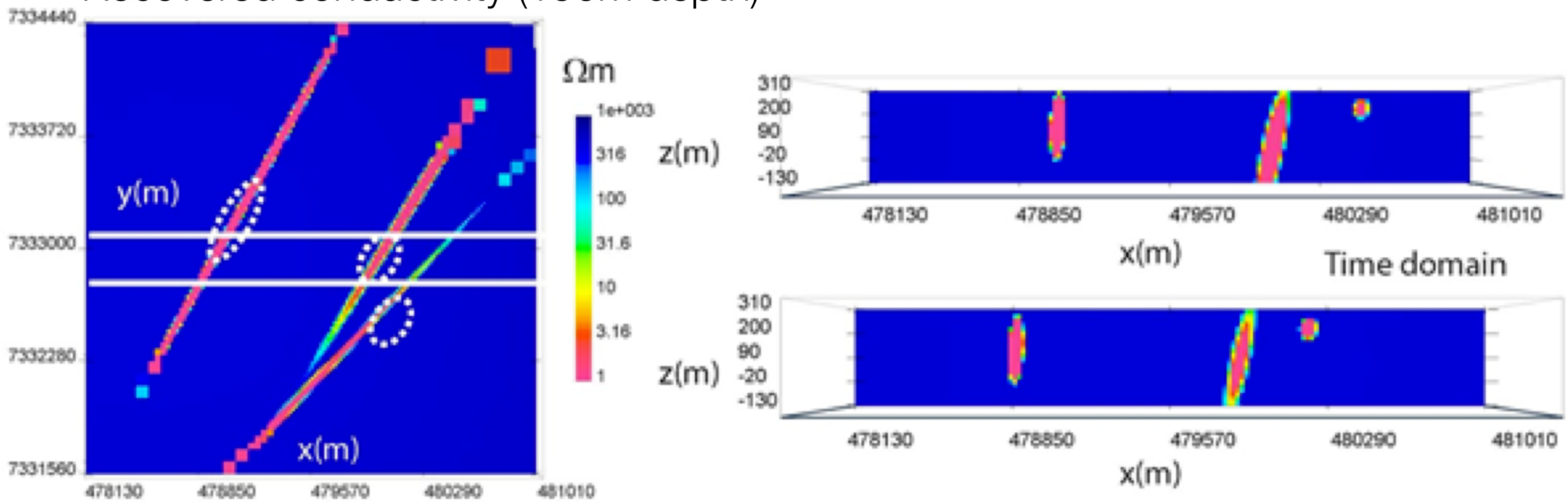


Processing: VTEM

- Parametric inversion
  - Parameterize dipping conductors as Gaussian ellipsoids
  - Invert for:
    - Resistivity: background and ellipsoid
    - Shape and location of ellipsoid

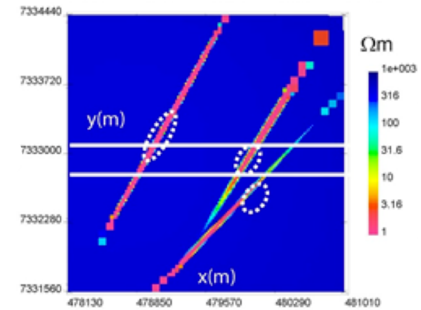


Recovered conductivity (190m depth)

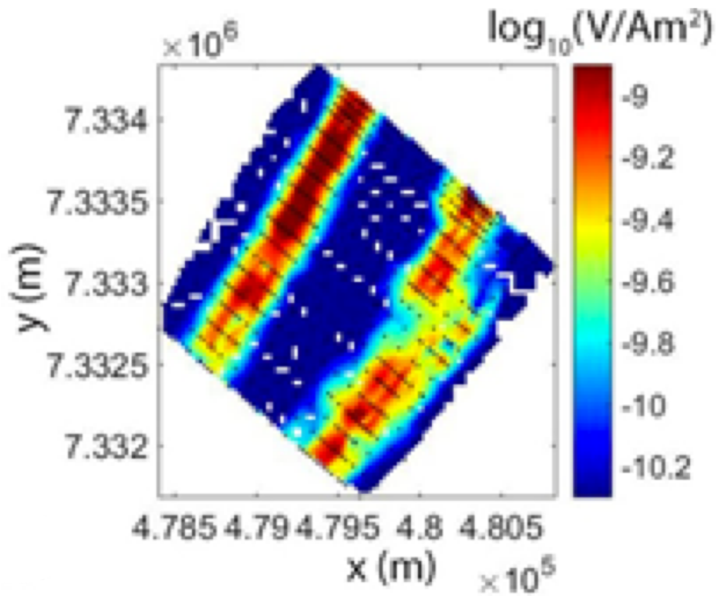


Dashed lines: Initial guess

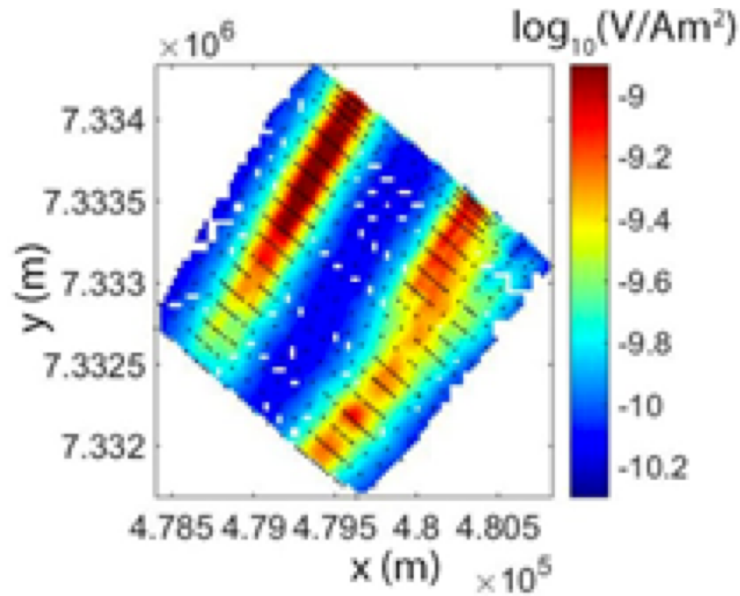
Processing: VTEM



Observed dBz/dt at 150μs



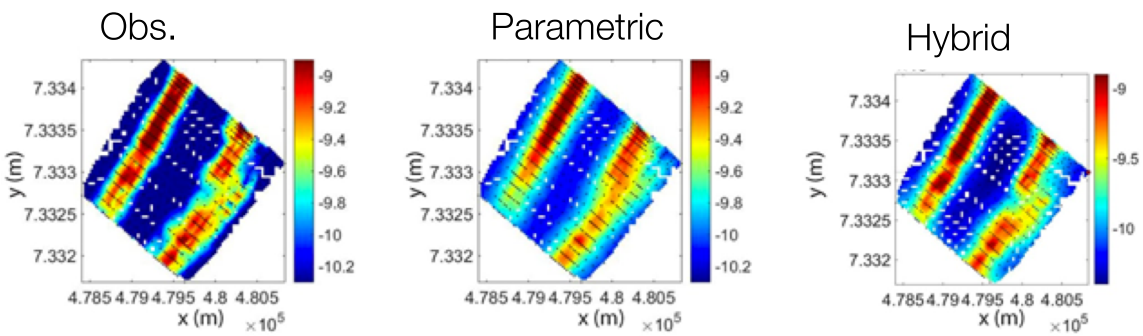
Predicted dBz/dt at 150 μs



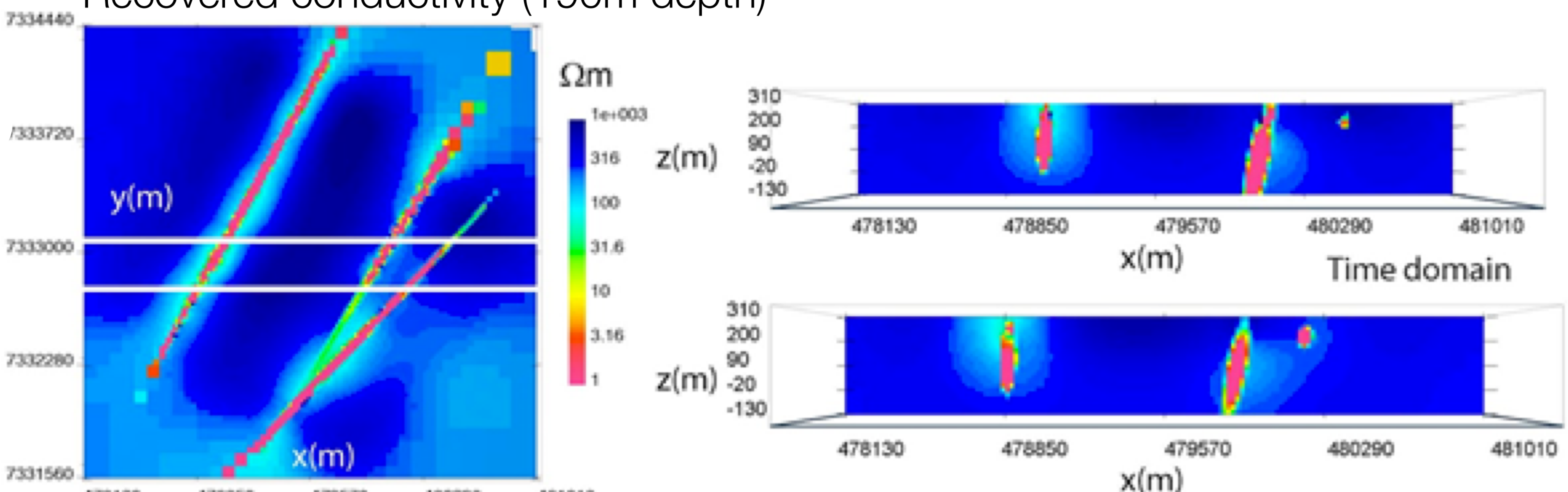
Parametric inversion too simple to explain heterogeneous earth

Processing: Hybrid Inversion

- Voxel inversion using parametric inversion result as initial and reference model

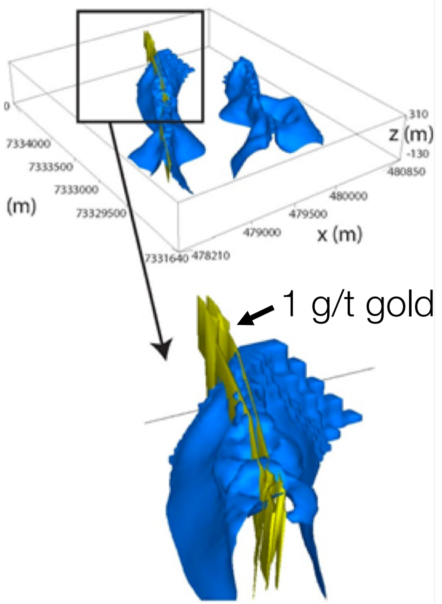


Recovered conductivity (190m depth)

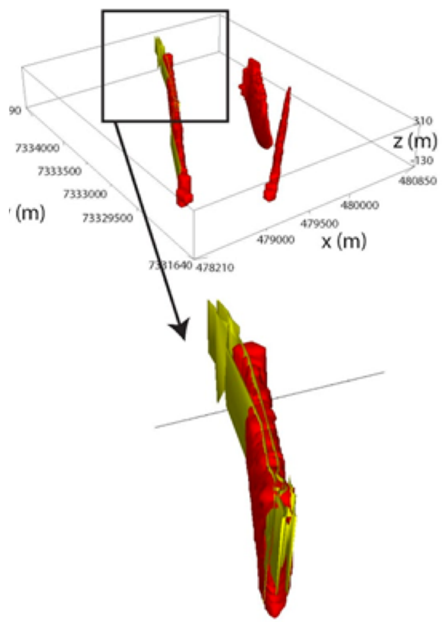


Interpretation: VTEM

Voxel inversion cut-off (30 Ωm)

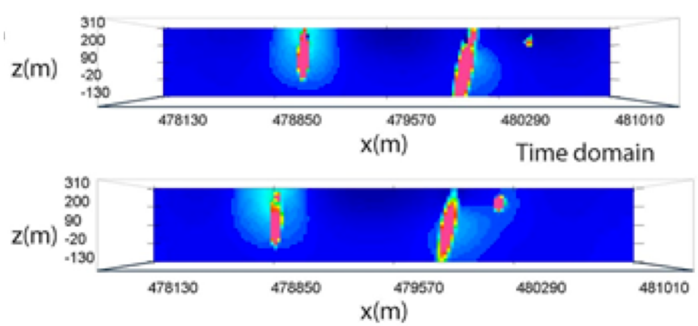


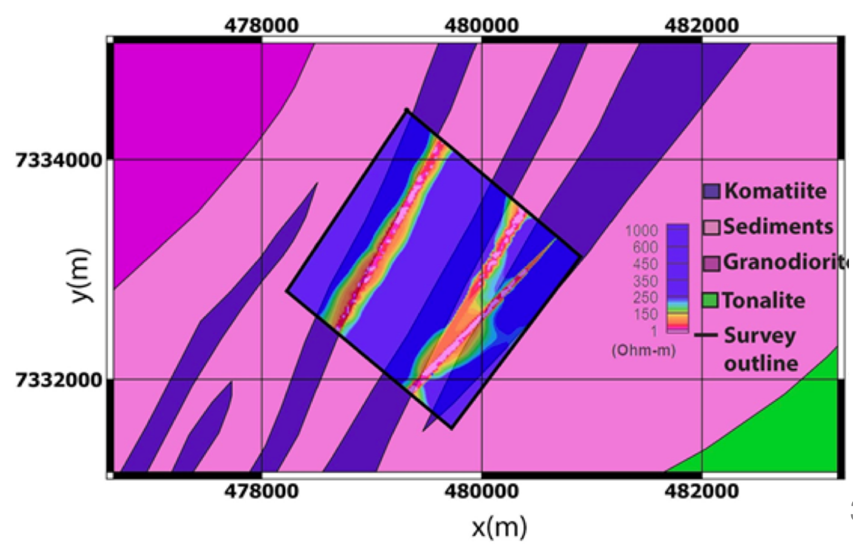
Hybrid inversion cut-off (30 Ωm)



- Voxel inversion: blurs conductors at depth
- Hybrid inversion
  - Dips recovered
  - Tighter boundary of the komatiite
  - Good agreement with gold grade

Hybrid inversion: vertical sections

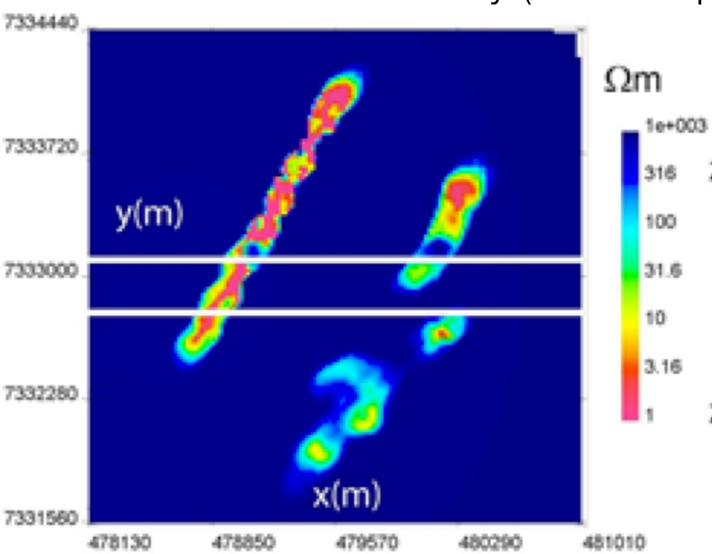


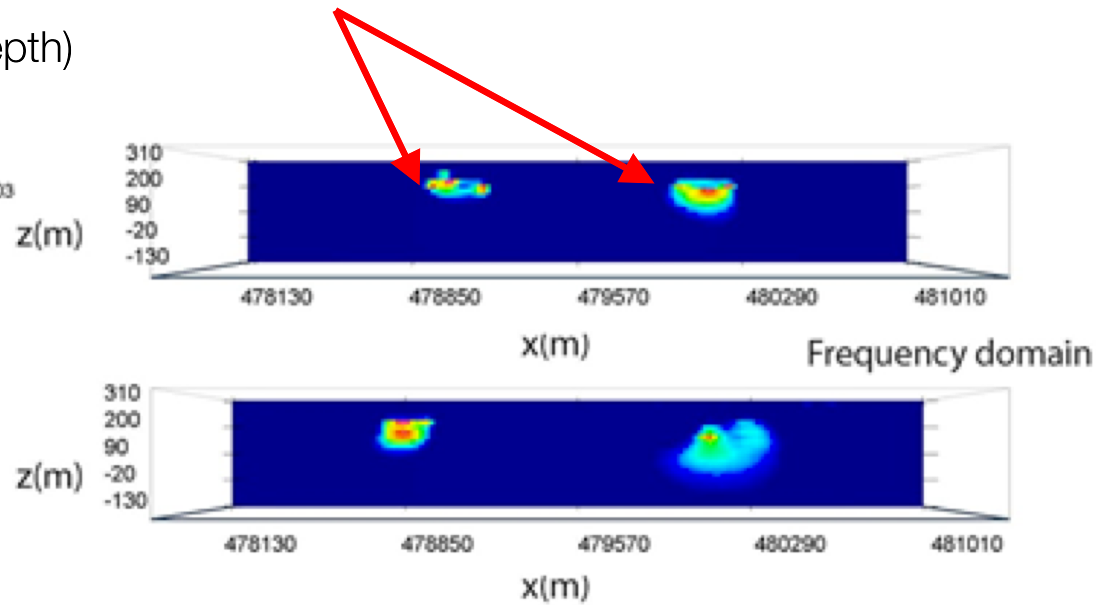


Processing: RESOLVE

- Voxel inversion
  - Starting model: 1000 Ωm
- Image conductors
- Smooth regularization blurs thin conductors

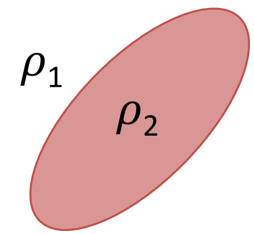
Recovered conductivity (190m depth)



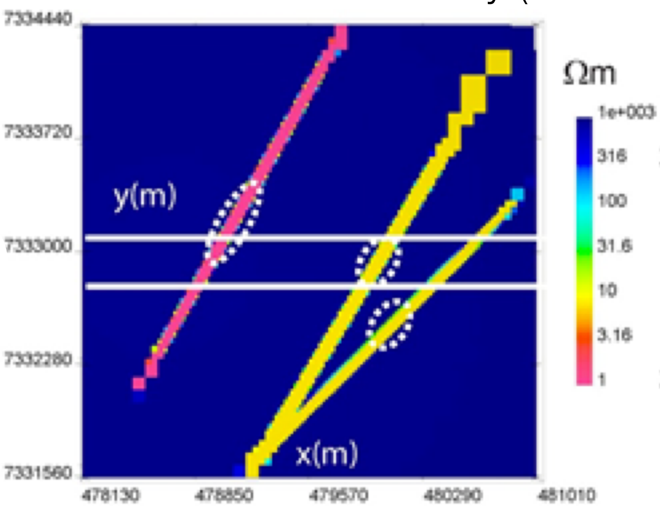


Processing: RESOLVE

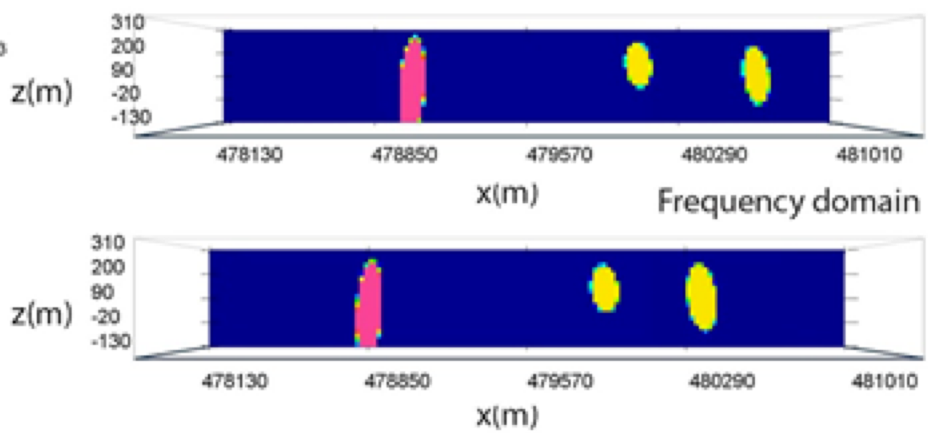
- Parametric inversion
  - Parameterize dipping conductors as Gaussian ellipsoids
  - Invert for:
    - Resistivity: background and ellipsoid
    - Shape and location of ellipsoid



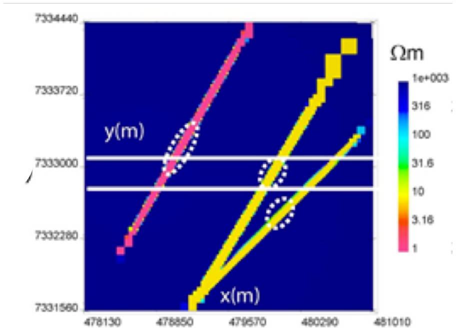
Recovered conductivity (190m depth)



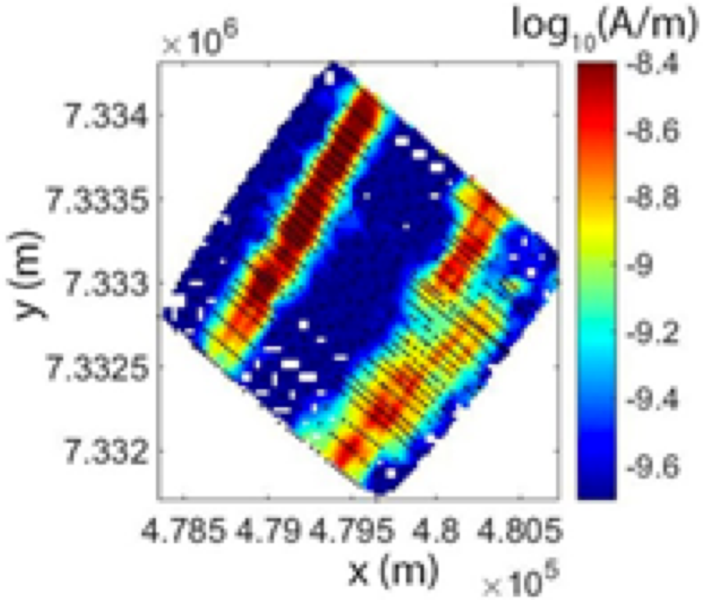
Dashed lines: Initial guess



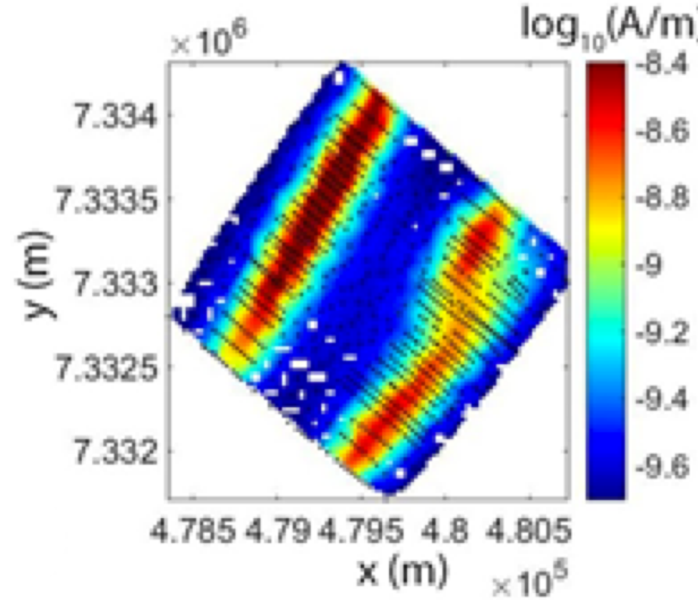
Processing: RESOLVE



Observed Bz Imag at 385 Hz



Predicted Bz Imag at 385 Hz

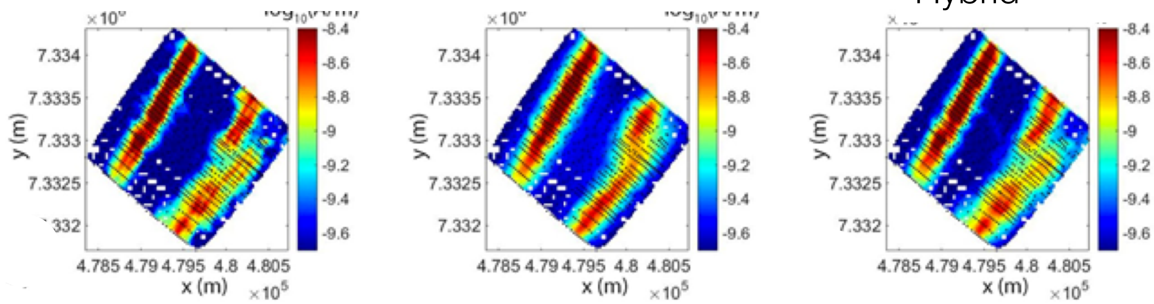


Parametric inversion too simple to explain heterogeneous earth

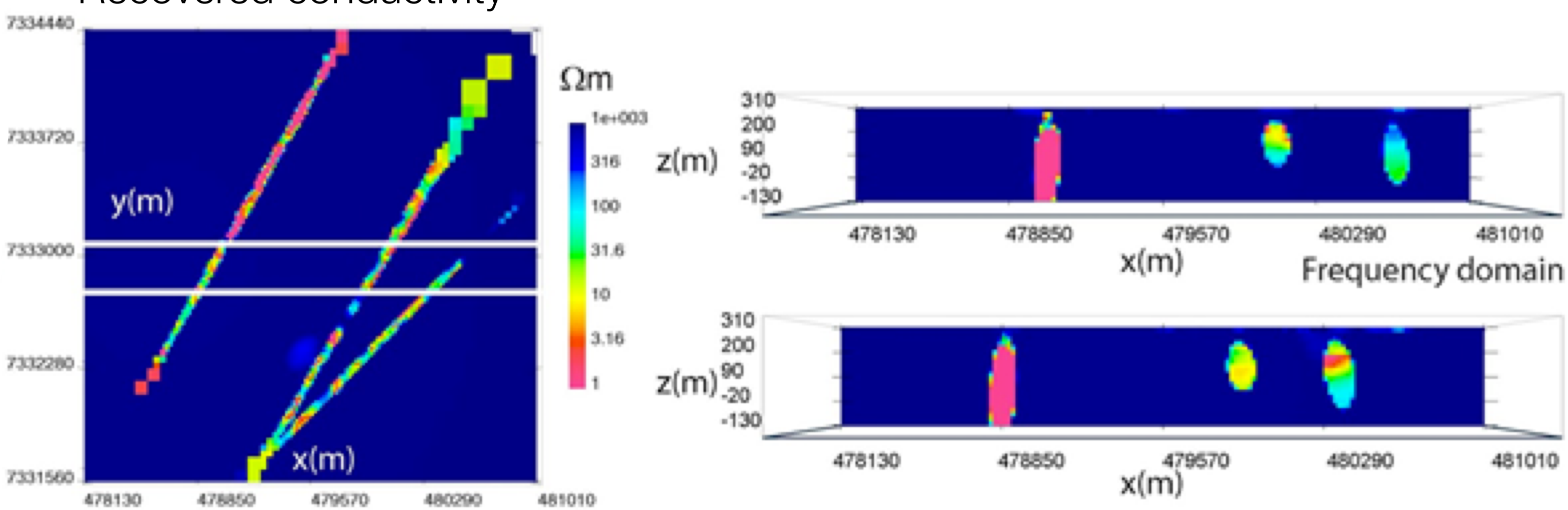
Processing: Hybrid Inversion

- Voxel inversion using parametric inversion result as initial and reference model

Obs. Parametric Hybrid

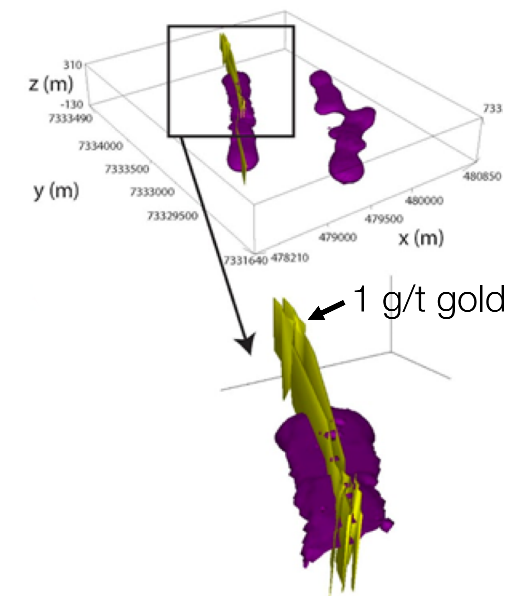


Recovered conductivity

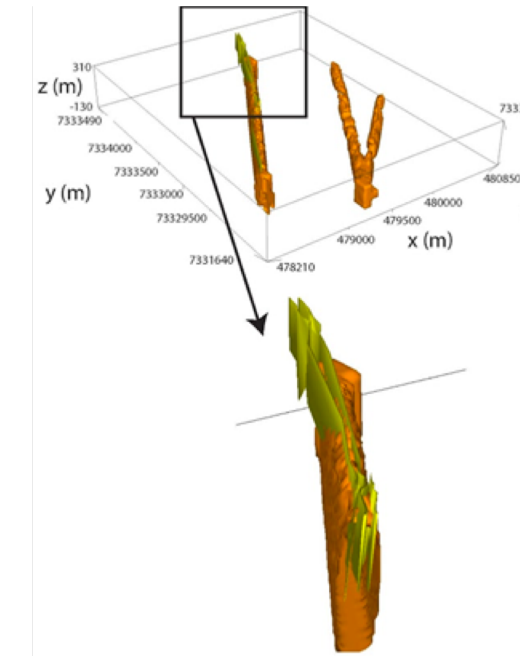


Interpretation: RESOLVE

Voxel inversion cut-off (30 Ωm)

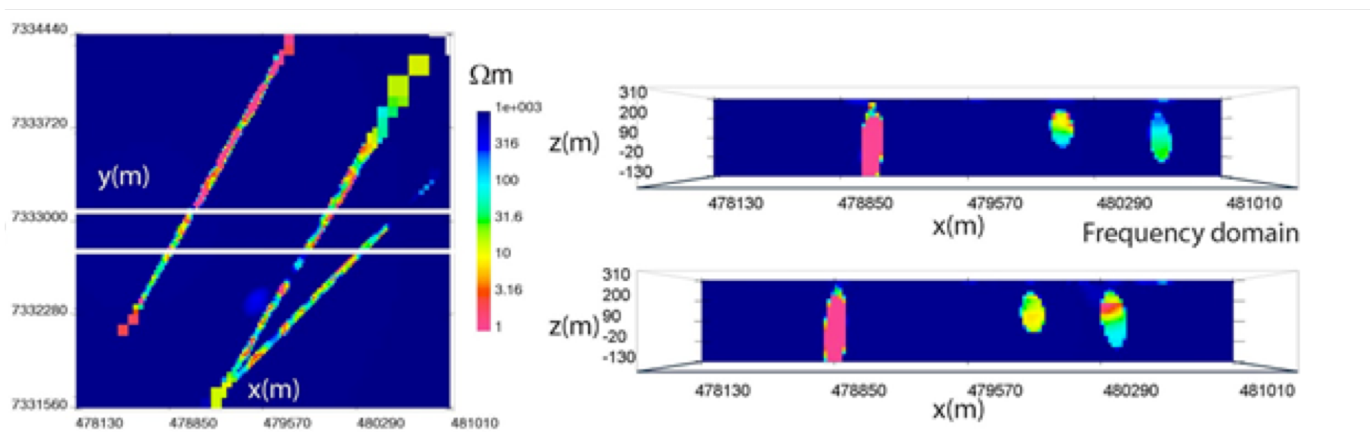


Hybrid inversion cut-off (30 Ωm)

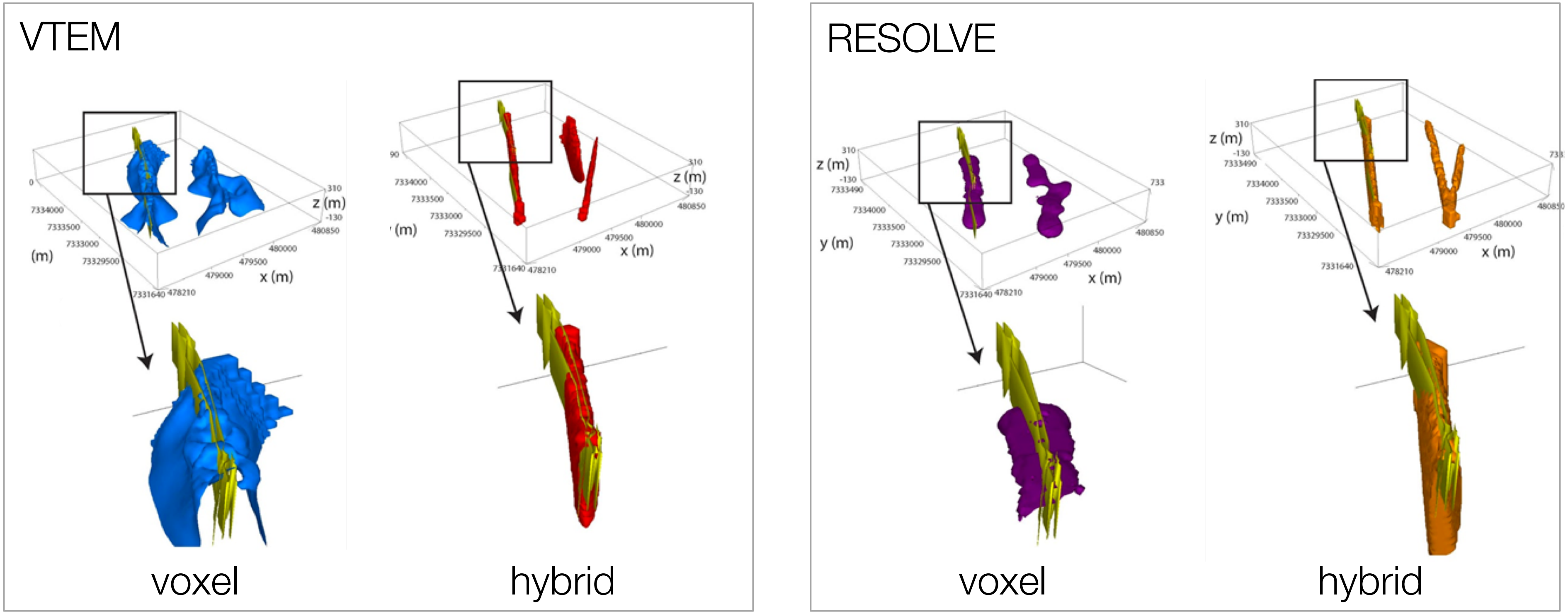


- Voxel inversion: blurs thin conductors
- Hybrid inversion
  - Dips recovered
  - Tighter boundary of the komatiite
  - Good agreement with gold grade

Hybrid inversion



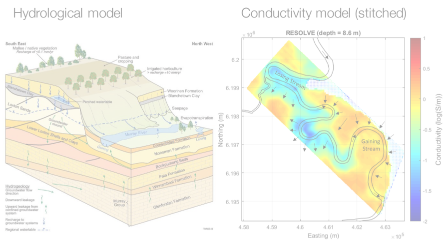
Synthesis



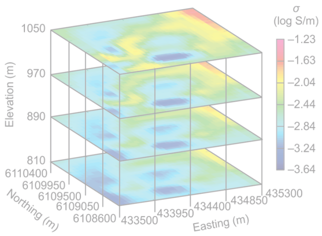
- TDEM and FDEM survey sensitive to conductors
- Hybrid inversion beneficial for imaging thin, dipping conductors
- 3D inversion is necesssary

1D or 3D?

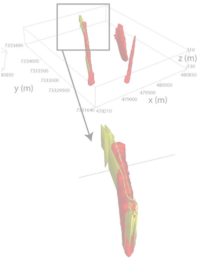
- Bookpurnong (moderately 1D)



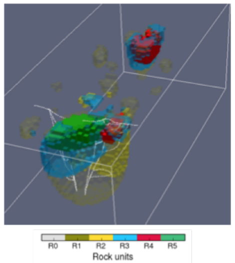
- Mt. Milligan (compact resistor)

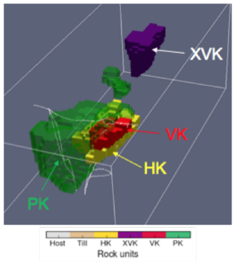


- West Plains
  (thin conductive intersecting structures)



- TKC (compact conductor and IP)



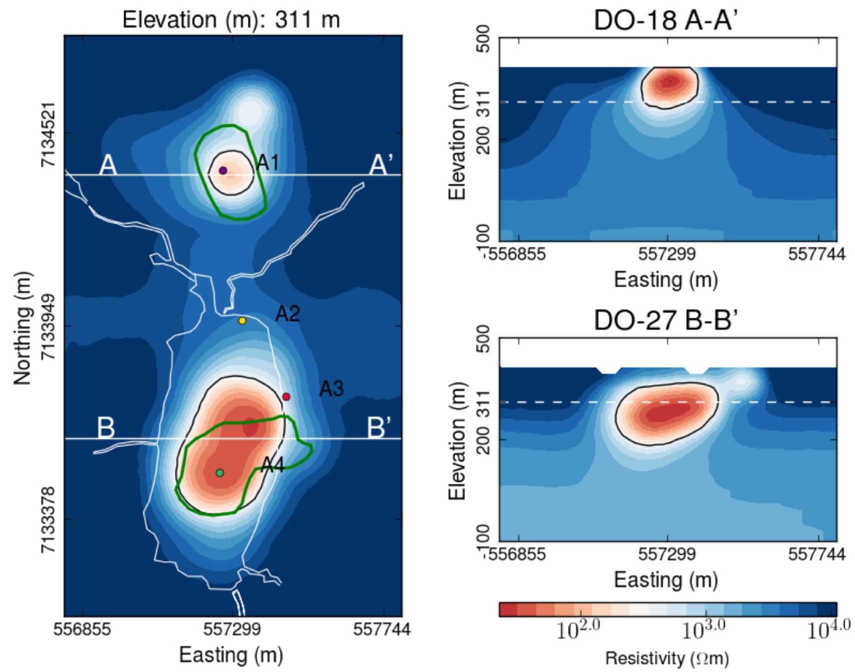


Workflow for airborne EM/IP

Invert TEM data,
to recover

Compute IP datum
Remove EM responses

Invert d^{IP} data,
recover pseudo-chargeability



Workflow for airborne EM/IP

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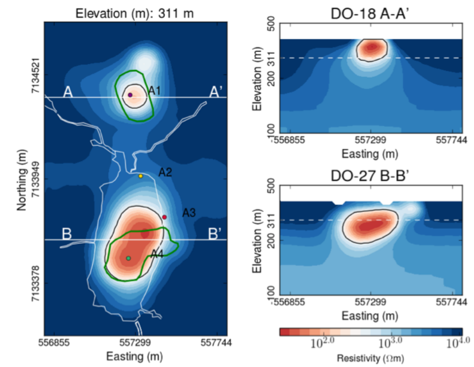
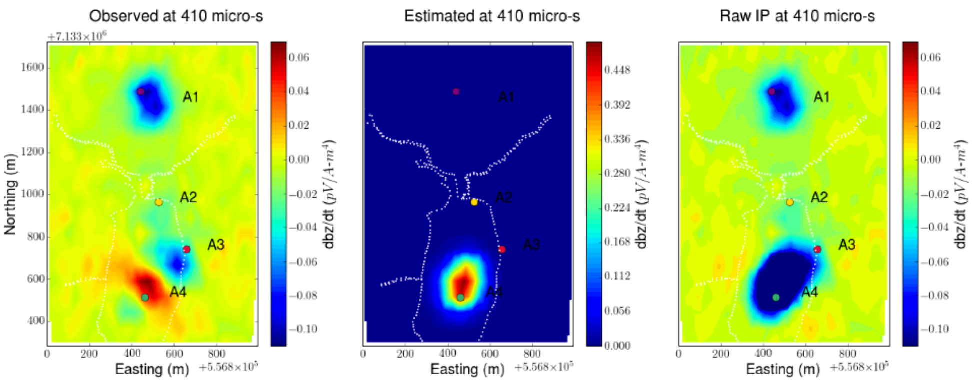


IP = Observation - EM

Observed | Predicted EM | IP

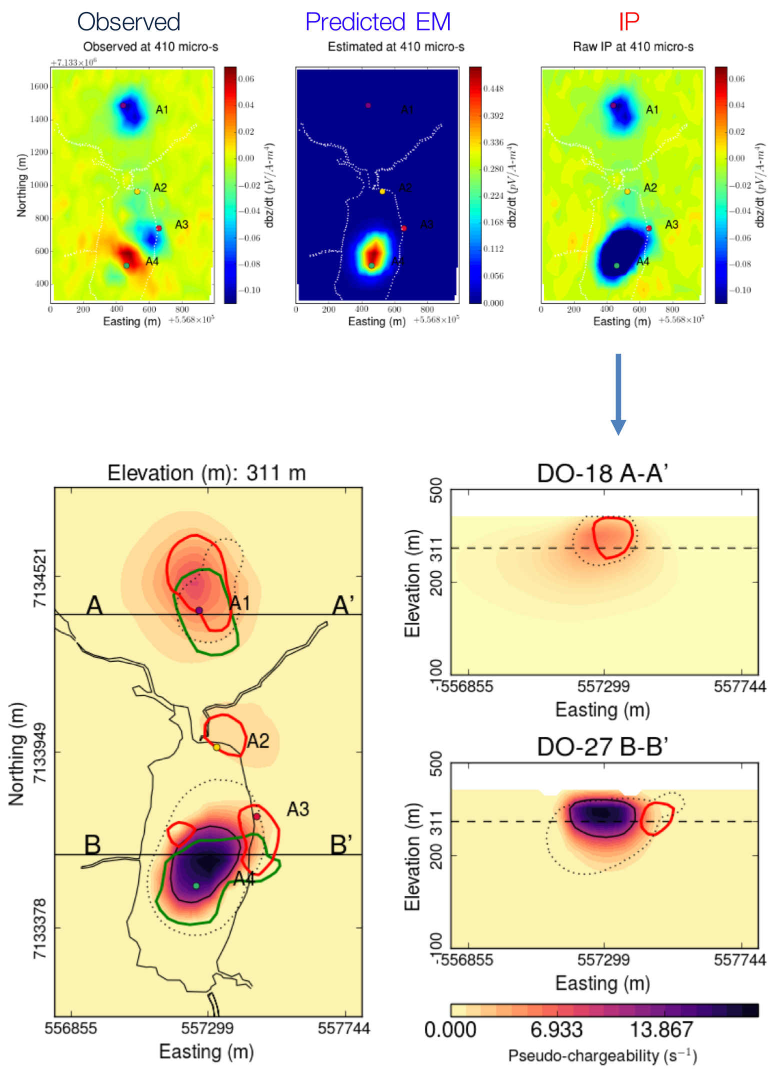


Workflow for airborne EM

Invert TEM data, to recover

Compute IP datum
Remove EM responses

Invert d^{IP} data, recover pseudo-chargeability

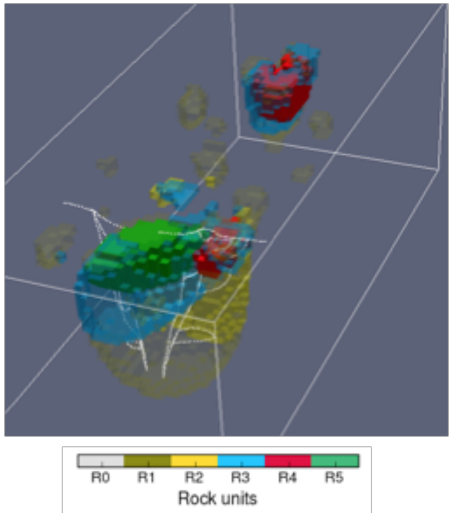


Case History:

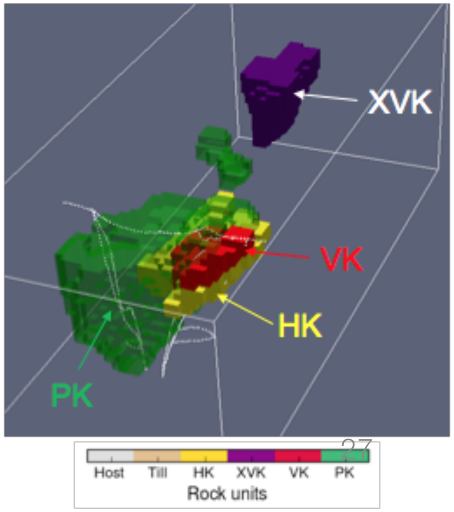
Inversion of airborne geophysical data over the Tli Kwi Cho kimberlite complex

[Devriese et al, 2017]; [Fournier et al, 2017]; [Kang et al, 2017]

Rock Model from Geophysics

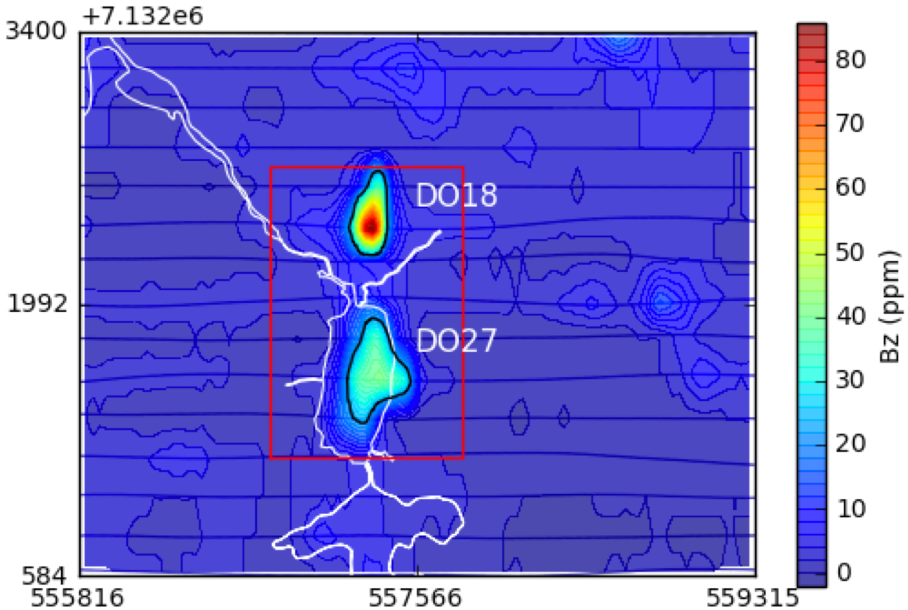


Rock Model from Drilling

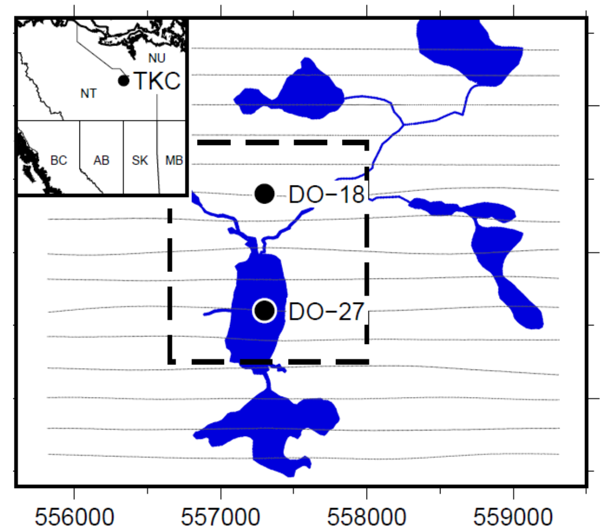


Discovery of Tli Kwi Cho (TKC)

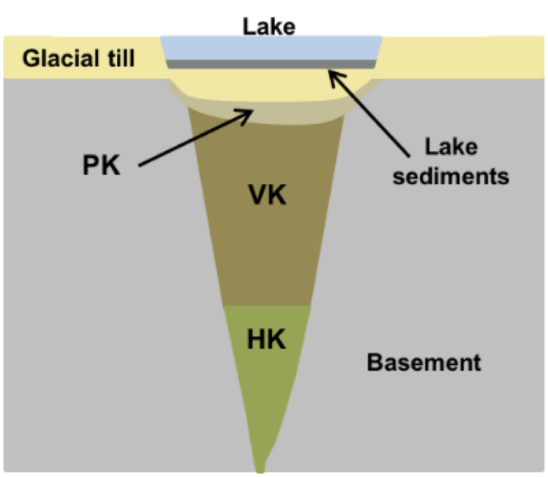
DIGHEM Q7200Hz



Location of TKC, NWT



Kimberlite pipe structure



Devriese et al. (2016)

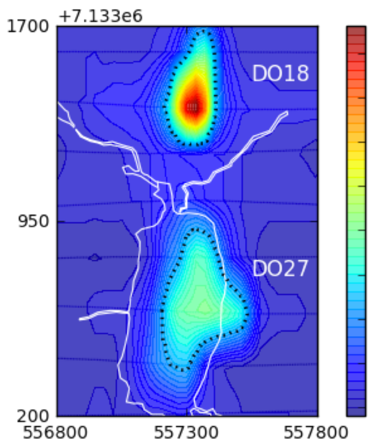
Time domain EM data

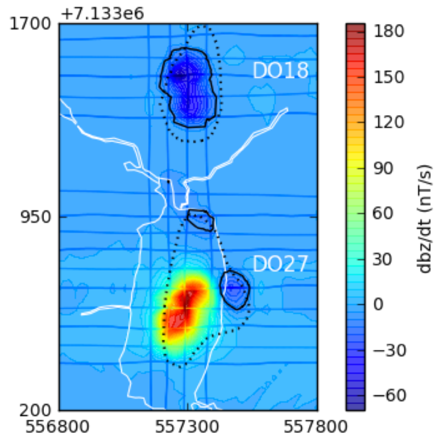
DIGHEM
(1992)

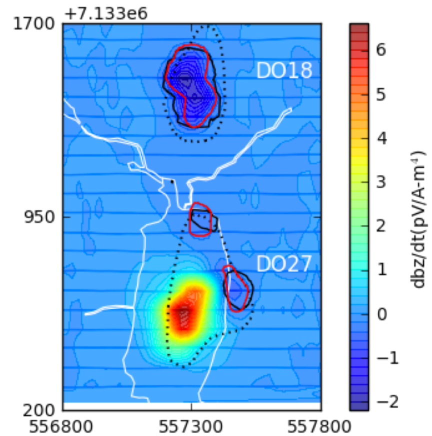
AeroTEMII
(2003)

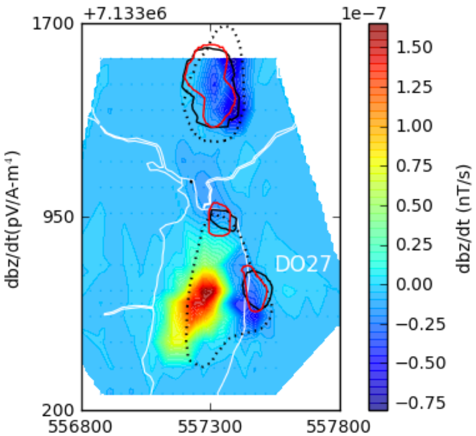
VTEM
(2004)

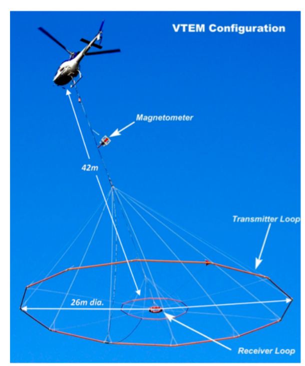
NanoTEM
(1993)



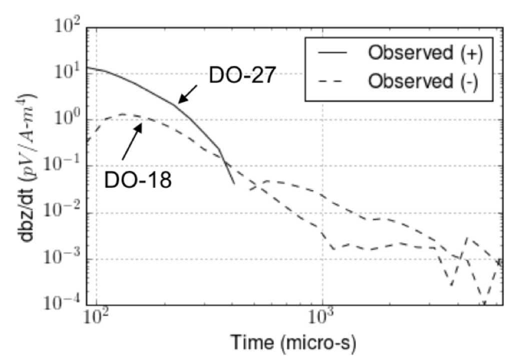






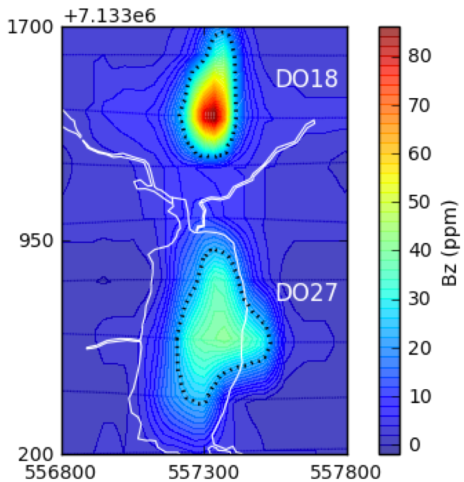


Decay curve

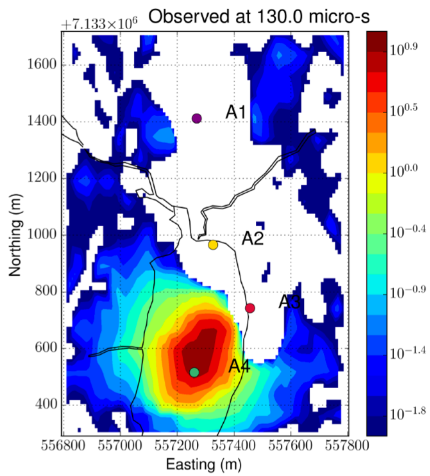


Step 1: Conductivity inversion

DIGHEM

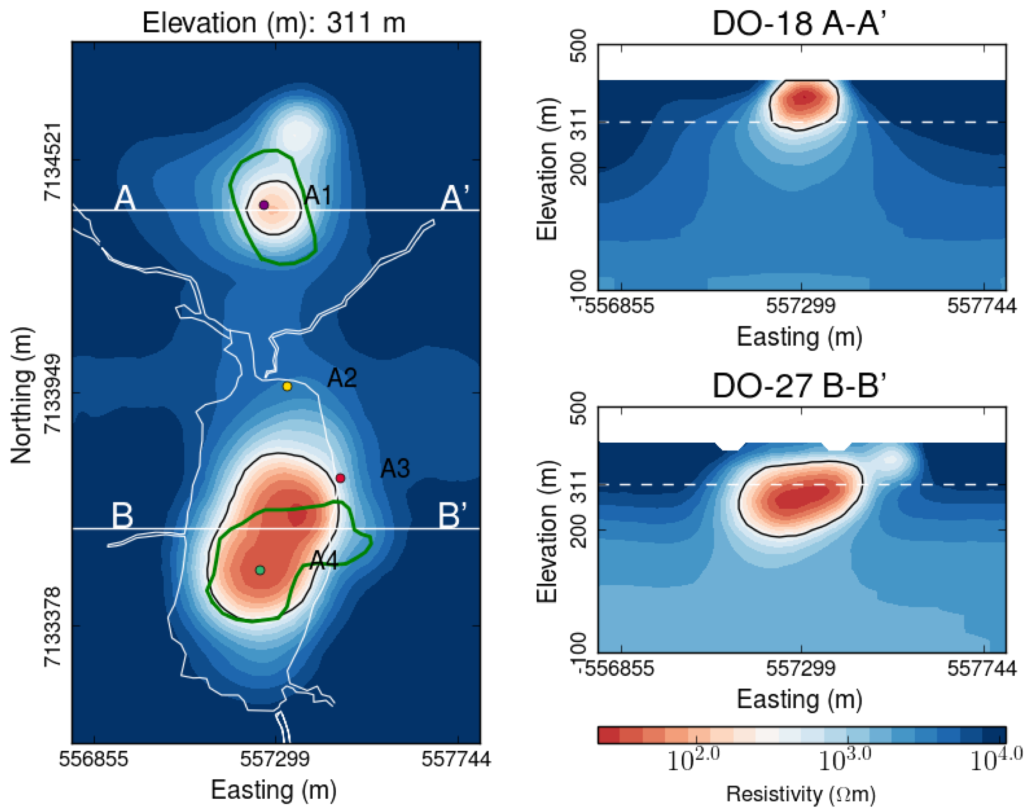


Positive VTEM
(EM-dominant)



Cooperative Inversion

Recovered 3D conductivity



Outline of two pipes

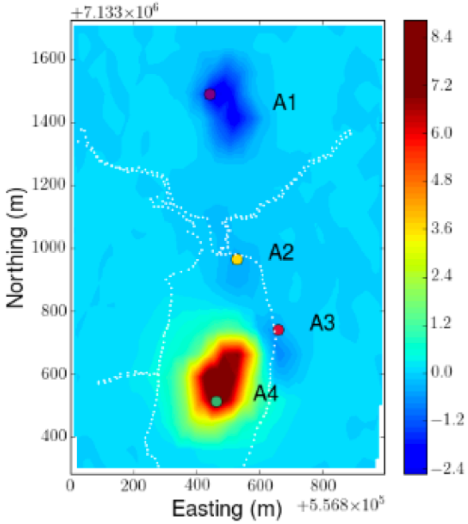
Step 2: EM-decoupling

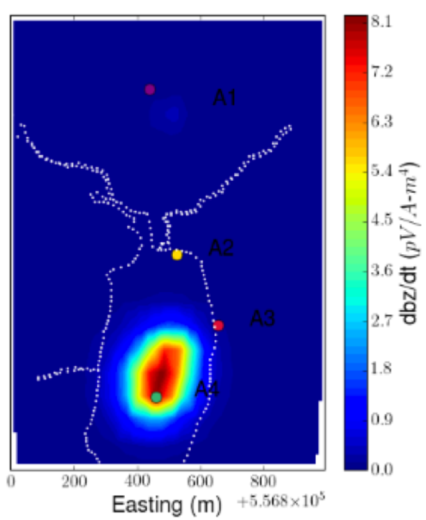
IP = Observation - EM

130 micro-s

Observed

Predicted EM





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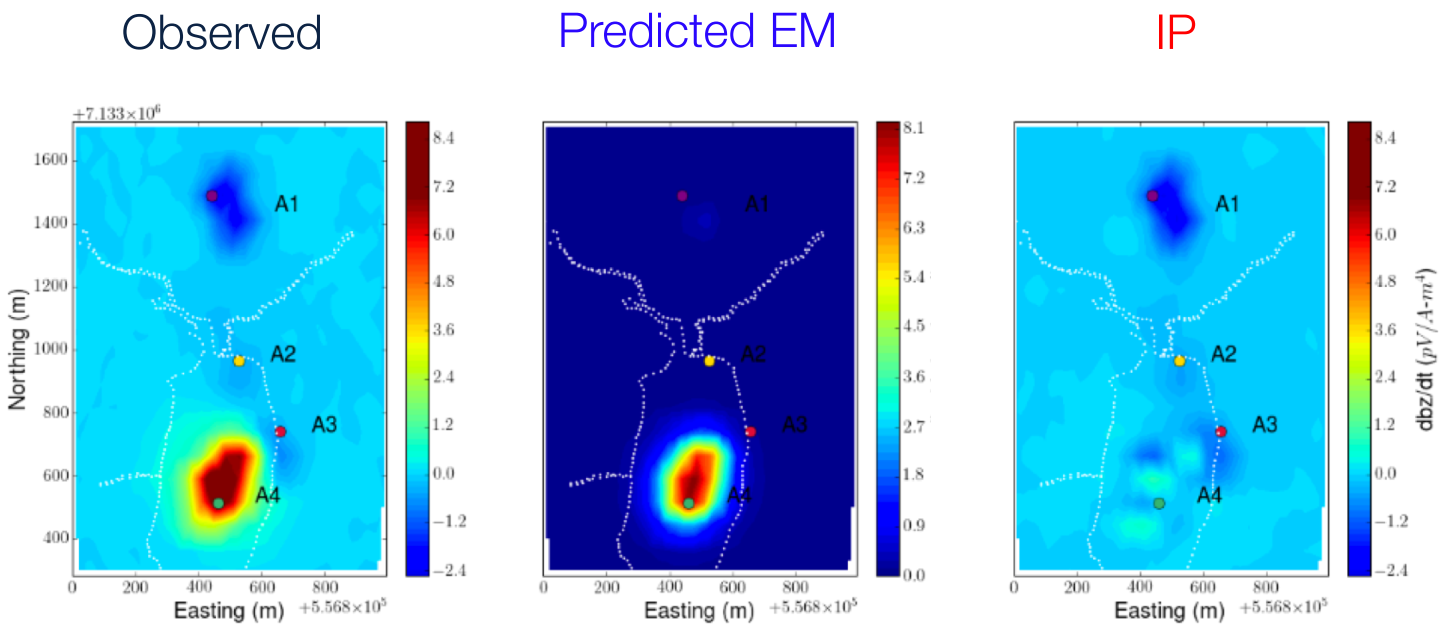
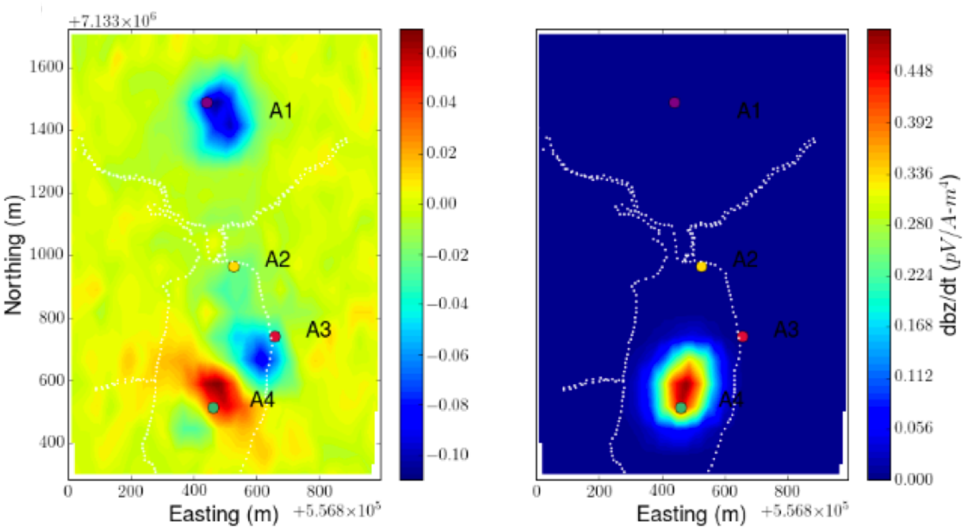


Step 2: EM-decoupling

IP = Observation - EM

410 micro-s

Observed Predicted EM

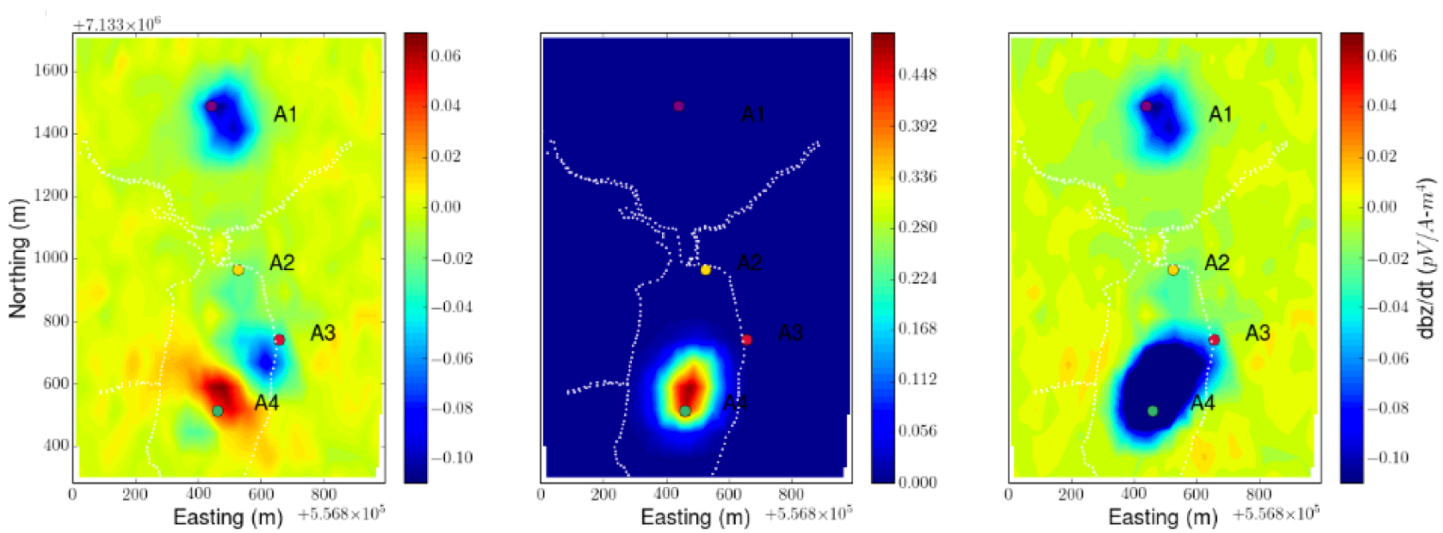


Step 2: EM-decoupling

IP = Observation - EM

410 micro-s

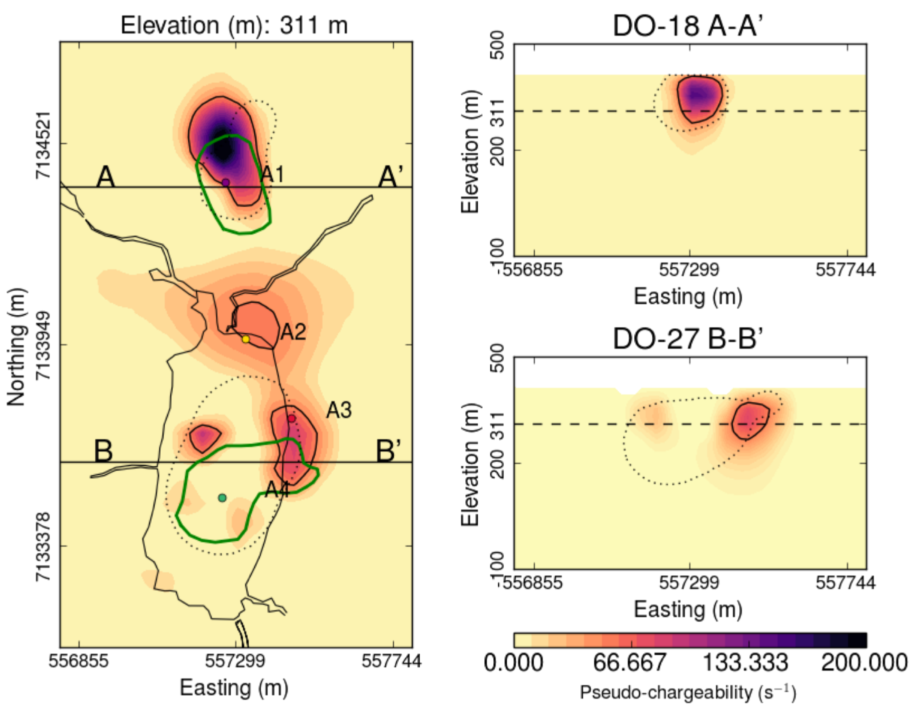
Observed | Predicted EM | IP



Step 3: 3D IP inversion

Recovered 3D pseudo-chargeability

130 micro-s

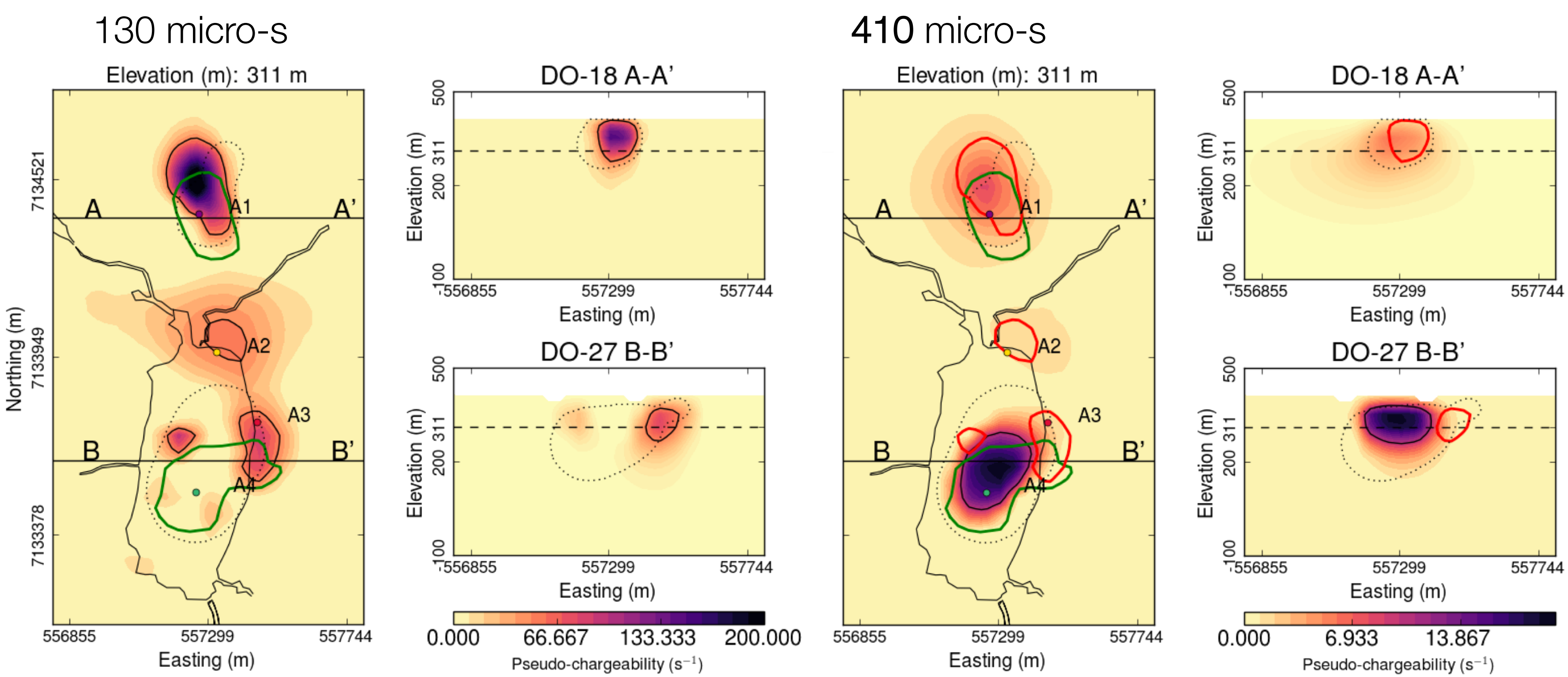


Outline of two pipes

Conductivity contour

Step 3: 3D IP inversion

Recovered 3D pseudo-chargeability

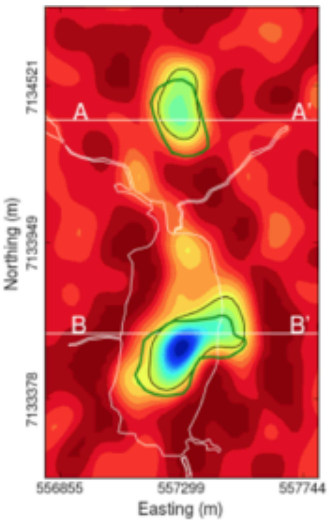


Outline of two pipes

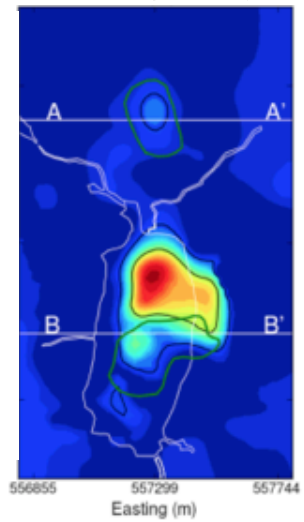
Conductivity contour

Data Integration: 5 physical property models

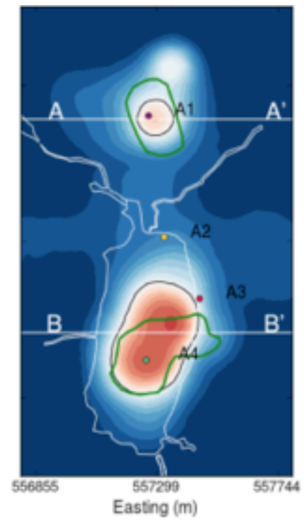
Density



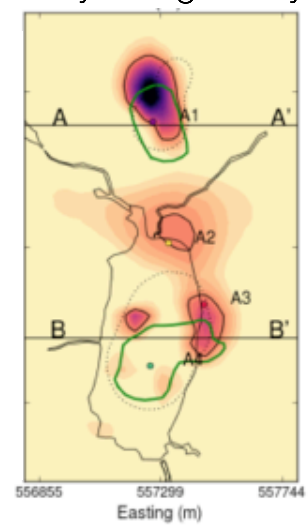
Susceptibility



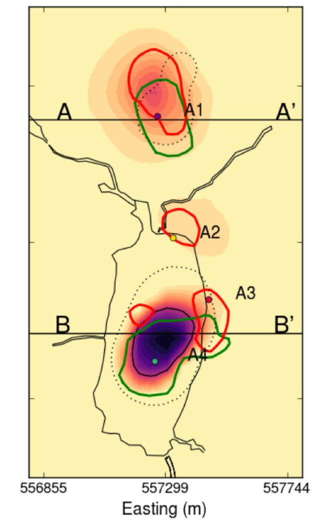
Conductivity



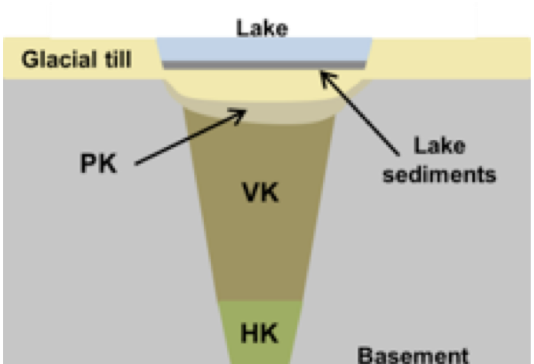
Early chargeability



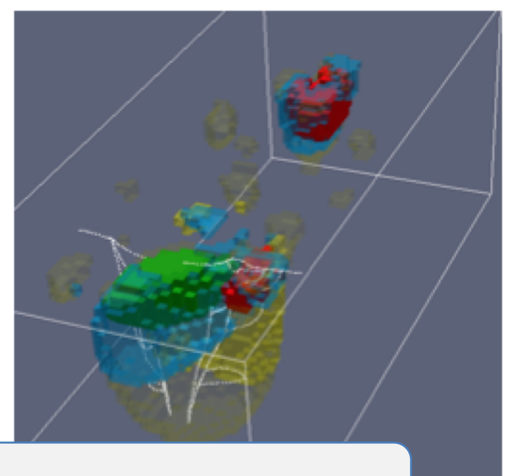
Late chargeability



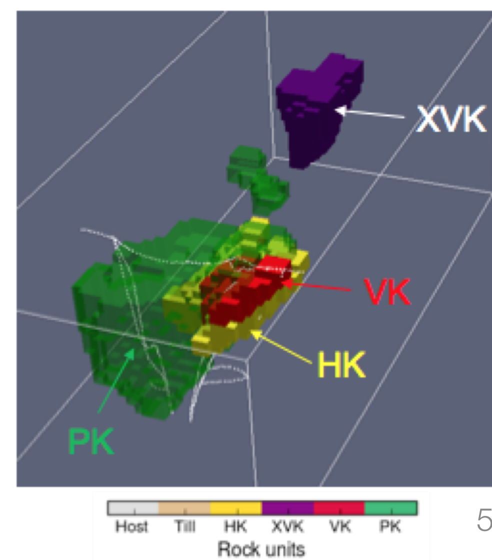
Kimberlite Model



Rock Model from Geophysics



Rock Model from Drilling



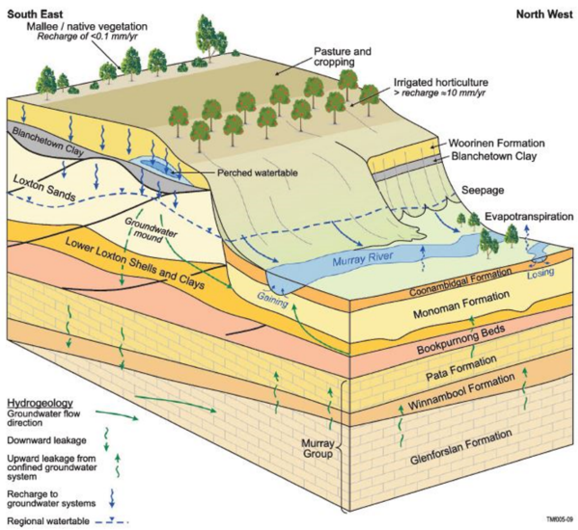
High quality 3D conductivity model was crucial

Rock units

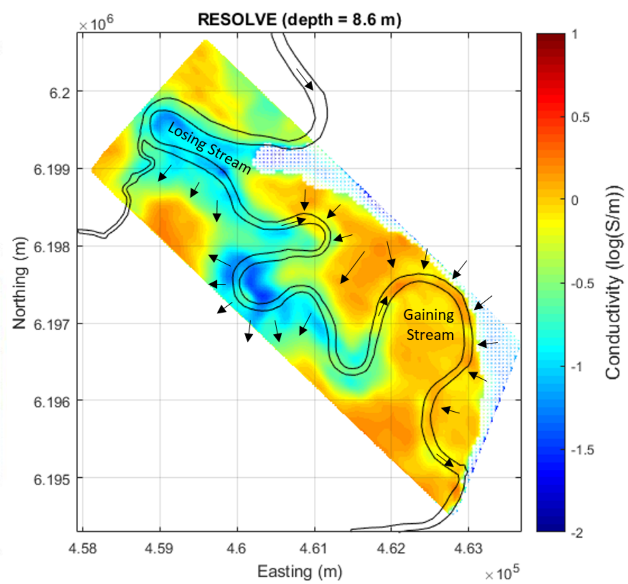
What we have covered?

- Bookpurnong (moderately 1D)

Hydrological model



Conductivity model (stitched)

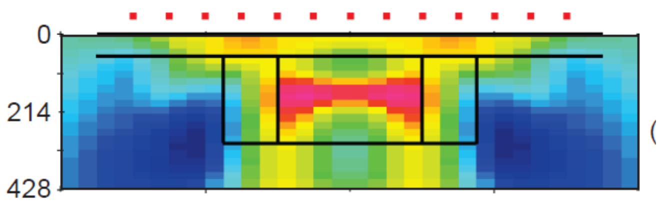


Using 1D inversion is effective

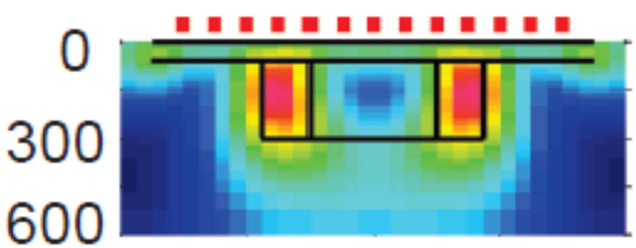
What we have covered?

- Mt. Milligan (compact resistor)

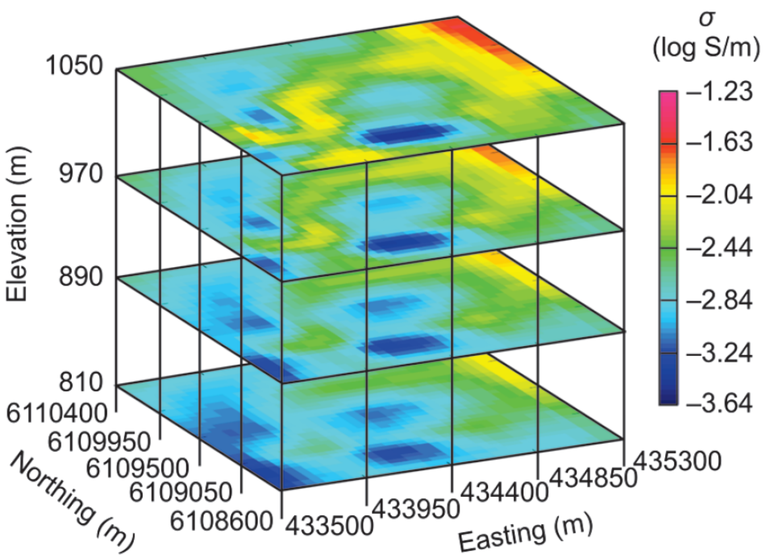
1D conductivity



3D conductivity



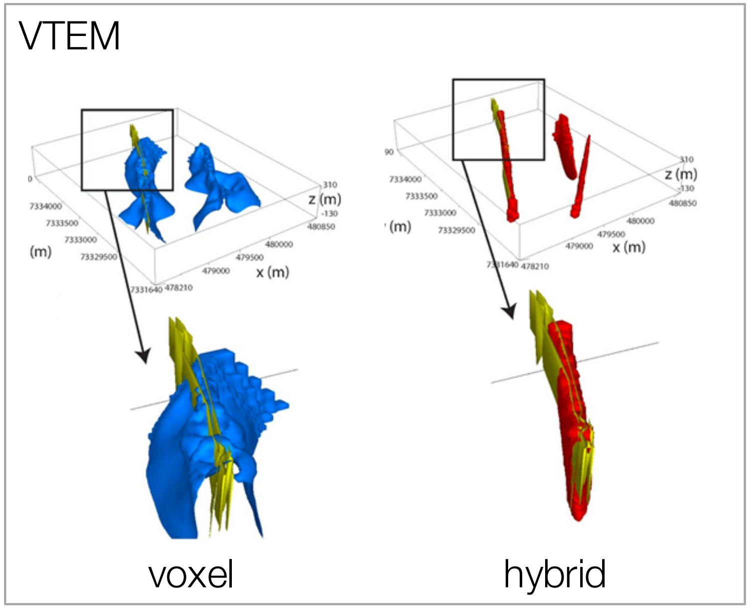
3D conductivity (Mt. Milligan)

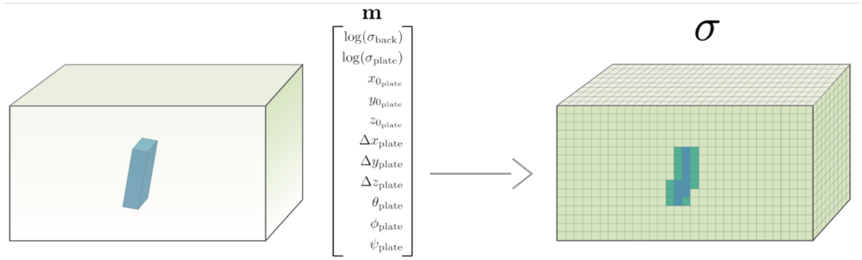


Requires 3D inversion to recover compact resistor

What we have covered?

- West Plains (thin conductive intersecting structures)



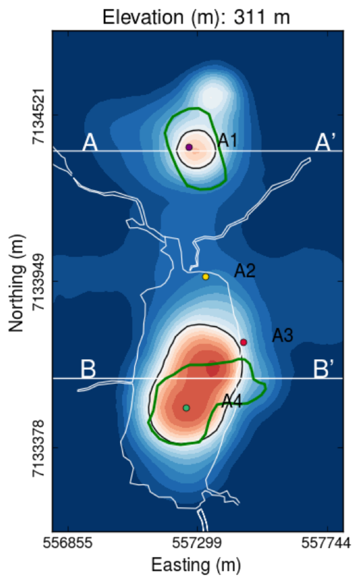


Parametric and voxel inversions can be combined

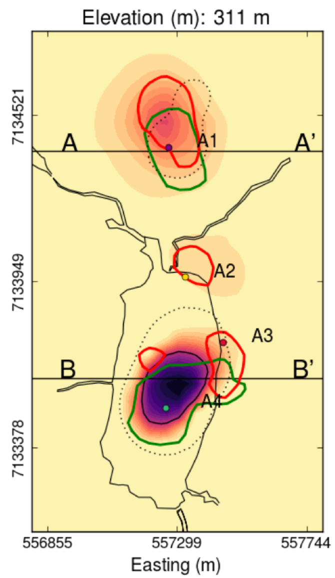
What we have covered?

- West Plains (thin conductive intersecting structures)

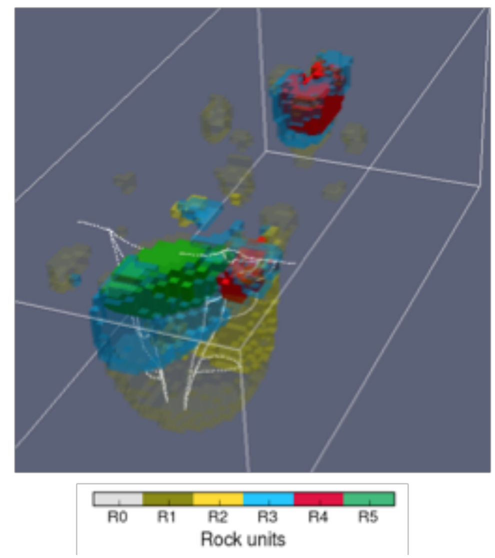
Conductivity



Chargeability



Rock model



3D conductivity inversion may be essential for airborne IP

Why don’t we work routinely in 3D?

Basic elements are in hand:

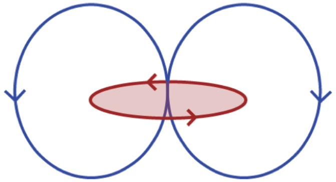
- Understand the physics
- Can simulate 3D for some circumstances
- Have solid methodology for the inverse problem

Why don't we work routinely in 3D?

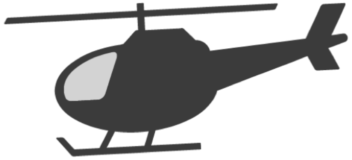
Roadblock: availability of software for

- 3D simulations
  - explore EM fields, fluxes, charges to understand observations
  - have realistic expectations for inversion

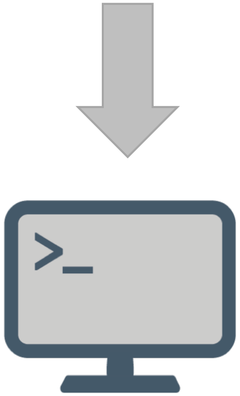
- Inversion
  - flexible
  - efficient
  - transparent (lots of potential parameters to adjust)
  - Non-uniqueness: Do users really understand inversion?



EM Induction



Field Examples



Computation

Open Source
Software