Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Case History- Groundwater, Hydrocarbons, Minerals

Frequency Domain EM

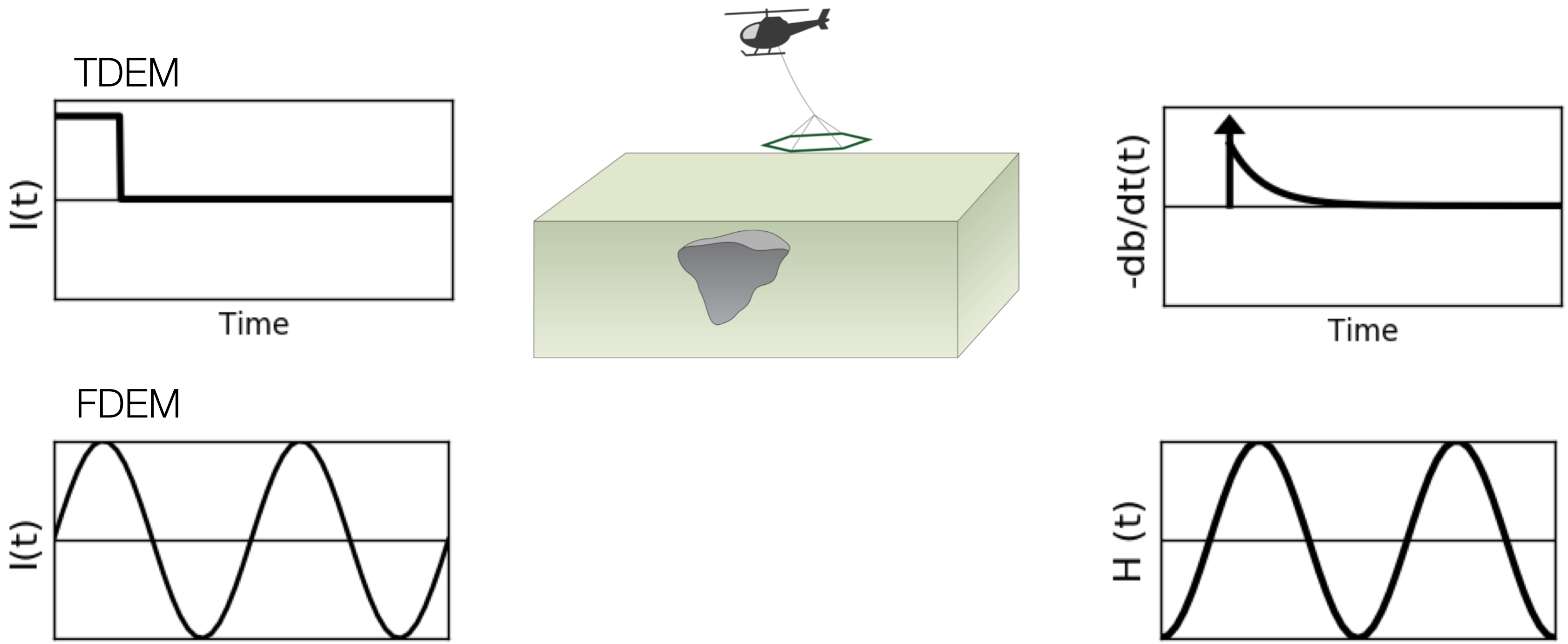
- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Groundwater, Hydrocarbons, Minerals

EM with Inductive Sources

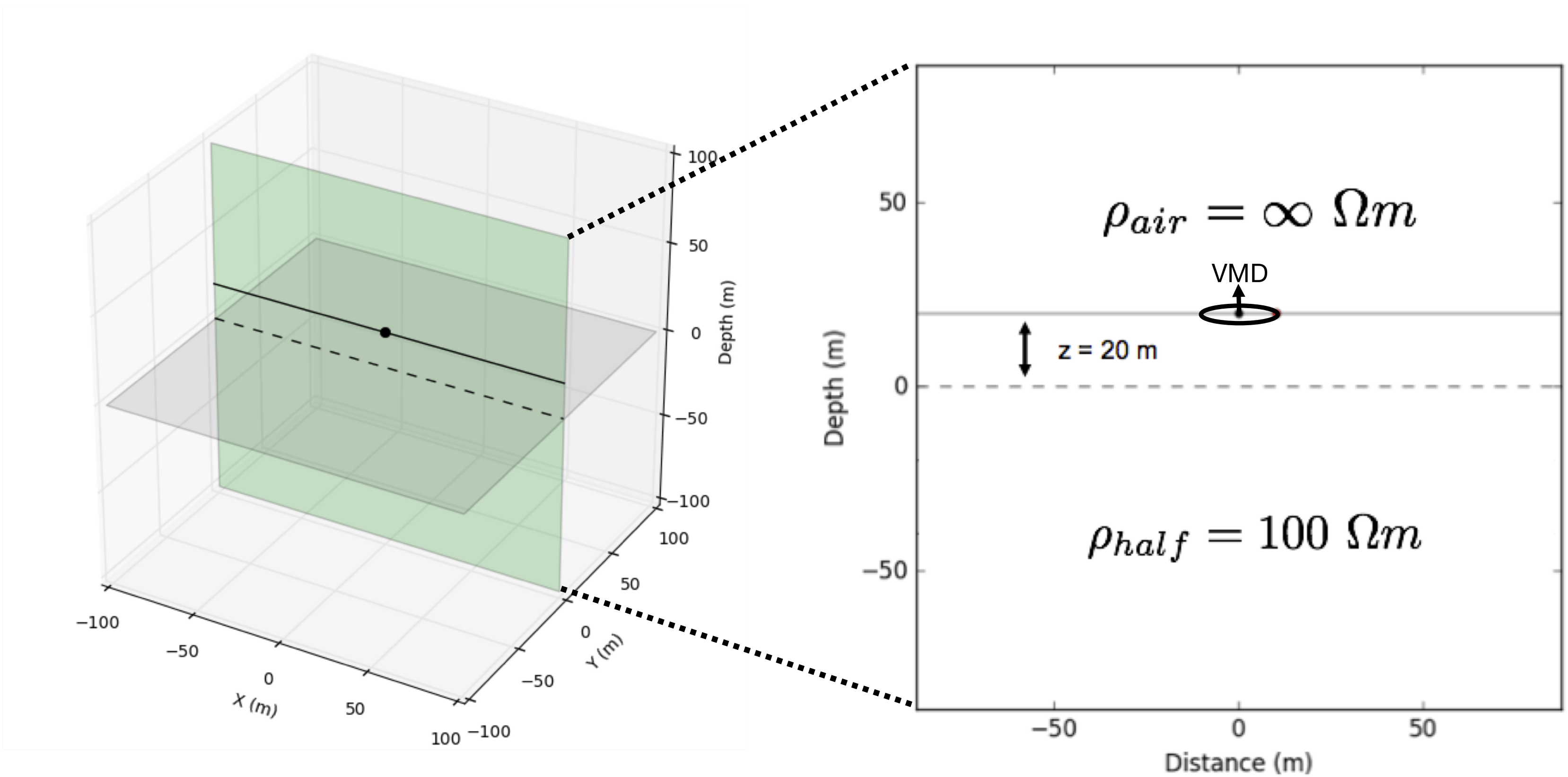
- Induction principles are the same for
  - TDEM: Time domain EM
  - FDEM: Frequency domain EM

Transmitter current

Receiver



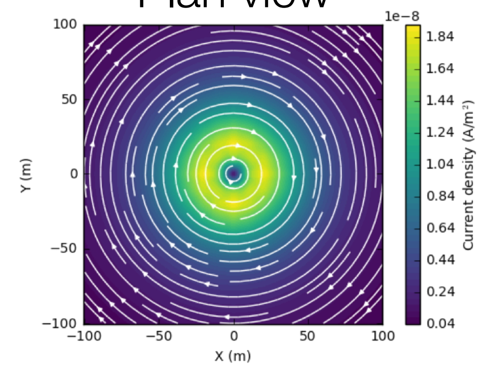
Vertical Magnetic Dipole over a halfspace (FDEM)



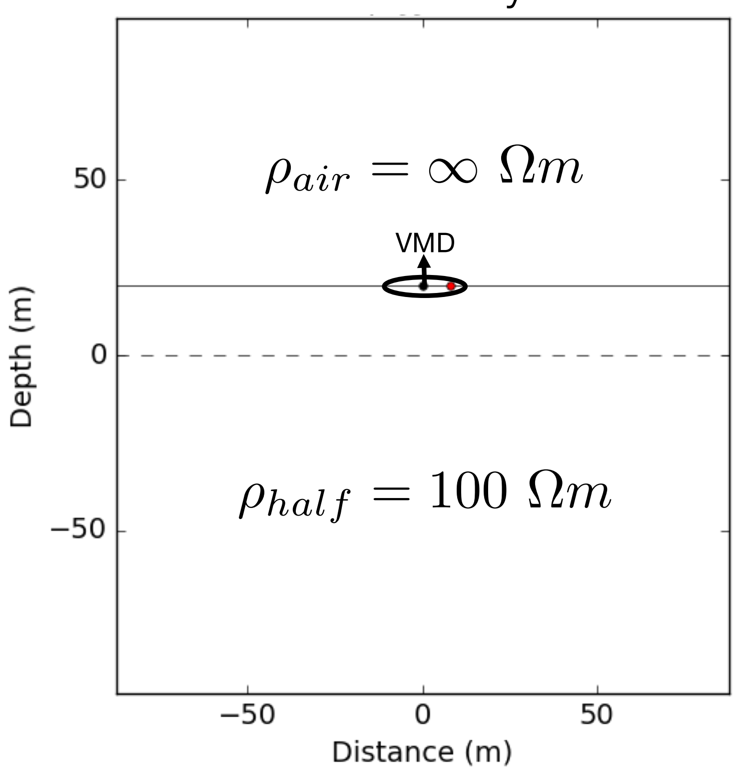
Current Density

- Frequency = 10 kHz
- Currents in the earth flow in planes parallel to the Tx

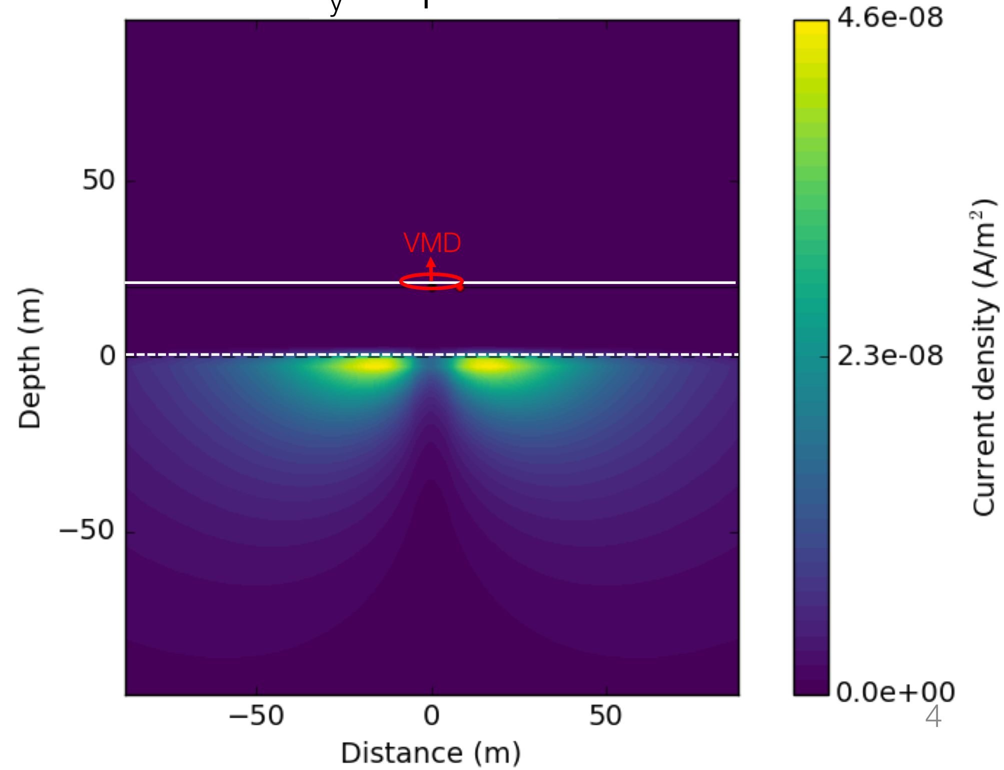
Plan view



Geometry

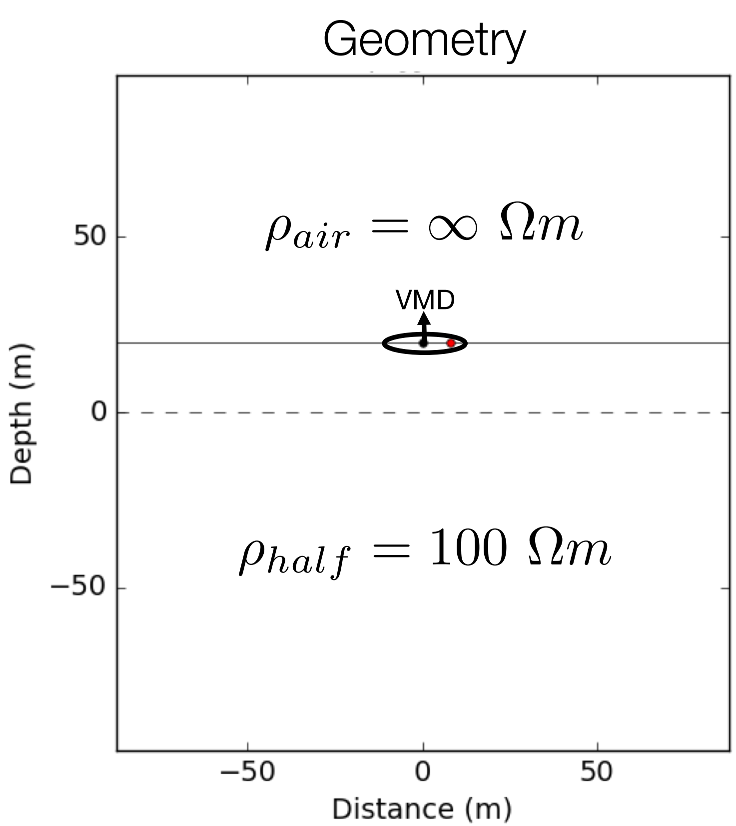


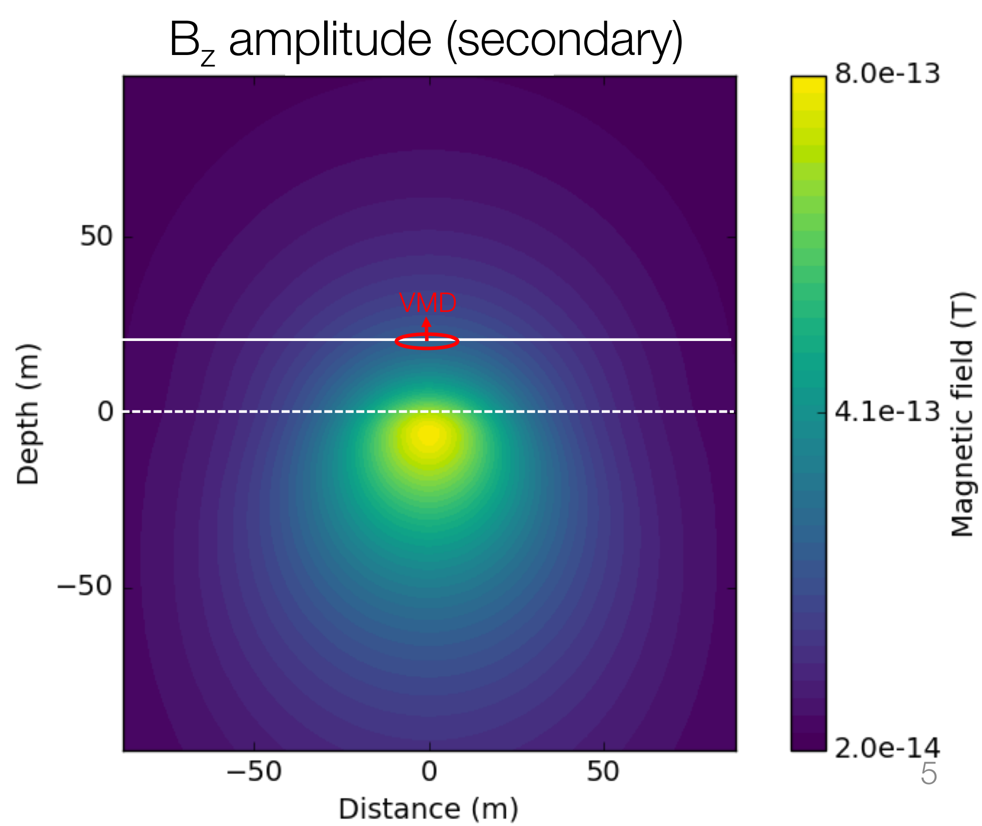
J_y amplitude



Secondary Magnetic Flux Density

- Frequency = 10 kHz

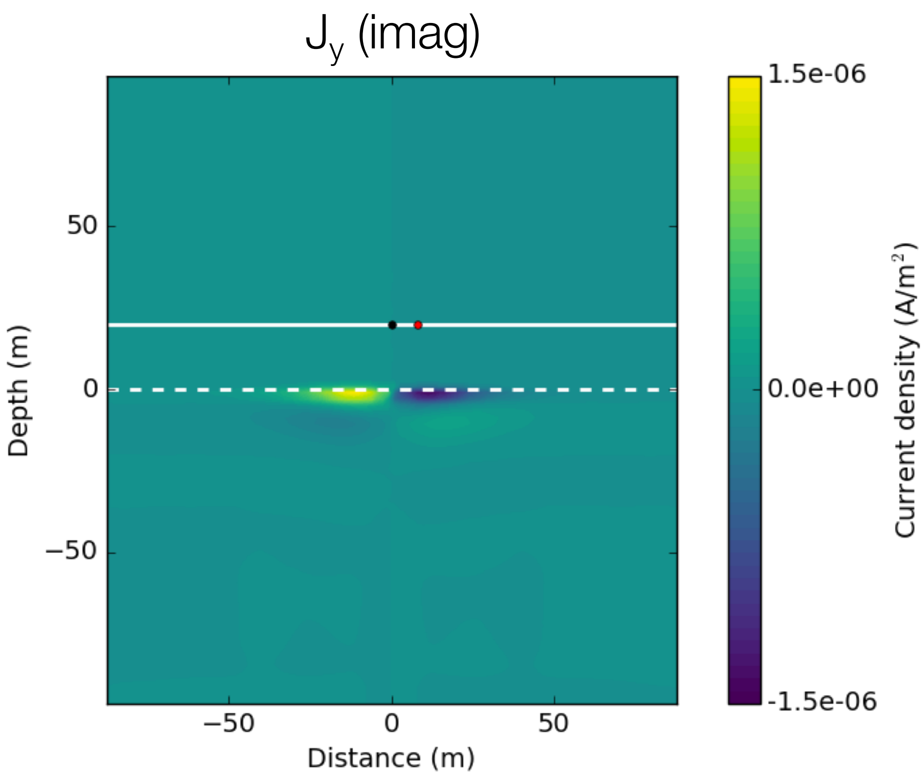


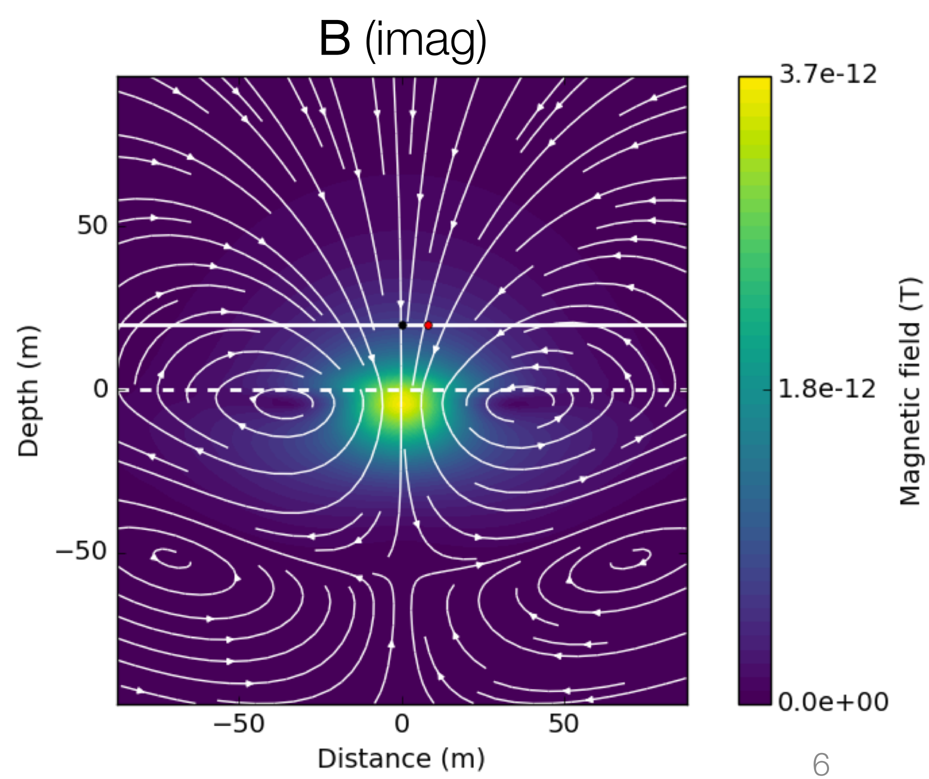


Effects of Frequency

- Frequency at 100 kHz
- Skin depth = 16 m
- Currents are concentrated at surface

$$\delta = 503\sqrt{\frac{\rho}{f}}$$

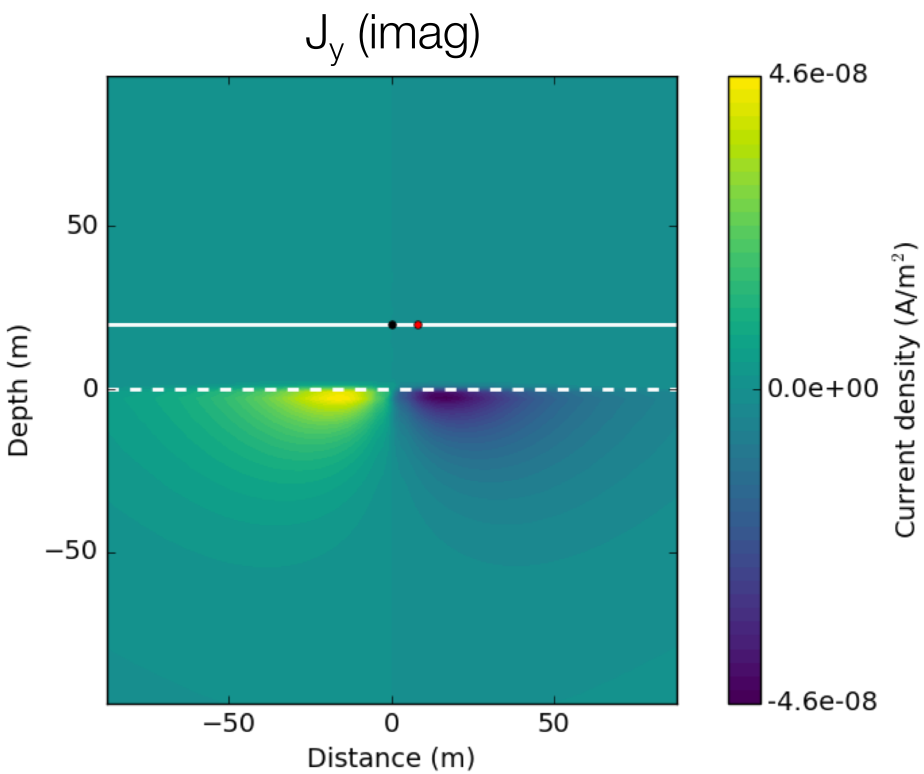


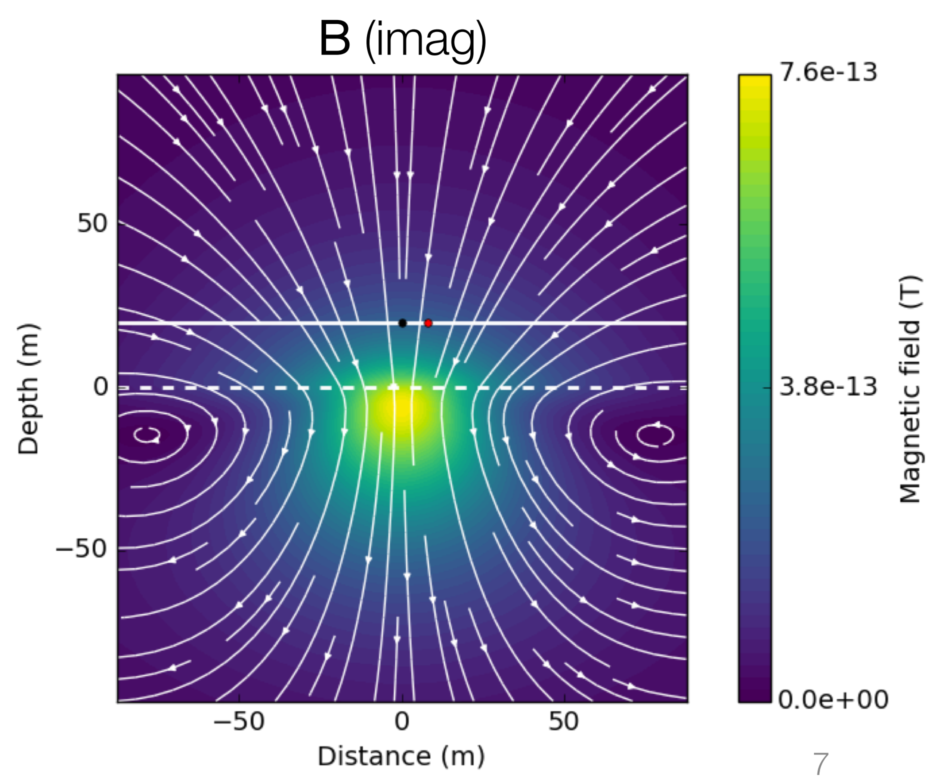


Effects of Frequency

- Frequency at 10 kHz
- Skin depth = 50 m
- Currents diffusing downward and outward

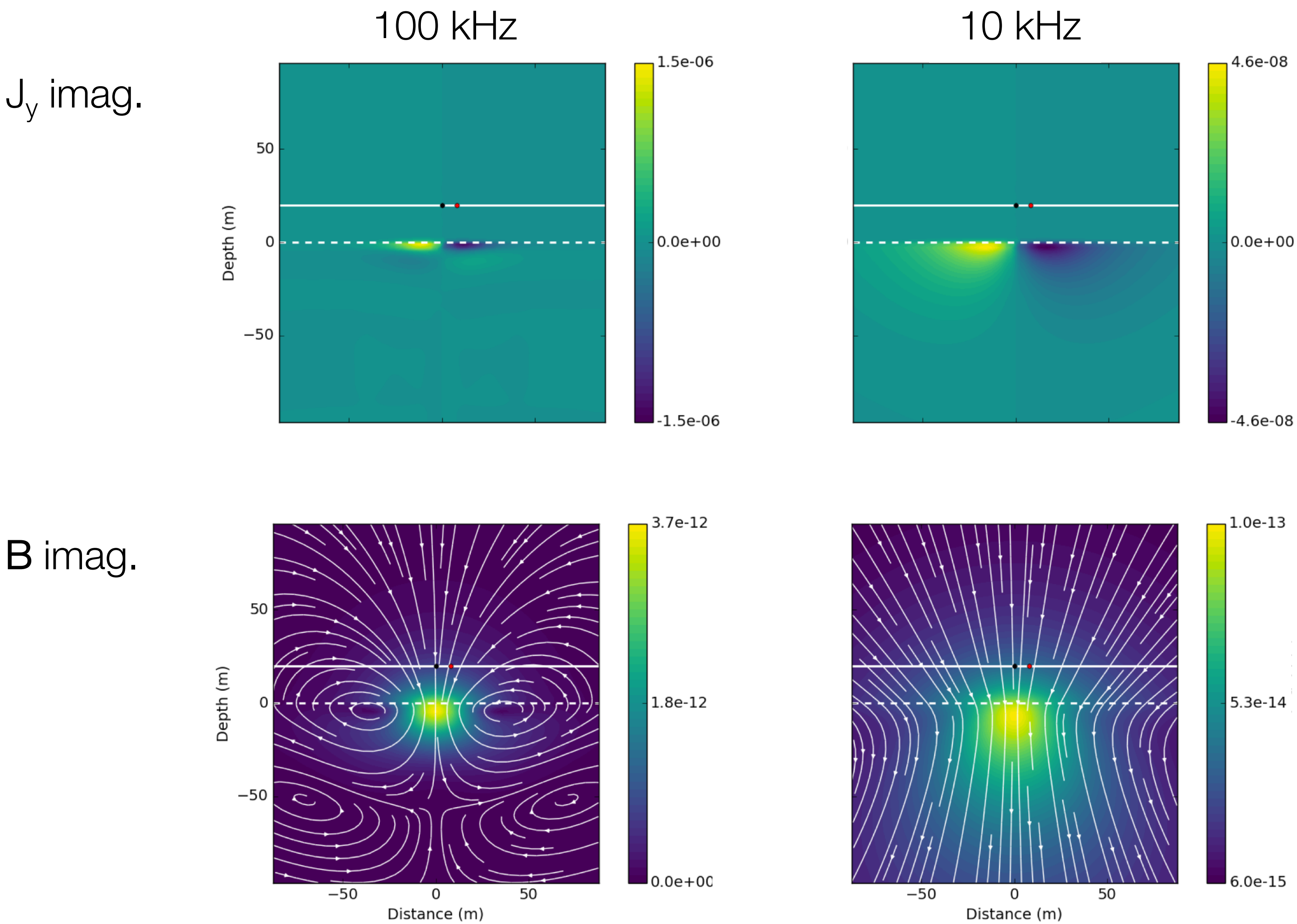
$$\delta = 503\sqrt{\frac{\rho}{f}}$$





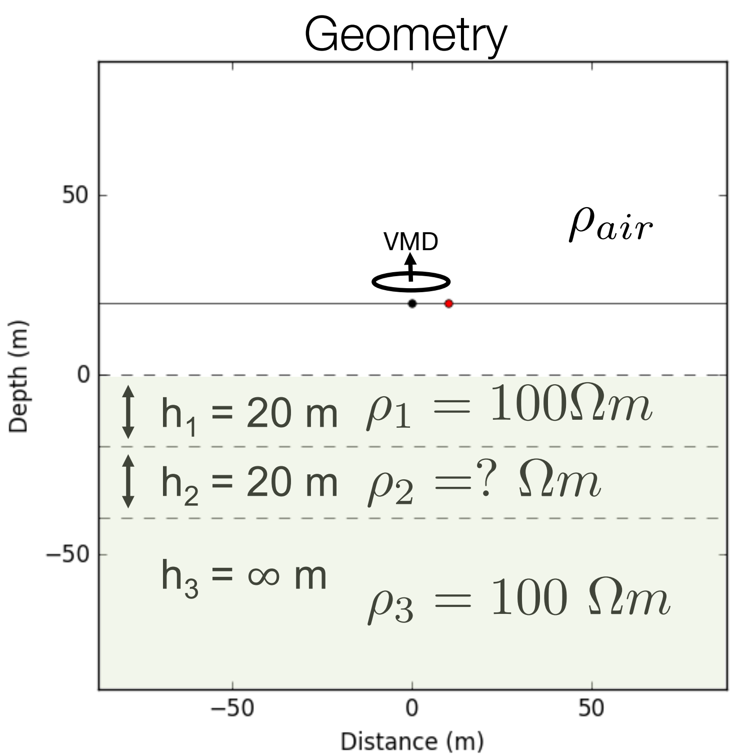
Summary: Effects of Frequency

$$\delta = 503\sqrt{\frac{\rho}{f}}$$



Layered earth

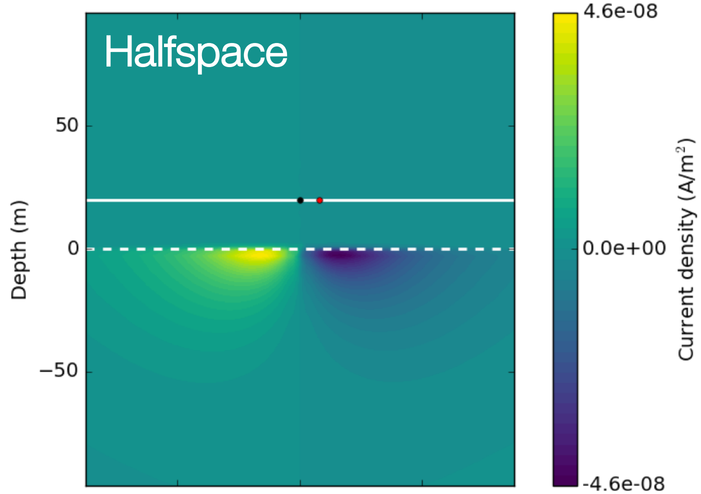
- 3 layers + air,
- ρ_2 varies



- Four different cases:
  - Halfspace
    $\rho_2 = 100\ \Omega\mathrm{m}$
  - Resistive
    $\rho_2 = 1000\ \Omega\mathrm{m}$
  - Conductive
    $\rho_2 = 10\ \Omega\mathrm{m}$
  - Very conductive
    $\rho_2 = 1\ \Omega\mathrm{m}$
- Fields
  - J_y imag
  - Secondary **B** imag

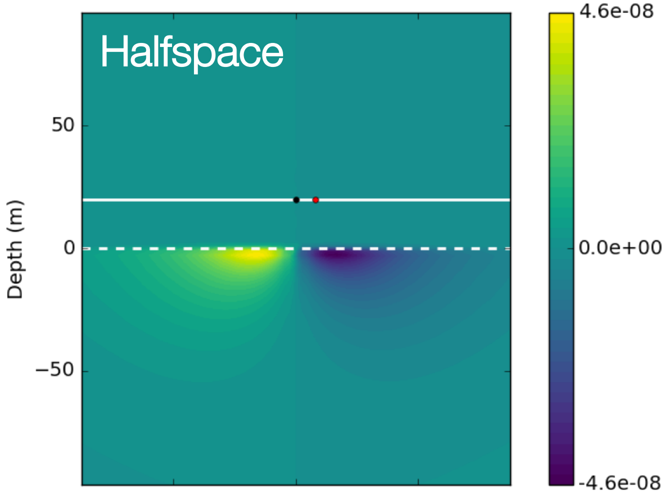
Current density (J_y imag)

$\rho_2 = 100\ \Omega\mathrm{m}$

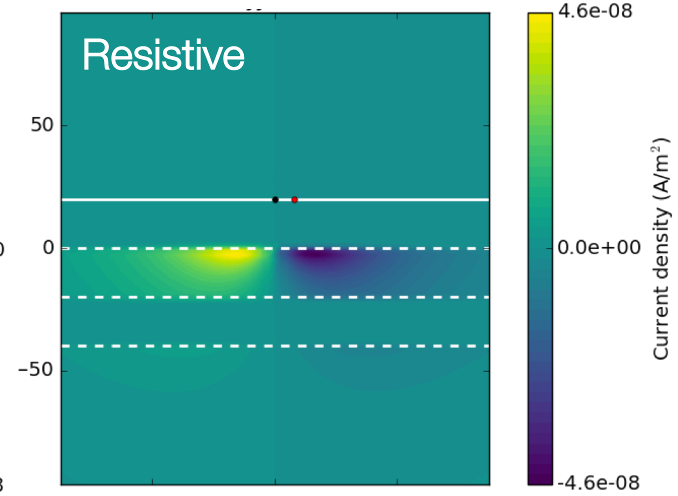


Current density (J_y imag)

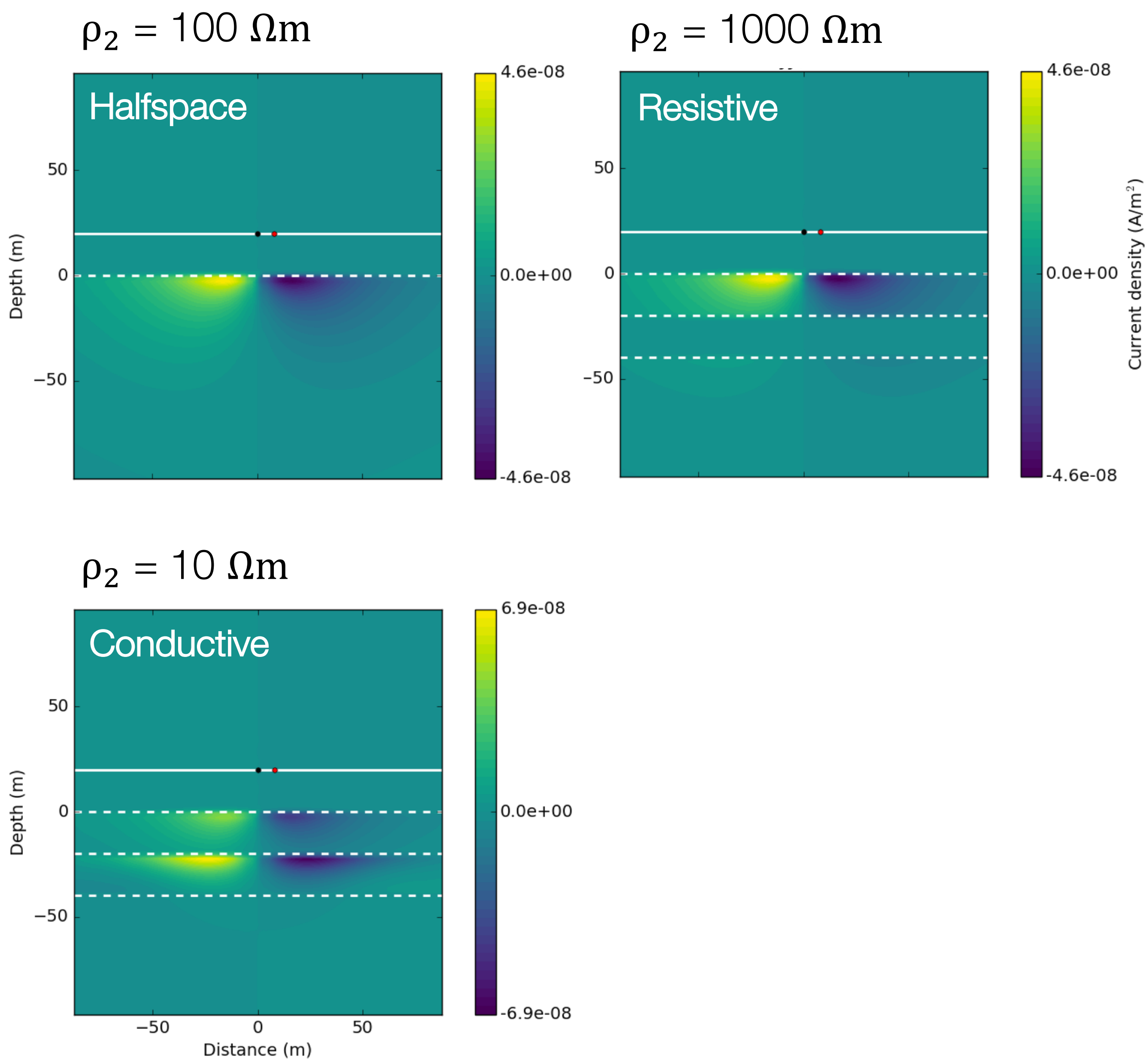
$\rho_2 = 100\ \Omega\text{m}$



$\rho_2 = 1000\ \Omega\text{m}$

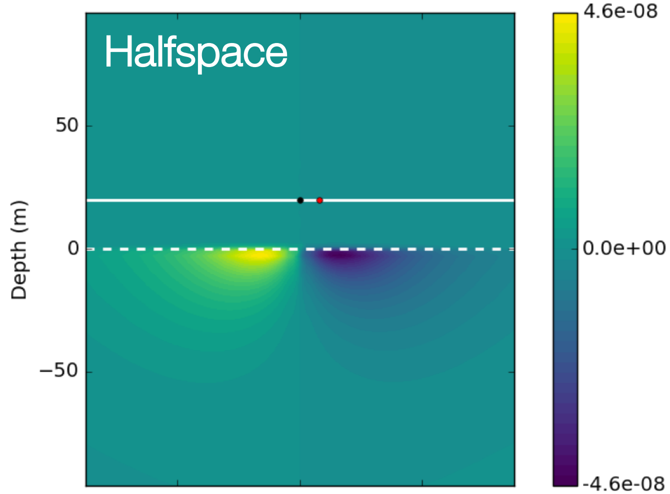


Current density (J_y imag)

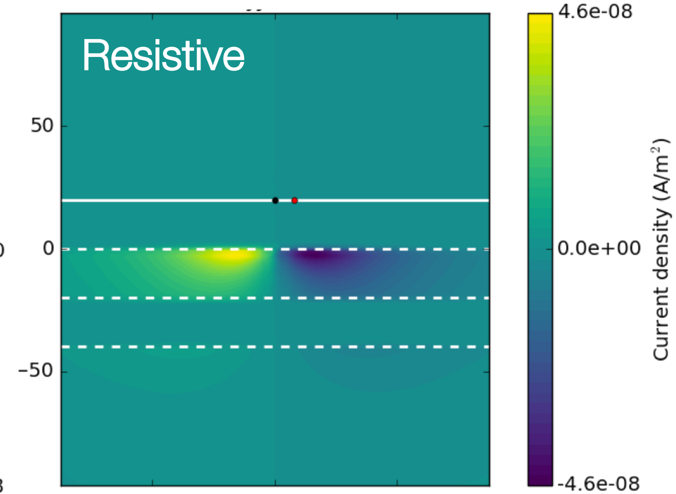


Current density (J_y imag)

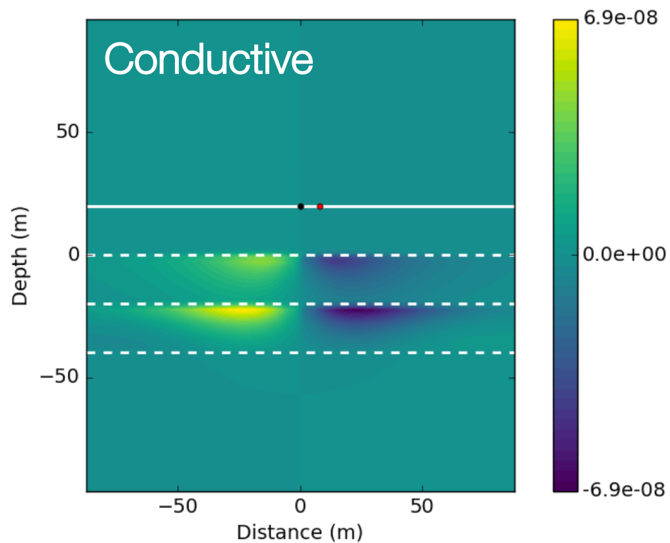
$\rho_2 = 100\ \Omega m$



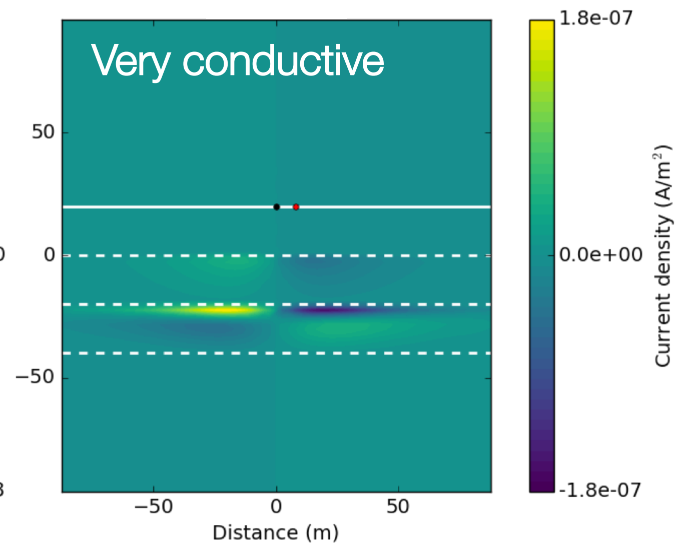
$\rho_2 = 1000\ \Omega m$



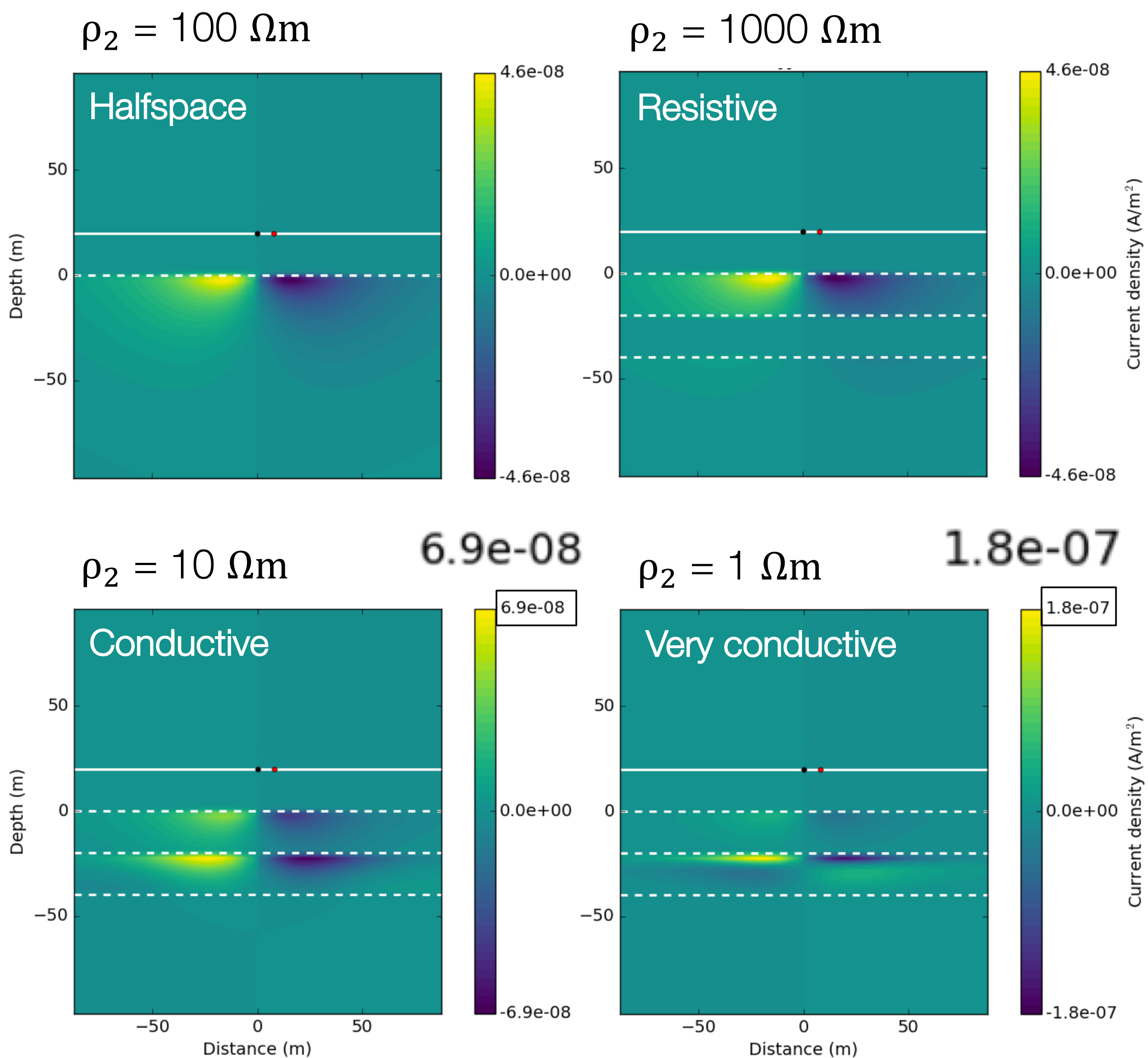
$\rho_2 = 10\ \Omega m$



$\rho_2 = 1\ \Omega m$

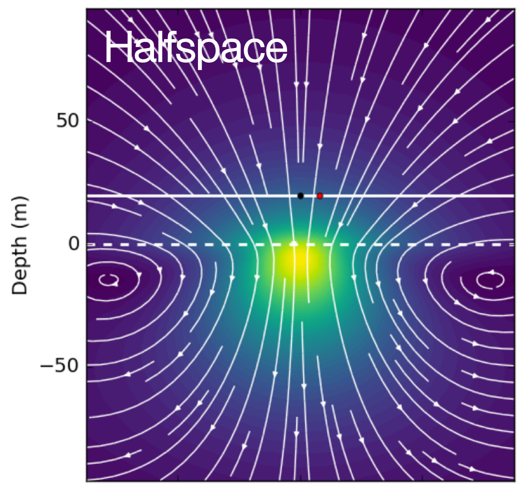


Current density (J_y imag)

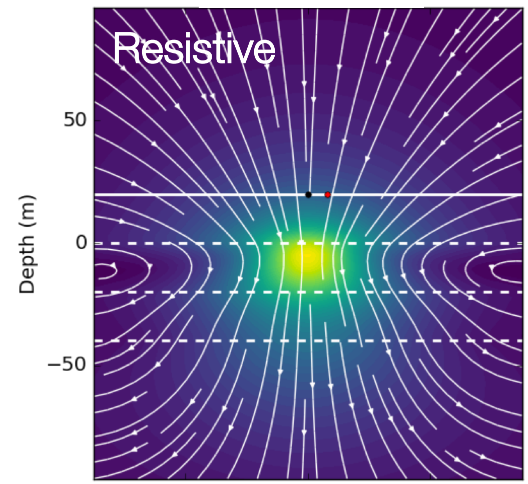


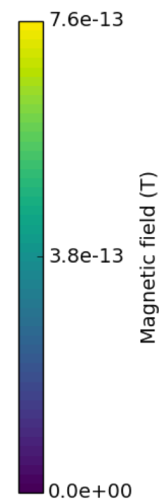
Magnetic flux density (**B** imag)

$\rho_2 = 100\ \Omega\text{m}$

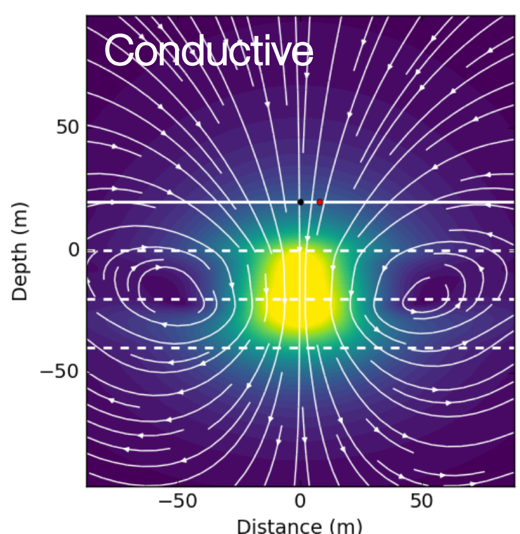


$\rho_2 = 1000\ \Omega\text{m}$

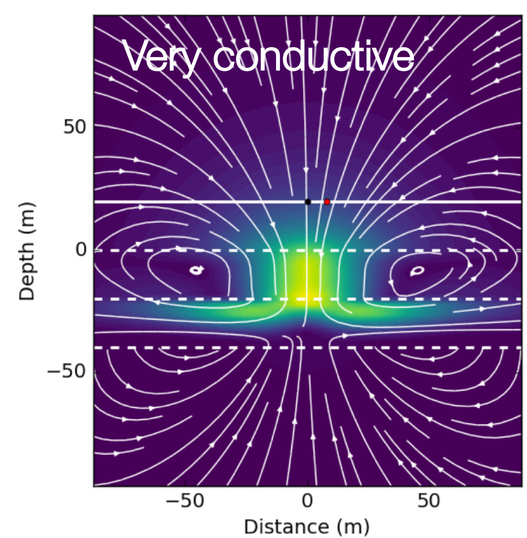




$\rho_2 = 10\ \Omega\text{m}$

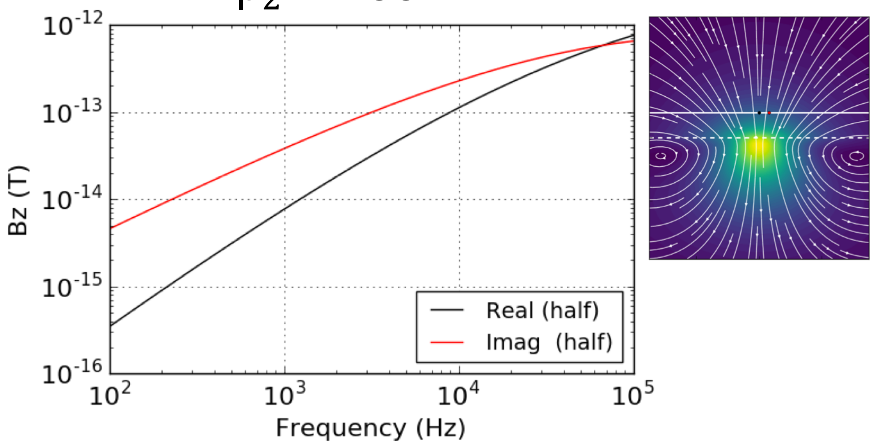


$\rho_2 = 1\ \Omega\text{m}$

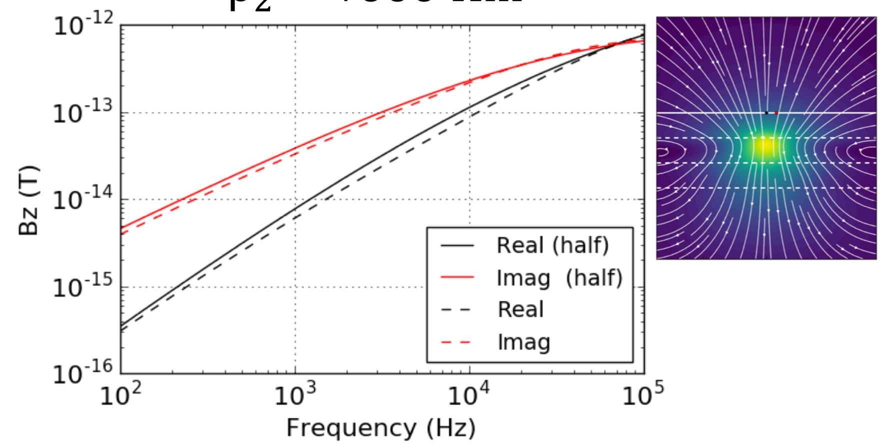


B_z sounding curves

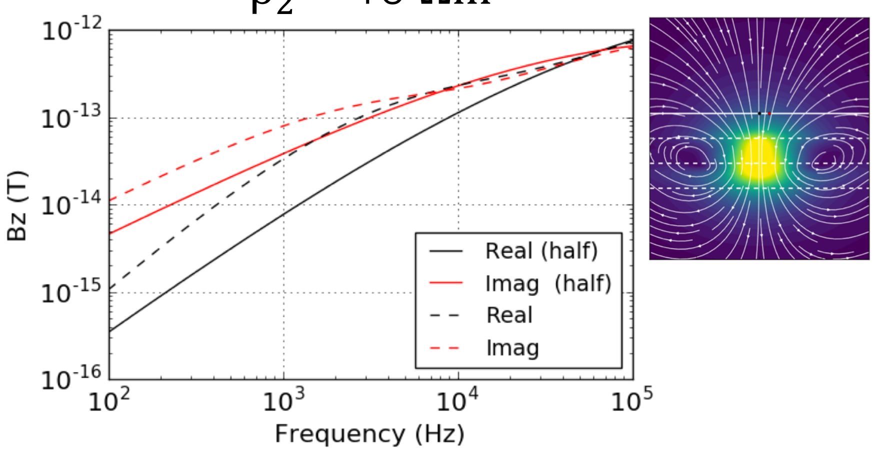
ρ_2 = 100 Ωm



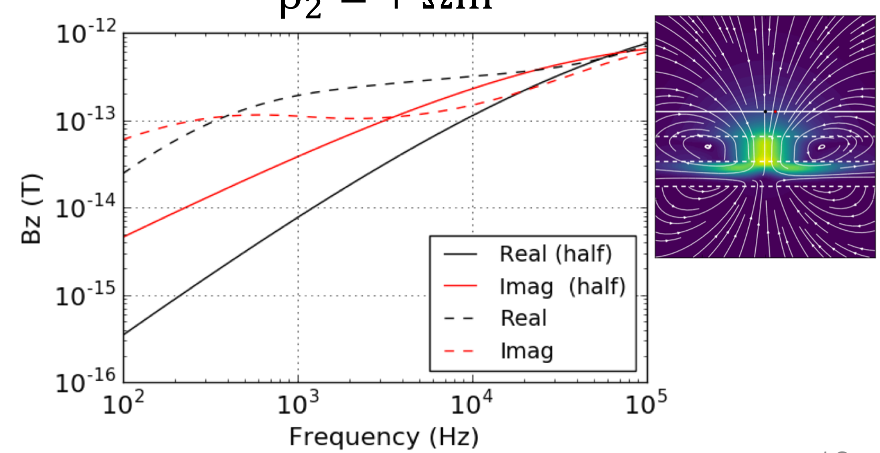
ρ_2 = 1000 Ωm



ρ_2 = 10 Ωm

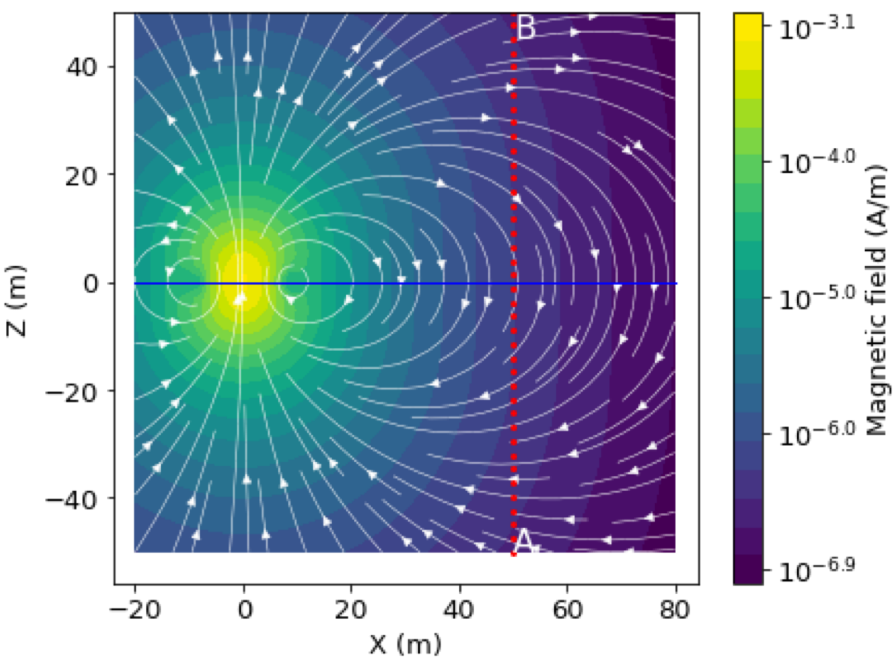


ρ_2 = 1 Ωm



Dipole Sources: connection to logging

- Same physical principles as induction well logging
  - Induction logs: often in frequency domain
  - Source is in the earth rather than above



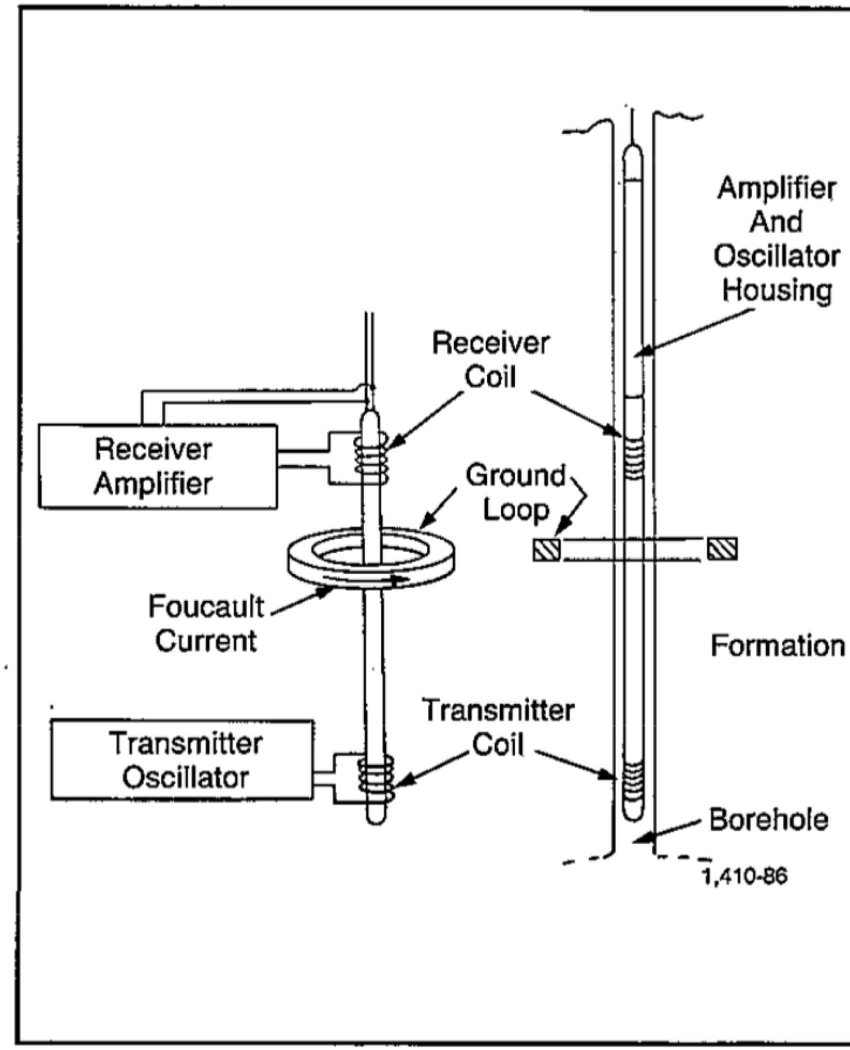
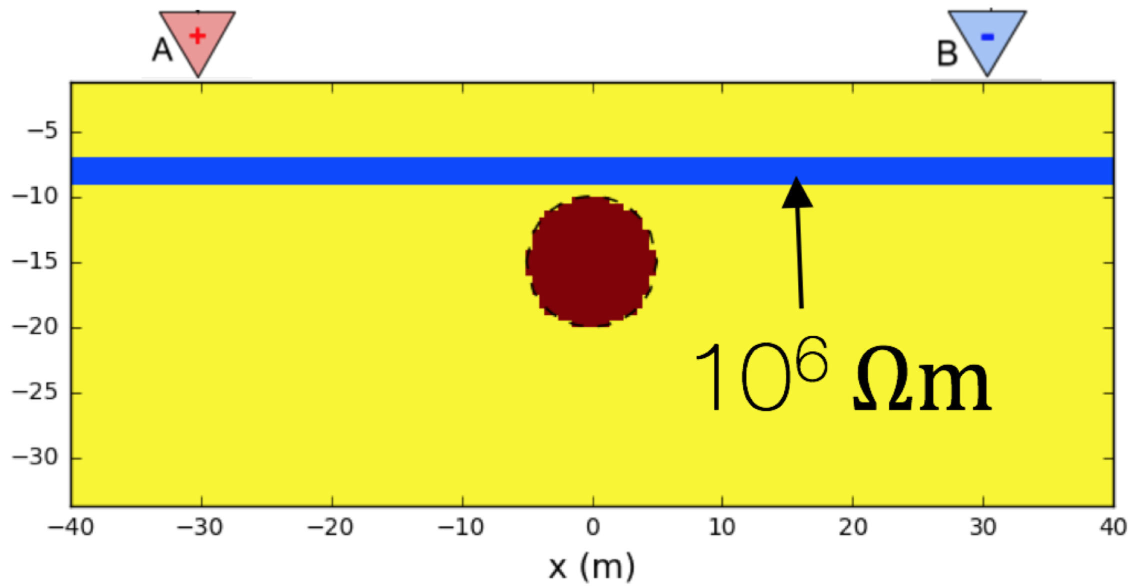


Fig. 7-18—Basic two-coil induction log system.

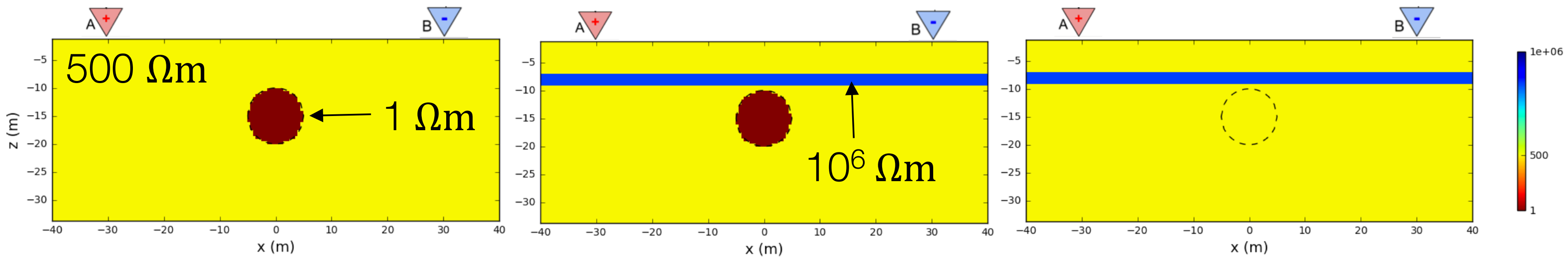
From Chapter 7 of the Schlumberger Log Interpretation Principles/Applications Textbook

Back to the “shielding” problem



Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)

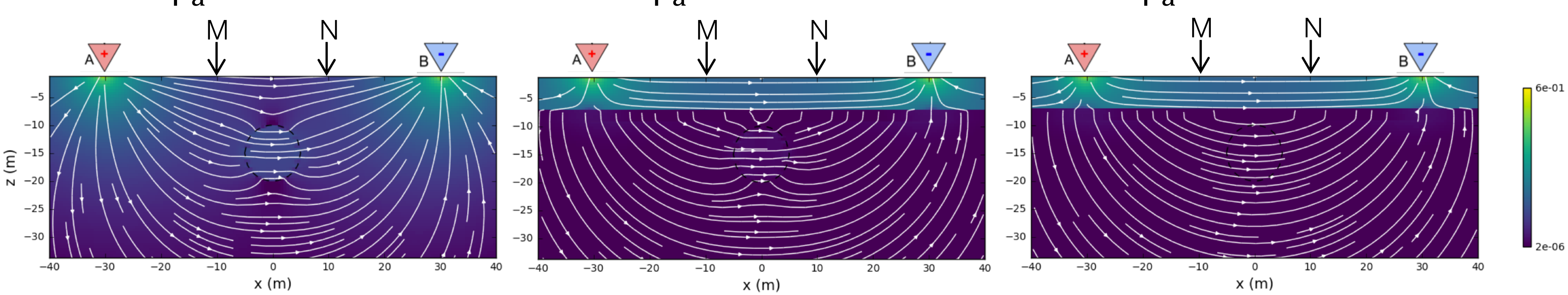


Currents and measured data at MN

ρ_a = 430 Ωm

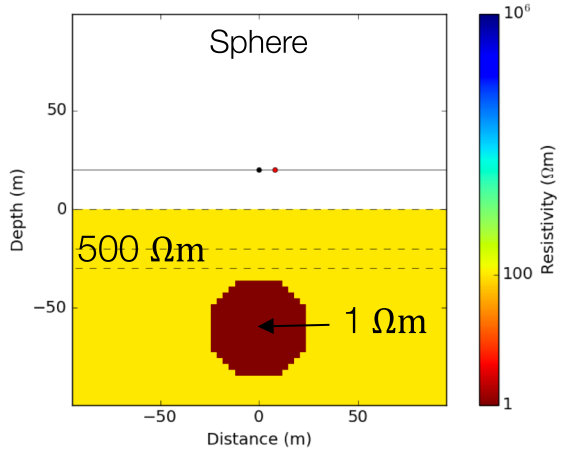
ρ_a = 1652 Ωm

ρ_a = 1654 Ωm

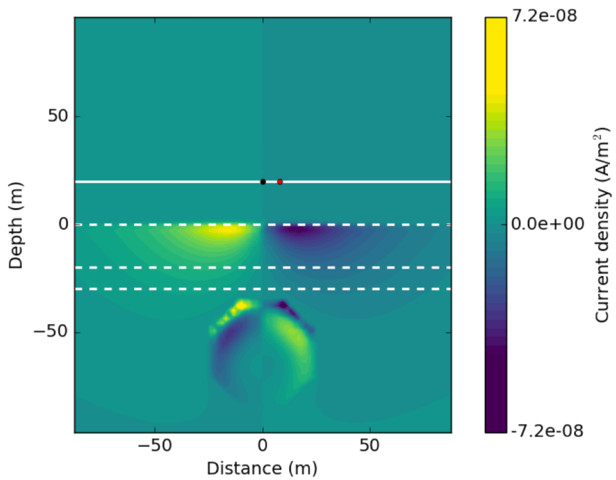


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

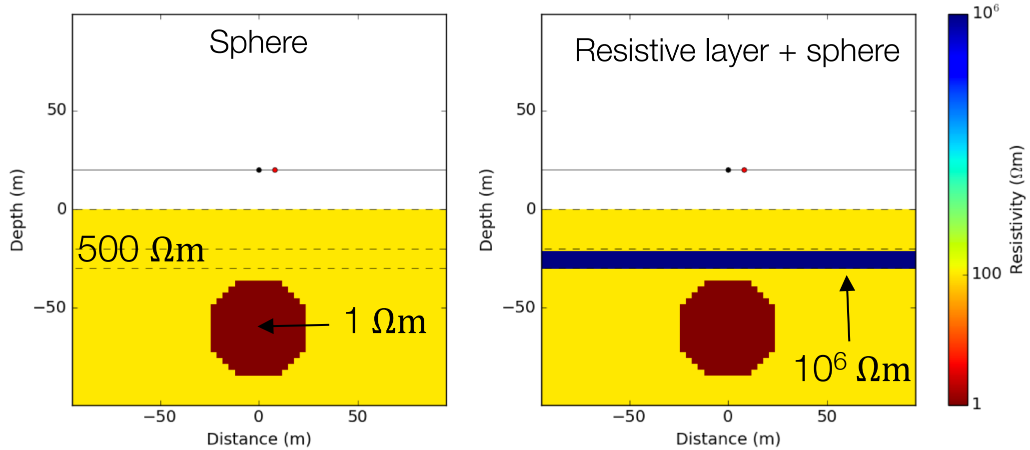


Currents (J_y imag)

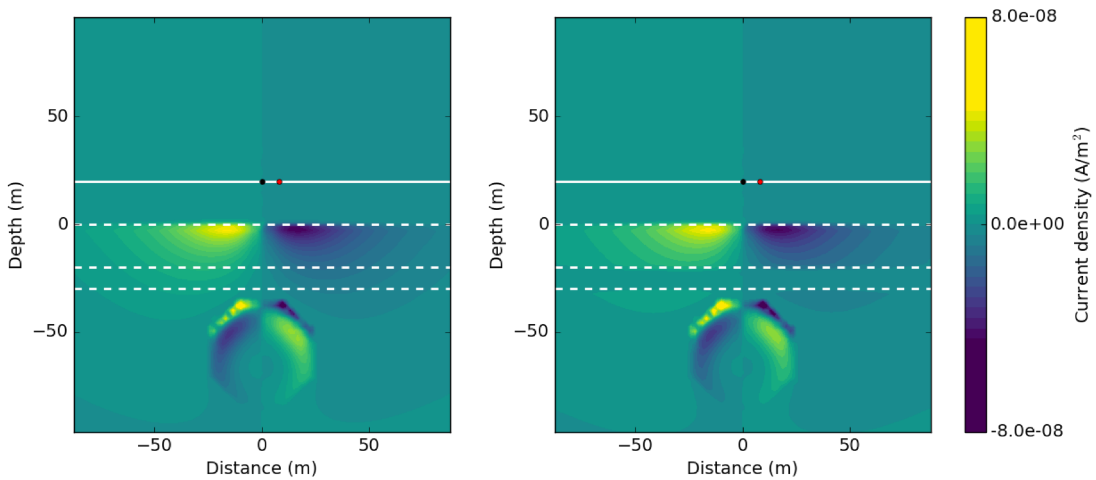


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

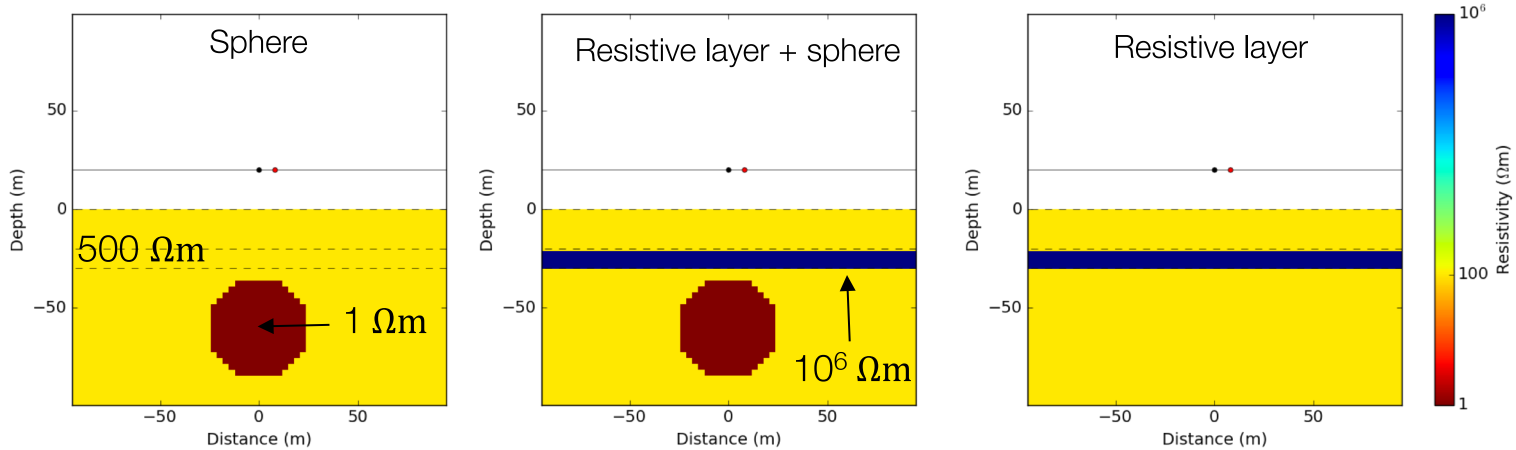


Currents (J_y imag)

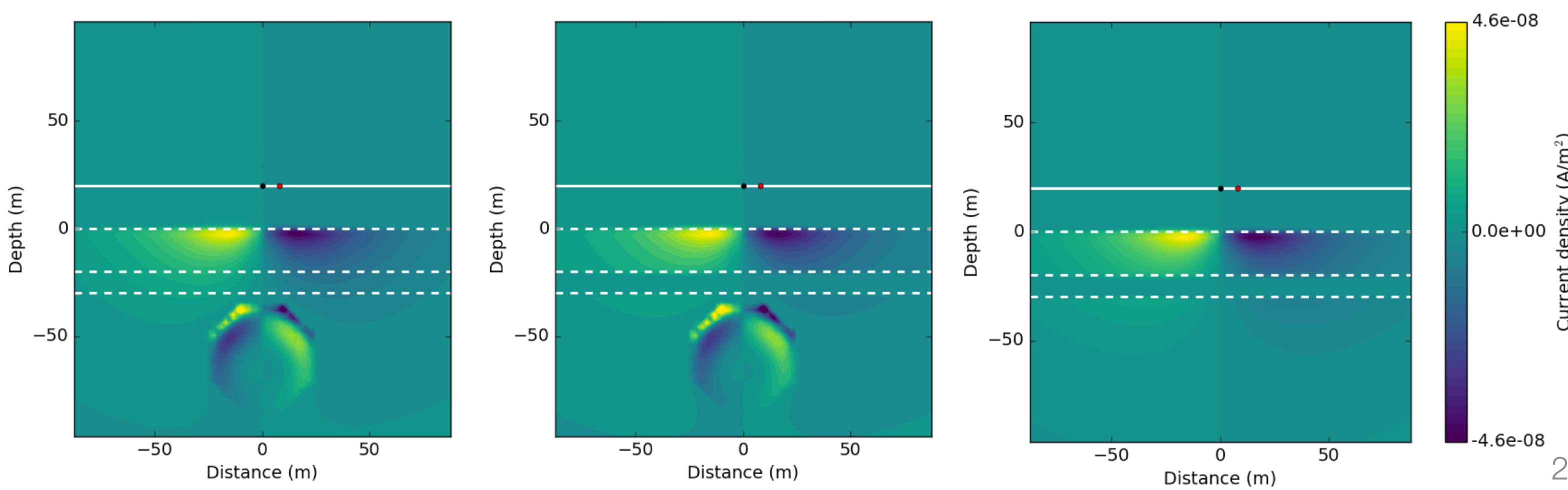


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

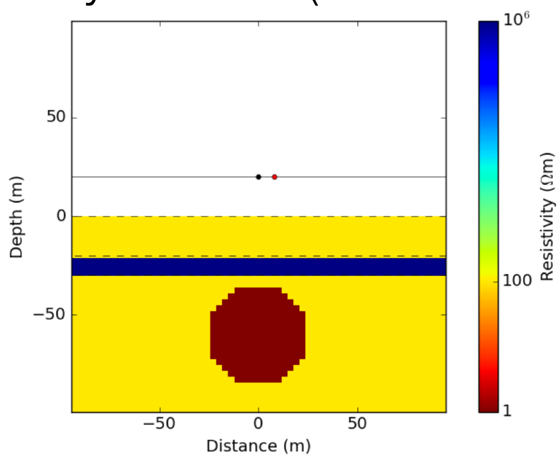


Currents (J_y imag)

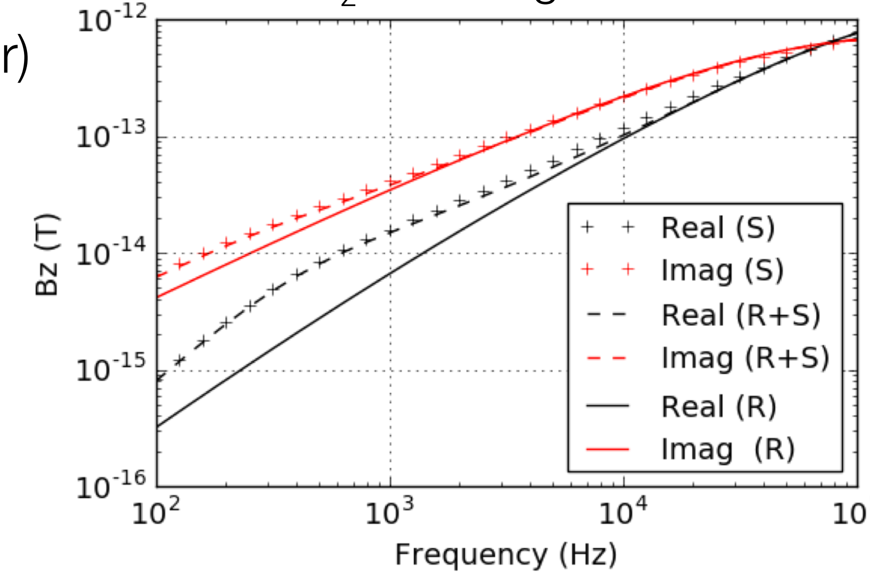


Shielding: EM with resistive layer

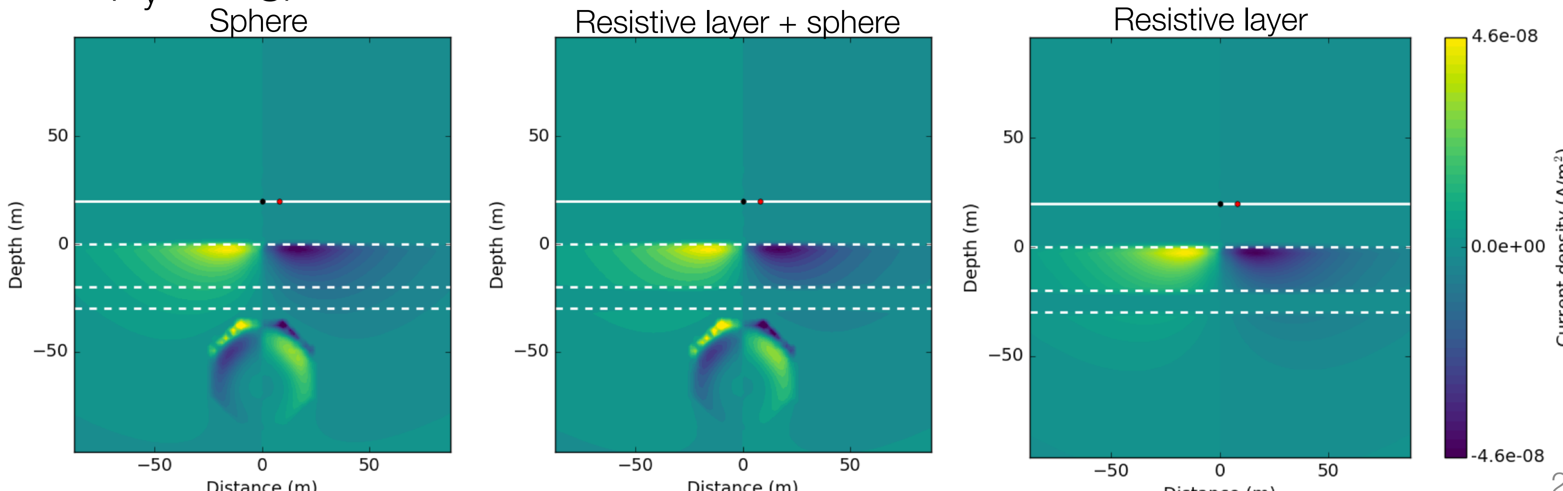
Resistivity models (thin **resistive** layer)



B_z sounding curves

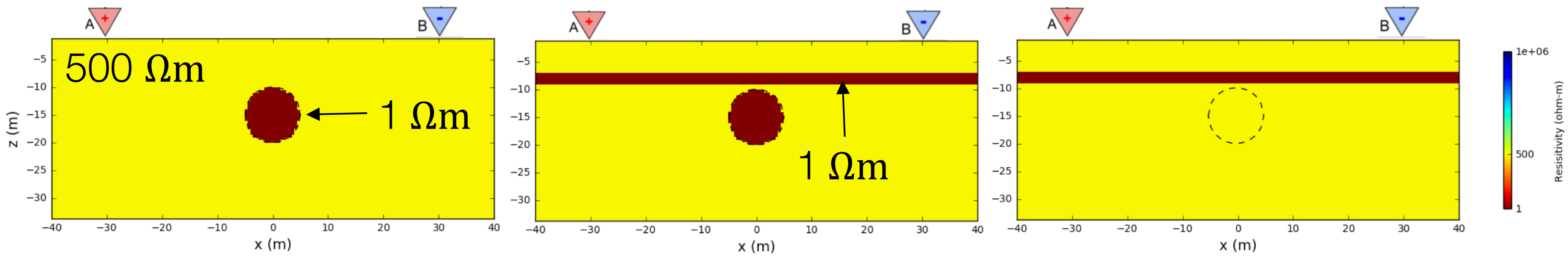


Currents (J_y imag)



Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)

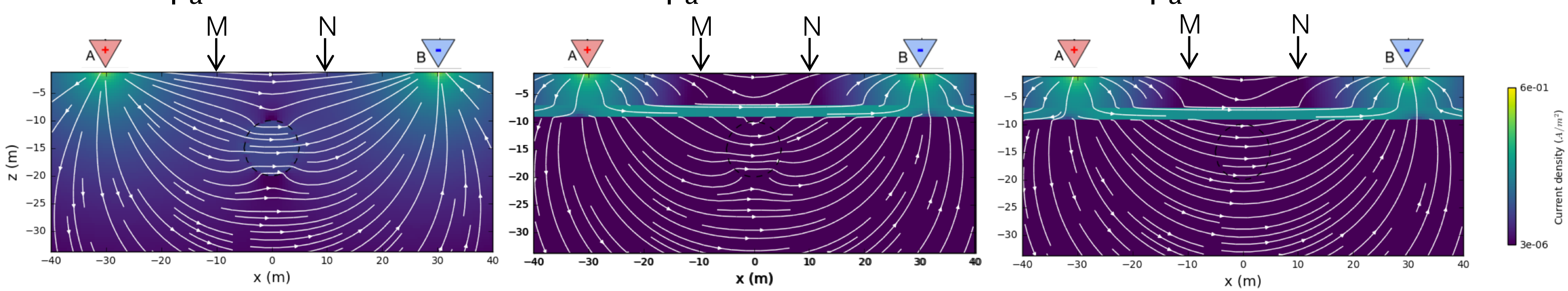


Currents and measured data at MN

ρ_a = 430 Ωm

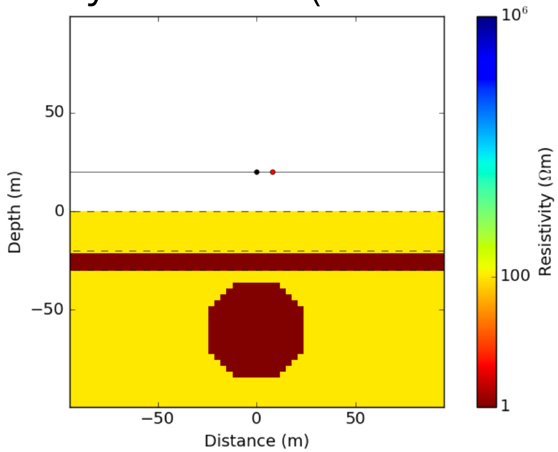
ρ_a = 47 Ωm

ρ_a = 47 Ωm

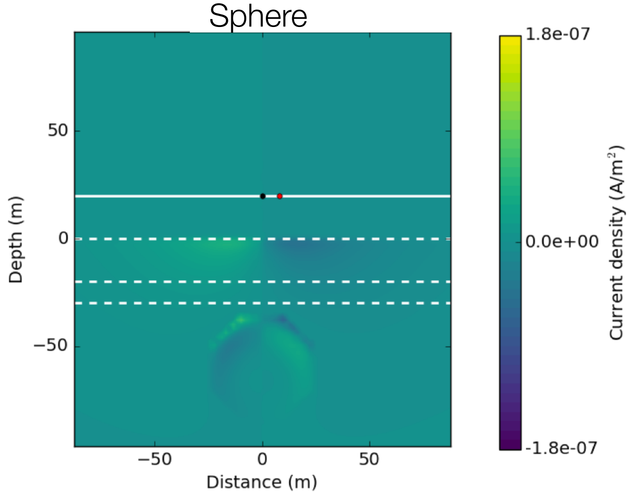


Shielding: EM with conductive layer

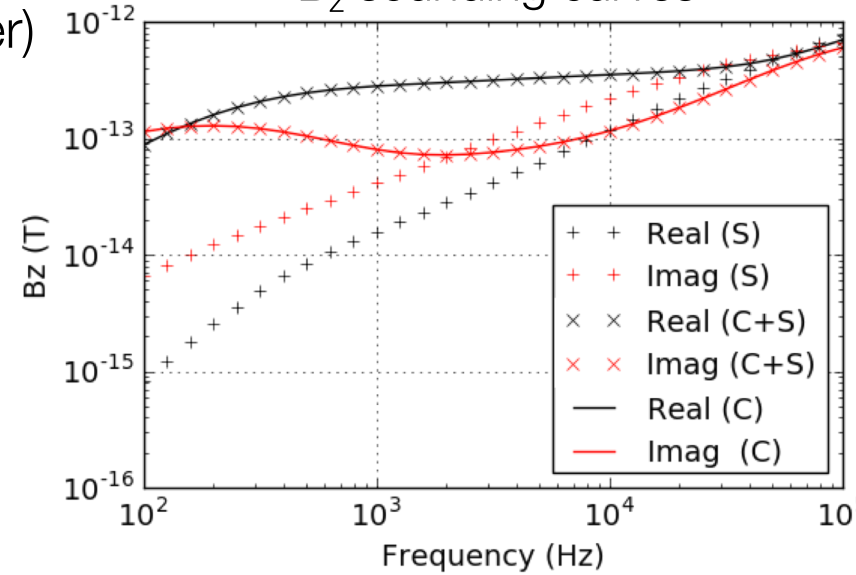
Resistivity models (thin **conductive** layer)



Currents (J_y imag)

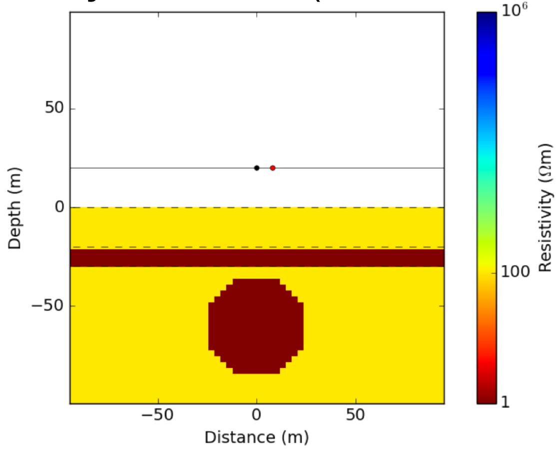


B_z sounding curves

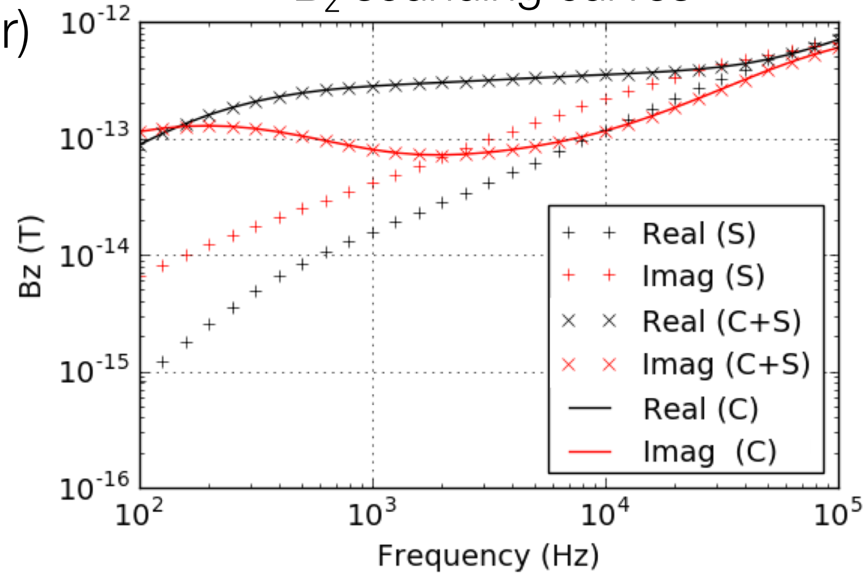


Shielding: EM with conductive layer

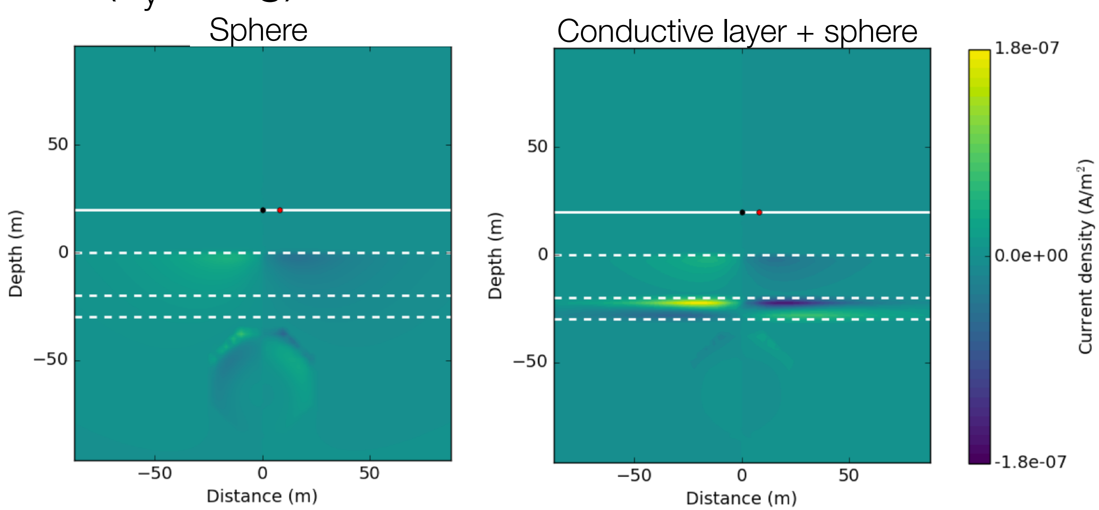
Resistivity models (thin **conductive** layer)



B_z sounding curves

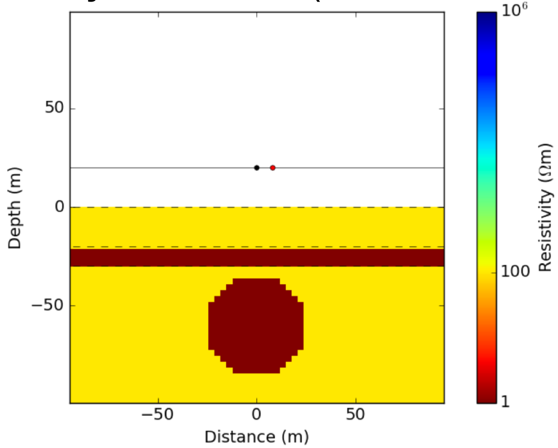


Currents (J_y imag)

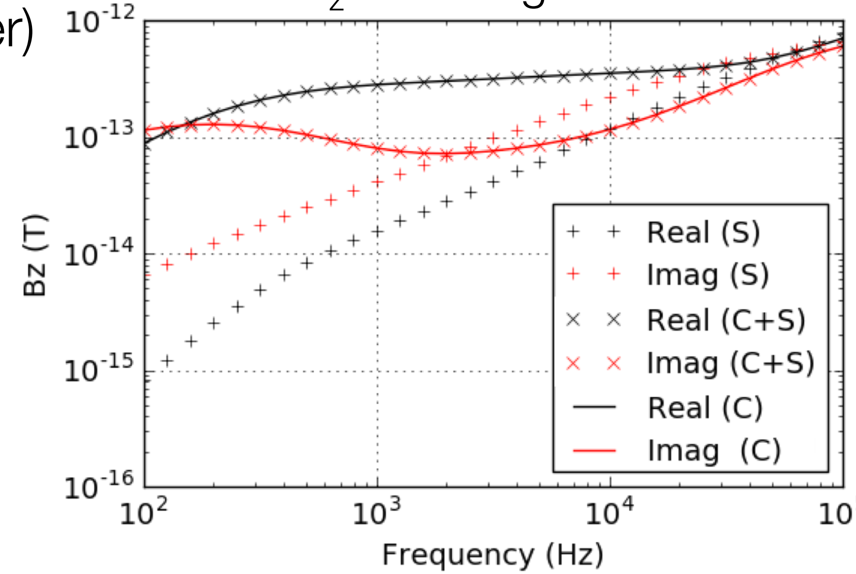


Shielding: EM with conductive layer

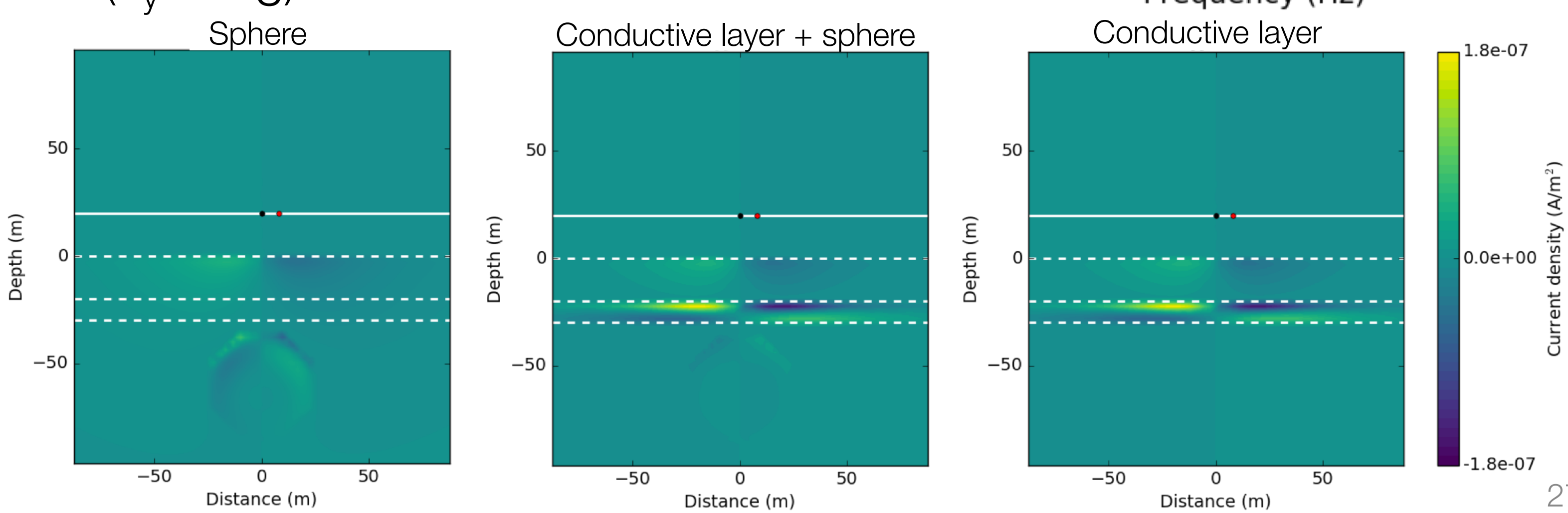
Resistivity models (thin **conductive** layer)



B_z sounding curves



Currents (J_y imag)



Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Case History

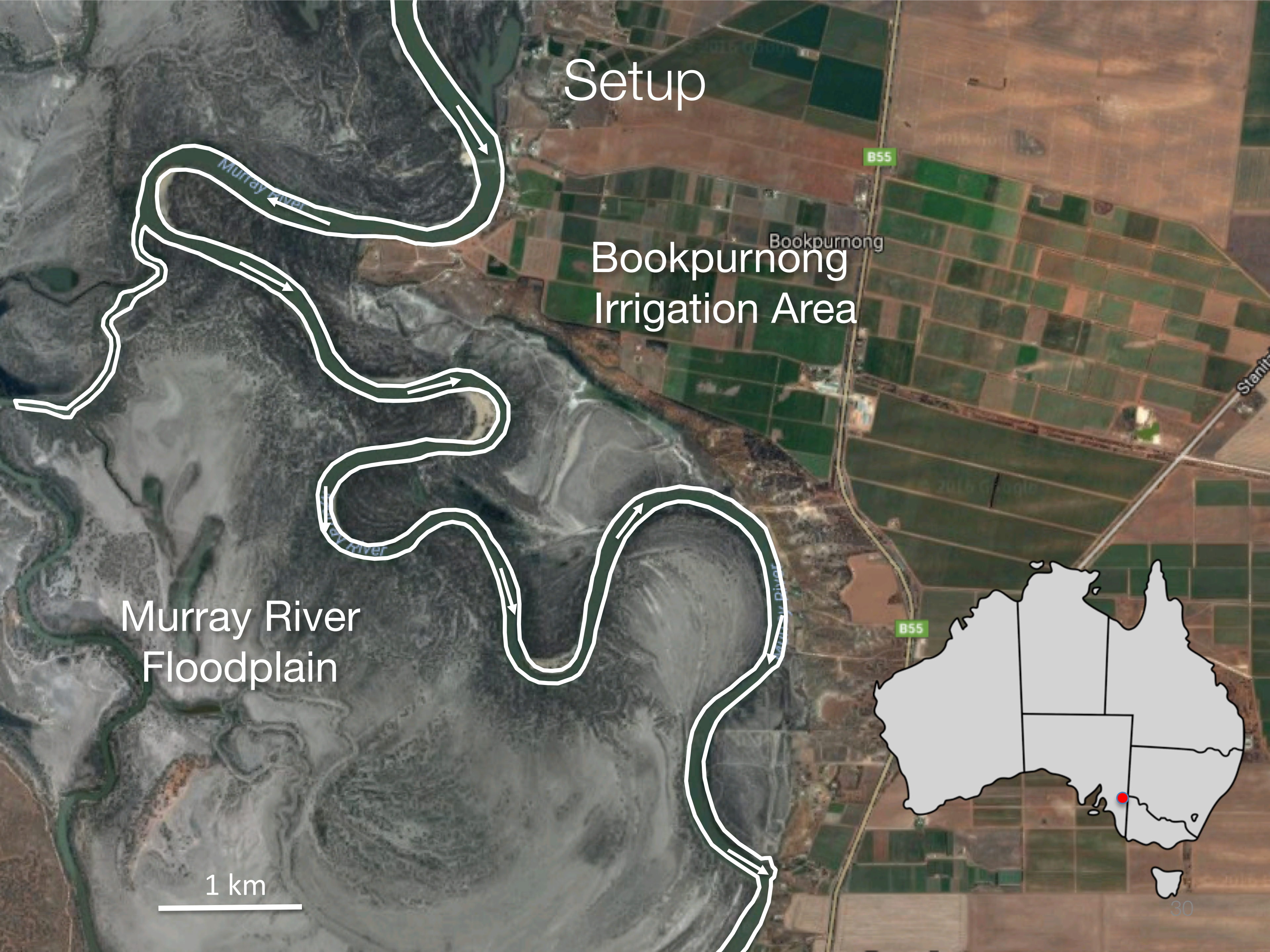
Frequency Domain EM

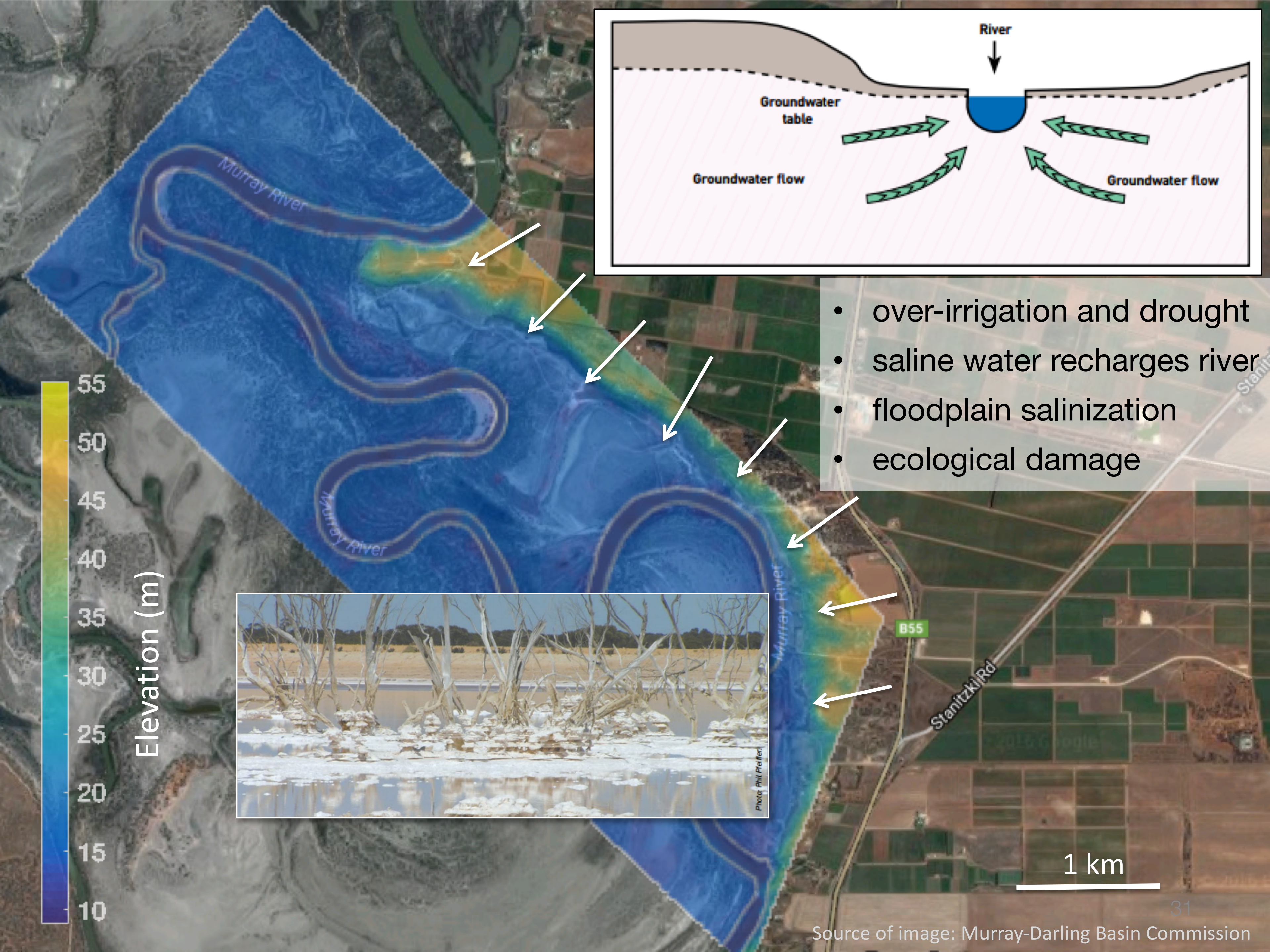
- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Groundwater, Minerals

Questions

Case History: Bookpurnong

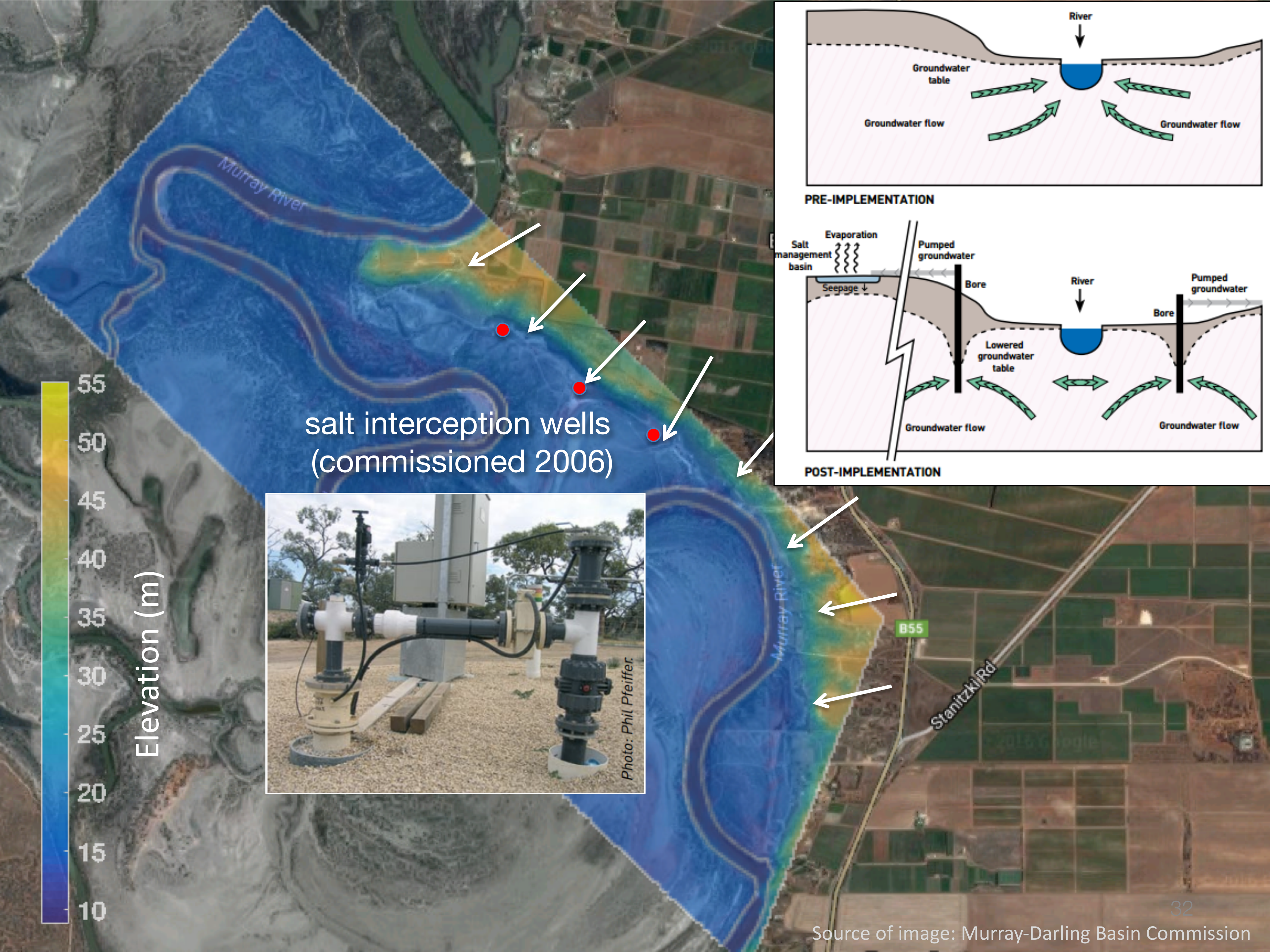
Viezzoli et al., 2009


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

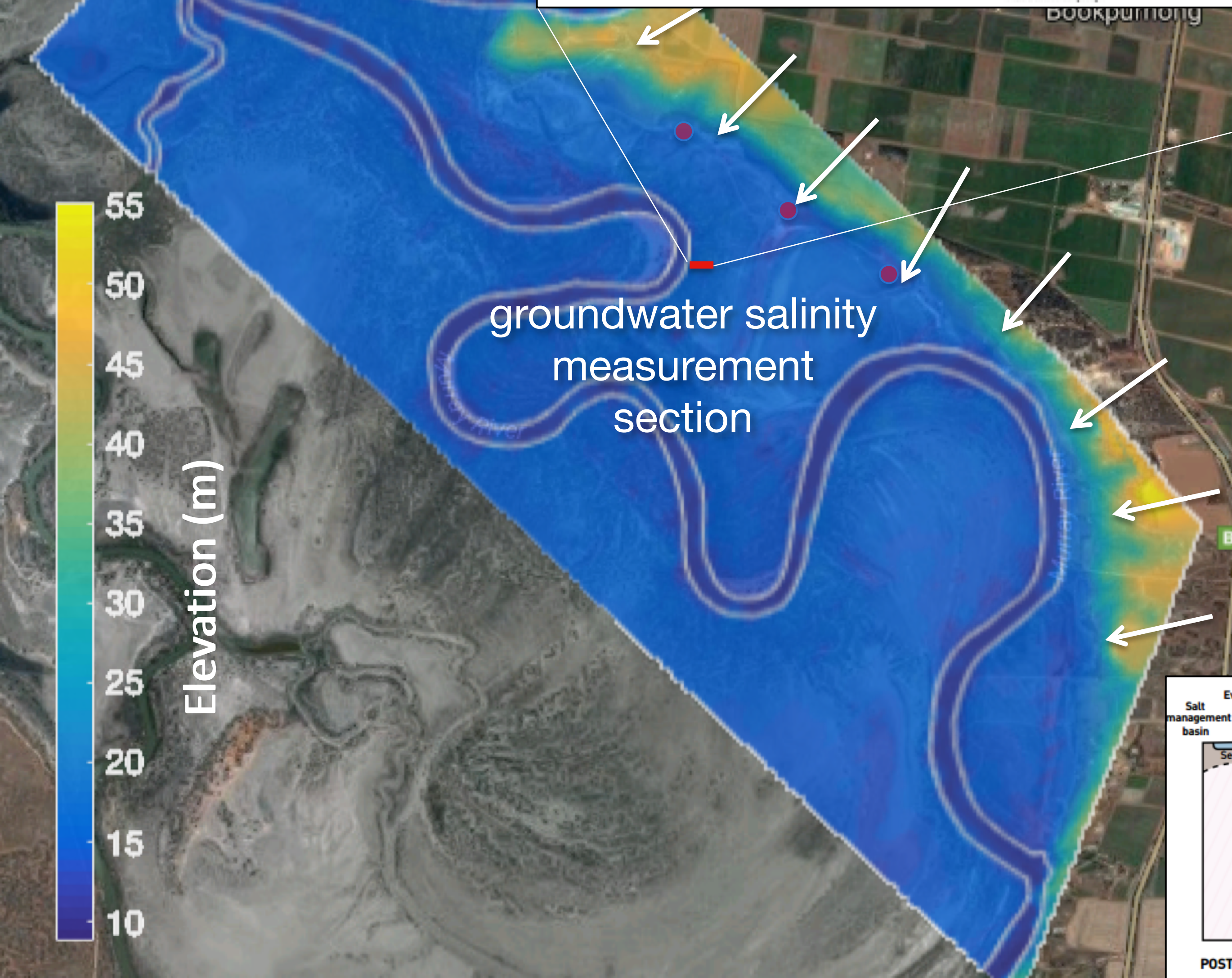


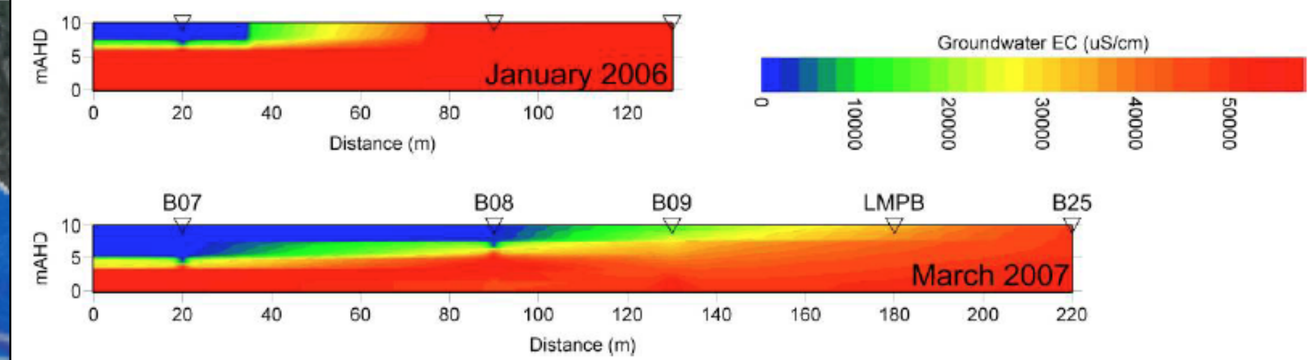
- over-irrigation and drought
- saline water recharges river
- floodplain salinization
- ecological damage

Source of image: Murray-Darling Basin Commission

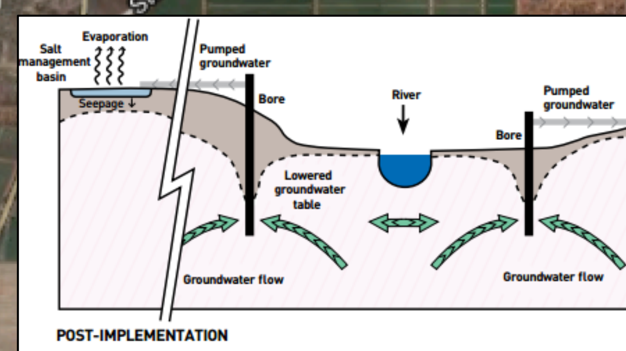


Murray River
salt interception wells
(commissioned 2006)
Photo: Phil Pfeiffer
Murray River
55
50
45
40
35
30
25
20
15
10
Elevation (m)
B55
Stanitzki Rd
River
Groundwater table
Groundwater flow
Groundwater flow
PRE-IMPLEMENTATION
Salt management basin
Evaporation
Seepage
Pumped groundwater
Bore
River
Pumped groundwater
Bore
Lowered groundwater table
Groundwater flow
Groundwater flow
POST-IMPLEMENTATION
Source of image: Murray-Darling Basin Commission



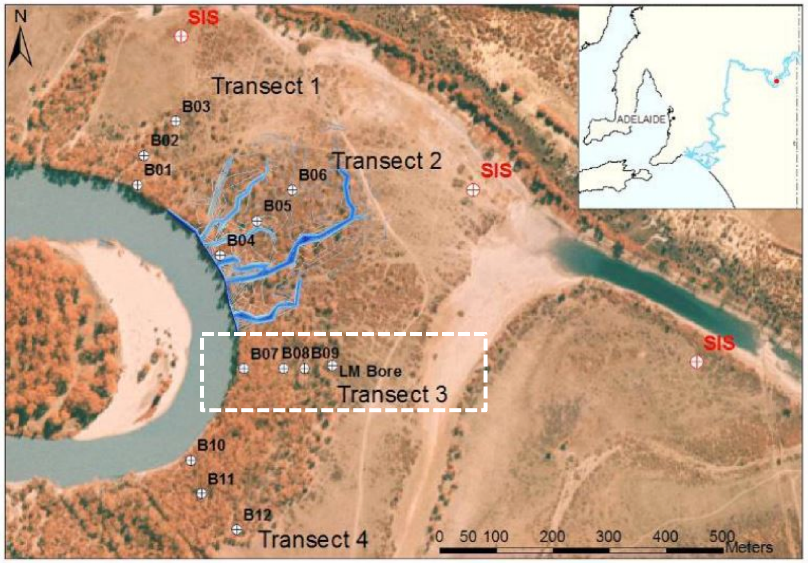


- pumping freshened shallow water near the river
- impractical to drill and sample the entire floodplain
- use airborne EM to quickly survey large areas



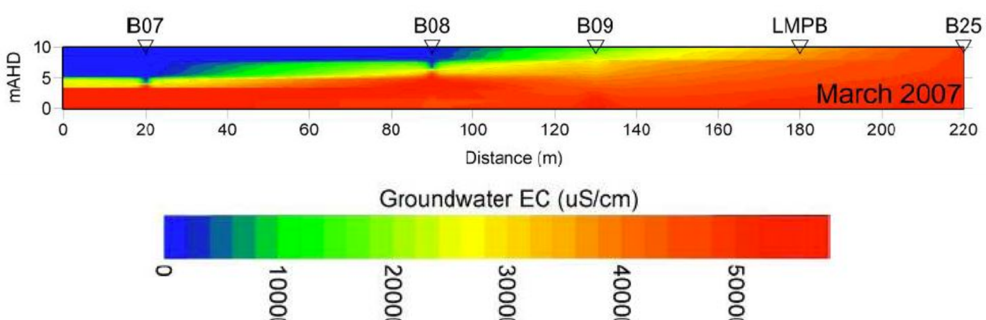
Properties

Location map for salinity measurements



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

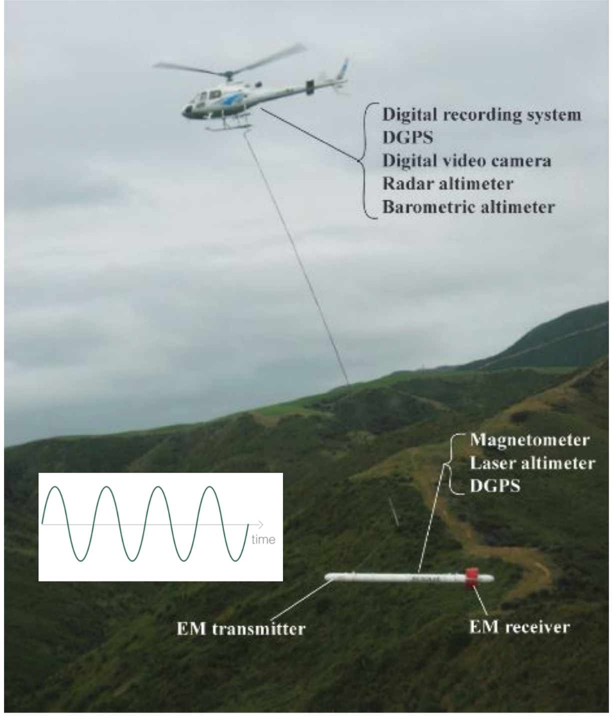
Conductivity from salinity measurements



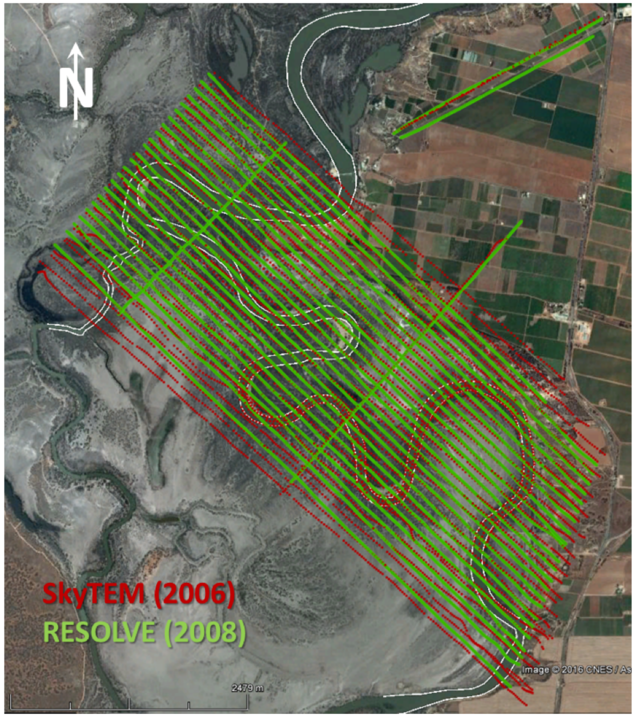
Holland et. al., 2008.

Survey

Resolve system (2008)



Flight lines

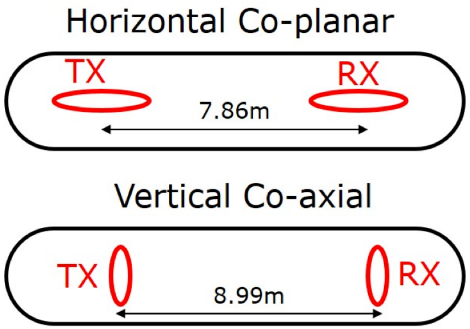


Horizontal Co-planar (HCP) frequencies:

- 382, 1822, 7970, 35920 and 130100 Hz

Vertical Co-axial (VCA) frequencies:

- 3258 Hz

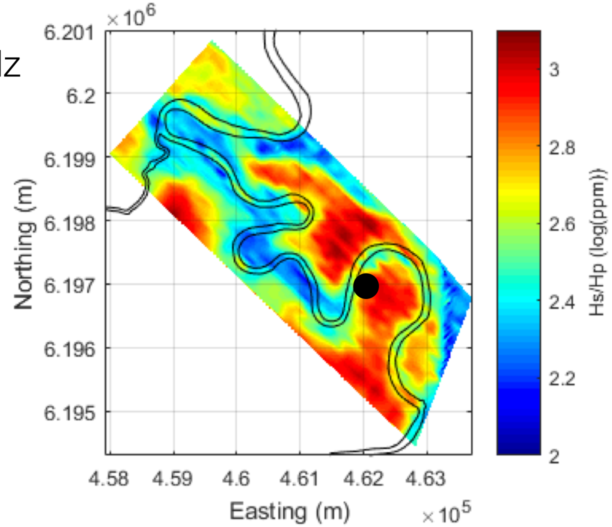


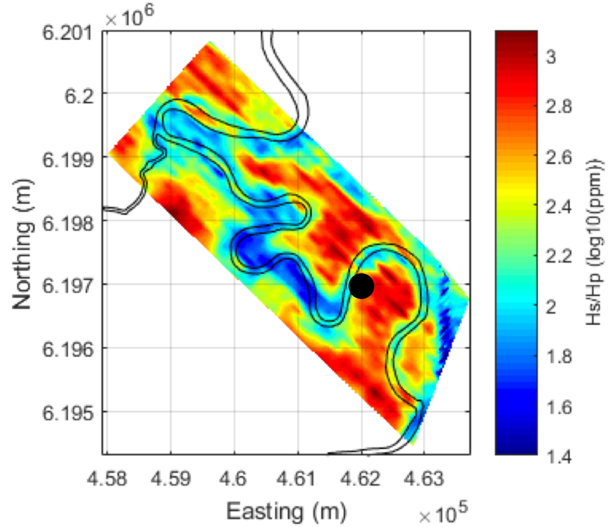
Horizontal Co-planar (HCP) data

In-Phase (Real)

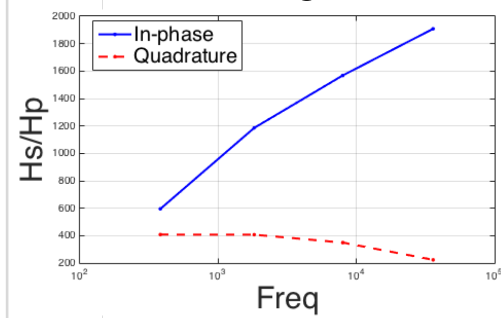
Quadrature (Imaginary)

382 Hz

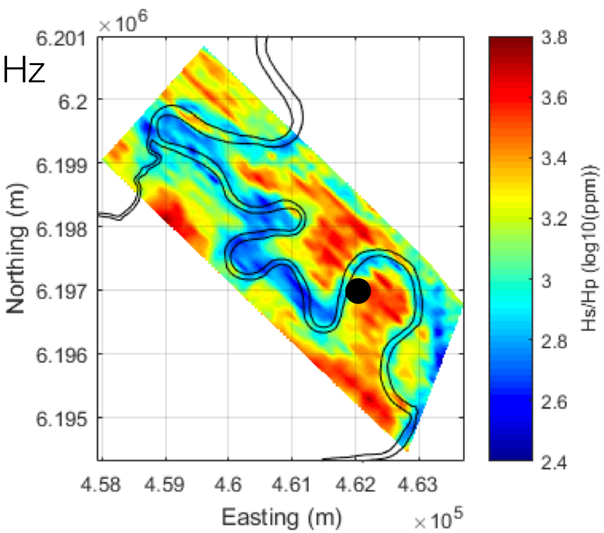


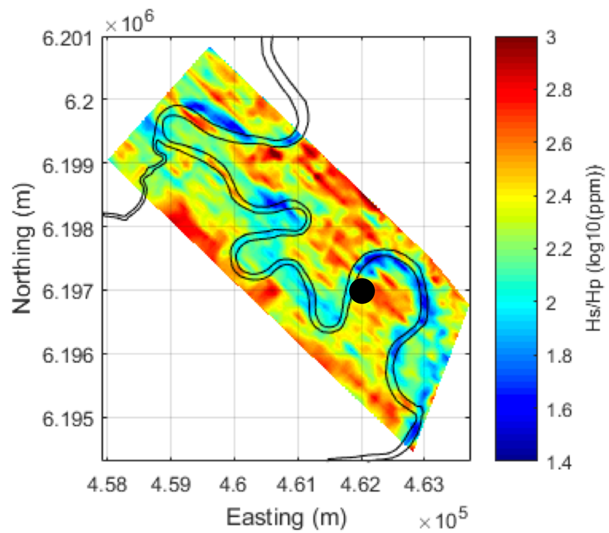


Sounding curve

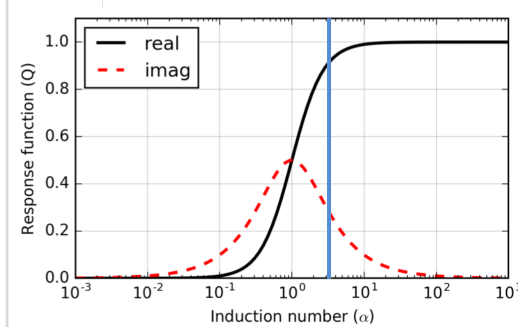


35920 Hz



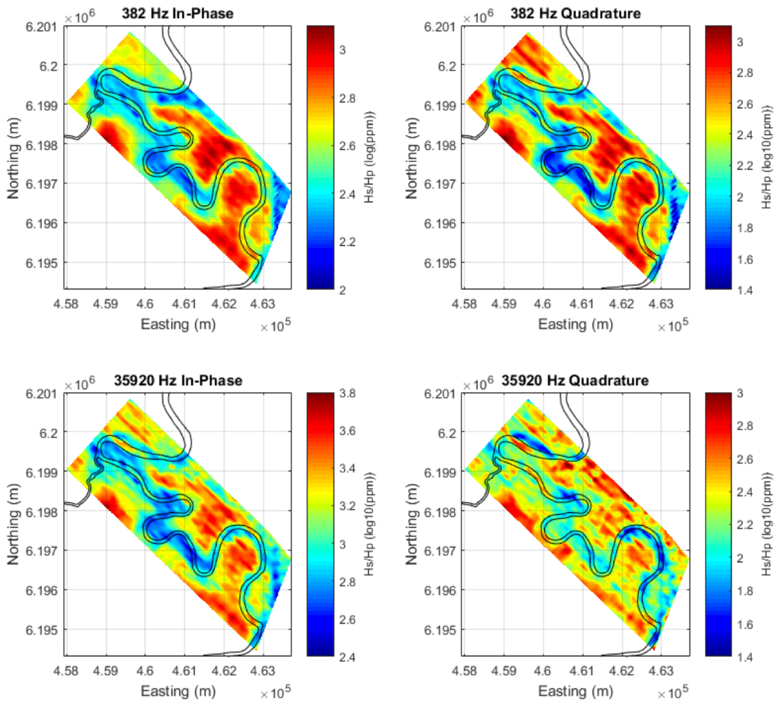


Response curve

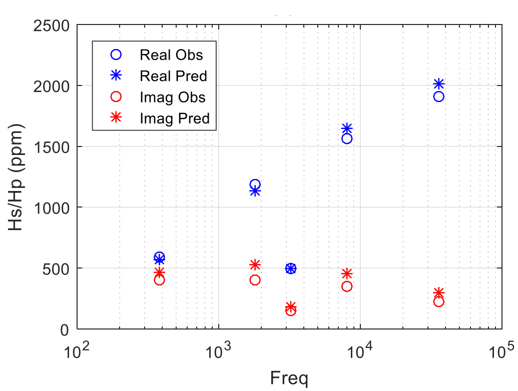


Processing: 1D inversion

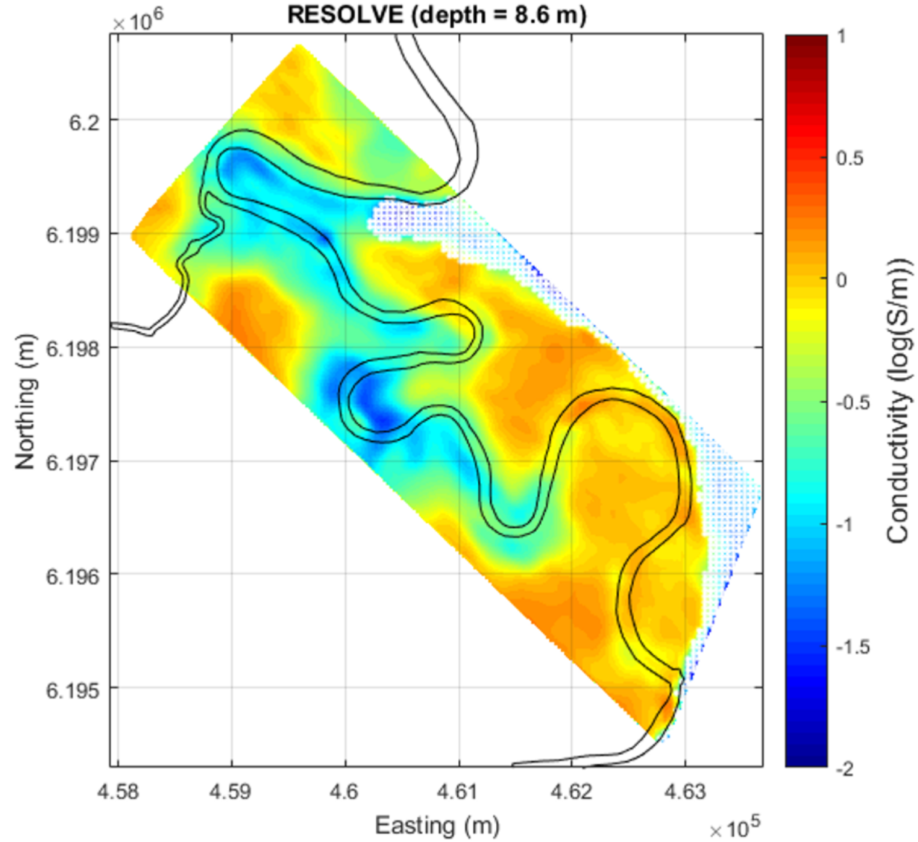
Data



Data fit

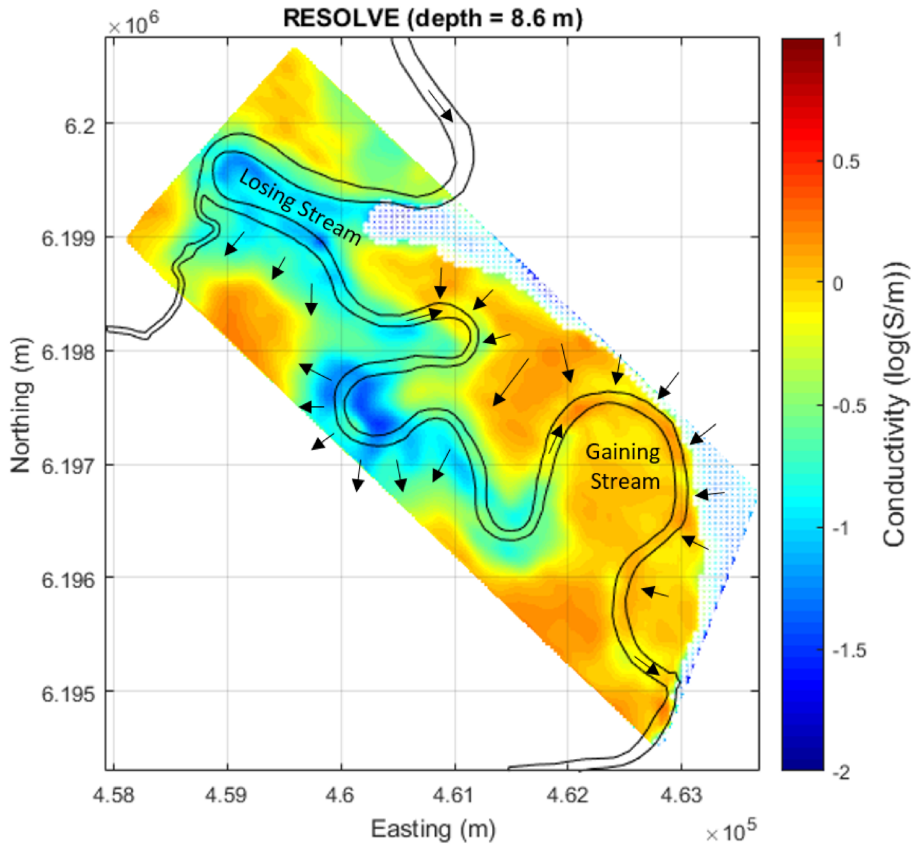


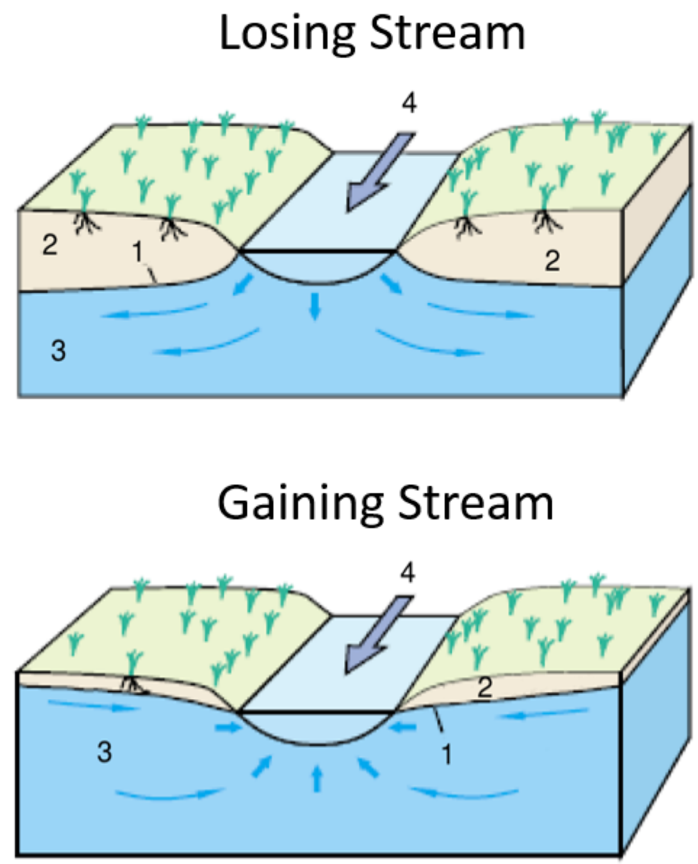
Conductivity model (stitched)



Interpretation

Conductivity model (stitched)



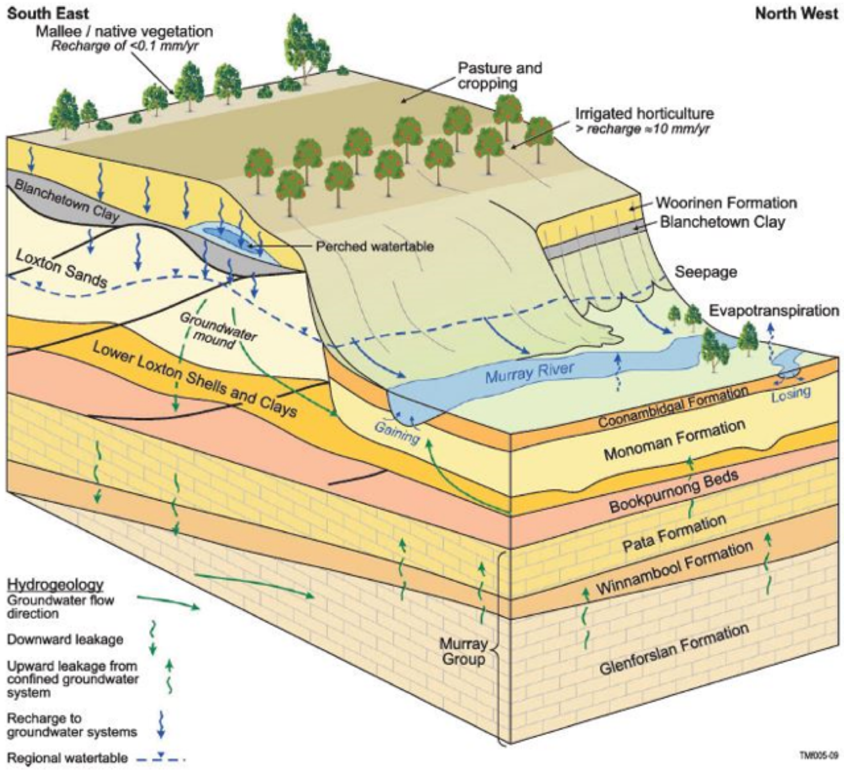


1 – Water table   2 – Unsaturated zone

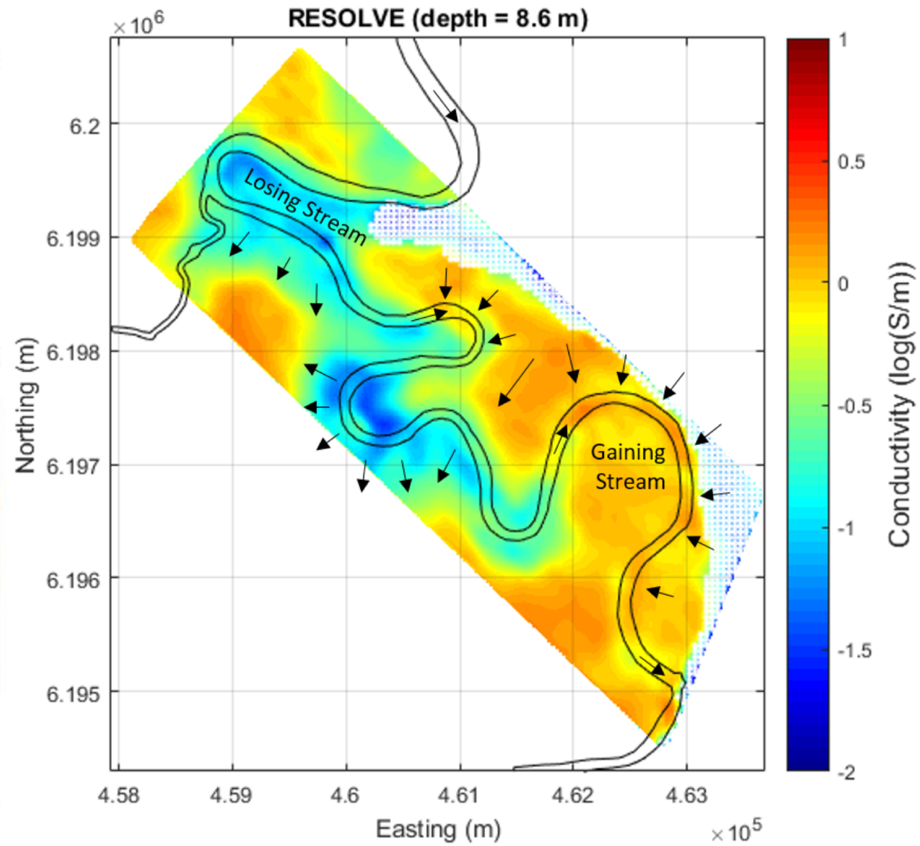
3 – Saturated zone   4 – Flow direction

Synthesis

Hydrological model



Conductivity model (stitched)



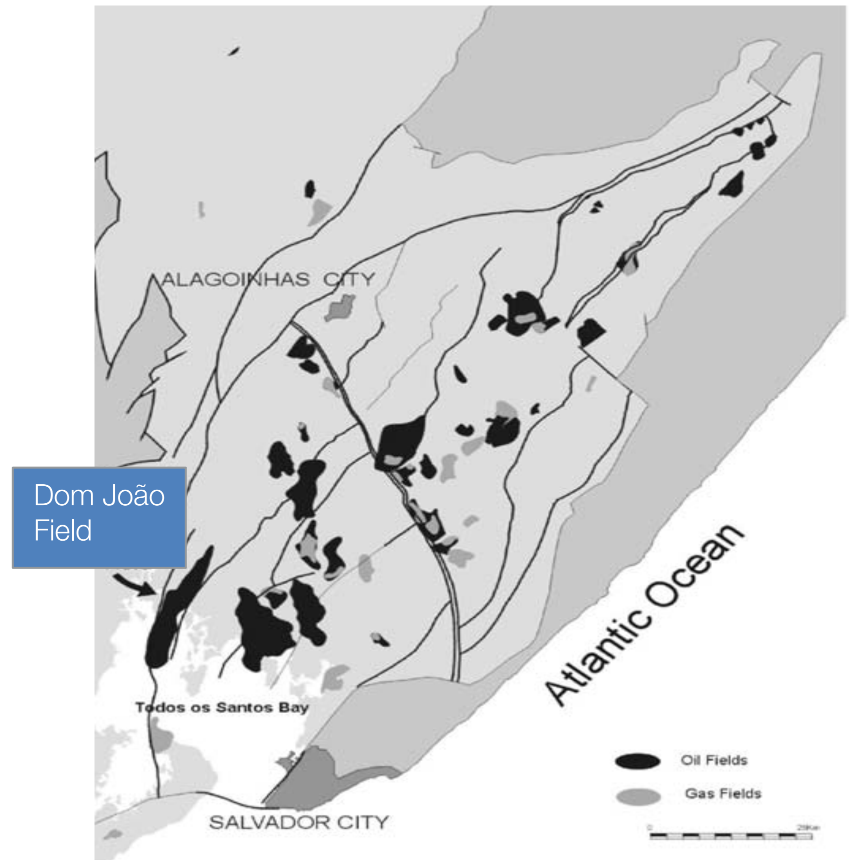
Case History: Crosswell EM Monitoring a water flood in Dom João, Brazil

Michael Wilt and Ping Zhang
Schlumberger EMI Technology Center
Paulo Netto, Jorge L. S. Queiroz, Jaciara B. Santos and Valterlene Oliveira,
Petrobras

2012

Setup: Dom João Oil Field

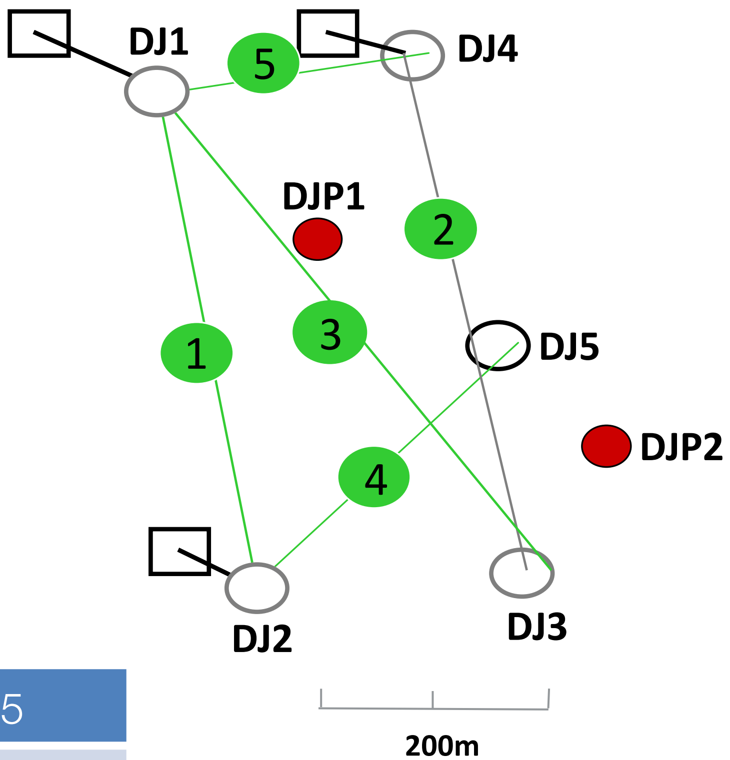
- Recôncavo is Brazil's largest on-shore oil basin
- Sedimentary Basin with multiple fields
  - Most production shallow <1km
- Dom João is the largest field
  - Sand/shale geology
  - More than 1 BBls produced from 1947 from natural water drive
- Recovery factor disappointing
  - suspected to be due to incomplete sweep of the reservoir layers + reservoir complexity



Strategy—Pilot test and monitor pattern water injection

Setup: Dom João Oil Field

- Enhanced recovery program
  - Pilot Pattern Water flood established in 2008
    - 5 injectors 2 producers (vertical/sub vertical)
    - Perforation at reservoir unit A
    - Water injection starts at 2009
  - Injector casings are EM "friendly" (fiberglass)



Well	DJ1	DJ2	DJ3	DJ4	DJ5
Rate (per day)	$70m^3$	$70m^3$	$60m^3$	$80m^3$	$100m^3$
Total	82.5k	82.5k	67.3k	89.7k	99.1k

Properties

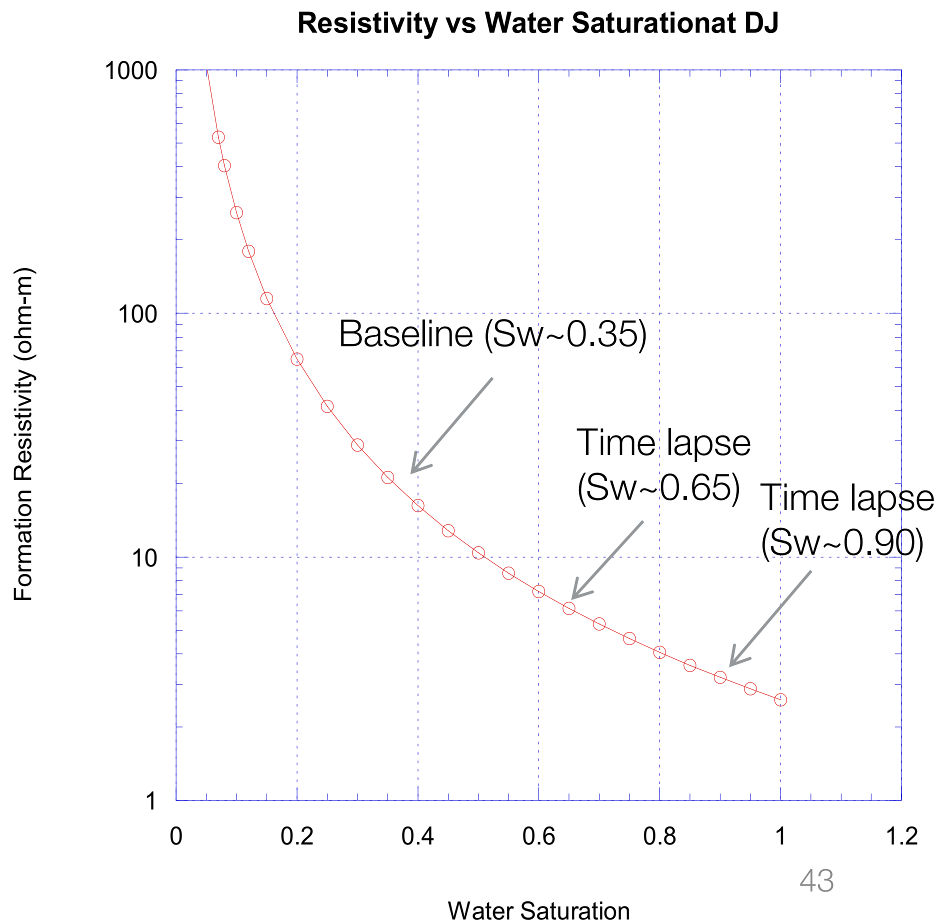
- Injection water is recycled formation water
  - R_w=0.18 Ωm

- Baseline Unit A saturations:
  - S_w=30-60%

- Time lapse expected: S_w= 65-90%
  - R from 15 to 7 Ωm (S_w= 65%)
  - R from 15 to 3 Ωm (S_w= 90%)

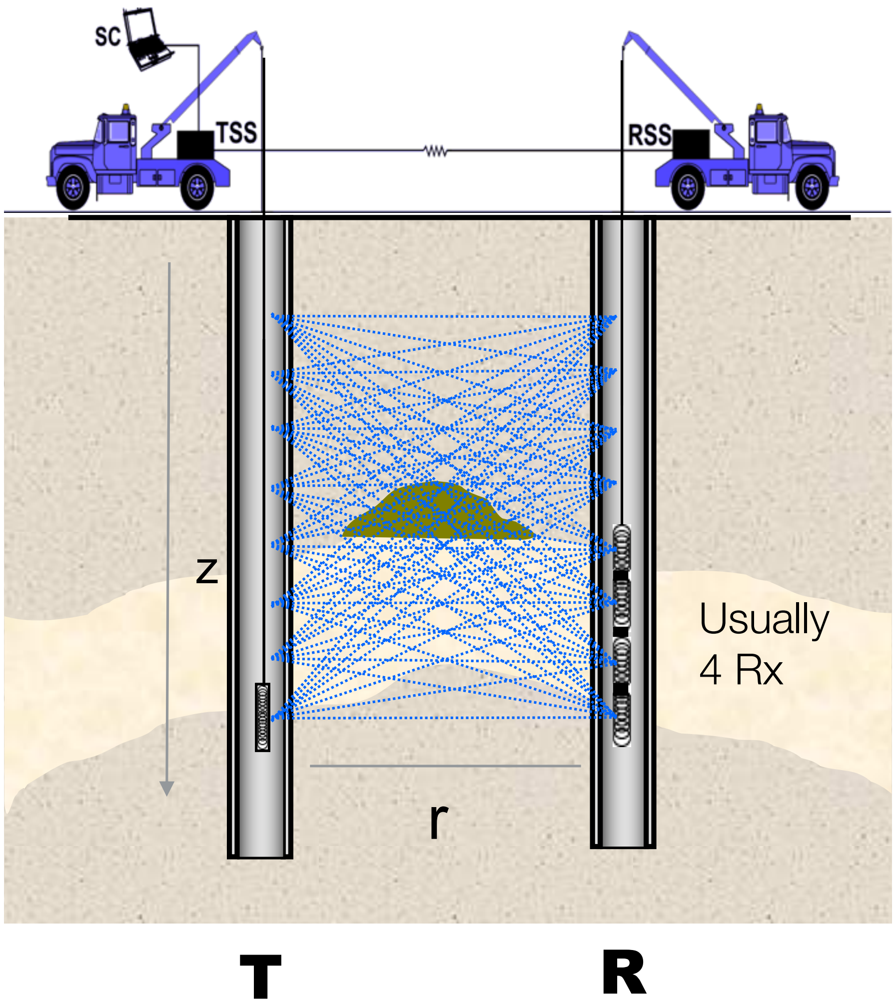
Archies' law:

- Assume m=n=2
- Rw=0.18 ohm-m
- Porosity=0.20



Survey: Time Lapse Crosswell EM

- Inductive source (VMD)
  - Used for fiberglass or uncased wells up to ~1km
  - If one well steel-cased, up to ~500m
- Interwell imaging is accomplished tomographically
  - 5 well pairs collected
    - Well spacing: 300-550m
    - Depth interval: 200-550m
  - 150 – 500 Hz
- Timeline
  - 2008: Baseline measurements
  - 2009: Injection starts
  - 2011: Time lapse measurements



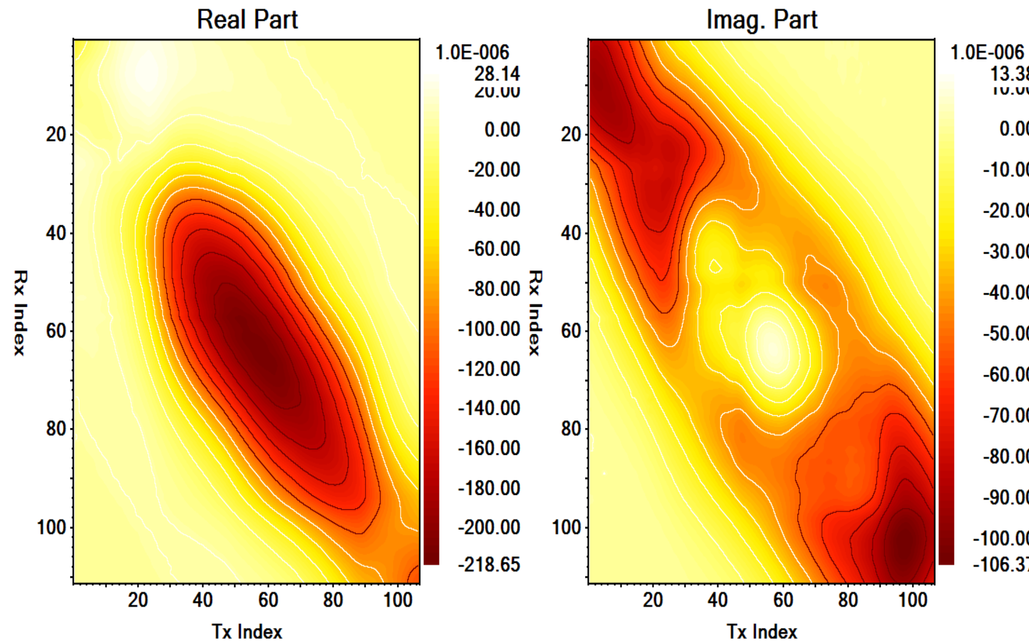
- Also: Time lapse induction logging

Data

- Expected crosswell EM responses
  - 10-12% for S_w= 65%
  - 20-25% for S_w= 90%

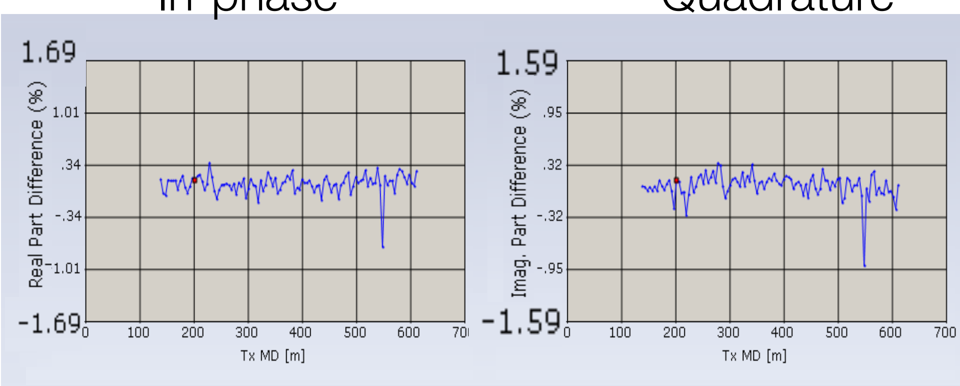
- Data quality for both baseline and time lapse surveys were excellent
  - Time-lapse profiles repeat to 0.3%!

Magnetic field in 2011 survey



In-phase

Quadrature



Data

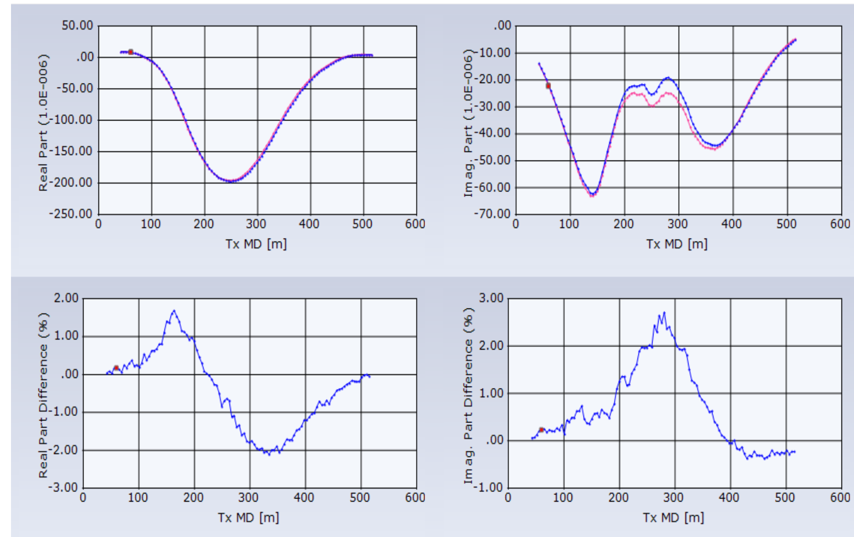
- Expected crosswell EM responses
  - 10-12% for S_w= 65%
  - 20-25% for S_w= 90%

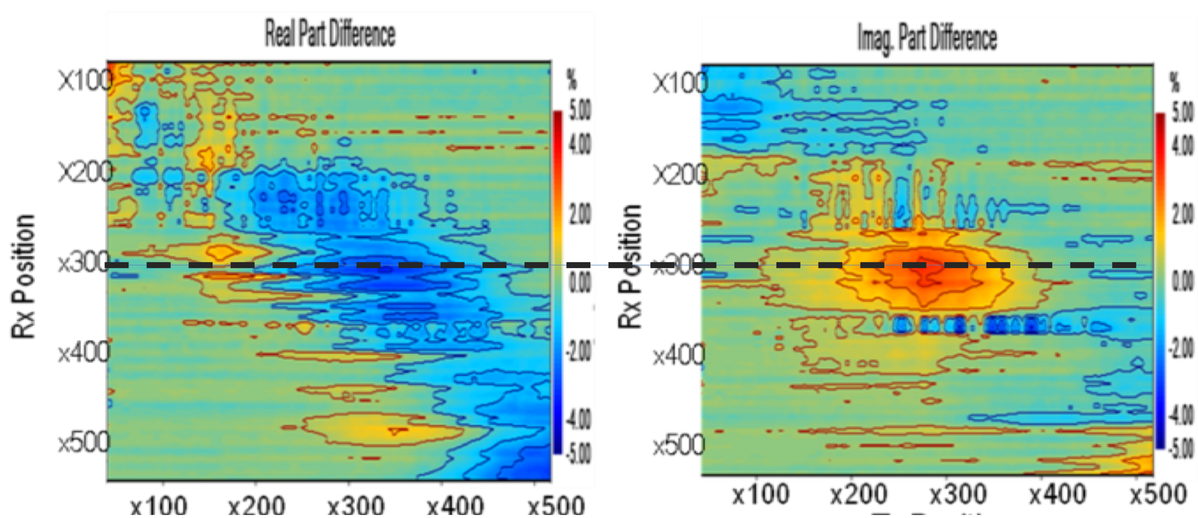
- Time lapse data show a consistent 2-5% data difference for profiles in the reservoir zone

- Good news: Clear anomaly on all 5 profiles

- Bad news: Anomaly much smaller than anticipated

Profile difference

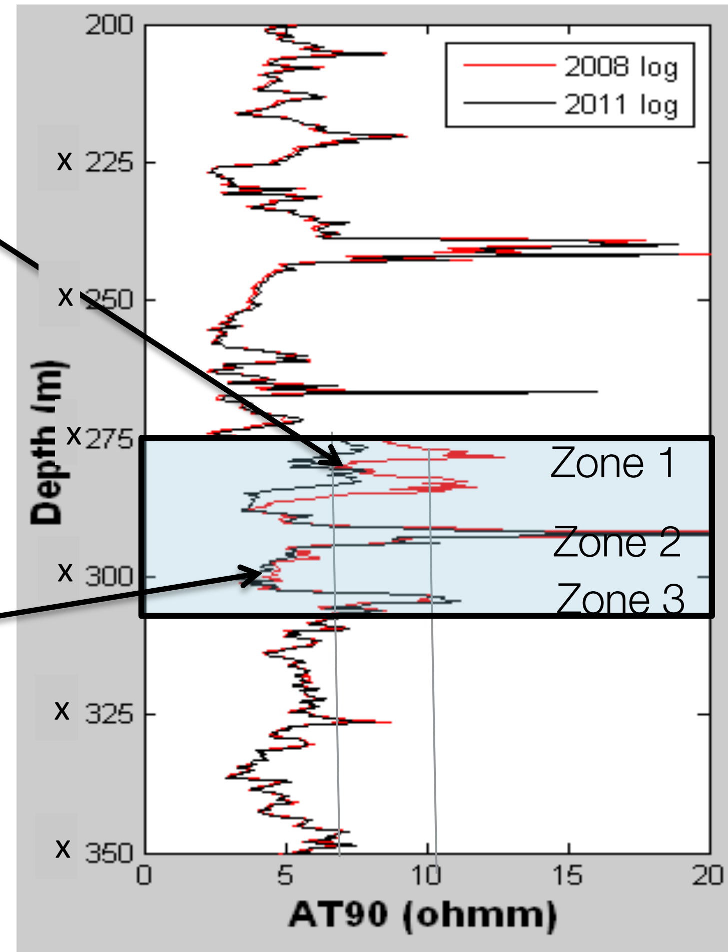




Data: Induction Logs

- Observe change from 10-15Ωm to 6-8 Ωm instead of 3 Ωm
  - Suggests that sweep is less than anticipated
  - Using Archie law and 7 Ωm suggests maximum Sw ~ 0.65

- Little difference in time lapse resistivity logs in Zone 2 → not swept?



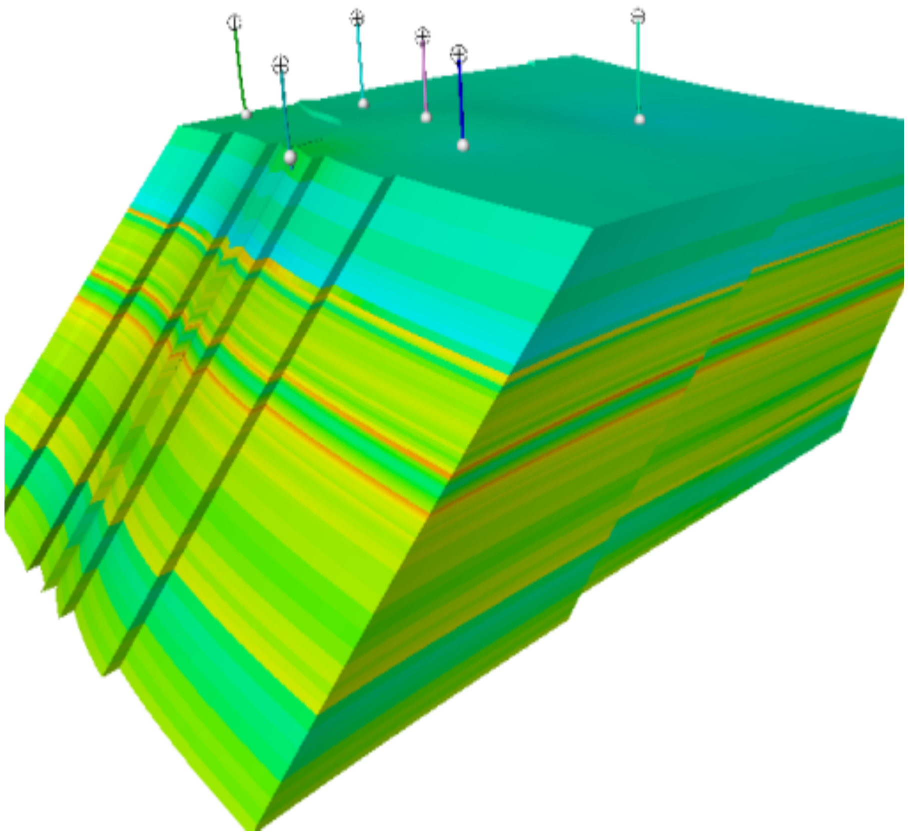
Processing

- Make 3D Geological model from logs and other geophysical data

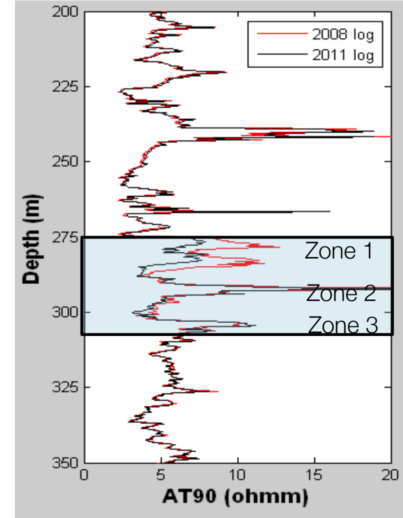
- Invert baseline data using geological model as a start

- Invert time lapse data using model from baseline inversion to start

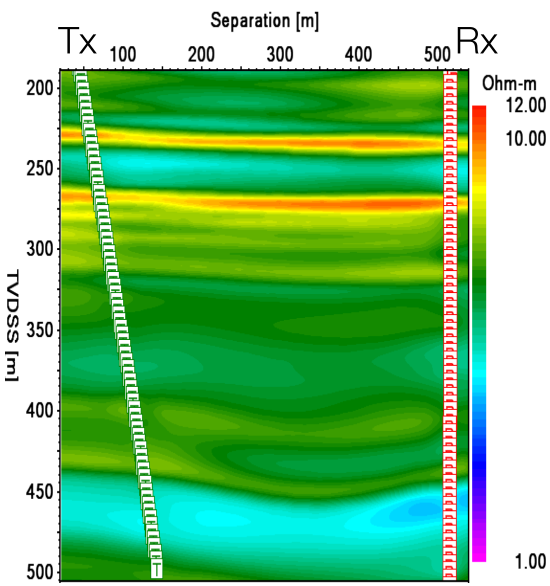
- Analyze resistivity difference (final model – start model)



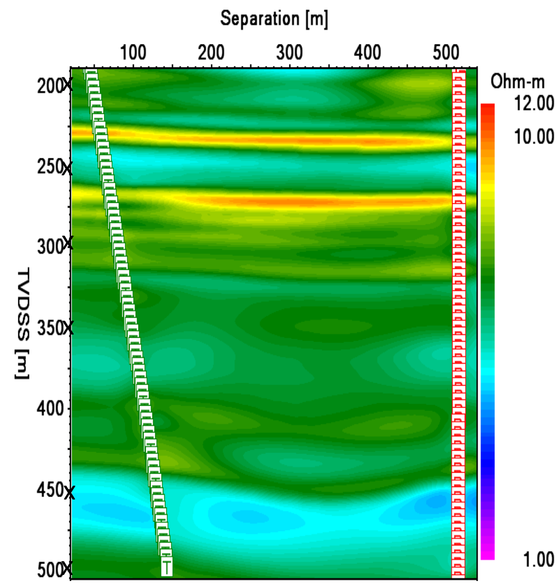
Processing: 2D inversions

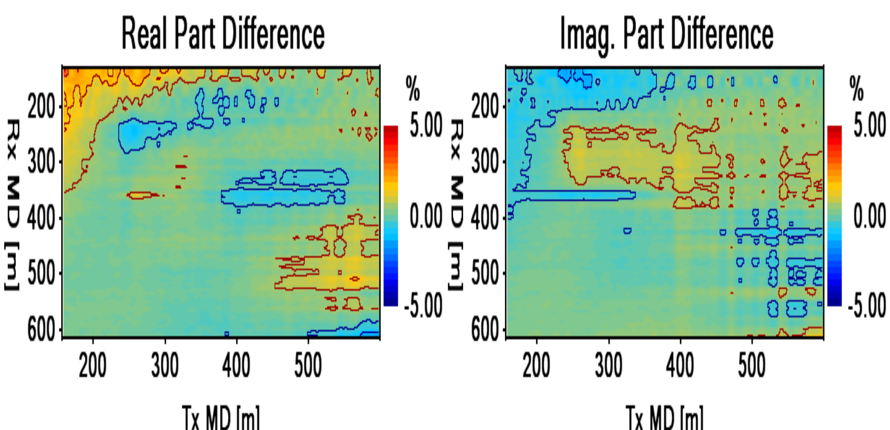


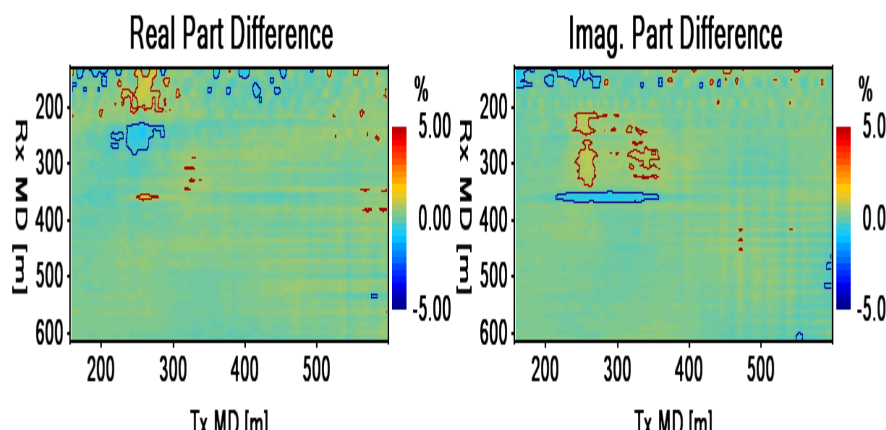
Starting model (2008)



Final model (2011)





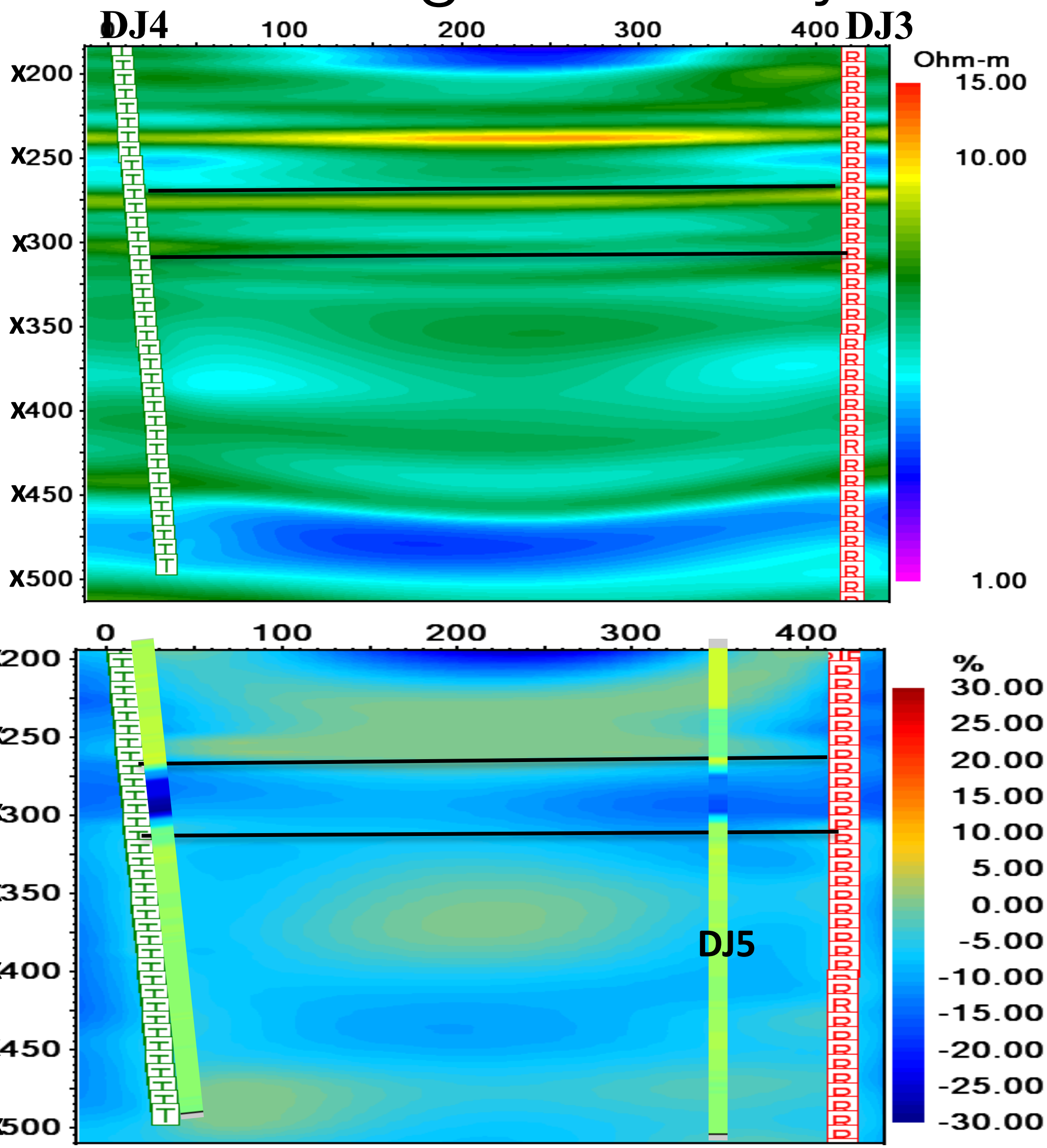


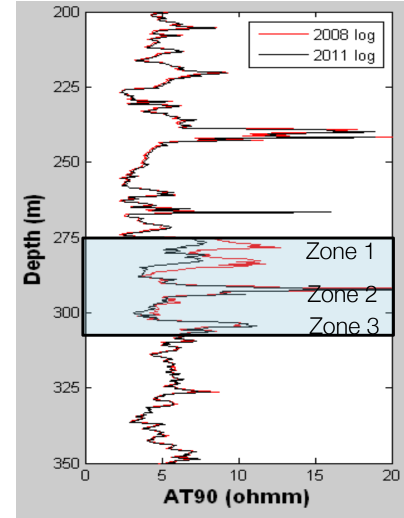
overall data misfit
2.0%

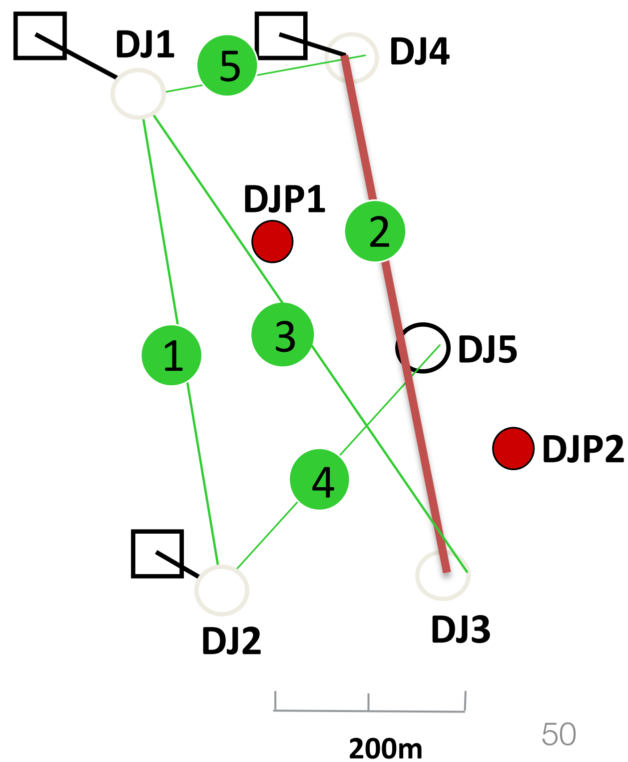
Well Pair DJ1-DJ2

overall data misfit
0.2%

Processing: Resistivity Difference

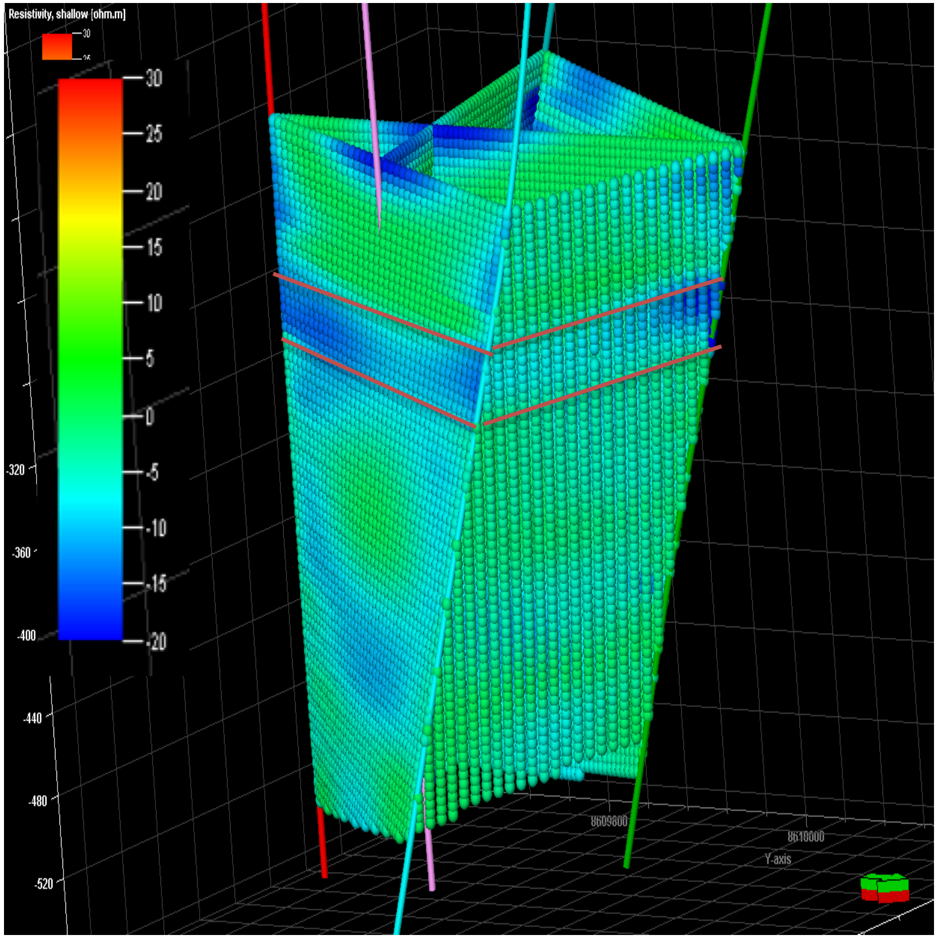


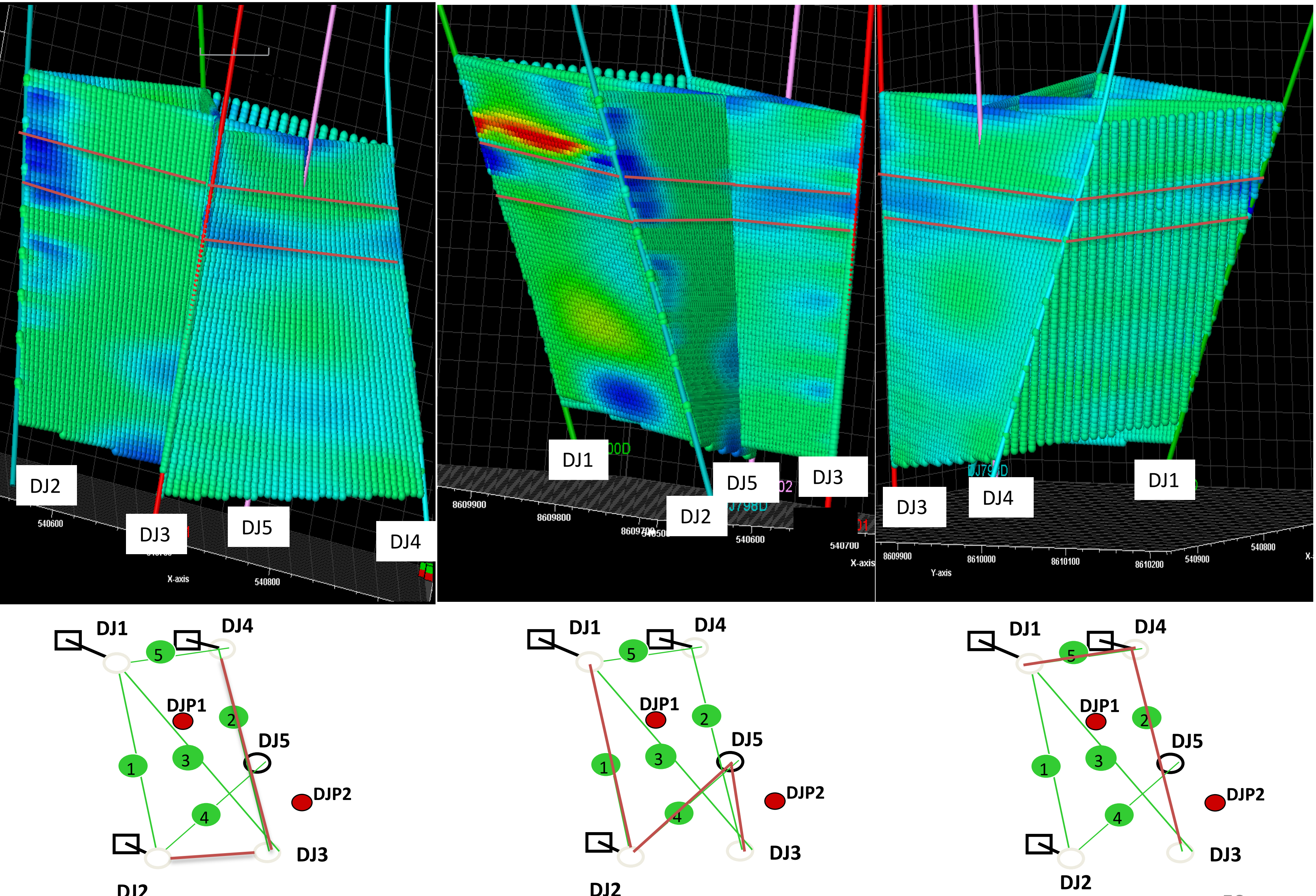




Interpretation

- Resistivity “fence diagram”
- Shows percentage resistivity difference for all 5 sections over 2.5 years period
  - Consistently shows 5-30% decrease in reservoir zone
  - Larger changes in upper parts of the reservoir
  - Smaller decreases in other zones mainly along wells
- Swept zone extends roughly 50m from injectors



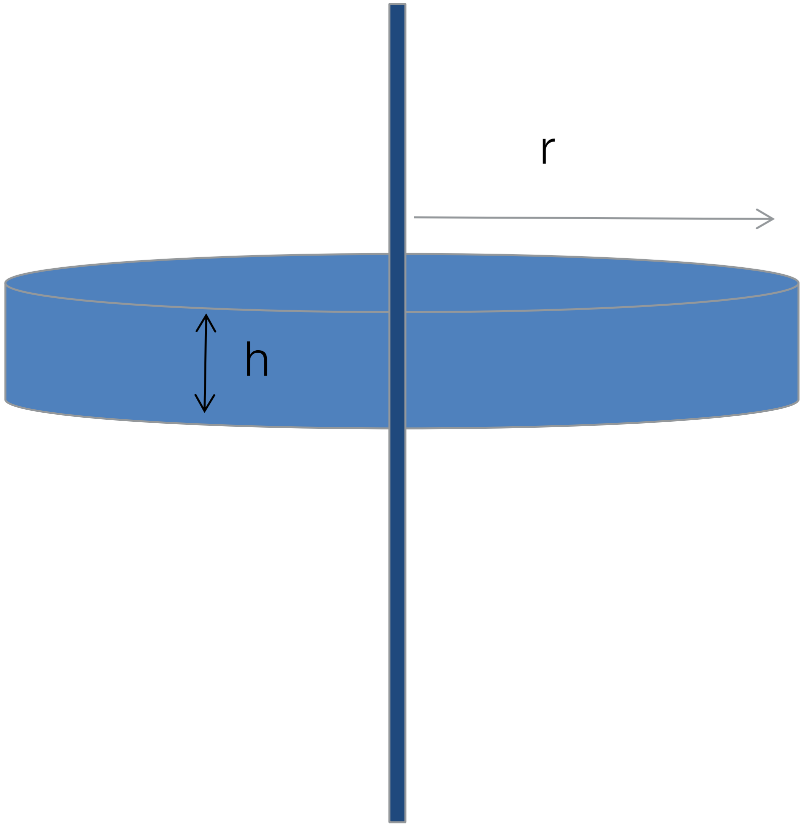


DJ2
DJ3
DJ5
DJ4
540600
X-axis
540800
DJ1
DJ5
DJ3
DJ2
8609900
8609800
540600
540700
X-axis
DJ3
DJ4
DJ1
8609900
8610000
8610100
8610200
Y-axis
540900
540800
DJ1
DJ4
5
DJP1
2
DJ5
1
3
DJP2
4
DJ2
DJ3
DJ1
DJ4
5
DJP1
2
DJ5
1
3
DJP2
4
DJ2
DJ3
DJ1
DJ4
5
DJP1
2
DJ5
1
3
DJP2
4
DJ2
DJ3

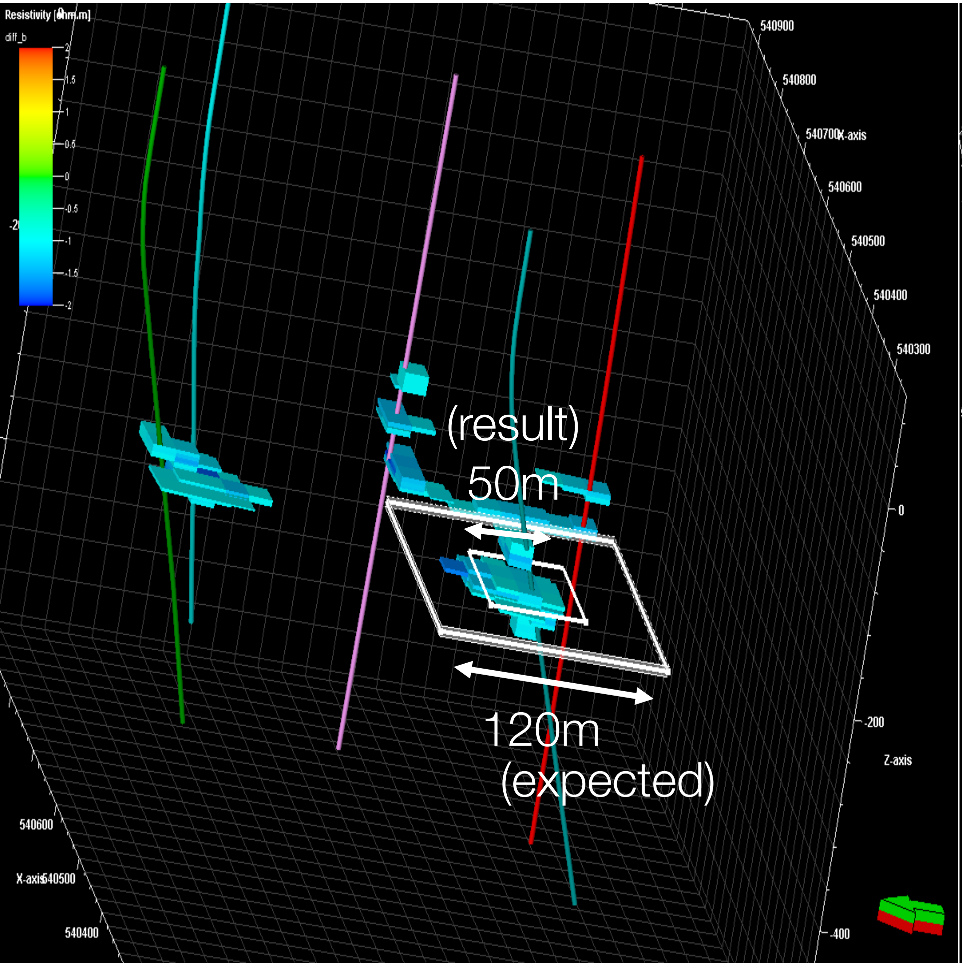
Interpretation

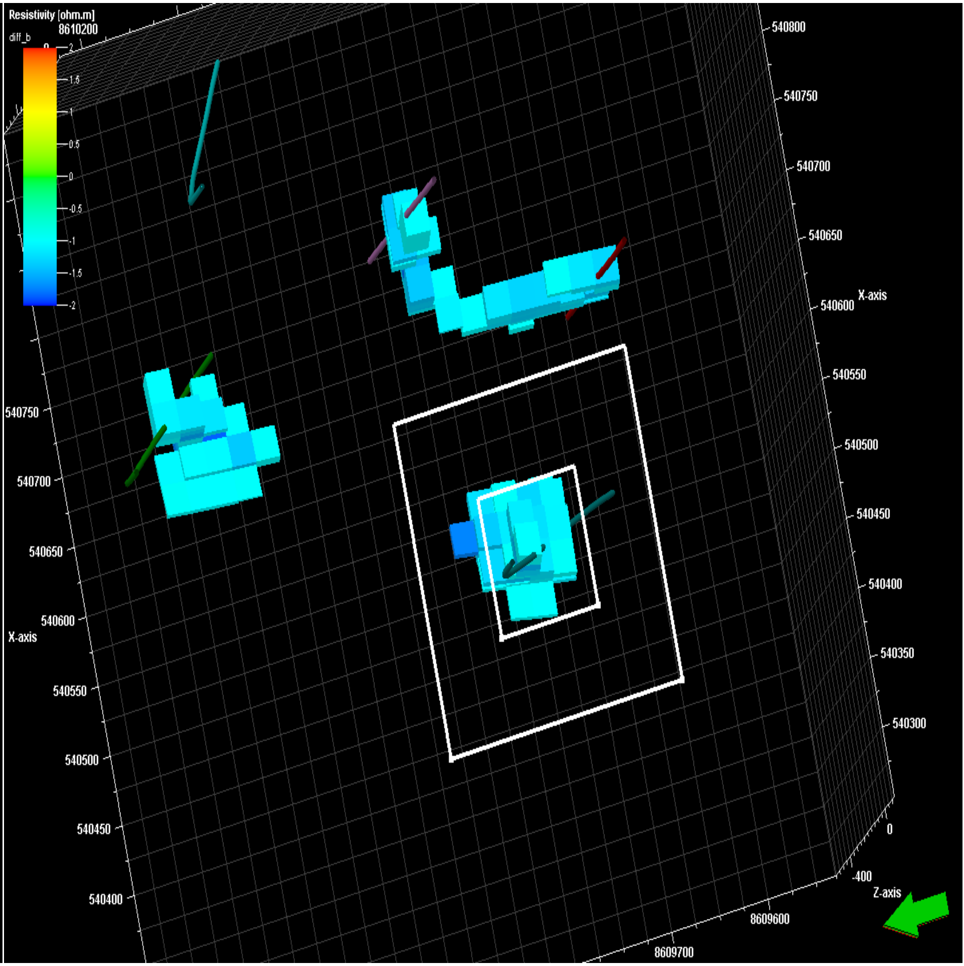
Maximum sweep radius per well:

- Total injection volume per well: ~80,000 m^3
- Swept volume (S_v) : Injected volume / (porosity x Sw)
  - Porosity=0.2, S_w=0.65
  - S_v ~600,000 m^3
- Assuming cylindrical sweep:
  - S_v = p x r^2 x h
  - where h=15m
- Expected swept radius: ~**120m**



Interpretation





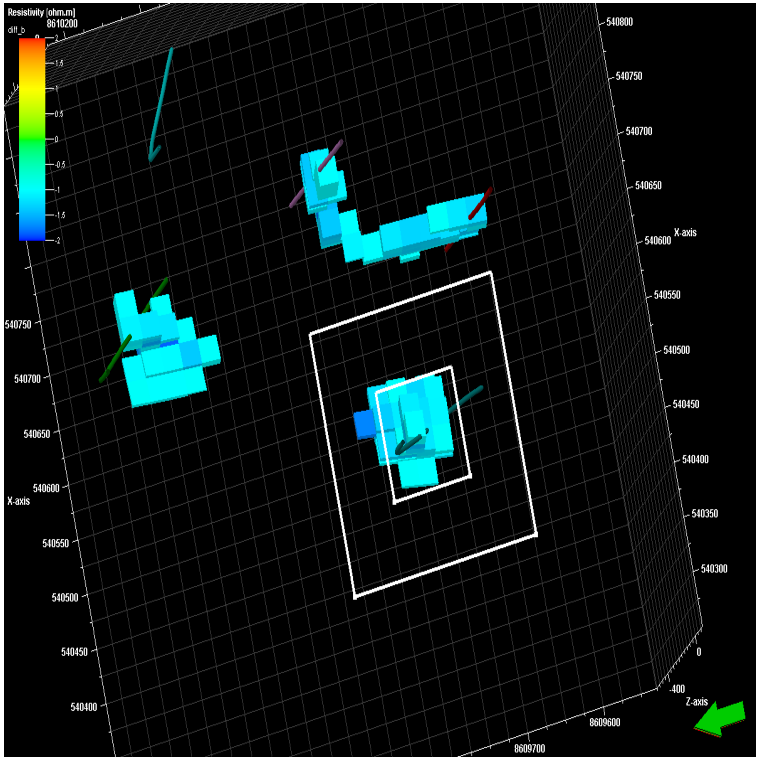
3D image of swept volume

Synthesis

- Excellent data quality
  - The data repeat within 0.5%.
  - Baseline and TL data reveal 3-5% anomaly by direct differencing.

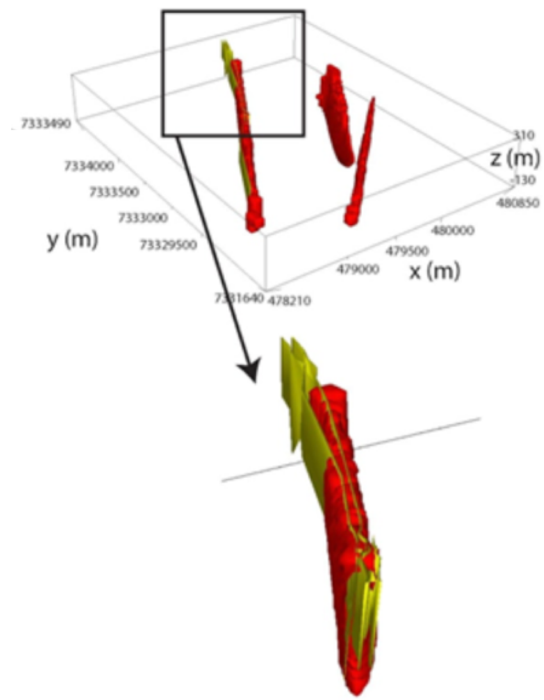
- Impact of the water injections: modest
  - Imaged swept area (~50m) smaller than anticipated, mostly in upper layer
  - Magnitude of the resistivity change is consistent with a S_w=0.65 model

- Much of the injected water likely bypassing oil bearing layers → flood is progressing slowly



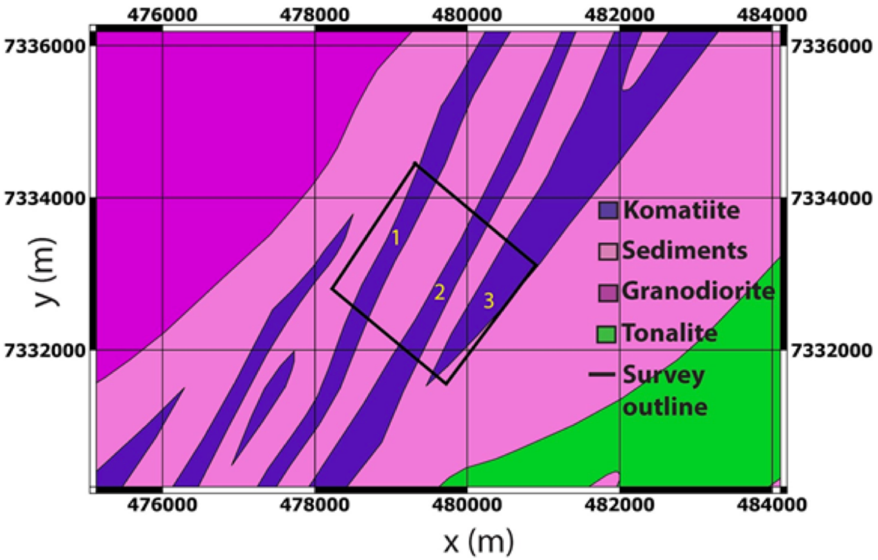
Case History:
VTEM survey over the West Plains orogenic gold region

McMillan et al, 2014



Setup

Geology map

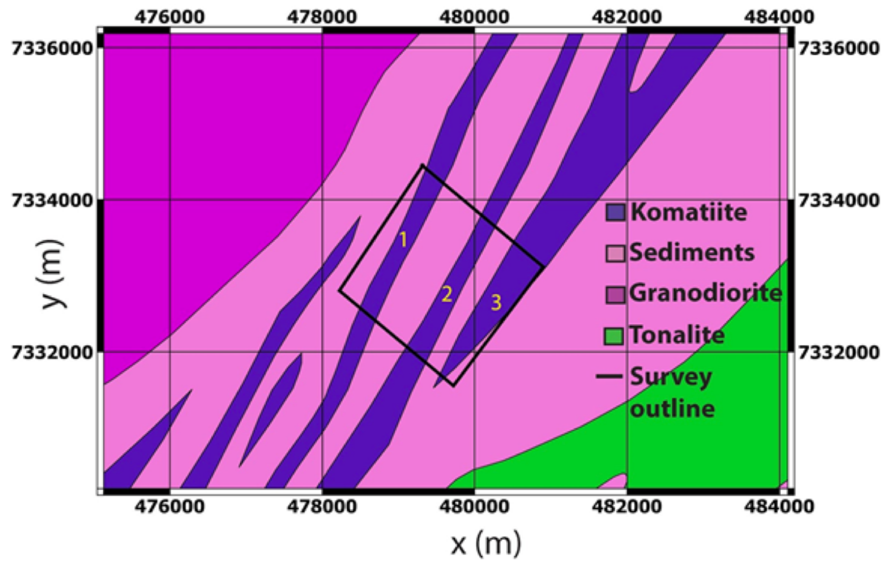


- Ultramafic komatiite units
  - steeply dipping
  - gold mineralization
- Area covered by thin layer of glacial material (outcrops scarce)
- Geology map from regional mag. survey
  - Low resolution; No dip information about the komatiite units

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

Properties

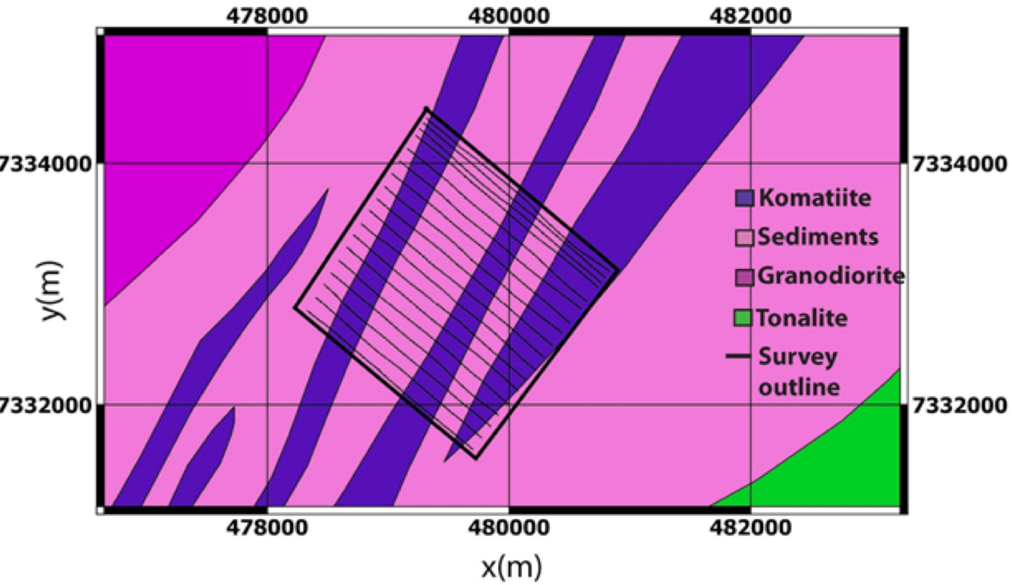
Geology map



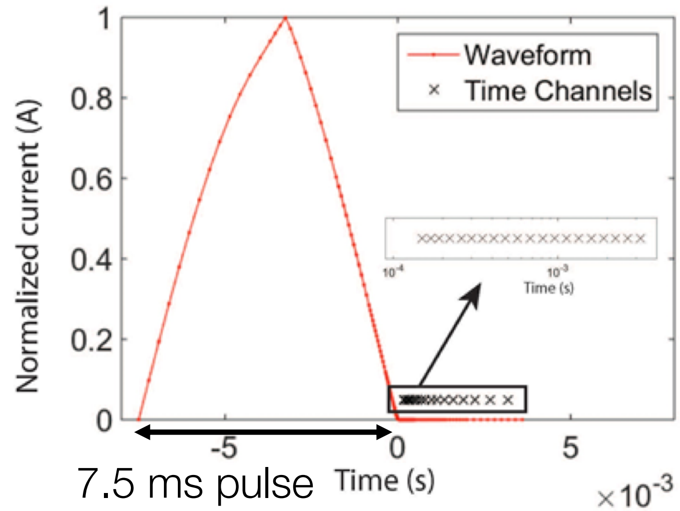
Units	Conductivity	Susceptibility
Komatiite	High	Moderate
Sediments	Moderate	Low
Granodiorite	Low	Low-Moderate
Tonalite	Low	Low-Moderate

Survey: VTEM

Survey lines



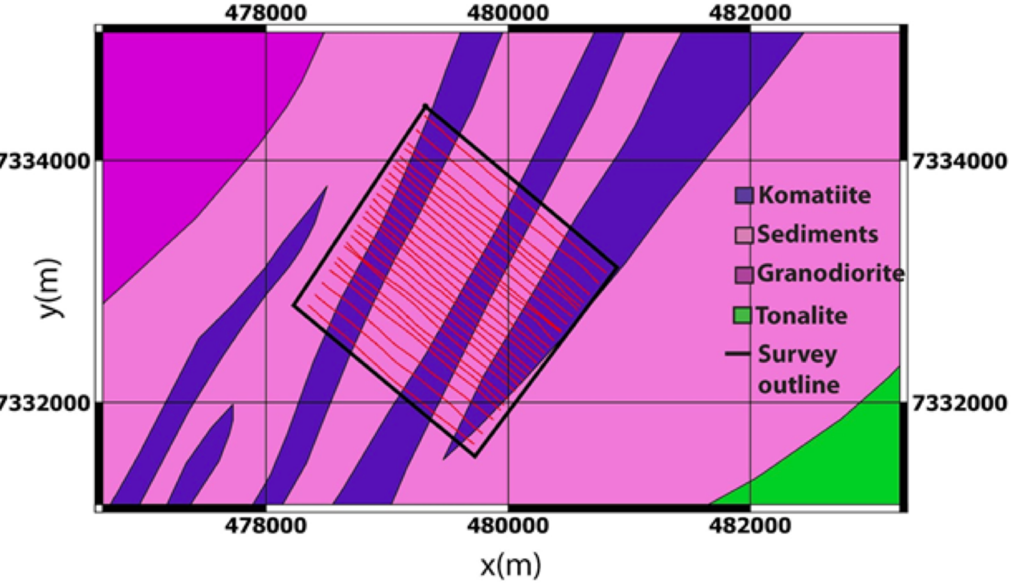
Current waveform



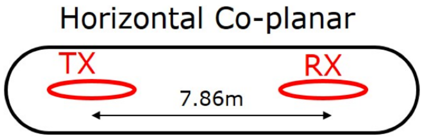
- VTEM (2003) system
  - Line spacing: 120 m; except several lines in the North part (60 m)
  - Line direction: 310 degree
  - Transmitter diameter: 18.5 m
  - Measured component: dBz/dt (26 time channels from 110-6340 μs)

Survey: RESOLVE

Survey lines



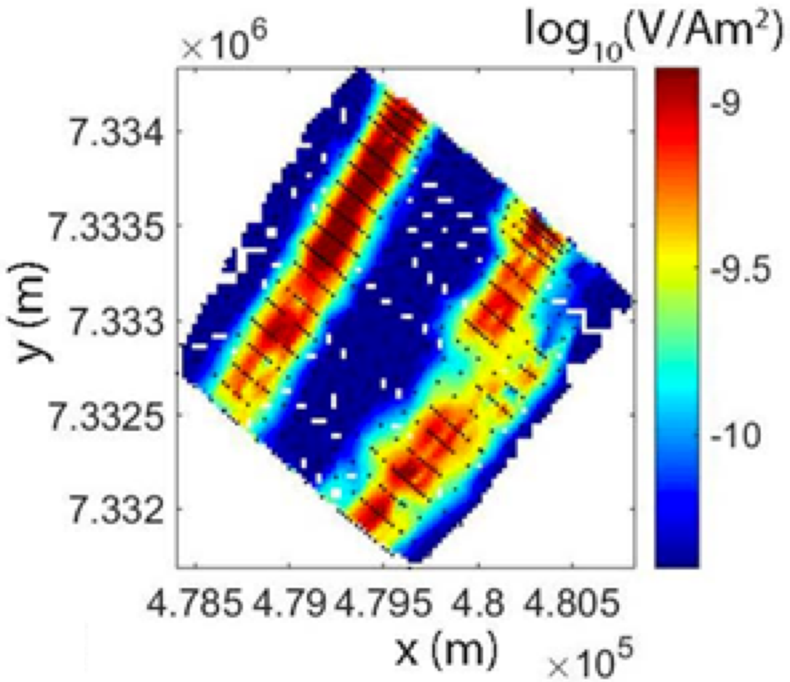
System



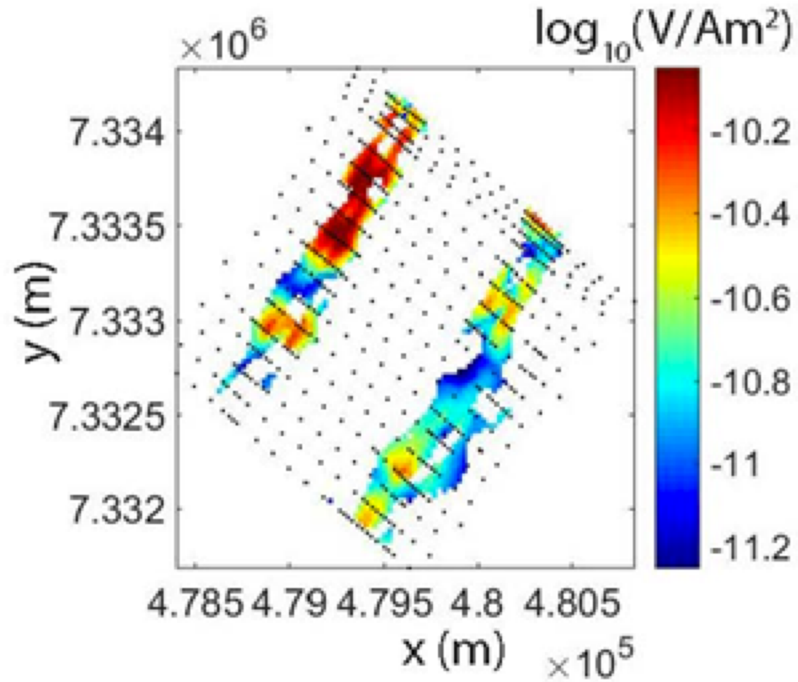
- RESOLVE (2005) system
  - Line spacing: 60 m
  - Line direction: 310 degree
  - Co-planar: 385-115,000 Hz (5 frequencies)

Data: VTEM

dBz/dt at 150 μs

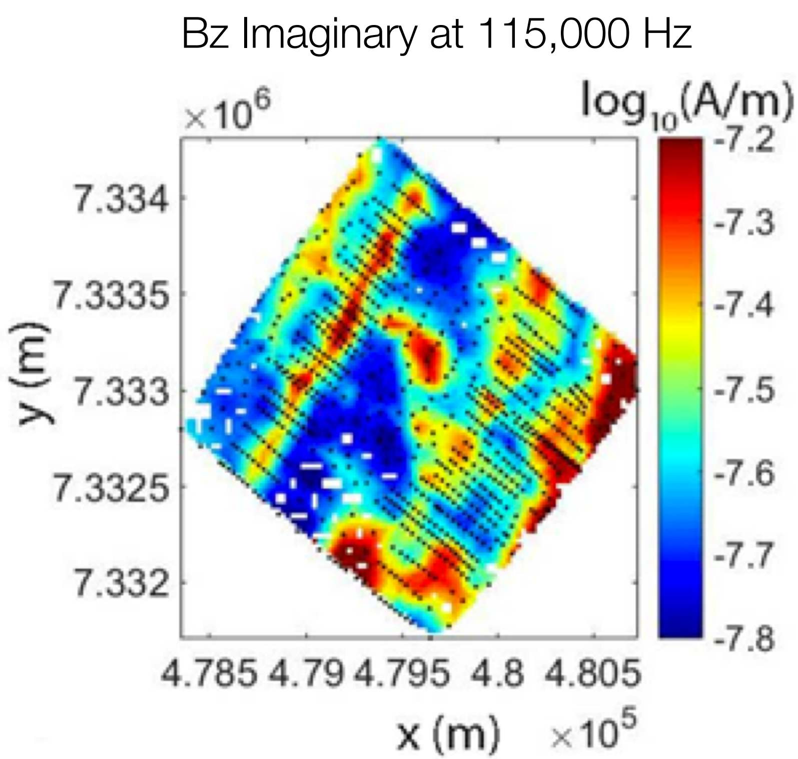


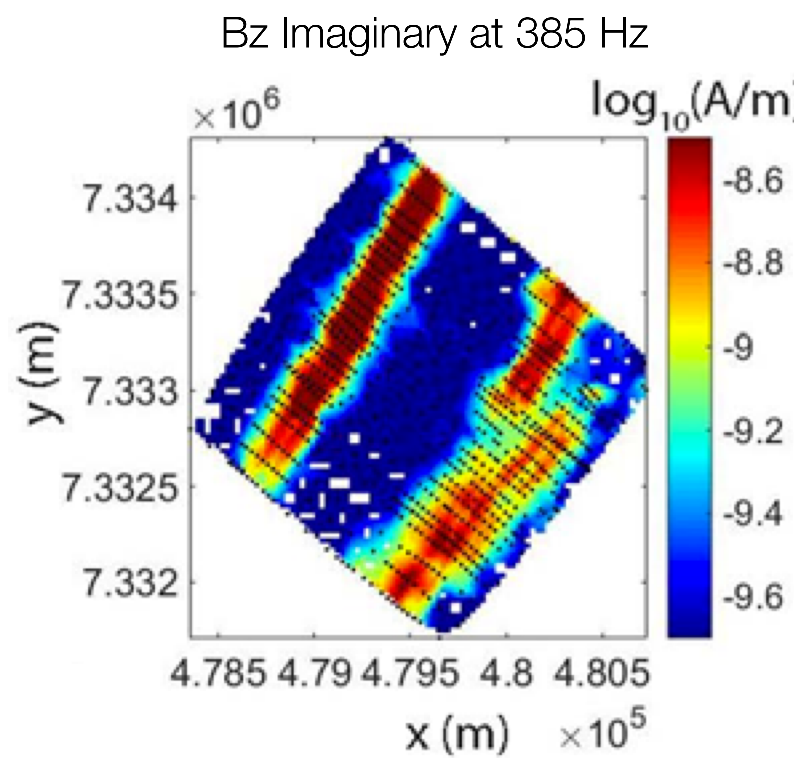
dBz/dt at 3180 μs



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

Data: RESOLVE





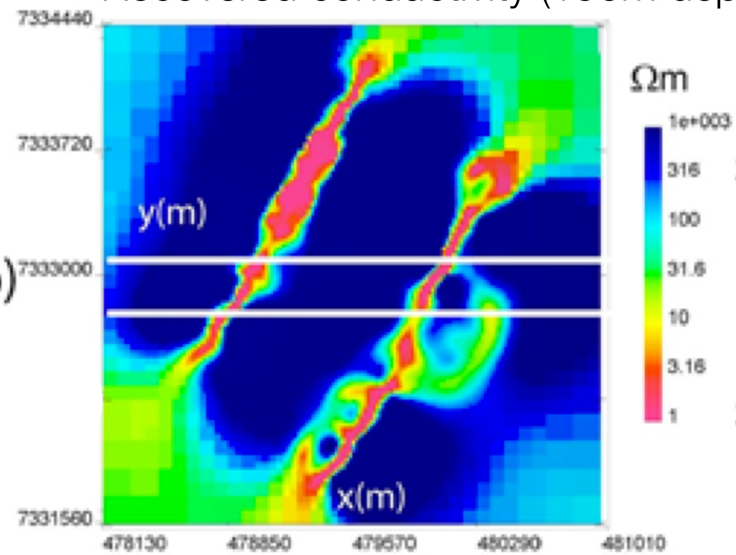
- 115,000 Hz data contains near-surface information
- 385 Hz data similar to the VTEM data at 150 μs

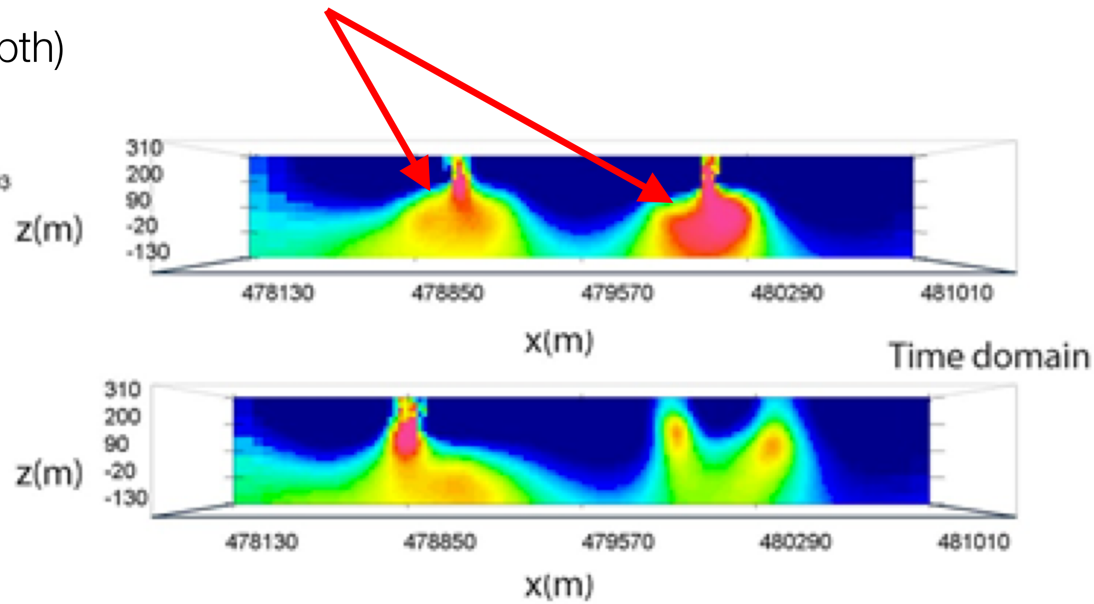
Processing: VTEM

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

Recovered conductivity (190m depth)

b)

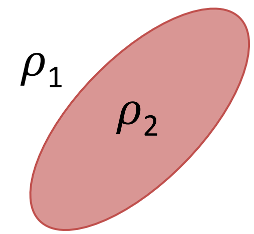




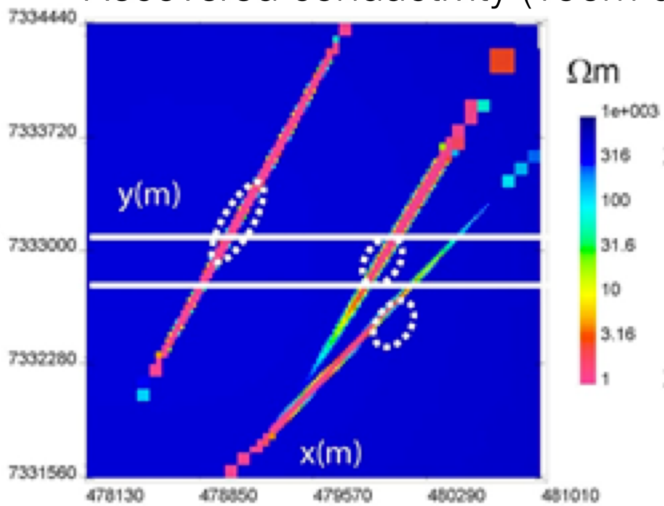
How do we image thin, dipping conductors in 3D?

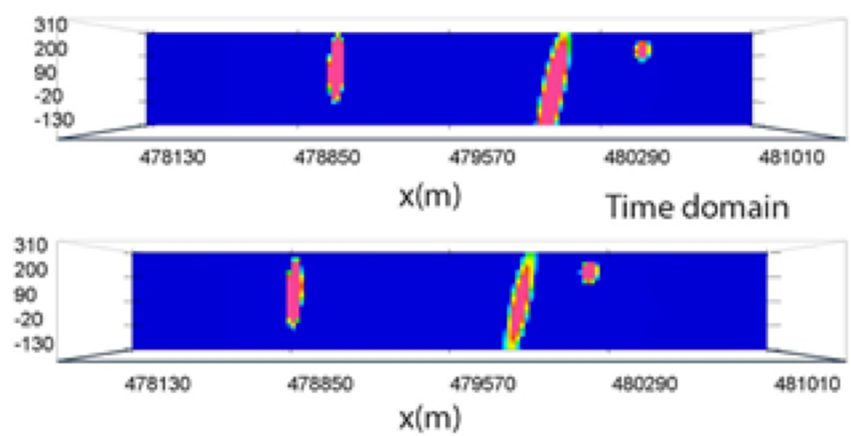
Processing: VTEM

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



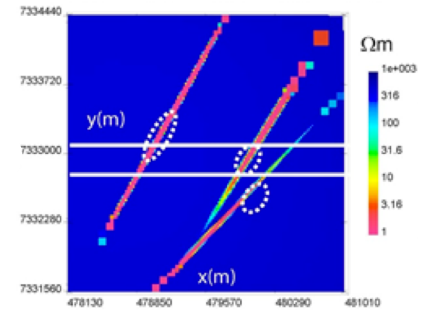
Recovered conductivity (190m depth)



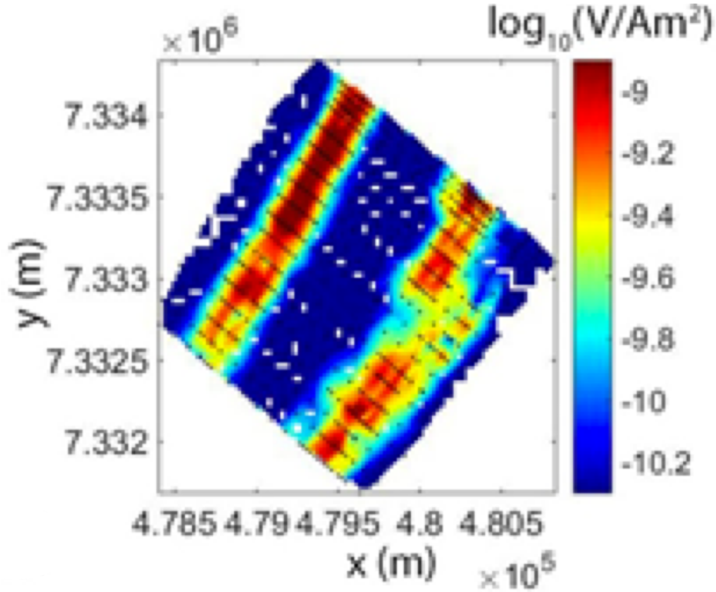


Dashed lines: Initial guess

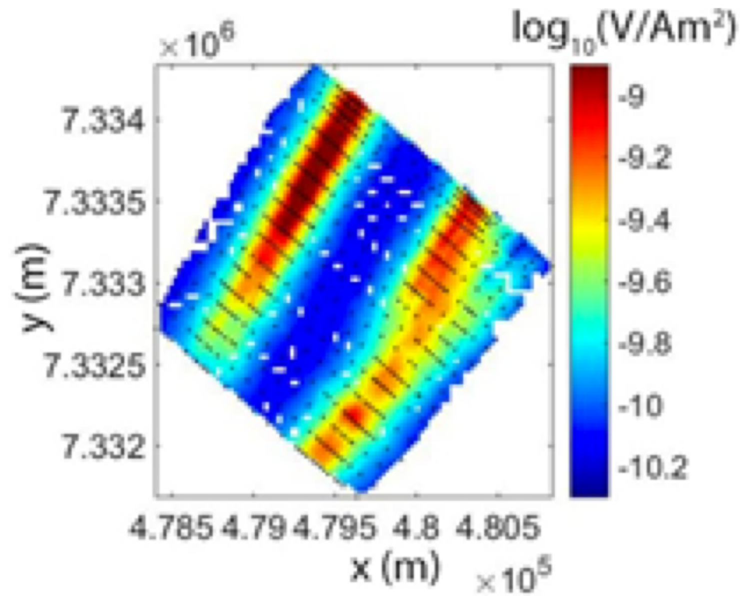
Processing: VTEM



Observed dBz/dt at 150μs



Predicted dBz/dt at 150 μs

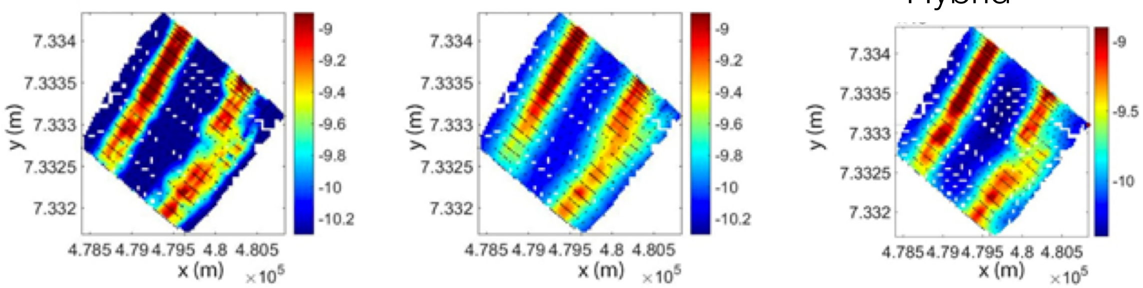


Parametric inversion too simple to explain heterogeneous earth

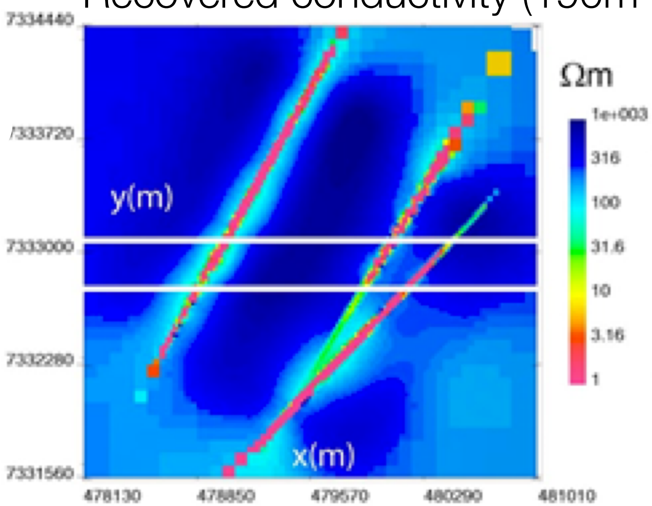
Processing: Hybrid Inversion

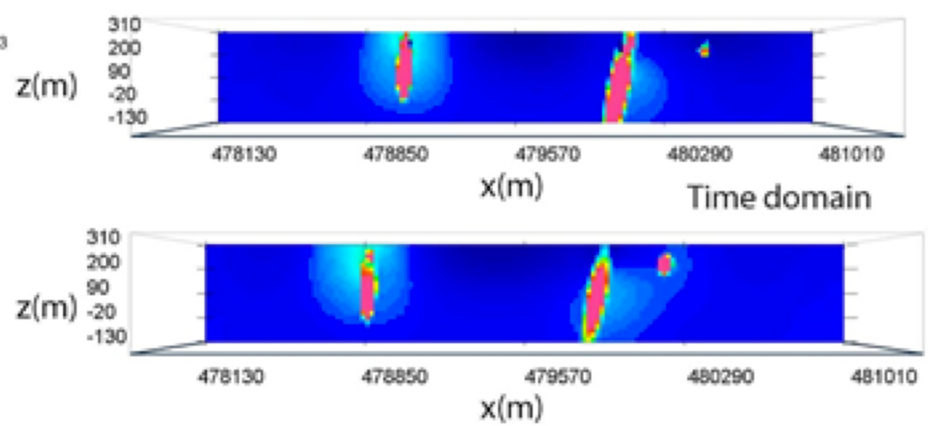
- Voxel inversion using parametric inversion result as initial and reference model

Obs. Parametric Hybrid



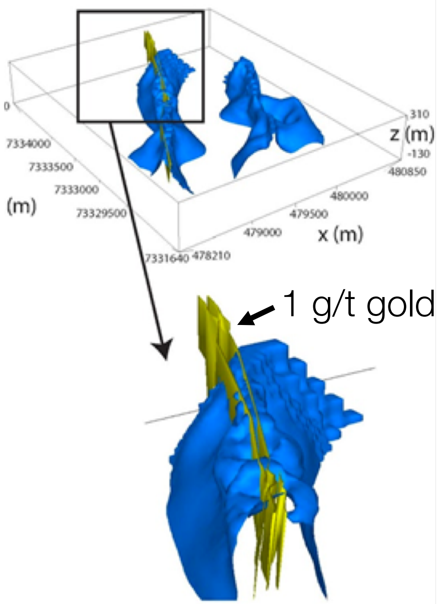
Recovered conductivity (190m depth)



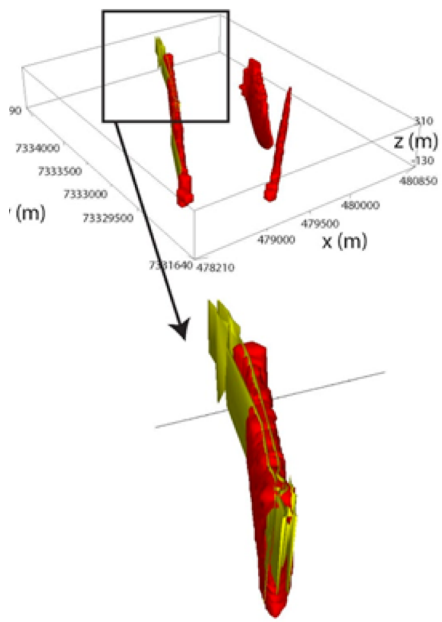


Interpretation: VTEM

Voxel inversion cut-off (30 Ωm)

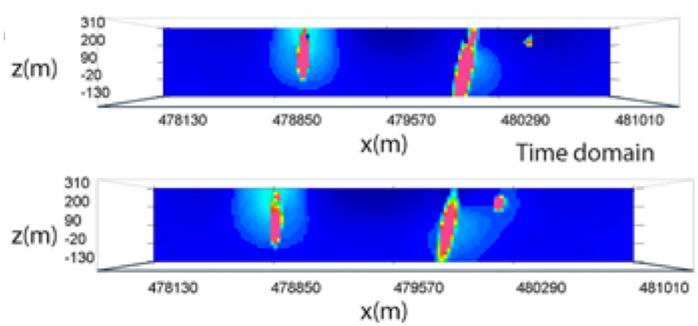


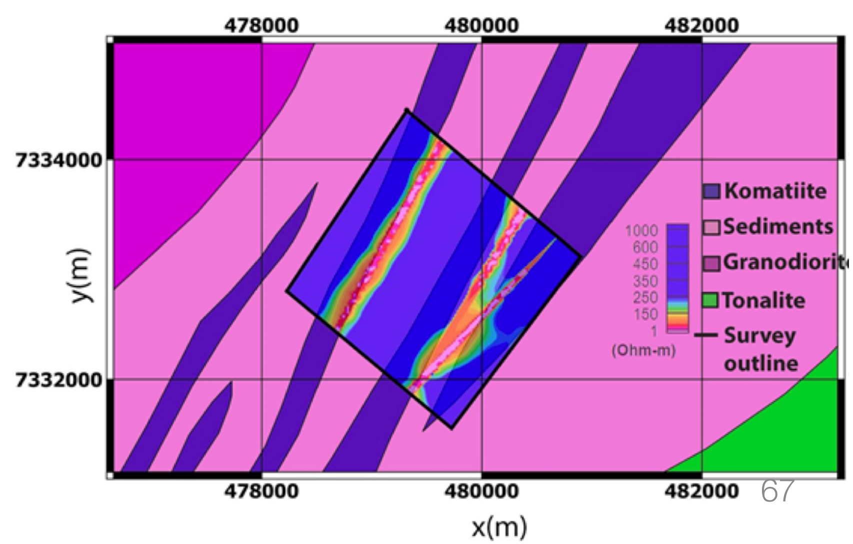
Hybrid inversion cut-off (30 Ωm)



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

Hybrid inversion: vertical sections

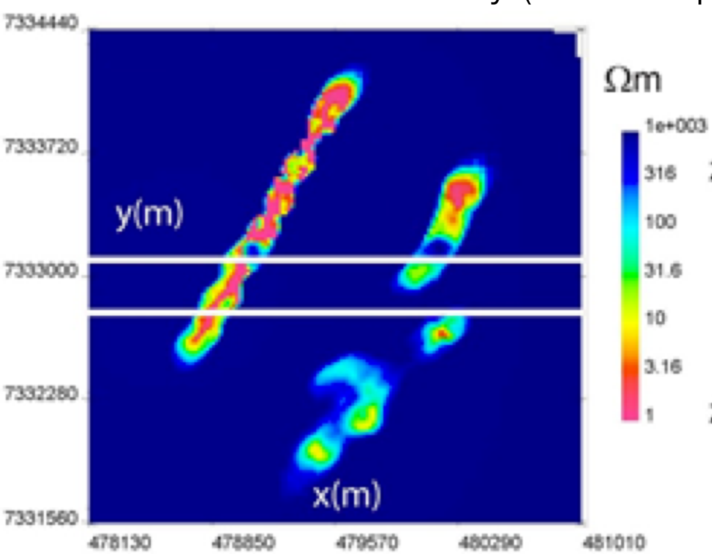


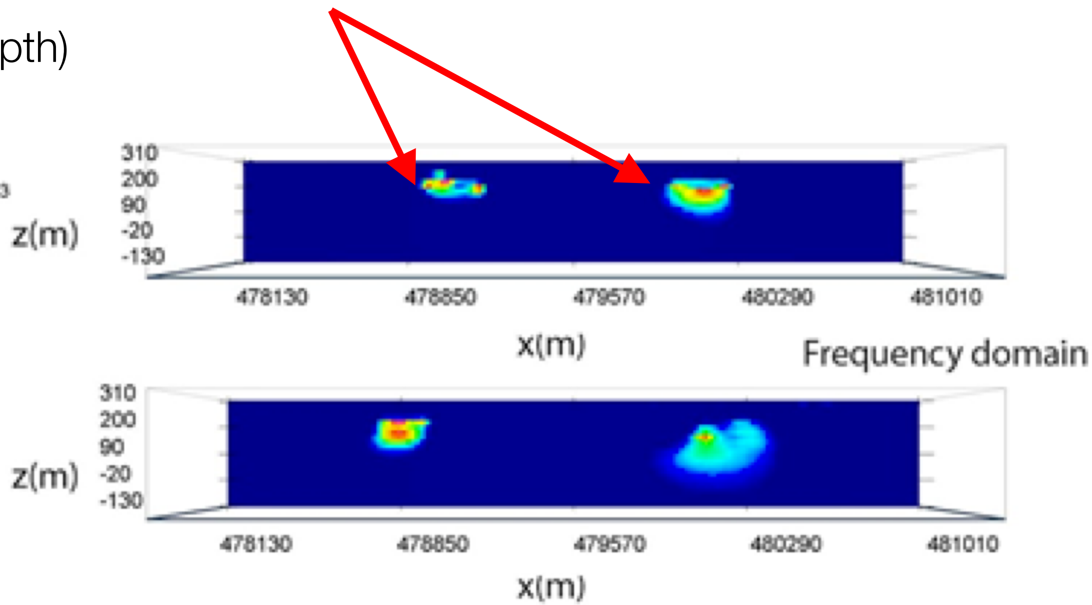


Processing: RESOLVE

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

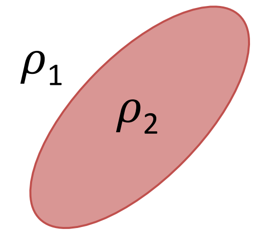
Recovered conductivity (190m depth)



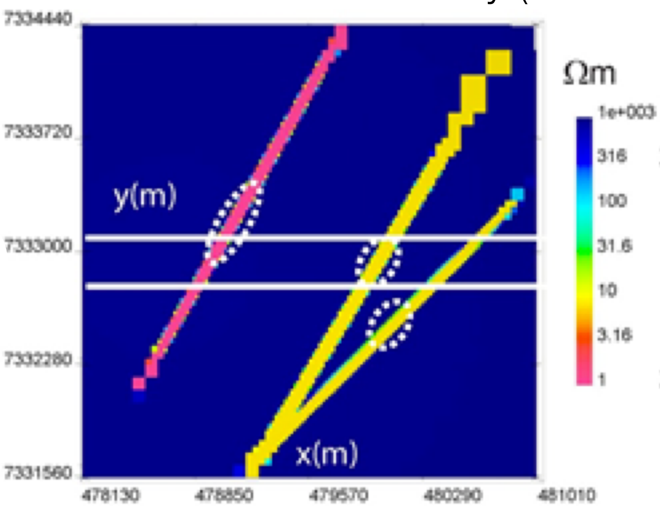


Processing: RESOLVE

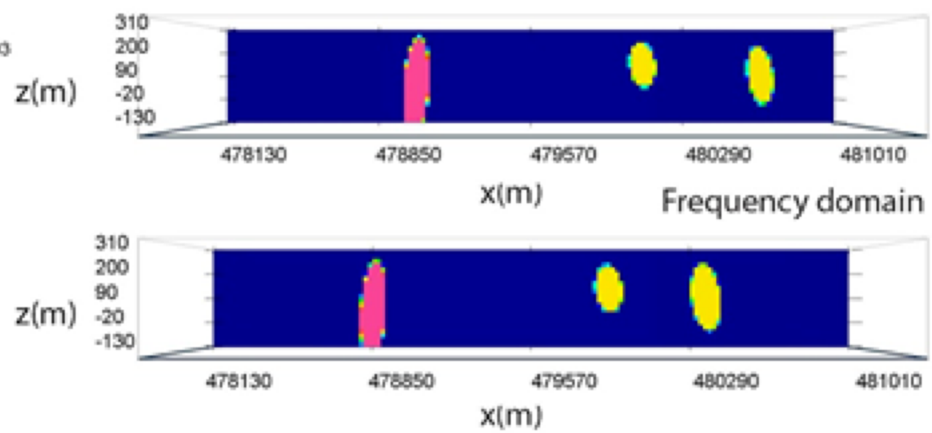
- Parametric inversion
  - Parameterize dipping conductors as Gaussian ellipsoids
  - Invert for:
    - Resistivity: background and ellipsoid
    - Shape and location of ellipsoid



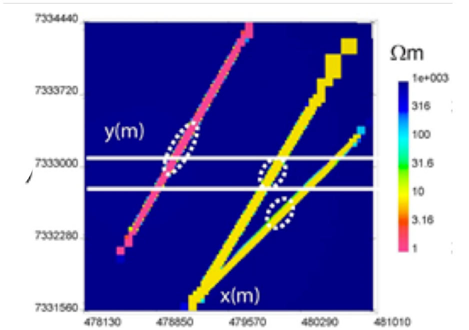
Recovered conductivity (190m depth)



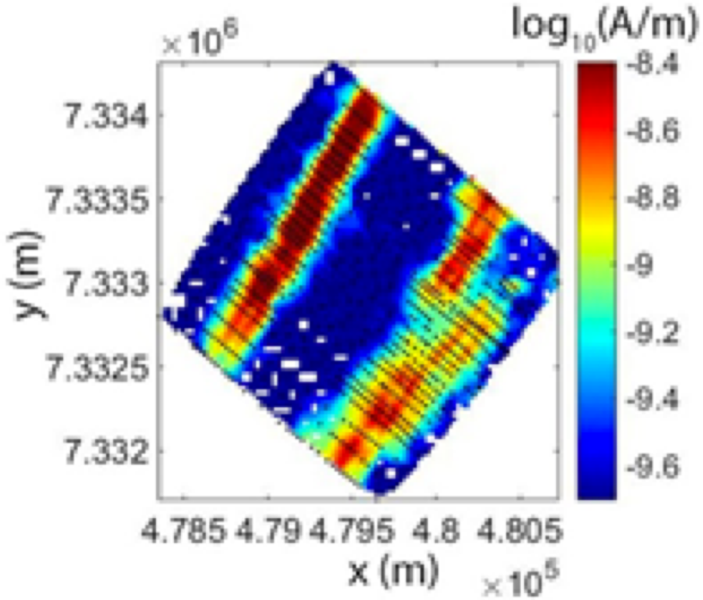
Dashed lines: Initial guess



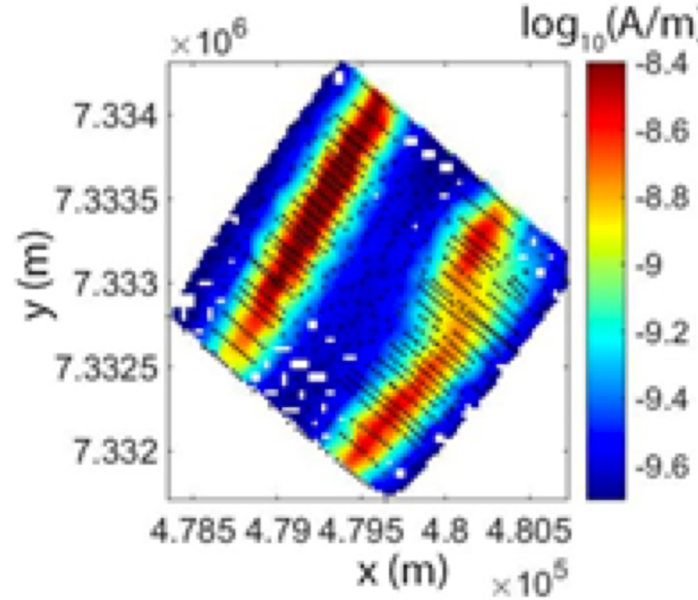
Processing: RESOLVE



Observed Bz Imag at 385 Hz



Predicted Bz Imag at 385 Hz

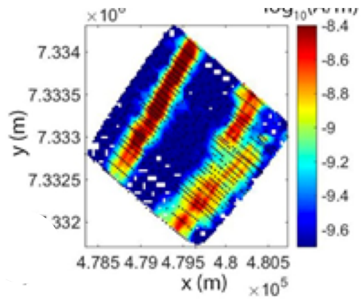


Parametric inversion too simple to explain heterogeneous earth

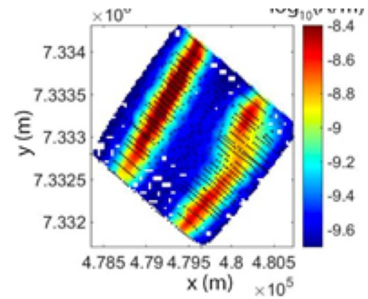
Processing: Hybrid Inversion

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

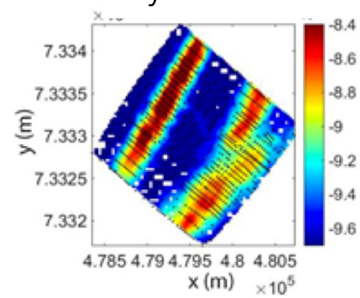
Obs.



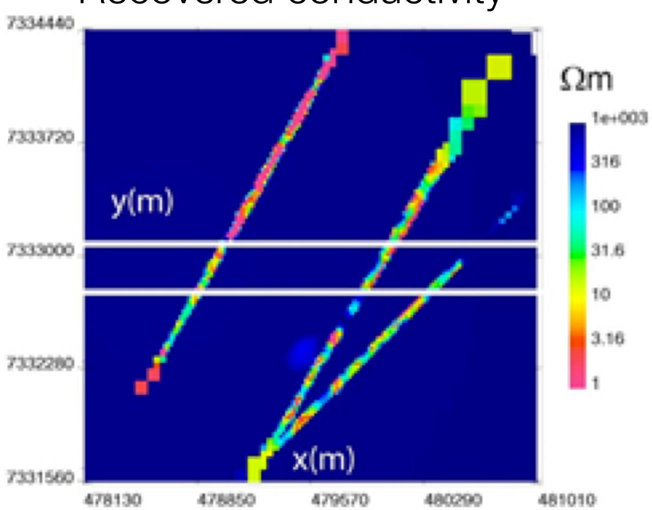
Parametric

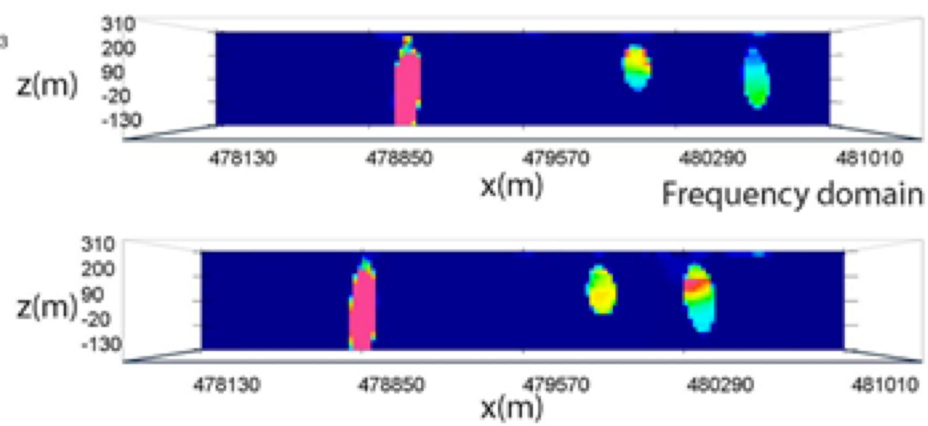


Hybrid



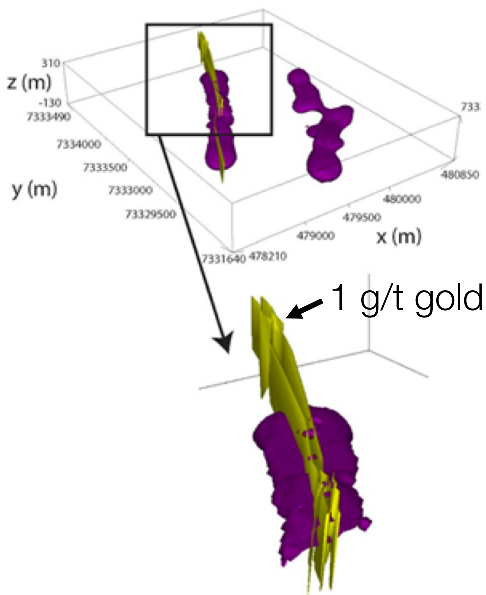
Recovered conductivity



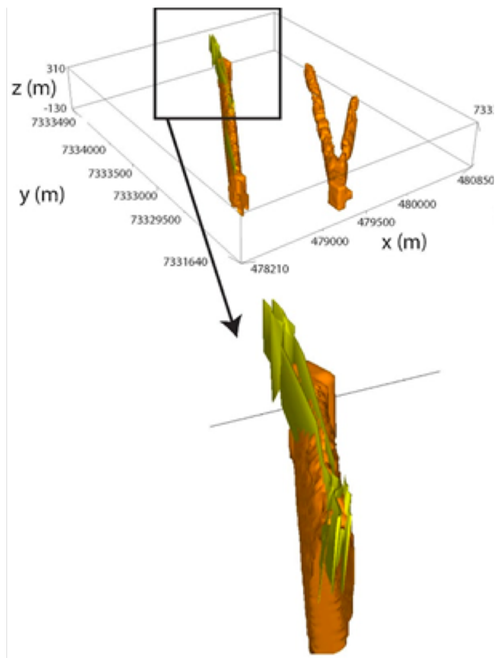


Interpretation: RESOLVE

Voxel inversion cut-off (30 Ωm)

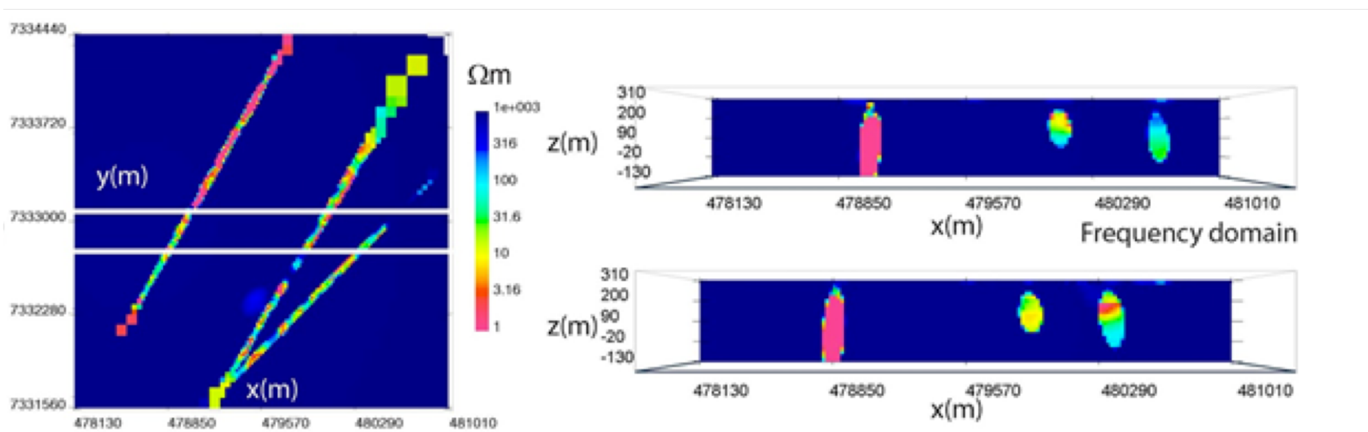


Hybrid inversion cut-off (30 Ωm)

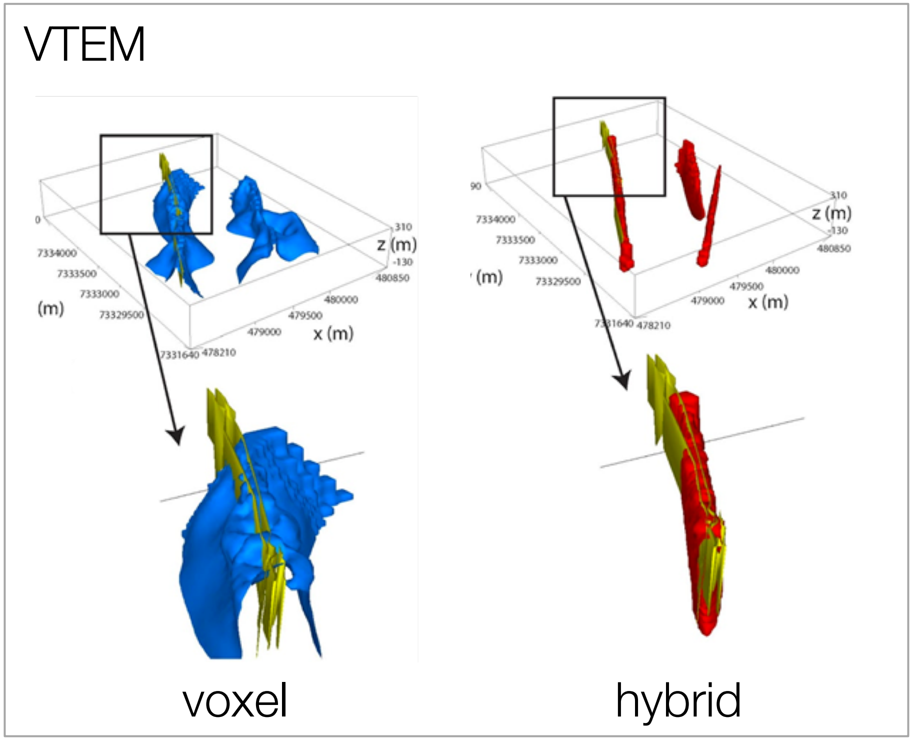


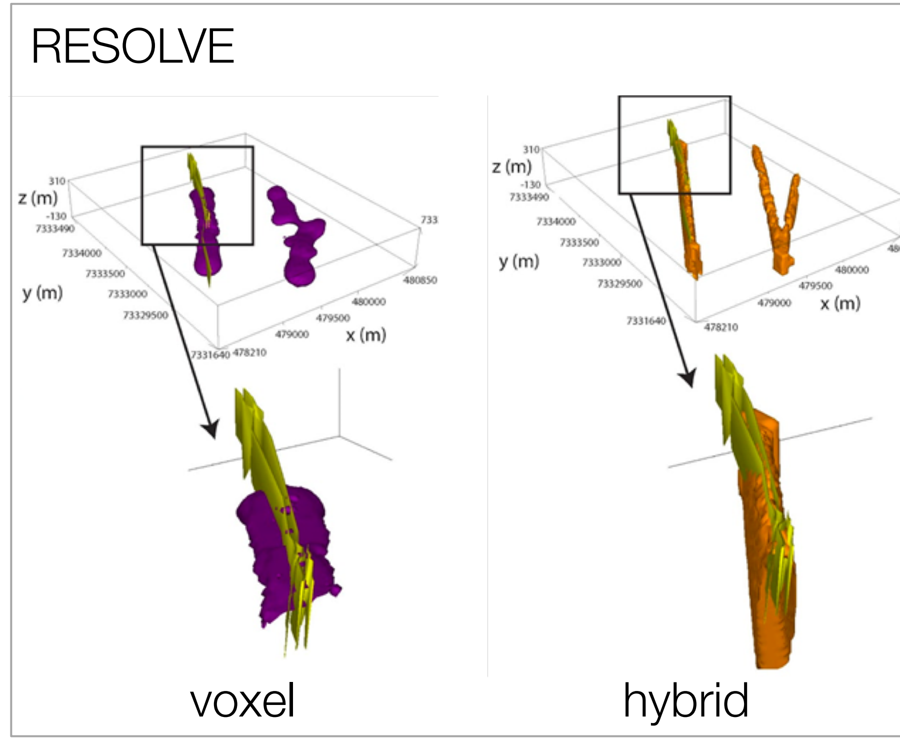
- Voxel inversion: blurs thin conductors
- Hybrid inversion
  - Dips recovered
  - Tighter boundary of the komatiite
  - Good agreement with gold grade

Hybrid inversion



Synthesis

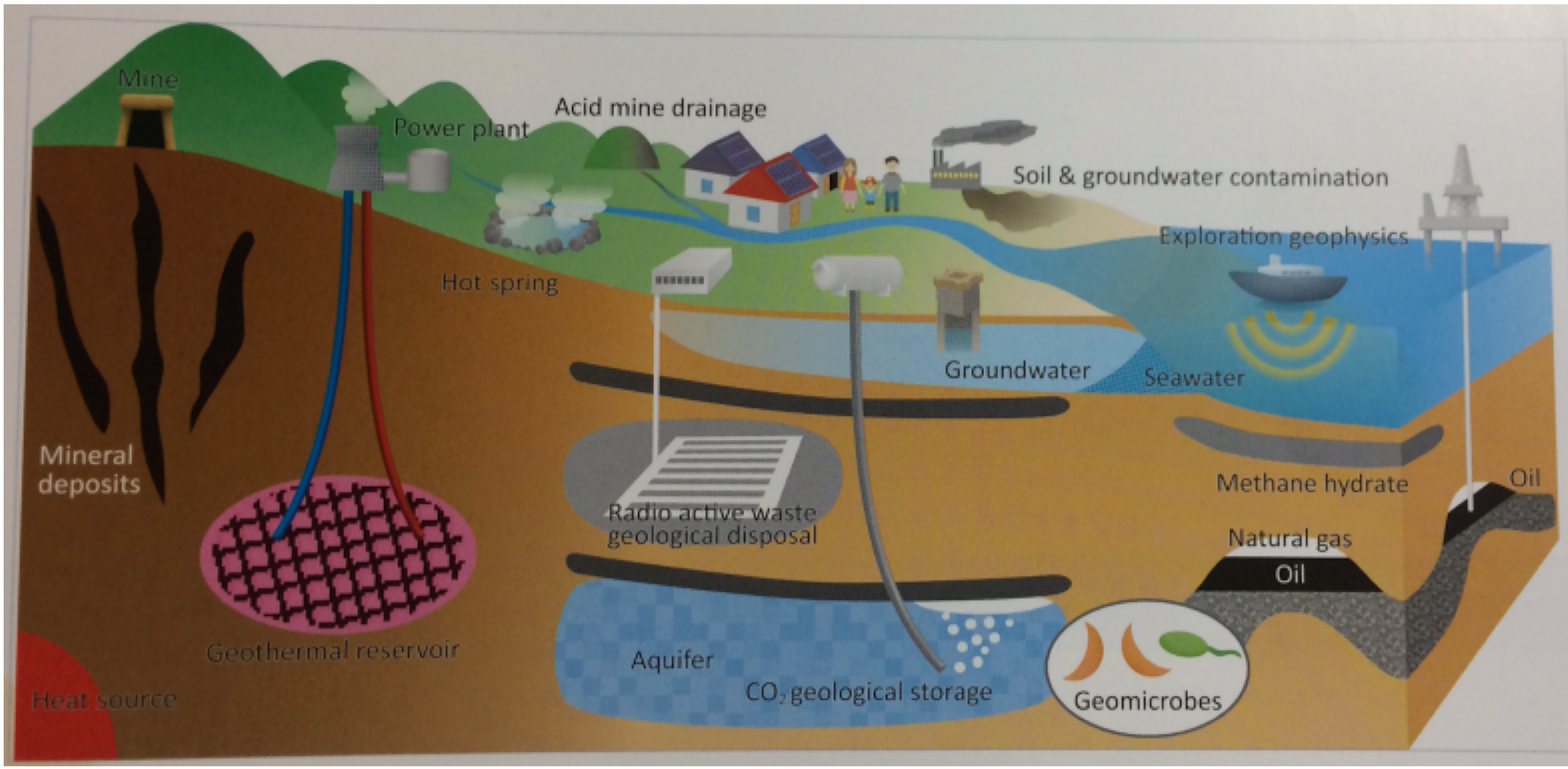




- TDEM and FDEM survey sensitive to conductors
- Hybrid inversion beneficial for imaging thin, dipping conductors

An example from DISC Tokyo

DISC Tokyo…

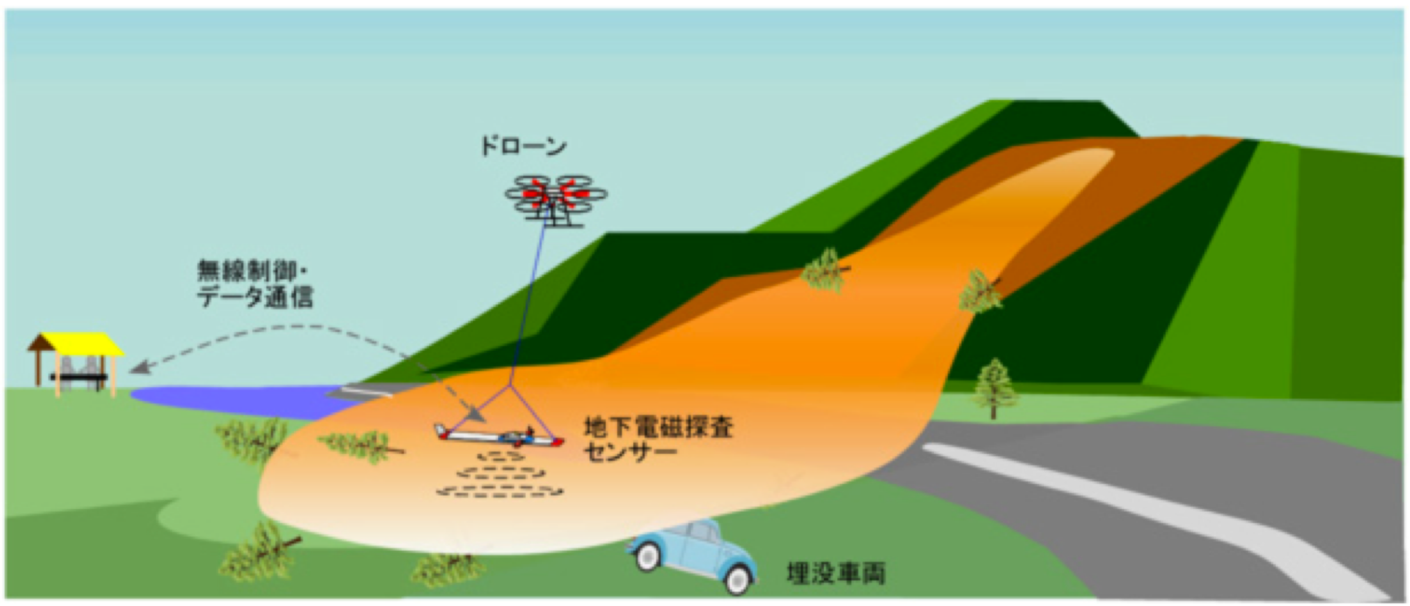


Mine
Power plant
Acid mine drainage
Soil & groundwater contamination
Exploration geophysics
Hot spring
Groundwater
Seawater
Mineral deposits
Methane hydrate
Oil
Radio active waste geological disposal
Natural gas
Oil
Geothermal reservoir
Aquifer
CO_2 geological storage
Geomicrobes
Heat source

EM Geophysics using Drone Technology: AIST

Setup:

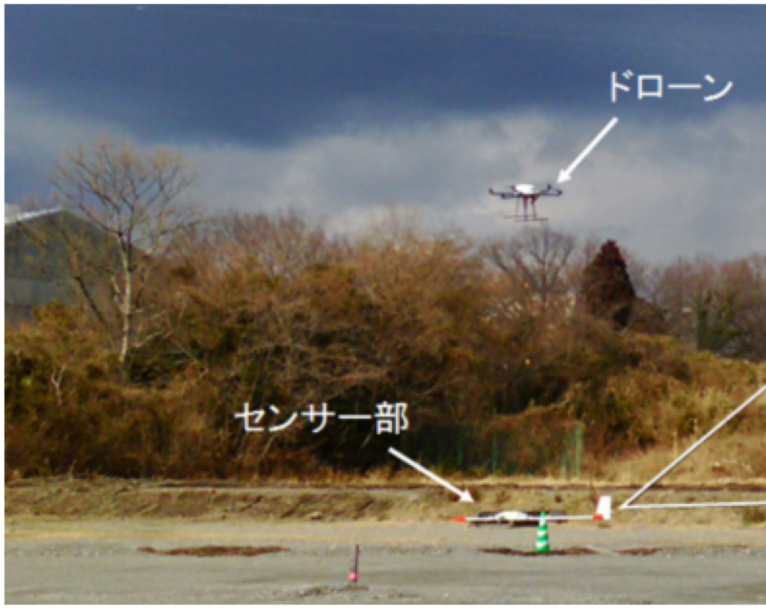
- Develop FDEM system for a drone
- Application: near surface geophysics problems
- Example: find automobiles buried in a landslide

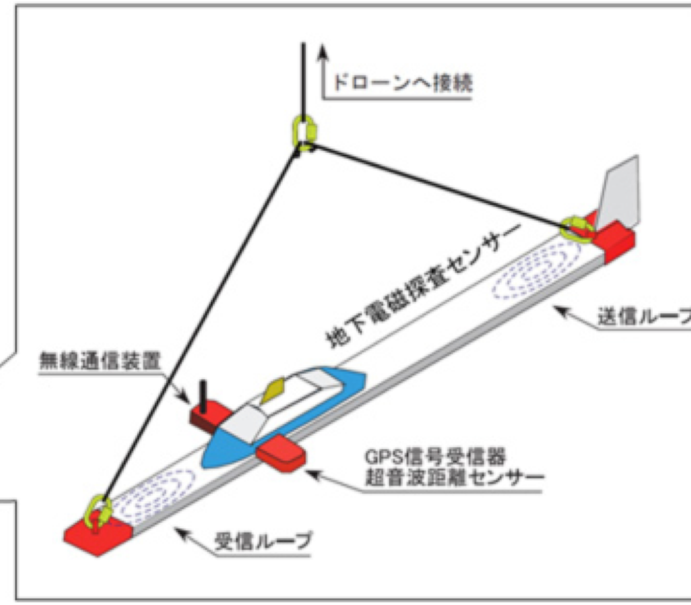


Exploration image of buried vehicles at the site of sediment-related disasters by developed system

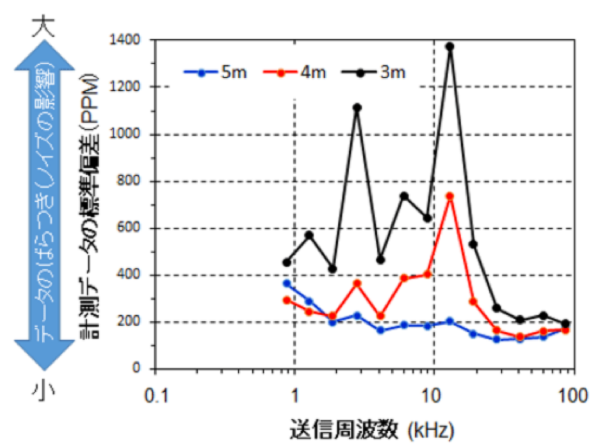
Survey equipment

Drone EM system





- System must be removed from the noise of the drone
- Sensor located 5 meters below drone



Data acquisition

System must be close to the ground (primary field $1/r^3$)

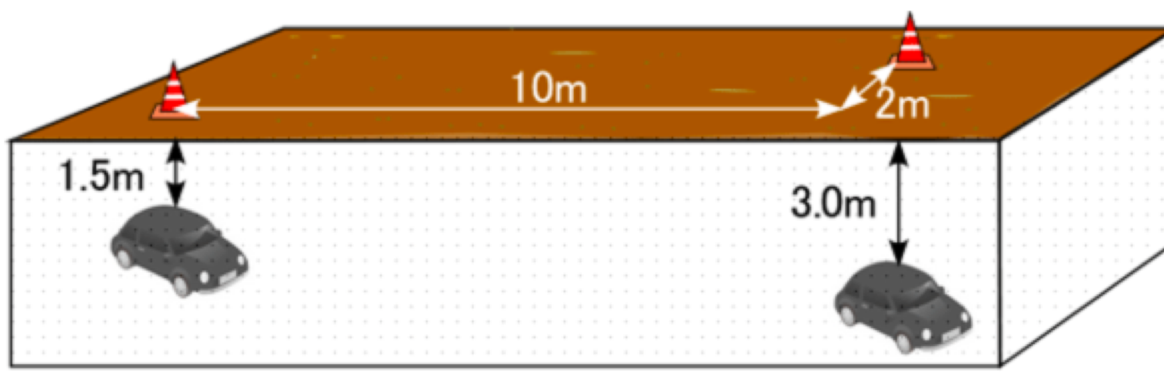


Fig. 4 Arrangement of the burial vehicle experiment site of the construction laboratory site
Two buried mini vehicles are buried in the ground of 1.5 m depth and 3.0 m depth, respectively.

Data and interpretation

- In-phase and quadrature phase data recorded at multiple frequencies.
- Metallic objects have high induction number
- Signal is mostly in the In-phase part
- Plot amplitude: both cars imaged

Fig. 6 Exploration data by precision drone navigation measurement (measurement frequency 60 kHz)

Logging While Drilling

SPWLA
2018
Log time in London

A New Ultra-deep Azimuthal Electromagnetic LWD Sensor for Reservoir Insight

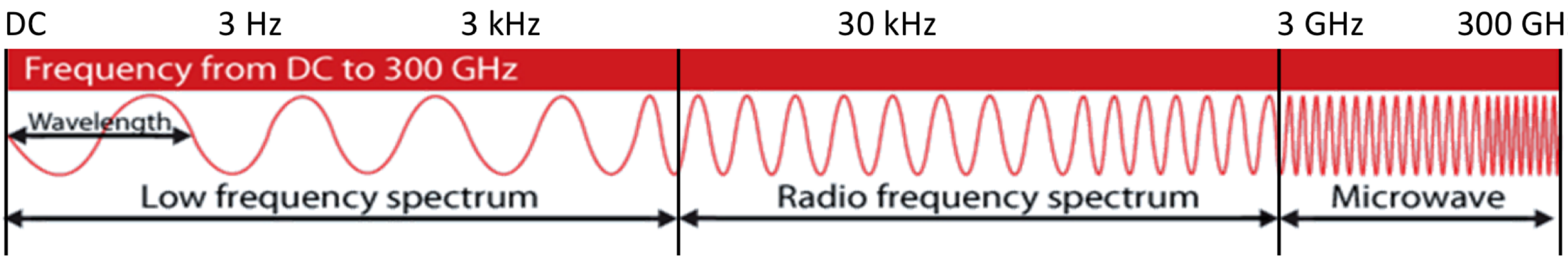
Hsu-Hsiang (Mark) Wu, Christopher Golla, Timothy Parker, and Nigel Clegg, Halliburton; Luc Monteilhet, ConocoPhillips

Slides courtesy of Glenn Wilson & Halliburton

Outline

- Background and motive
- Principles of the ultra-deep electromagnetic resistivity tool
  - Tool design and concept
  - Improved one-dimensional (1D) inversion algorithm
- Geosteering service
- Field trials: depth of investigation(DOI) >200 ft
- Conclusions

Background: Electromagnetic Resistivity Measurements



Galvanic resistivity [wireline and logging while drilling (LWD)]

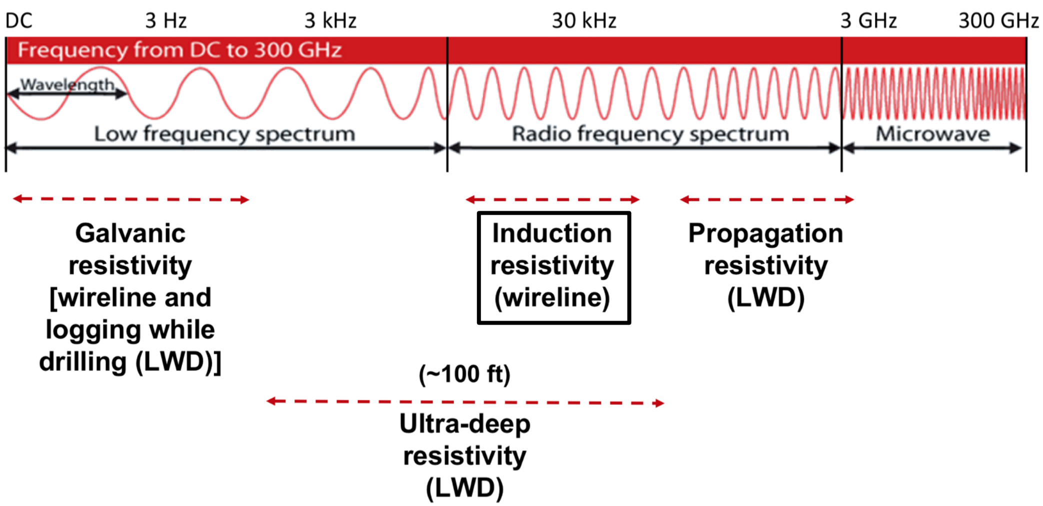
Induction resistivity (wireline)

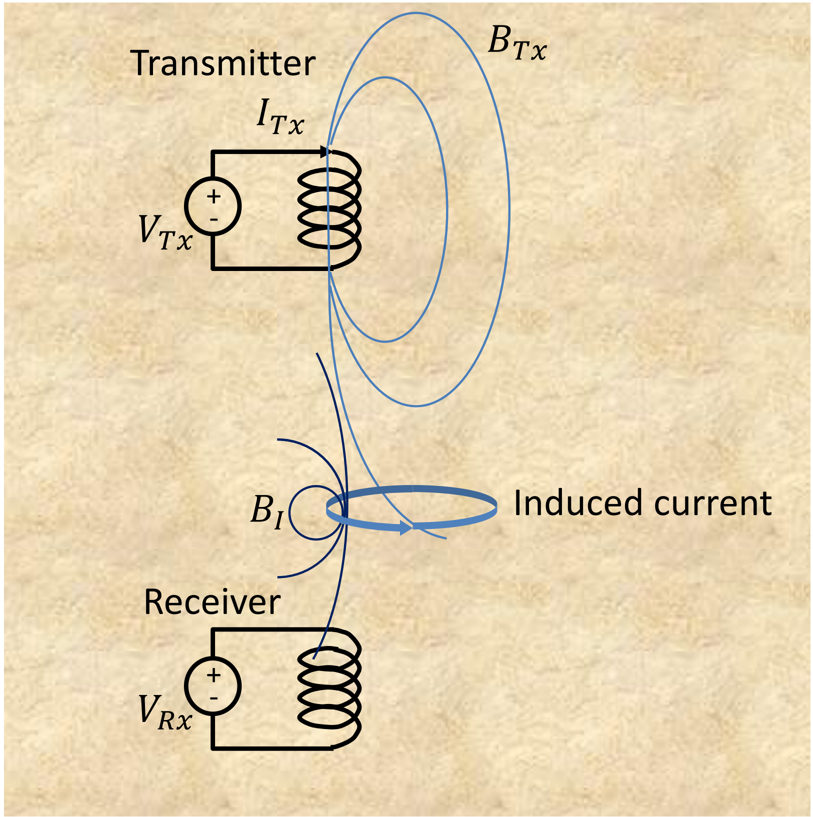
Propagation resistivity (LWD)

(~100 ft)

Ultra-deep resistivity (LWD)

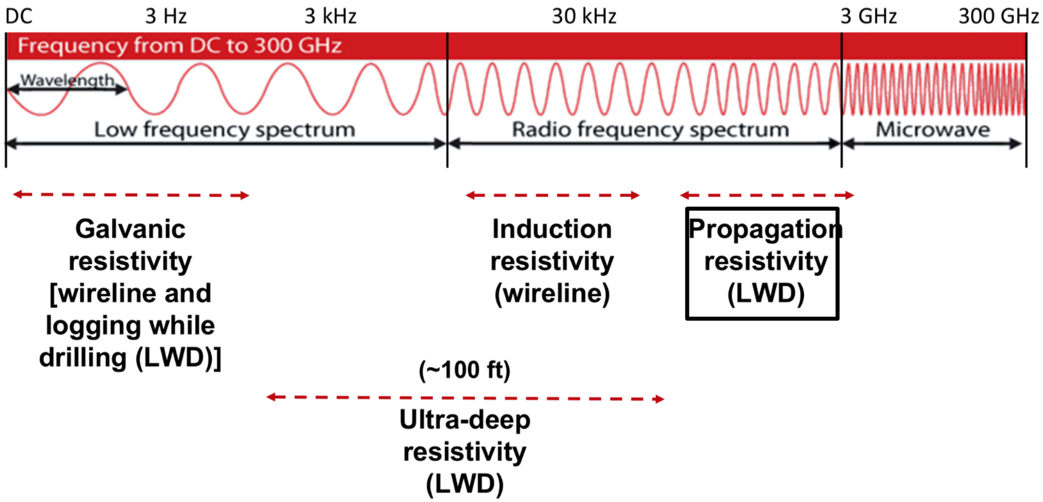
Background: Induction Resistivity

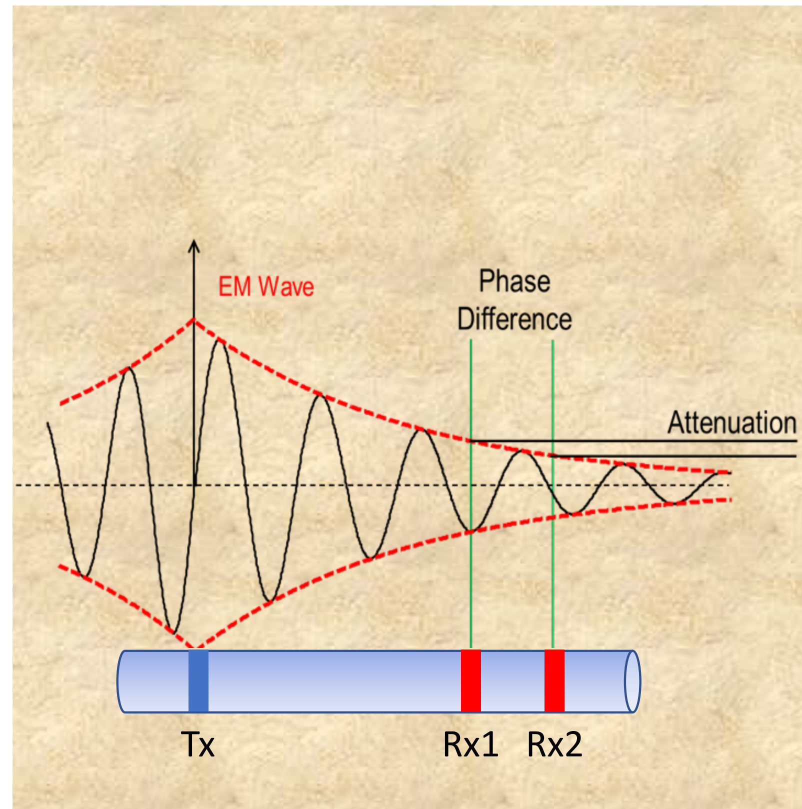




1. Current in the transmitter coil induces eddy currents in the formation
2. Induced current in the formation generates a magnetic field in receiver coils
   – Main coil
   – Bucking coil

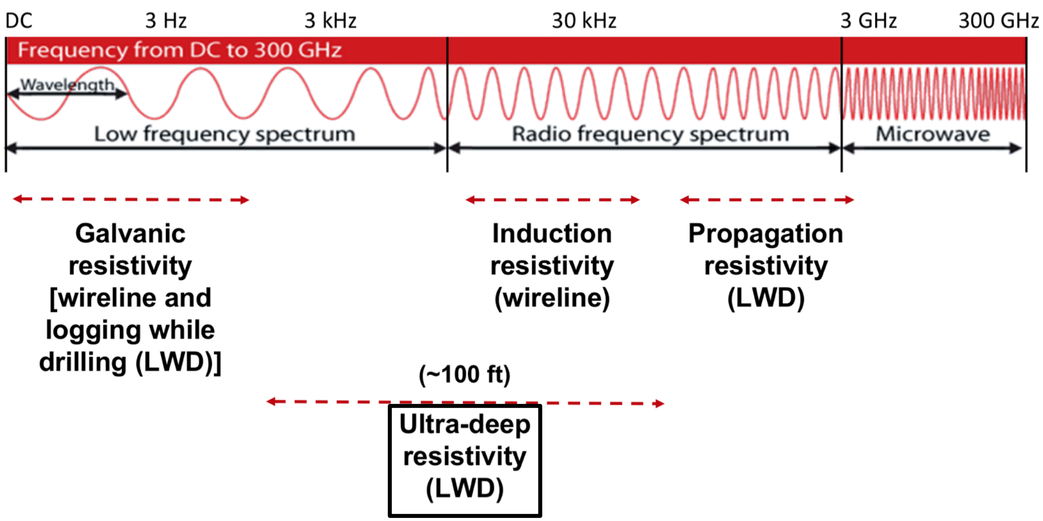
Background: Propagation Resistivity





- Uses phase shift and attenuation because of skin depth to determine formation resistivity

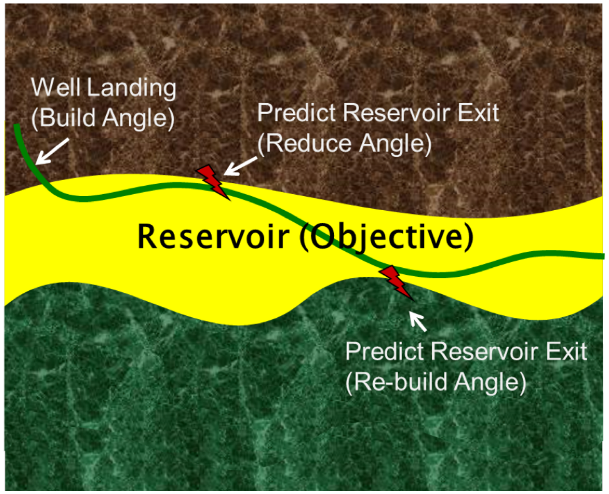
Background: Ultra-deep Resistivity



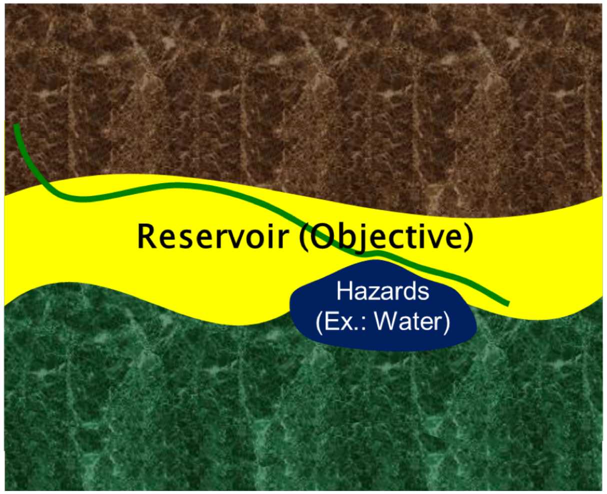
1) Combination of induction and propagation resistivity concepts
2) Multi-antenna subs with various separations
3) Multiple antenna orientations

Motive: Proactive Geosteering to Maximize Production

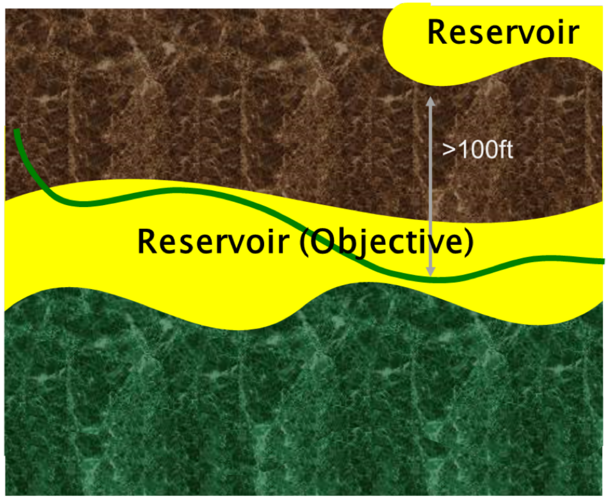
(1) Landing and geomapping a reservoir



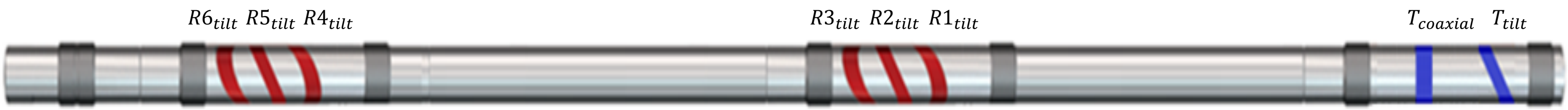
(2) Geostopping hazards



(3) Identifying more reservoir from a single wellbore

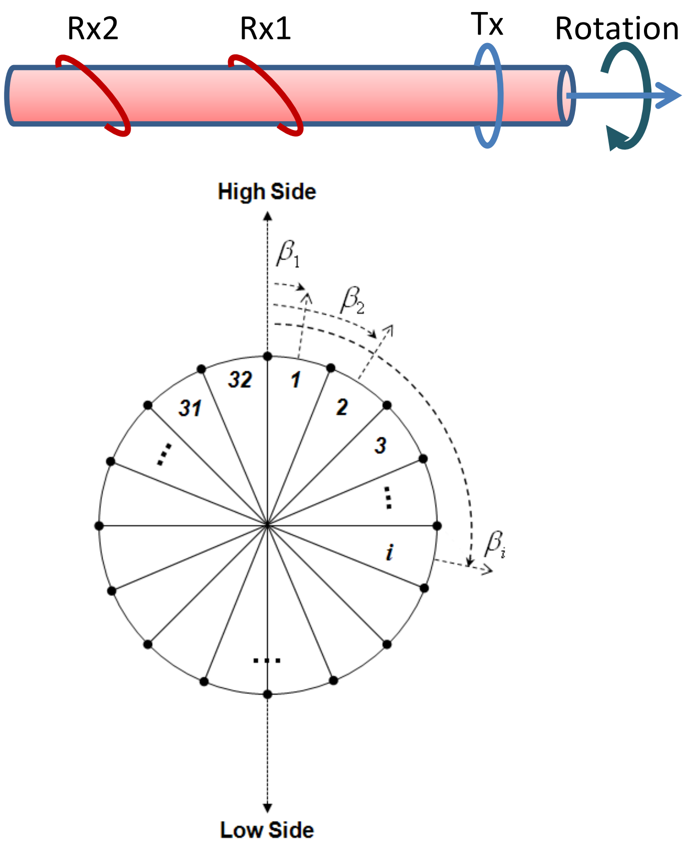


Principles: Tool Design and Concept

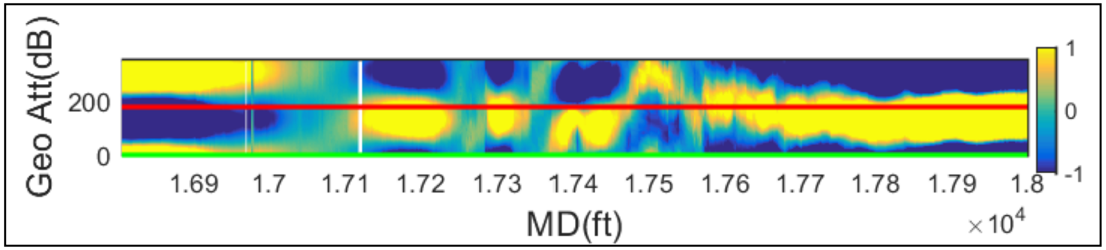


- T_{tilt} and $R1_{tilt}$~$R6_{tilt}$
  - High signal-to-noise ratio (SNR) and sensitive signals used in 1D distance to bed boundary (DTBB) inversion
- $T_{coaxial}$ and $R1_{tilt}$~$R6_{tilt}$
  - Pure raw signals to three-dimensional (3D) formations
  - 360° Imaging of ultra-deep azimuthal geosignal and resistivity

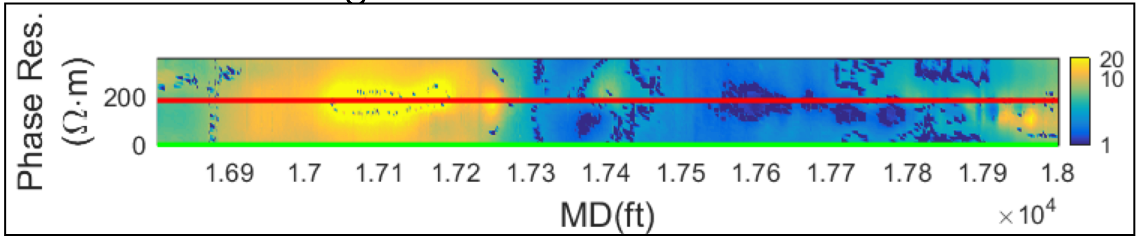
Principles: Tool Design and Concept—Azimuthal Signals



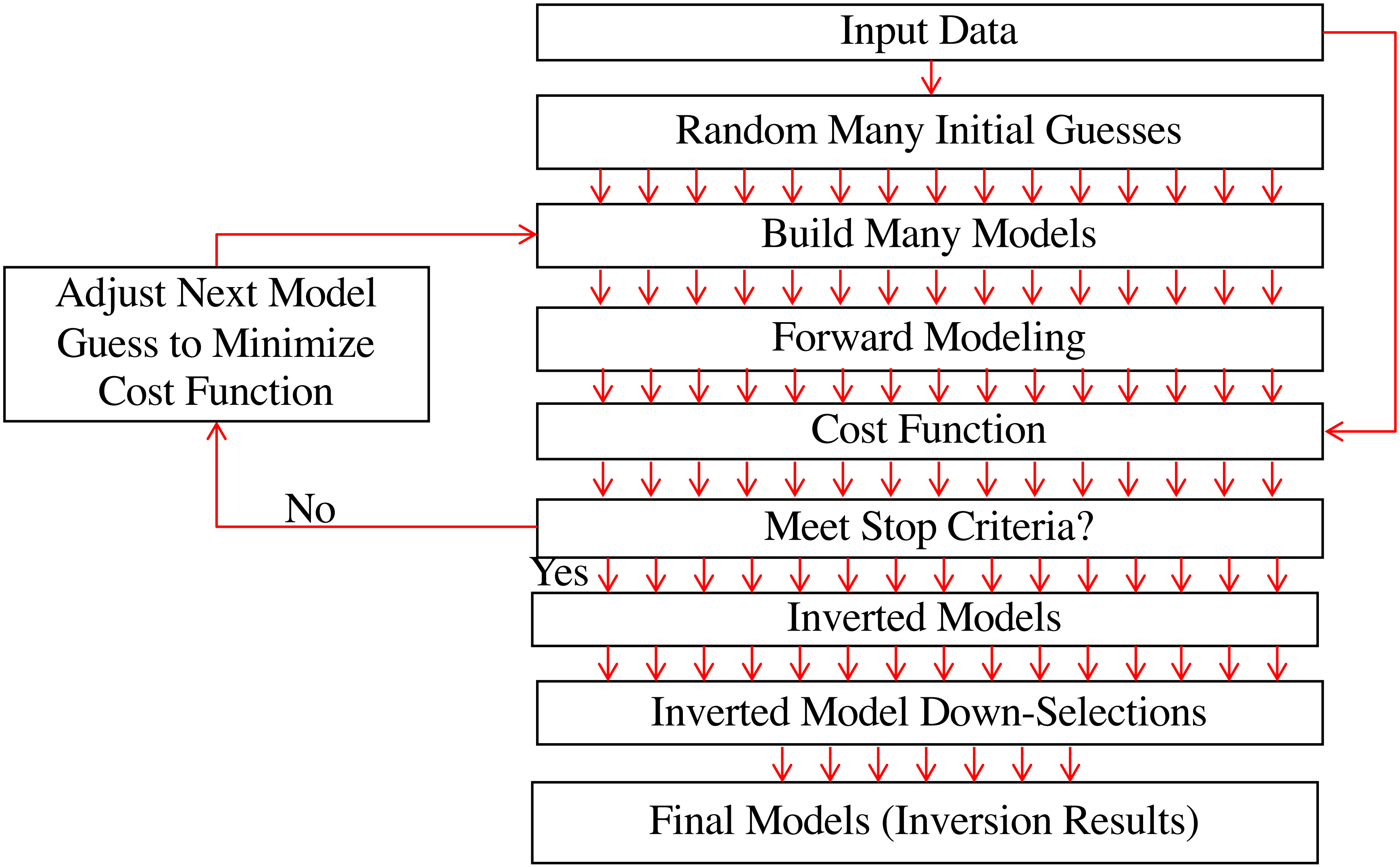
- Azimuthal phase and attenuation geosignal
  - Tx and Rx1 or Tx and Rx2
  - Ratio signal among 360° raw complex voltages



- Azimuthal phase and attenuation resistivity
  - Tx, Rx1 and Rx2
  - Ratio signal between Tx-Rx1 and Tx-Rx2



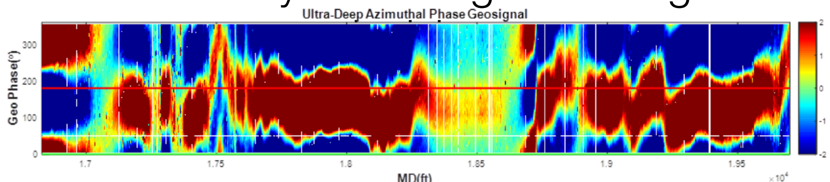
Principles: Improved 1D Inversion Algorithm



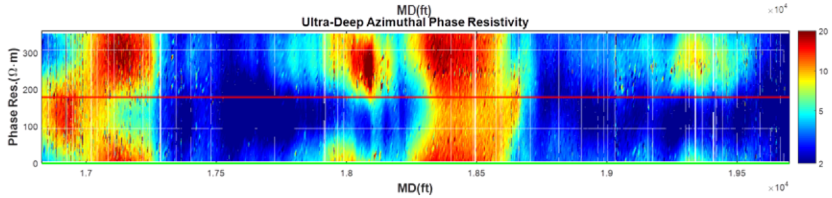
Geosteering Service

Primary data for geosteering

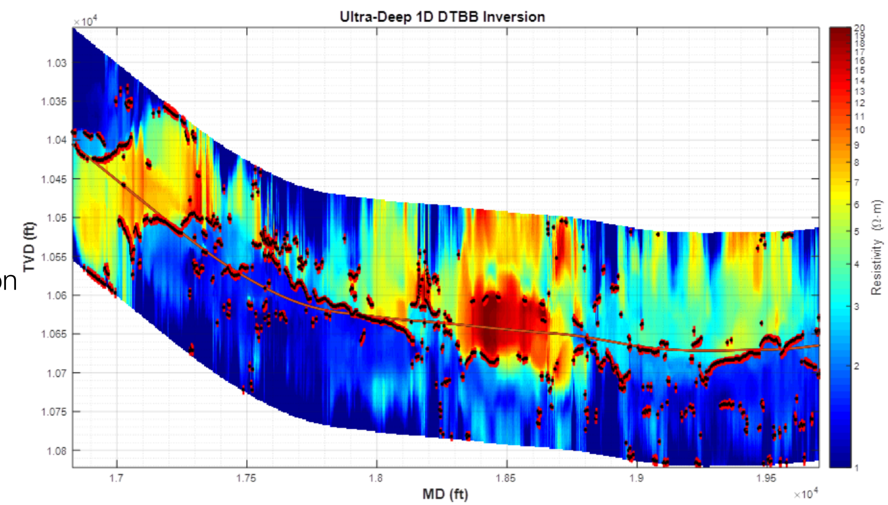
Ultra-deep phase geosignal



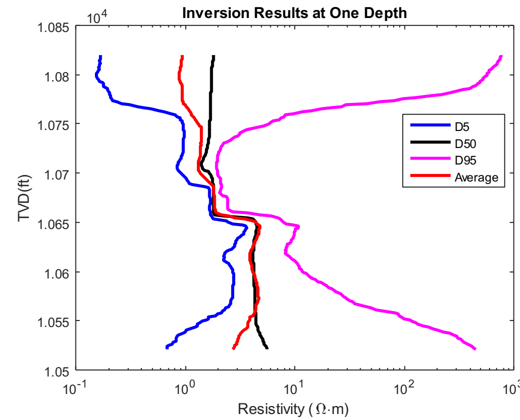
Ultra-deep phase resistivity

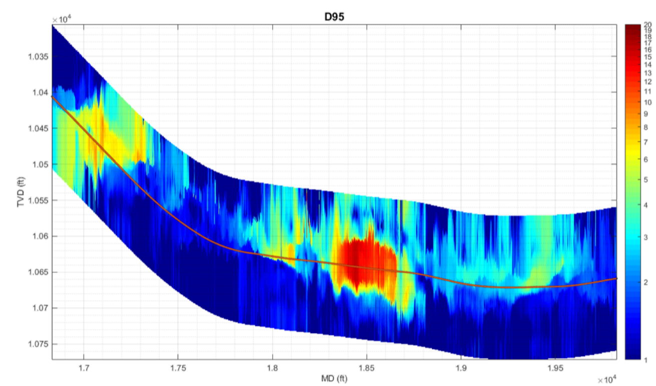


Ultra-deep 1D DTBB inversion

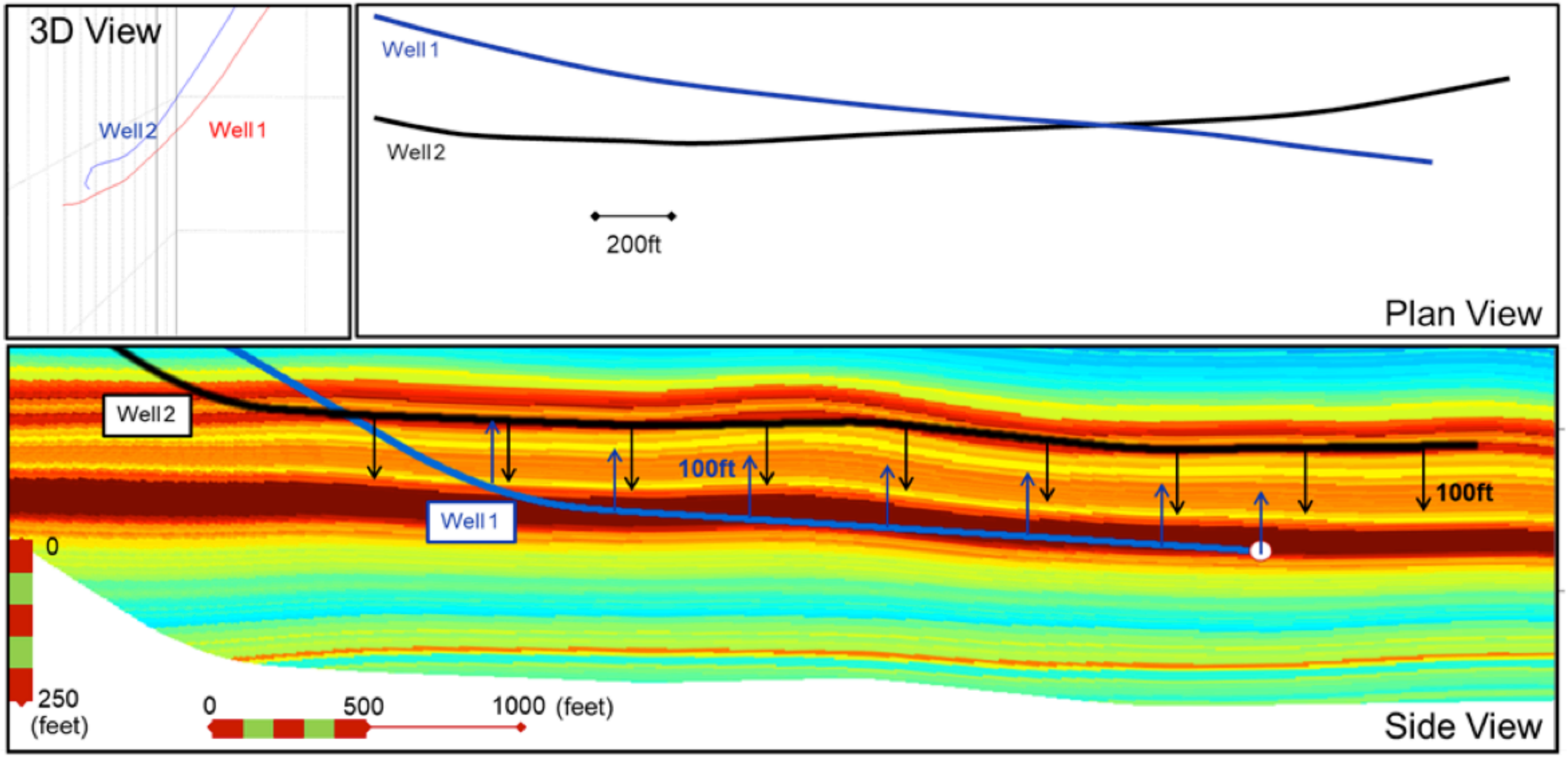


Inversion uncertainty



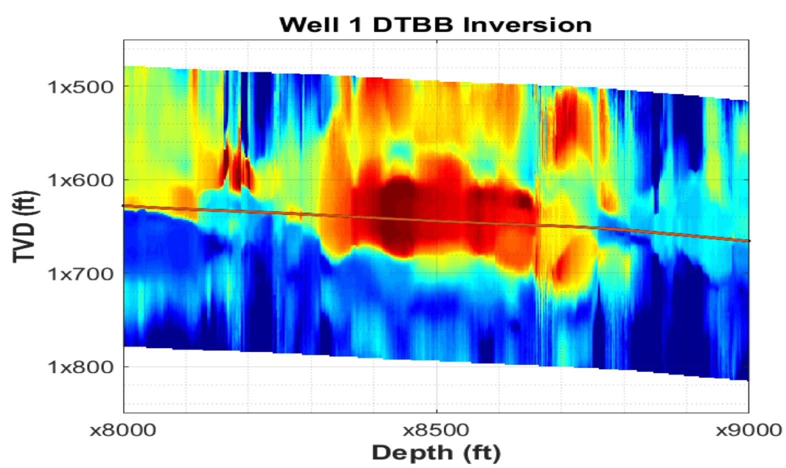


Field Trials: Trajectory of Two Wells



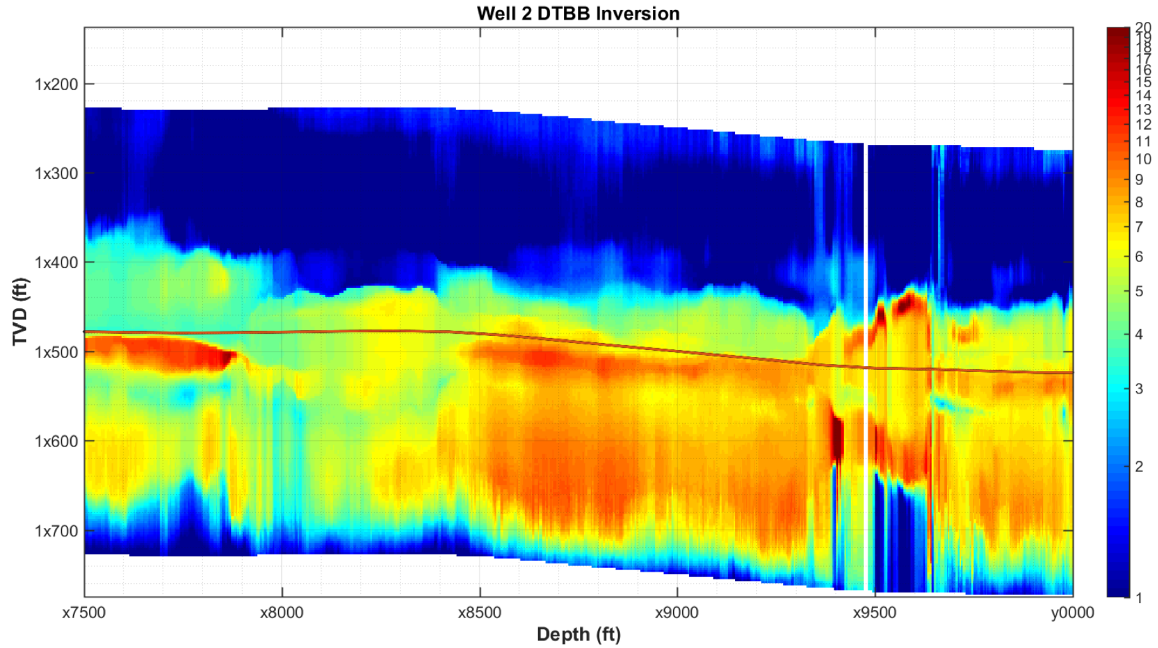
Field Trials: DOI > 200 ft

1D DTBB inversion of Well 1

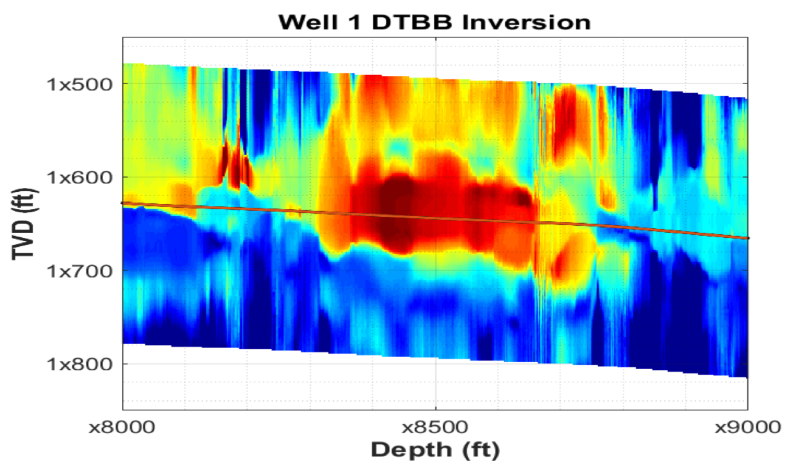


Field Trials: DOI > 200 ft

1D DTBB inversion of Well 2

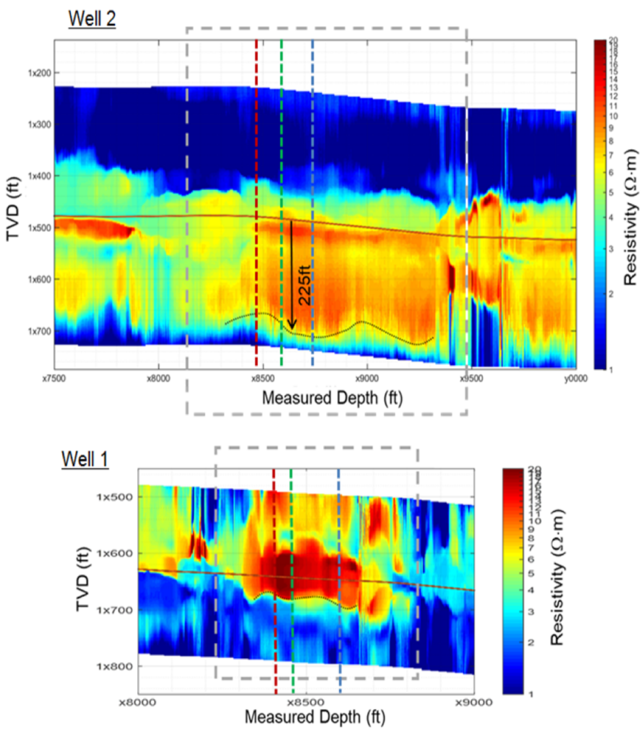


1D DTBB inversion of Well 1

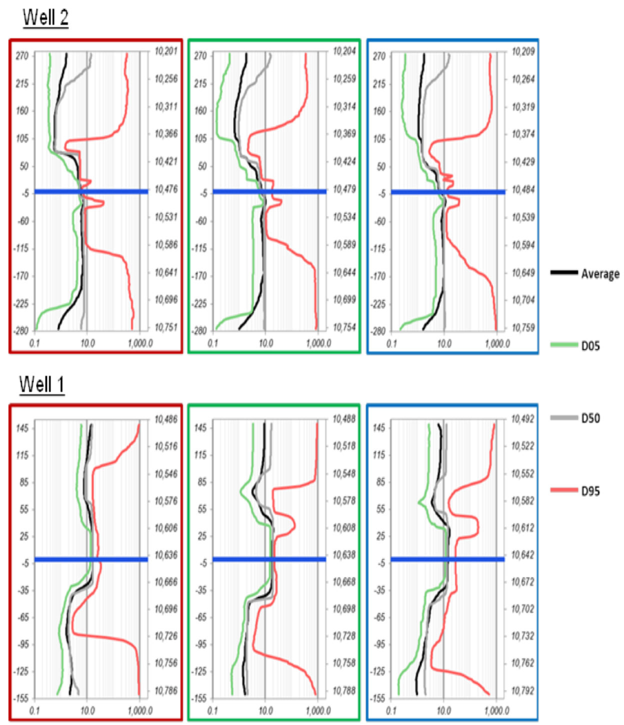


Field Trials: DOI > 200 ft

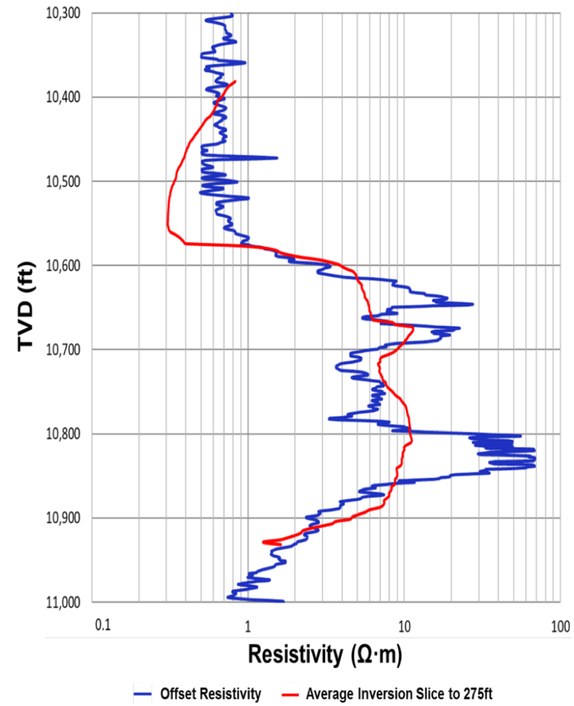
1D DTBB inversion of two wells



1D uncertainty at particular depths



Well 2 inversion compared to offset logs



Conclusions

- A new ultra-deep electromagnetic LWD tool is introduced
- It provides an improved 1D DTBB inversion algorithm
- Field trials to demonstrate DOI > 200 ft
  – Set a new performance benchmark
- More than 50 successful field runs have been performed in various locations

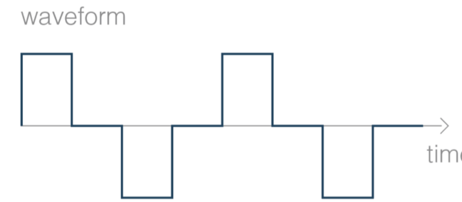
Acknowledgements

- PL018 partnership
  - ConocoPhillips Skandinavia AS
  - Total E&P Norge AS
  - ENI Norge AS
  - Equinor Energy AS
  - Petoro AS

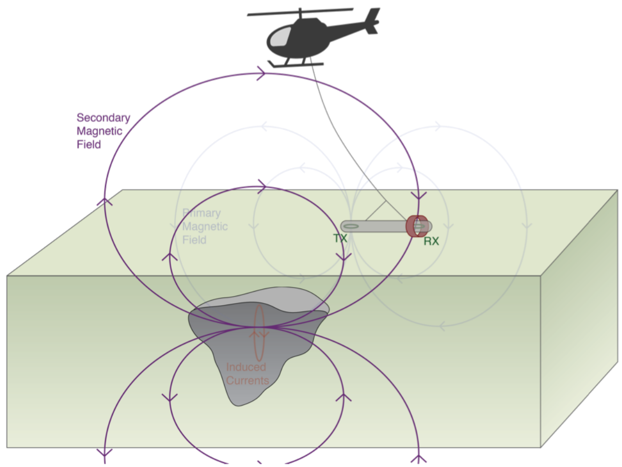
- Colleagues at ConocoPhillips

- Halliburton
  - Ultra-deep resistivity team
  - Colleagues

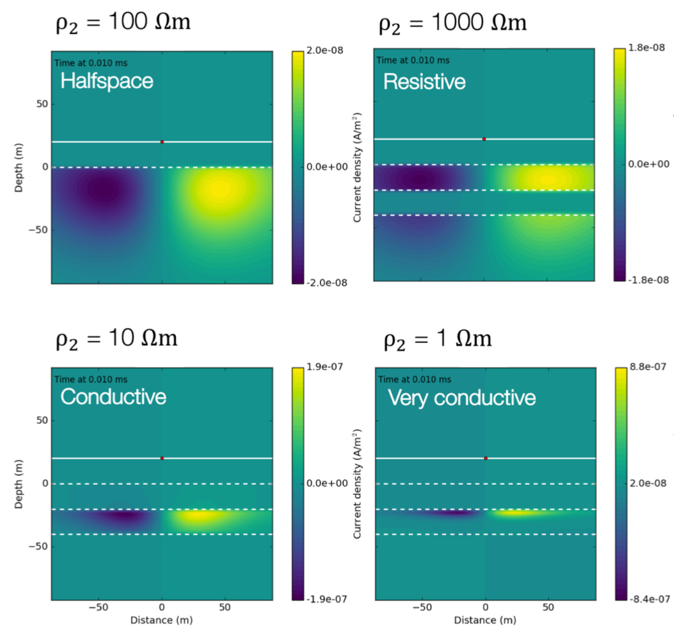
Summary



Basic experiment

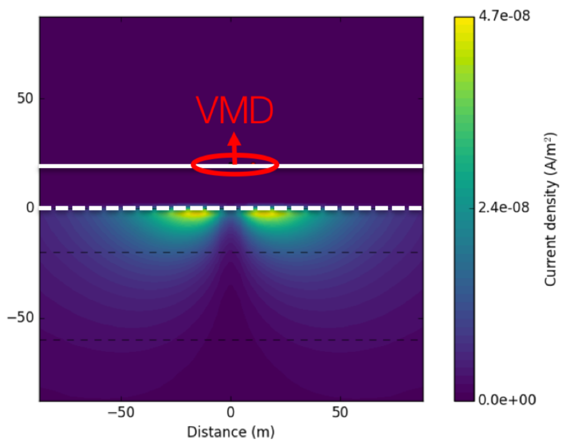


VMD over a layered earth

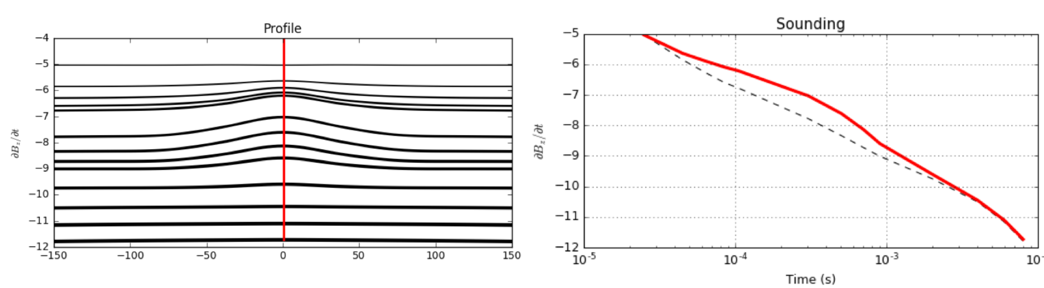


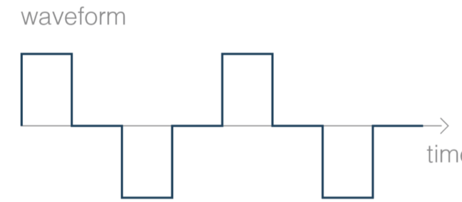
Footprint of an Airborne EM

Current density



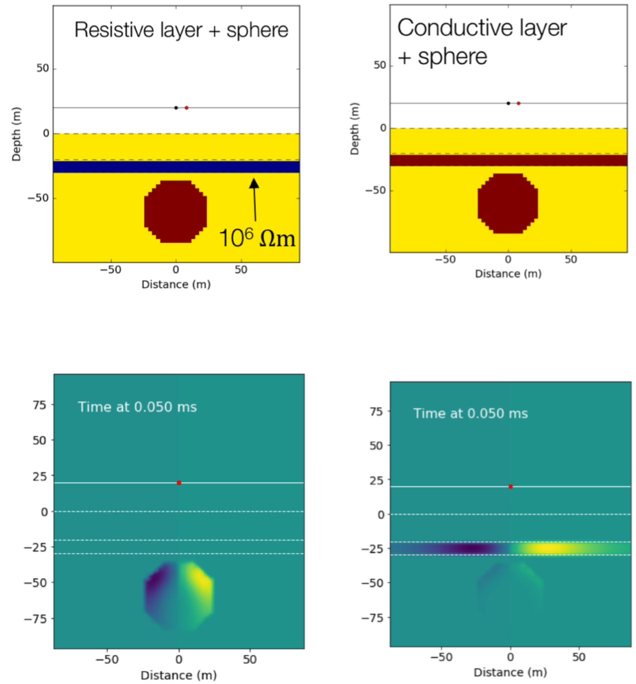
AEM data over a target



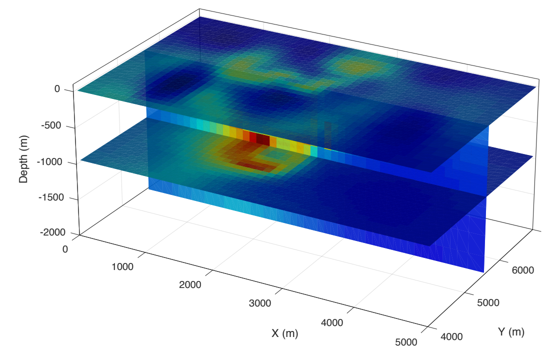


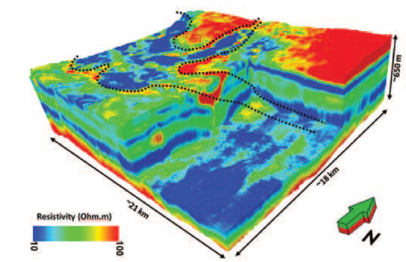
Summary

Shielding

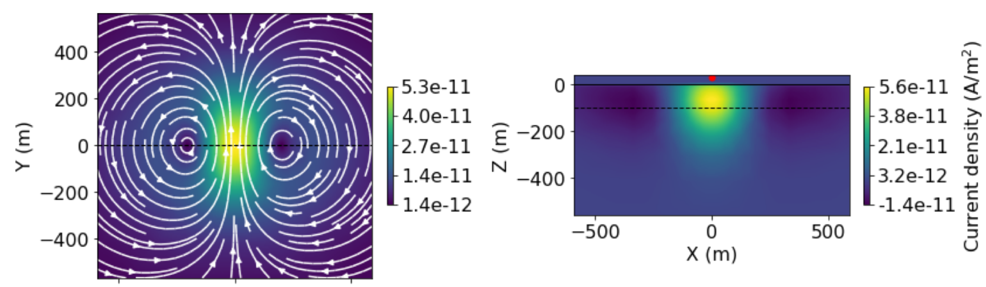


Case Histories: Lalore, Wadi Sahba

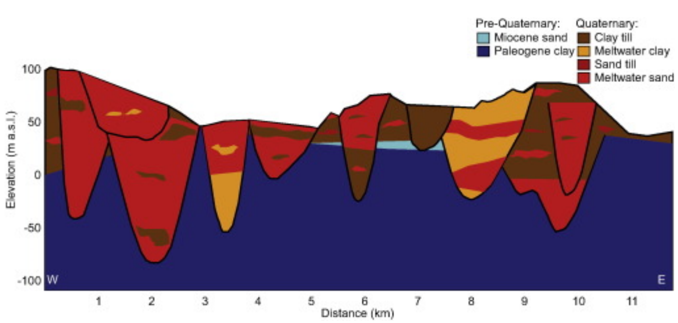




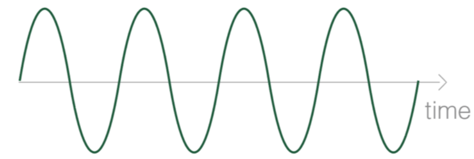
Horizontal Magnetic Dipole



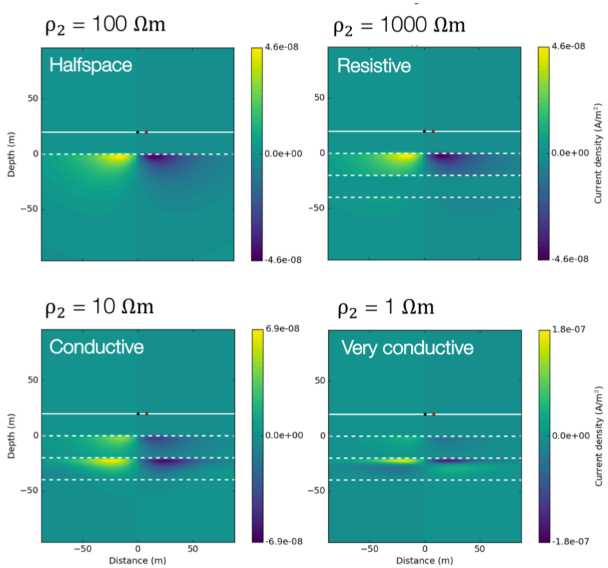
Case History: Kasted



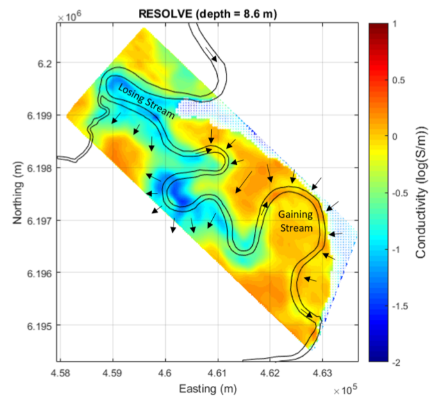
Summary

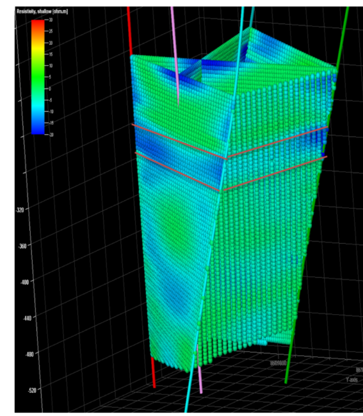


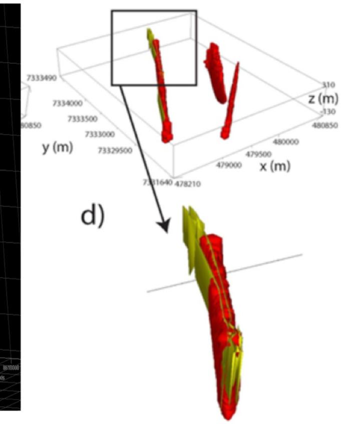
Vertical magnetic dipole



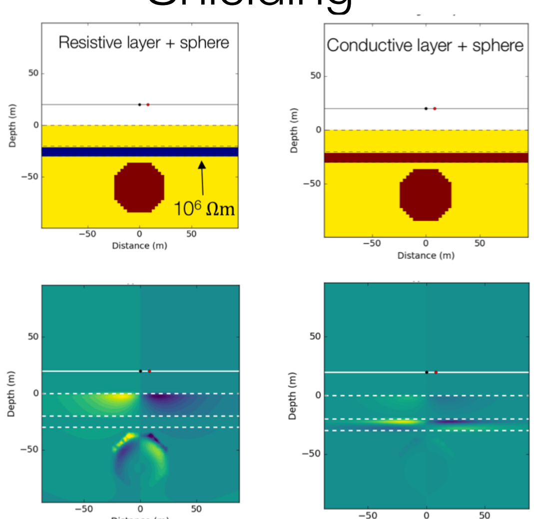
Case Histories: Bookpurnong, Dom João, West Plains



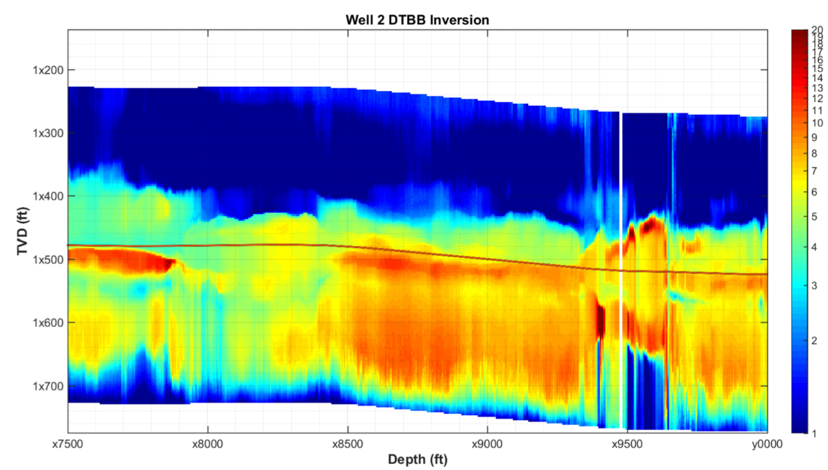




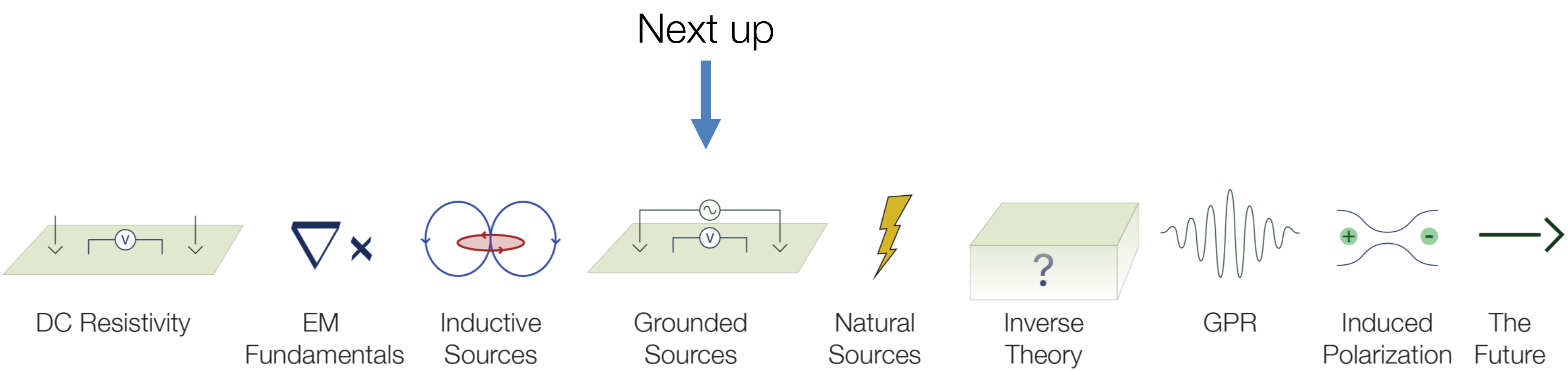
Shielding



Logging While Drilling



End of Inductive Sources



Additional Material

- Tutorial on UXO
- Case Histories:
  - Pole Mountain (UXO)
  - Austria (Landslides)

Unexploded Ordnance (UXO)

Unexploded Ordnance (UXO)

Definition: a munition that was armed, fired and remains unexploded

Sources:
- Regions of military conflict
- Munitions/bombing ranges
- Avalanche control

Countries Significantly Impacted by UXOs

http://www.nohowinc.com/

http://www.centennialofflight.gov

http://www.dma.state.mn.us/

Various Types of UXO

- Landmines
- Bombs
- Bombies (from cluster bombs)
- Rocket-propelled grenades (RPG)
- Hand-held grenades
- Mortars

How do we find UXO?

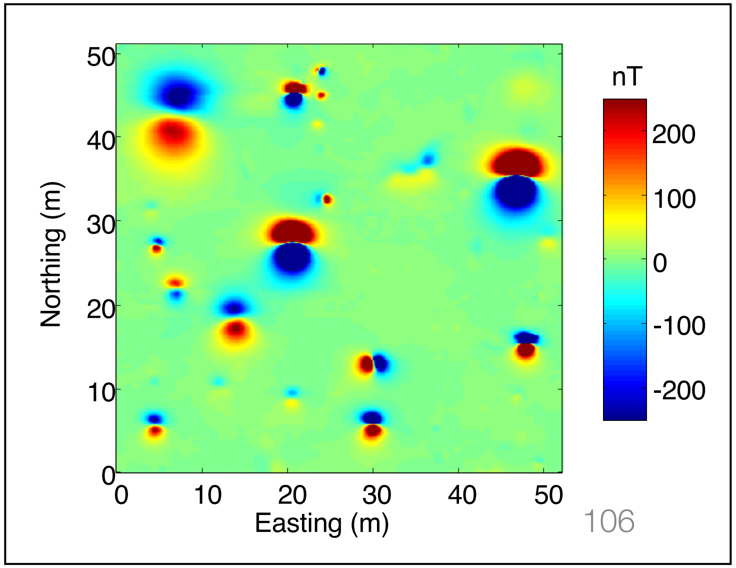
Magnetic Surveys: Locate Anomalies

- Analogue data
- Flag anomaly locations

Ferrex

- Digital data
- Look for magnetic dipoles

TM4



Magnetic Survey: Dig Anomalies

Digital UXO Location and Classification

Problem

- Most anomalies are not UXO
- Digging every anomaly is expensive

Goal

- Classify anomalies
- Dig only UXOs

Strategy

- Need more information than provided by magnetics
- UXO: composed of steel
  - conductive and magnetic

➡ Use electromagnetics

Fundamental Physics: EM Survey

- Controlled source generates primary magnetic field
- Primary field induces eddy currents within UXO
- Eddy currents decay over time
- Eddy current produce a secondary field which decays over time

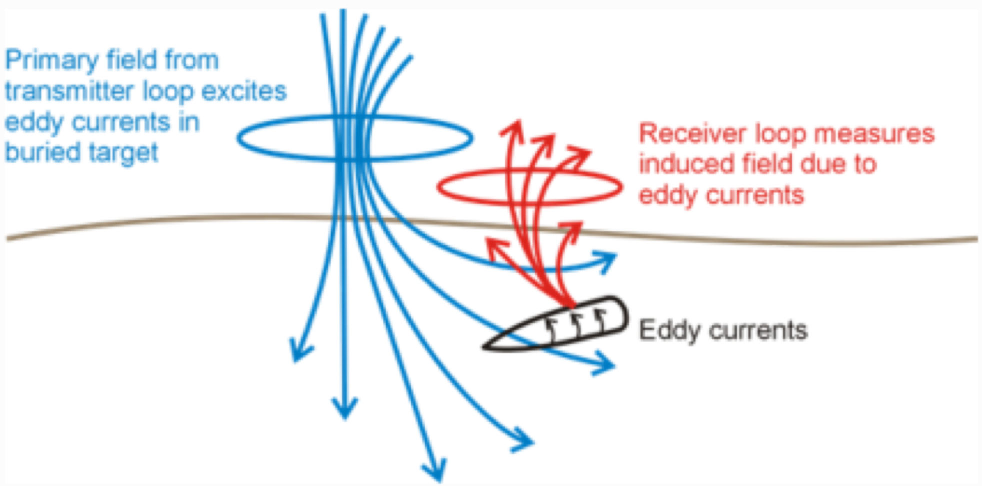
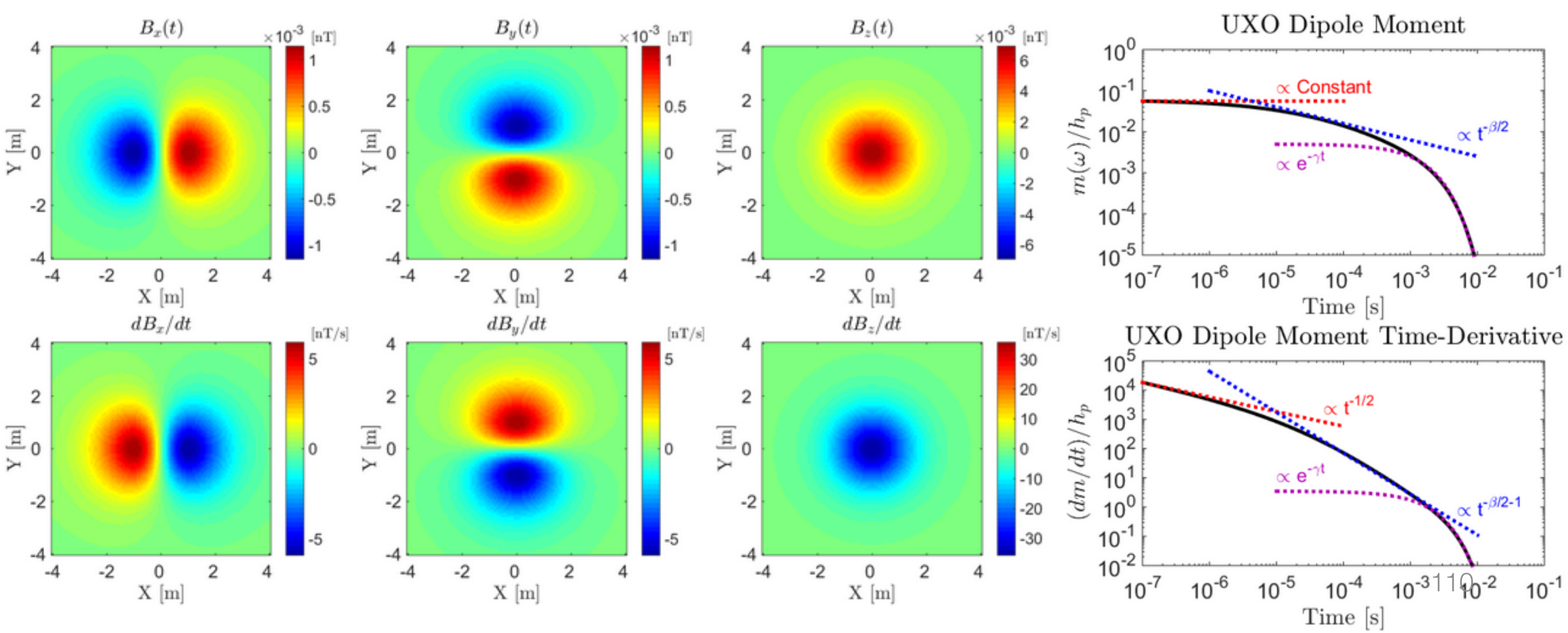


Fig. 260 Electromagnetic induction (EMI) survey for UXO location.

Fundamental Physics: EM Survey

- UXO responses modeled as magnetic dipoles
- Dipoles decay with time
- Rate of decay is indicative of the type of object
- UXOs have characteristic early, mid and late-time decay behaviours



Dipole Model and Polarization Tensor

- UXO response modeled as dipole:

$$\mathbf{b_s}(t) = \frac{\mu_0}{4\pi}\left[\frac{3\mathbf{r}\big[\mathbf{r}\cdot\mathbf{m}(t)\big]}{r^5} - \frac{\mathbf{m}(t)}{r^3}\right]$$

- m(t) is dipole moment (decays with time)

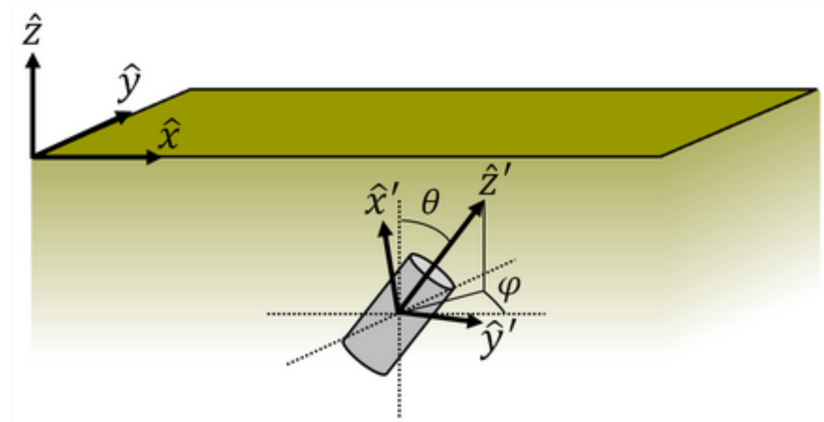
- m(t) depends on:
  1. Orientation of the inducing field
  2. The polarization tensor

$$\mathbf{m}(t) = \mathbf{A^T L A h_p}$$

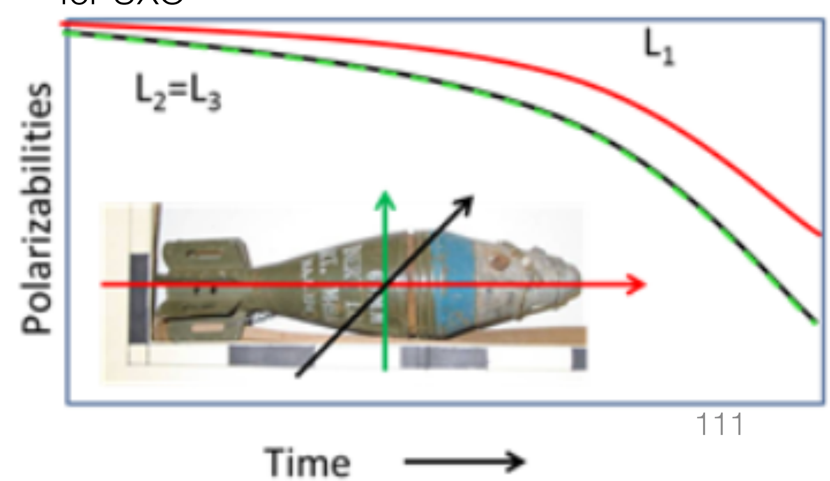
- The polarization tensor L:

$$\mathbf{L}(t) = \begin{bmatrix} L_1(t) & 0 & 0 \\ 0 & L_2(t) & 0 \\ 0 & 0 & L_3(t) \end{bmatrix}$$

Field and UXO coordinate systems

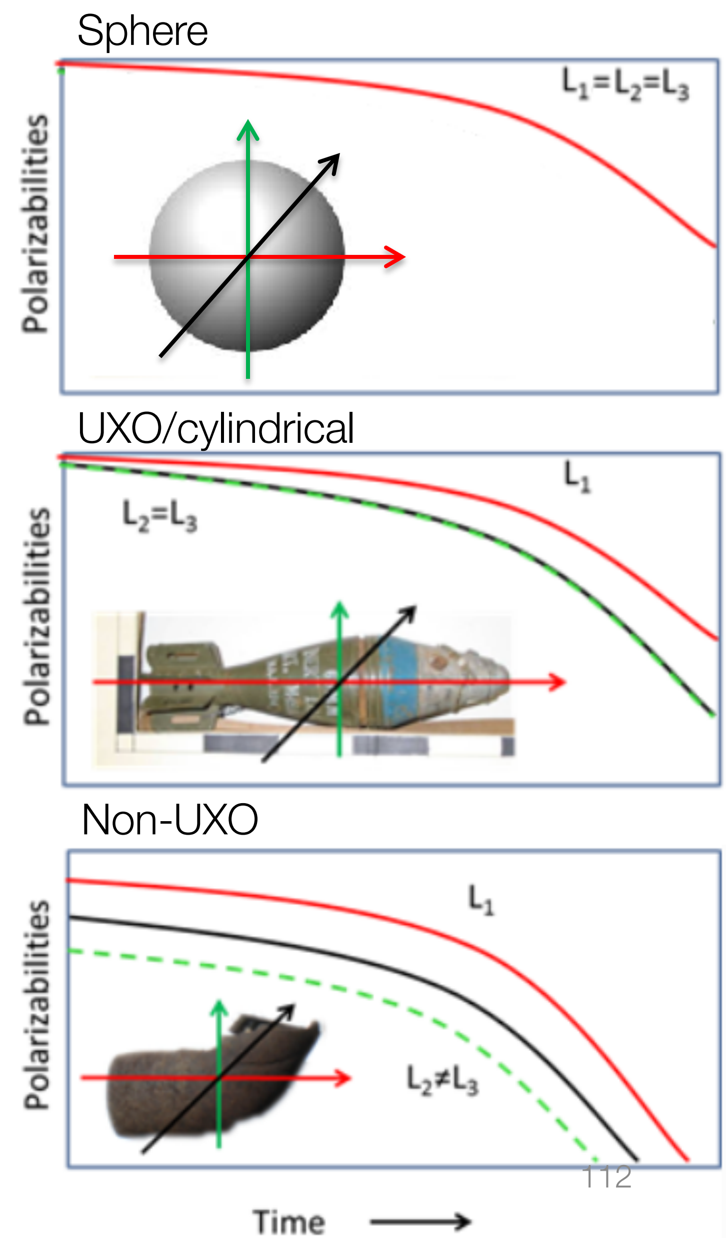


Primary (L1) and secondary (L2,L3) polarizations for UXO



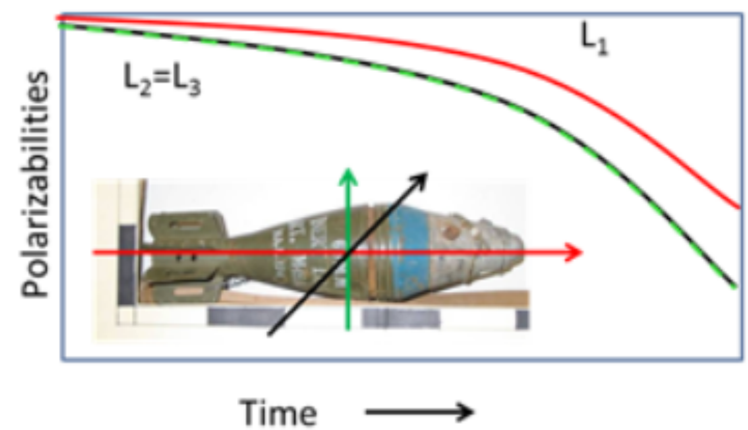
Objects and Polarization Tensors

- Polarization tensor characterizes decay and provides information about dimensionality
- Sphere:
  - Polarization strength independent of primary field direction
  - $L1 = L2 = L3$
- UXO:
  - Cylindrical in shape
  - Stronger polarization along primary axis
  - $L1 > L2 = L3$
- Non-UXO:
  - Arbitrary shape
  - Polarization different along different orientations
  - $L1 \neq L2 \neq L3$



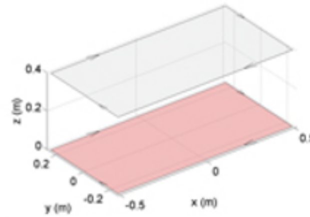
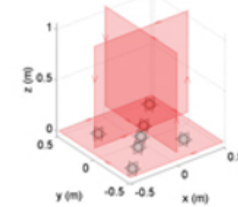
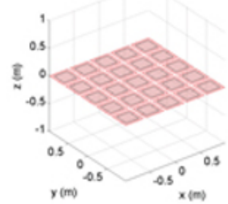
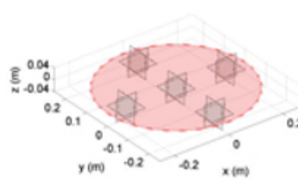
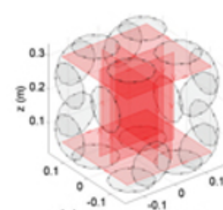
UXO Classification in Practice

- Survey area and pick targets
- Collect high-resolution data over a target
- Recover the elements of the polarization tensor
- Use the polarization tensor to infer information about the object's shape
- Match the recovered polarization tensor to those of object stored in a library to classify



To carry out inversion for polarization tensor need data:
- multiple transmitters (orientations)
- multiple components of data

Common Systems

	Sensor	Geometry	Time channels
EM-61	EM-61 		$t_{min} = 0.2\ ms$ $t_{max} = 1.5\ ms$ $N = 4$
MetalMapper	MetalMapper 		$t_{min} = 0.1\ ms$ $t_{max} = 10\ ms$ $N = 42$
TEMTADS	TEMTADS 		$t_{min} = 0.1\ ms$ $t_{max} = 20\ ms$ $N = 115$
MPV	MPV 		$t_{min} = 0.1\ ms$ $t_{max} = 20\ ms$ $N = 32$
BUD	BUD 		$t_{min} = 0.1\ \mathrm{ms}$ $t_{max} = 1.5\ ms$ $N = 45$

Survey Design

Line and Station Spacing:

- Depends on dimensions and depth of targets and system being used.
- Insufficient sampling makes locating and classifying targets more challenging.

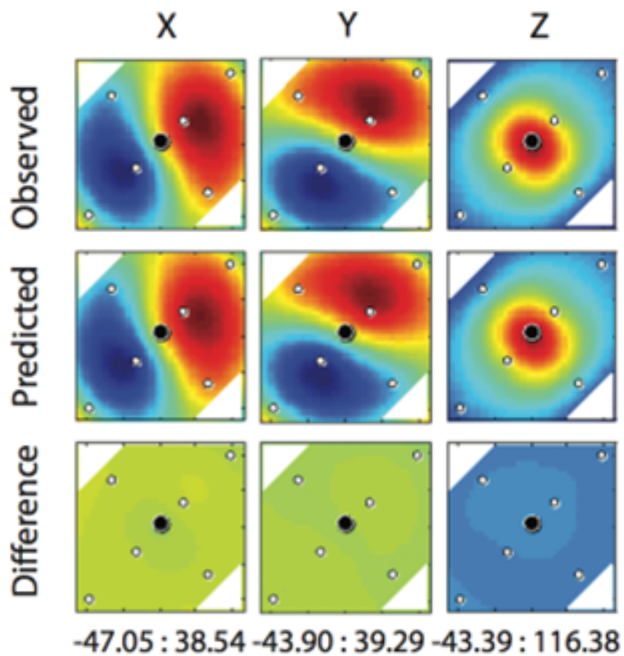
Excitation Orientation

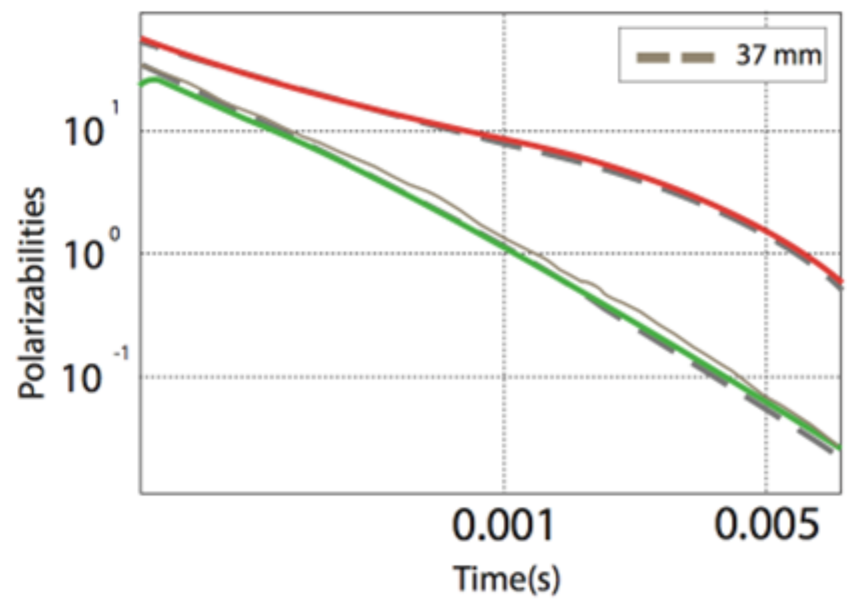
- To recover polarization tensor, target must be polarized from as many angles as possible.
- May require multiple passes with single transmitter or use of multi-transmitter system.

Time Channels

- Sufficient time-channels required to characterize decay behaviour.

Example: Metal Mapper Data

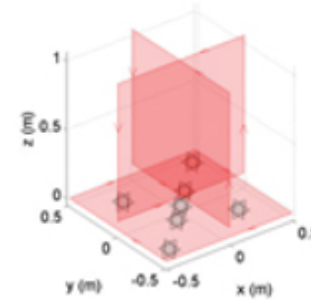


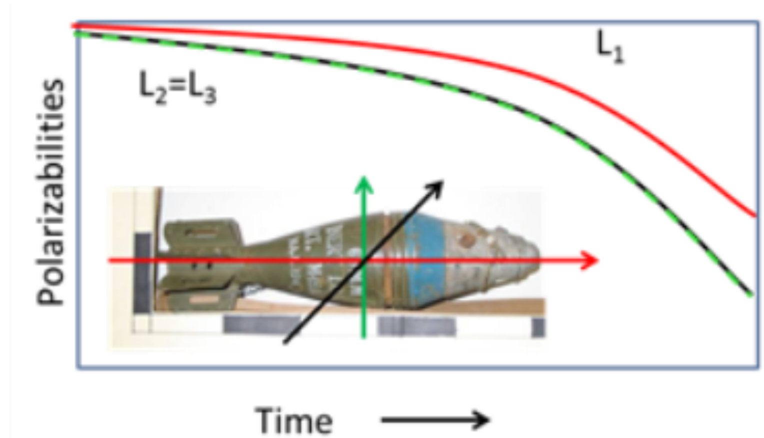


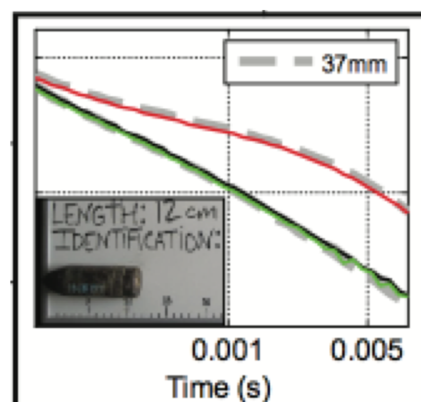
- Polarizations indicate a cylindrical object
- Predicted data using recovered polarization tensor fits the observed data
- Recovered polarizations match those of a 37 mm projectile

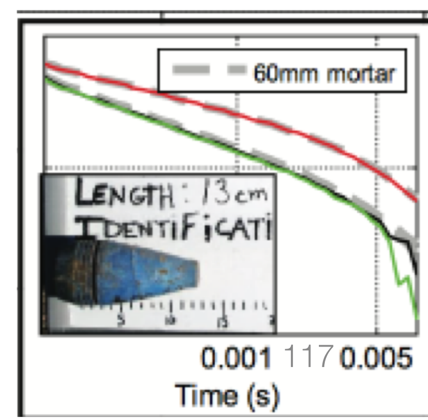
Summary

- UXO are compact conductive permeable objects
- EM is ideal survey
- Requires multiple transmitters and receivers
- Processing yields polarization curves
- Discrimination









Field Example: Pole Mountain

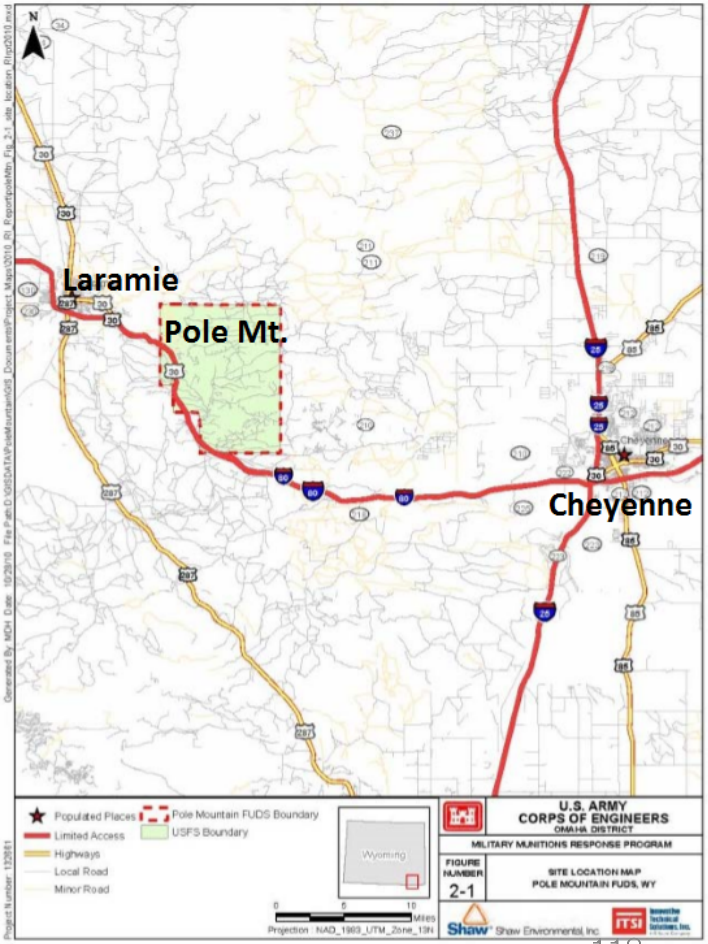
History

- Periods of military use 1897-1961
- Many types of munitions (explosive projectiles, mortars, small arms)
- Land reclamation currently not possible

Goals:

- Test classification algorithm on different objects
- Determine dig/no dig list for targets

Location of Pole Mt., Wyoming, US



Field Example: Pole Mountain

EM61-MK2:

- Efficient over rugged terrain
- Single Tx and Rx loops
- Located 2,368 anomalies

Metal Mapper:

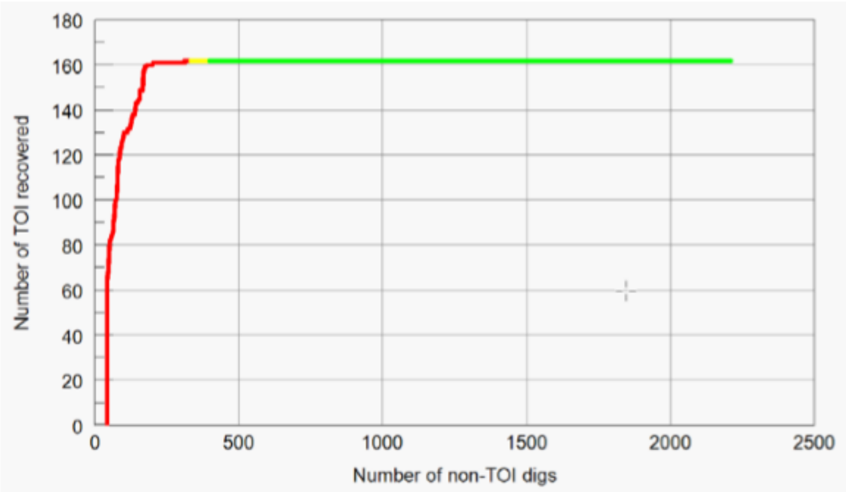
- Multiple Tx and Rx loops
- Cued interrogation data over anomalies
- Data used for classification and prioritize dig list

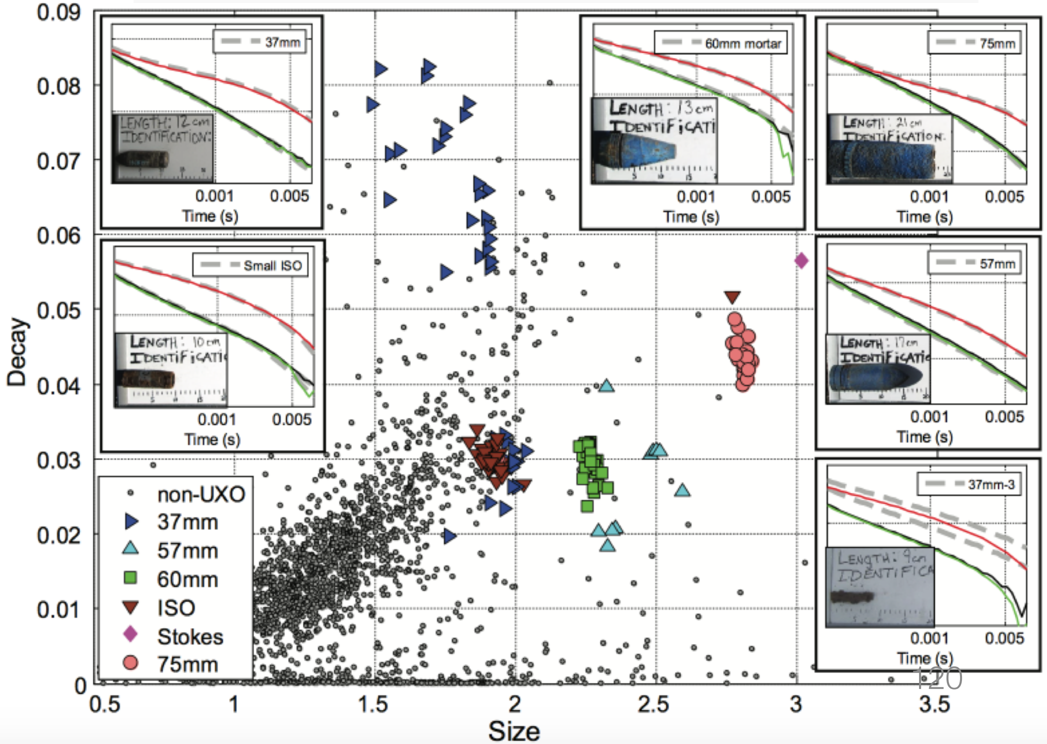
EM61-MK2 (locate anomalies)

Metal Mapper (cued interrogation)

Field example: Pole Mountain

- All 2,368 TEM anomalies were dug to verify
- 1,829 correctly identified as clutter or assigned to no dig through classification
- Only 453 non-munition items dug before all 160 munition items dug.
- 99% of munition items located within first ~300 digs
- Correctly identified all types of munititons.



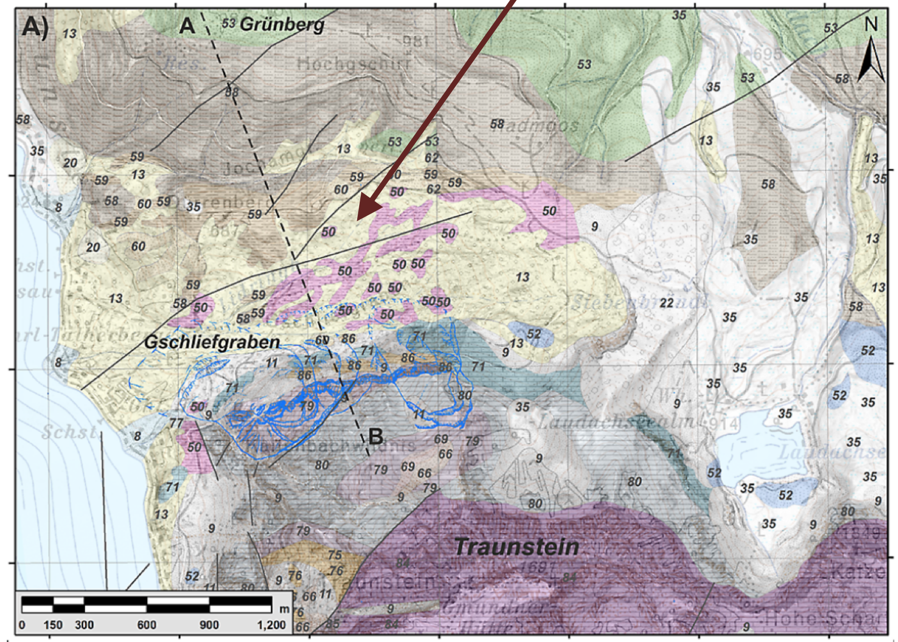


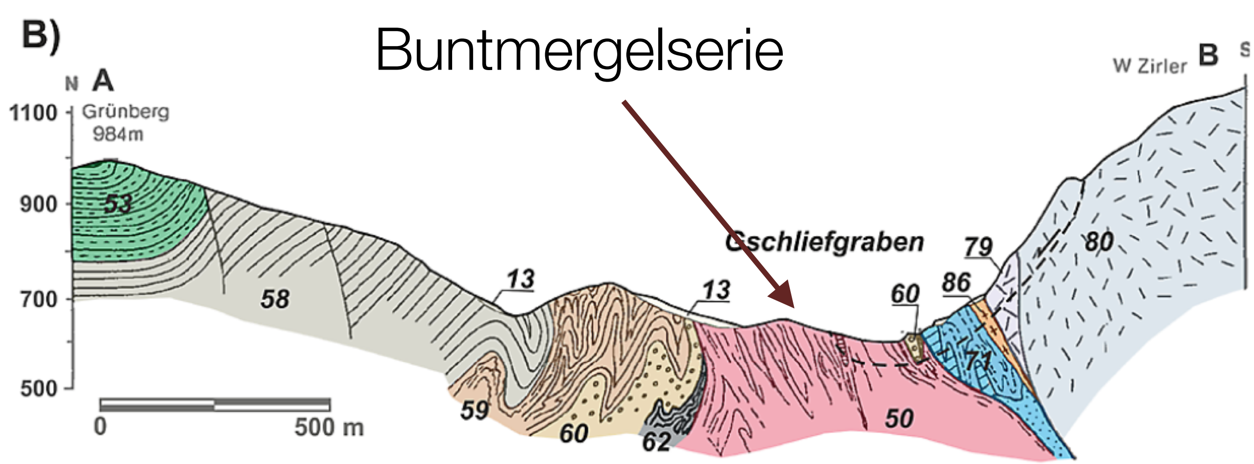
Case History: Airborne geophysical mapping for landslide investigation

Supper et al., 2013

Setup

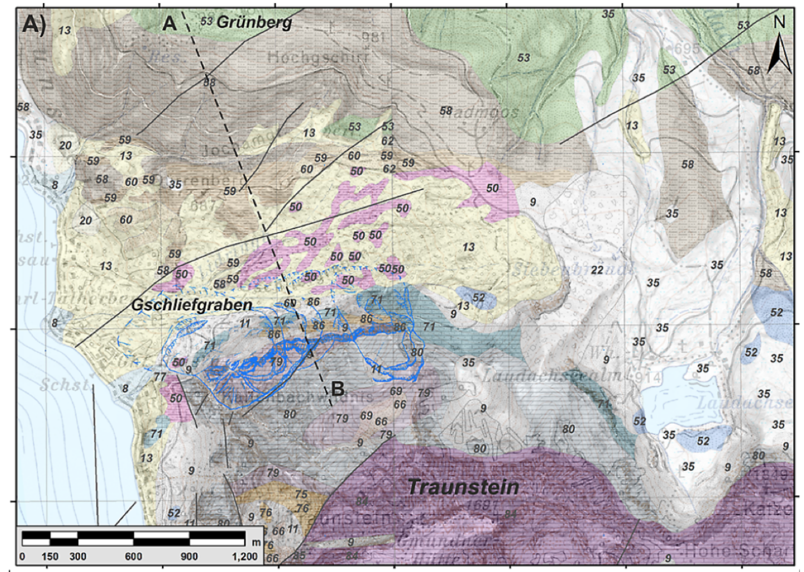
- Gschliefgraben area: most prominent recent landslide of Austria
- Clay layers absorb water → become a plane of weakness and result in a landslide
- SafeLand Project: evaluate airborne geophysics



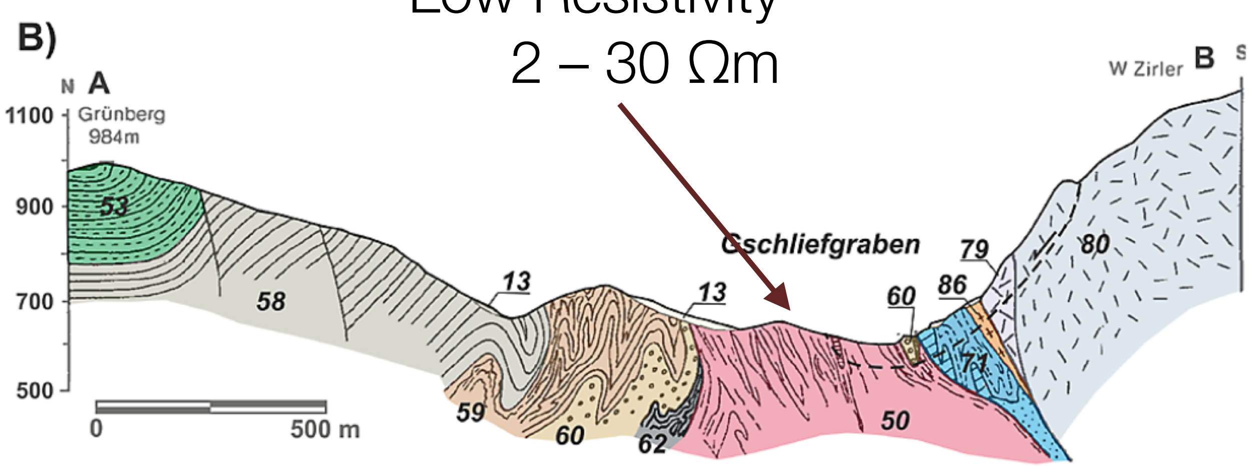


Properties

Deformed variegated marl, claystone, … (target unit)	2 – 30 Ωm
Claystone, marl	50 – 100 Ωm
Intermediate Sandstone	> 150 Ωm

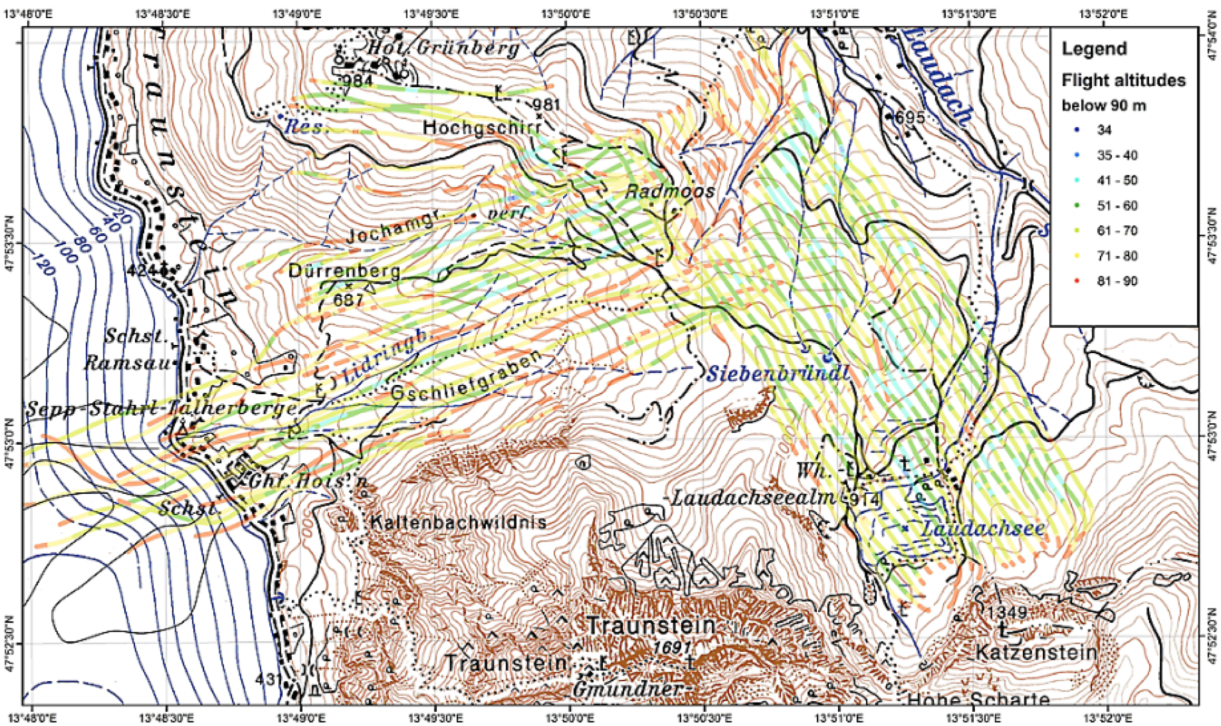


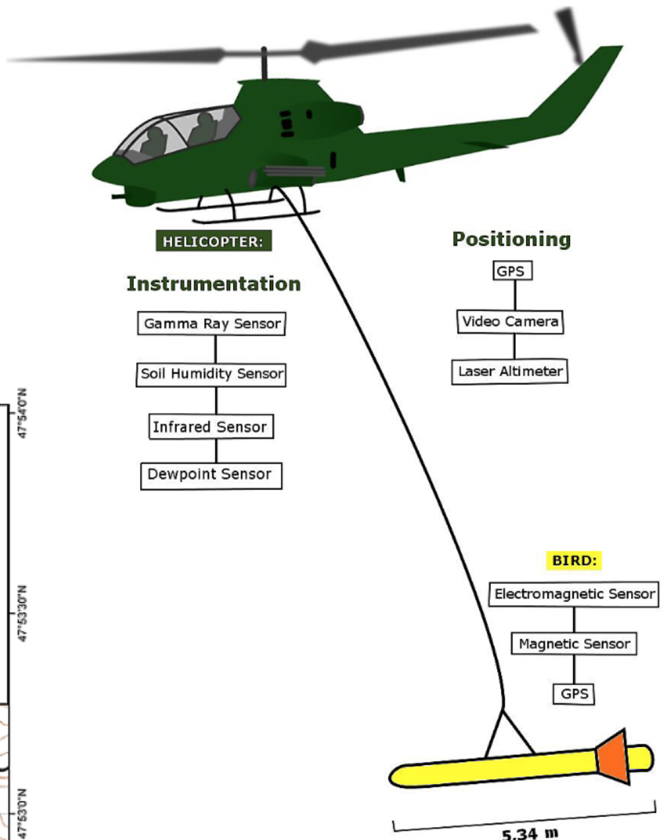
Buntmergelserie
Low Resistivity
2 – 30 Ωm



Survey

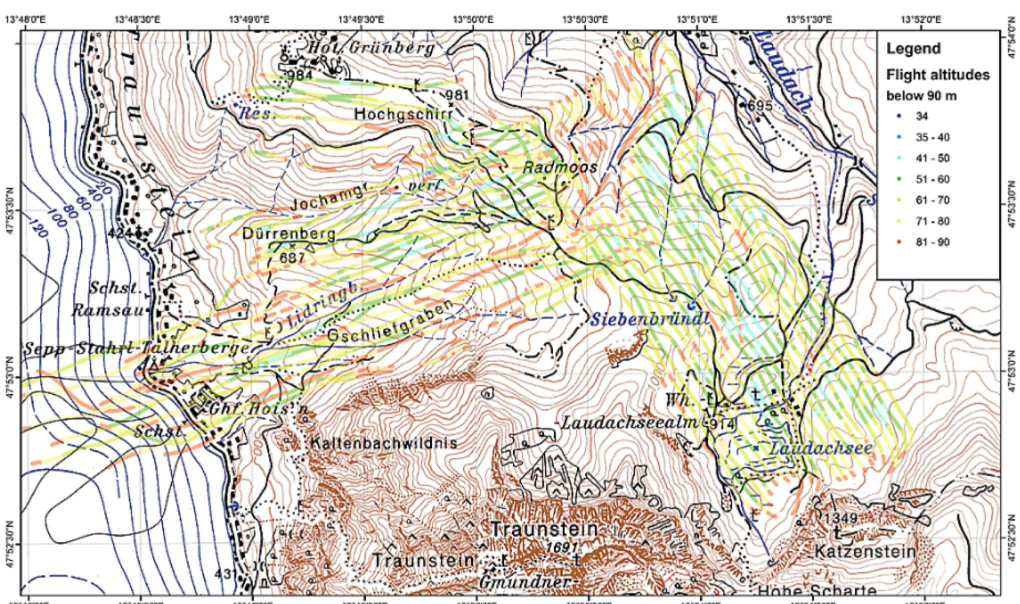
- Multiple airborne sensors
  - **Airborne EM**
  - Gamma Ray
  - Magnetics
  - Passive Microwave

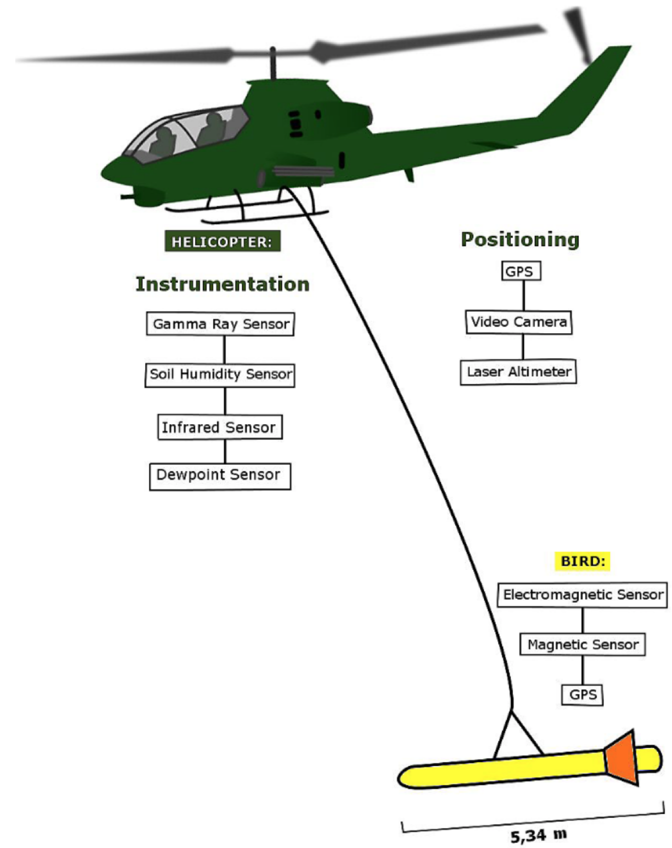




Survey: Airborne EM

- Frequency domain system
  - Frequencies: 340 Hz, 3200 Hz, 7190 Hz and 28 850 Hz
- Sensor height needs to be < 90 m
- Rough topography → flown only uphill (2x flight time)

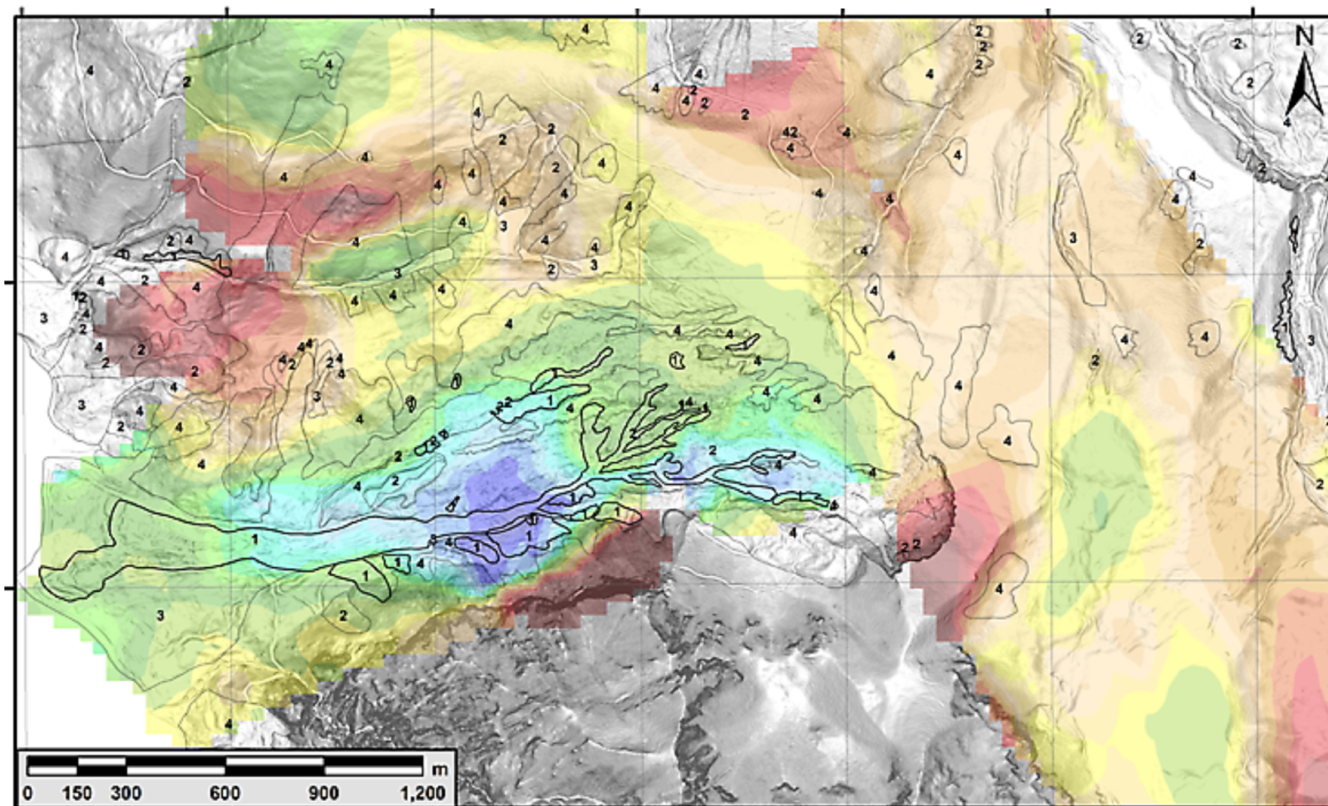




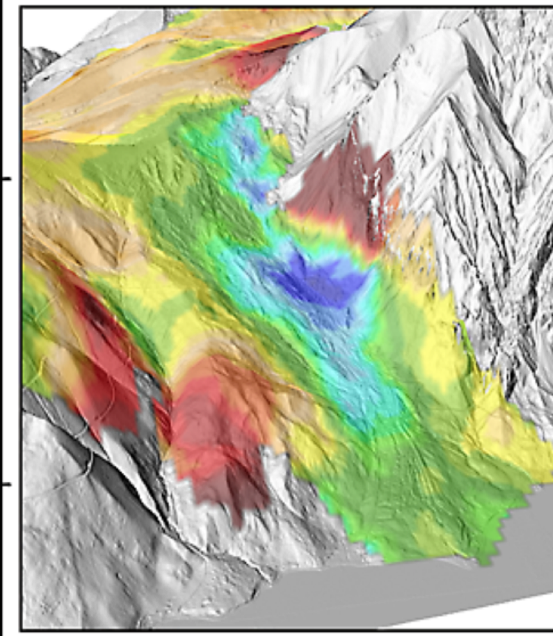
Data & Processing

- Data inverted in 1D

resistivity 0 – 2m below surface



3D view



Legend:

Resistivity [Ohmm]:

2.5 - 5
5.1 - 10
10.1 - 15
15.1 - 20
20.1 - 25
25.1 - 30
30.1 - 35
35.1 - 40
40.1 - 45
45.1 - 50
50.1 - 55
55.1 - 60
60.1 - 75
75.1 - 100
100.1 - 120
120.1 - 135
135.1 - 150
150.1 - 175
175.1 - 200
200.1 - 250
250.1 - 300
300.1 - 350
350.1 - 500
500.1 - 750
750.1 - 1000

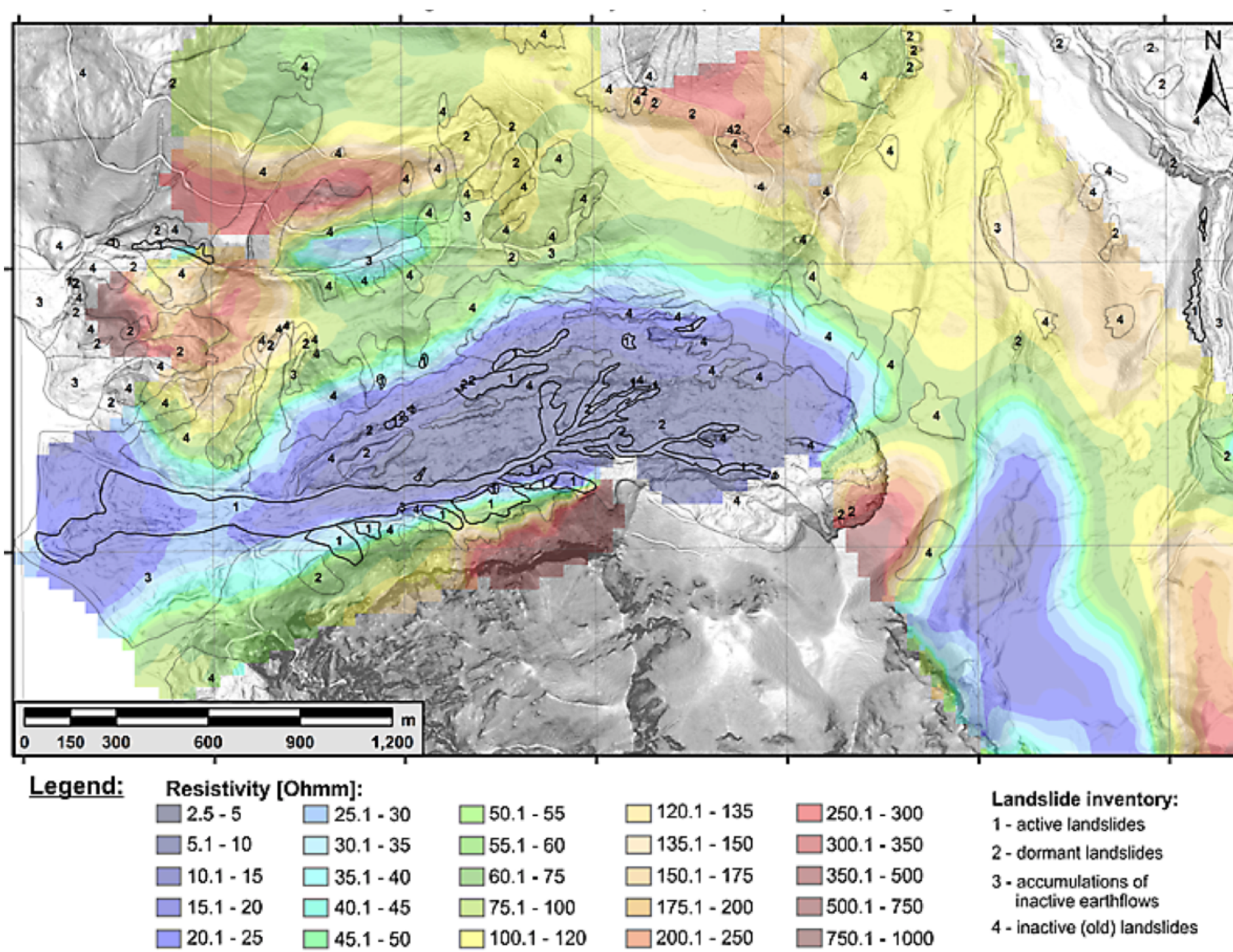
Landslide inventory:

1 - active landslides
2 - dormant landslides
3 - accumulations of inactive earthflows
4 - inactive (old) landslides

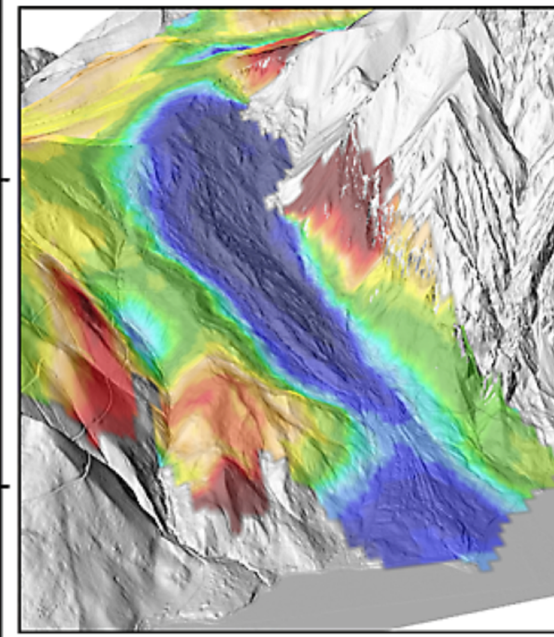
Data & Processing

- Data inverted in 1D

resistivity 20m below surface



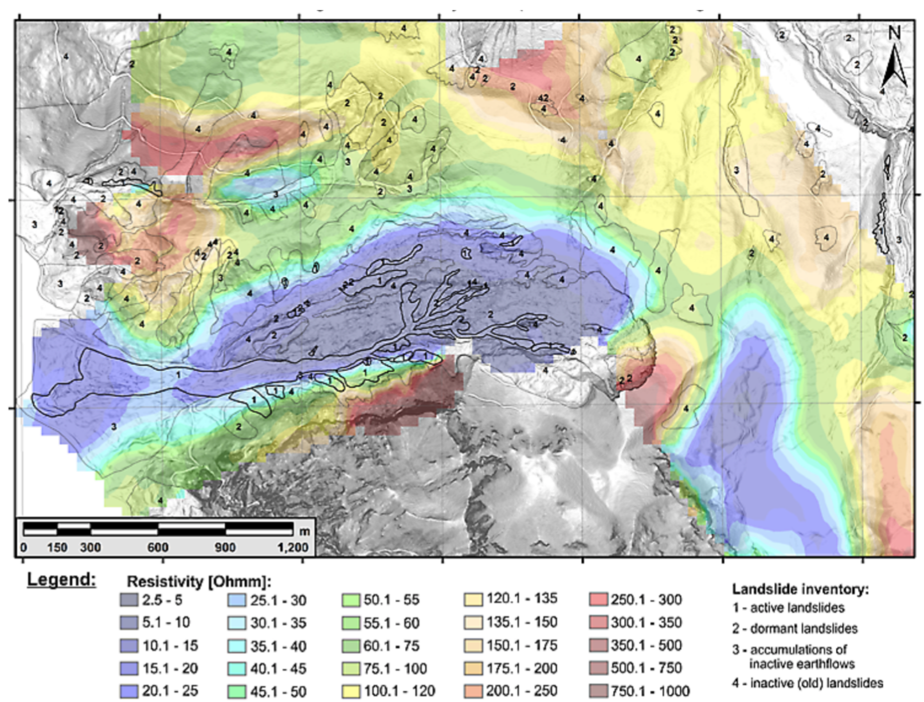
3D view



Interpretation

- 2 – 30 Ωm contour delineates the Buntmergelserie
  - landslide inventory map shows recent landslides are associated with Buntmergelserie
  - Low resistivities show this is most incompetent unit
- Buntmergelserie: highly tectonised
  - Anti-synclinal fold
  - Strongly west-east dipping axis

resistivity 20m below surface



Synthesis

- Airborne EM provided better understanding of the spatial and depth structure of geologic units

- Available model for landslides was significantly improved
  - helped to design proper location of sensors for early warning network for the Gschliefgraben area