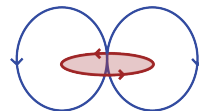
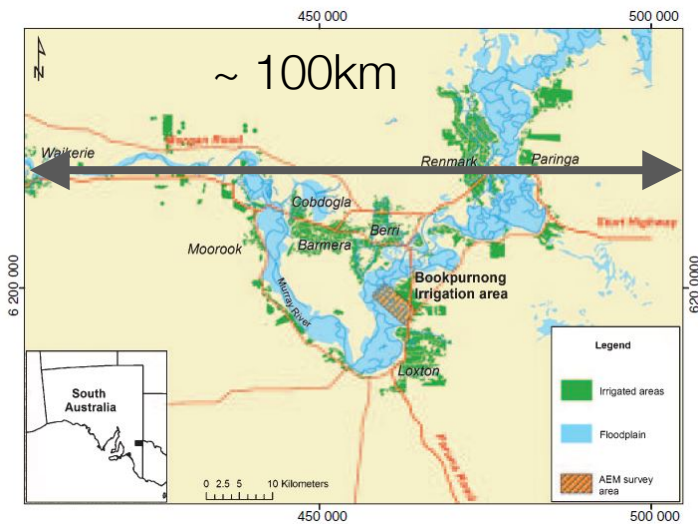


EM: Inductive Sources

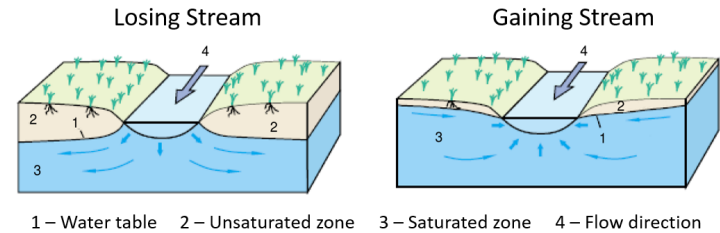


Motivation

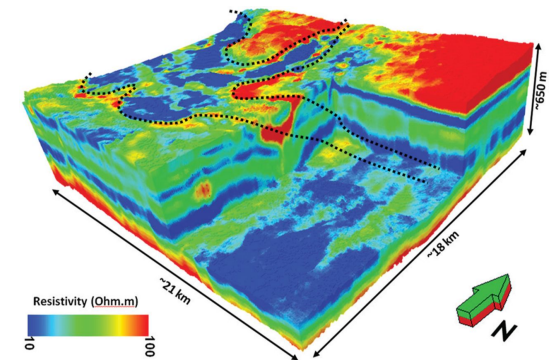
Large areas to be covered



Groundwater



High resolution near surface



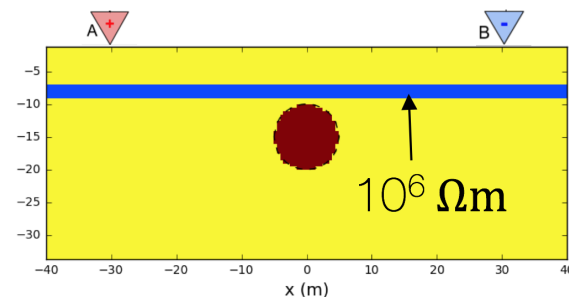
Rugged terrain



Minerals



Shielding problem



Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

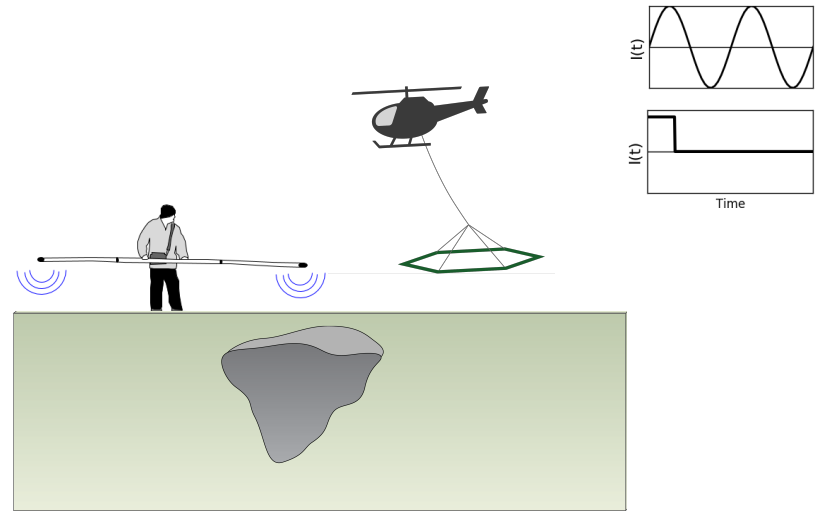
- Vertical Magnetic Dipole
- Propagation with Time
- Case History – Groundwater, Hydrocarbons

Frequency Domain EM

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

Important questions

- What is the target?
 - at the surface? At depth?. 1D, 2D, 3D?
- Transmitter
 - Location: surface? in the air?
 - Waveform: frequency or time?
 - “Size” and orientation?
- Exciting the target
 - Conductivity of the target and host
 - Geometry of the target (Coupling)
- Receiver and data
 - What fields to measure?
 - What instrument?
- Where to collect data? How many? How accurate?
- What is depth of investigation?
- What is the “footprint” of the transmitter?
 - These are questions of **SURVEY DESIGN**



Basic Experiment

- **Transmitter:**

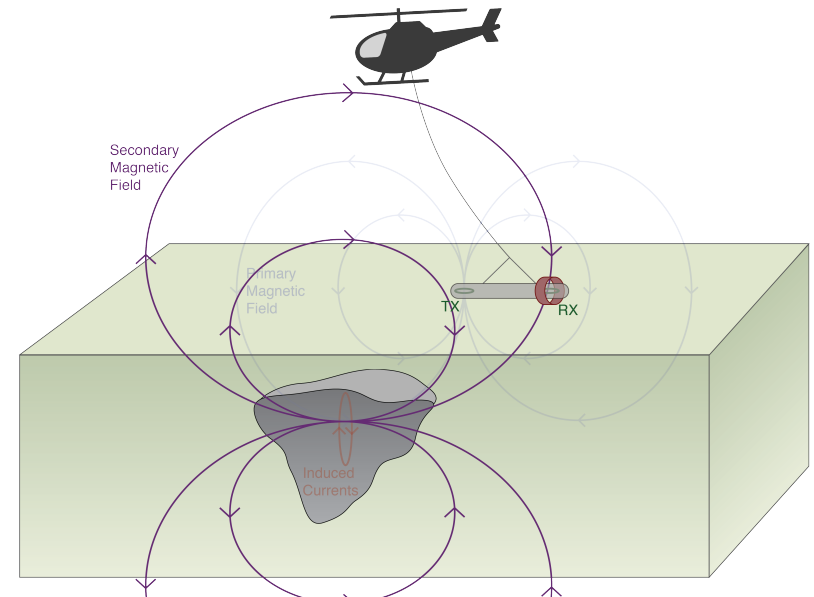
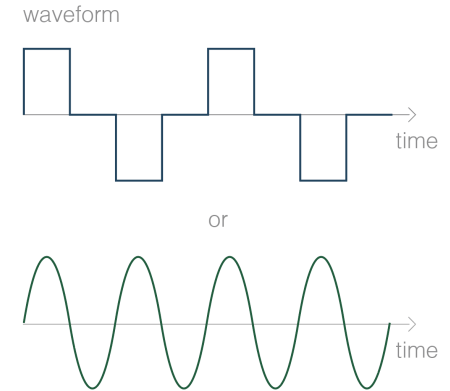
- Produces a primary magnetic field

- **Exciting the target:**

- Time varying magnetic fields generate electric fields everywhere
- Producing currents in conductors

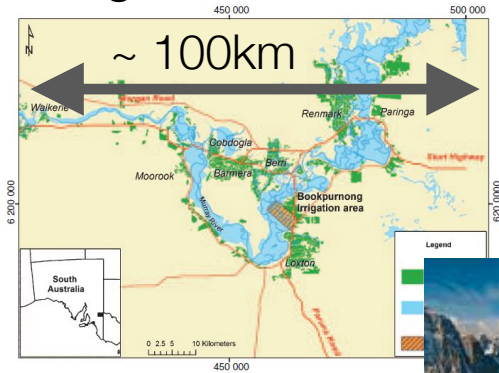
- **Receiver:**

- Induced currents produce secondary magnetic fields



Transmitter

Large areas



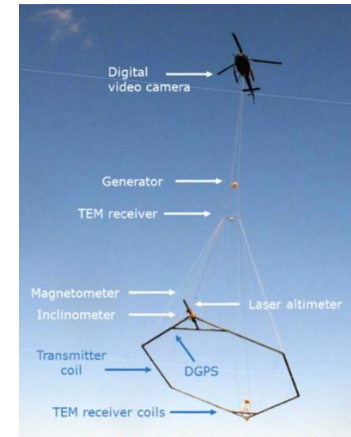
Rugged terrain



Airborne Survey

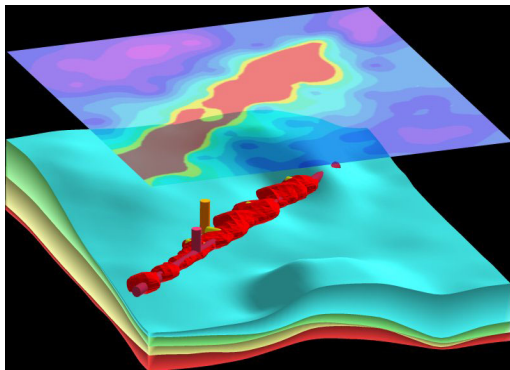


Resolve

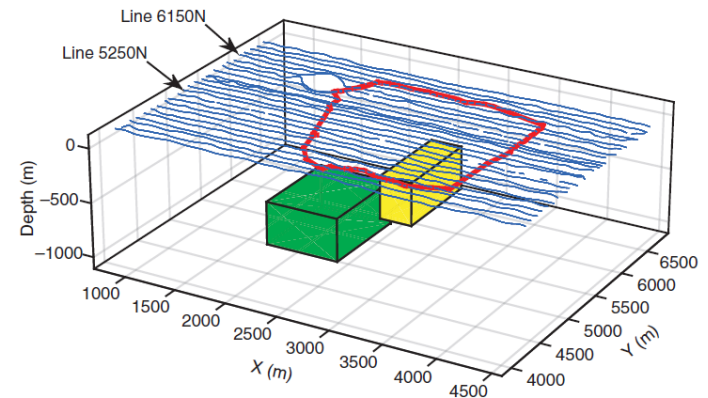


SkyTEM

Deep Targets

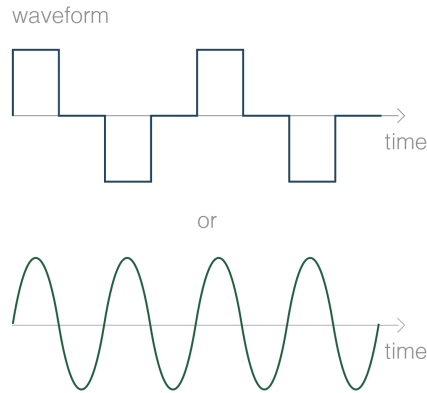


Large Loop



Transmitter

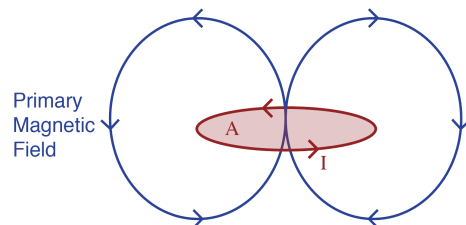
- Time or frequency?



- Key factor is moment

$$m = I \text{ (current)} A \text{ (area)} N \text{ (\# of turns)}$$

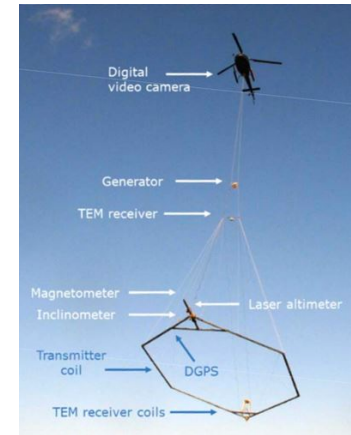
$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \left(\frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3} \right)$$



Airborne Survey

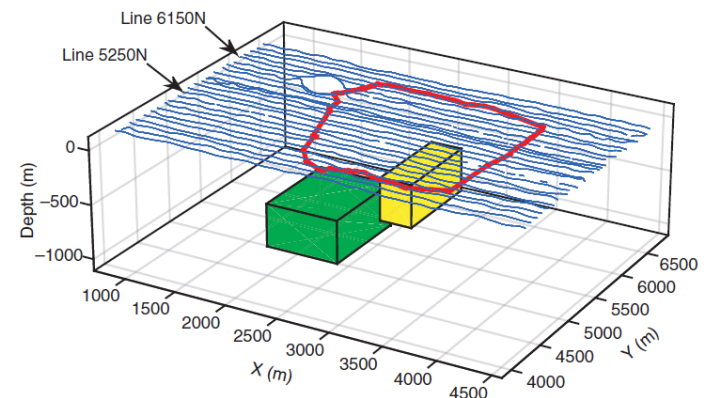


Resolve



SkyTEM

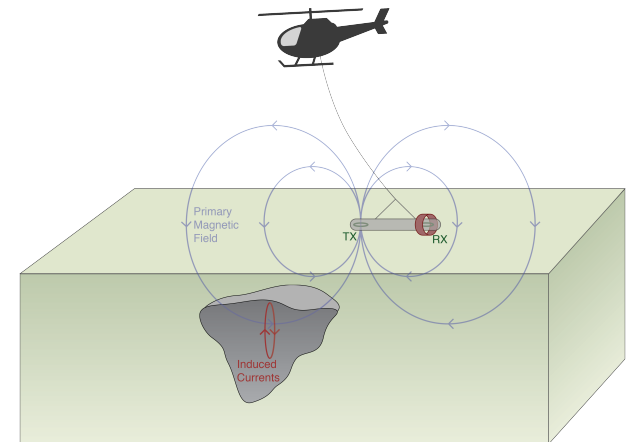
Large Loop



Exciting the target

- Primary field from a loop
- Fields fall off
 - $1/r^3$ geometric decay
 - Attenuation
- Want to be as close as possible to target
 - Ground based systems
 - Helicopter
 - Fixed wing aircraft
- Always concerned about coupling

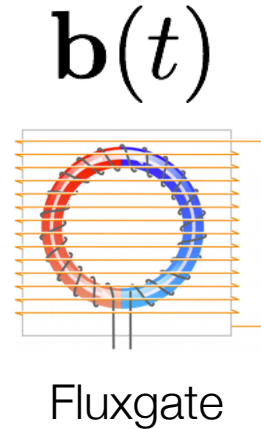
$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \left(\frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3} \right)$$



Receiver and Data

Magnetometer

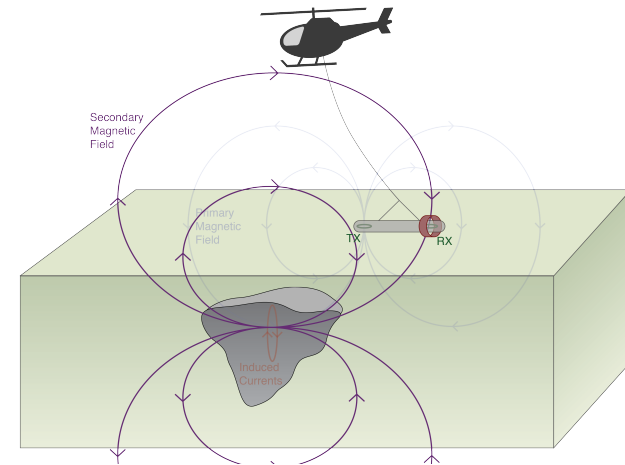
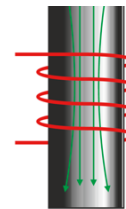
- Measures:
 - Magnetic field
 - 3 components
- eg. 3-component fluxgate



Coil

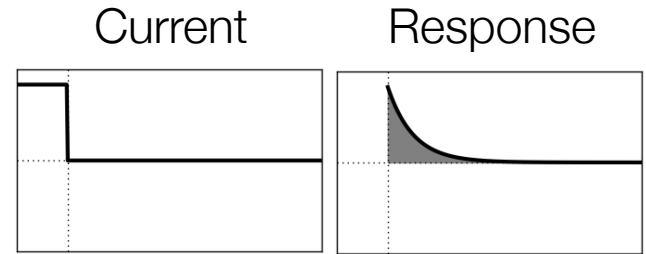
- Measures:
 - Voltage
 - Single component that depends on coil orientation
 - Coupling matters
- eg. airborne frequency domain.
 - ratio of H_s/H_p is the same as V_s/V_p

$$\frac{\partial b}{\partial t}$$

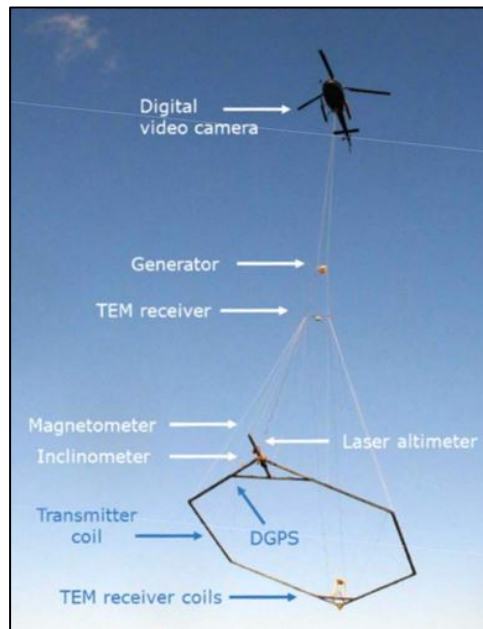


Receiver: Time Domain

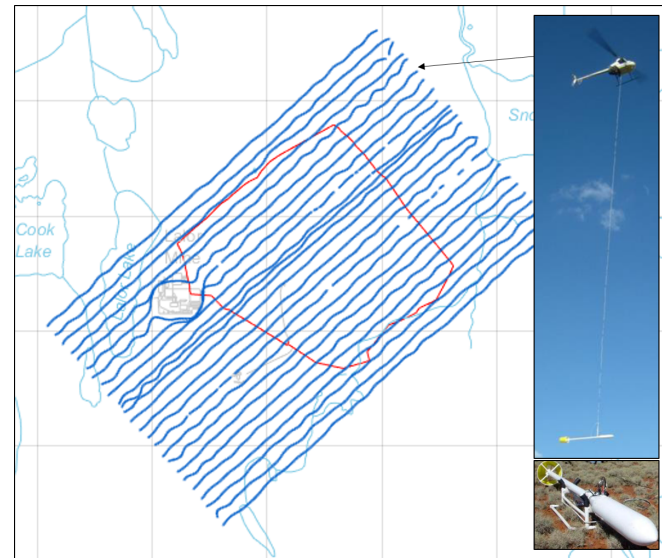
- Primary field has off-time
- Measure secondary fields
- Receivers can be mounted on transmitter loop or above it



SkyTEM

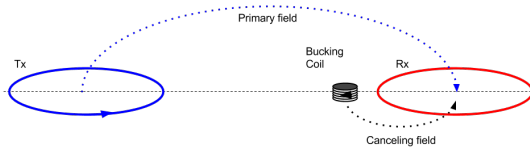


HeliSAM

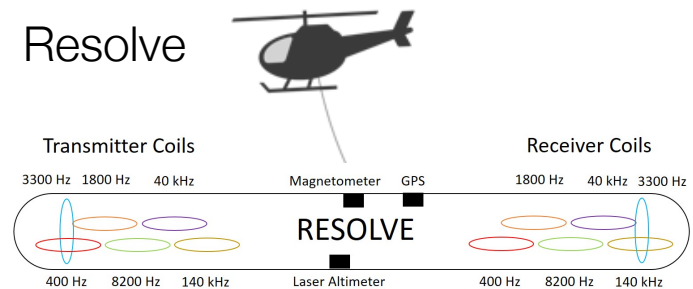
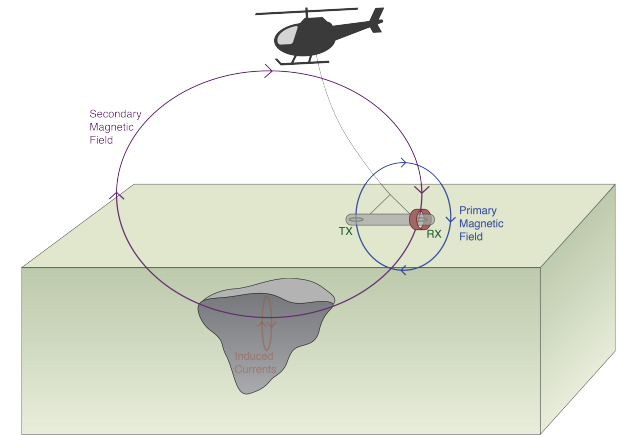


Receiver: Frequency Domain

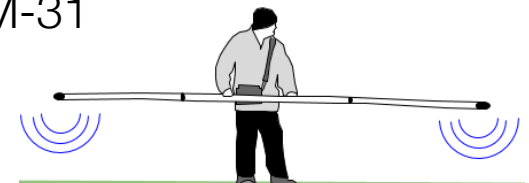
- Primary field
 - always “on”
 - large compared to secondary fields
- Primary removal
 - Compute and subtract
 - Bucking coil



- Main requirement:
 - Know positions of Tx and Rx
 - Keep them in one unit

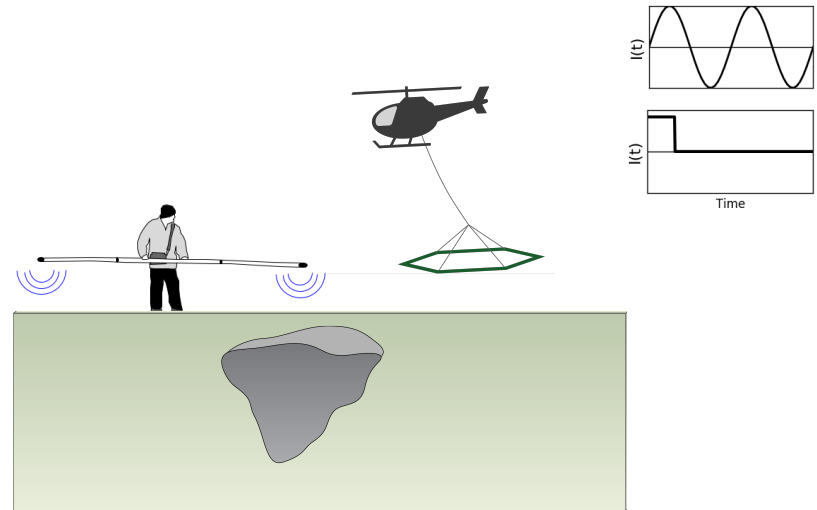


EM-31



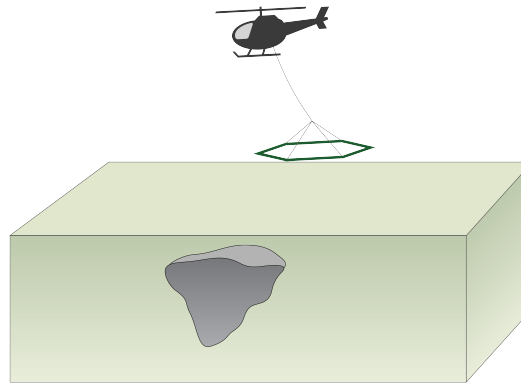
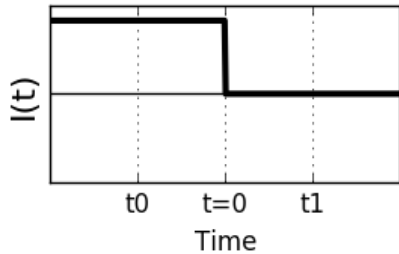
Important questions

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 - at the surface? At depth?. 1D, 2D, 3D?
- Transmitter
 - Location: surface? in the air?
 - Waveform: frequency or time?
 - “Size” and orientation?
- Exciting the target
 - Conductivity of the target and host
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- What is the “footprint” of the transmitter?
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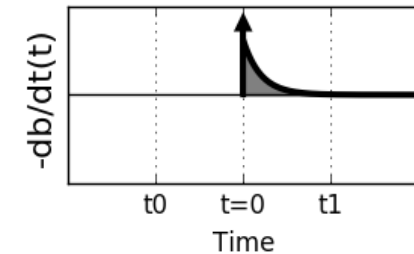
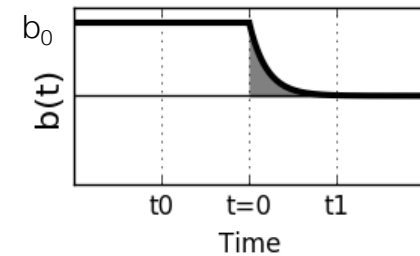


EM with Inductive Sources: Time Domain

Transmitter current



Receiver

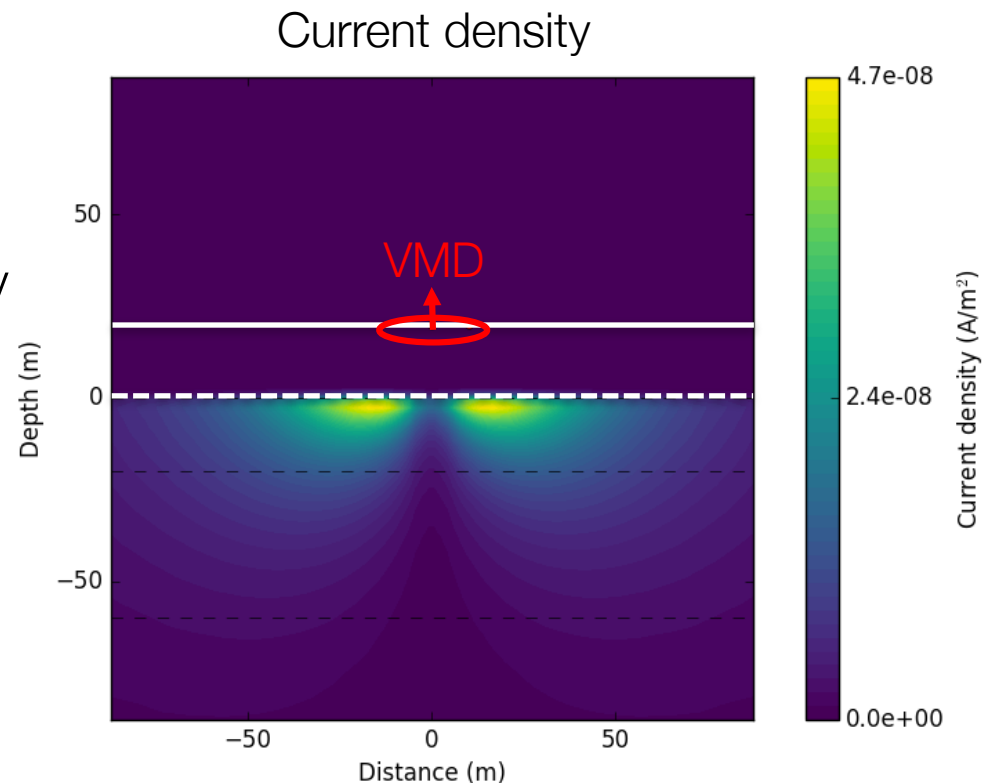


time	b	db/dt
$t < 0$	b_0	0
$t = 0$	b_0	$-b_0\delta(t)$
$t > 0$	secondary	secondary

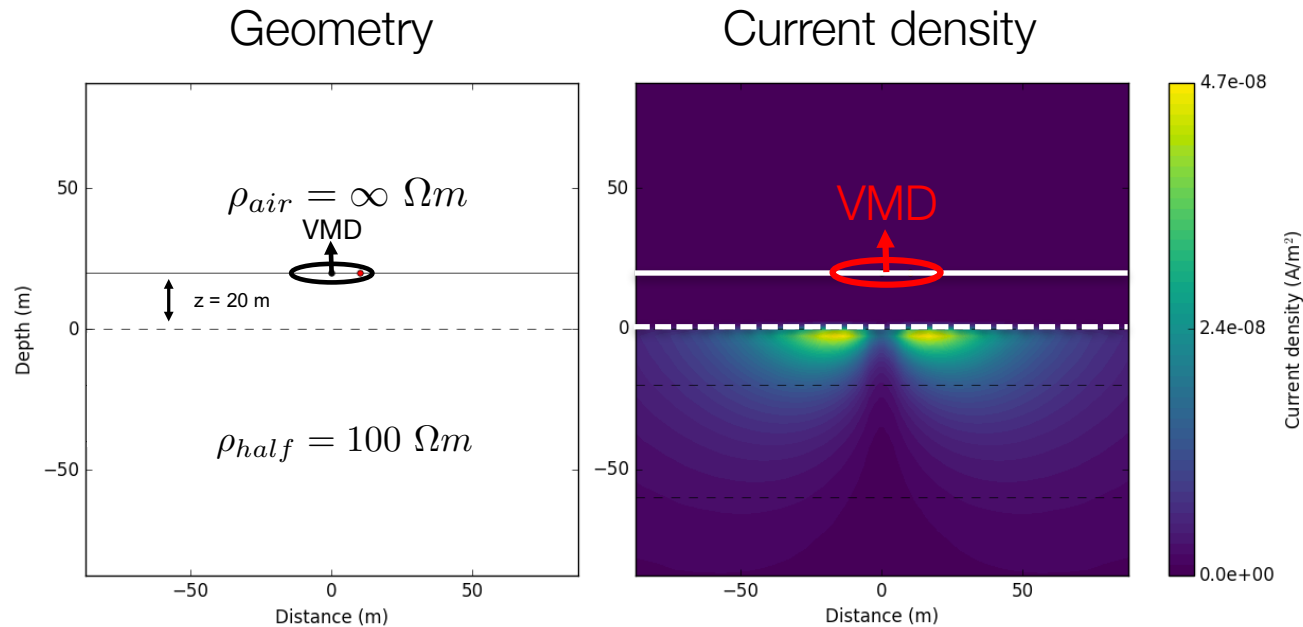
$\delta(t)$: Dirac-delta function

Footprint of Airborne EM system

- What volume of earth is “seen” by the airborne system?
 - Where are the currents?
- Currents depend on
 - Transmitter
 - Waveform: time or frequency
 - Background conductivity
- Simple case: loop source over homogeneous earth

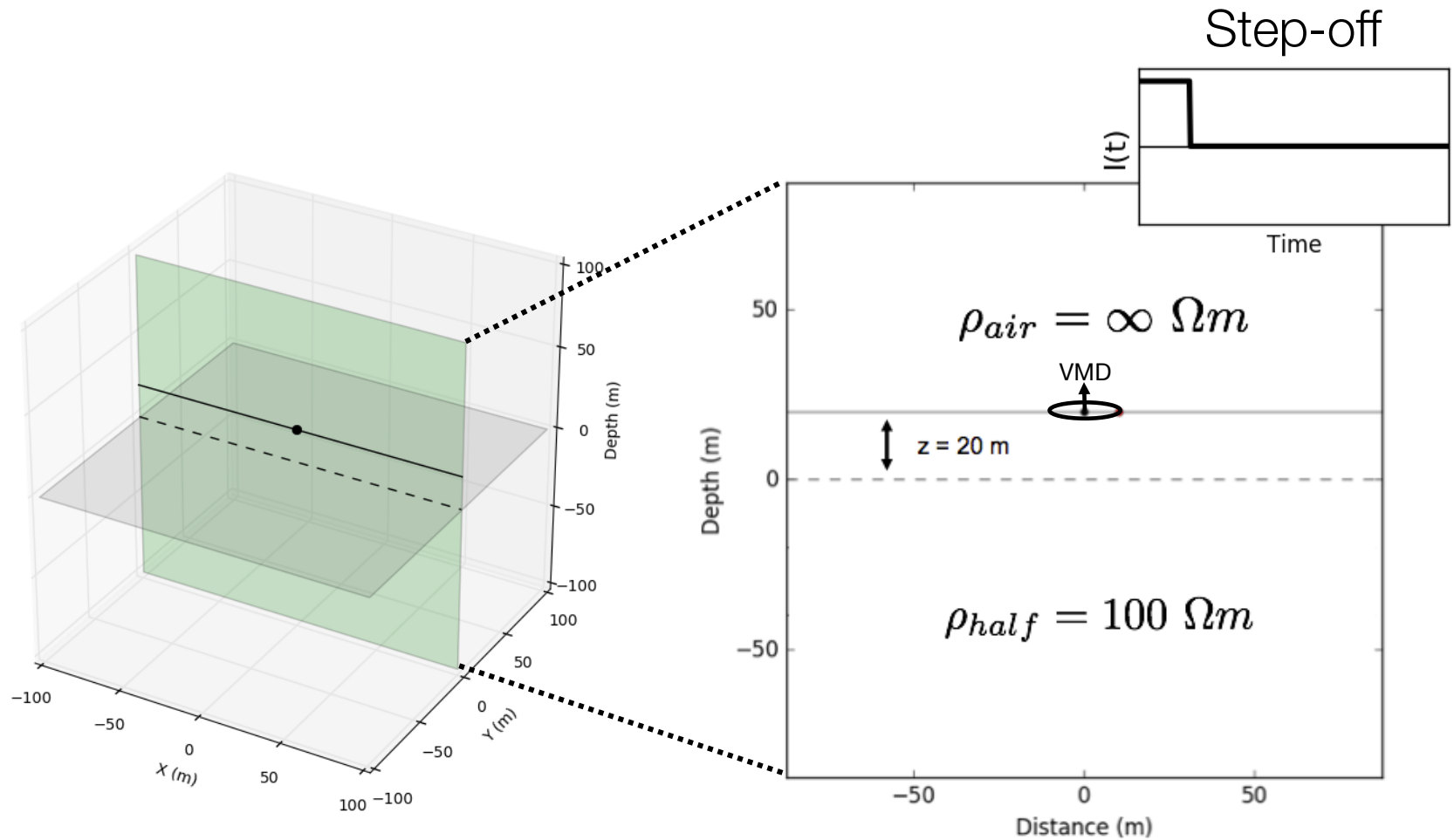


Vertical Magnetic Dipole (VMD)



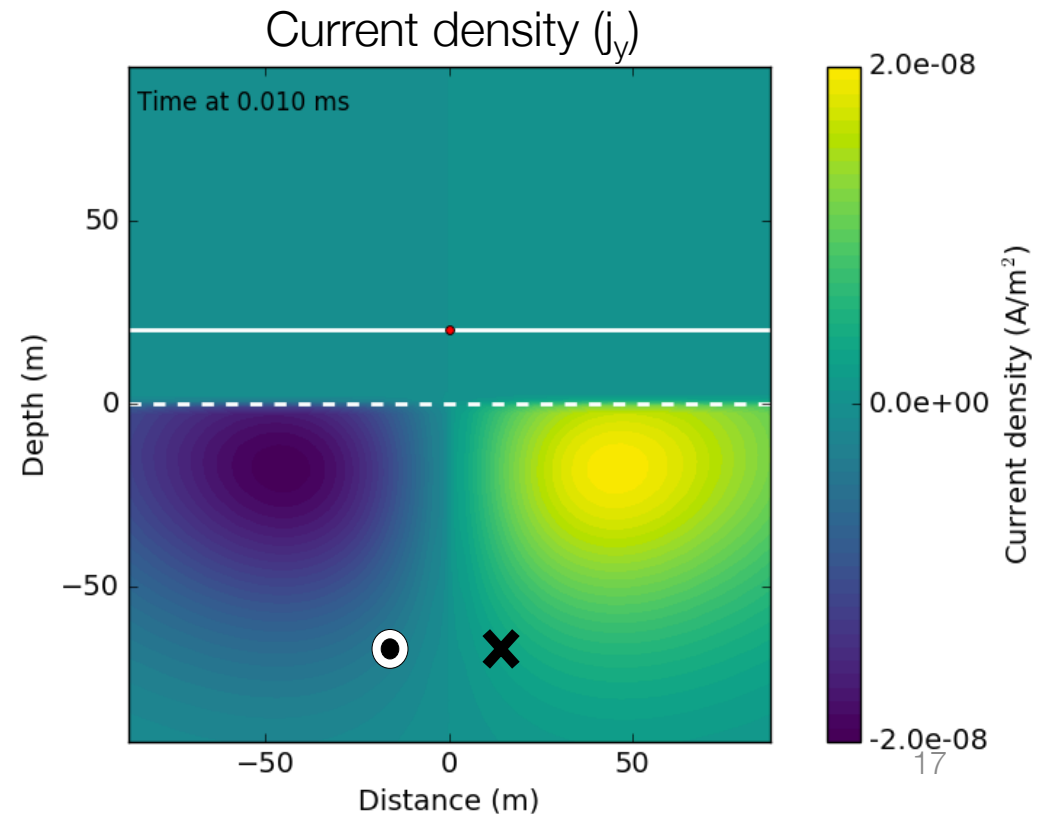
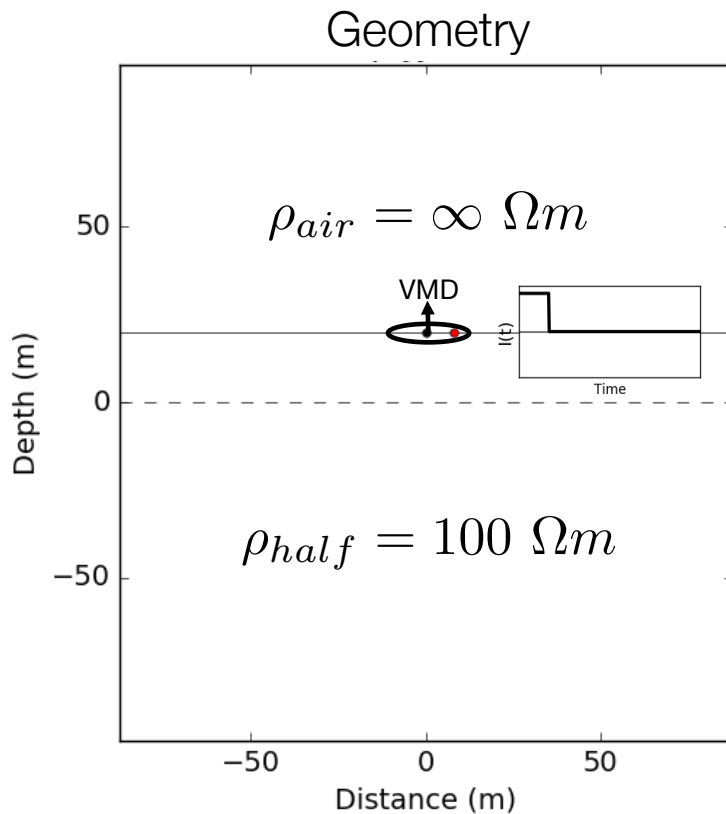
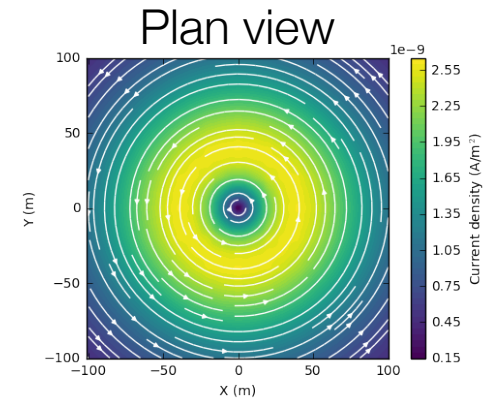
- Some questions
 - Where, and how strong, are the currents?
 - How do they depend upon the conductivity?
 - What do the resulting magnetic fields look like?

Vertical Magnetic Dipole over a halfspace (TDEM)



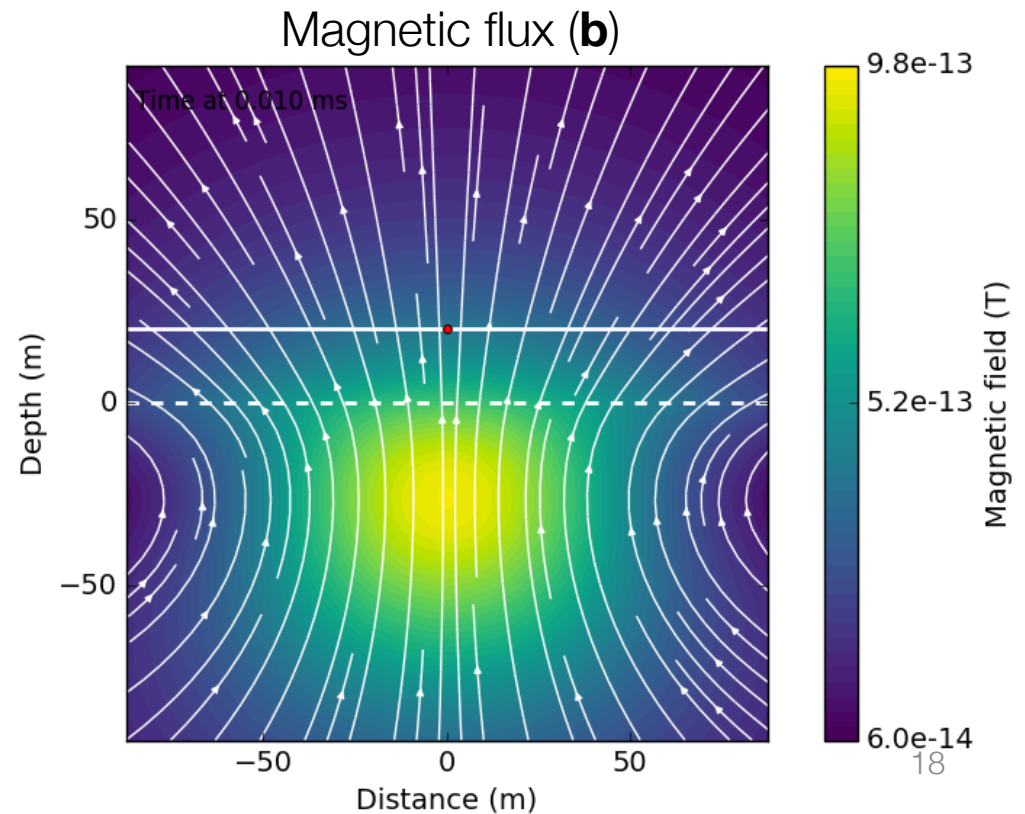
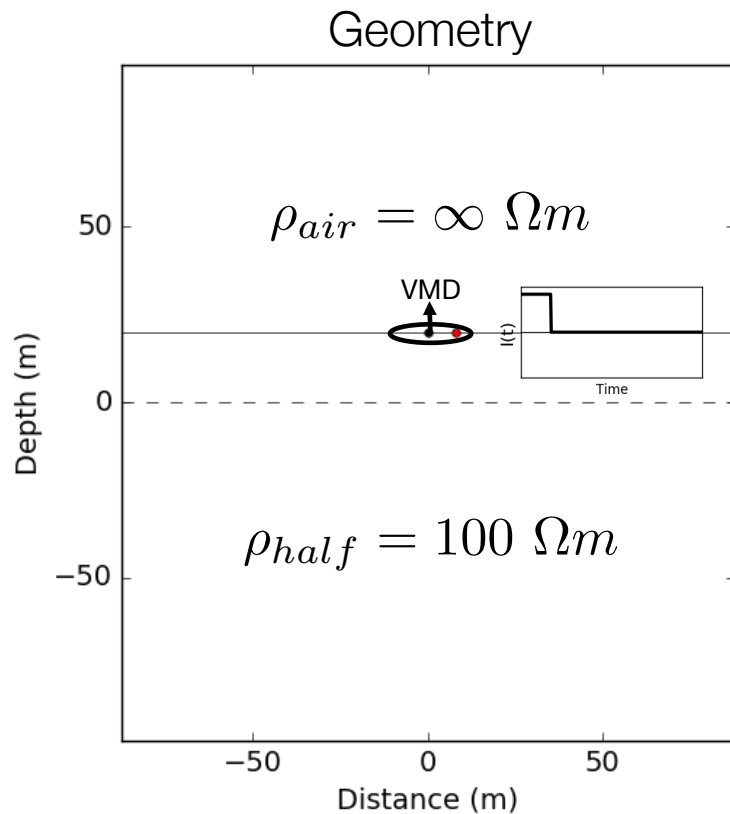
Current Density

- Time: 0.01ms



Magnetic flux density

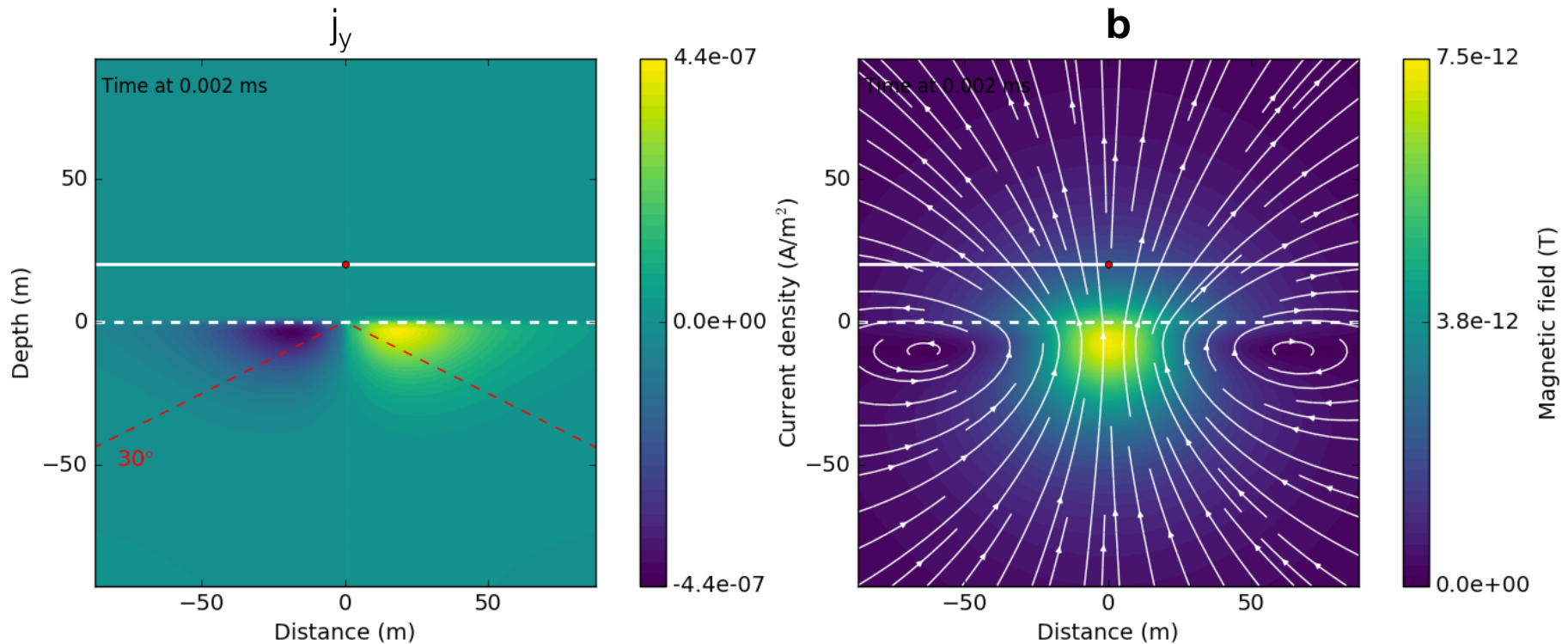
- Time: 0.01ms



Propagation through time

- Time: 0.002ms
- diffusion distance = 18 m

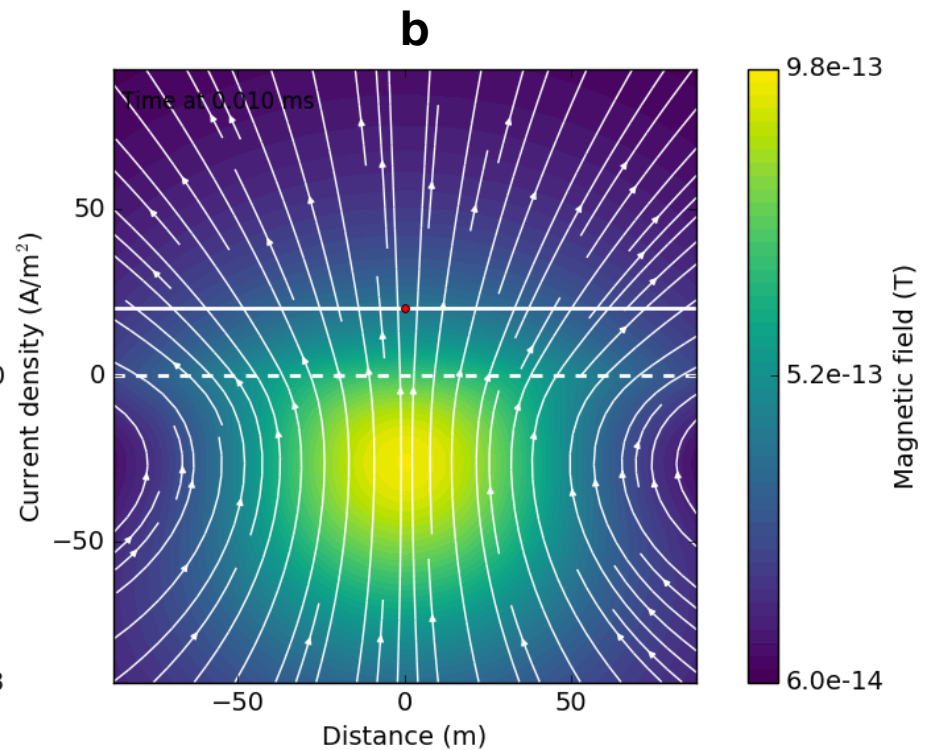
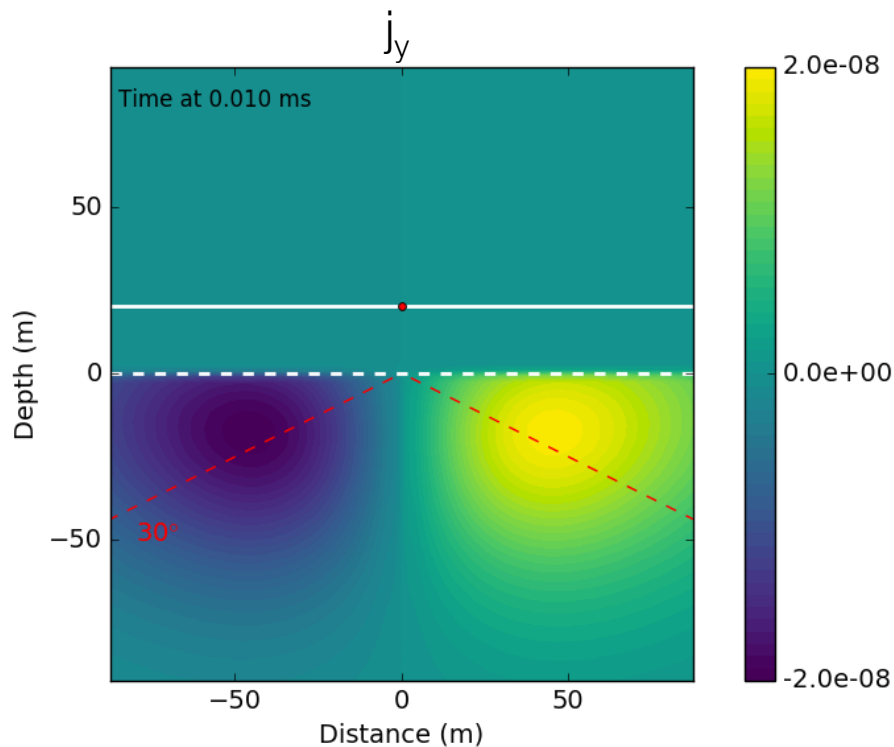
$$d = 1260\sqrt{t\rho}$$



Propagation through time

- Time: 0.01ms
- diffusion distance = 38 m

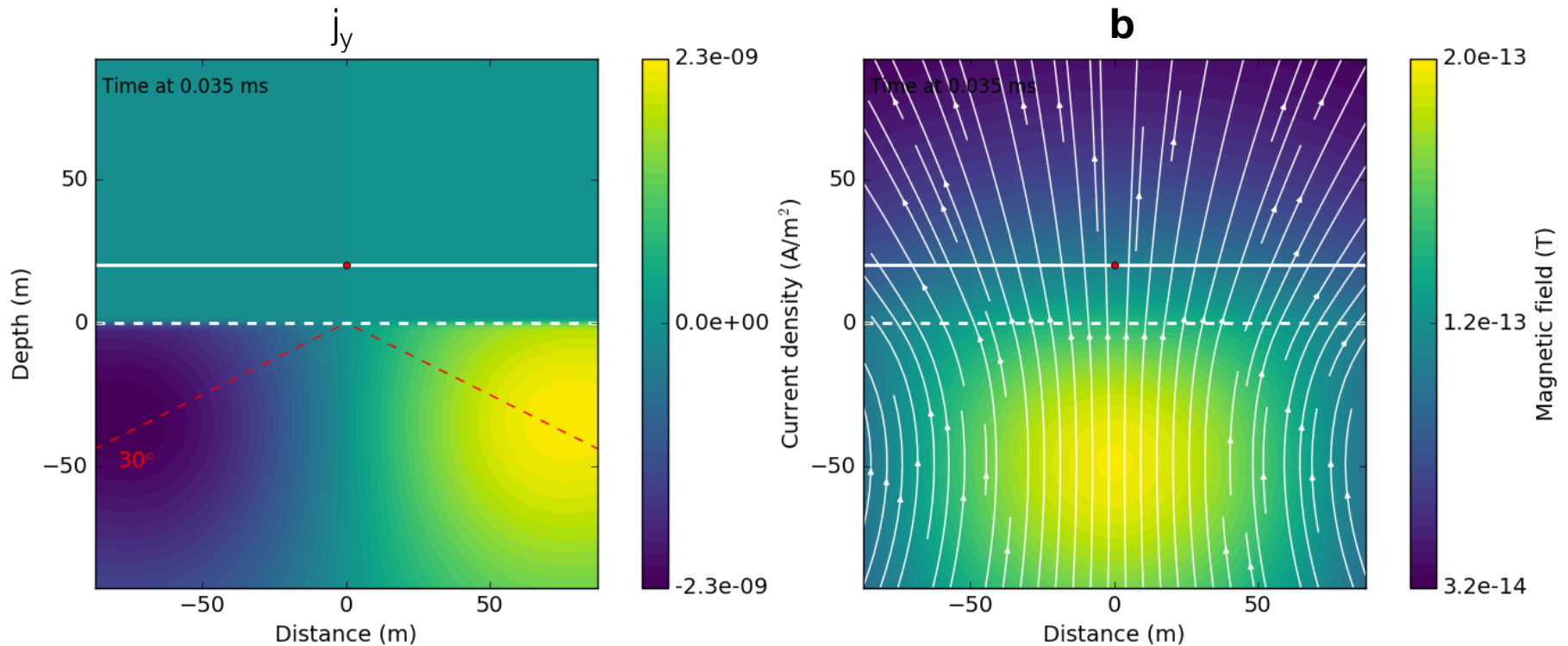
$$d = 1260\sqrt{t\rho}$$



Propagation through time

- Time: 0.035ms
- diffusion distance = 75 m

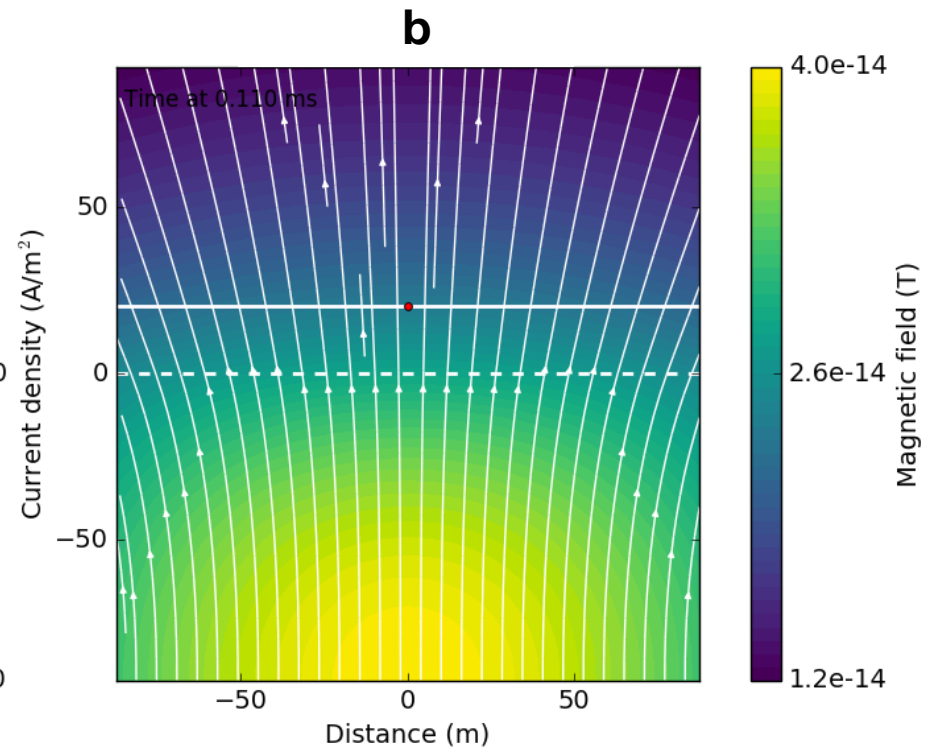
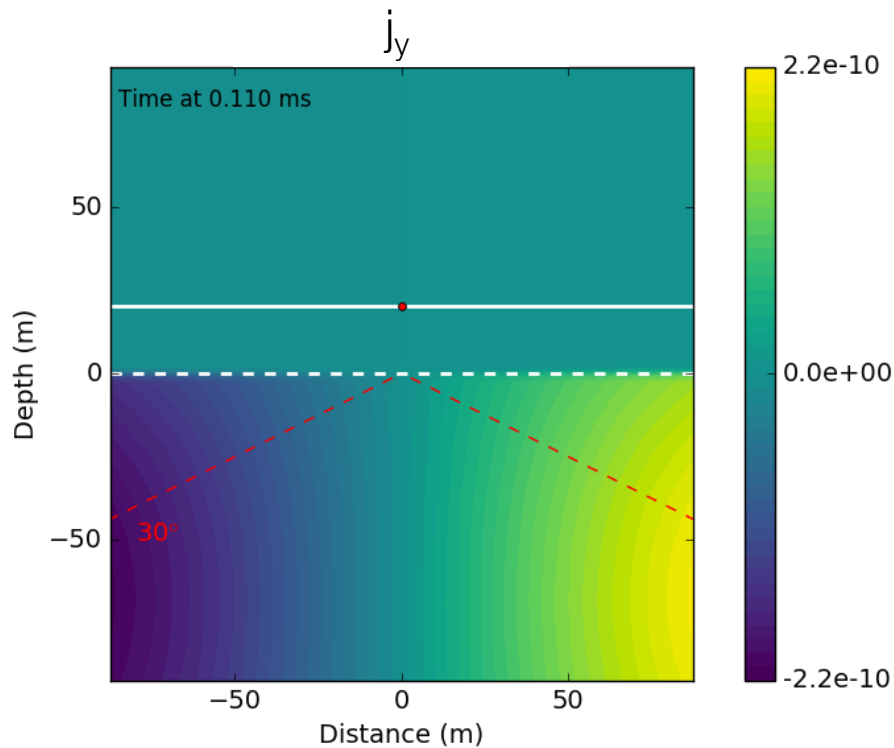
$$d = 1260\sqrt{t\rho}$$



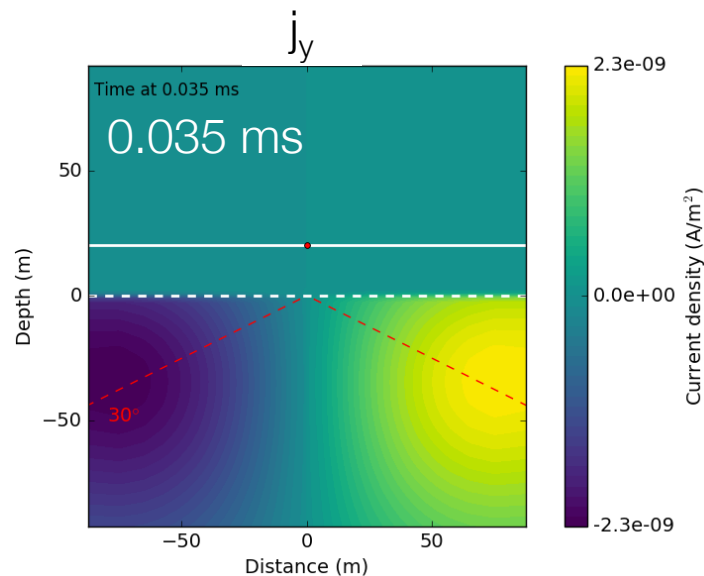
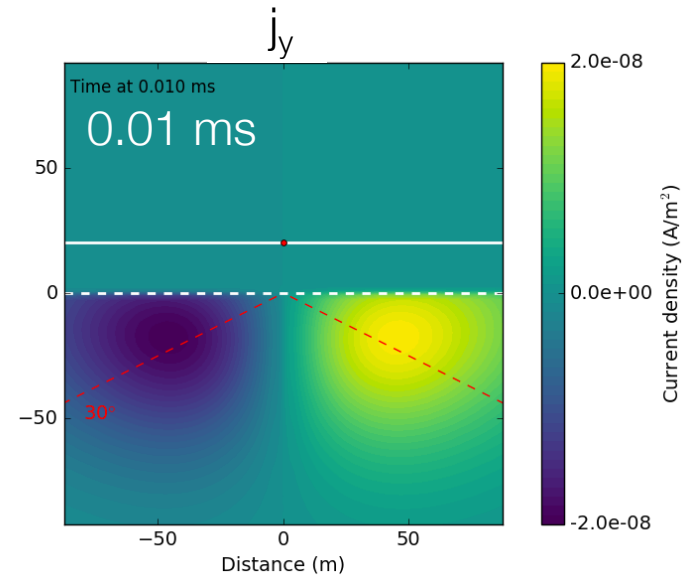
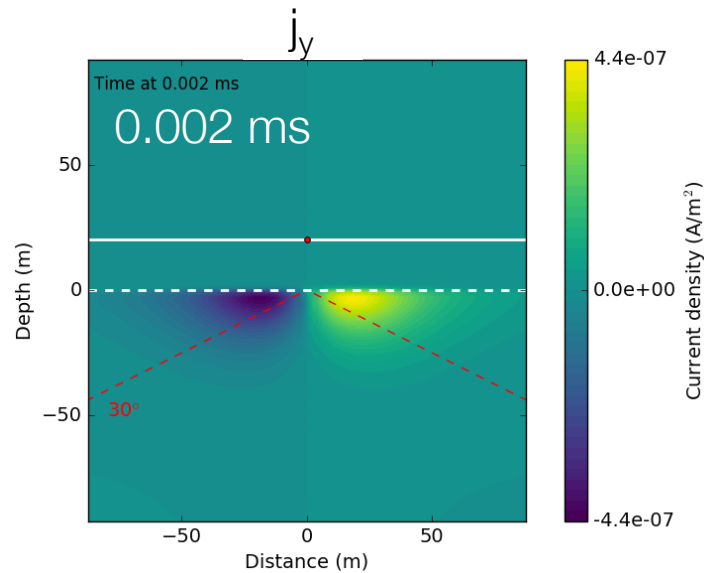
Propagation through time

- Time: 0.110ms
- diffusion distance = 132 m

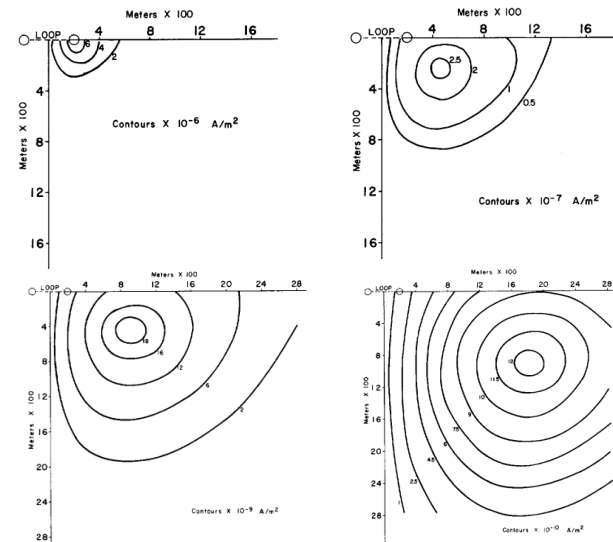
$$d = 1260\sqrt{t\rho}$$



Summary: propagation through time



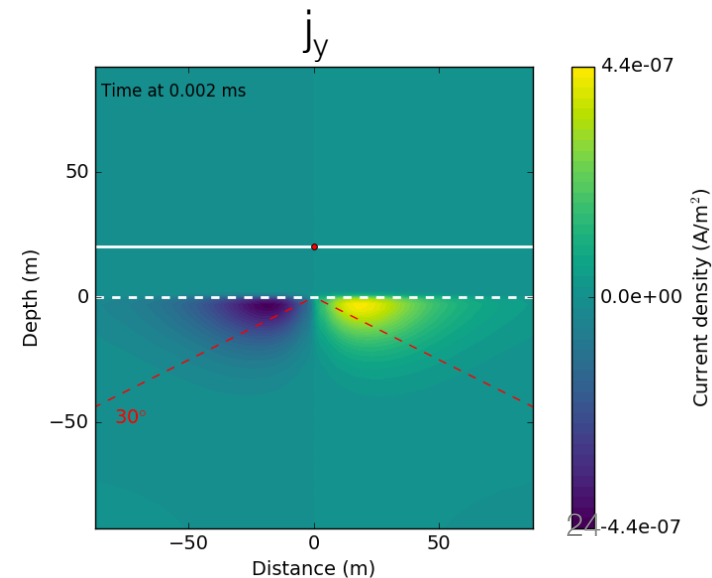
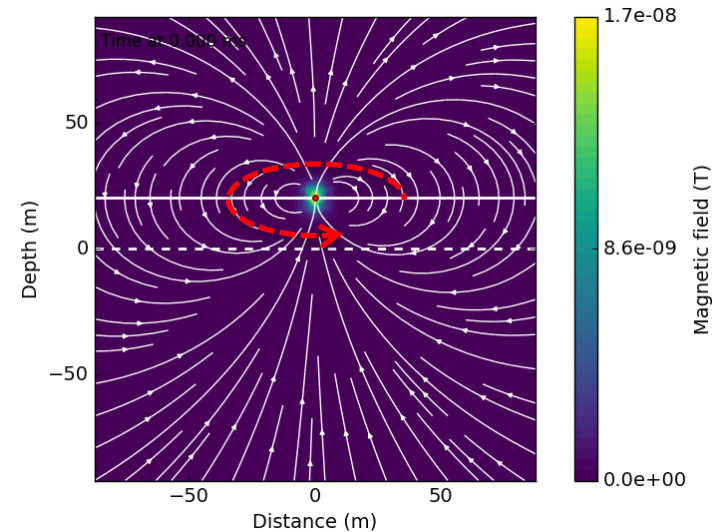
Nabighian (1979)



Important points

- Currents flow in same plane as transmitter currents
- Currents diffuse outward downward
- Each transmitter has a “footprint”
- Max resolution controlled by earliest time
- Depth of investigation controlled by latest time

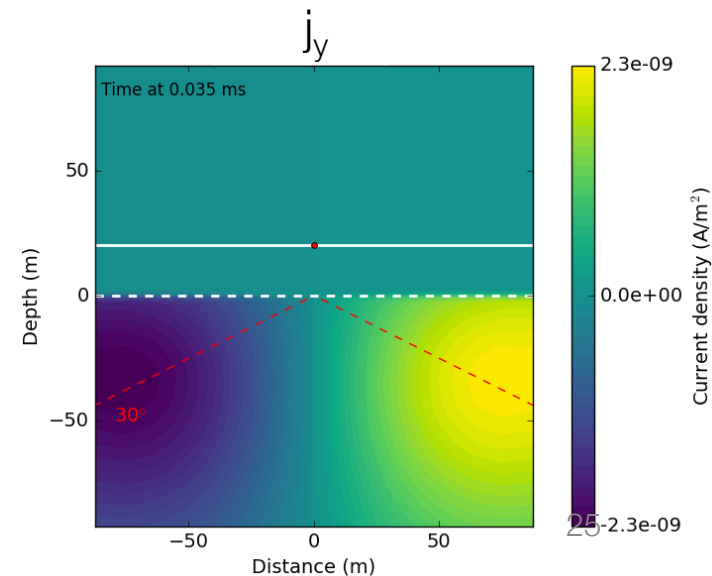
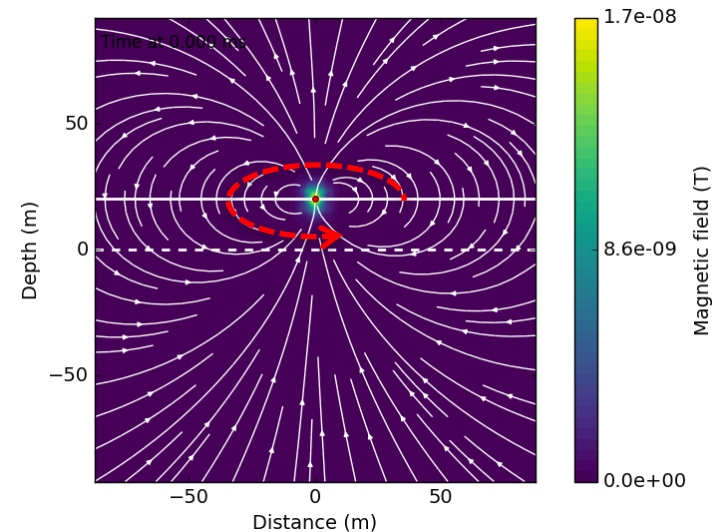
magnetic field (on-time)



Important points

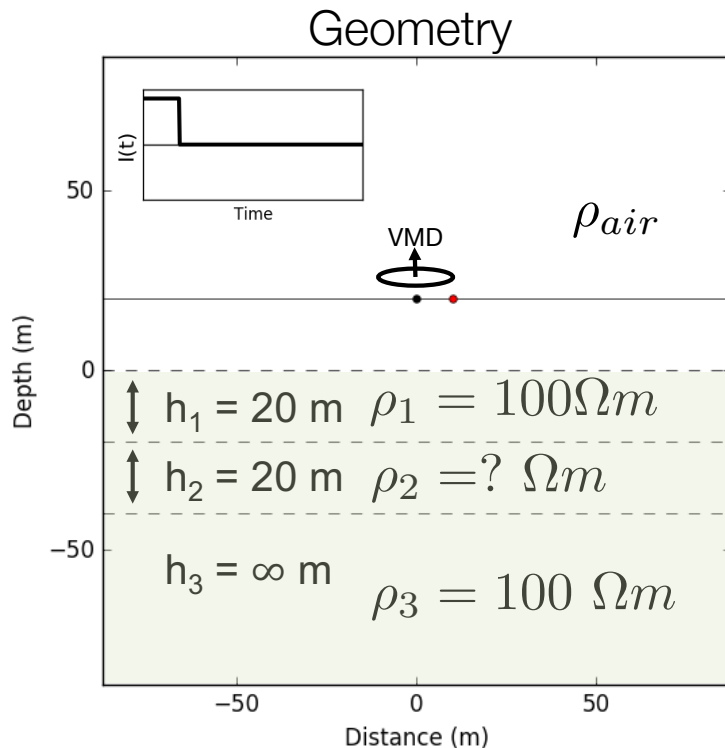
- Currents flow in same plane as transmitter currents
- Currents diffuse outward downward
- Each transmitter has a “footprint”
- Max resolution controlled by earliest time
- Depth of investigation controlled by latest time

magnetic field (on-time)



Layered earth

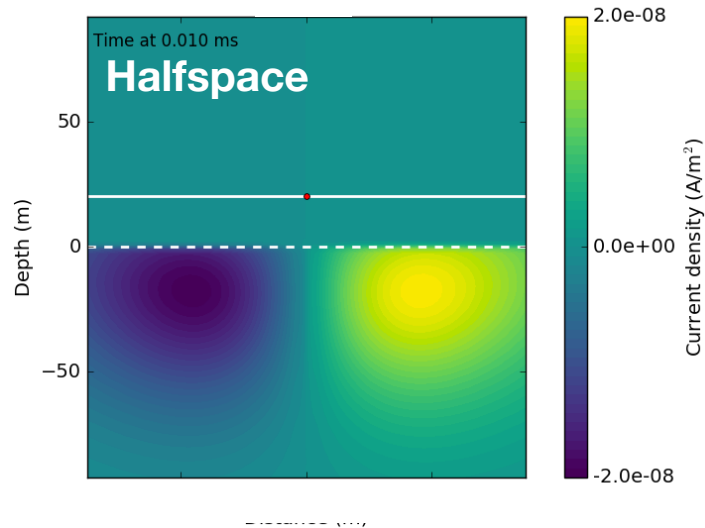
- 3 layers + air,
- ρ_2 varies



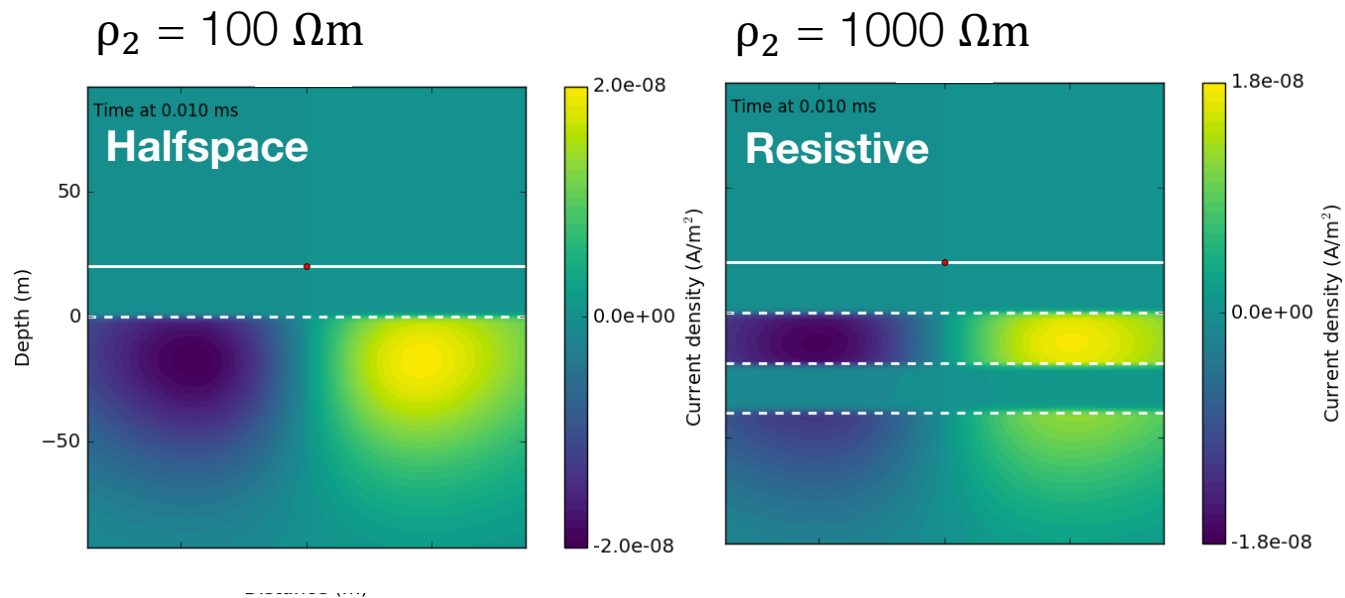
- Four different cases:
 - Halfspace
 - $\rho_2 = 100 \Omega m$
 - Resistive
 - $\rho_2 = 1000 \Omega m$
 - Conductive
 - $\rho_2 = 10 \Omega m$
 - Very conductive
 - $\rho_2 = 1 \Omega m$
- Fields
 - j_y off-time
 - **b** off-time

Layered earth currents (j_y)

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

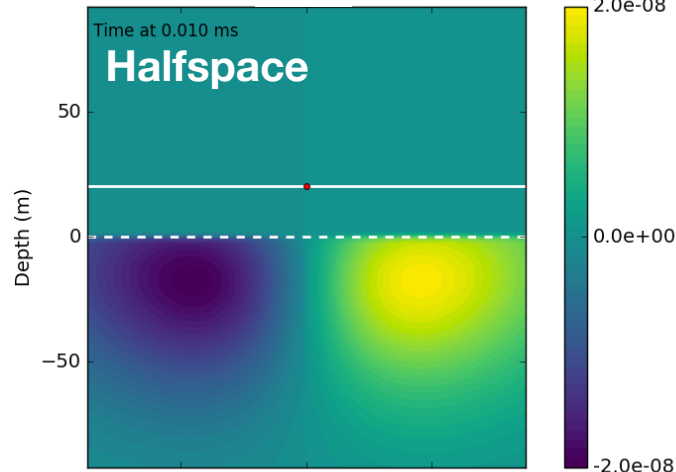


Layered earth currents (j_y)

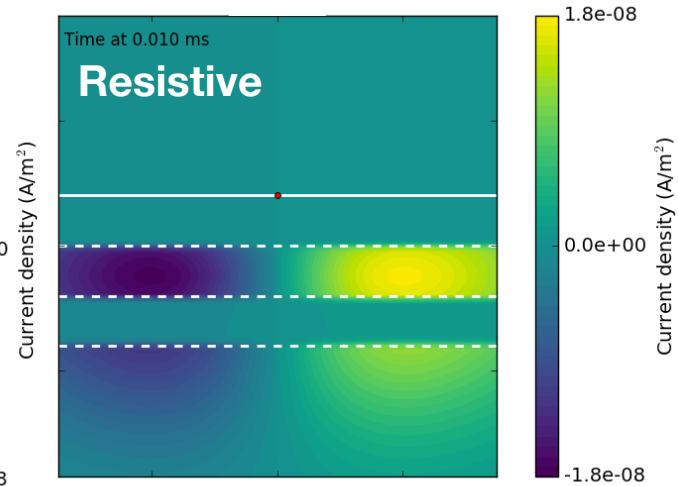


Layered earth currents (j_y)

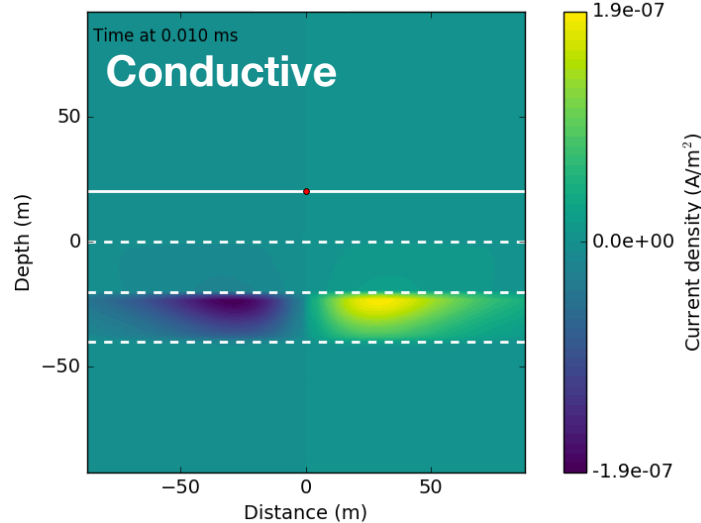
$\rho_2 = 100 \, \Omega\text{m}$



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

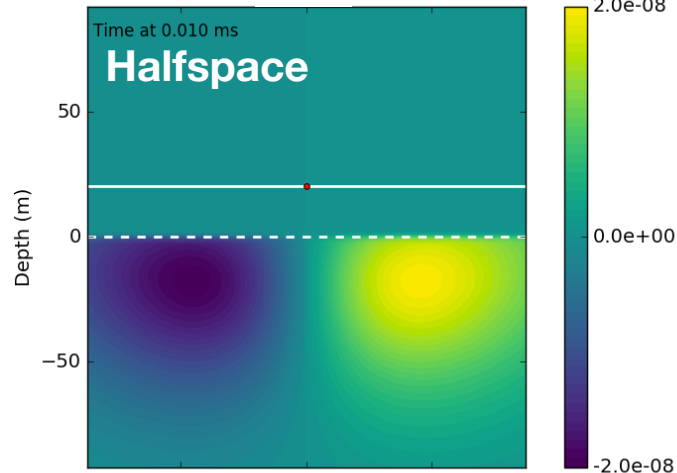


$\rho_2 = 10 \, \Omega\text{m}$

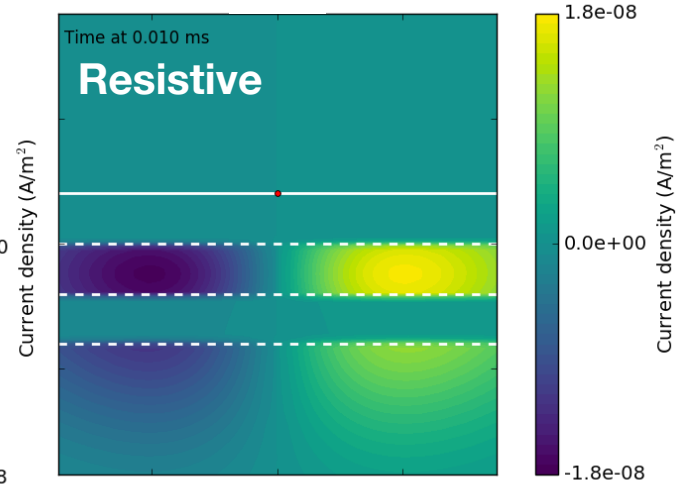


Layered earth currents (j_y)

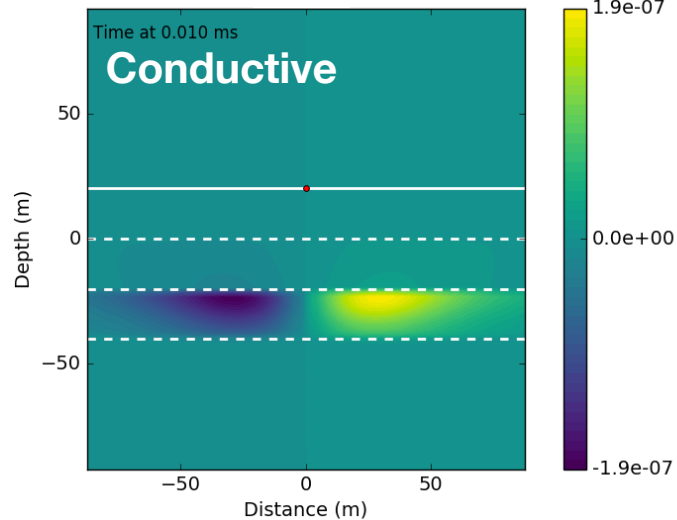
$\rho_2 = 100 \, \Omega\text{m}$



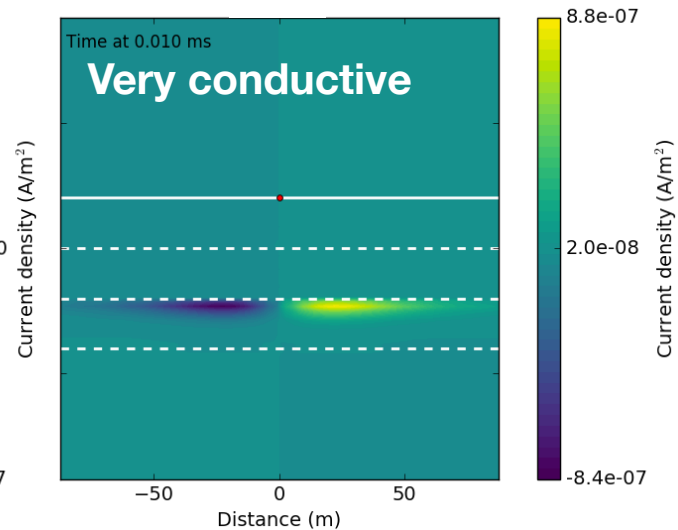
$\rho_2 = 1000 \, \Omega\text{m}$



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

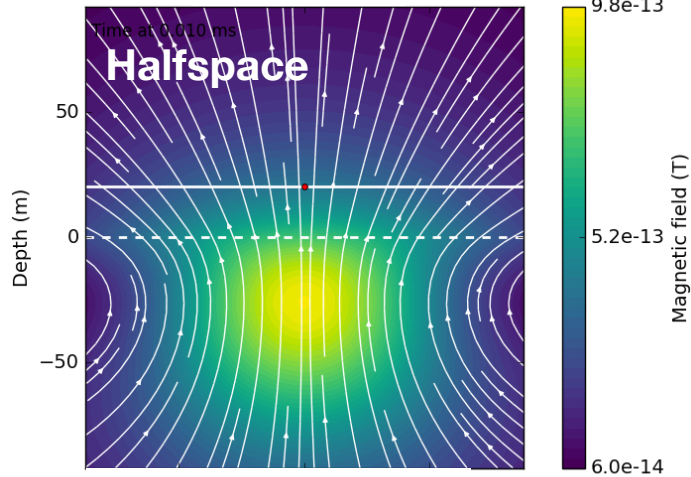


$\rho_2 = 1 \, \Omega\text{m}$

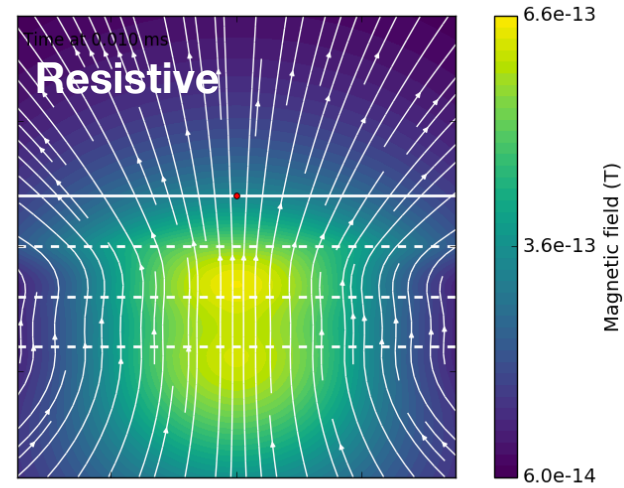


Layered earth mag. fields (**b**)

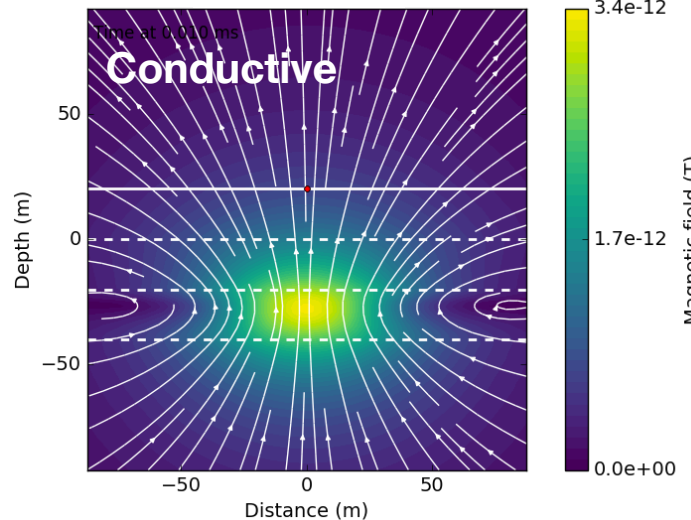
$\rho_2 = 100 \Omega\text{m}$



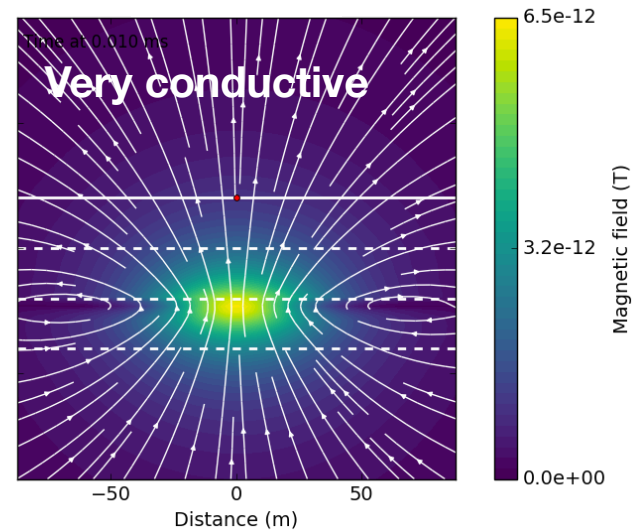
$\rho_2 = 1000 \Omega\text{m}$



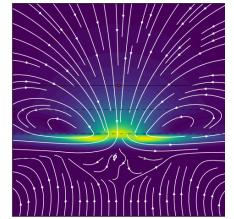
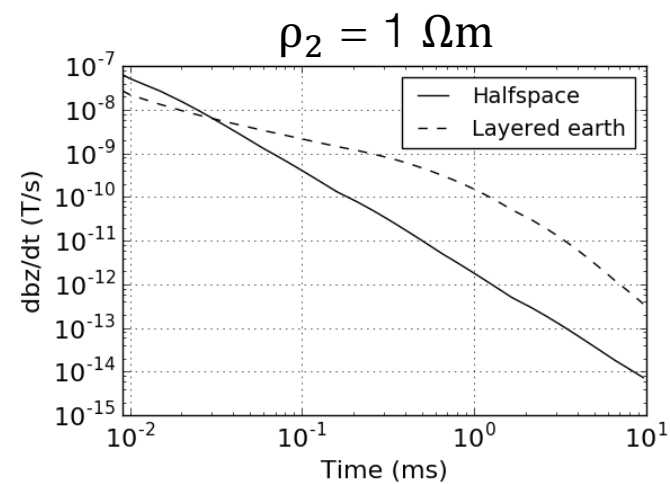
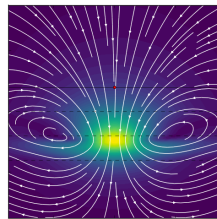
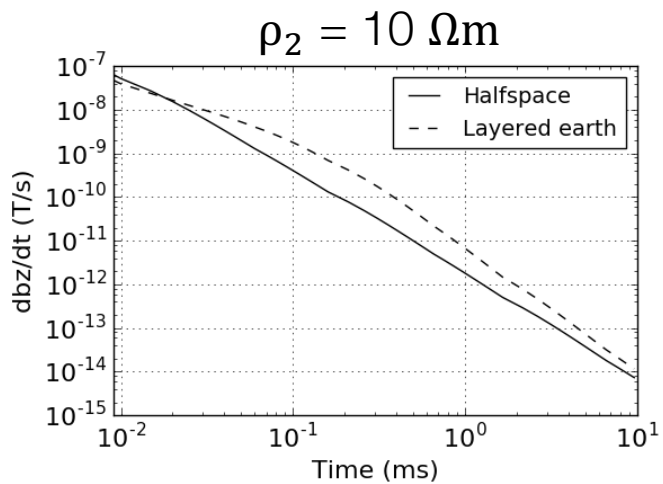
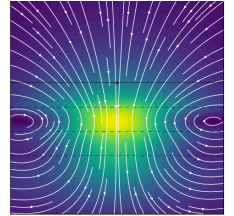
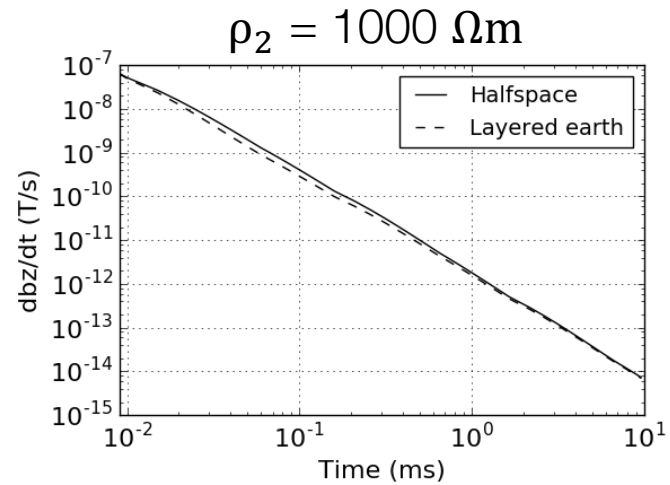
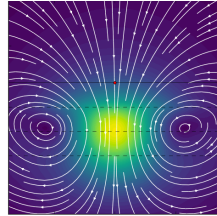
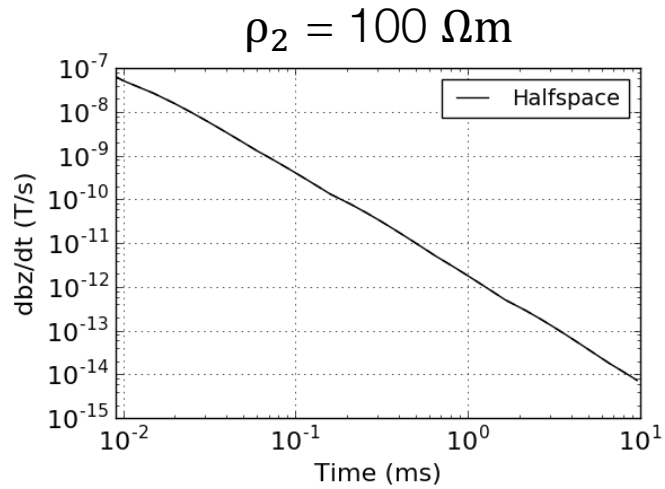
$\rho_2 = 10 \Omega\text{m}$



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

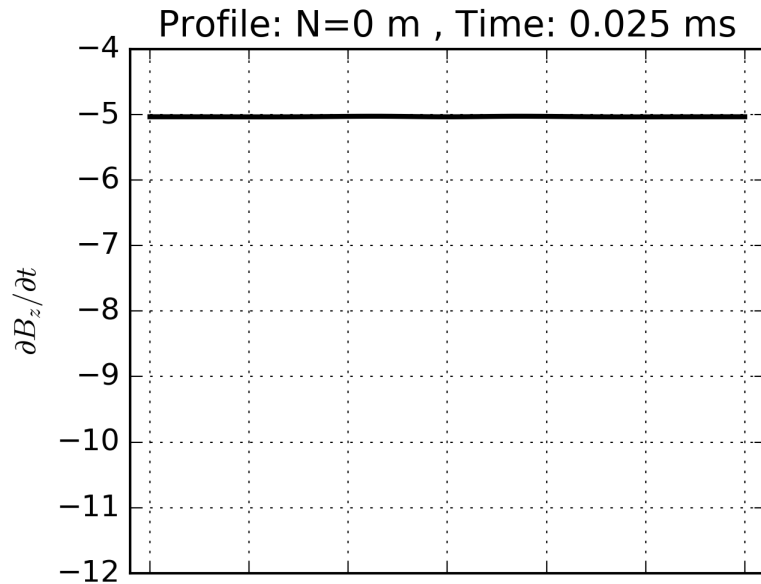


db_z/dt sounding curves

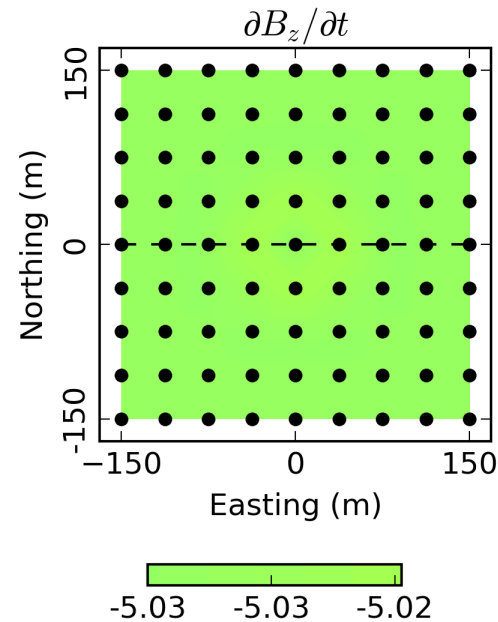


Airborne example: conductive sphere

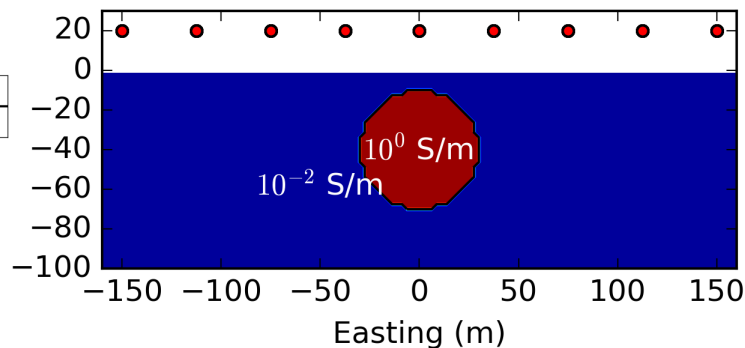
Data profile



Data map



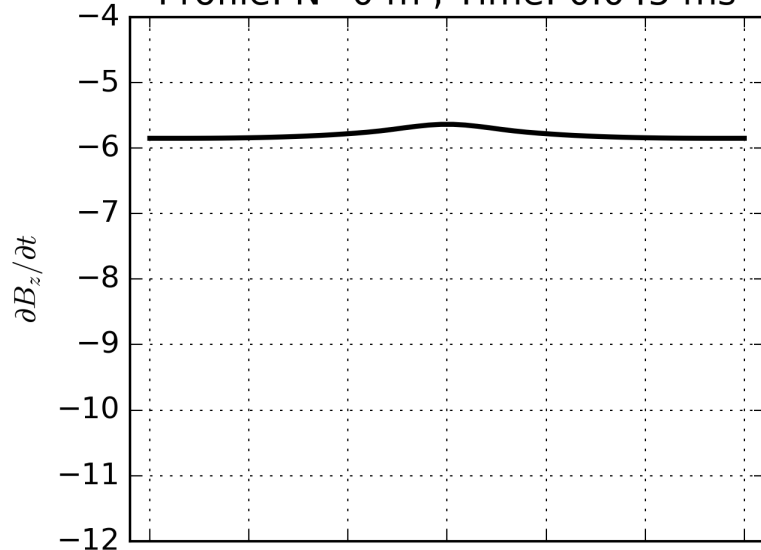
Conductivity



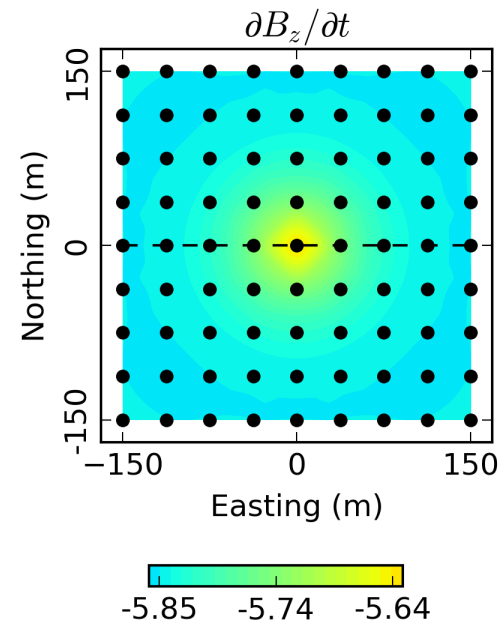
Airborne example: conductive sphere

Data profile

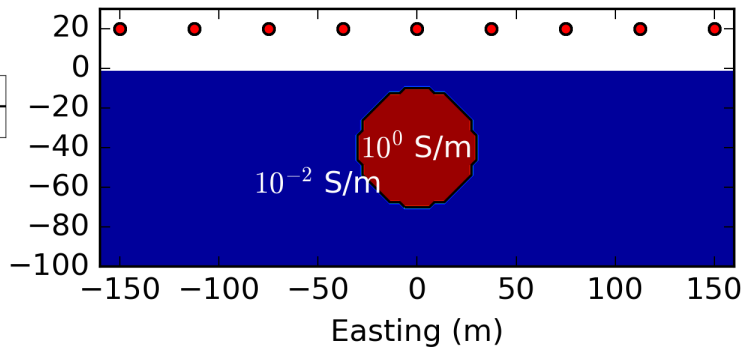
Profile: N=0 m , Time: 0.045 ms



Data map



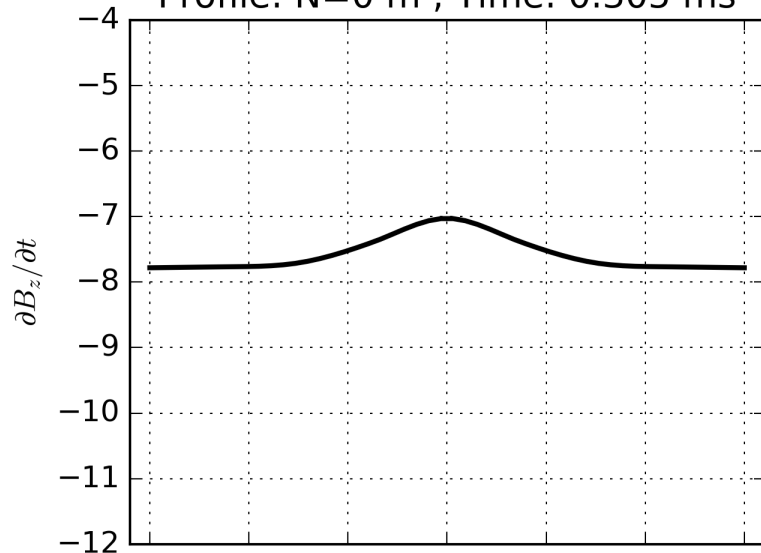
Conductivity



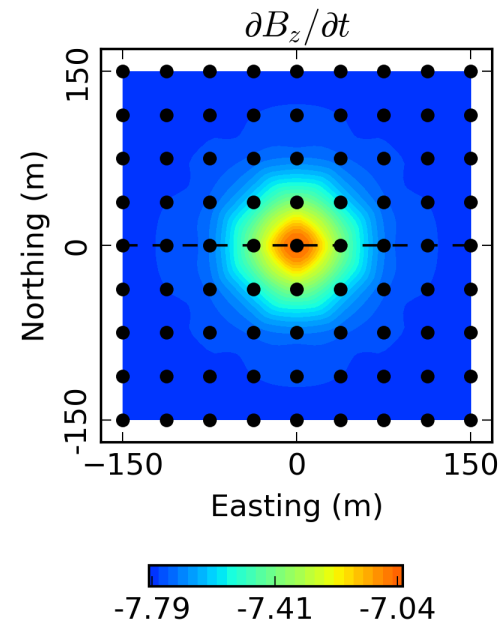
Airborne example: conductive sphere

Data profile

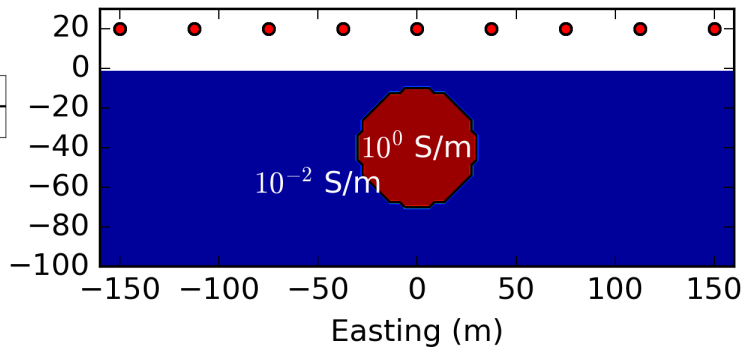
Profile: N=0 m , Time: 0.305 ms



Data map



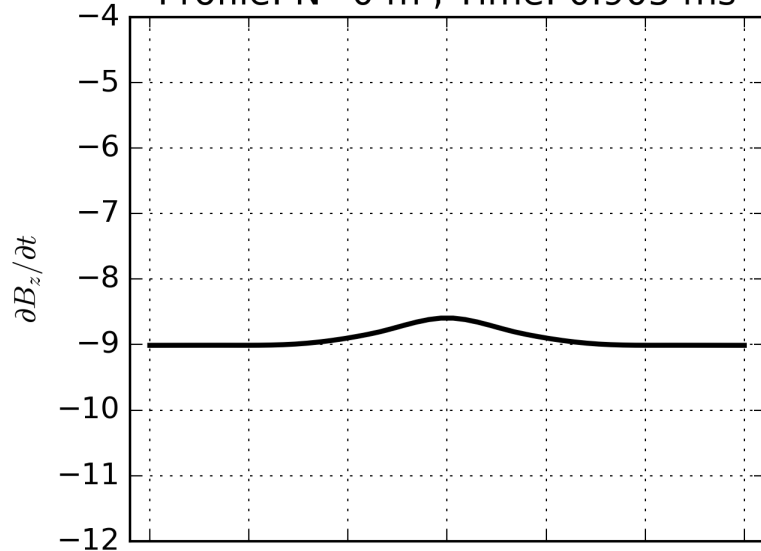
Conductivity



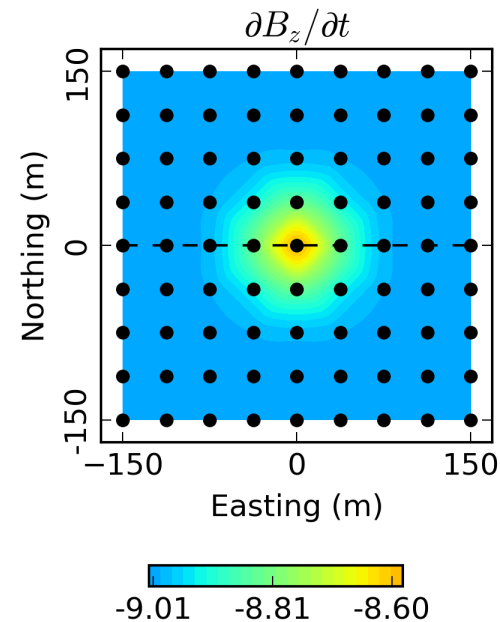
Airborne example: conductive sphere

Data profile

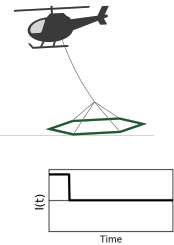
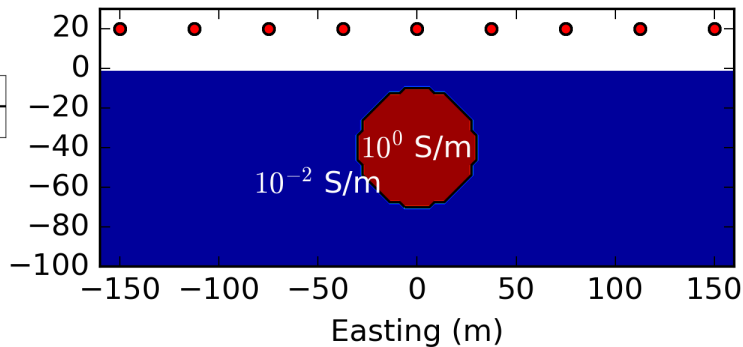
Profile: N=0 m , Time: 0.905 ms



Data map



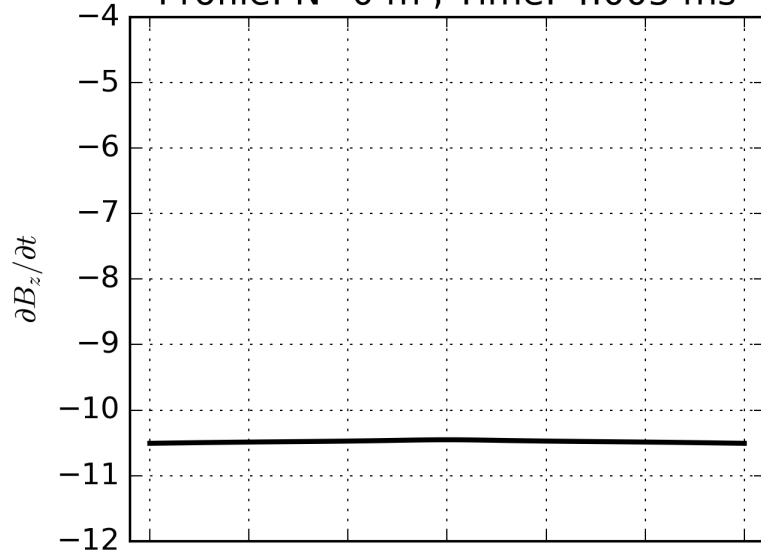
Conductivity



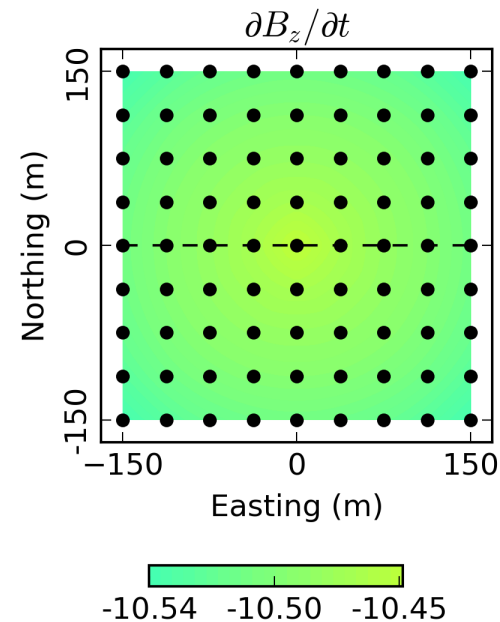
Airborne example: conductive sphere

Data profile

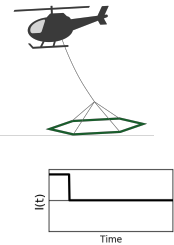
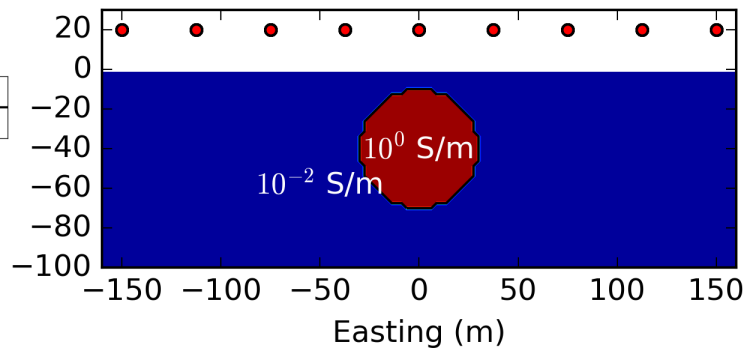
Profile: N=0 m , Time: 4.005 ms



Data map

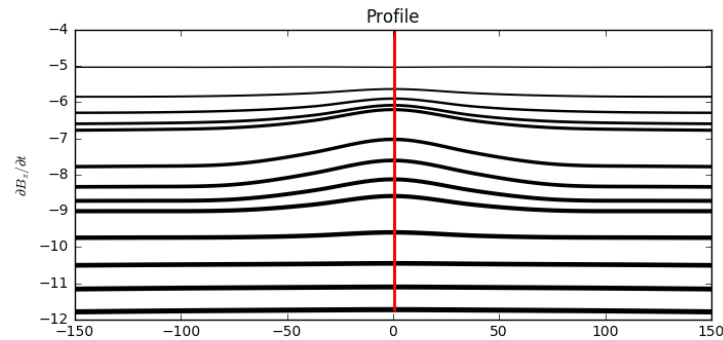


Conductivity

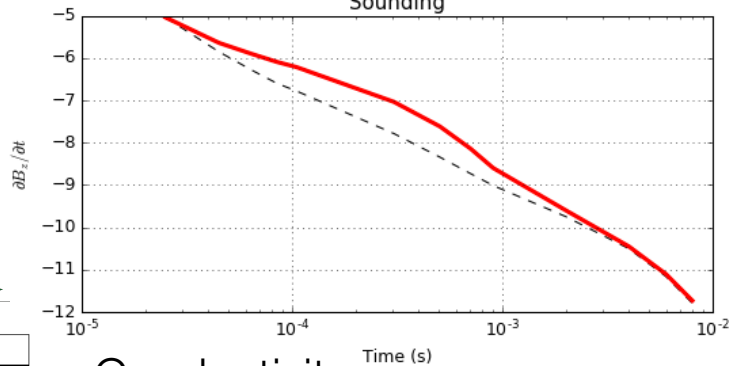


Summary: airborne example

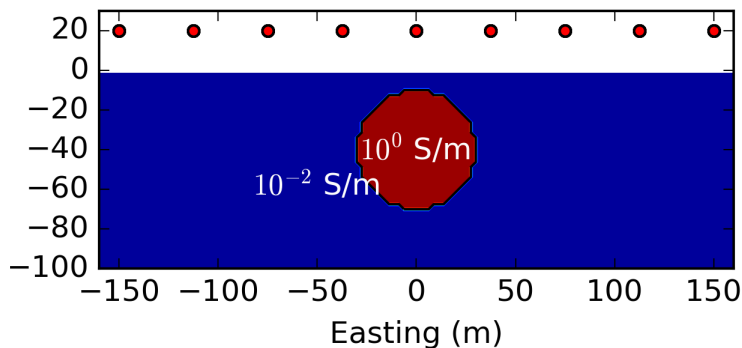
Data profile



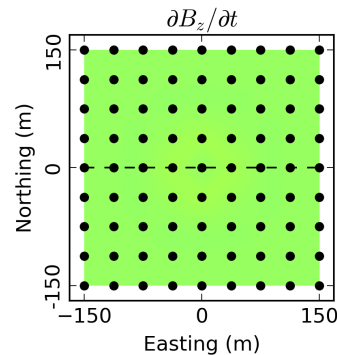
Sounding



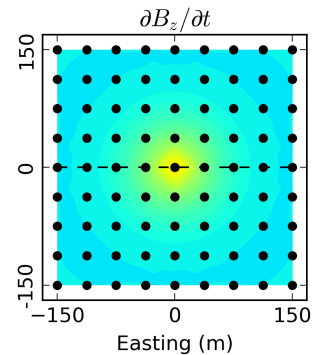
Conductivity



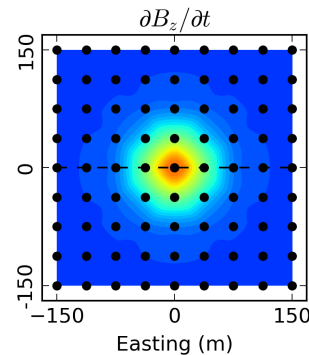
0.025 ms



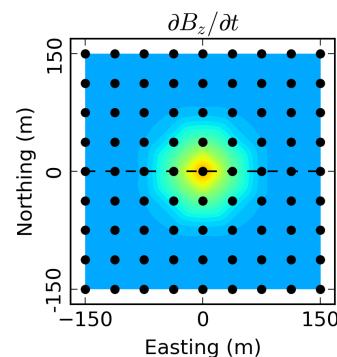
0.045 ms



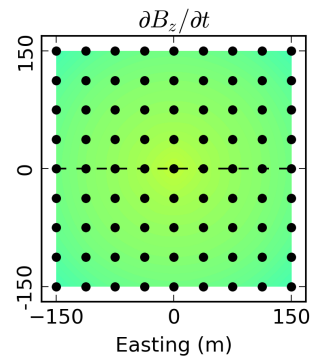
0.305 ms



0.905 ms

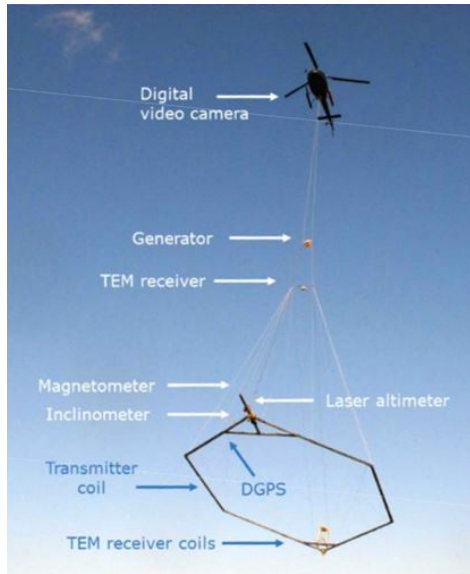


4.005 ms



Some Airborne TDEM Systems

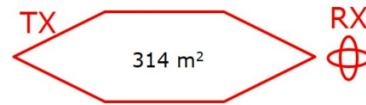
SkyTEM (2006)



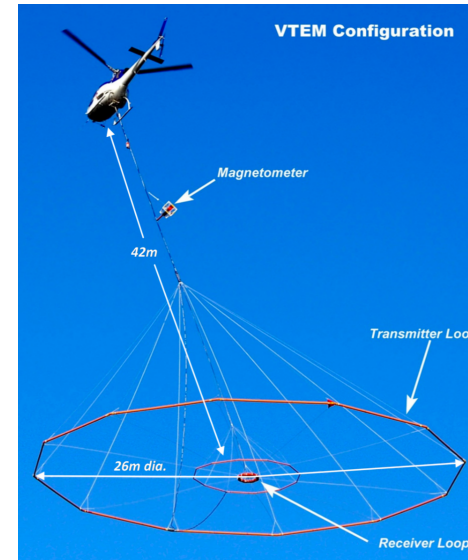
Area = 314 m²

Peak dipole moment:

- HM: 113040 NIA
- LM: 12560 NIA



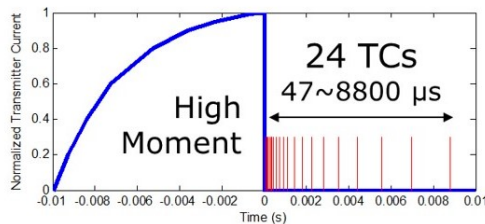
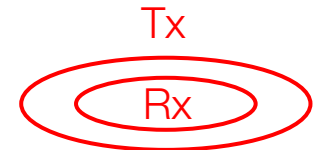
VTEM (2007)



Area = 535 m²

Peak dipole moment:

- 503,100 NIA

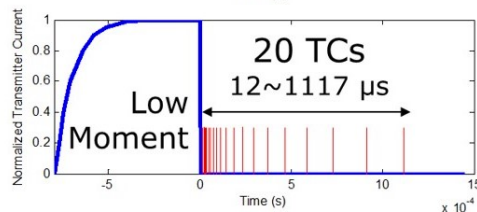


Peak current: 90 A

Turns: 4

On-time: 10 ms

Off-time: 10 ms

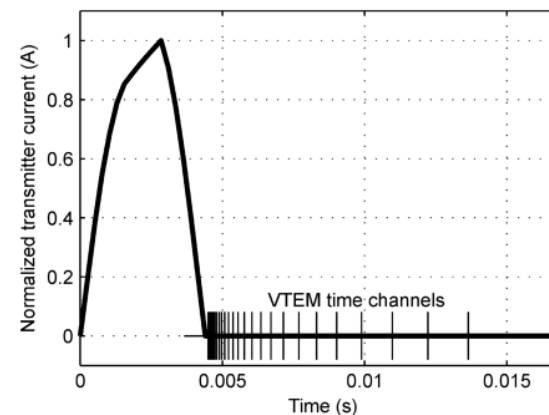


Peak current: 40 A

Turns: 1

On-time: 0.8 ms

Off-time: 1.45 ms



Peak current: 235 A

Turns: 4

On-time: 4.5 ms

Off-time: 9.1 ms

Outline

Setup

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Effects of Background Conductivity
- Transmitters and receivers
- Decay Curves
- Case History: Groundwater, Hydrocarbons

Frequency Domain EM

Questions

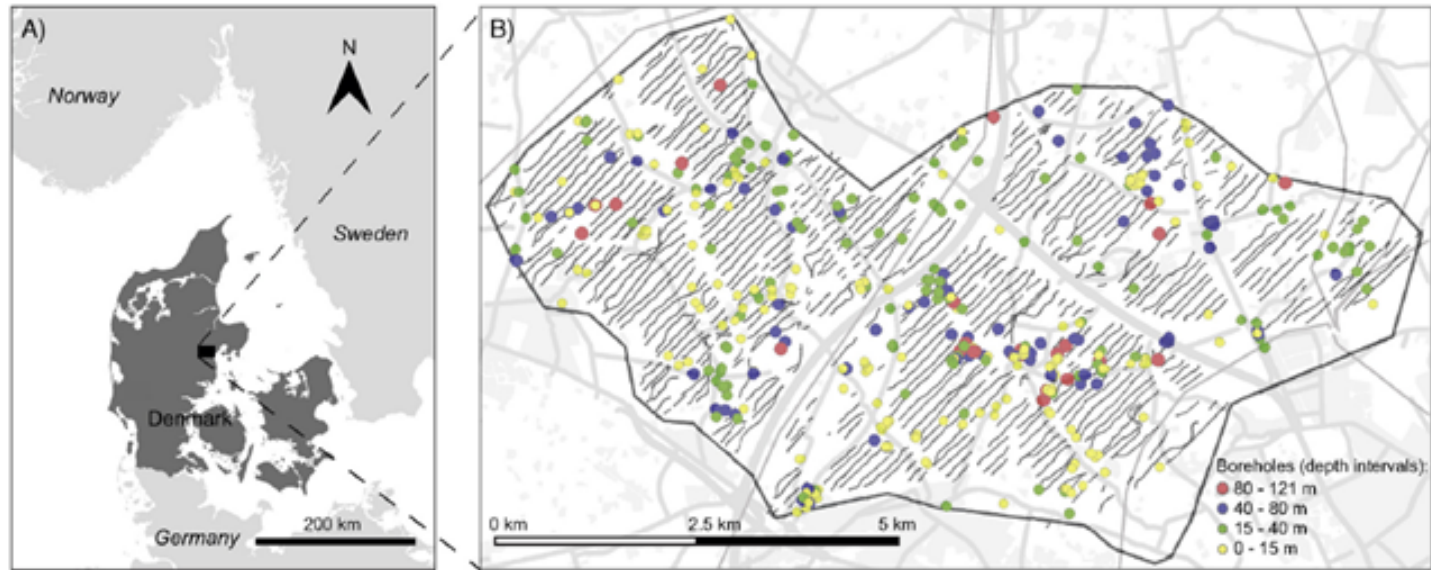
Case History: Kasted

Vilhelmsen et al. (2016)

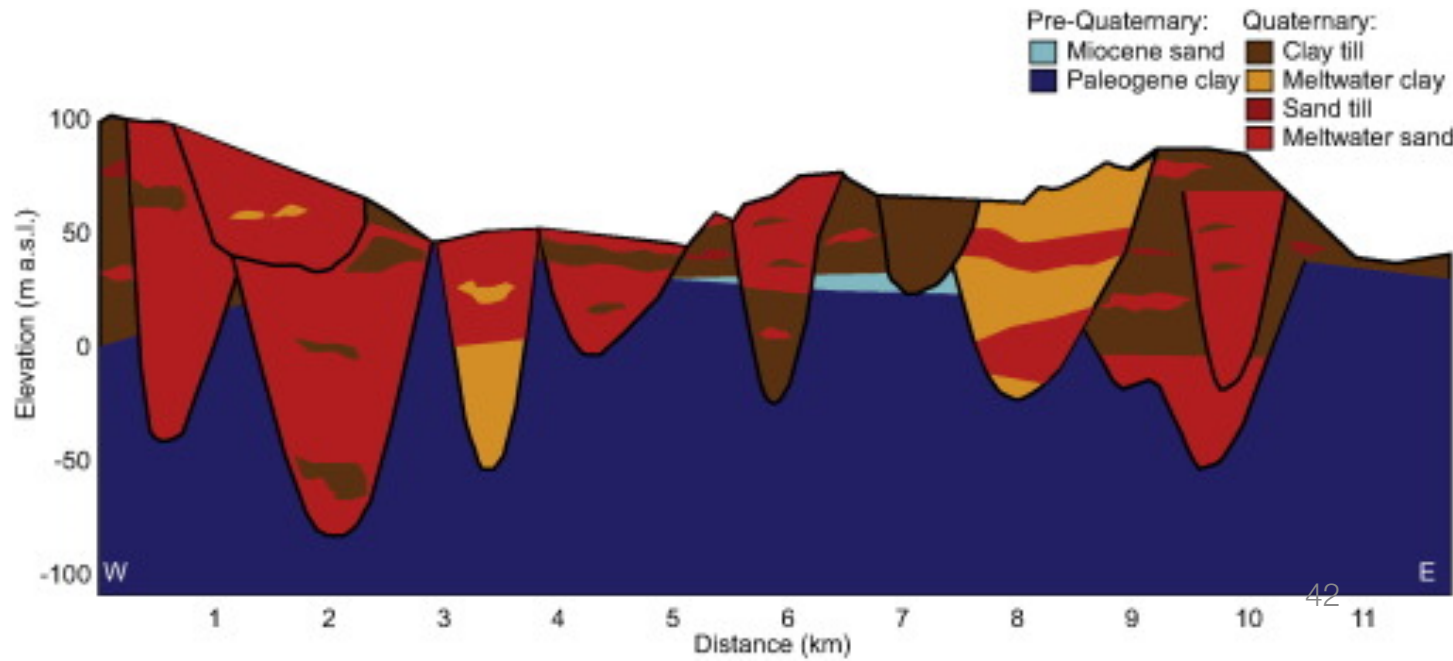
Setup

A) Survey Area:
Kasted,
Demark

B) Borehole
locations

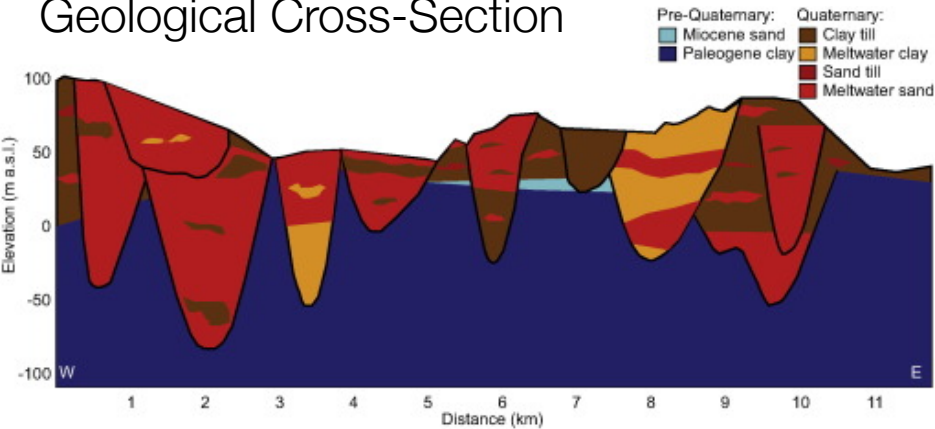


Local Geology:
W-E cross-section



Properties

Geological Cross-Section

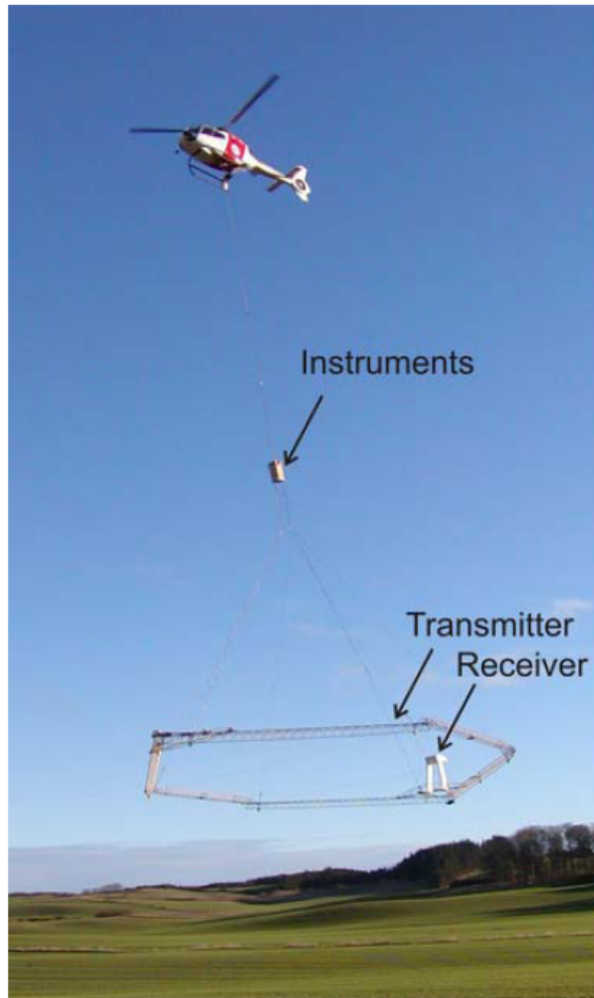


- Buried valleys with clays beneath
- Infill (water-bearing): coarse sand and gravel
- Clays are conductive (1-40 Ωm)
- Water-bearing sands and gravels are more resistive (>40 Ωm)

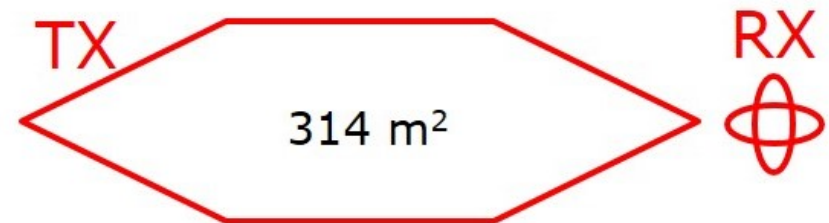
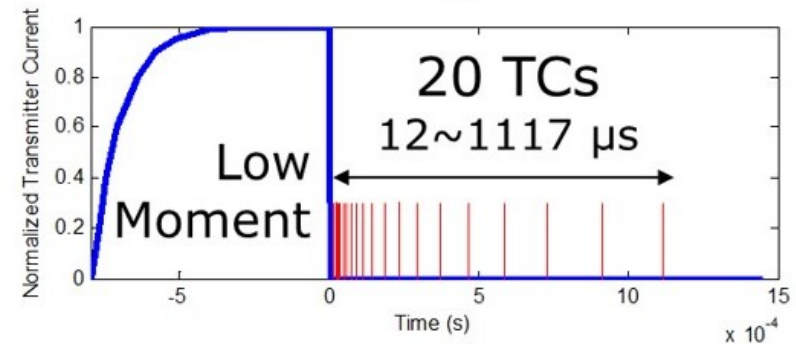
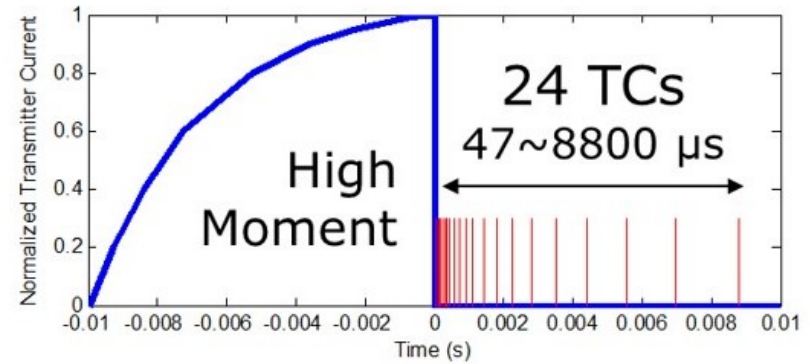
Geological Units	Resistivity (Ωm)
Palaeogene Clay	1-10
Clay Till	25-60
Sand Till	>50
Meltwater Sand and Gravel	>60
Glaciolacustrine Clay	10-40
Miocene Silt and Sand	>40
Miocene Clay	10-40
Sand	>40
Clay	1-60

Survey

SkyTEM System



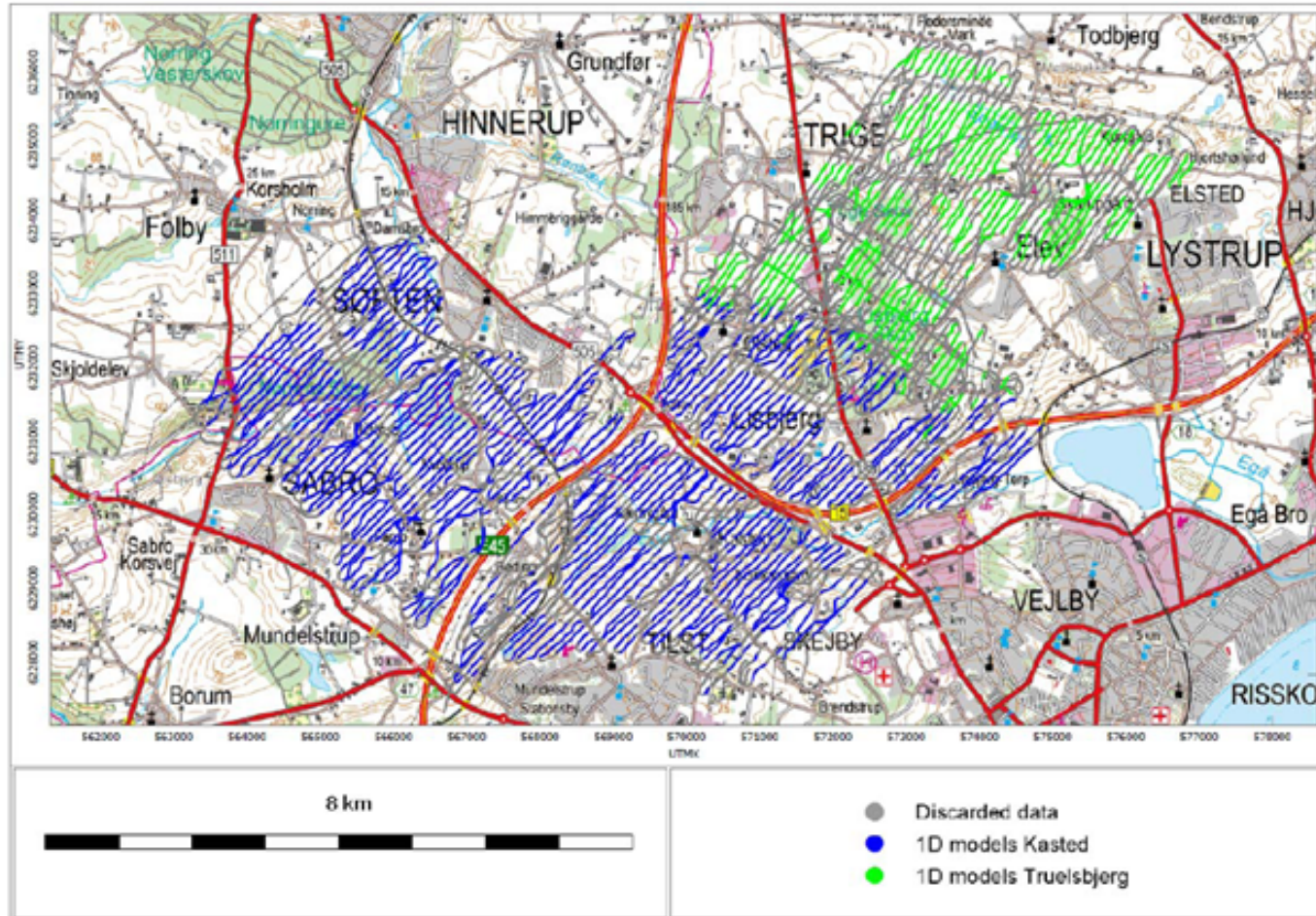
System Configuration



- Low moment (LM) used to image near surface structures
- High moment (HM) used to image deeper structures

Data

Blue: data used for Kasted study

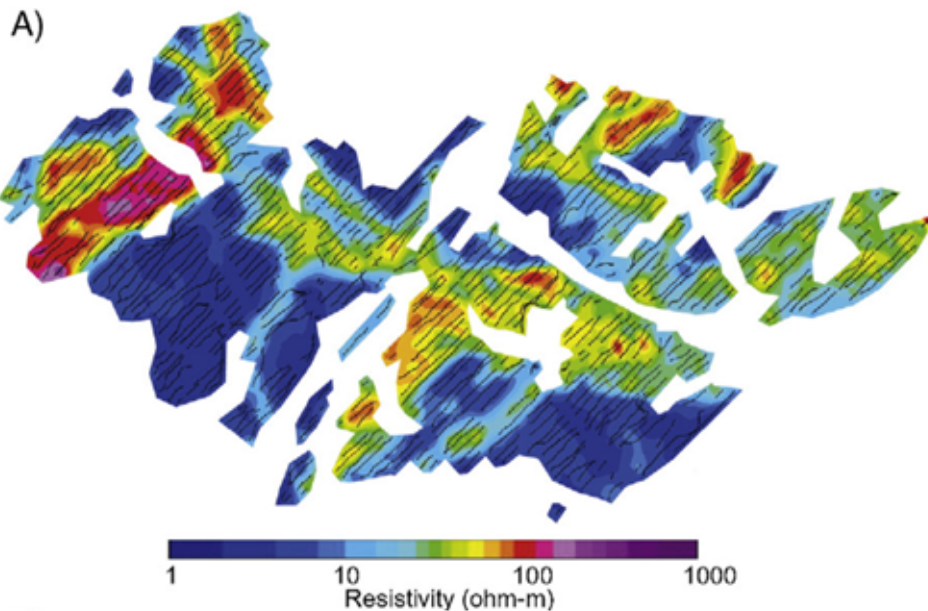


- 333 line km of data, 100 m line-spacing
- Data points with strong coupling to cultural noise were removed (~30%)

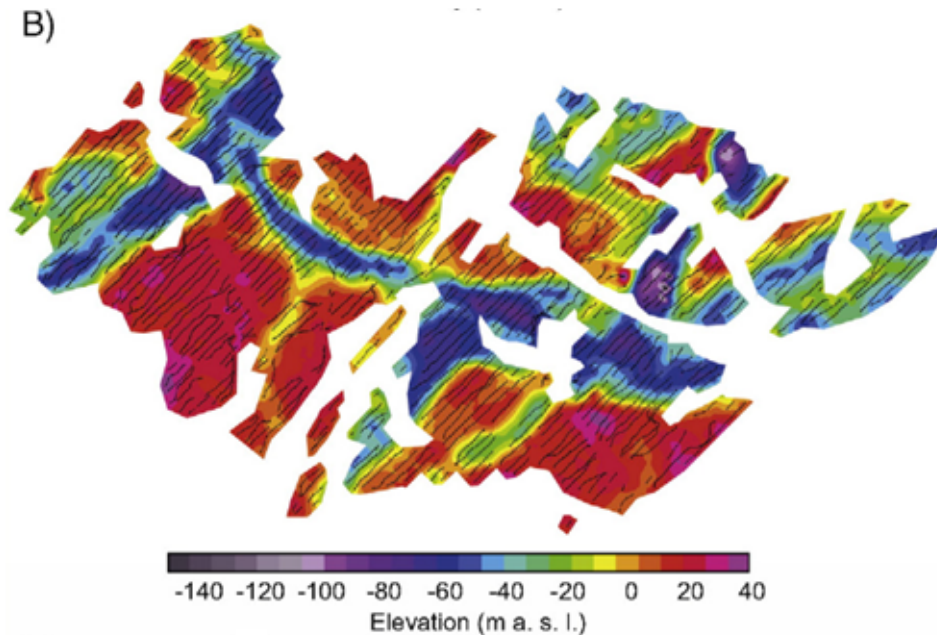
Processing (inversion)

- Spatially constrained 1D inversion → quasi-3D approach
- 9,500 soundings were inverted using 25 layers

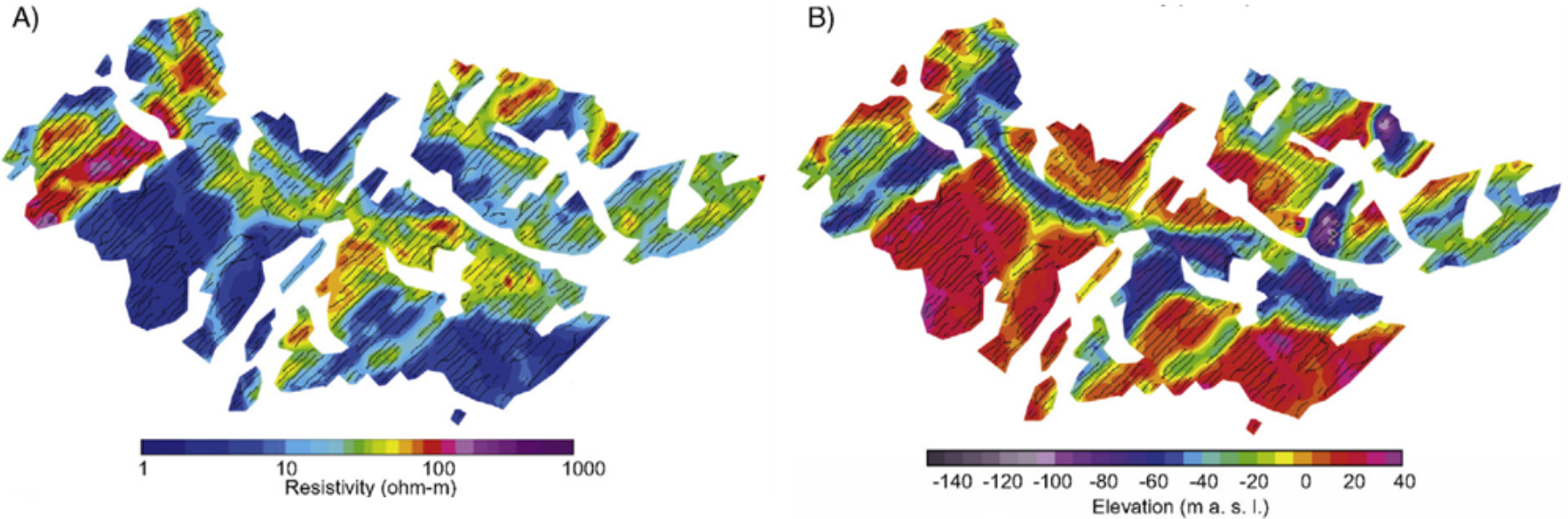
Depth slice 5 m above sea-level



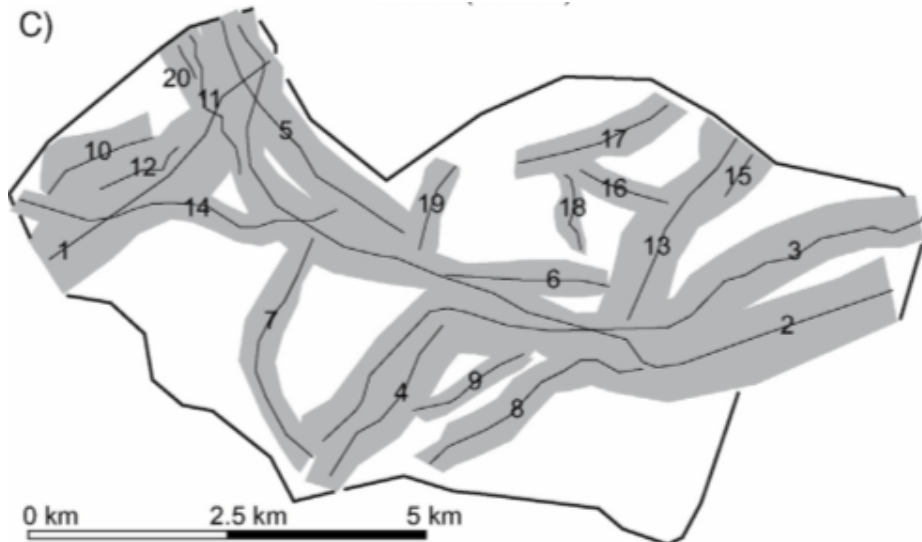
Approximate depth to the top of Paleogene clay layer



Interpretation

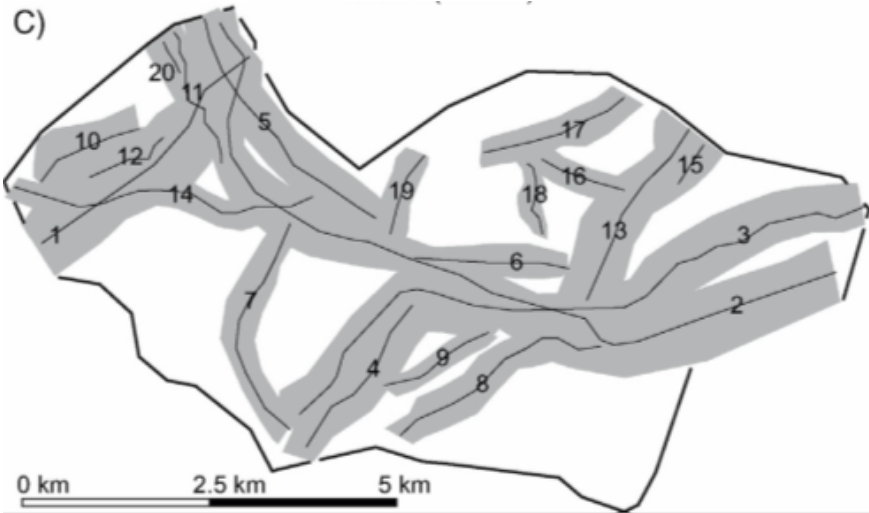


Delineation of valley structures

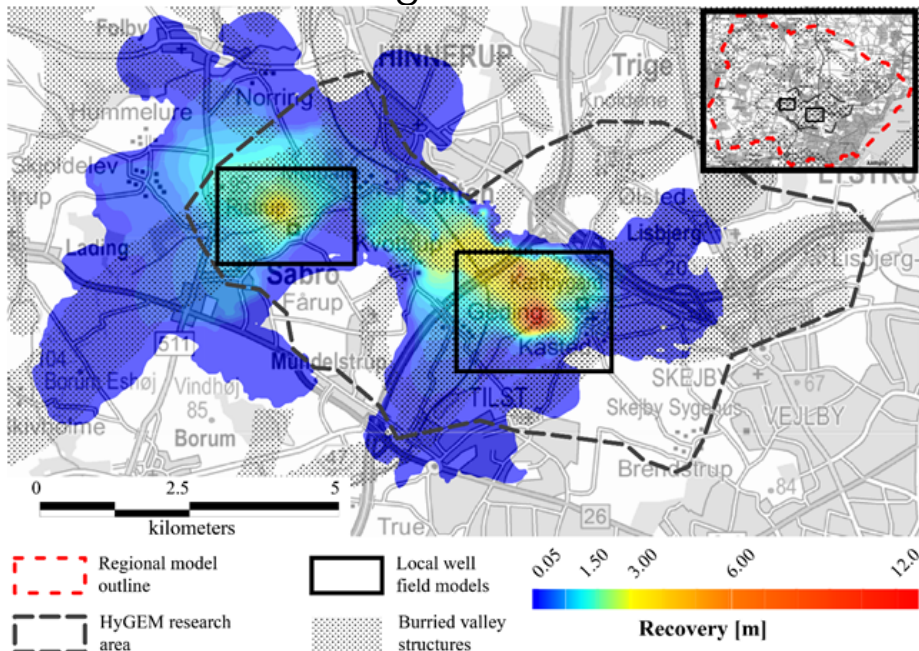


- Inversion results used to construct geological model.
- Delineated 20 buried and cross-cutting valley structures.

Synthesis



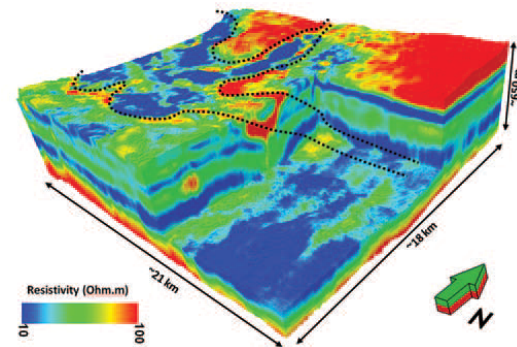
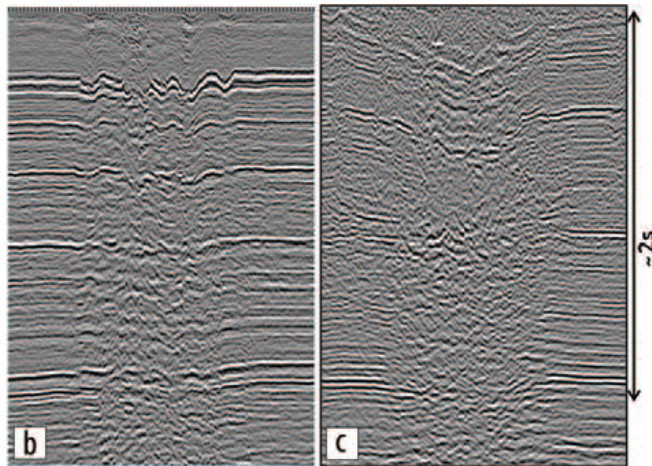
MODFLOW-USG groundwater model



- 3D geologic model incorporated into MODFLOW-USG groundwater modeling tool
- Extracted water from 2 wells.
- Dewatering between the two wells correlated with the resistive valley structures

Case History: Wadi Sahba

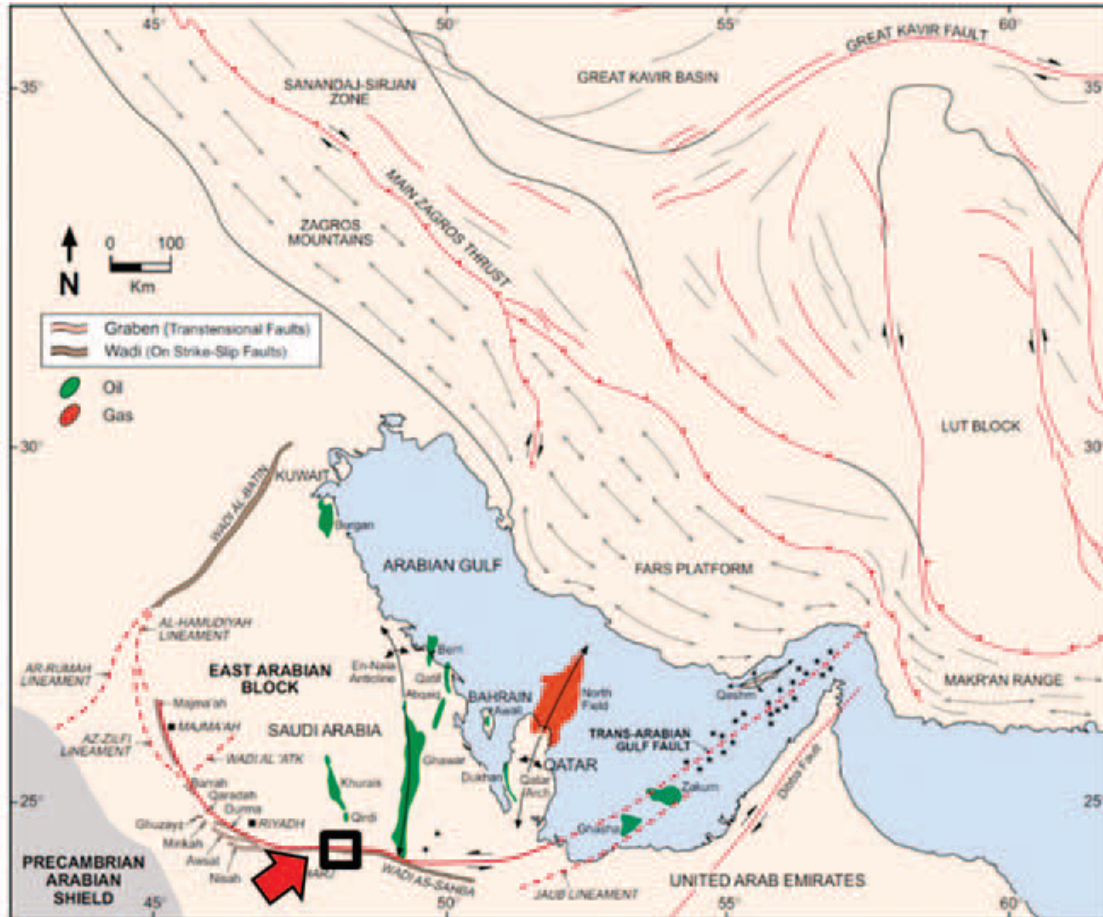
Colombo et al. 2016



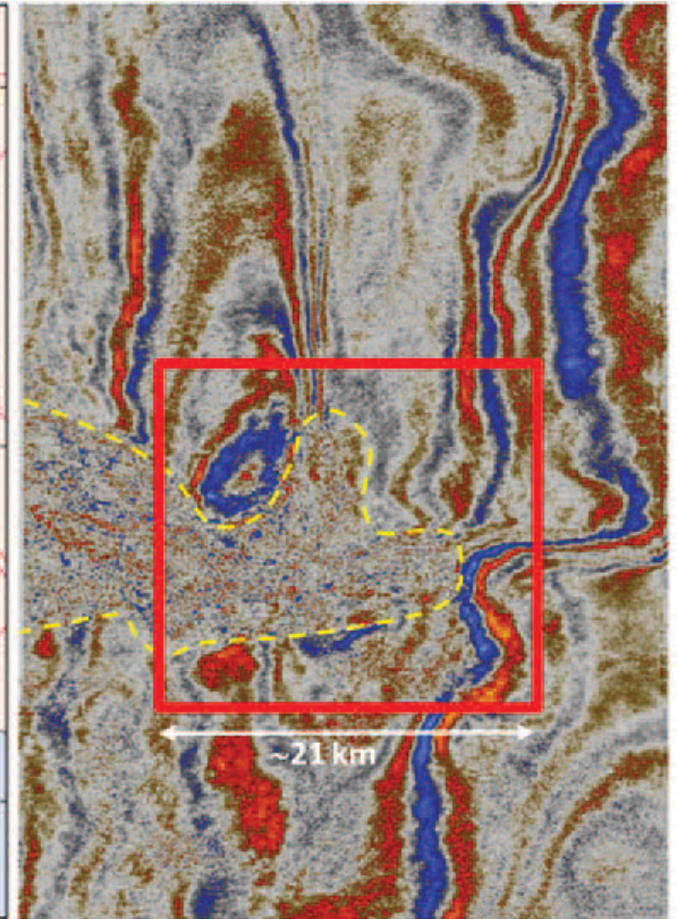
?

Setup

Location of Wadi area, Saudi Arabia



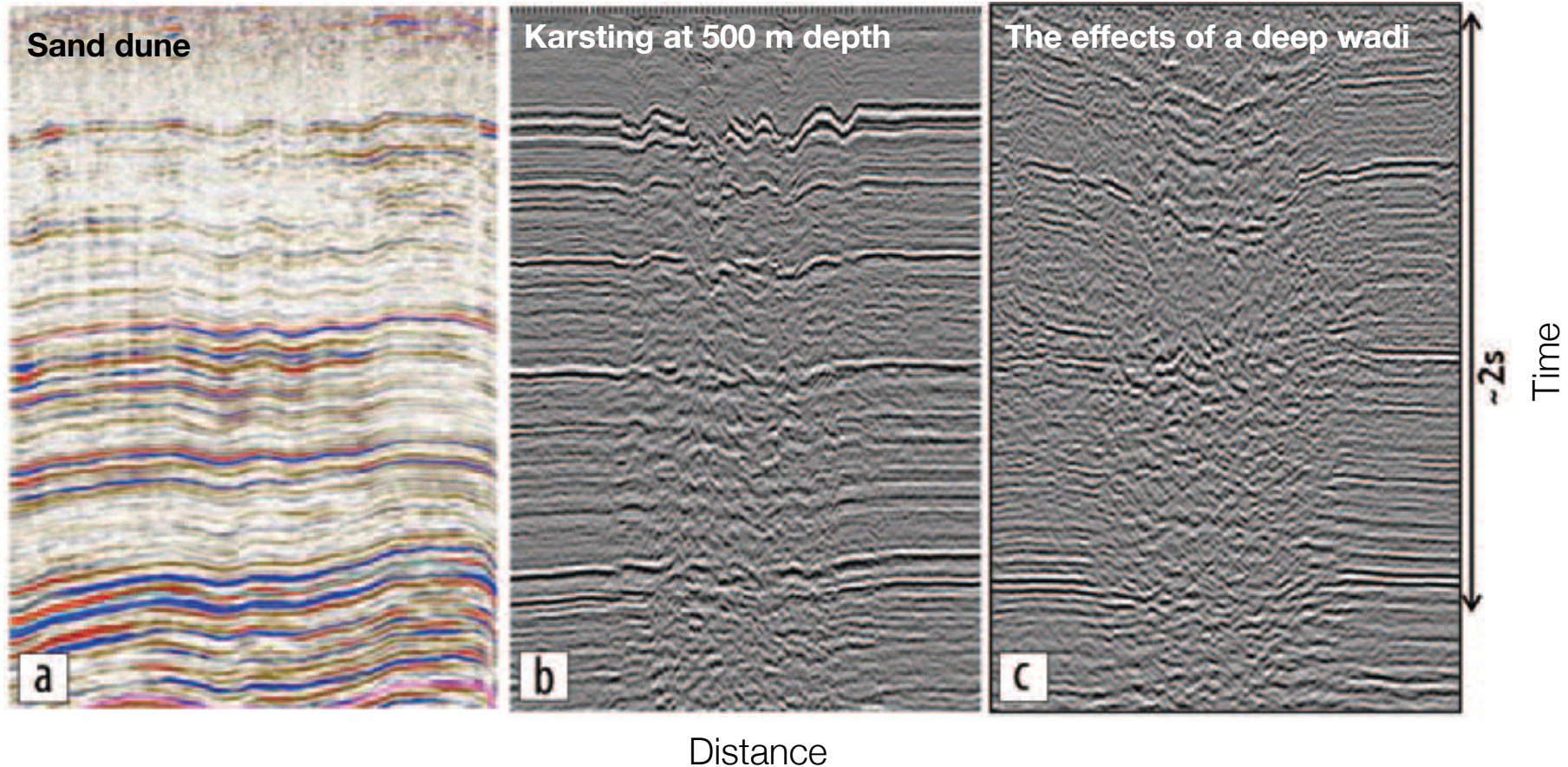
Seismic slice



- Oil and gas exploration in the Middle East: Focus is now stratigraphic traps and low relief structures

Challenges for processing seismic data

Example seismic sections



- Strong effects from near surface anomalies even after static corrections

Properties

- P-velocity and conductivity:

$$v_p = g(\phi)$$

$$\sigma = f(\phi)$$

v_p : P-velocity

ϕ : porosity

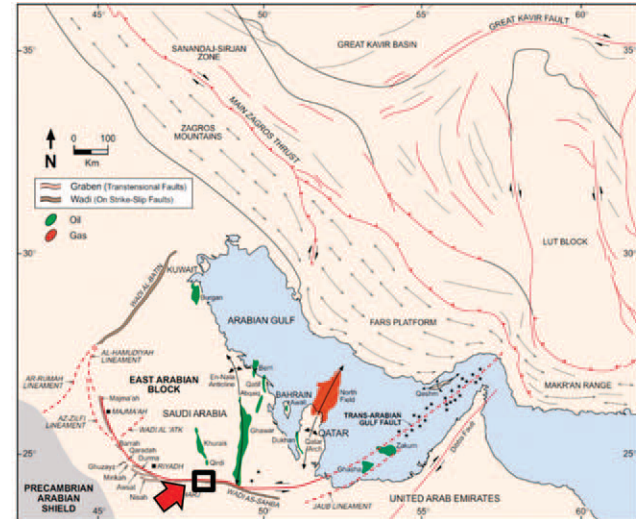
- Poor seismic data:

- strong scattering effects probably caused by flower faults
- velocity inversions (high to low v_p)

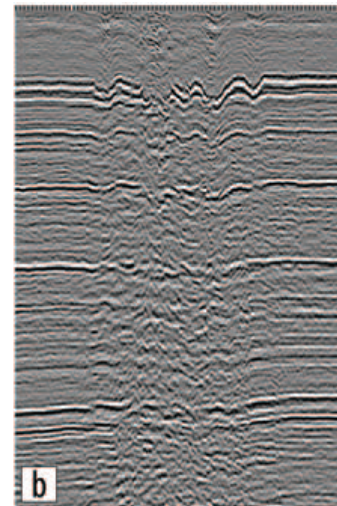
- From previous multi-physics analyses:

- strong structural similarity between the inverted resistivity, and the existing seismic results

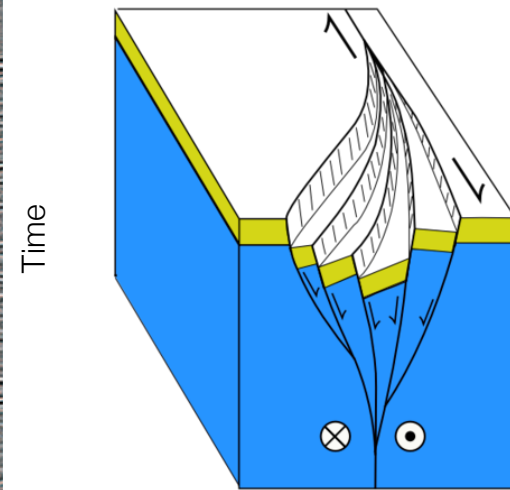
Geologic map



Seismic section



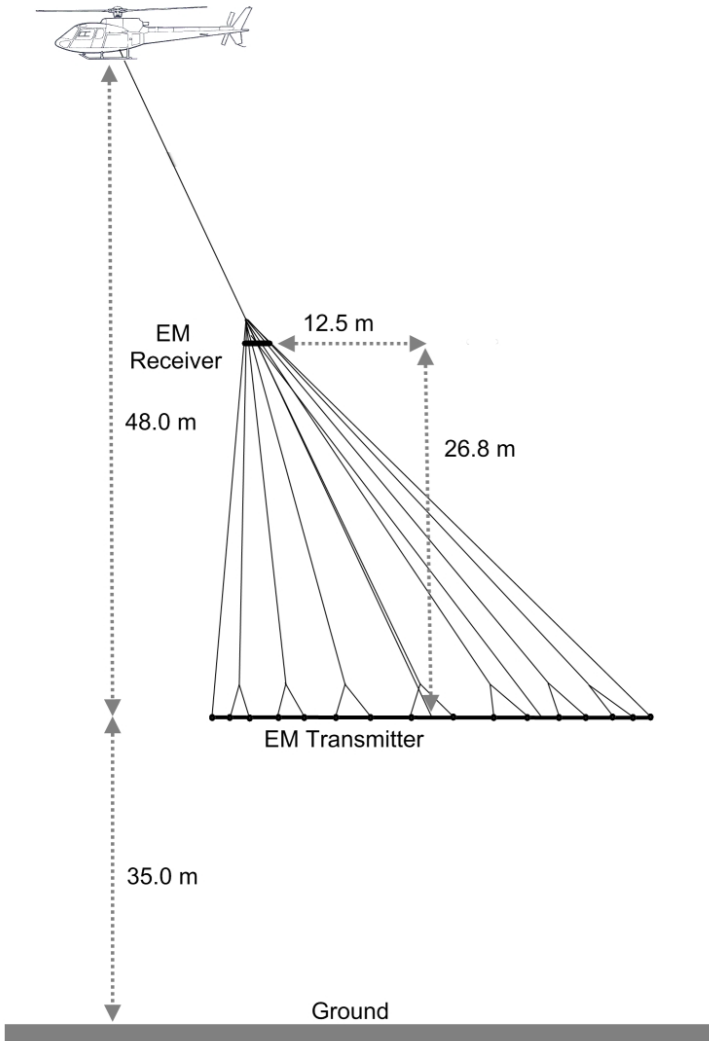
Flower faults



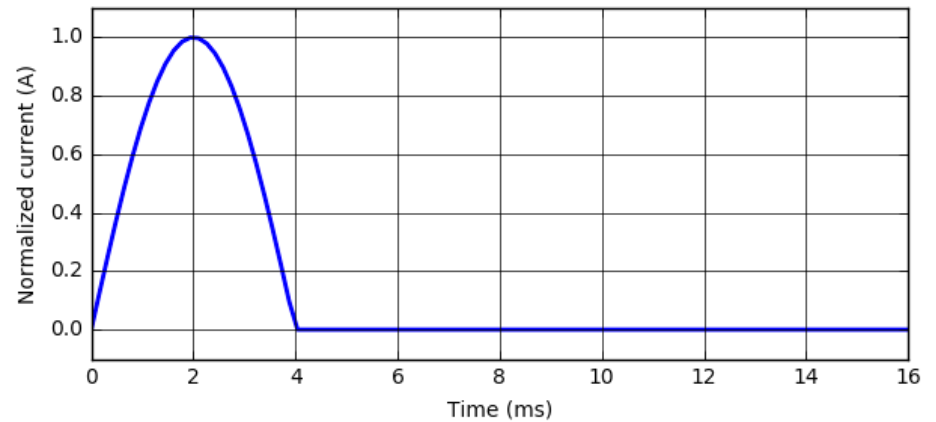
Distance

Survey

HELITEM

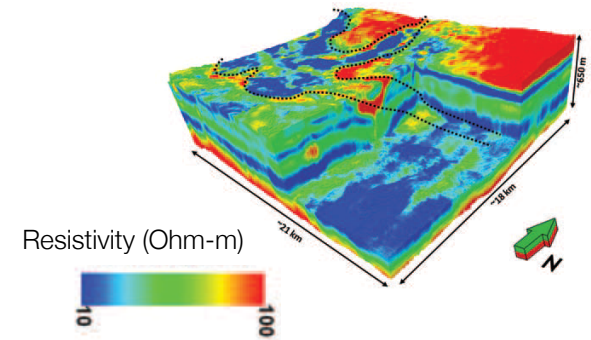


System Configuration

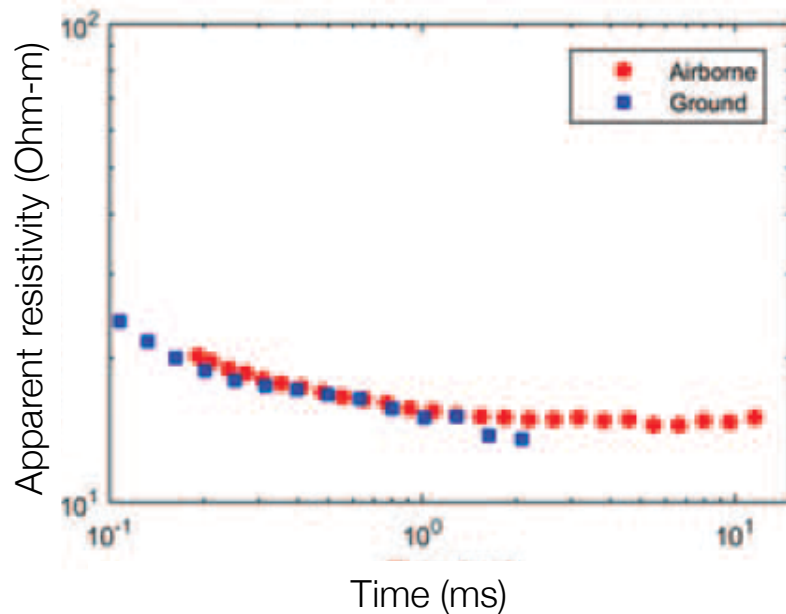


- Peak Tx current: 1200 A
- Dipole moment: $1.7 \times 10^6 \text{ A-m}^2$
- Stacked TEM curve spacing: $\sim 2.7 \text{ m}$
- Total soundings: $\sim 1.6 \text{ million}$

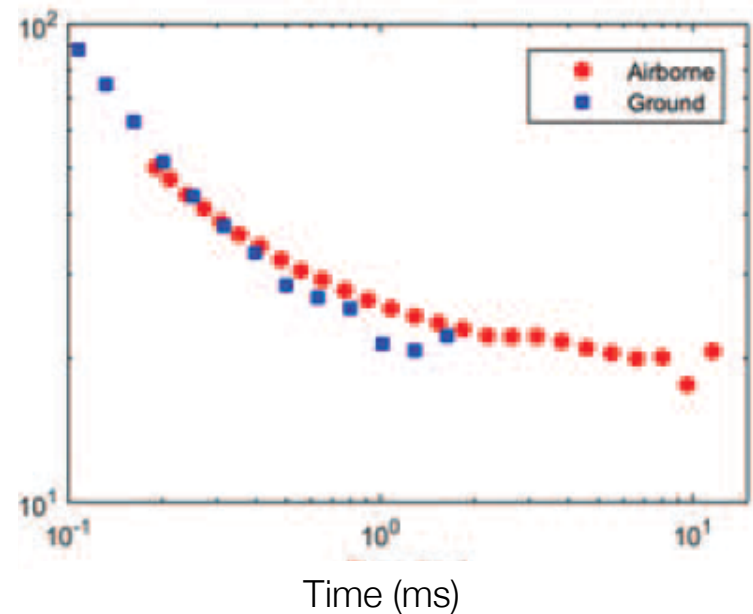
Comparisons: airborne and ground EM



Conductive area

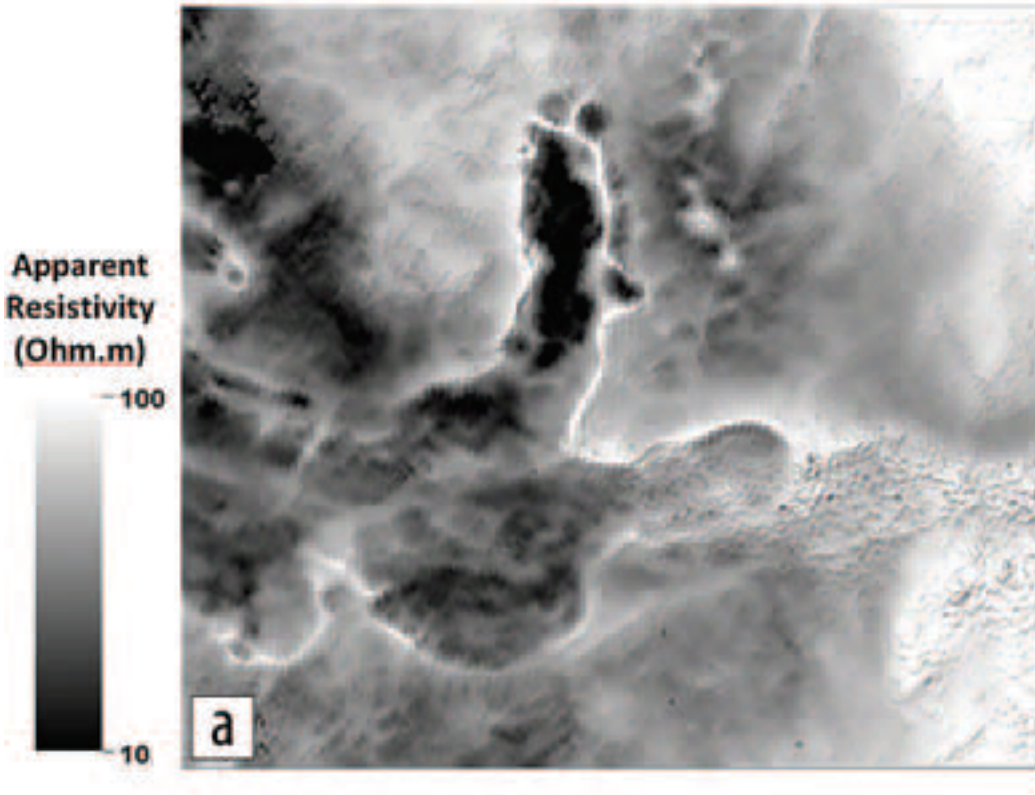


Resistive area



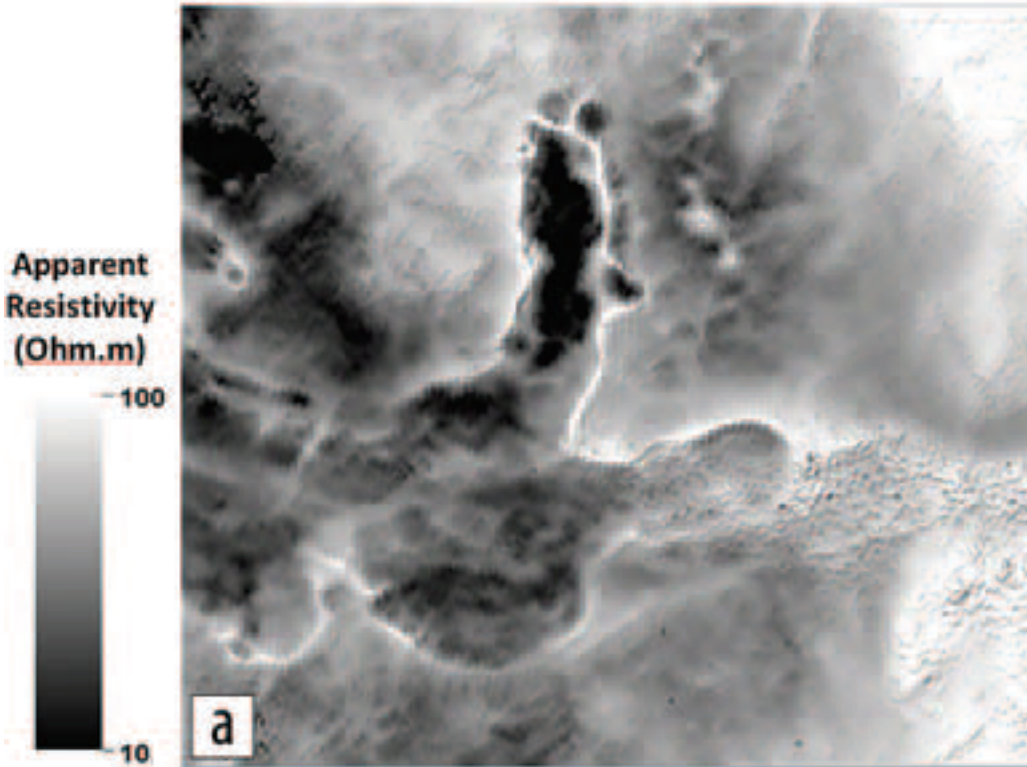
EM data

Apparent resistivity map

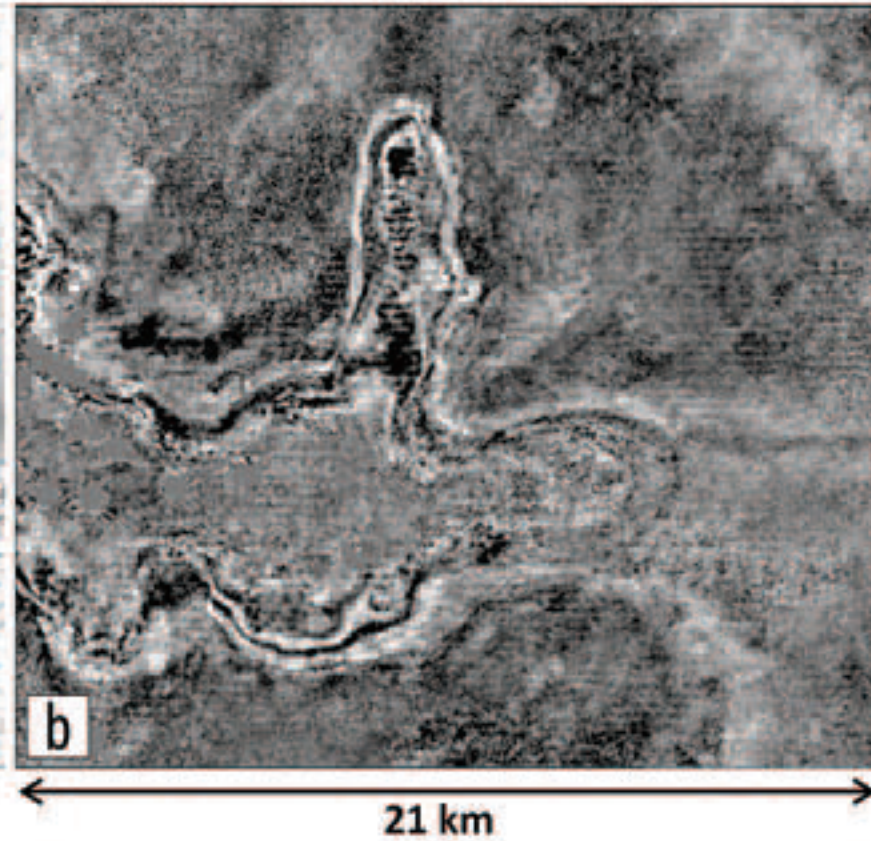


Comparison: EM and Seismic data

Apparent resistivity map

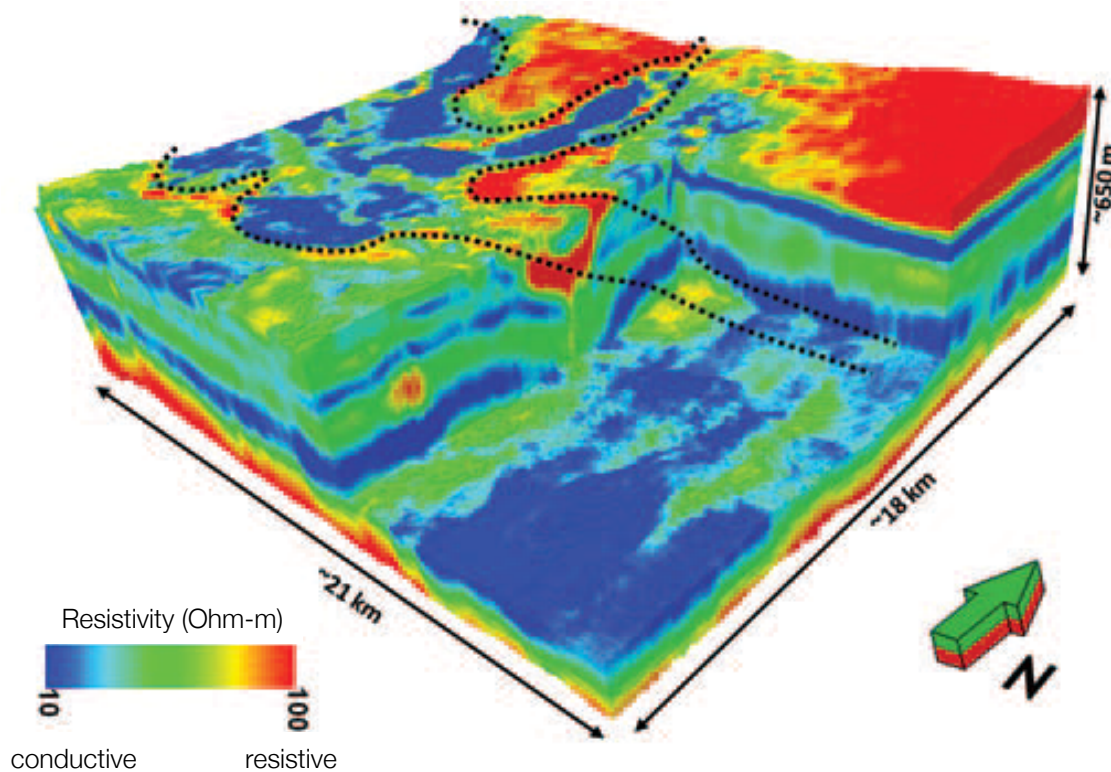


Seismic time slice



Processing: EM inversion

Conductivity model



- 1D inversion for each sounding location
- Lateral constraint is used

Cooperative inversion: Seismic + EM

- How **EM** can help seismic tomography inversion?

Velocity (v_p): high to low (significant challenge)

Conductivity (σ): high to low

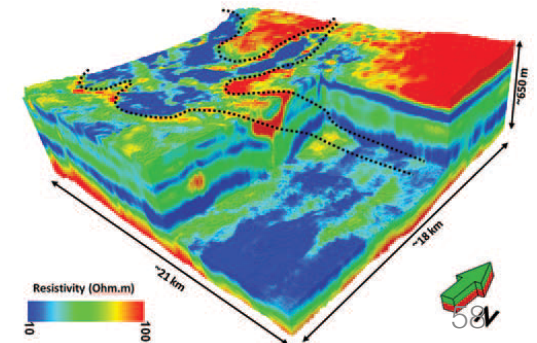
$$\begin{aligned} v_p &= g(\phi) \\ \sigma &= f(\phi) \end{aligned} \quad \phi: \text{porosity}$$

$\mathbf{m}_s$: Slowness
 $\mathbf{m}_\sigma$: Conductivity

$$\psi(\mathbf{m}_s, \mathbf{m}_\sigma) = \psi_m(\mathbf{m}_s) + \frac{1}{\lambda_1} \psi_d(\mathbf{m}_s) + \underbrace{\frac{1}{\lambda_2} \psi_x(\mathbf{m}_s, \mathbf{m}_\sigma)} + \frac{1}{\lambda_3} \psi_{rp}(\mathbf{m}_s, \mathbf{m}_\sigma)$$

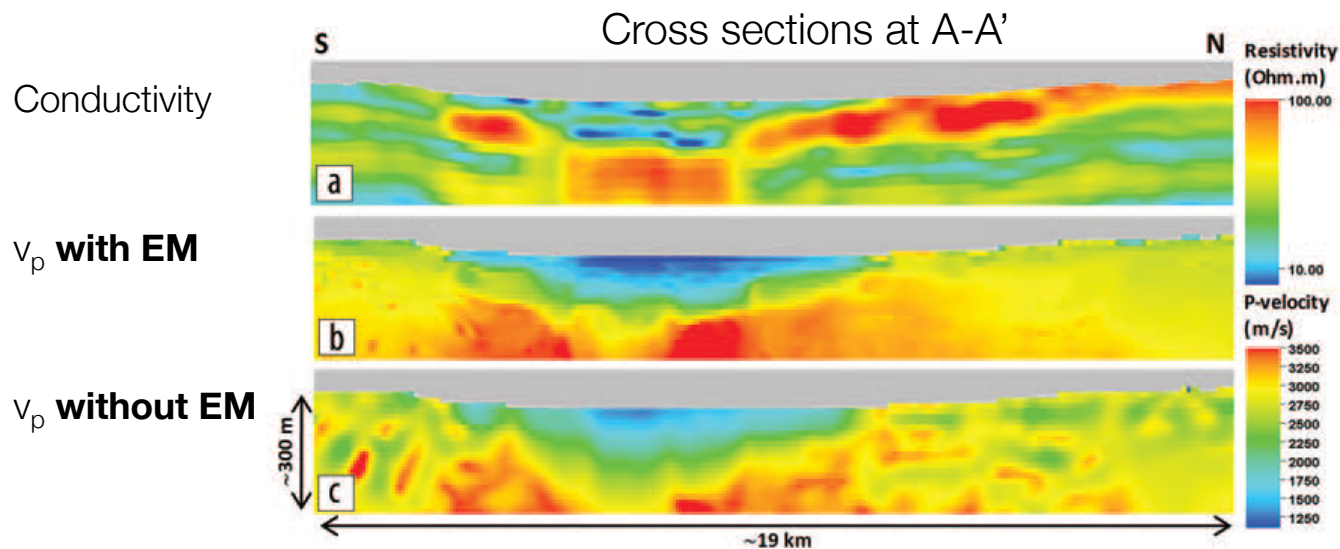
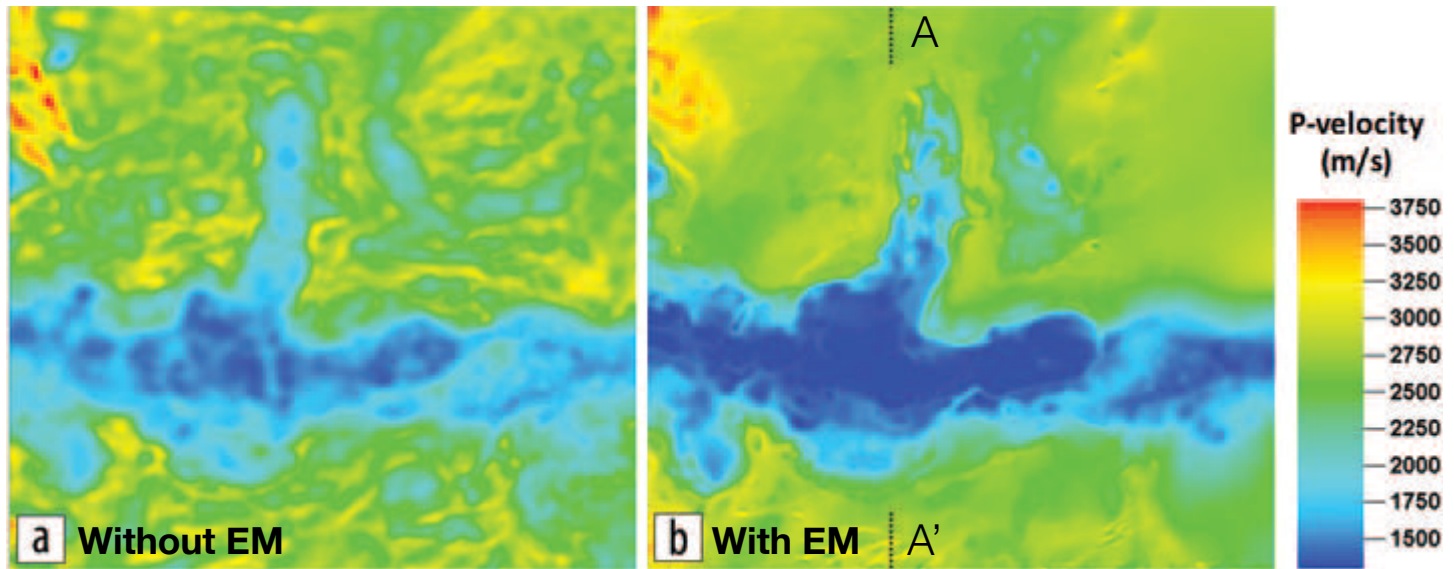
$$\|\nabla \mathbf{m}_s \times \nabla \mathbf{m}_\sigma\|_2^2$$

Gallardo and Meju, 2004



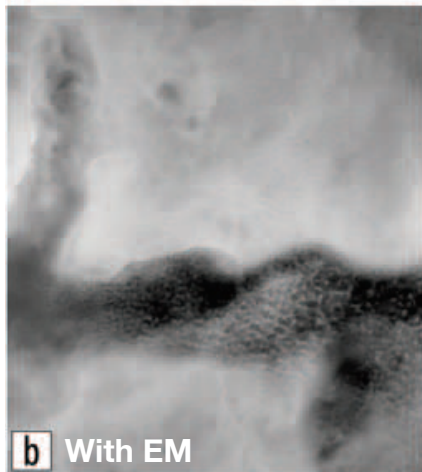
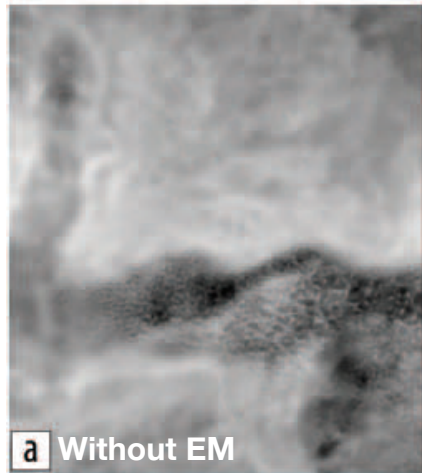
Cooperative inversion: Seismic + EM

V_p depth slices at 340 m below sea level

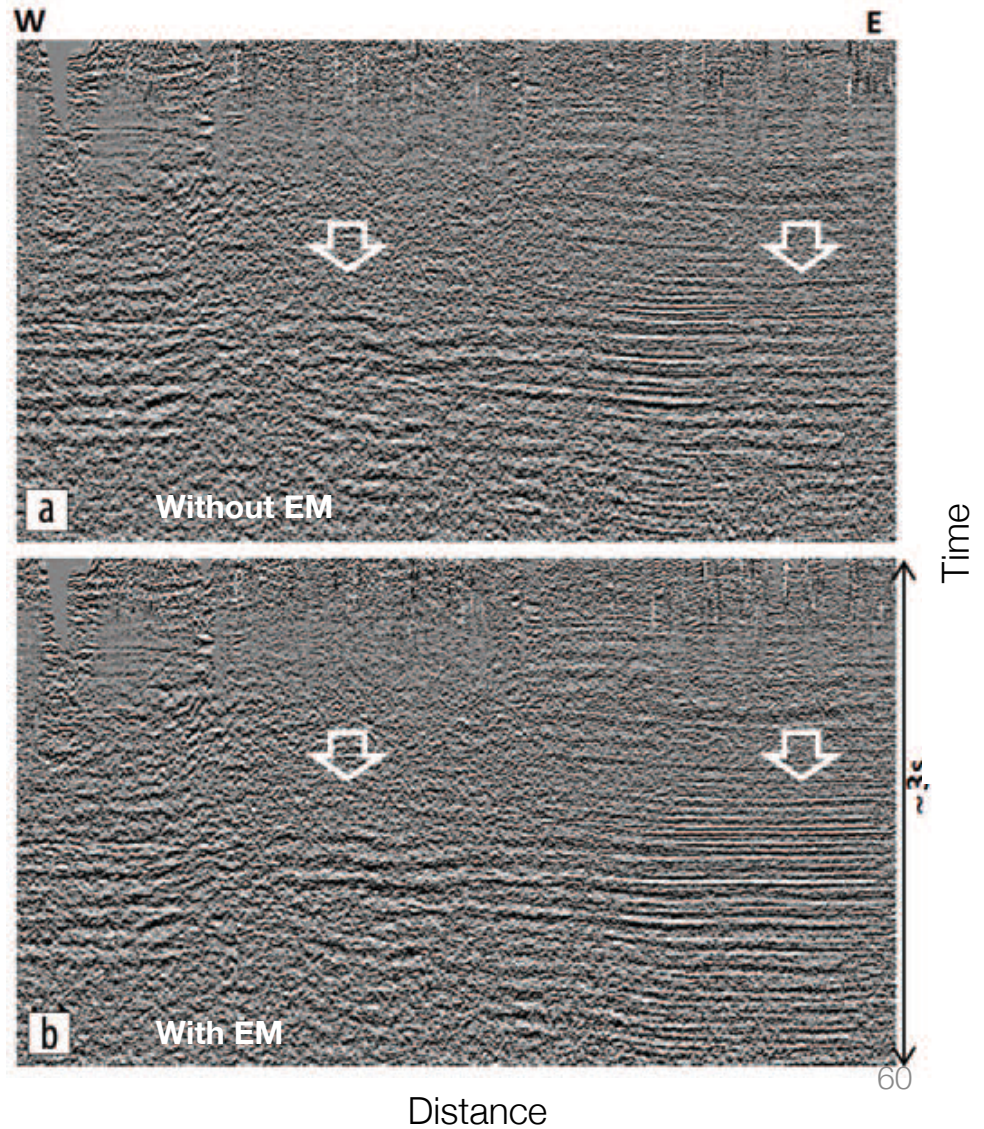


Static correction

Estimated statics on plan map



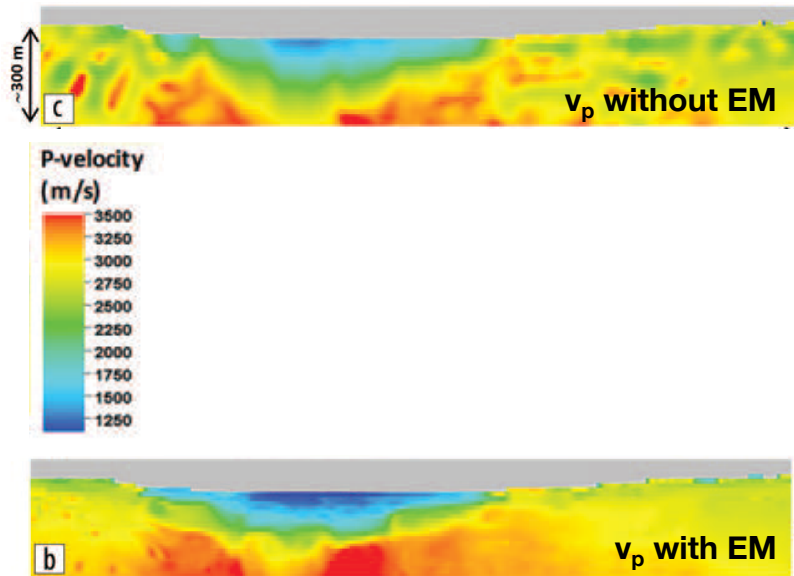
Static corrected sections



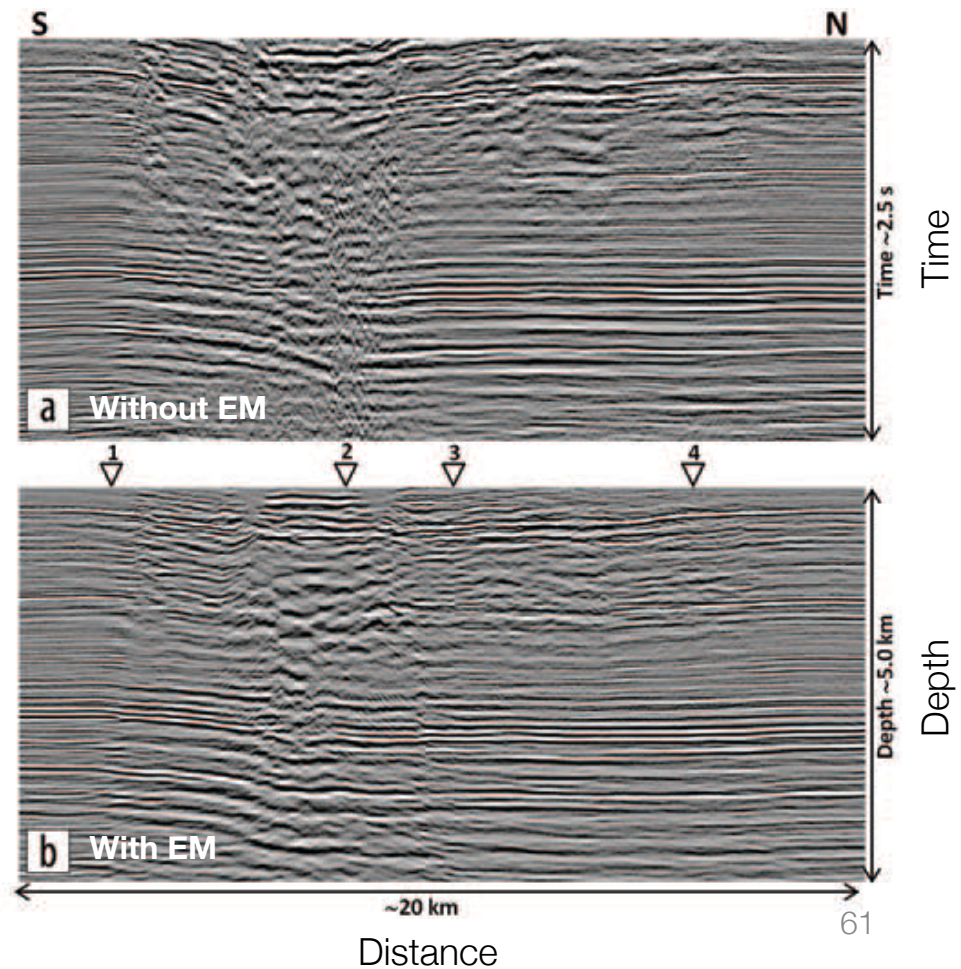
Pre-stack depth migration

- Impact of the improved v_p model to a pre-stack depth migration:

v_p cross sections at A-A'

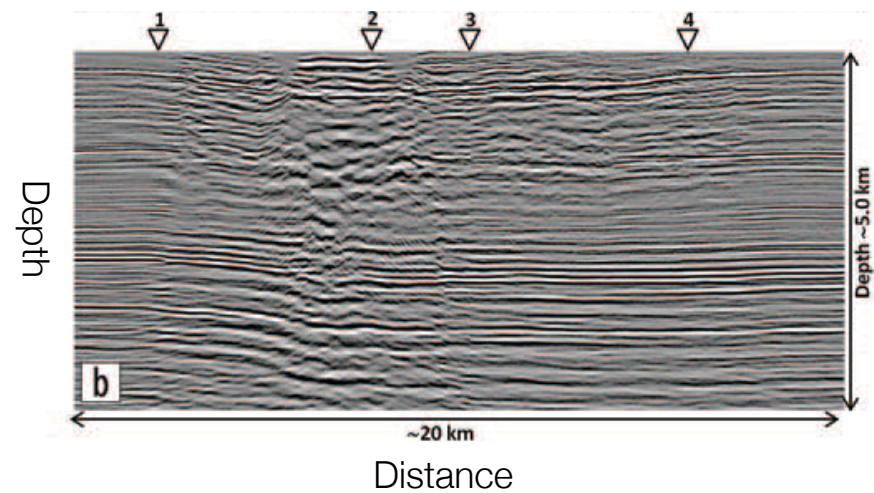


Cross sections at A-A'

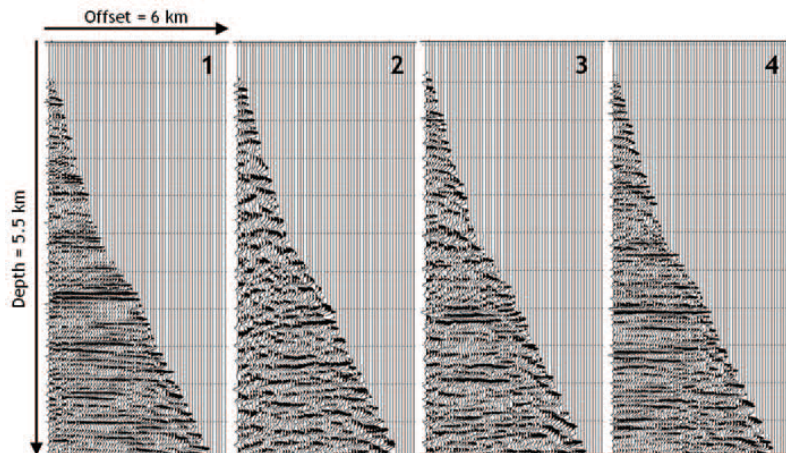


Interpretation and Synthesis

Depth section at A-A'

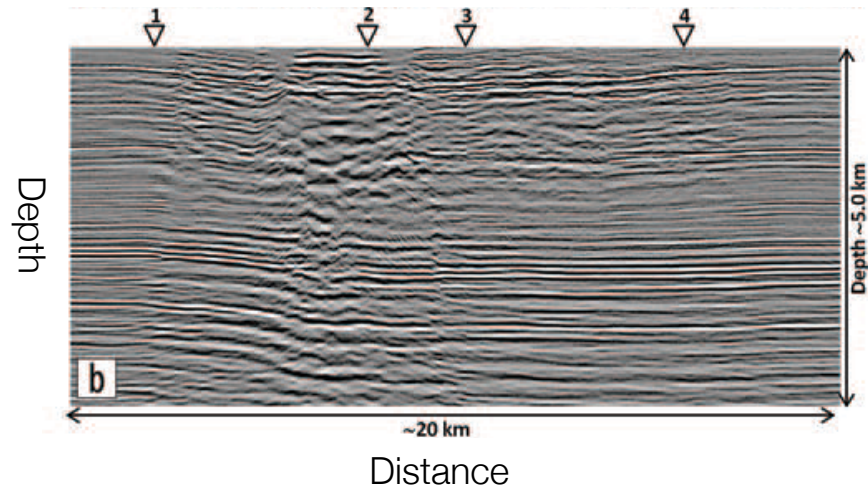


Common image gathers

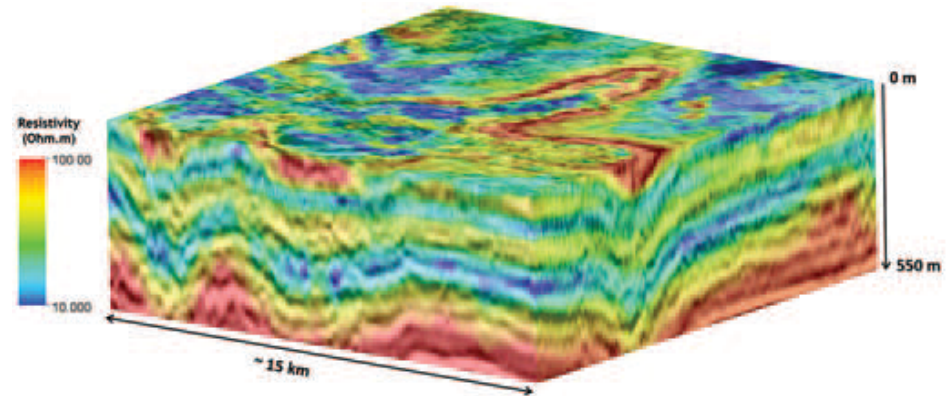


Interpretation and Synthesis

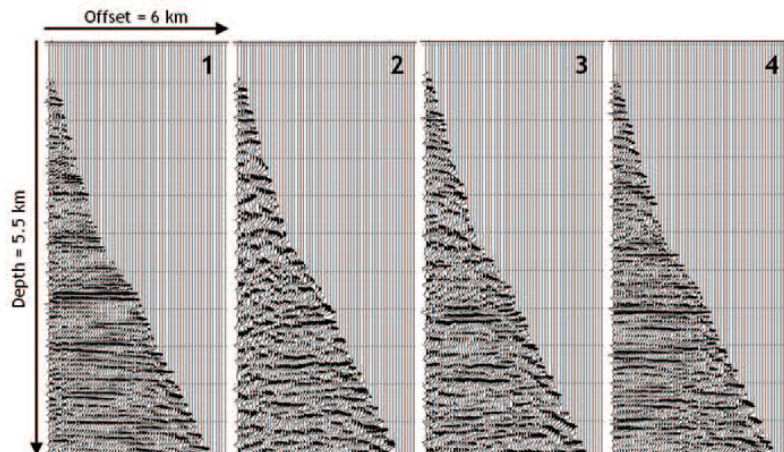
Depth section at A-A'



3D prestack depth migration co-rendered with EM



Common image gathers



- High resolution near surface conductivity from EM improves velocity model
- Helps seismic imaging:
 - Static correction
 - Pre-stack depth migration

Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Case History

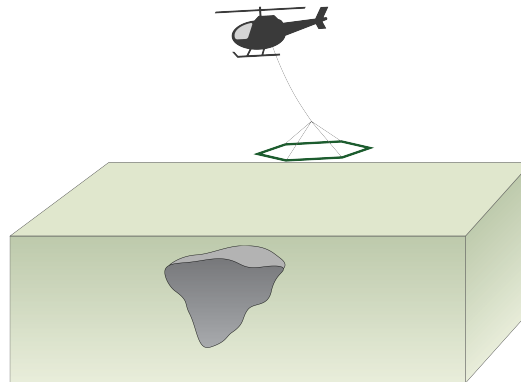
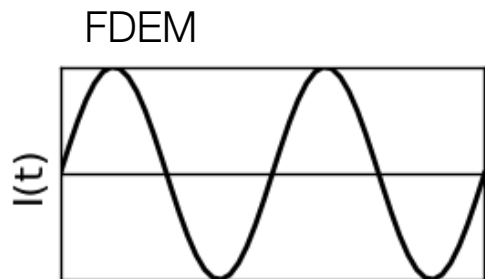
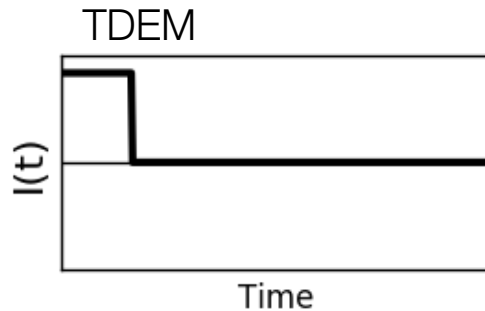
Frequency Domain EM

- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Ground water

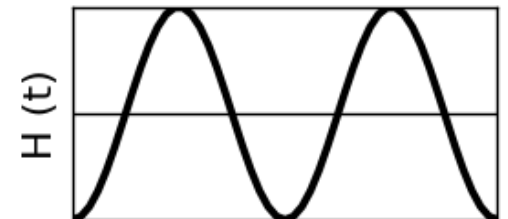
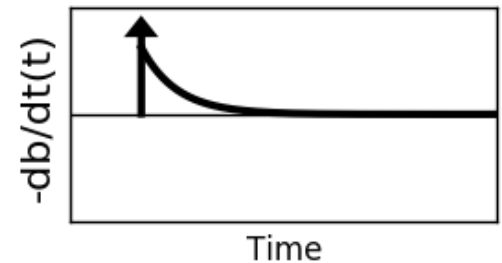
EM with Inductive Sources

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

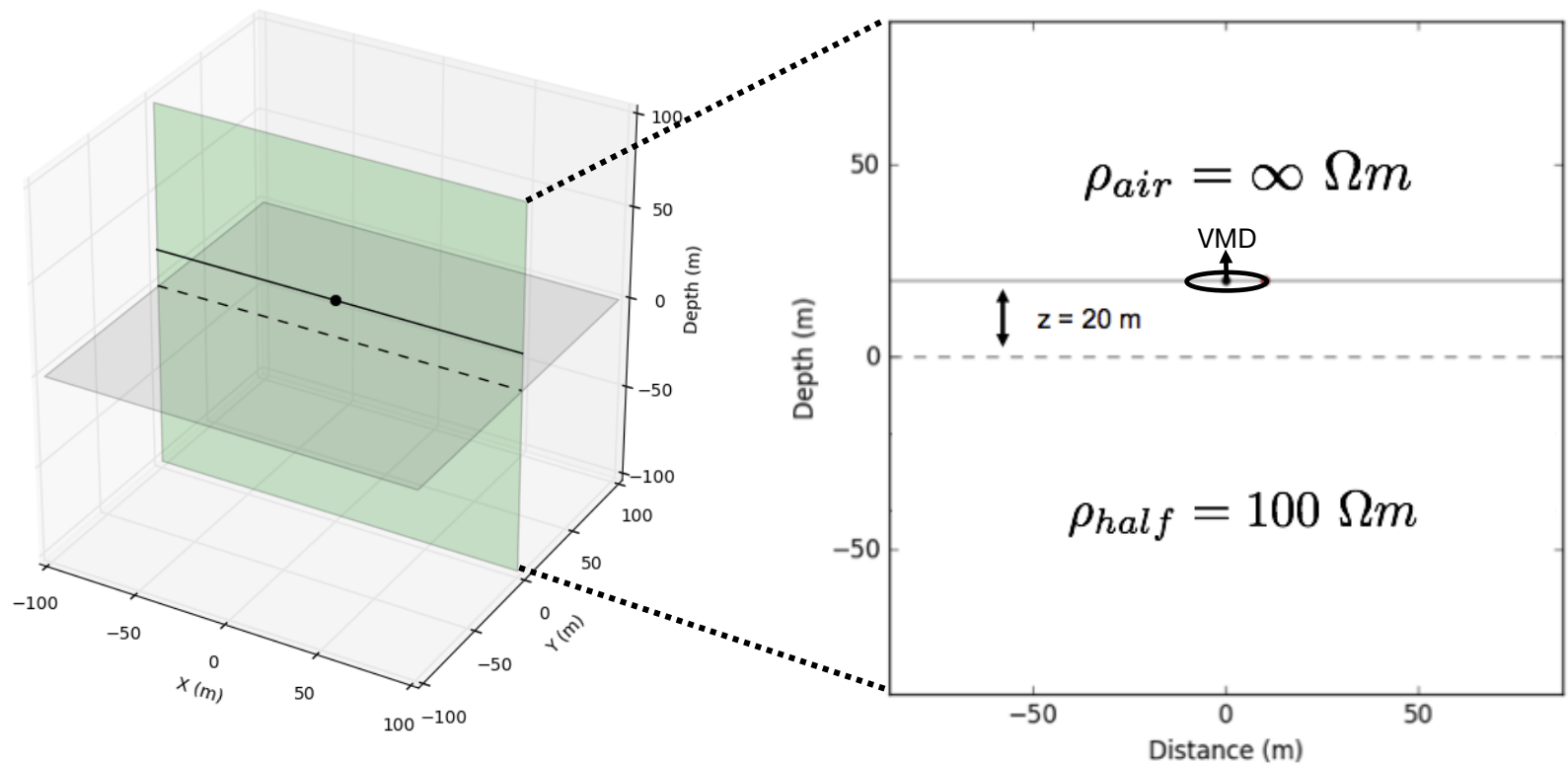
Transmitter current



Receiver

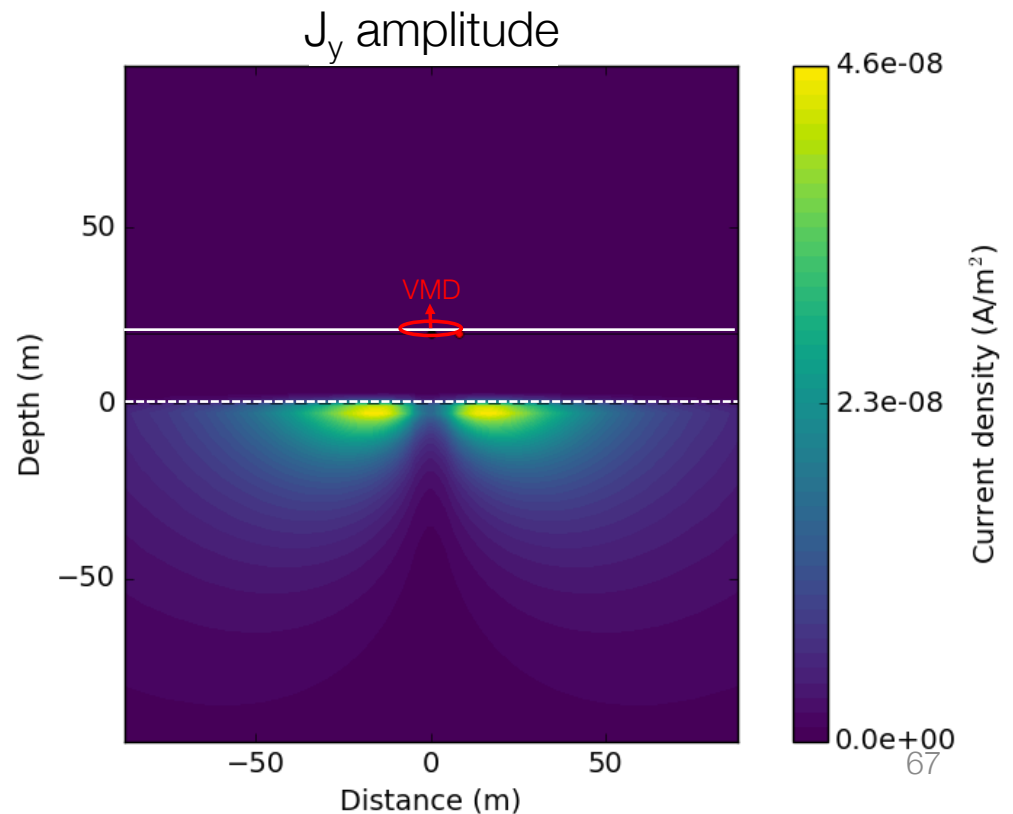
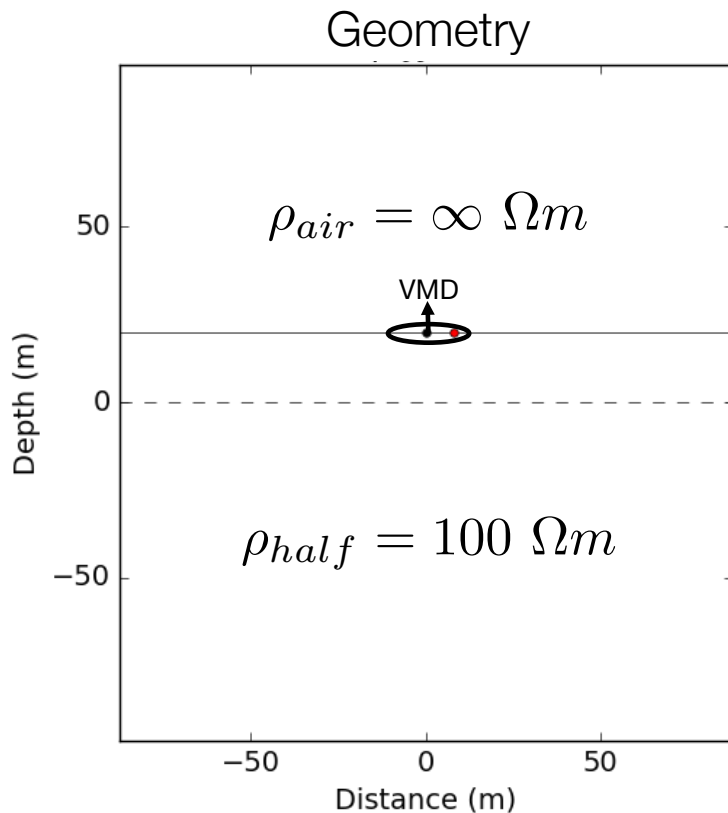
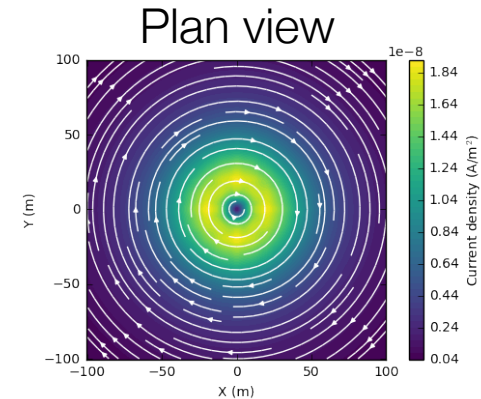


Vertical Magnetic Dipole over a halfspace (FDEM)



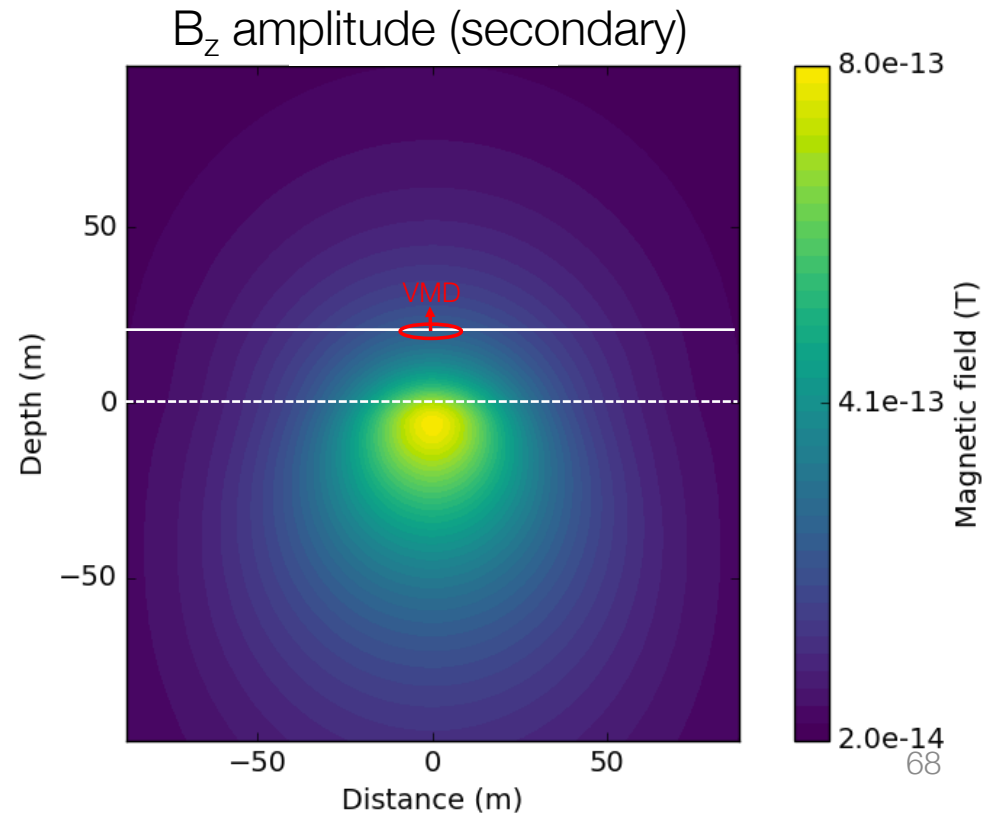
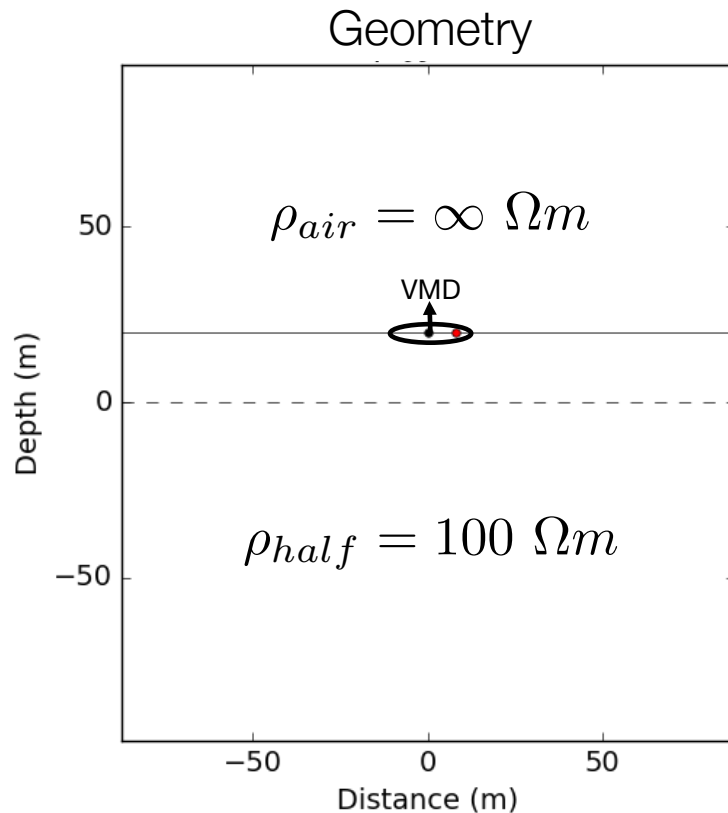
Current Density

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



Secondary Magnetic Flux Density

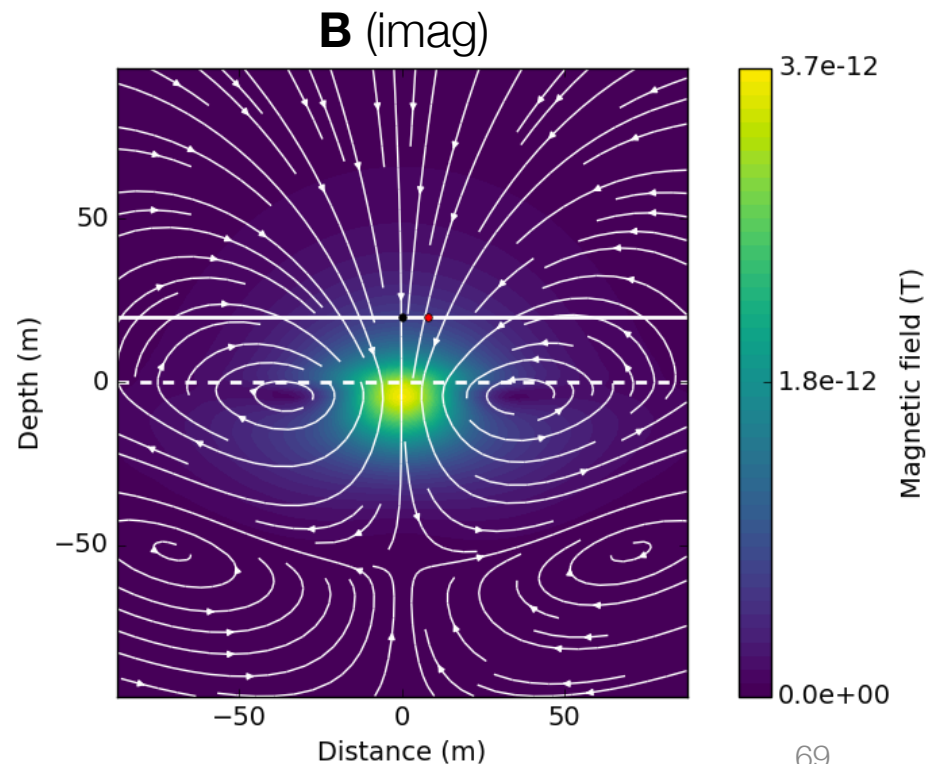
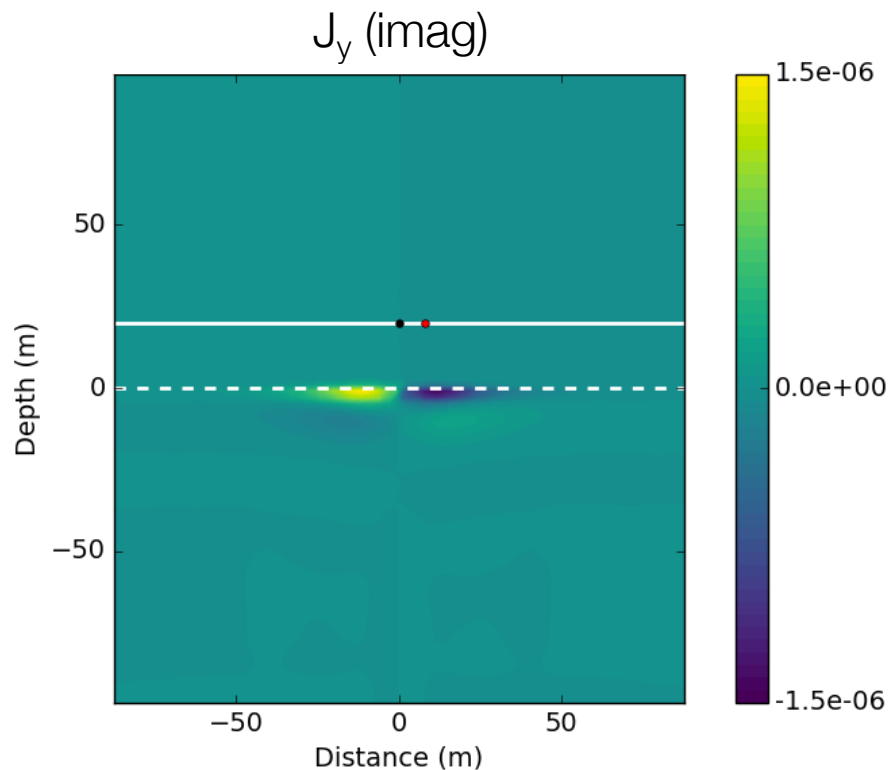
- Frequency = 10 kHz



Effects of Frequency

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

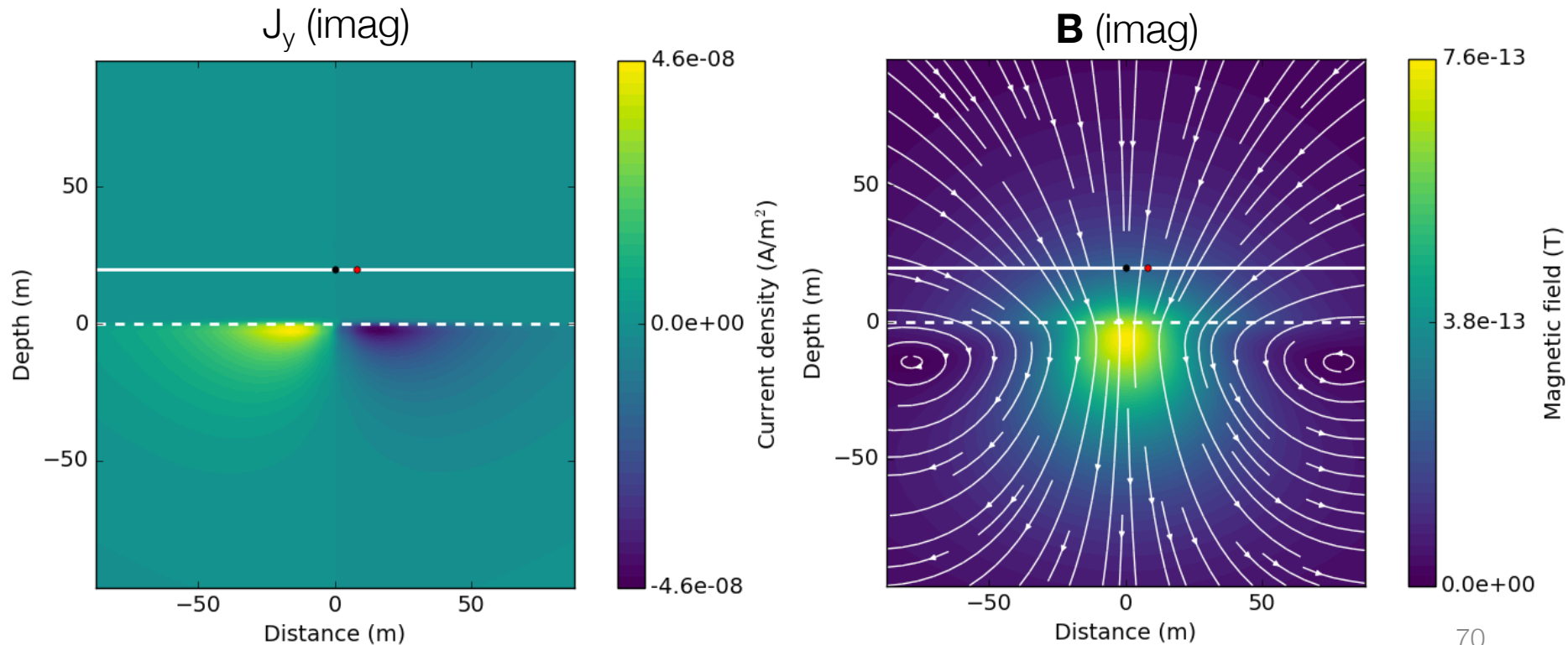
$$\delta = 503 \sqrt{\frac{\rho}{f}}$$



Effects of Frequency

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

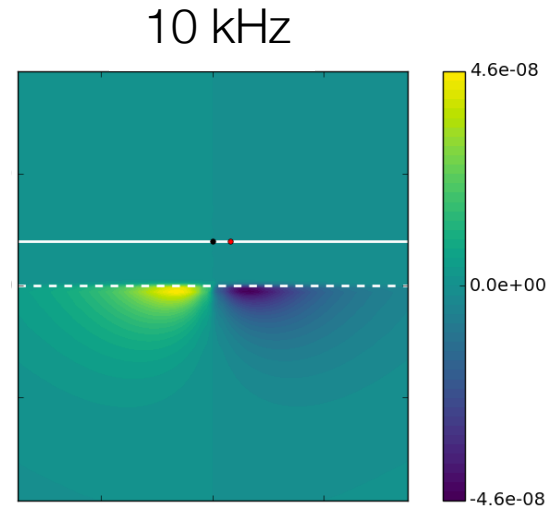
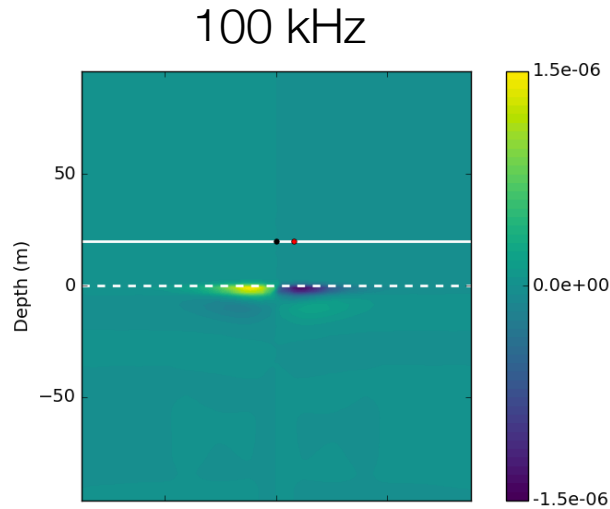
$$\delta = 503 \sqrt{\frac{\rho}{f}}$$



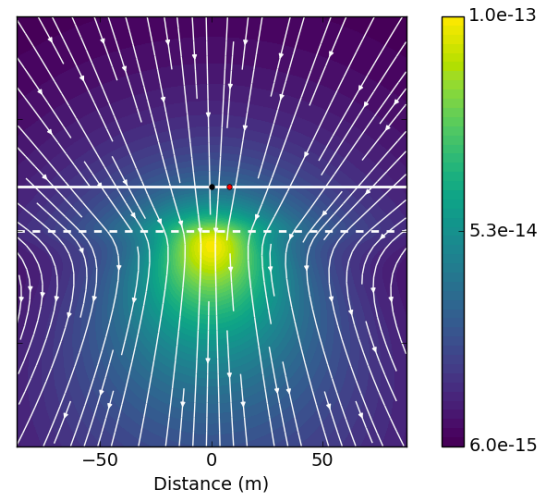
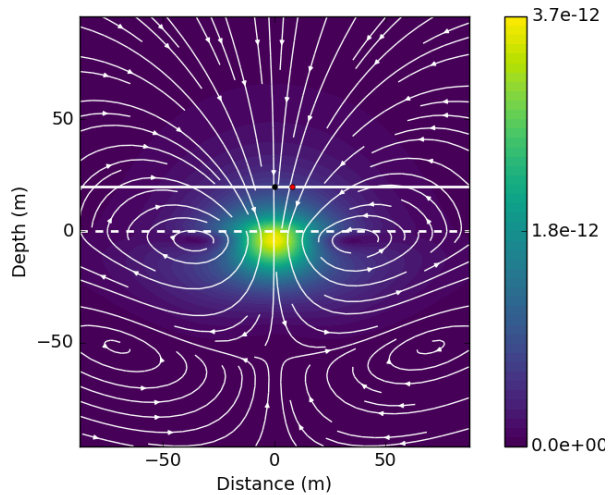
Summary: Effects of Frequency

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

J_y imag.

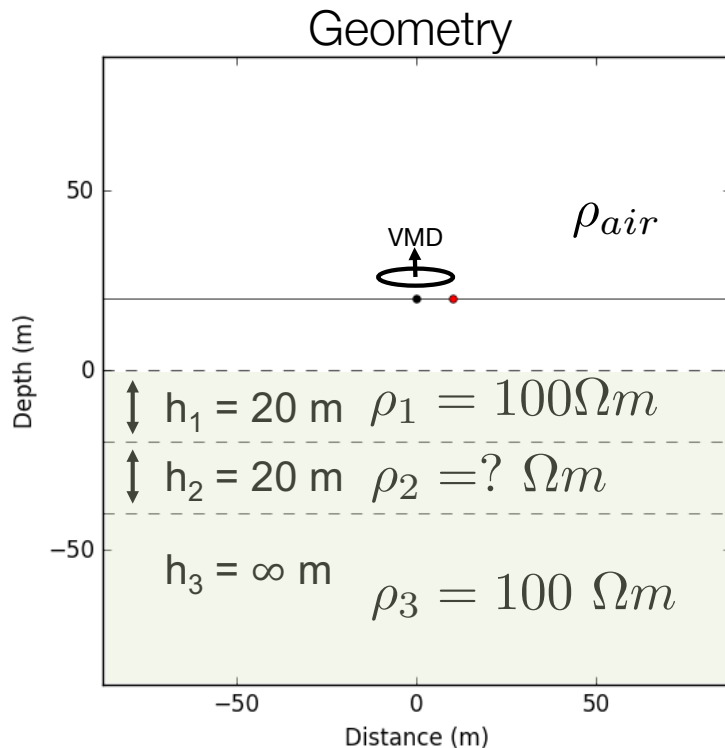


B imag.



Layered earth

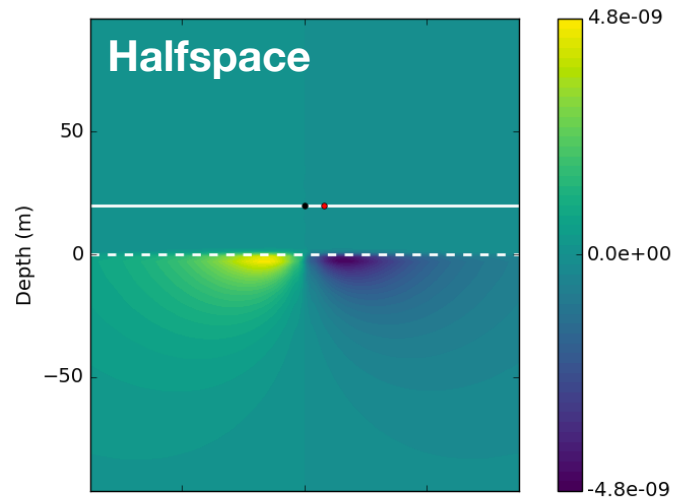
- 3 layers + air,
- ρ_2 varies



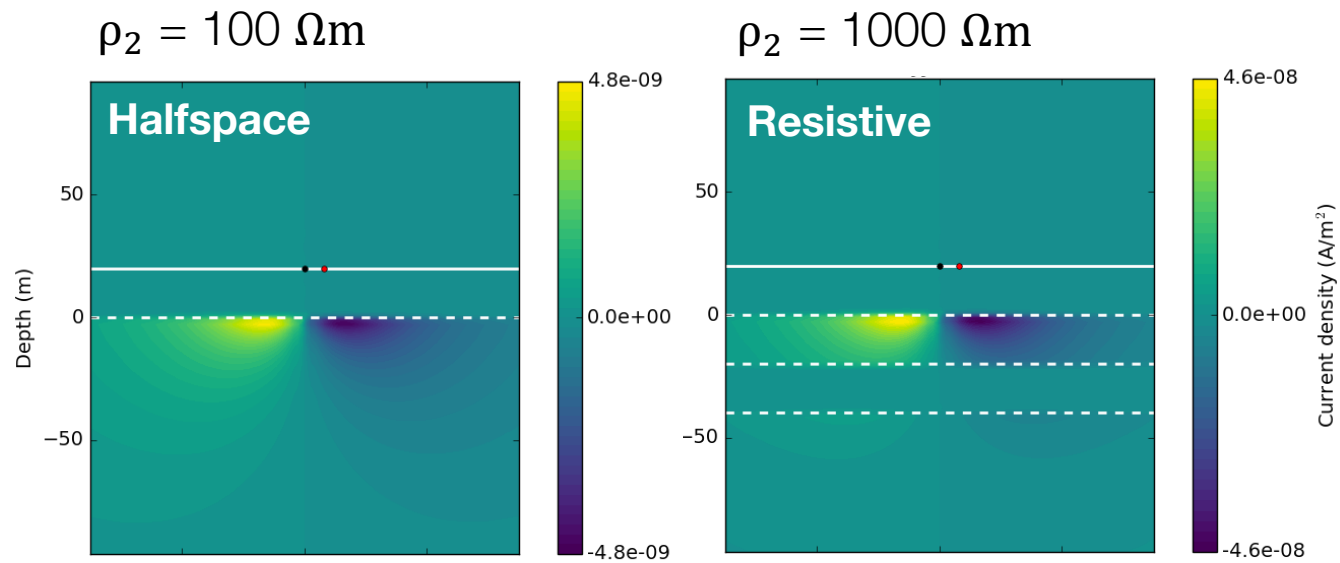
- Four different cases:
 - Halfspace
 $\rho_2 = 100 \Omega m$
 - Resistive
 $\rho_2 = 1000 \Omega m$
 - Conductive
 $\rho_2 = 10 \Omega m$
 - Very conductive
 $\rho_2 = 1 \Omega m$
- Fields
 - J_y imag
 - Secondary **B** imag

Current density (J_y imag)

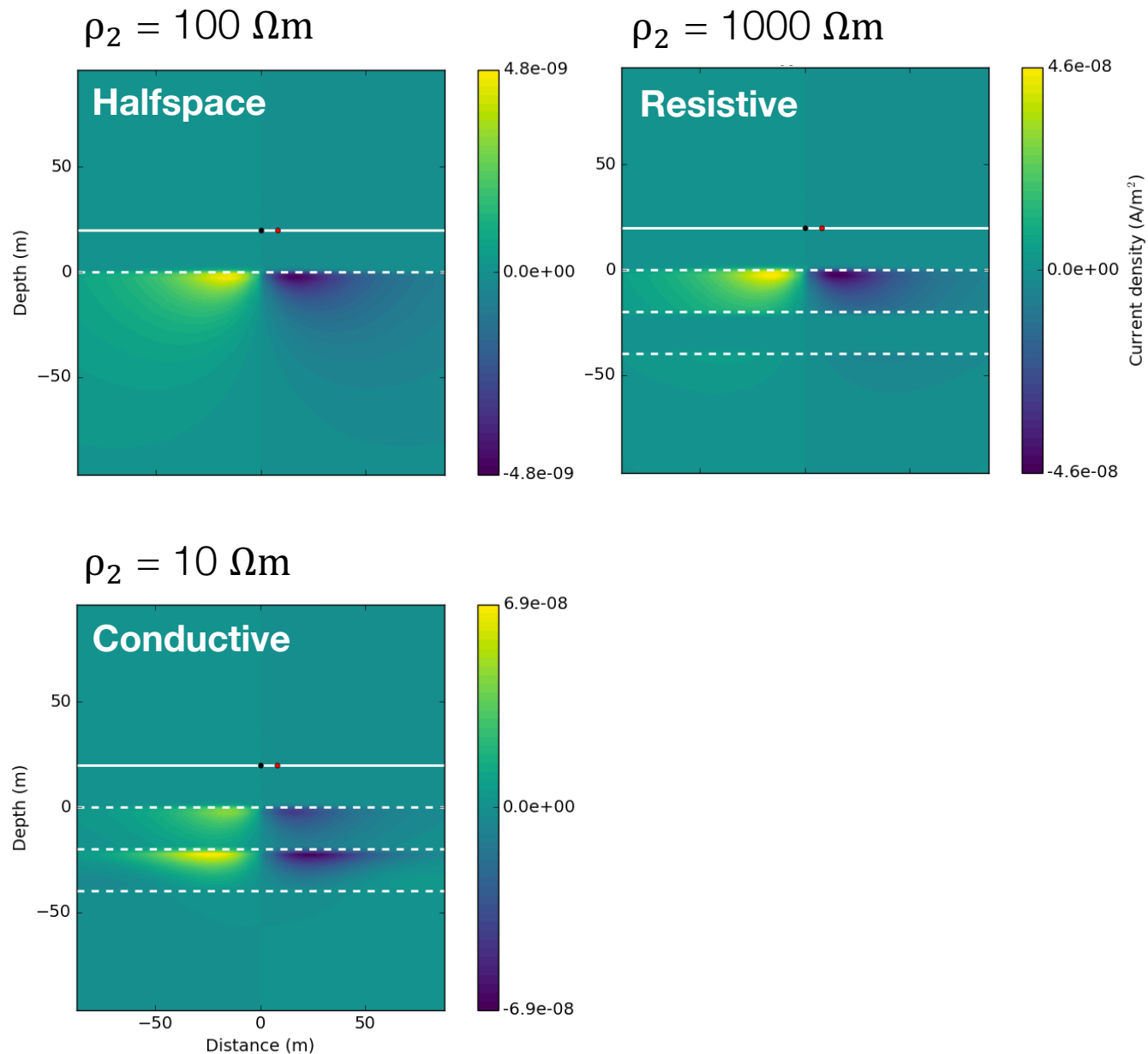
$$\rho_2 = 100 \, \Omega\text{m}$$



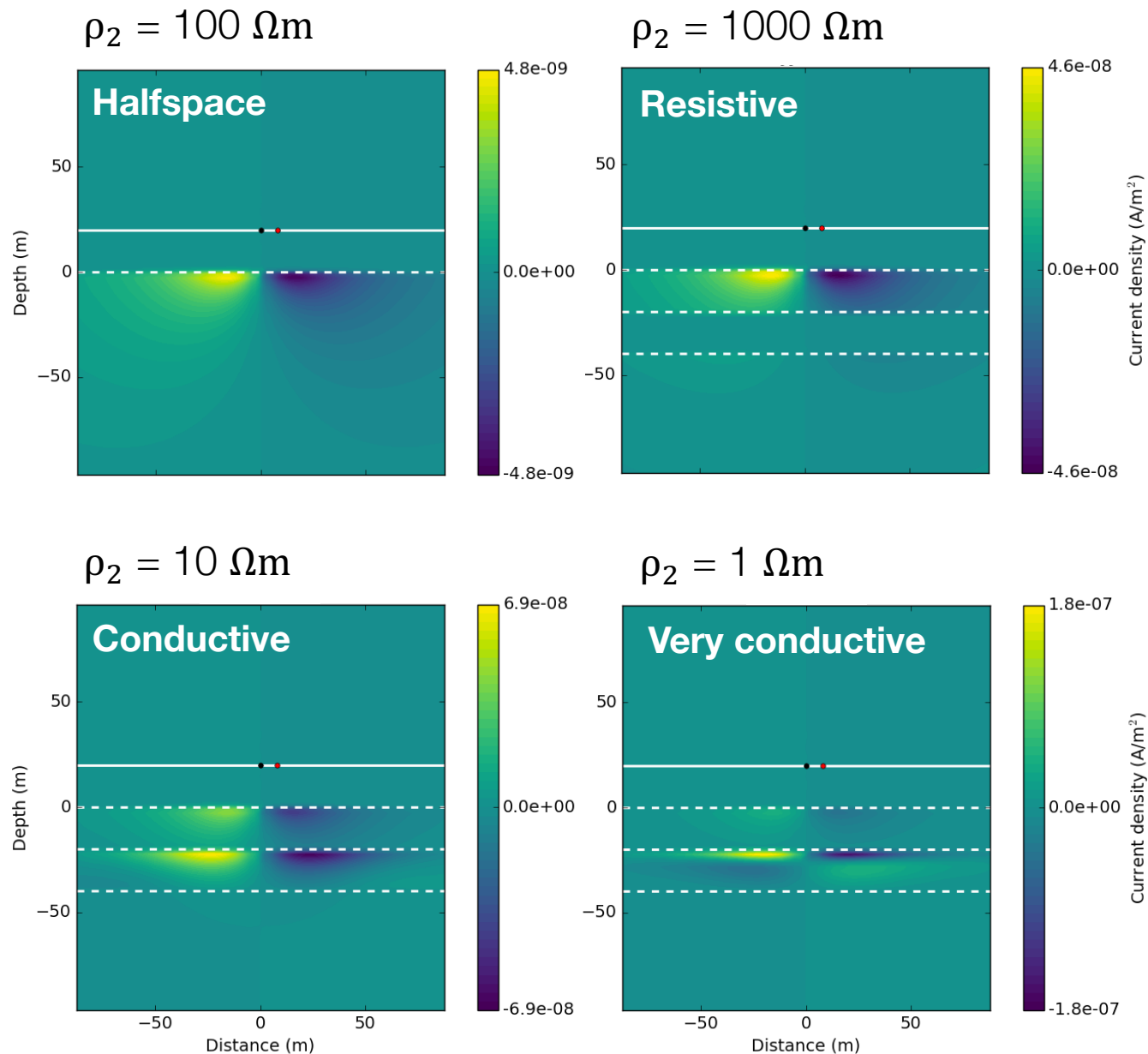
Current density (J_y imag)



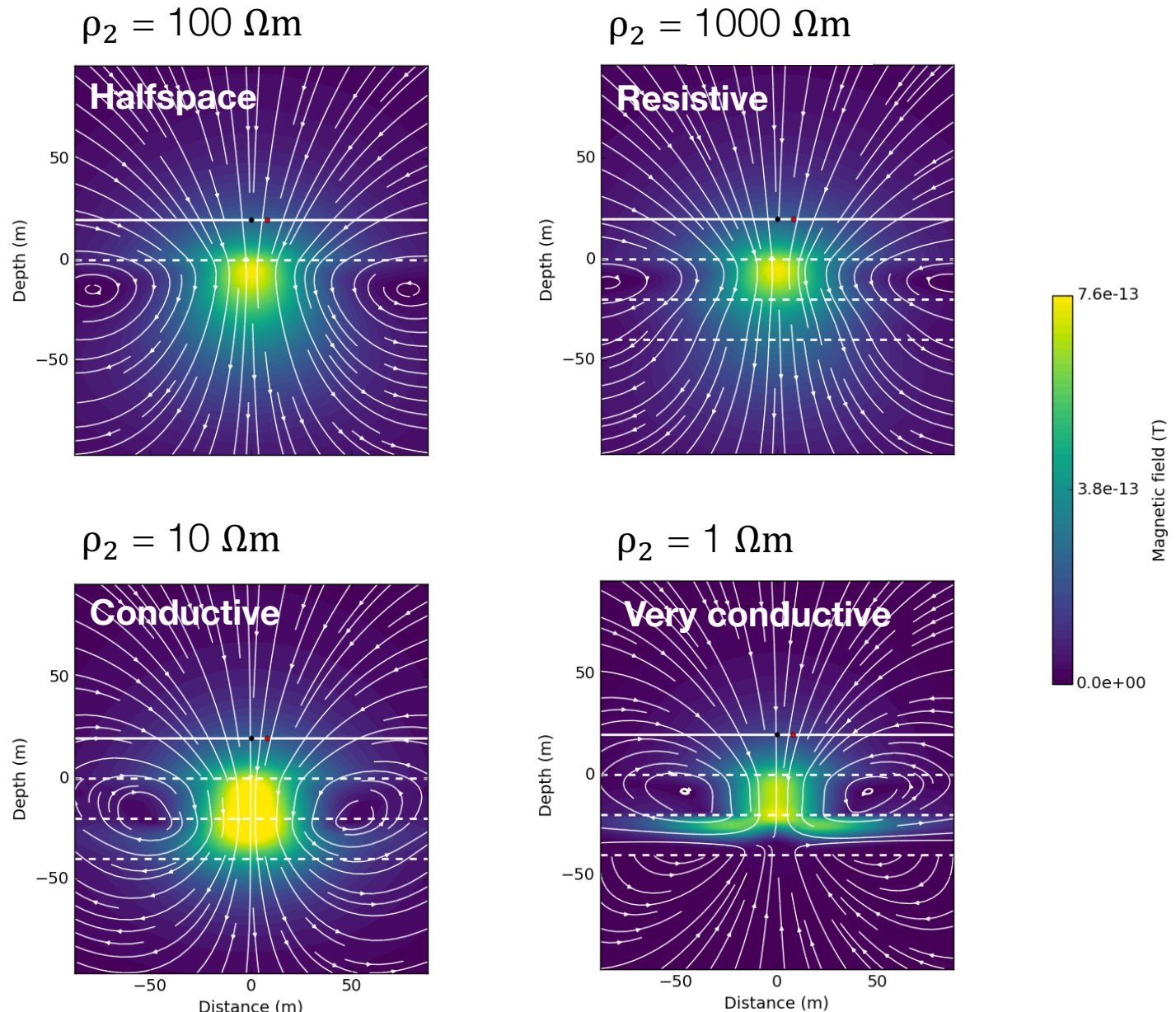
Current density (J_y imag)



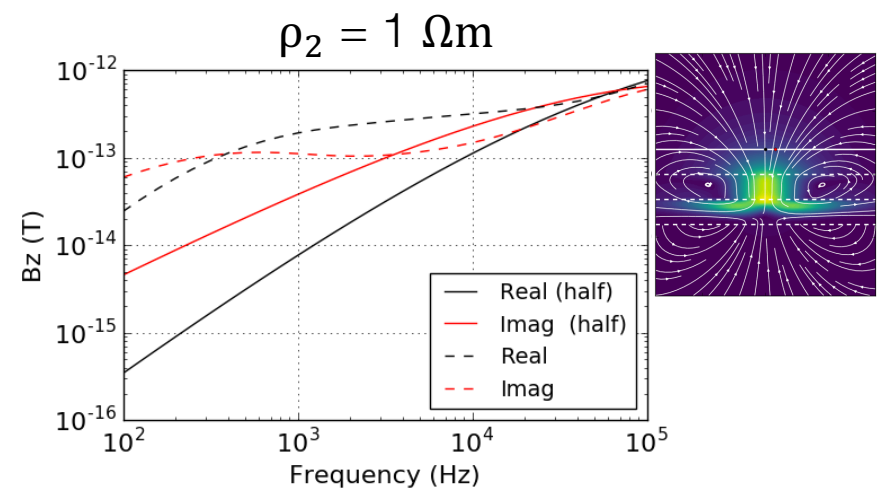
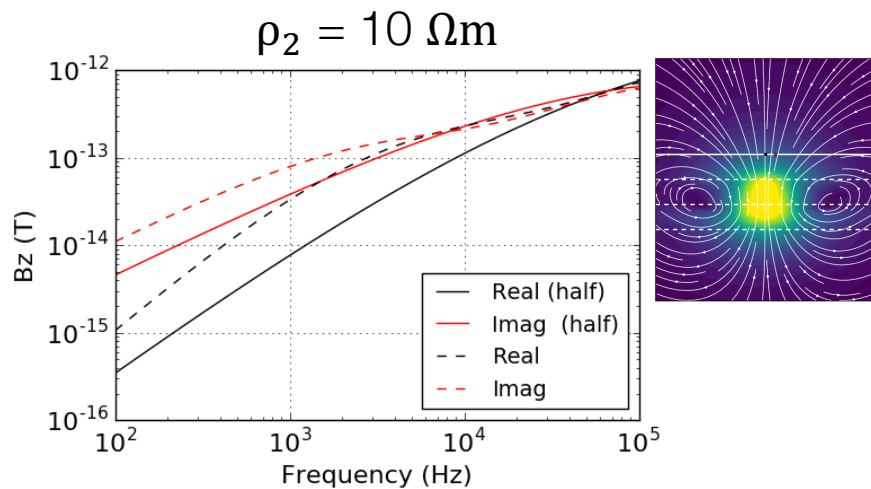
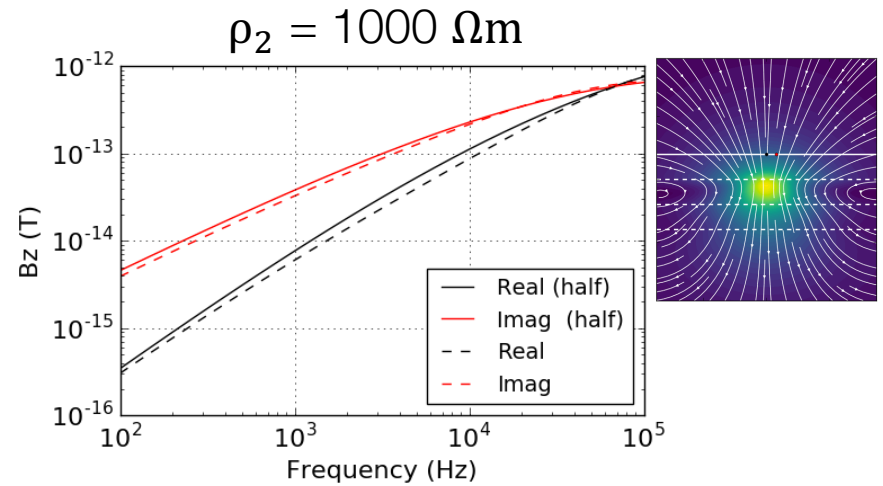
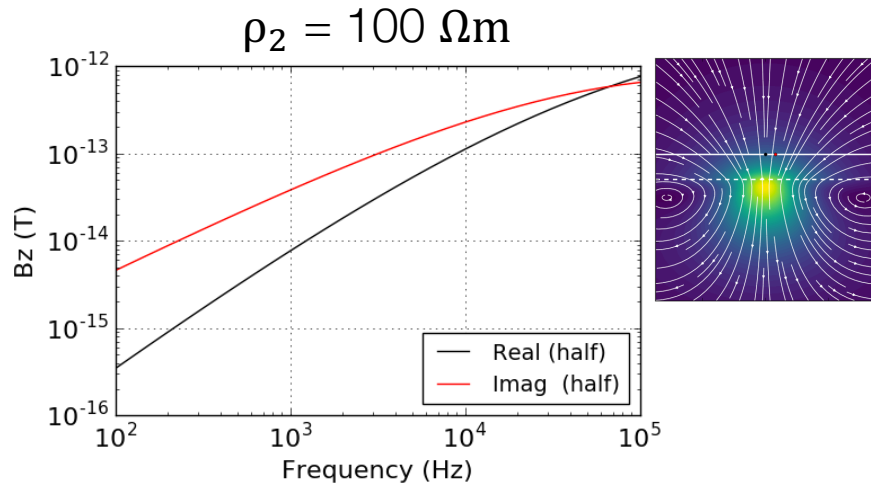
Current density (J_y imag)



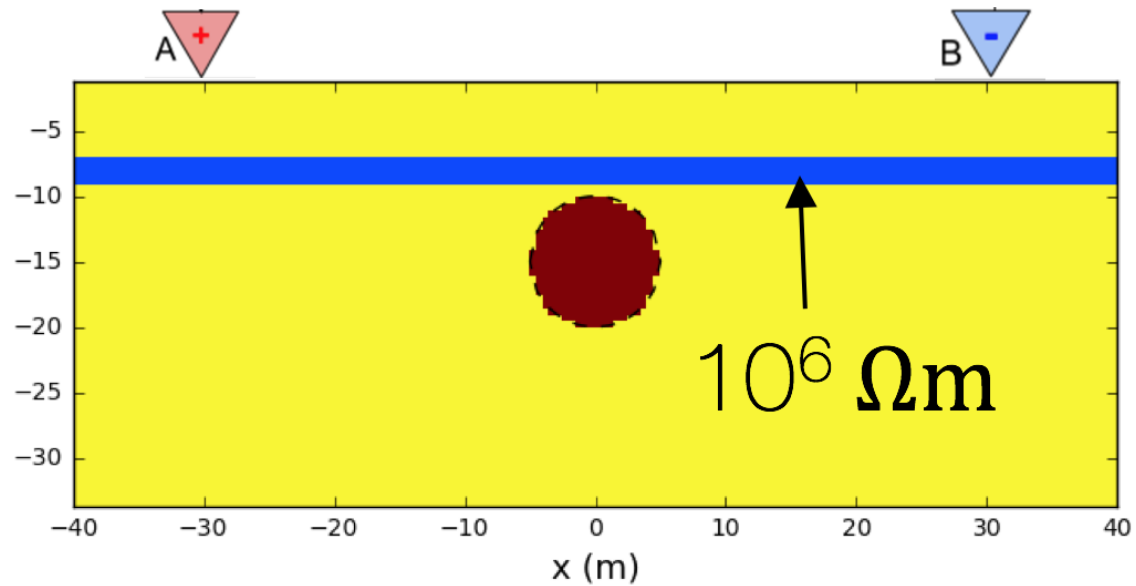
Magnetic flux density (**B** imag)



B_z sounding curves

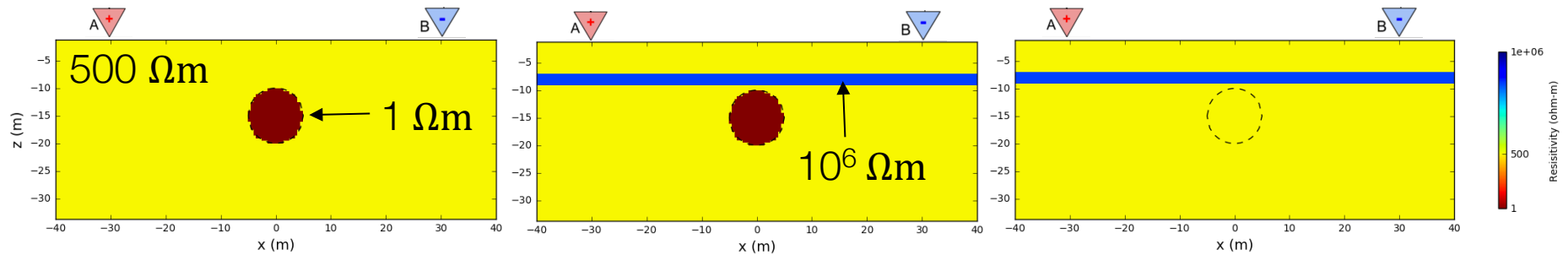


Back to the “shielding” problem

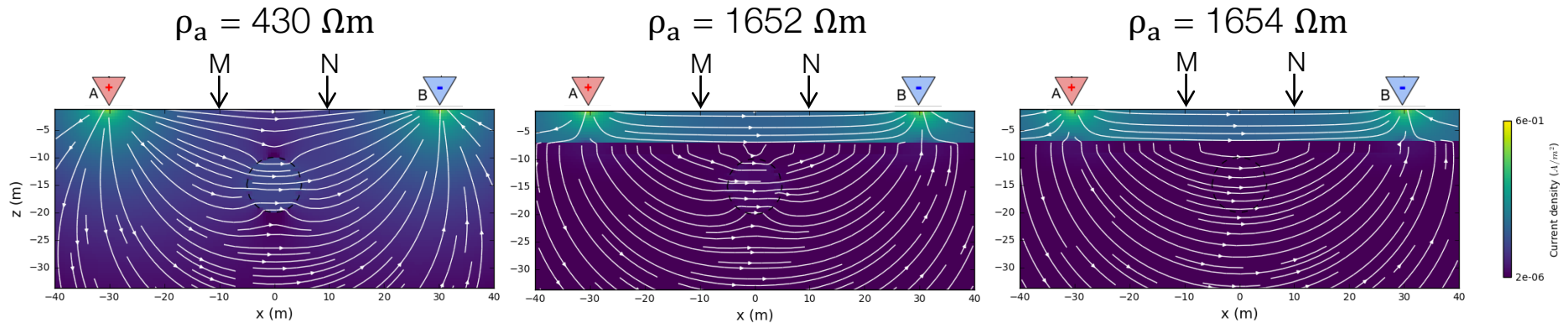


Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)

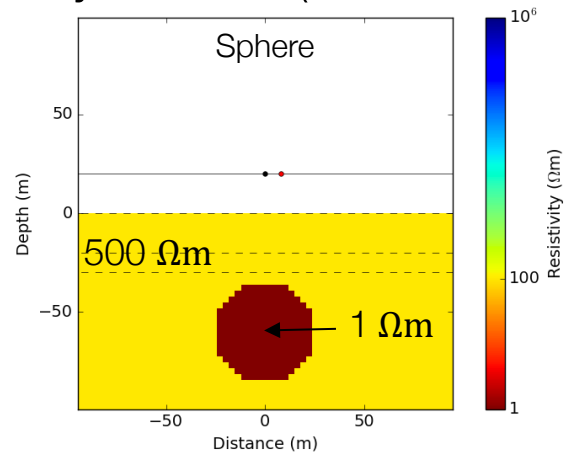


Currents and measured data at MN

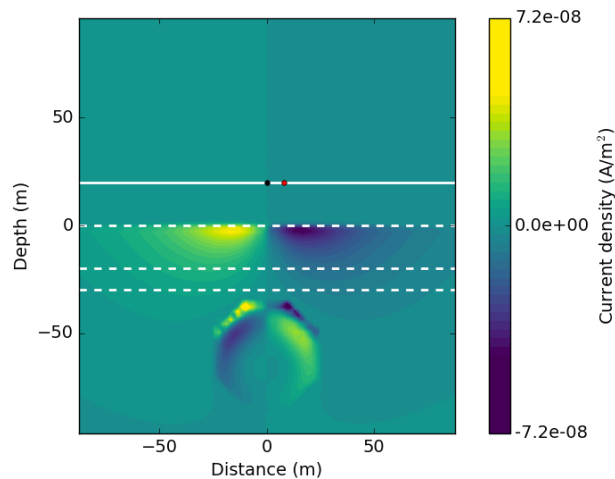


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

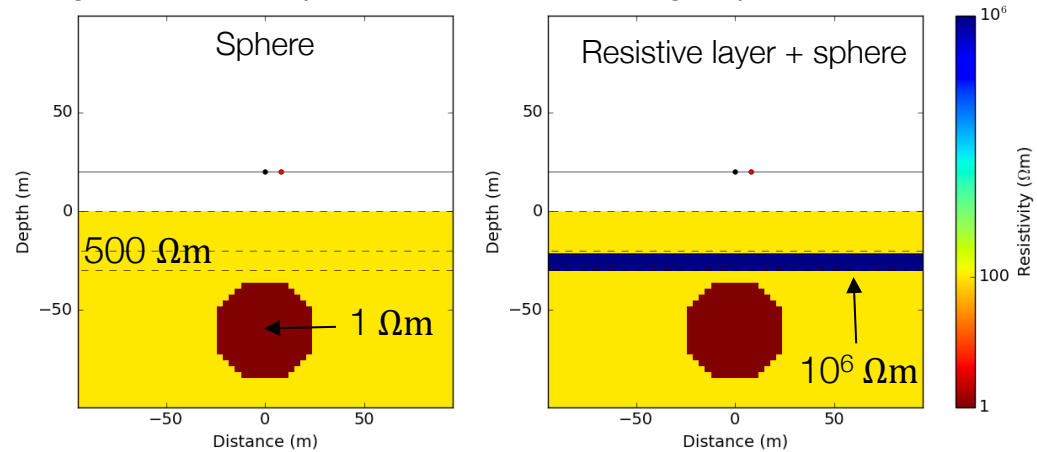


Currents (J_y imag)

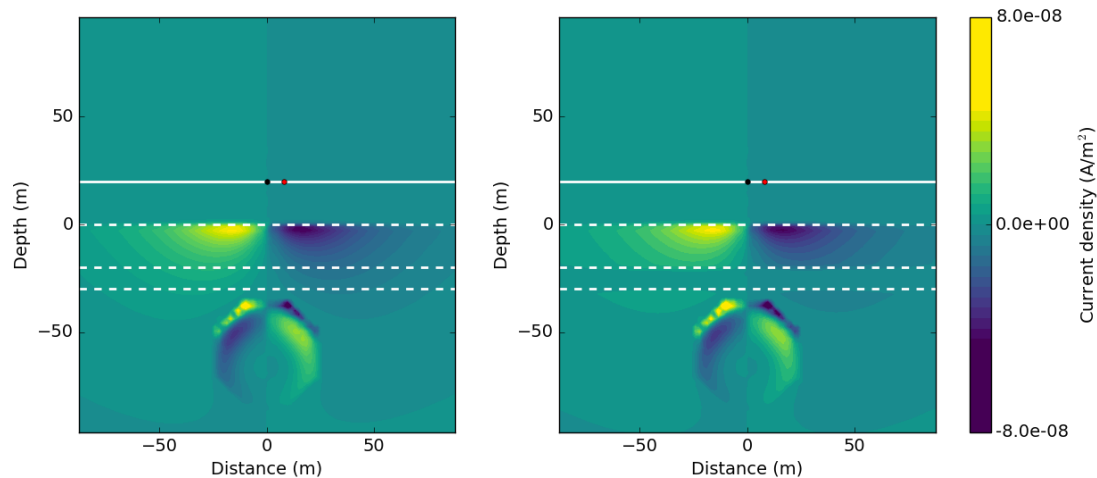


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

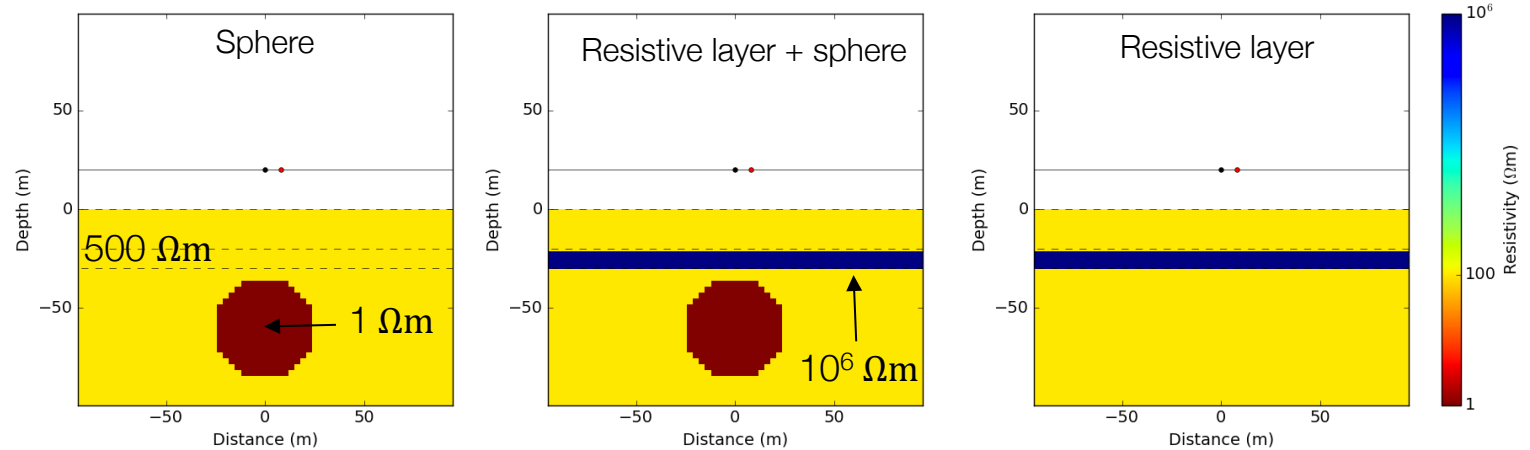


Currents (J_y imag)

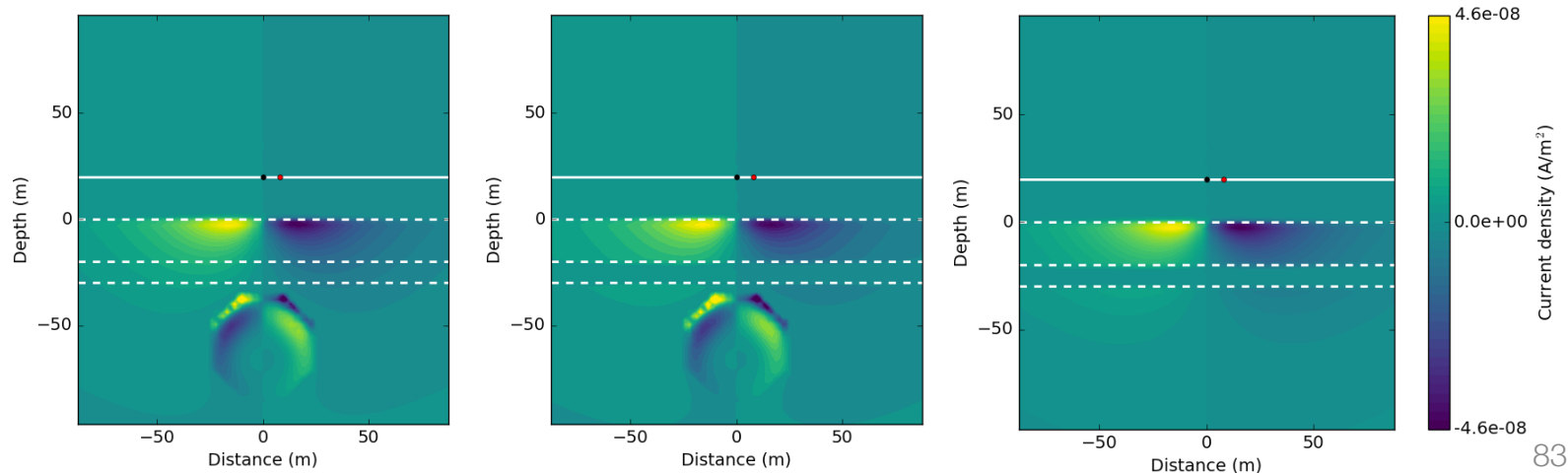


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

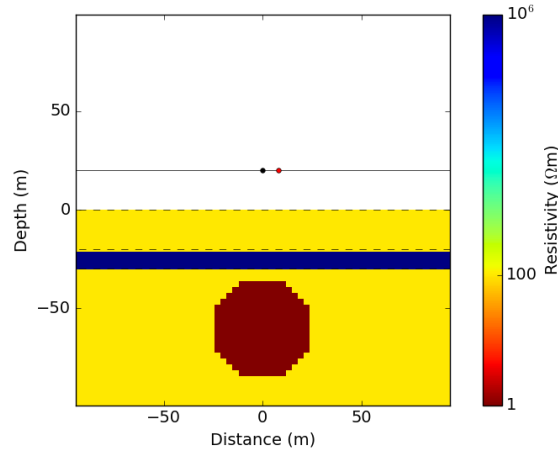


Currents (J_y imag)

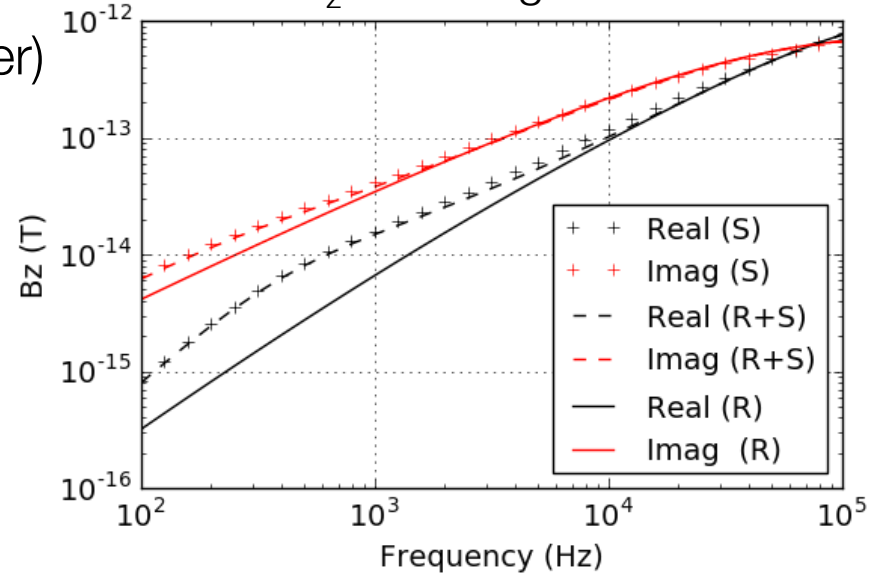


Shielding: EM with resistive layer

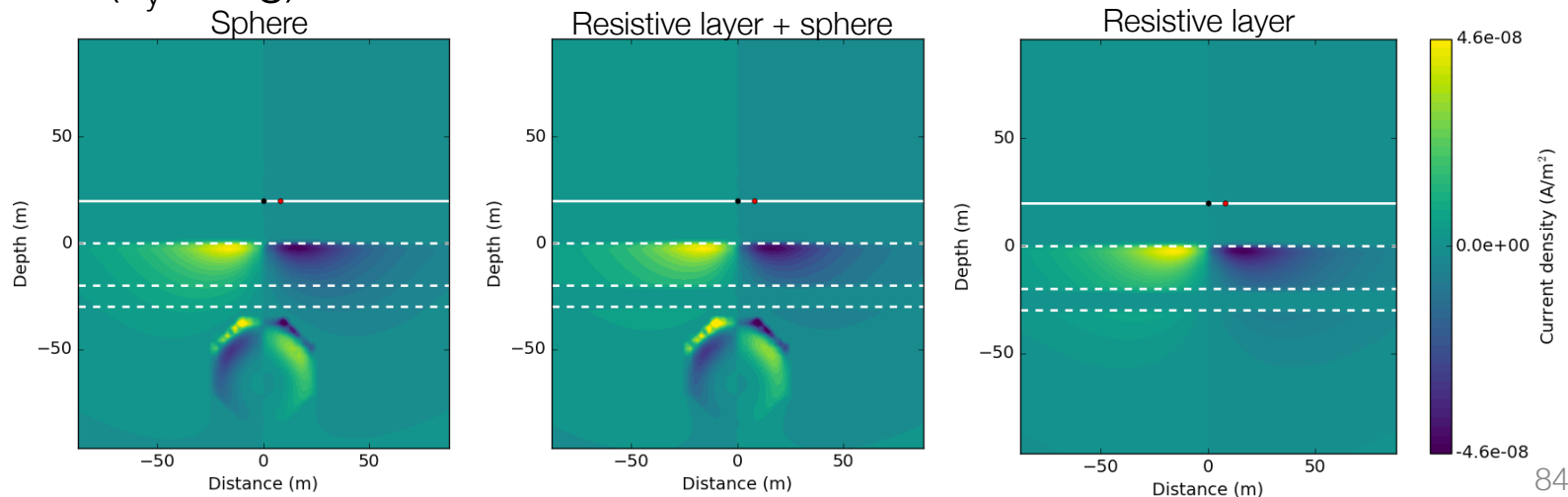
Resistivity models (thin **resistive** layer)



B_z sounding curves

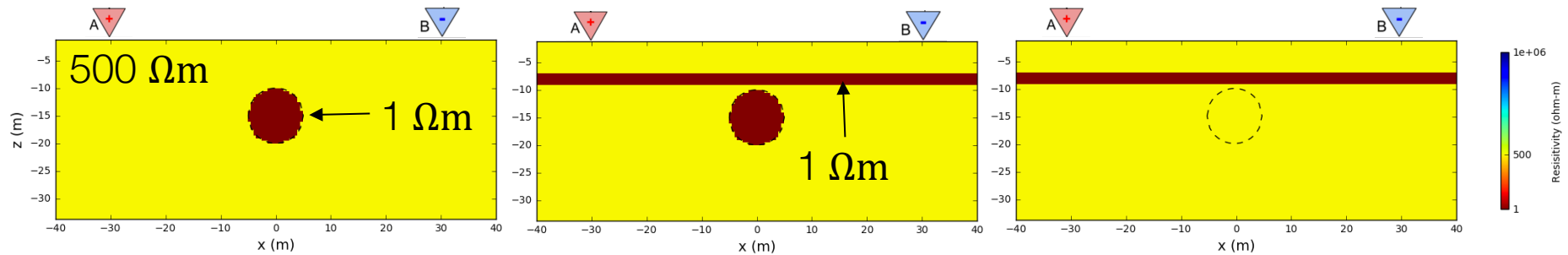


Currents (J_y imag)

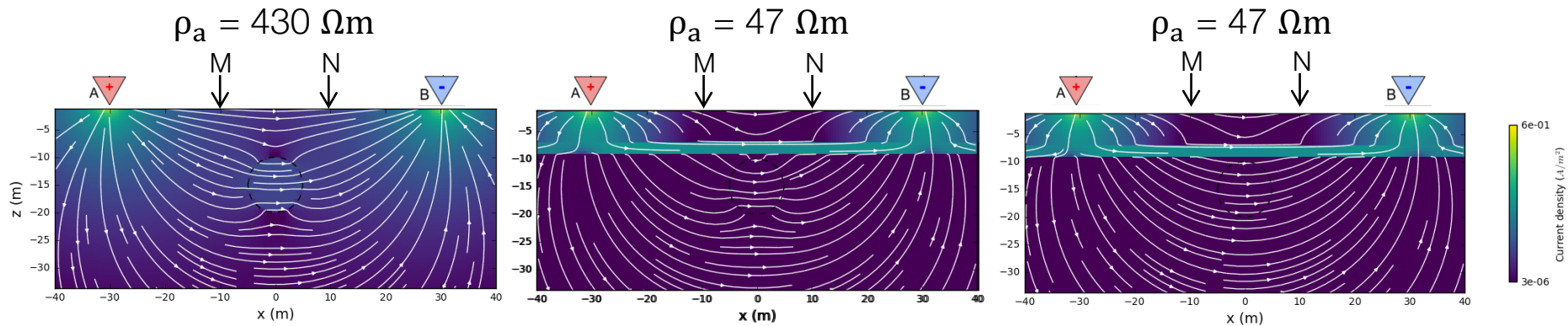


Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)

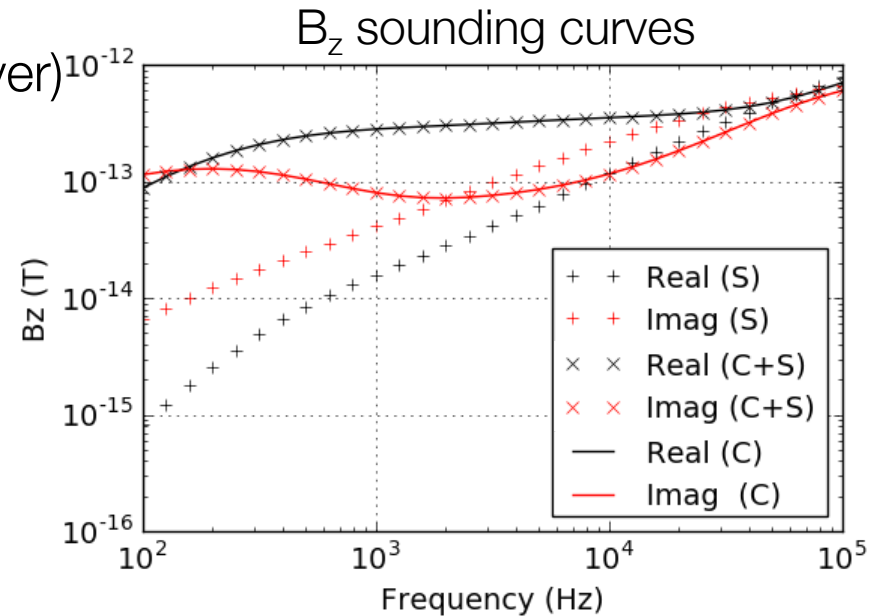
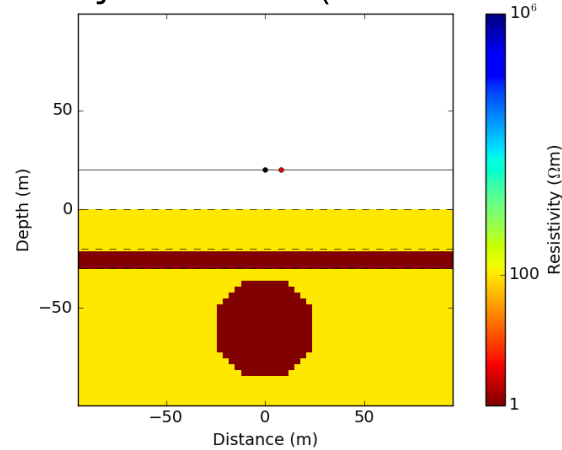


Currents and measured data at MN

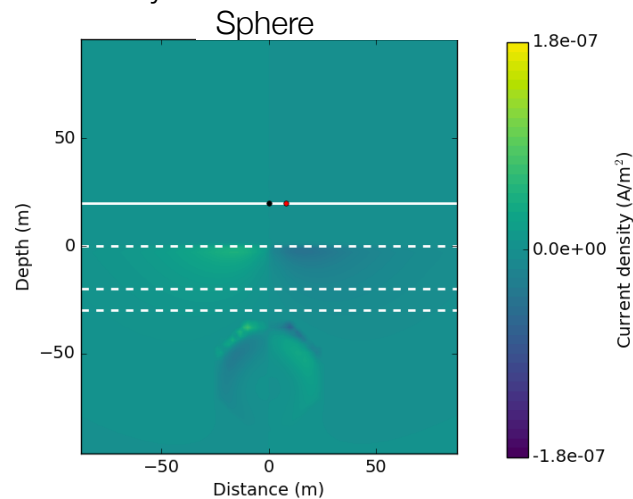


Shielding: EM with conductive layer

Resistivity models (thin **conductive** layer)

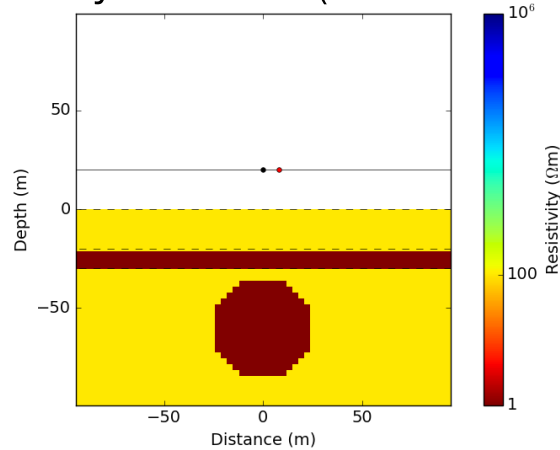


Currents (J_y imag)

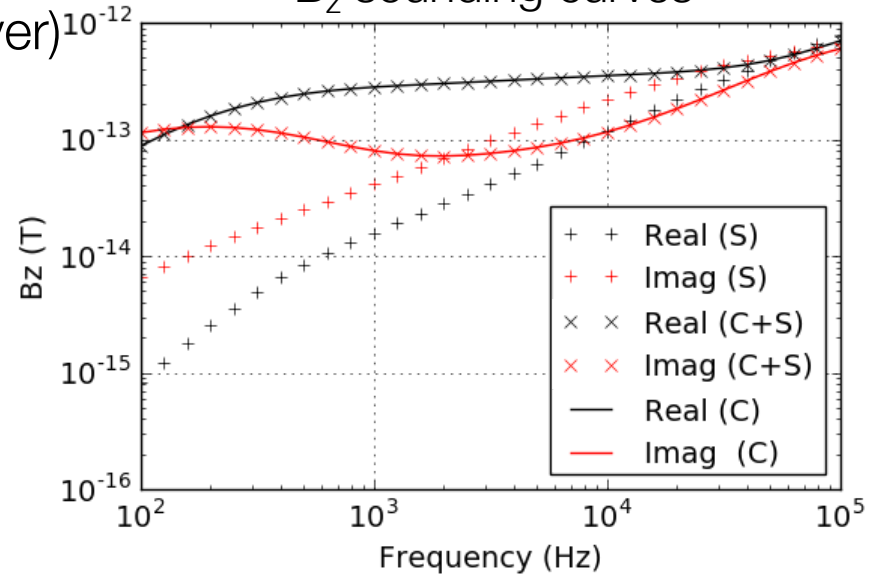


Shielding: EM with conductive layer

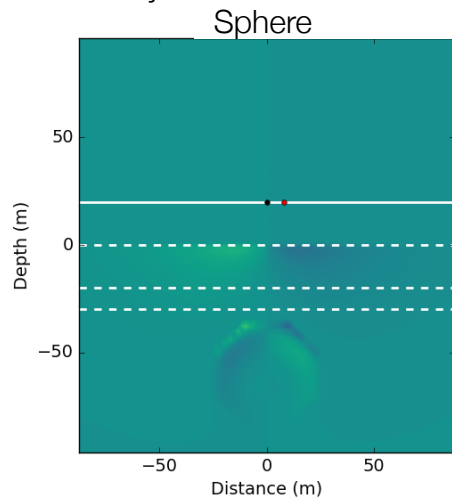
Resistivity models (thin **conductive** layer)



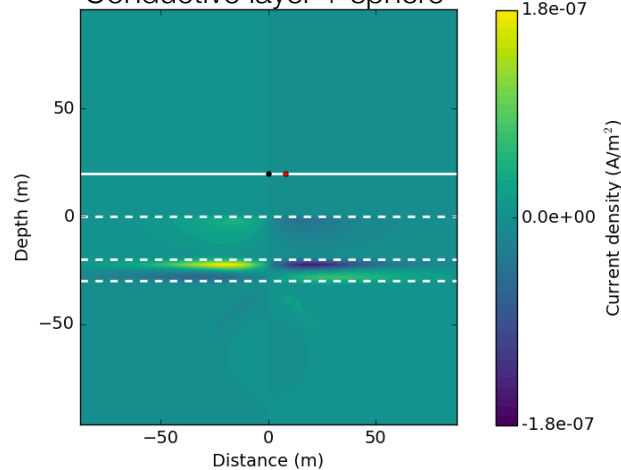
B_z sounding curves



Currents (J_y imag)

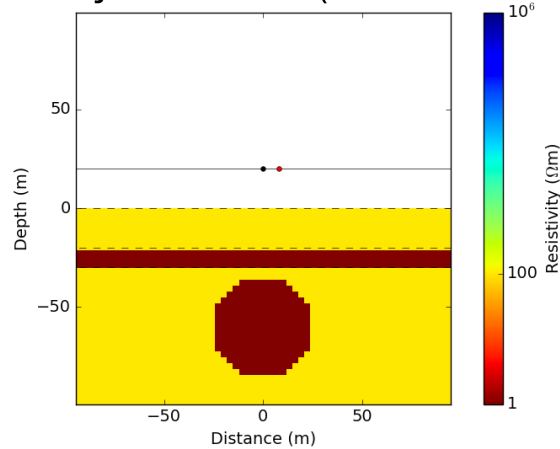


Conductive layer + sphere

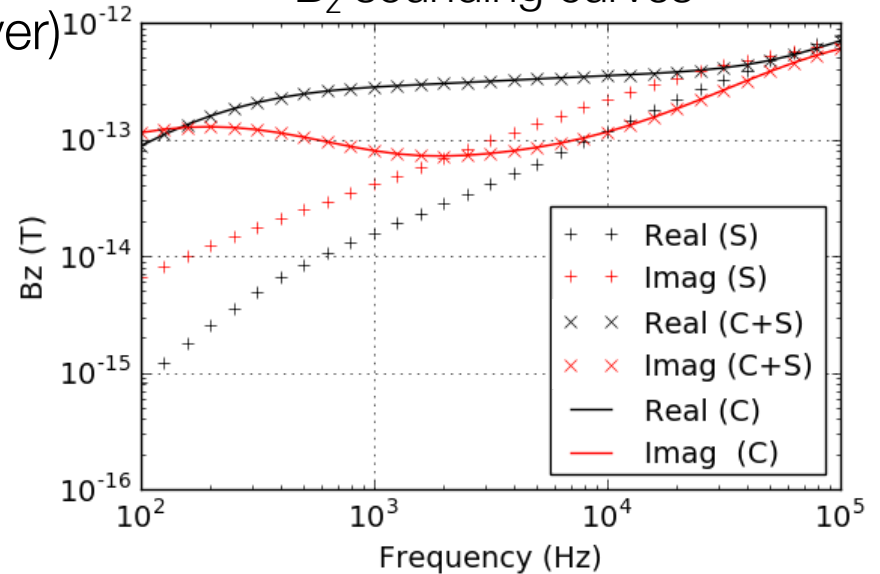


Shielding: EM with conductive layer

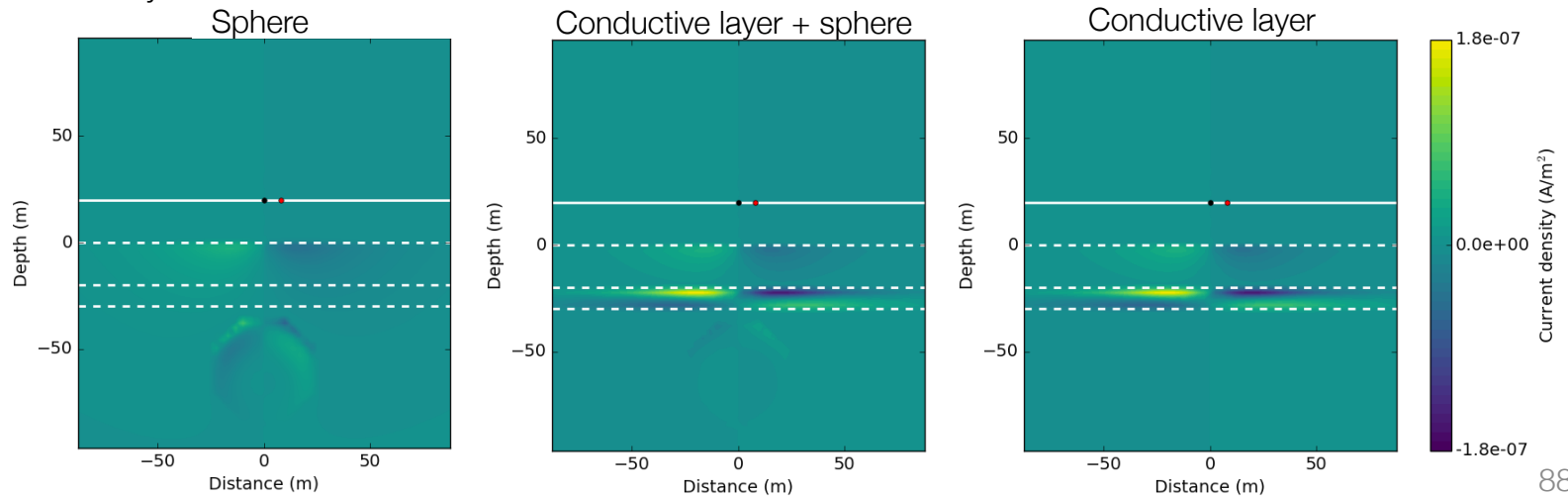
Resistivity models (thin **conductive** layer)



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

Questions

Case History: Bookpurnong

Viezzoli et al., 2009

Setup

Bookpurnong
Irrigation Area

Murray River
Floodplain

1 km

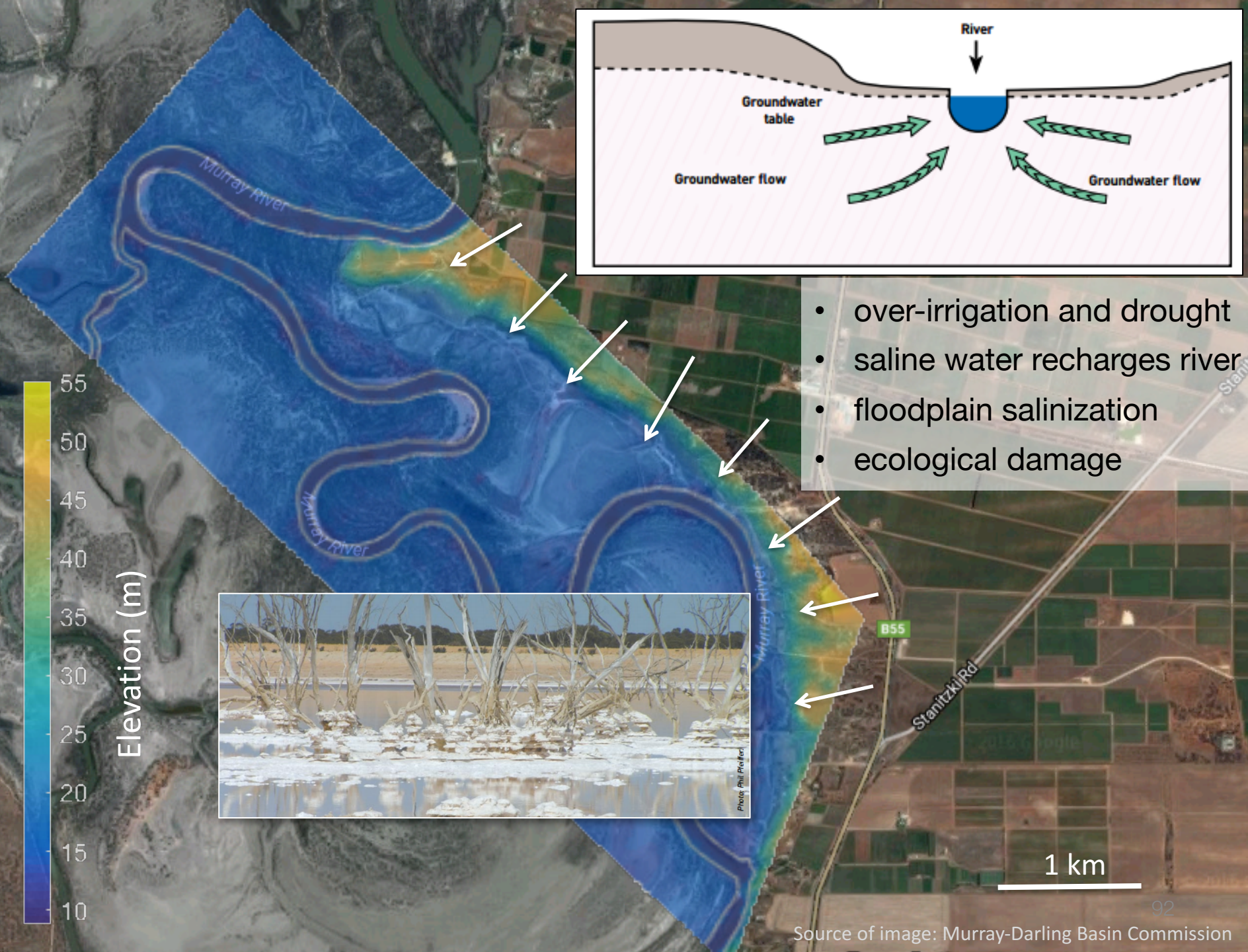
B55

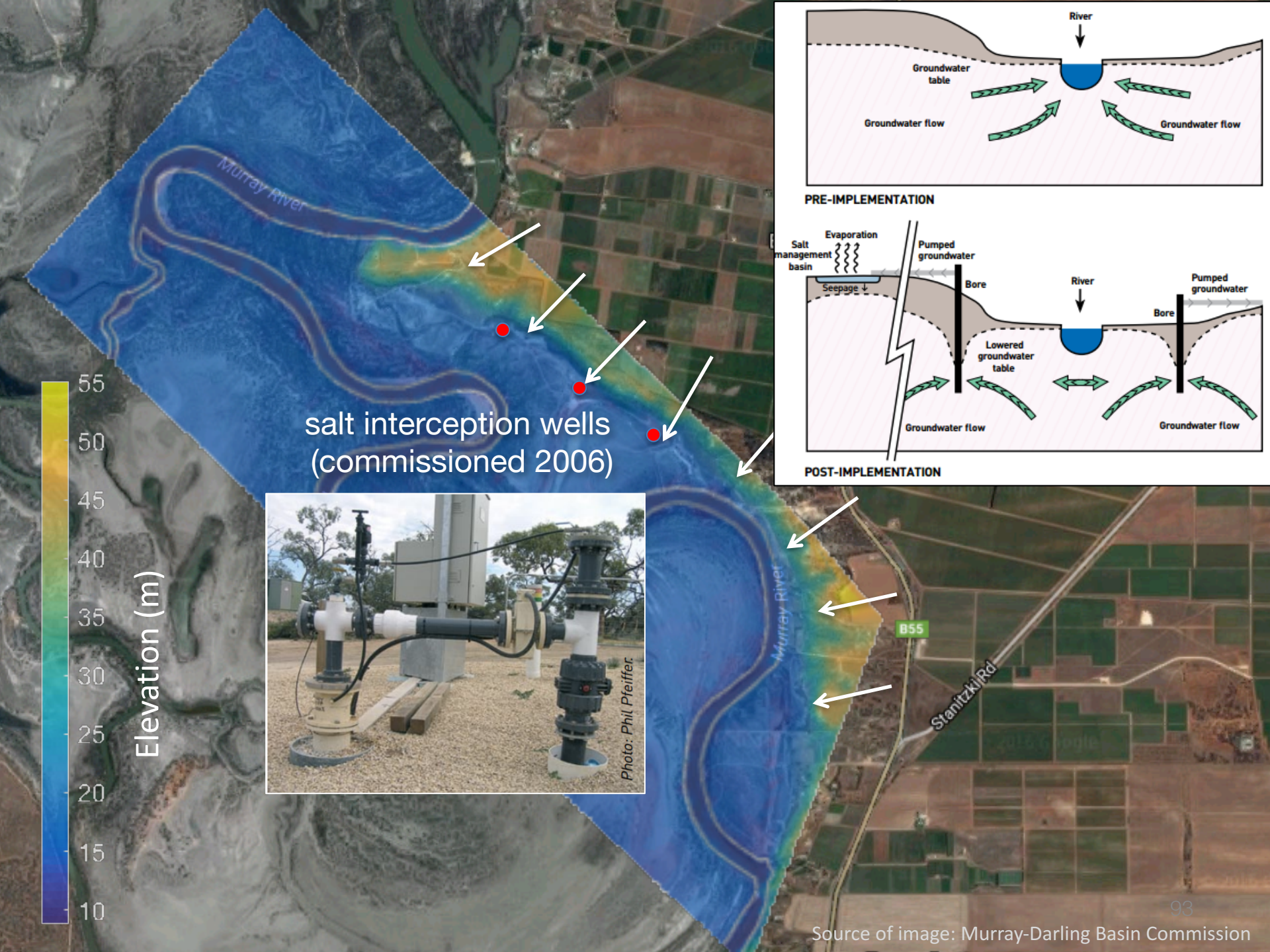
Bookpurnong

Staniford

B55







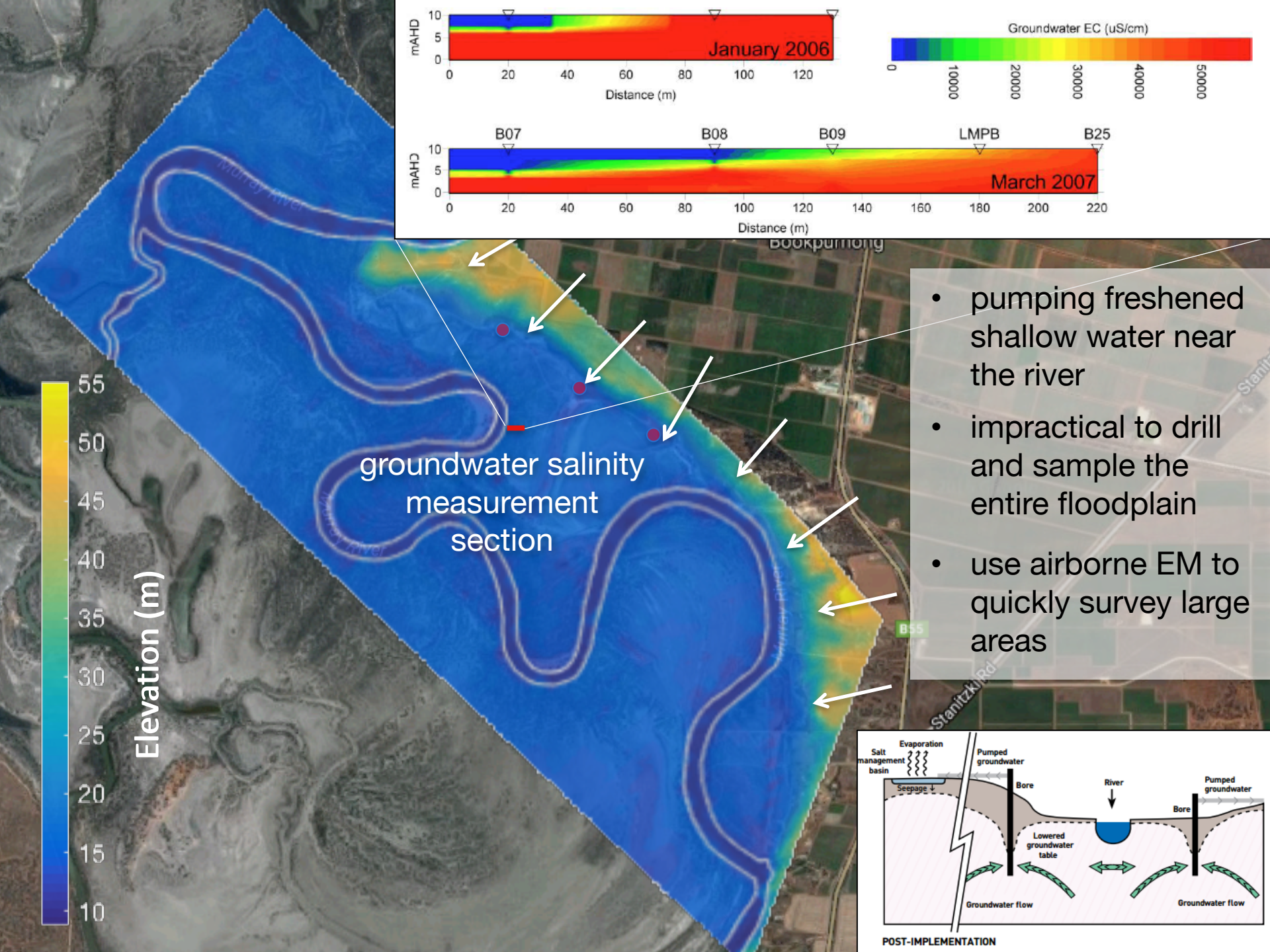
salt interception wells
(commissioned 2006)

Elevation (m)

Photo: Phil Pfeiffer.

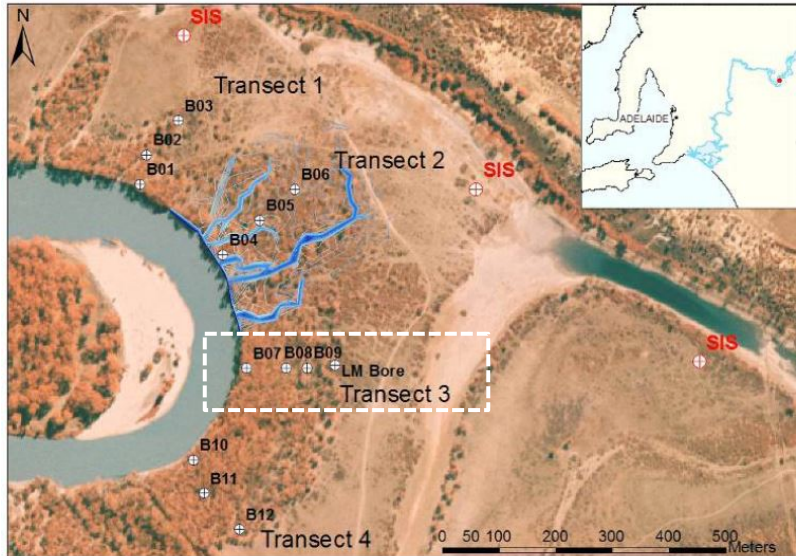
PRE-IMPLEMENTATION

POST-IMPLEMENTATION



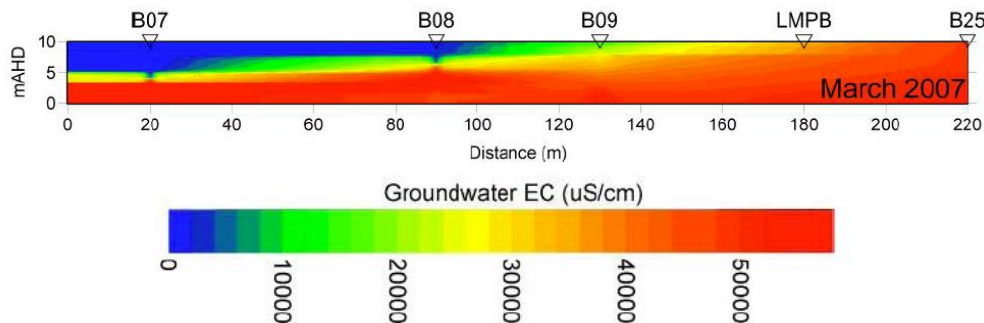
Properties

Location map for salinity measurements



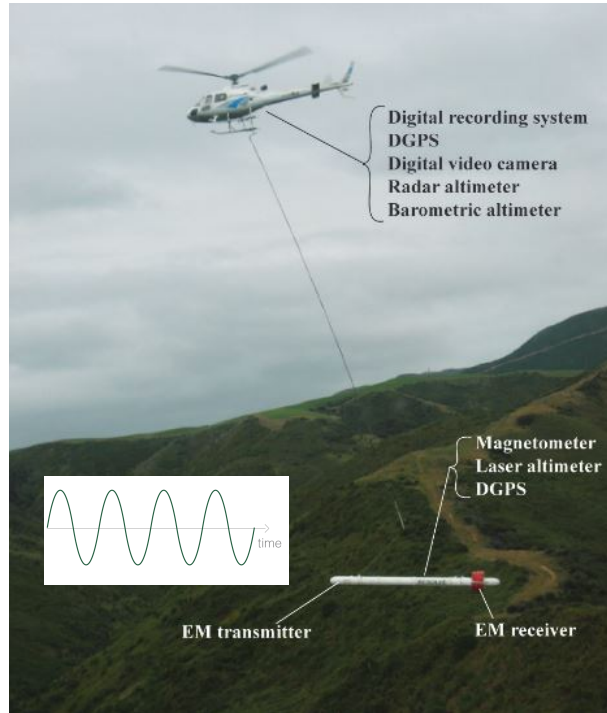
Unit	Conductivity
Saline water	High, 3 - 5 S/m
Fresh water	Low, 0.01 S/m

Conductivity from salinity measurements

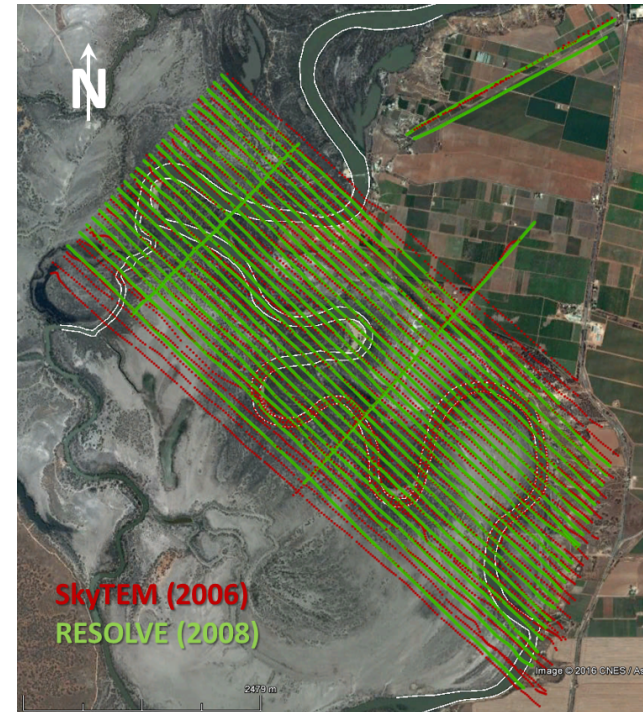


Survey

Resolve system (2008)



Flight lines



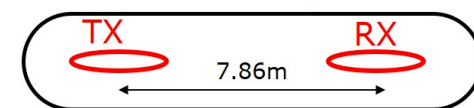
Horizontal Co-planar (HCP) frequencies:

- 382, 1822, 7970, 35920 and 130100 Hz

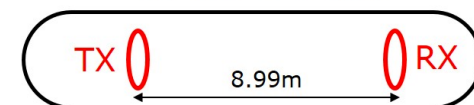
Vertical Co-axial (VCA) frequencies:

- 3258 Hz

Horizontal Co-planar



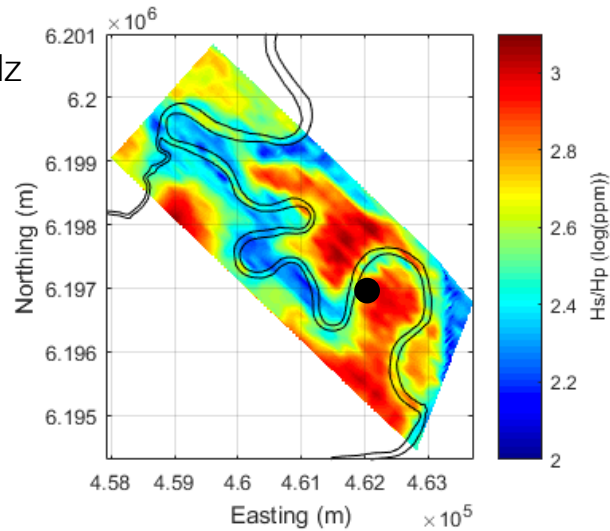
Vertical Co-axial



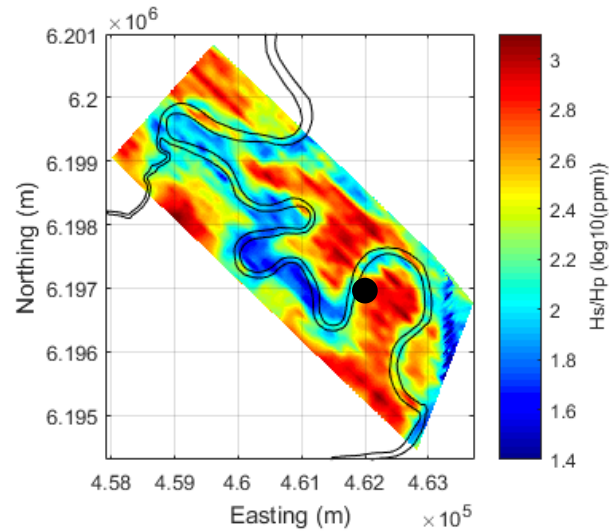
Horizontal Co-planar (HCP) data

In-Phase (Real)

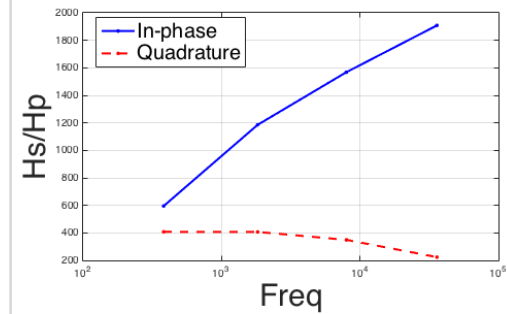
382 Hz



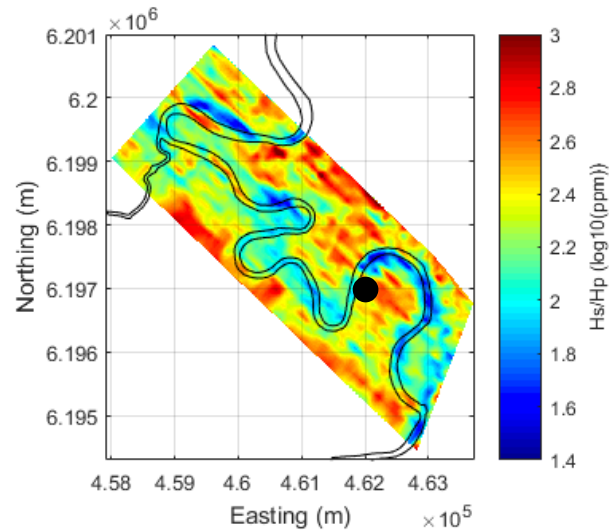
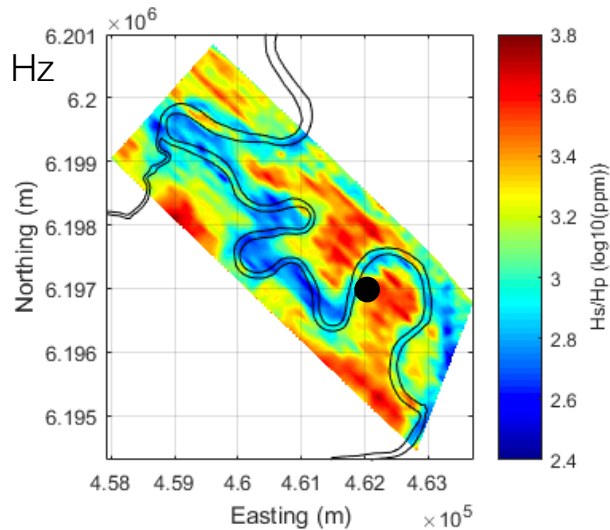
Quadrature (Imaginary)



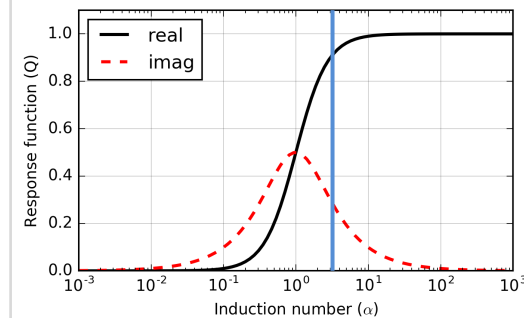
Sounding curve



35920 Hz

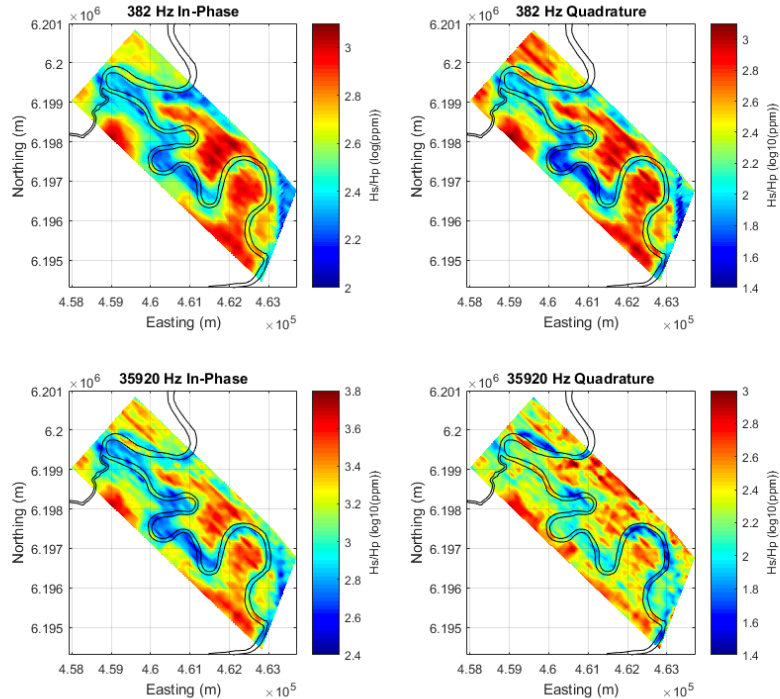


Response curve

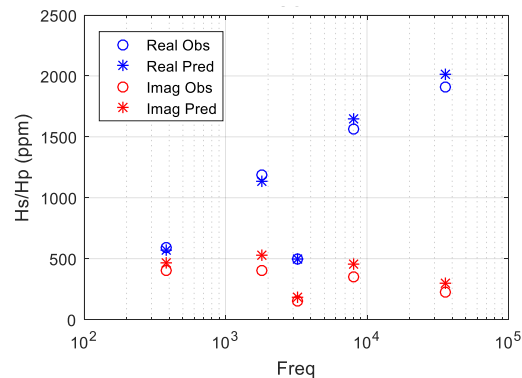


Processing: 1D inversion

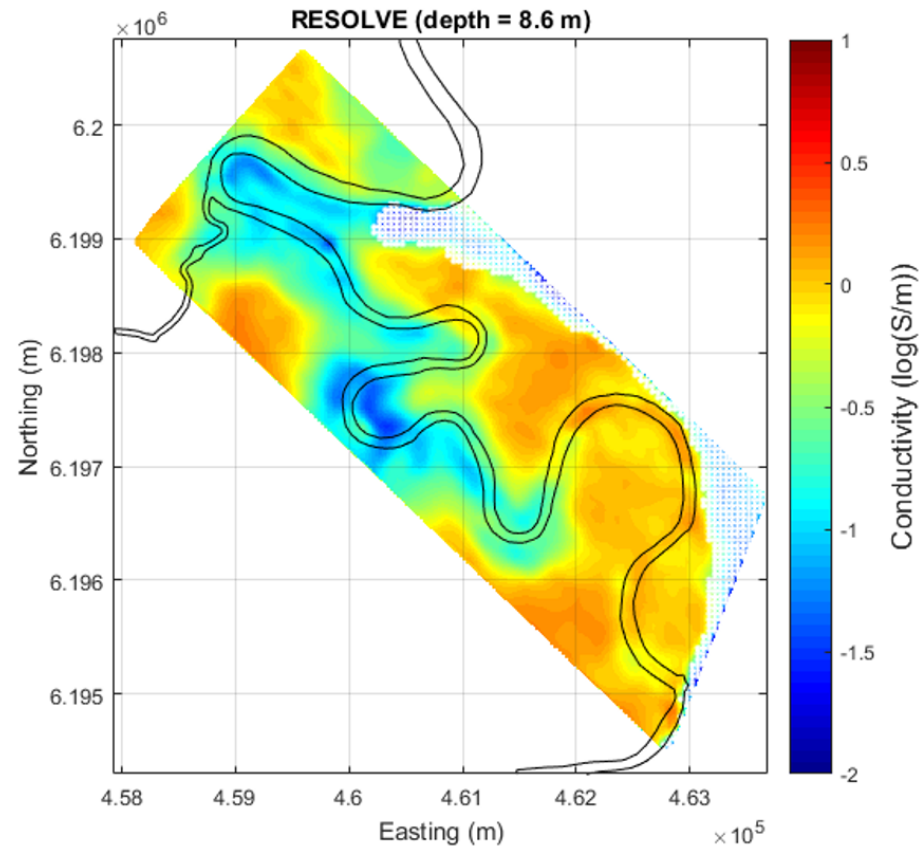
Data



Data fit

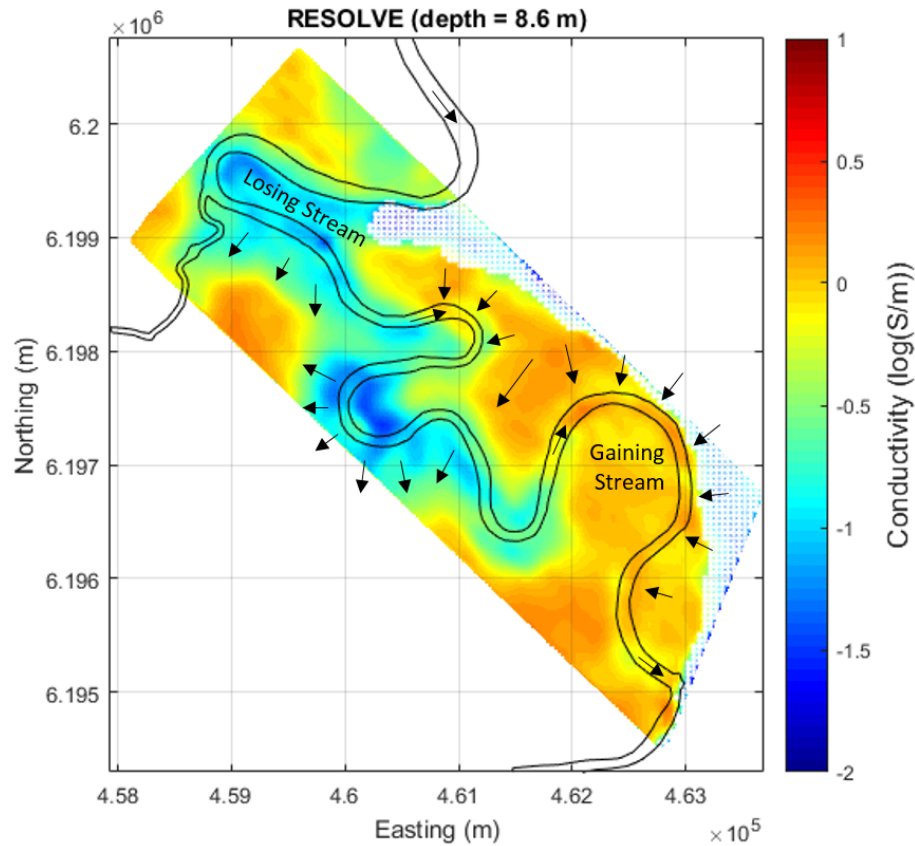


Conductivity model (stitched)

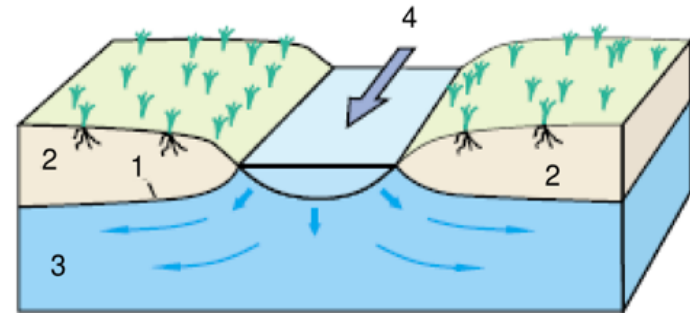


Interpretation

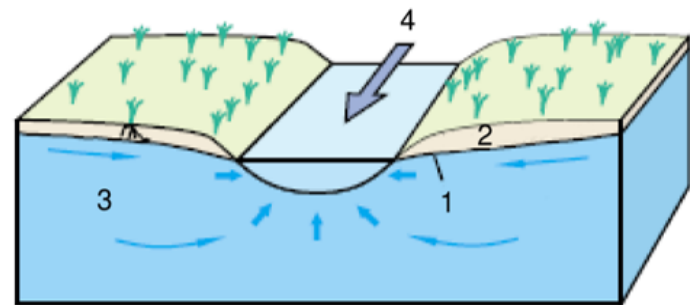
Conductivity model (stitched)



Losing Stream



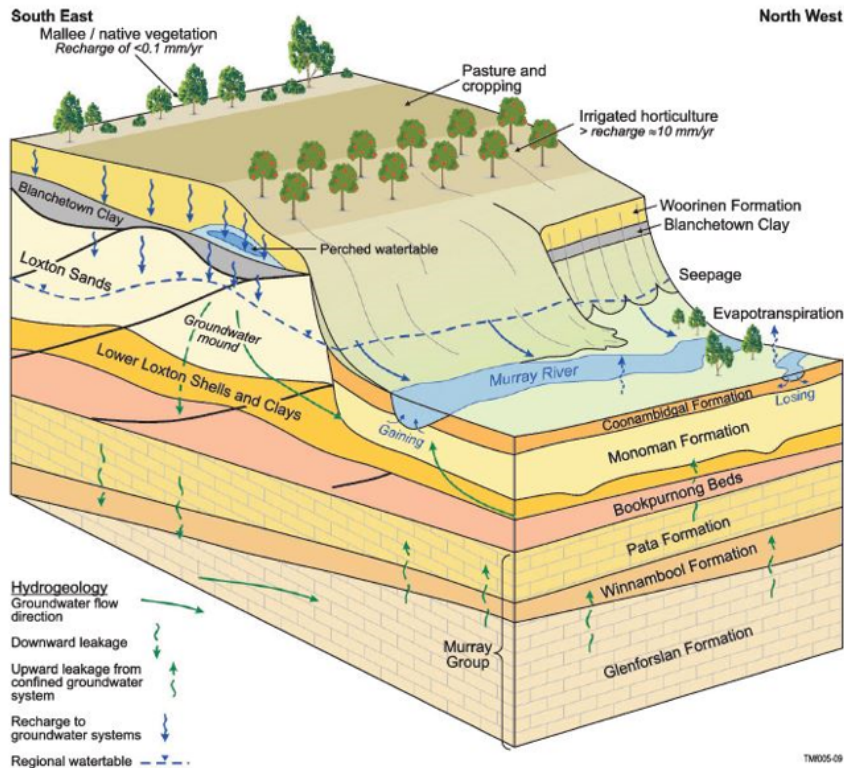
Gaining Stream



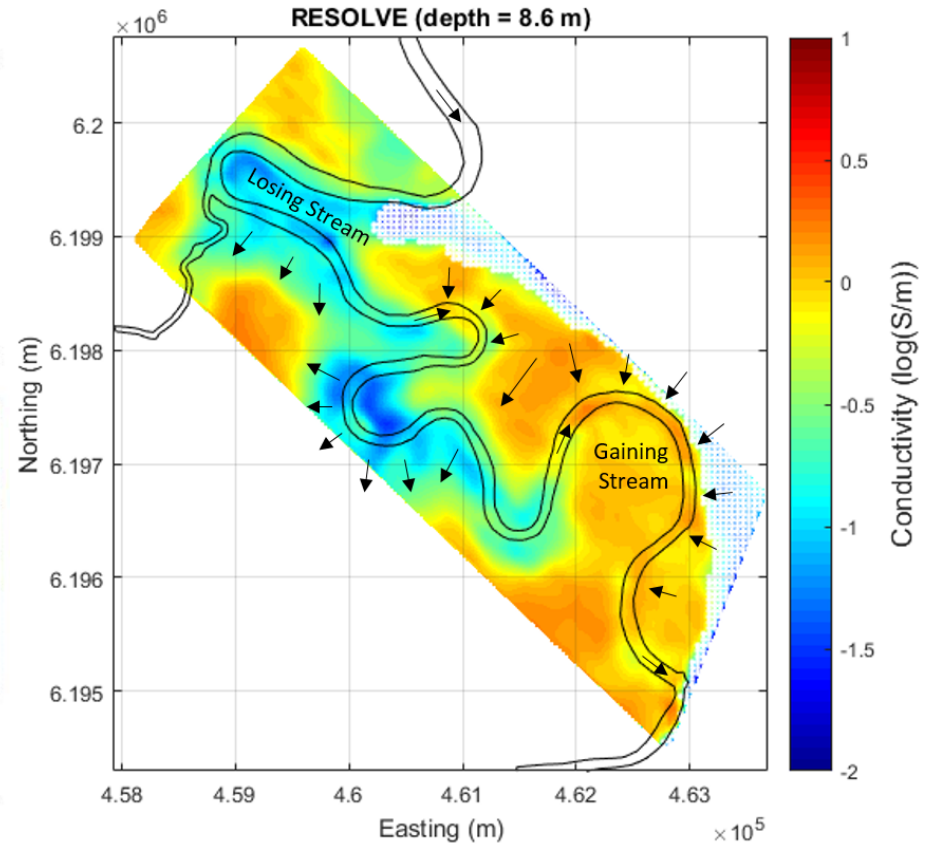
- 1 – Water table 2 – Unsaturated zone
3 – Saturated zone 4 – Flow direction

Synthesis

Hydrological model

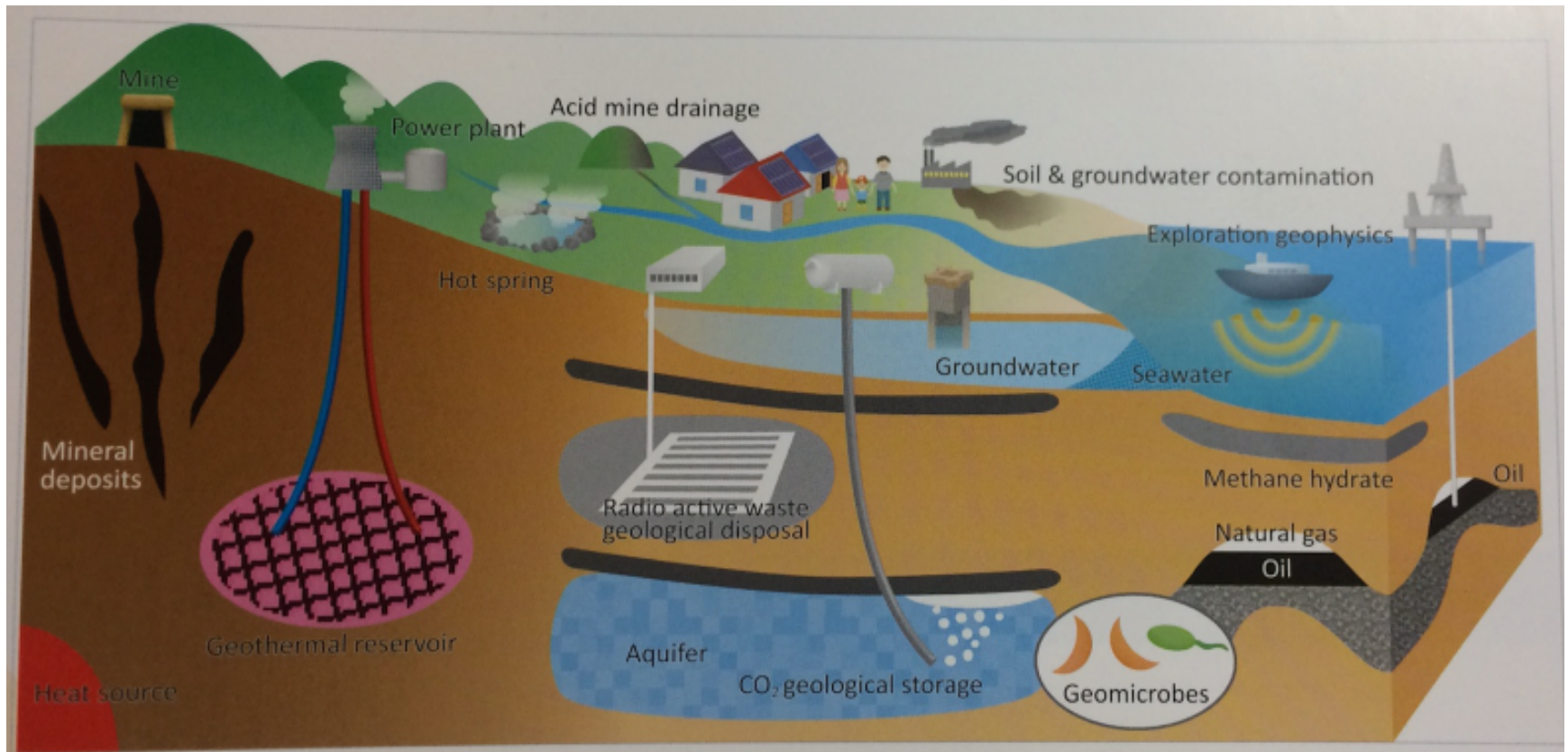


Conductivity model (stitched)



An example from DISC Tokyo

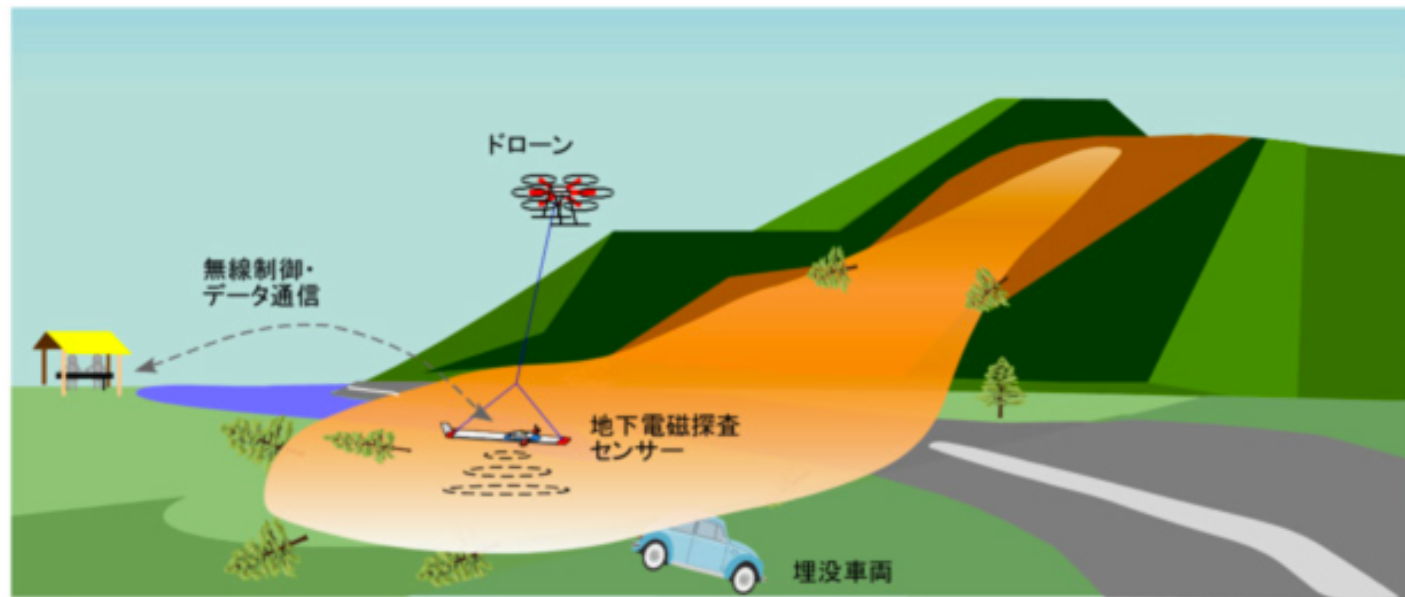
DISC Tokyo...



EM Geophysics using Drone Technology: AIST

Setup:

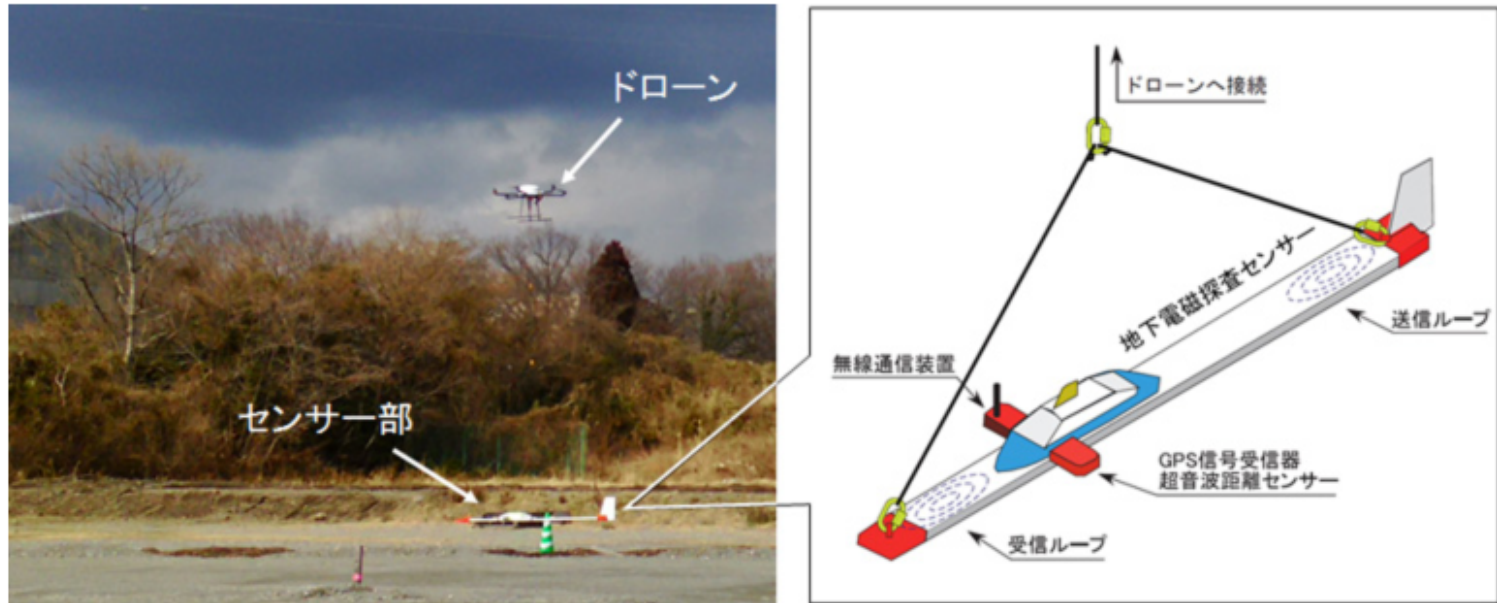
- Develop FDEM system for a drone
- Application: near surface geophysics problems
- Example: find automobiles buried in a landslide



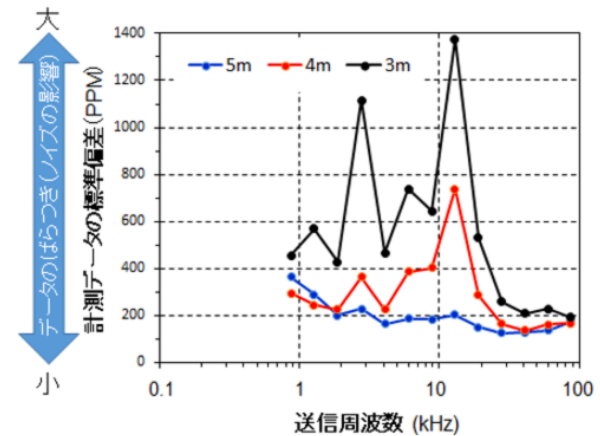
Exploration image of buried vehicles at the site of sediment-related disasters by developed system

Survey equipment

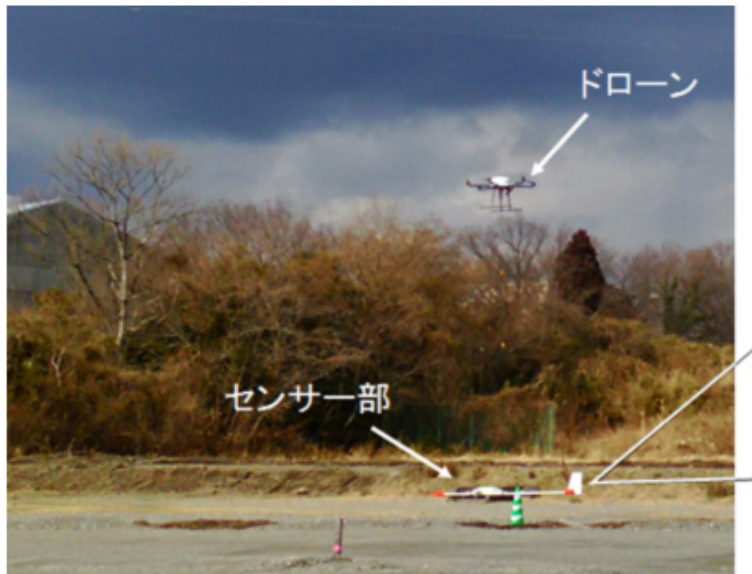
Drone EM system



- 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 $1/r^3$)

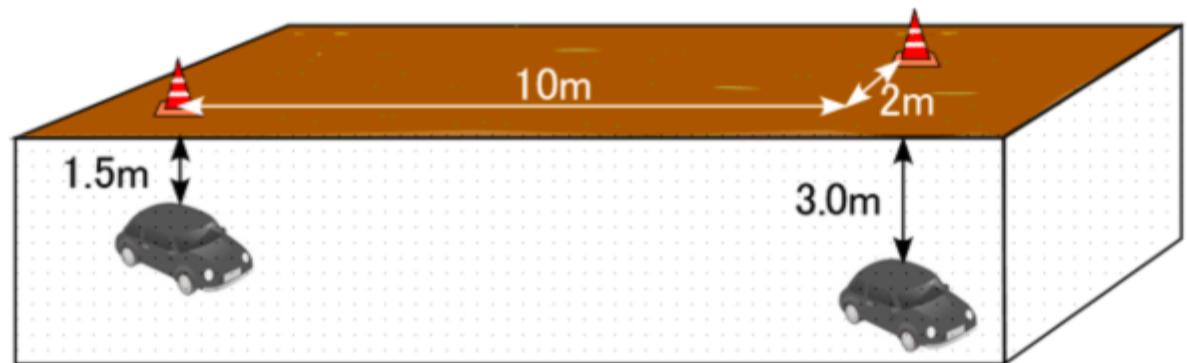


Fig. 4 Arrangement of the burial vehicle experiment site of the construction laboratory site
Two buried mini vehicles are buried in the ground of 1.5 m depth and 3.0 m depth, respectively.

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

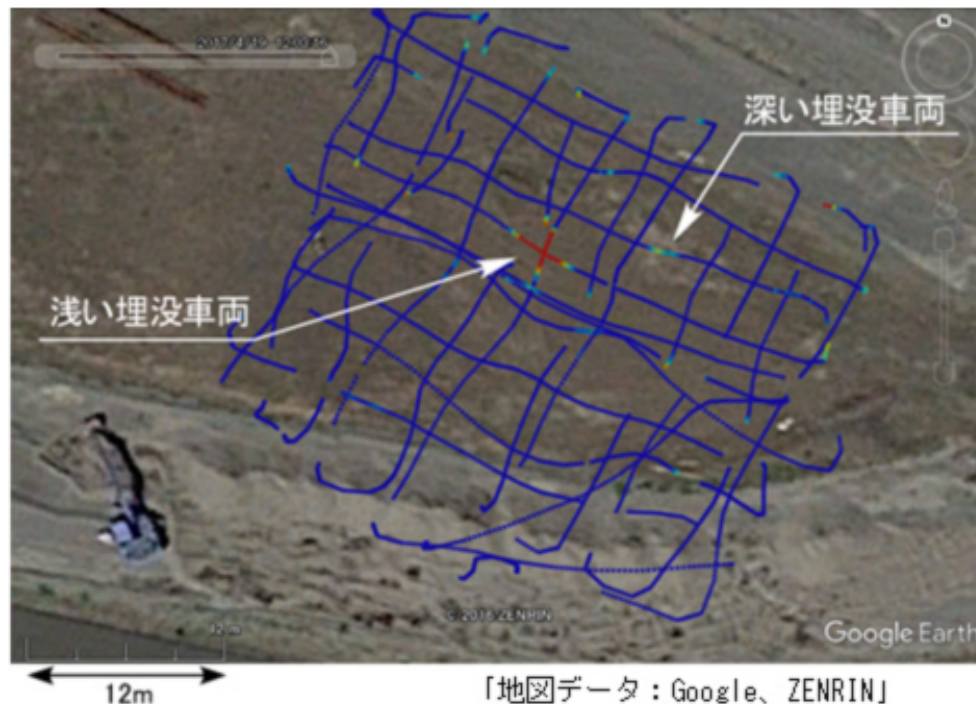


Fig. 6 Exploration data by precision drone navigation measurement (measurement frequency 60 kHz)

Additional Material

- Tutorial on UXO
- Case History:
 - Pole Mountain (UXO)
 - HeliSam (Minerals)
 - La Magdalena (Minerals)

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



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



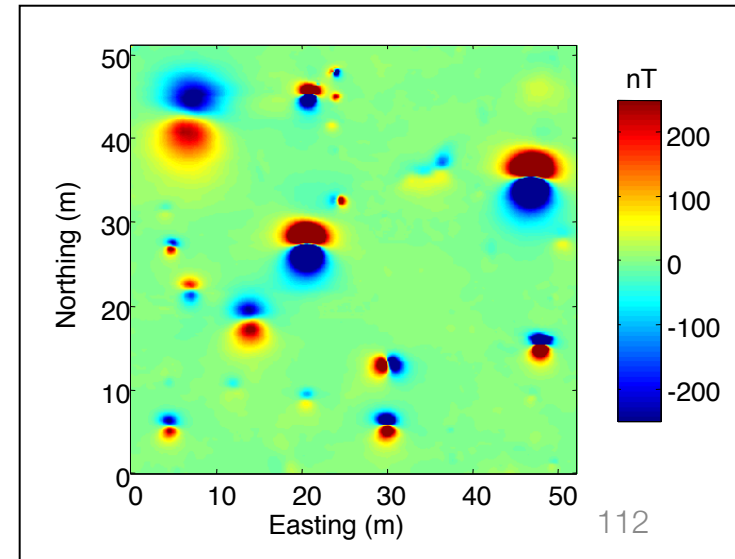
Ferrex



- Digital data
- Look for magnetic dipoles



TM4



Magnetic Survey: Dig Anomalies



76mm
High Cap

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

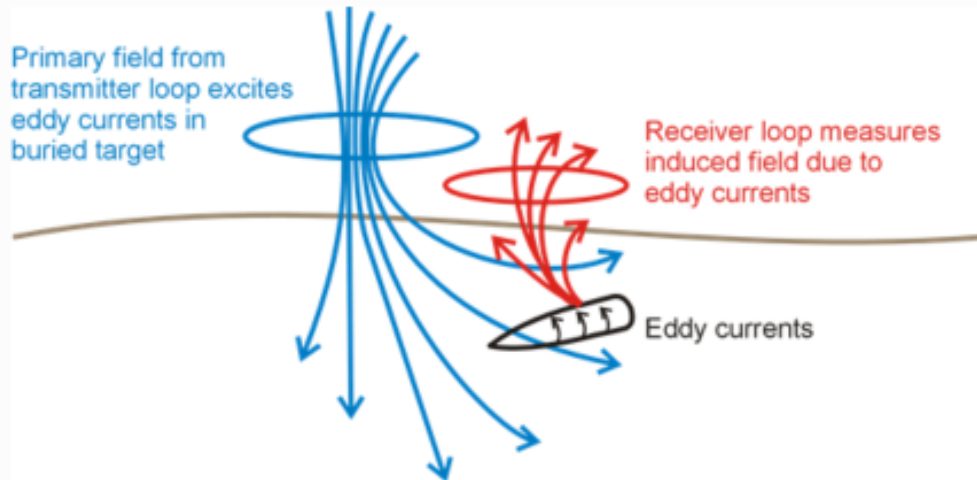
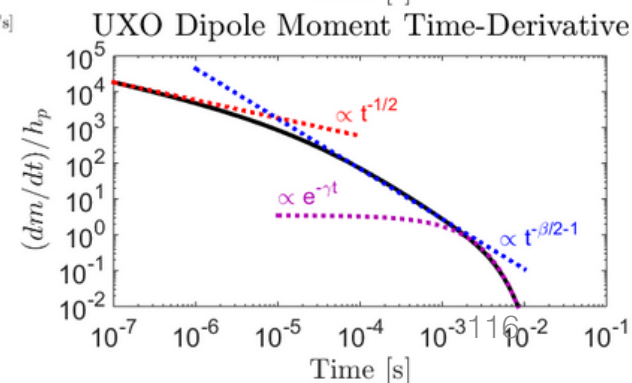
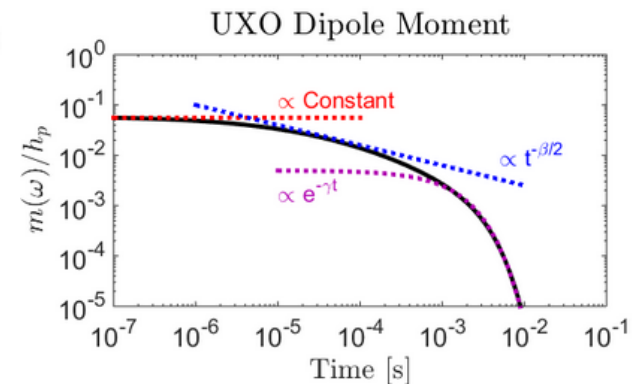
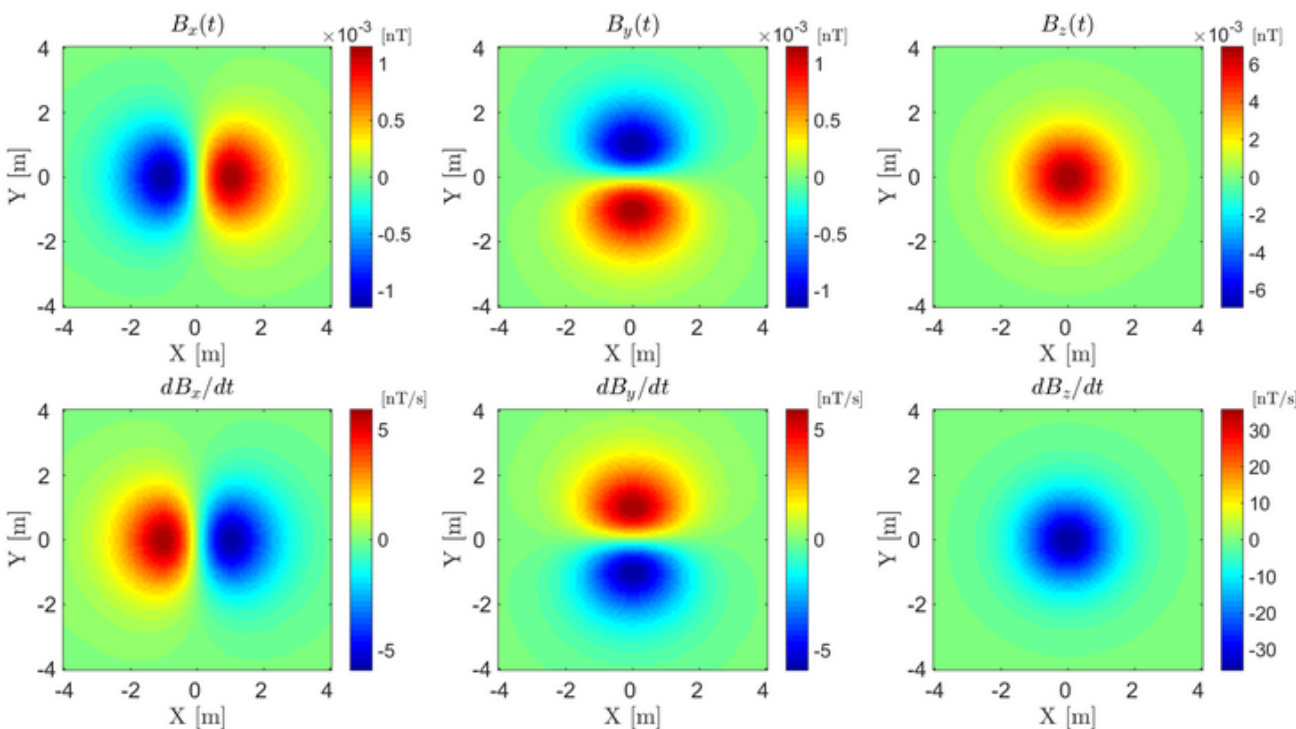


Fig. 260 Electromagnetic induction (EMI) survey for UXO location.



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:

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

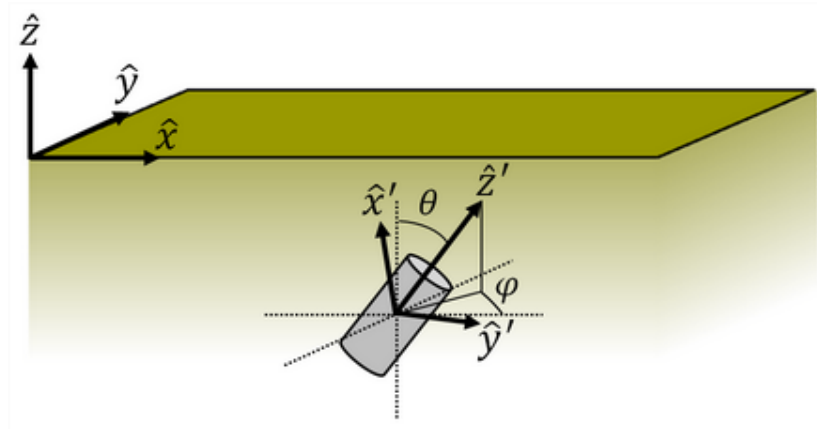
- $\mathbf{m}(t)$ is dipole moment (decays with time)
- $\mathbf{m}(t)$ depends on:
 1. Orientation of the inducing field
 2. The polarization tensor

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

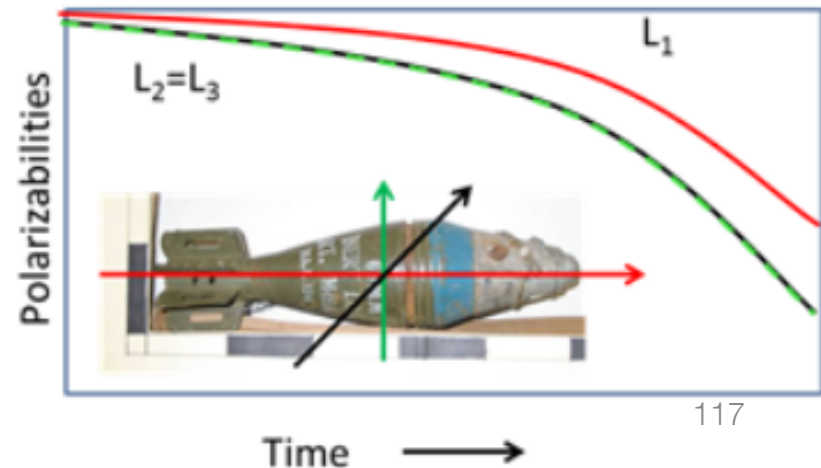
- The polarization tensor $\mathbf{L}$:

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

Field and UXO coordinate systems

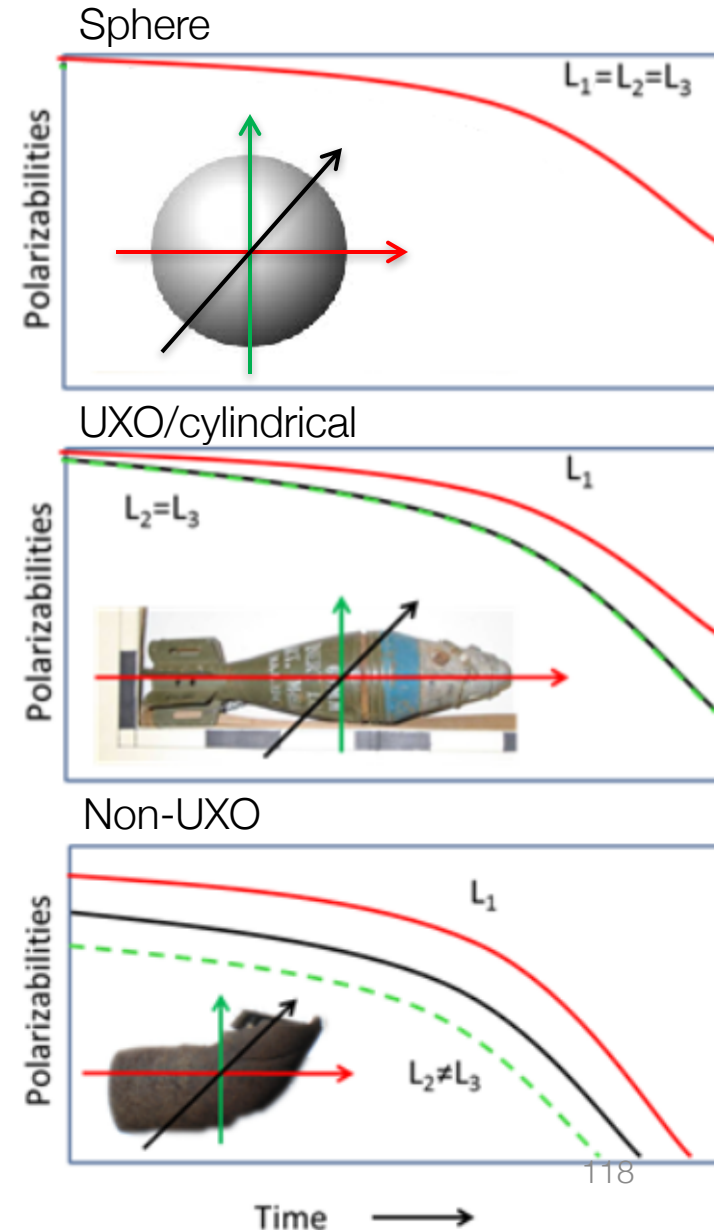


Primary (L1) and secondary (L2,L3) polarizations for UXO



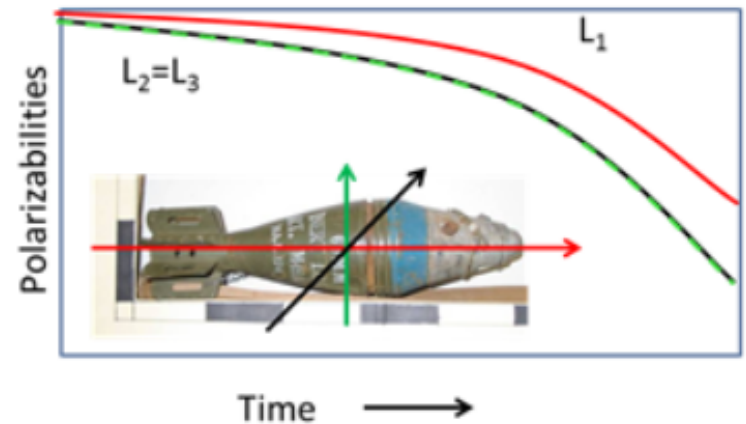
Objects and Polarization Tensors

- Polarization tensor characterizes decay and provides information about dimensionality
- Sphere:
 - Polarization strength independent of primary field direction
 - $L_1 = L_2 = L_3$
- UXO:
 - Cylindrical in shape
 - Stronger polarization along primary axis
 - $L_1 > L_2 = L_3$
- Non-UXO:
 - Arbitrary shape
 - Polarization different along different orientations
 - $L_1 \neq L_2 \neq L_3$



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

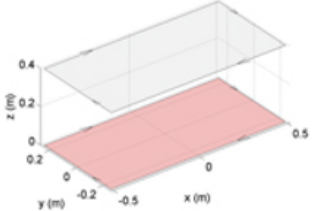
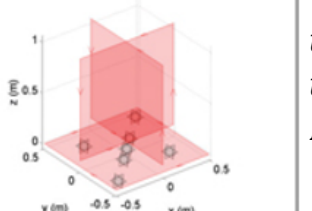
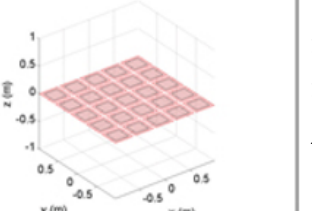
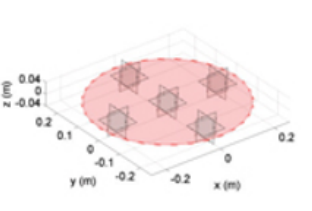
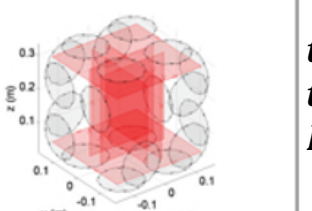


To carry out inversion for polarization tensor need data:

- multiple transmitters (orientations)
- multiple components of data

Common Systems

EM-61

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

MetalMapper

TEMTADS

MPV

BUD

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

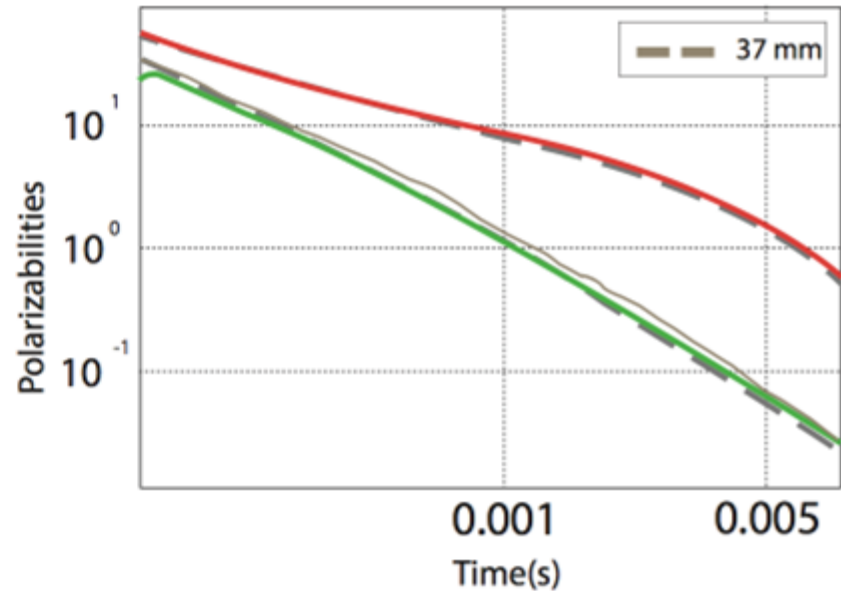
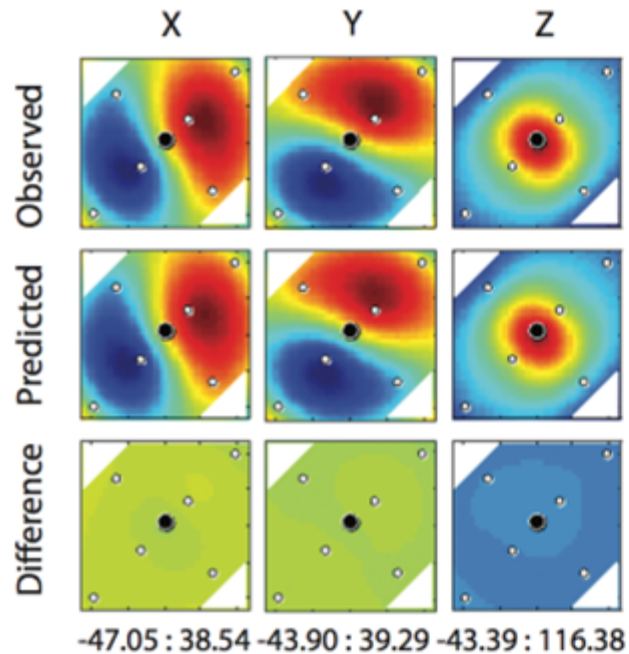
- To recover polarization tensor, target must be polarized from as many angles as possible.
- May require multiple passes with single transmitter or use of multi-transmitter system.

Time Channels

- Sufficient time-channels required to characterize decay behaviour.



Example: Metal Mapper Data

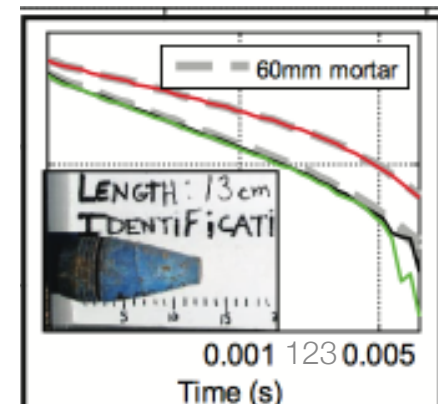
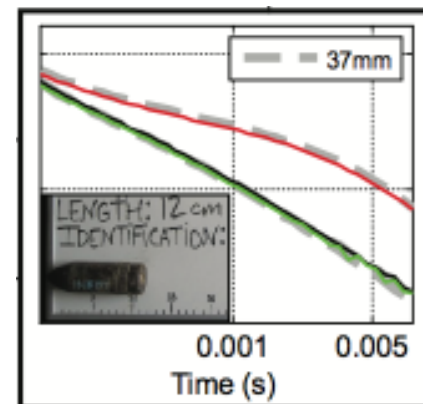
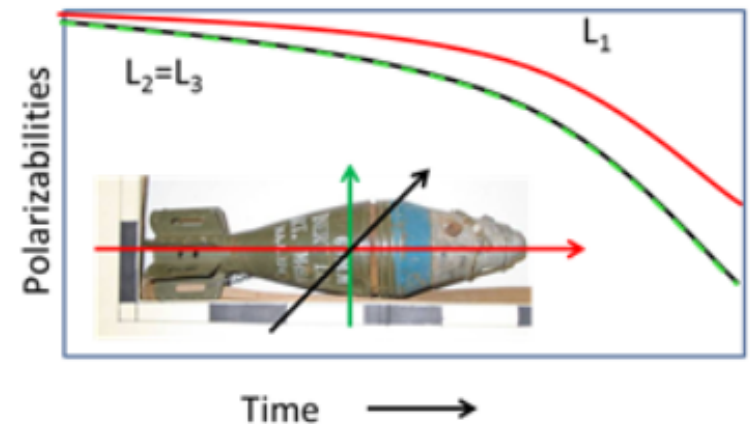
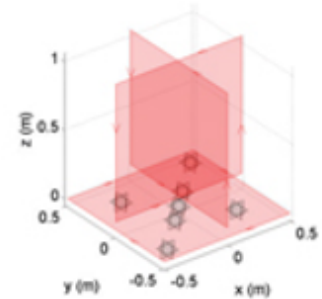


- Polarizations indicate a cylindrical object
- Predicted data using recovered polarization tensor fits the observed data
- Recovered polarizations match those of a 37 mm projectile

Summary

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

MetalMapper



Field Example: Pole Mountain

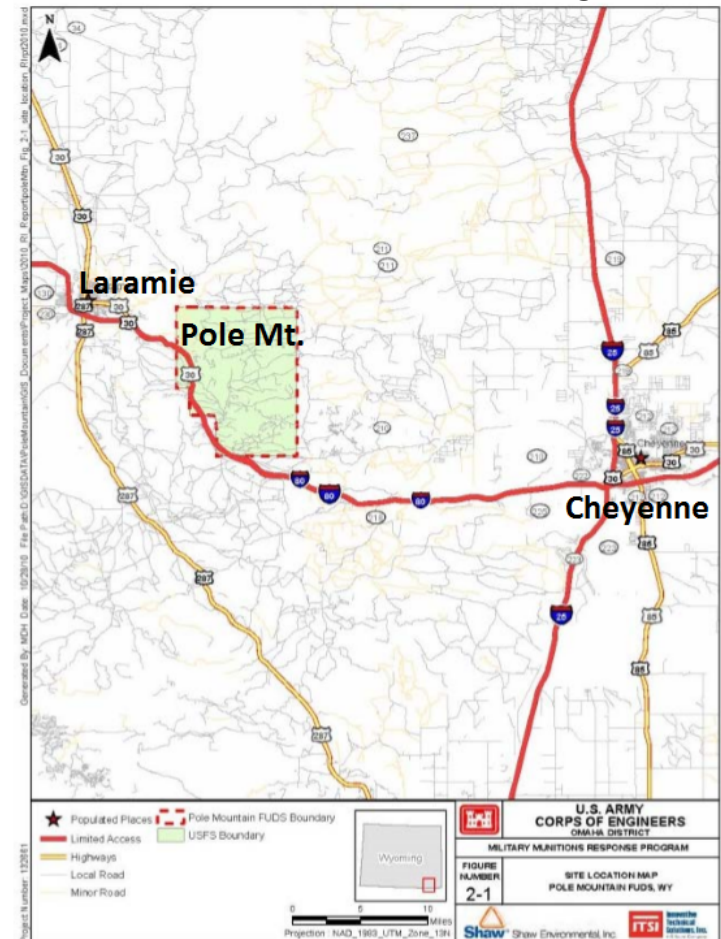
History

- 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)

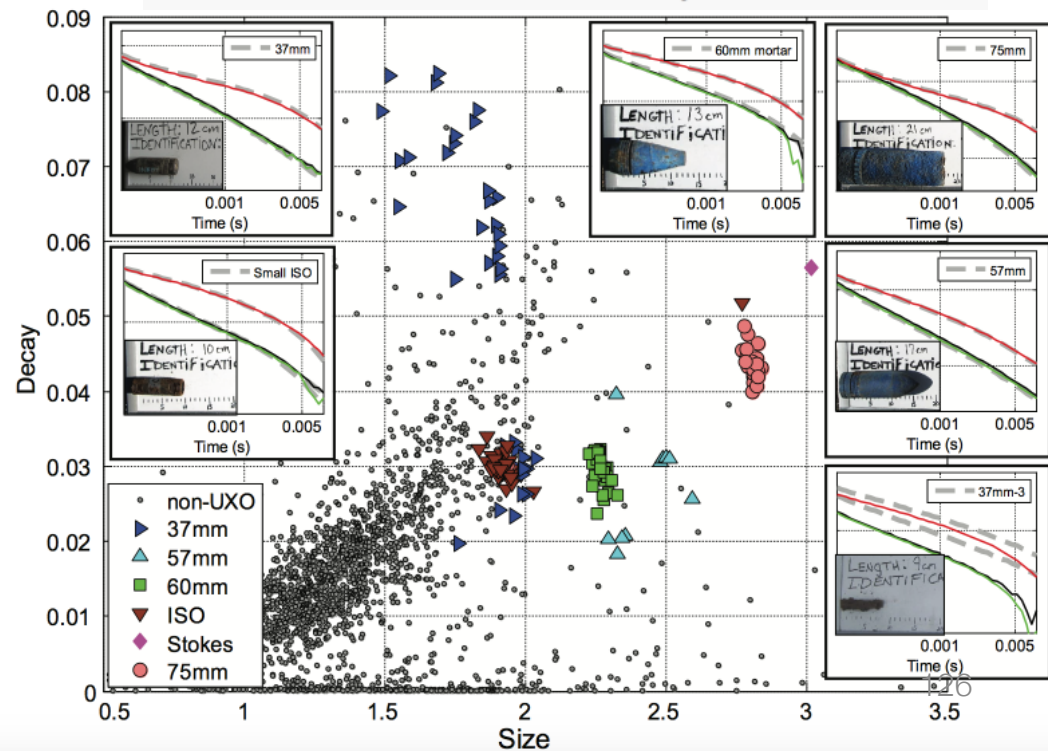
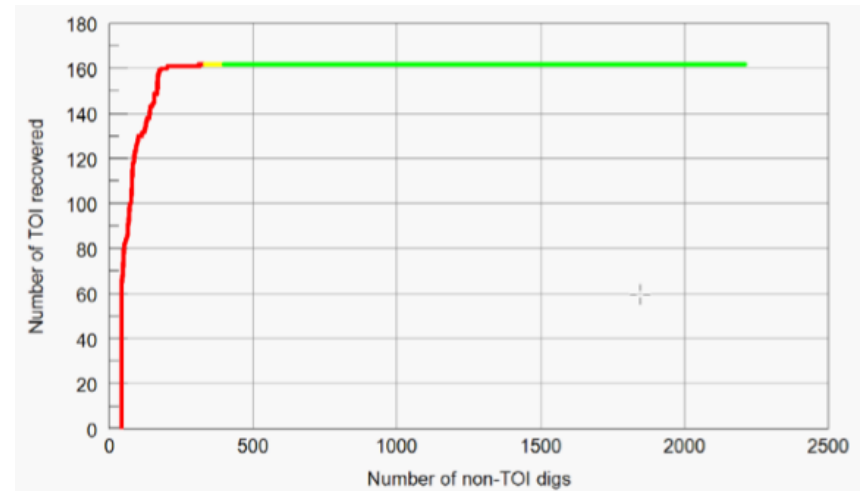


Metal Mapper (cued interrogation)



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 munitions.



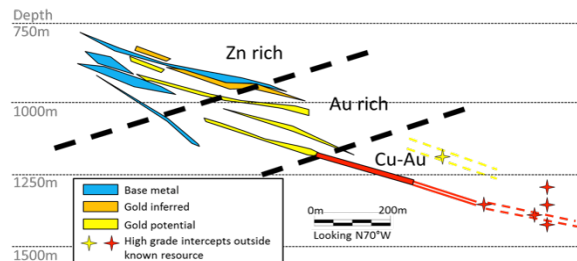
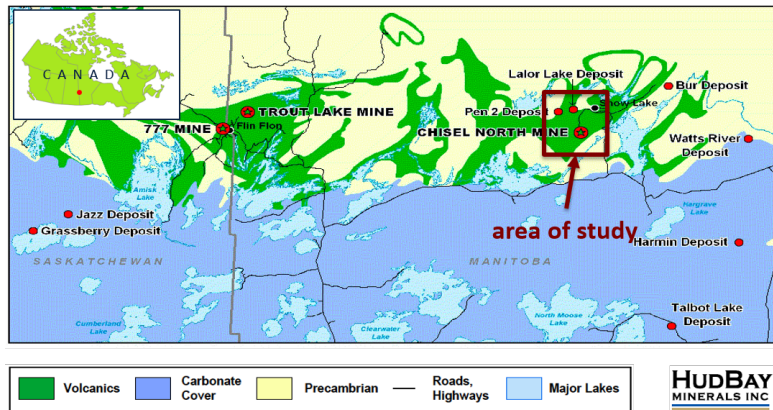
Case History: HeliSAM at Lalore

Yang & Oldenburg, 2016

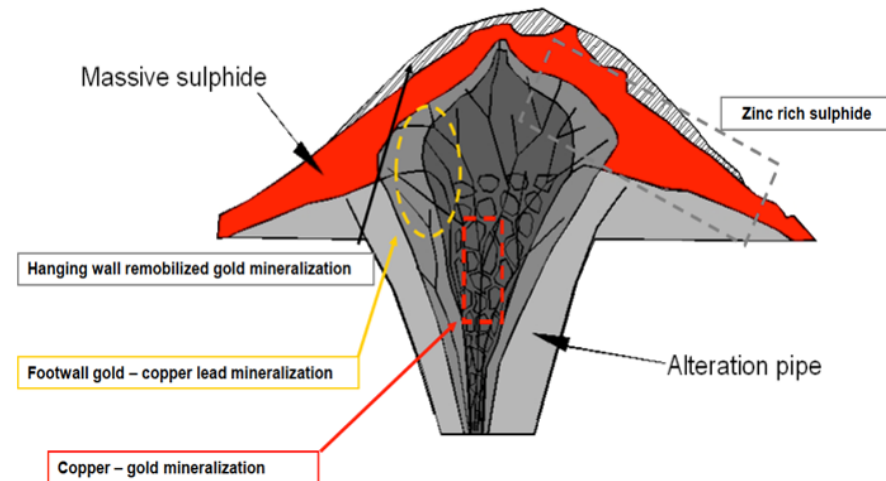
Setup

Geological framework

- Zinc-rich massive sulfides (Cap)
- Cu-Au sulfides: (stringers) within pipe
- Disseminated sulfides around deposit



Typical cross-section

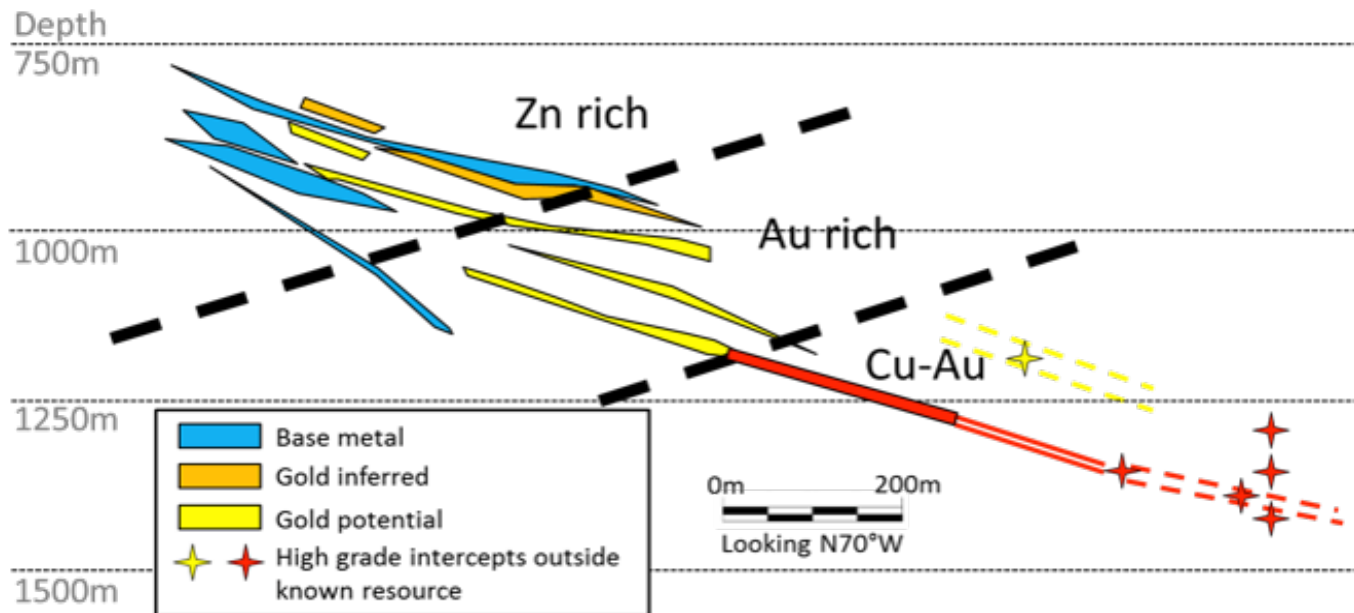


Goal:

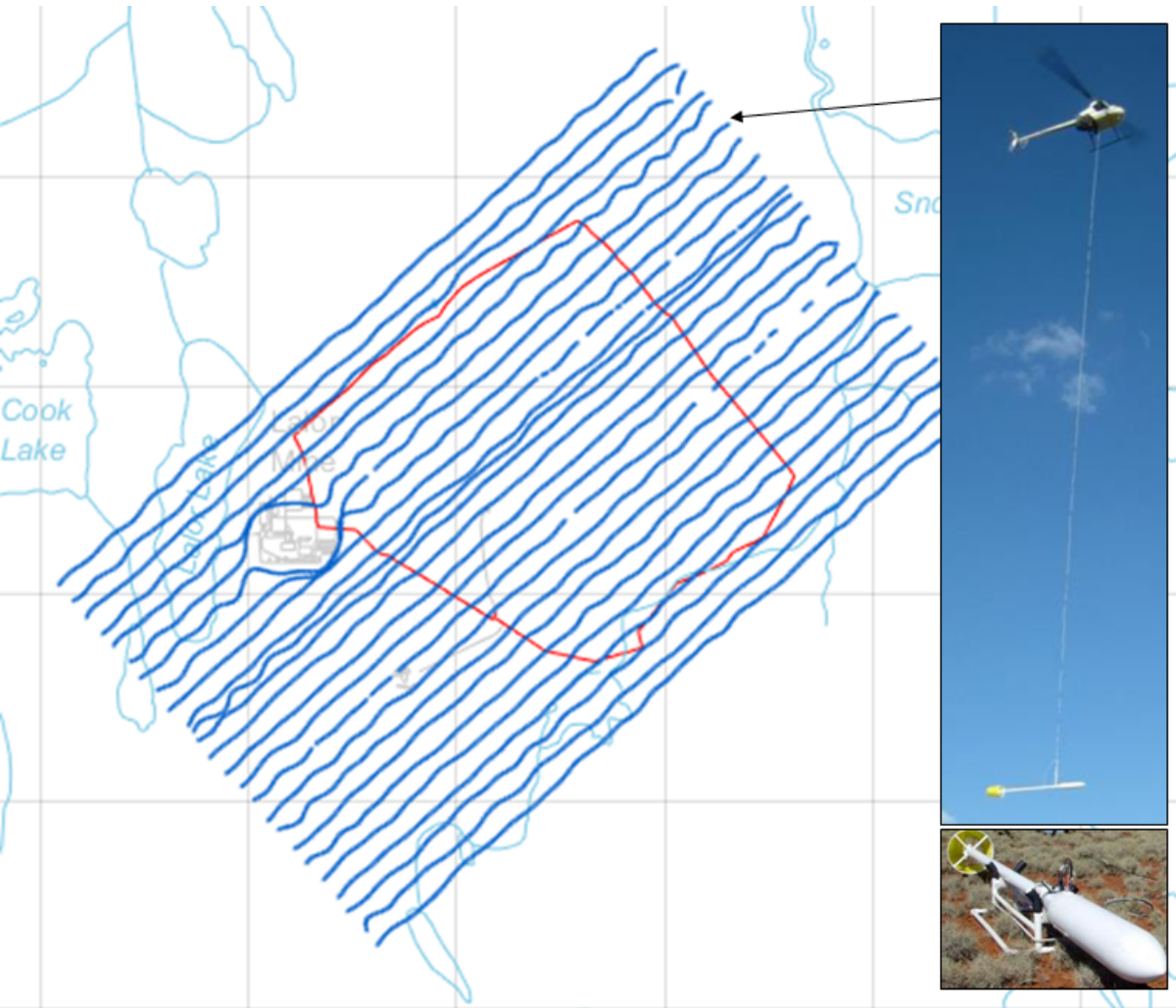
- Find deposits
- TDEM to find deeper off-hole targets

Properties

Rocks/minerals	Resistivity
volcanics	$\sim 1000 \Omega\text{m}$
sulfides	$\sim 1 \Omega\text{m}$



Survey: HeliSAM



Transmitter: (Red)

- Ground loop (~2km)
- Waveform: 7.5 Hz, 50%
- Ramp turn-off 0.4ms

Receiver:

- Cesium Vapor Mag
- 16 Time Ch: 0.42-27 ms

Flight lines: (Blue)

- 100 m spacing,
- Data every 5 m

Data

- Measure total field

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_a + \mathbf{B}_{em}$$

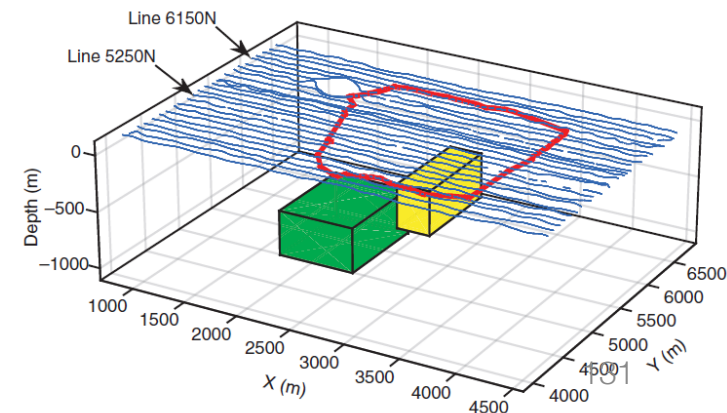
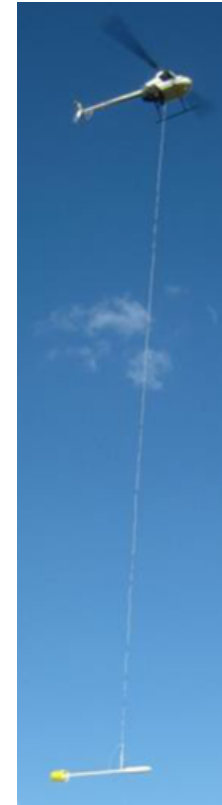
earth's magnetic field $\rightarrow \mathbf{B}_0$
 anomalous earth's field $\rightarrow \mathbf{B}_a$
 induced EM field $\rightarrow \mathbf{B}_{em}$

- Project secondary fields onto $\hat{\mathbf{B}}_0$

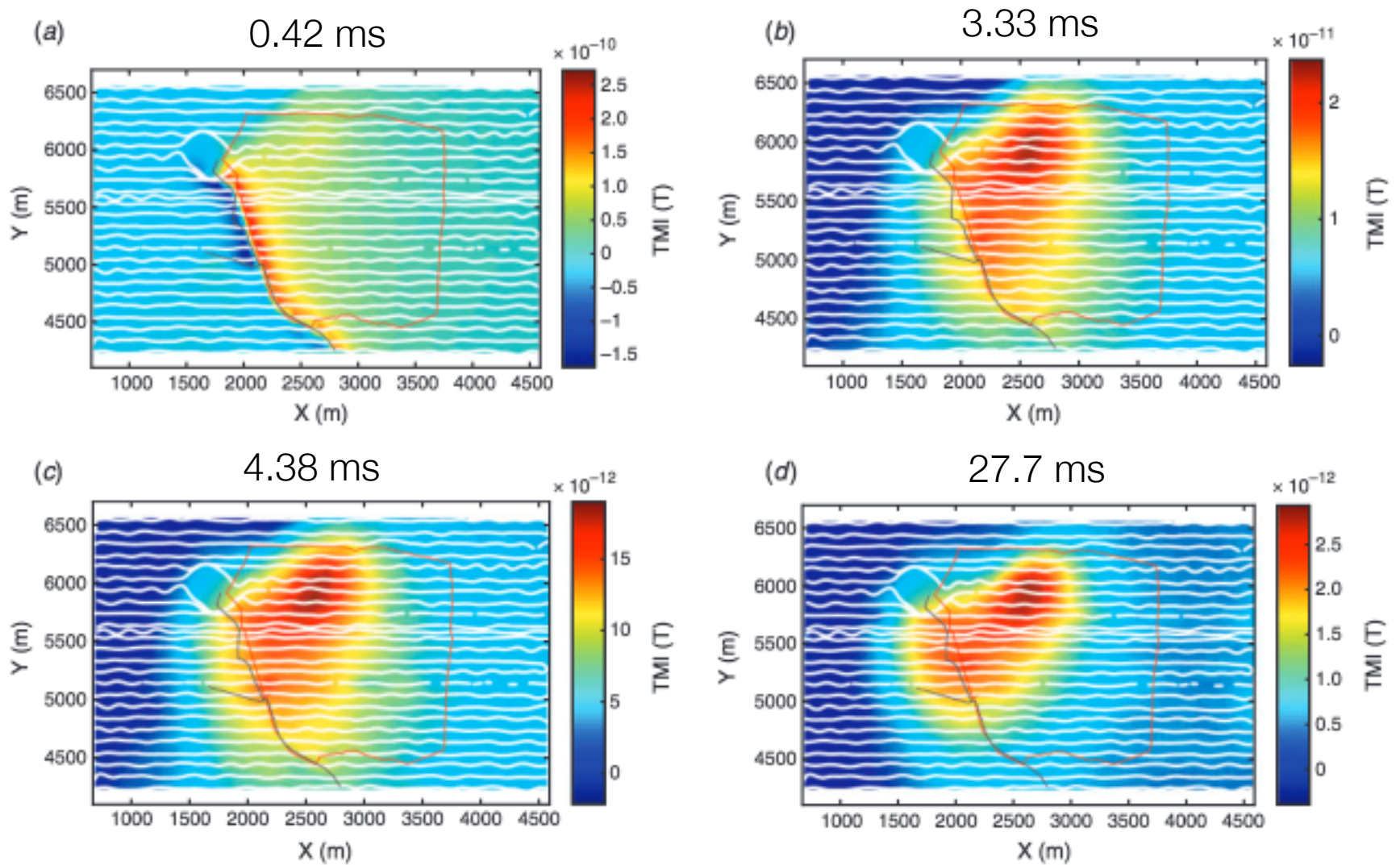
$$\begin{aligned}\Delta|\mathbf{B}| &= |\mathbf{B}_0 + \mathbf{B}_a + \mathbf{B}_{em}| - |\mathbf{B}_0| \\ &\approx (\mathbf{B}_a + \mathbf{B}_{em}) \cdot \hat{\mathbf{B}}_0\end{aligned}$$

- Change polarity on TX
- Subtract to obtain HeliSAM data

$$\Delta|\mathbf{B}| \approx \mathbf{B}_{em} \cdot \hat{\mathbf{B}}_0$$

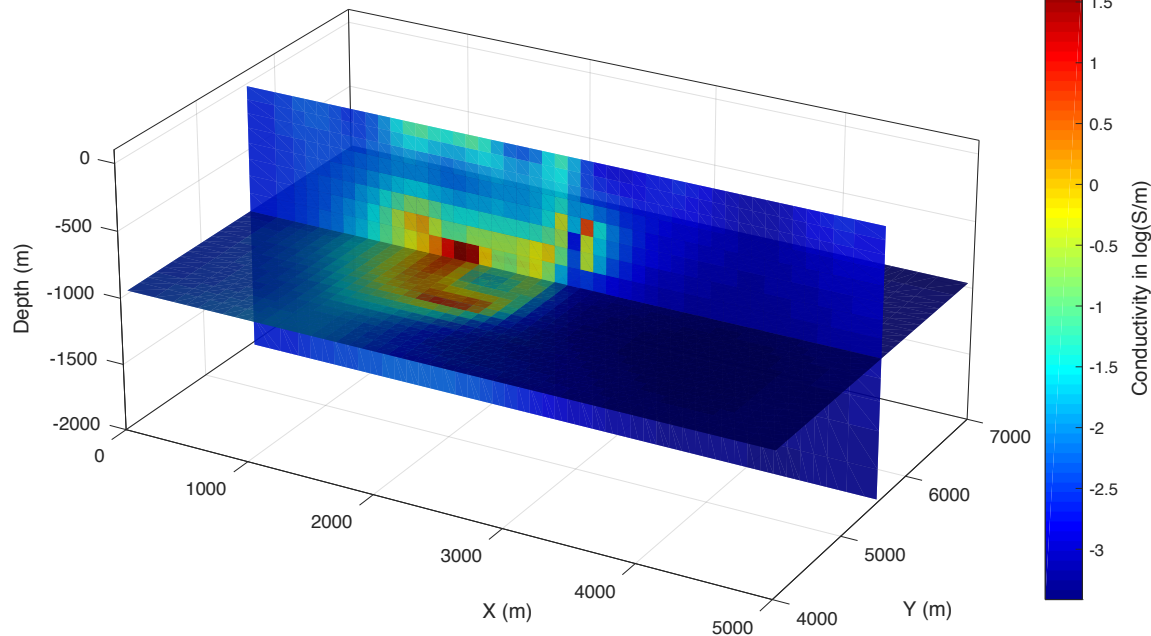
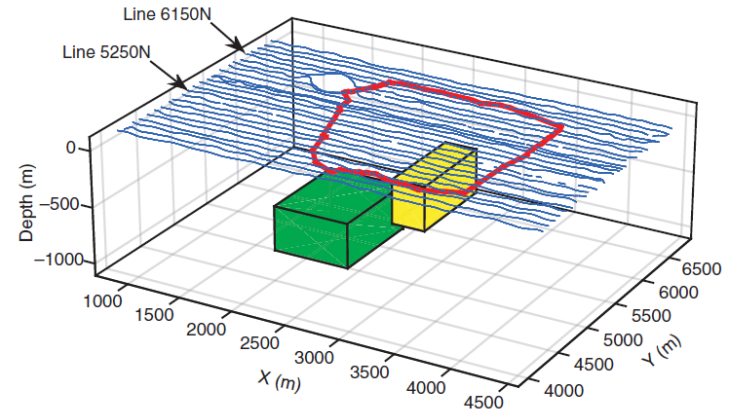


Data



Processing: Inversion of Late Time Data

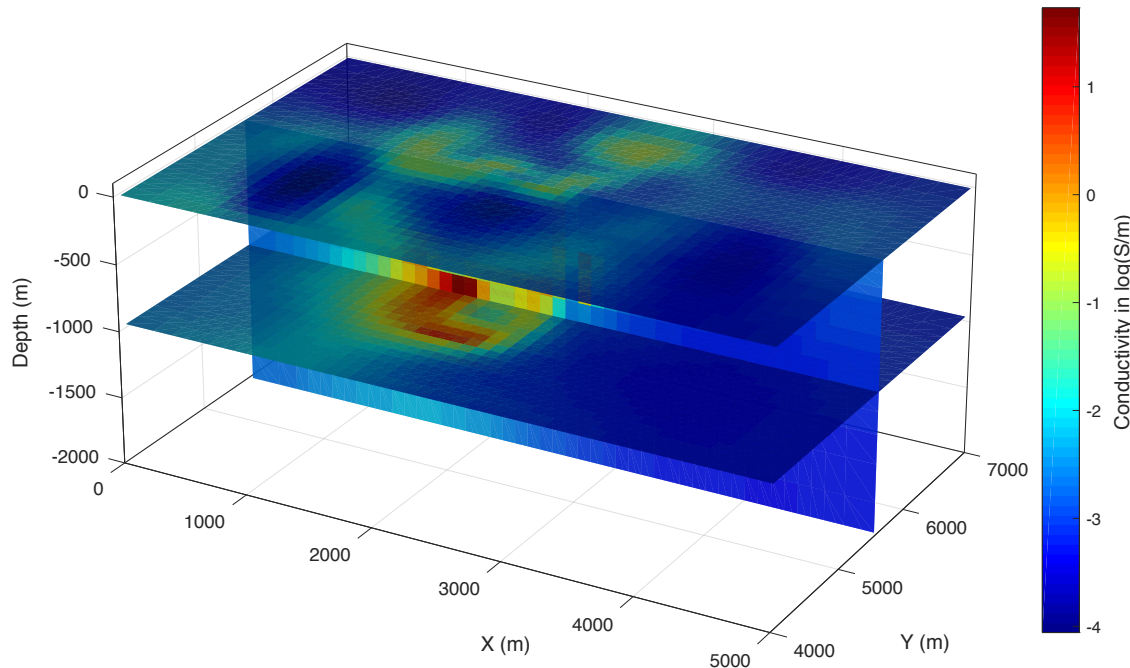
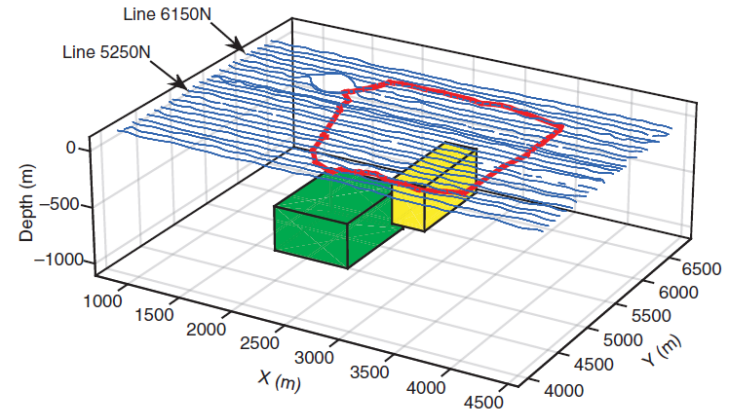
- Discard early time data
 - Contaminated by infrastructure
- Invert Time Ch 8-16 (4.44-28 ms)
- Inversion needs a “warm start”
 - Maxwell used to generate 2 prisms



- Image deep structure

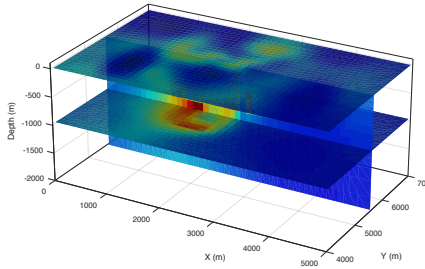
Processing: Inversion of Late Time Data

- Discard early time data
 - Contaminated by infrastructure
- Invert Time Ch 8-16 (4.44-28 ms)
- Inversion needs a “warm start”
 - Maxwell used to generate 2 prisms



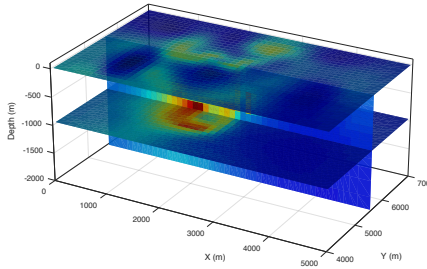
- Image deep structure
- See near surface conductive features

Processing: Inversion of Early Time Data



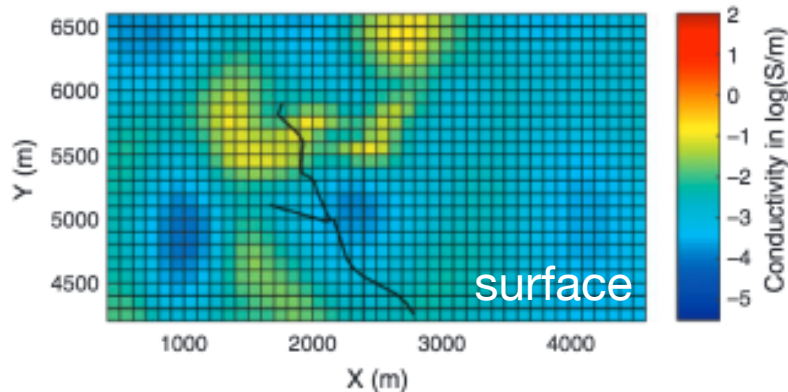
- Late-time inversion sees deep structure
- Some conductive features near surface
- **What is the effect of throwing away the early time data?**

Processing: Inversion of Early Time Data



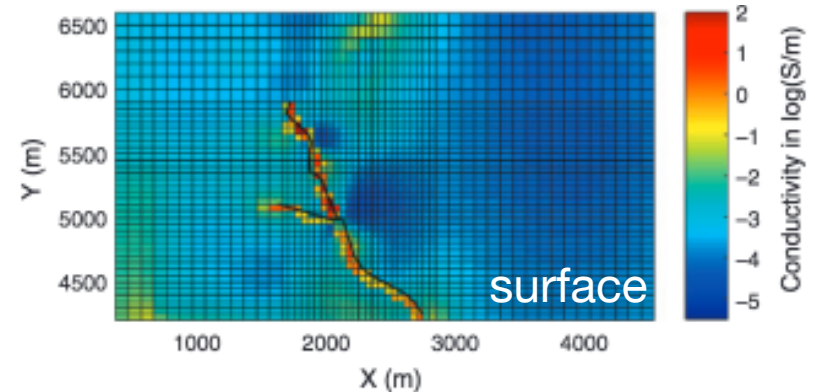
- Late-time inversion sees deep structure
- Some conductive features near surface
- **What is the effect of throwing away the early time data?**

Inverting late time data
TC 8 – 15 [4.4 – 28 ms]



- erroneous near surface structure

Inverting early time data
TC 1-7 [0.4 – 3.3 ms]

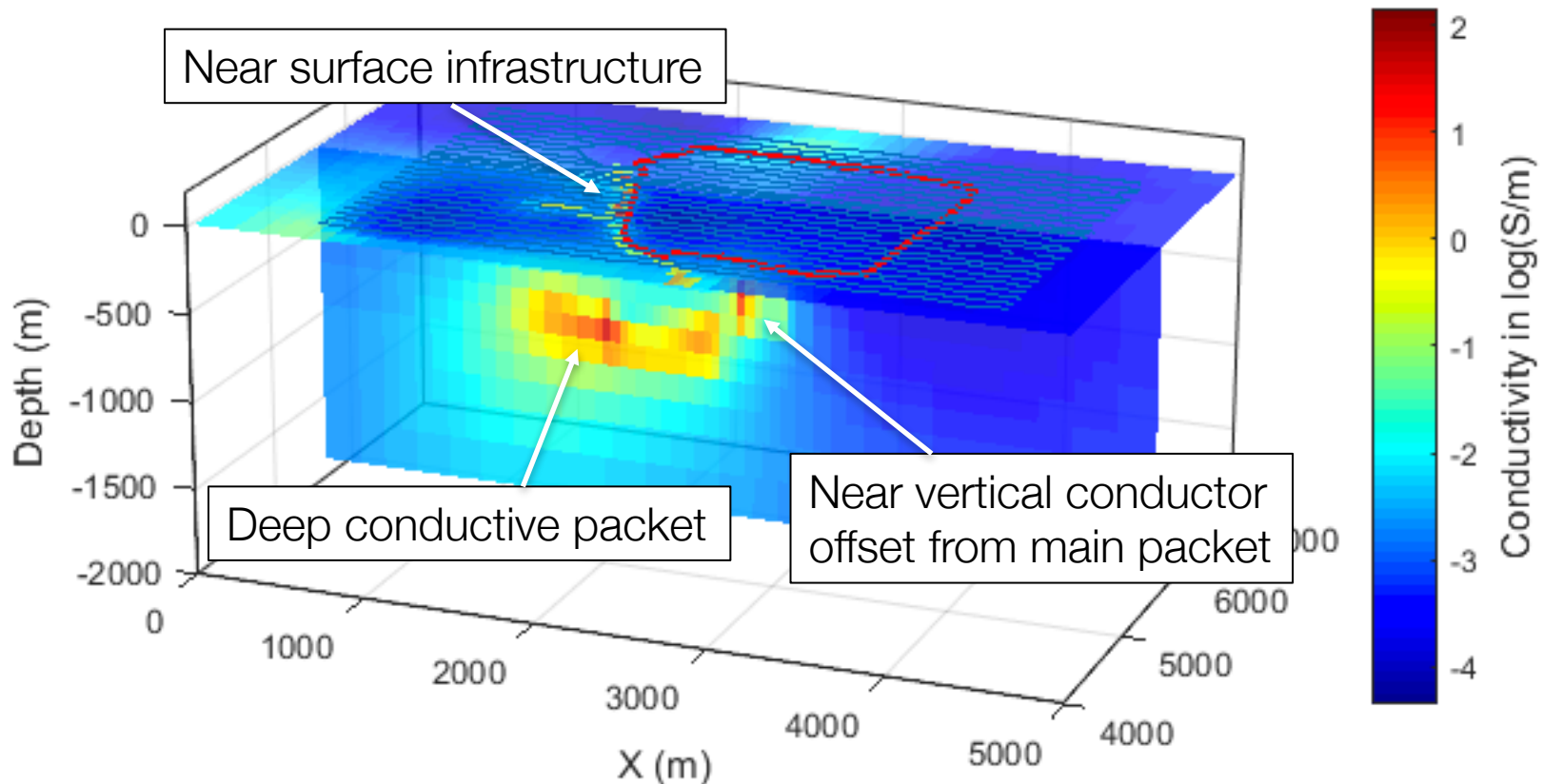


- information about infrastructure and near-surface conductivity

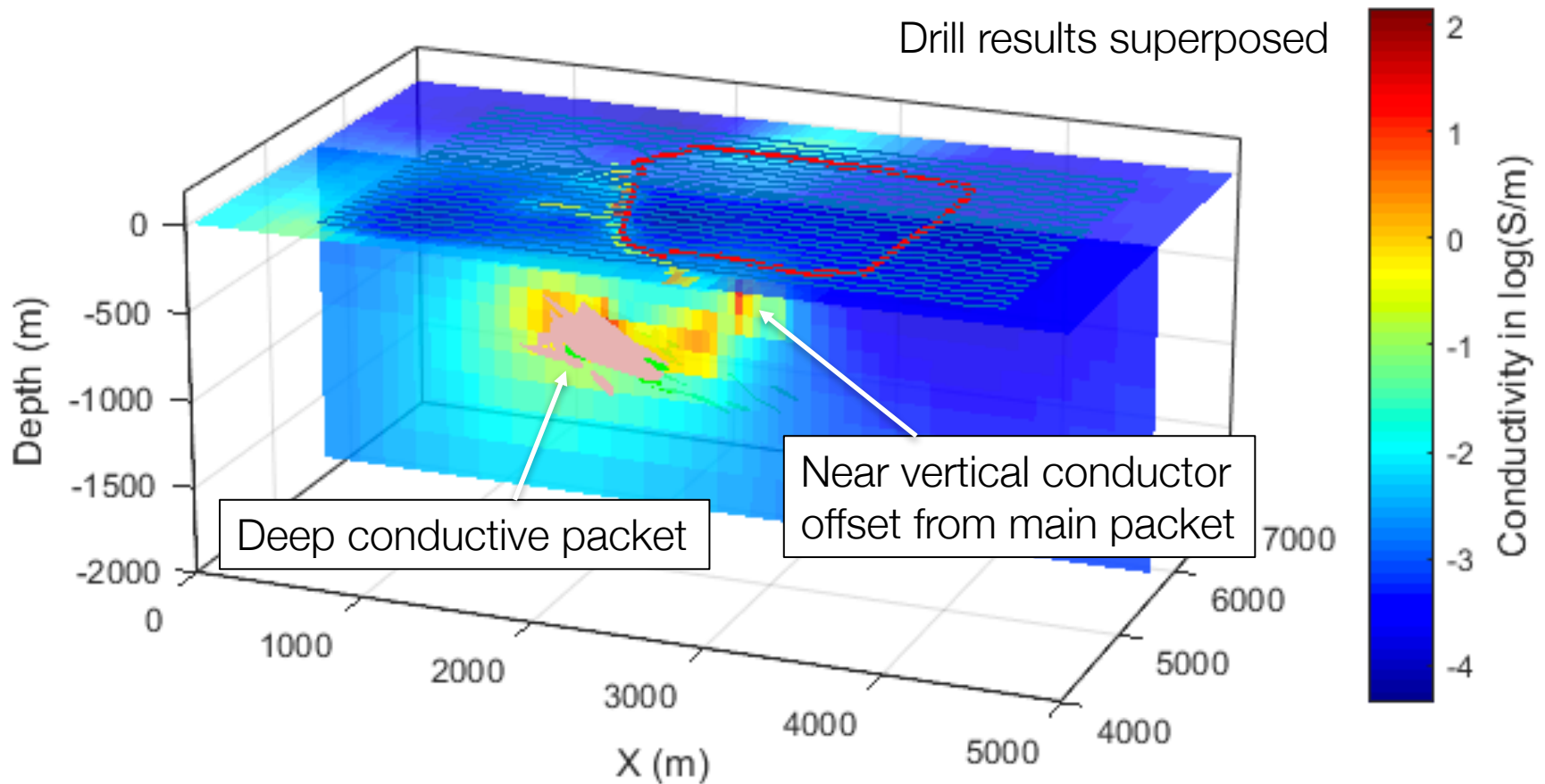
Processing: Inversion of all time channels

Starting and reference model:

- High conductivity from early time inversion
- Two conductive blocks

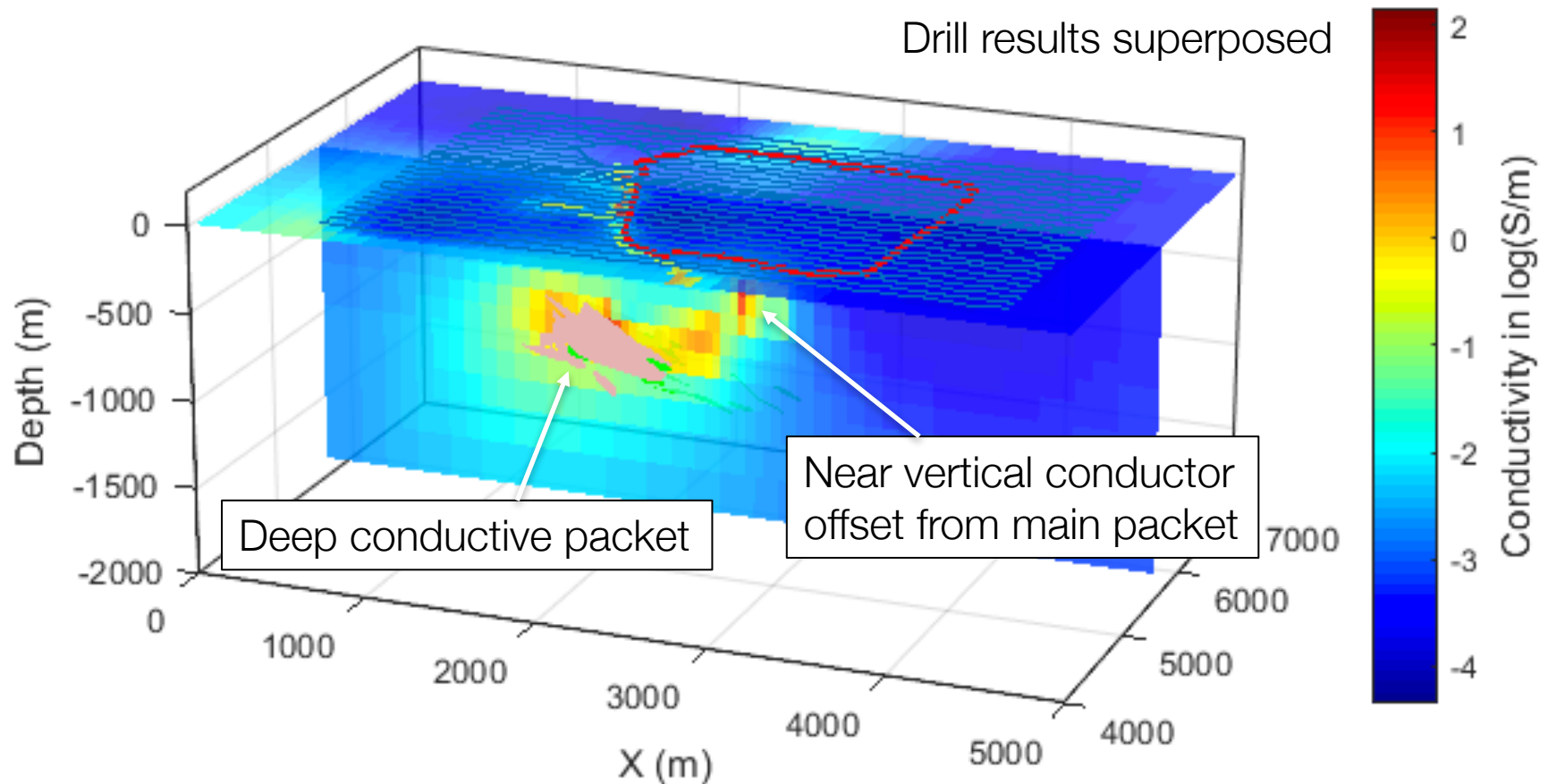


Synthesis



- Imaged main known conductive bodies
- Second conductor: recently drilled and contained sulfides (argillite)

Takeaways



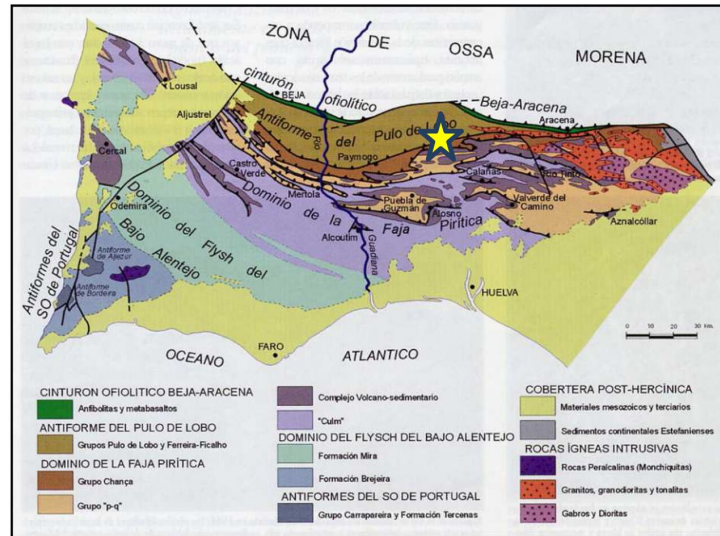
- Early time data:
 - constrain near surface structure infrastructure
 - Improved inversion for late time
- Warm start of inversion was necessary for deep conductors

Case History: La Magdalena

Granda et al., 2016

Setup

Geological setting

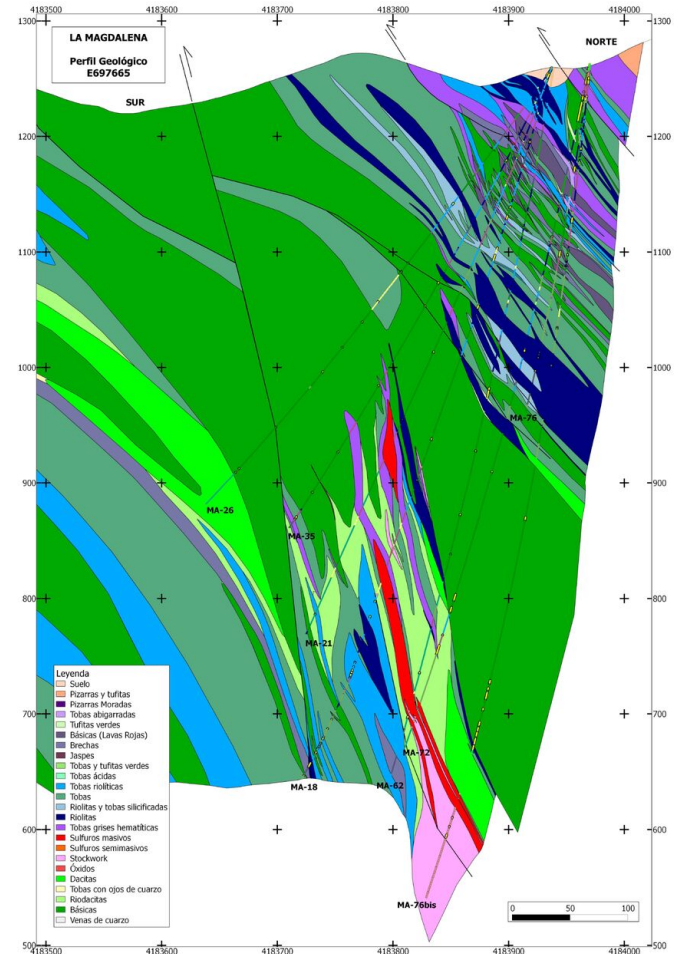


- Volcano-Sedimentary (VS) mineralization
- Thin, steeply dipping veins

Goal: Find deposits

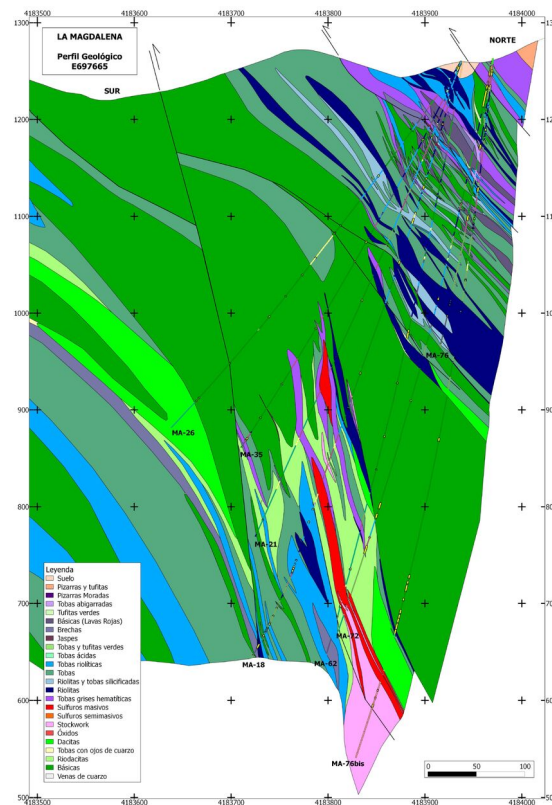
- Use borehole TDEM to find deeper, off-hole targets

Typical cross section



Properties

Rock type	Resistivity	Density	Mag sus
Sulfide bodies	Low (<10 Ωm)	High (> 4g/cc)	Low
Host Rock (VS)	High		Low



Surveys: Strategic Campaigns

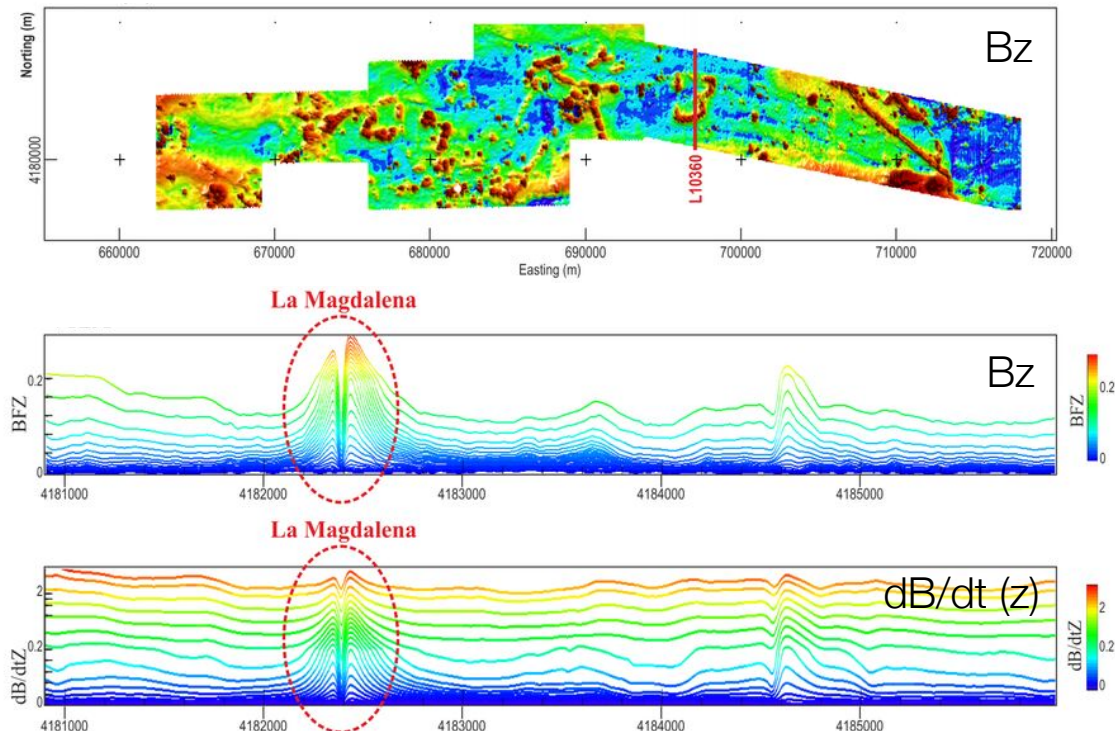
Goal	Survey	Detail
Find potential targets	VTEM	350 km ²
Evaluate continuity of mineralization	Mise-a-la-Masse	Single current in ore body
Methodological Tests	ERT	Pole-dipole along a single line
	Surface TEM: Turam configuration	
	Surface TEM: Slingram configuration	
Find off-hole conductors	Borehole TDEM	Surface transmitter Borehole receivers

Initial Discovery: VTEM

- VTEM airborne survey
 - 350 km² area
 - N-S lines, 100m - 200m spacing
 - Measure:
 - dB/dt (x, z)
 - B_z , B_x
 - Mag.

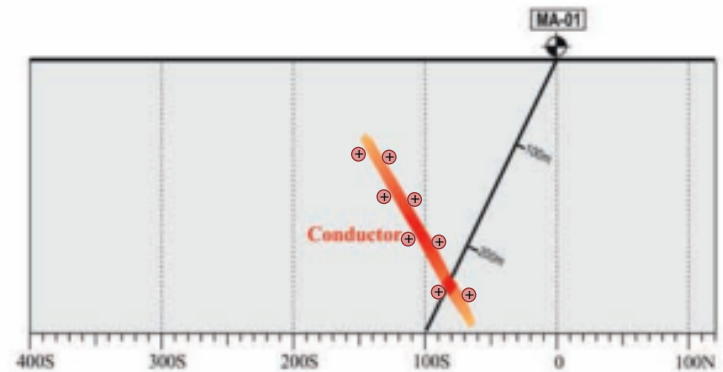
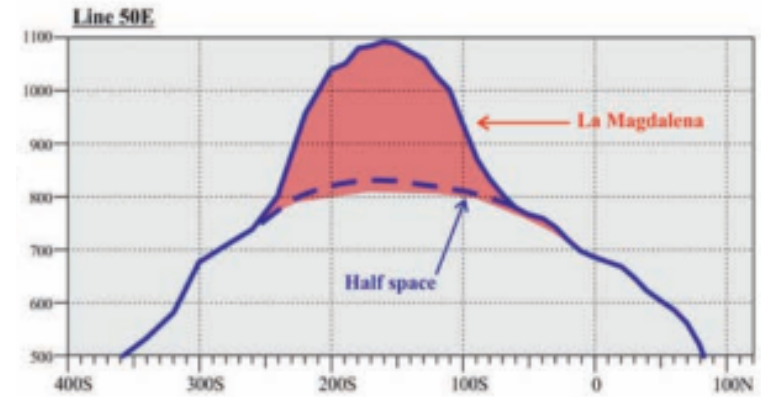
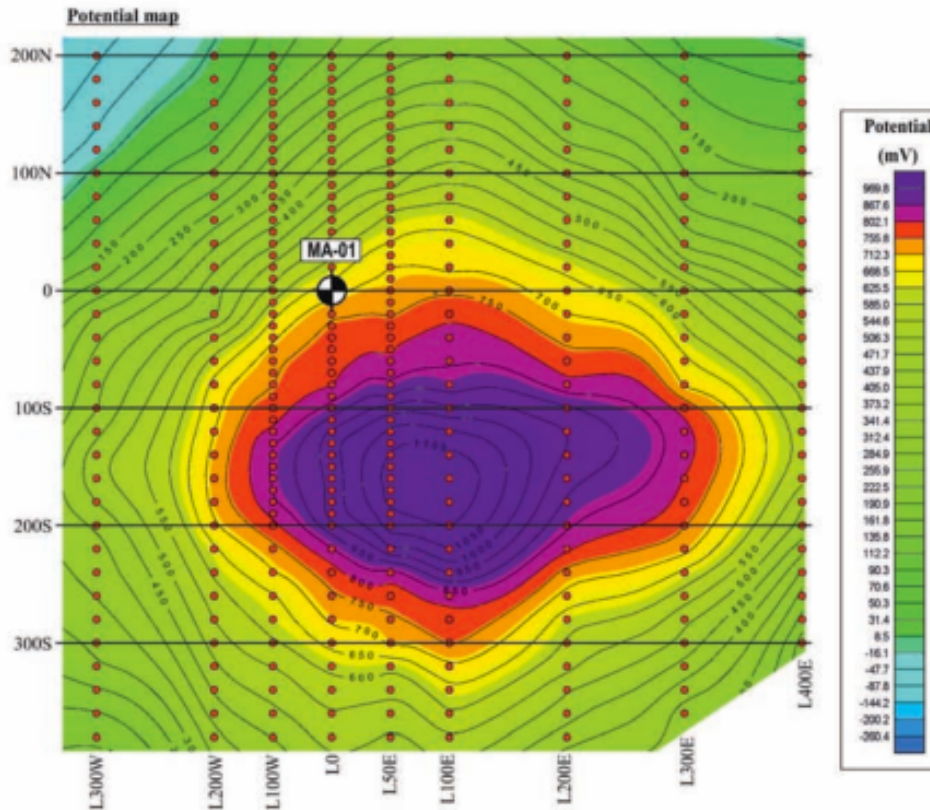
Survey Parameters

Sensor height	50 m
TX radius	17.5 m
Current Peak in TX	234 A
Magnetic Moment in TX	900.437 nA
Z oriented RX radius	0.6m
Z oriented RX # turns	100
X oriented RX radius	0.16m
X oriented RX # turns	245



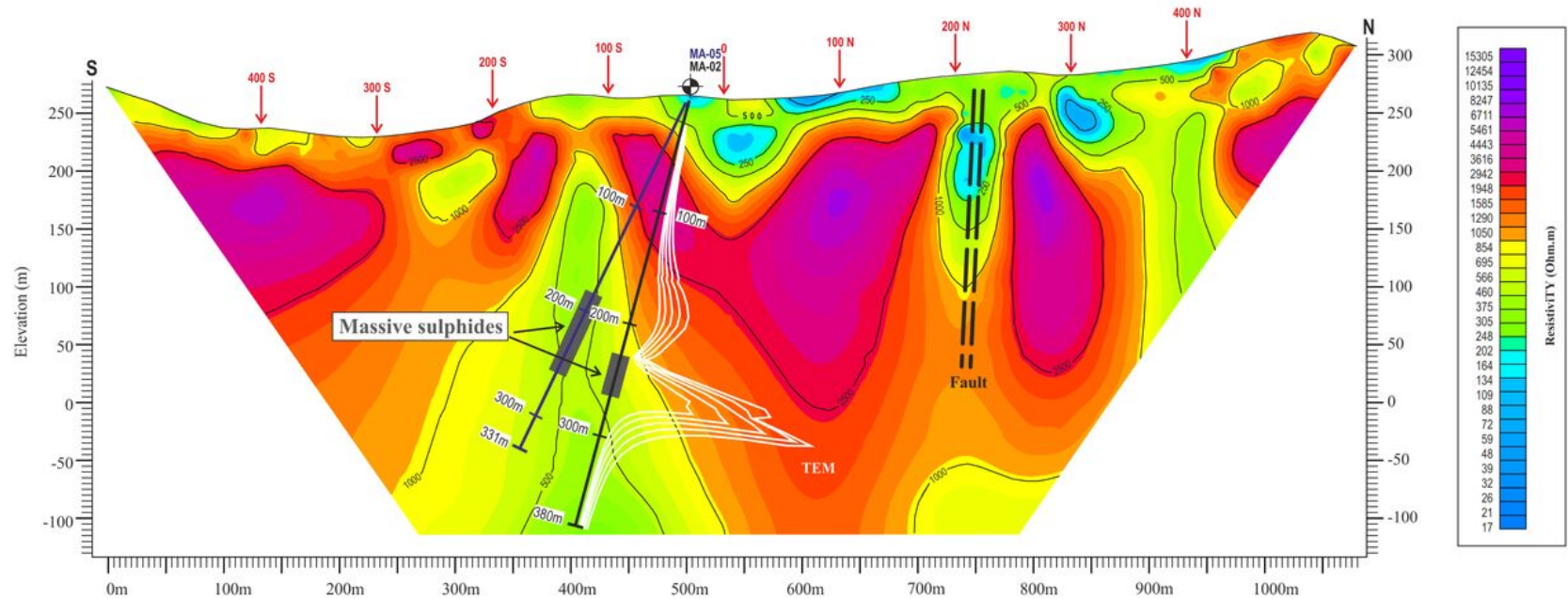
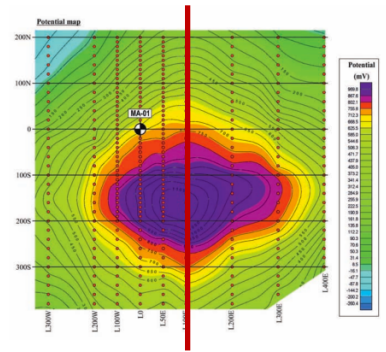
Evaluation: Mise-a-la-masse

- Electrode coupled to massive sulphides at 230m
- Measure potentials (gradient mode) on surface



Methodological Test: ERT

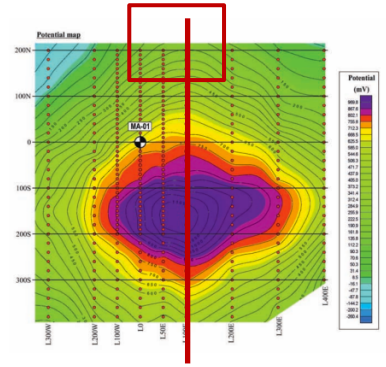
- Pole-dipole
 - $a = 20\text{m}$ and $n = 40$



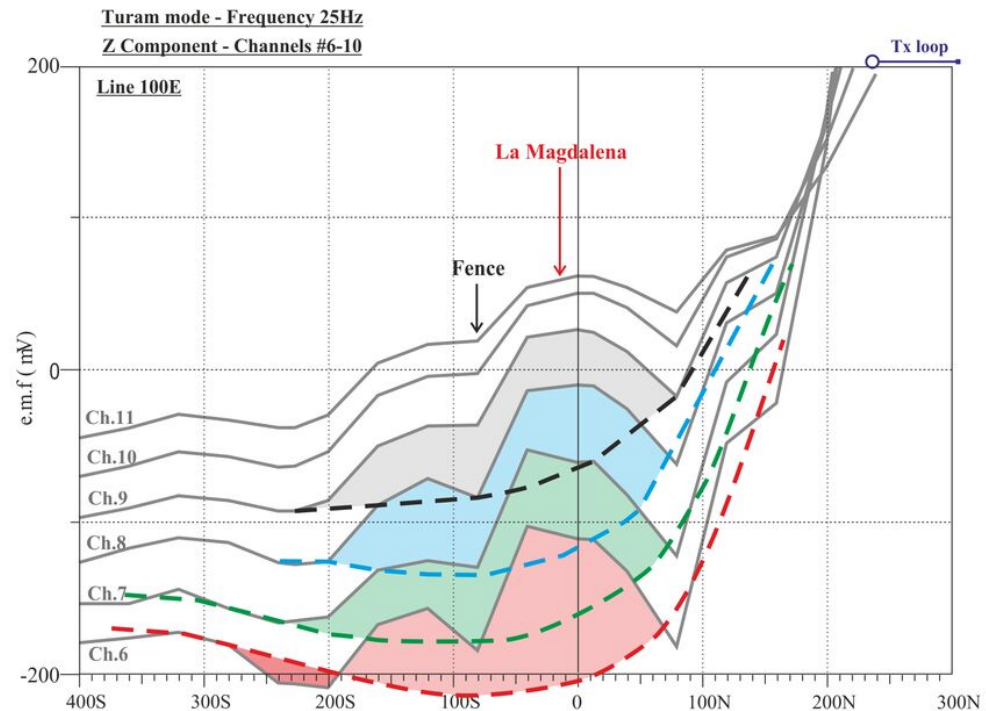
Results: found a moderately low resistivity region, not as low as anticipated 146

Methodological Test: Turam

- Ground based, fixed loop: Turam
- PROTEM induction coil
 - RX Equivalent area: 100 m²
- TX located several hundred meters north of mineralization
 - (ensure good EM coupling)



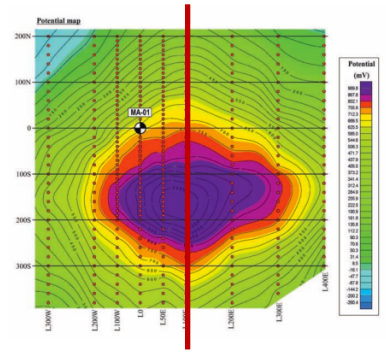
Specification	Turam
TX Loop size	700 m x 400 m
TX-RX synchronization	Crystal
Current pulses	15.5 A
T/O time	295 μ s
Measured parameters	dBdt (z, x)
Base frequency	Hi: 25 Hz MD: 6.25 Hz
Measurement mode	Off time



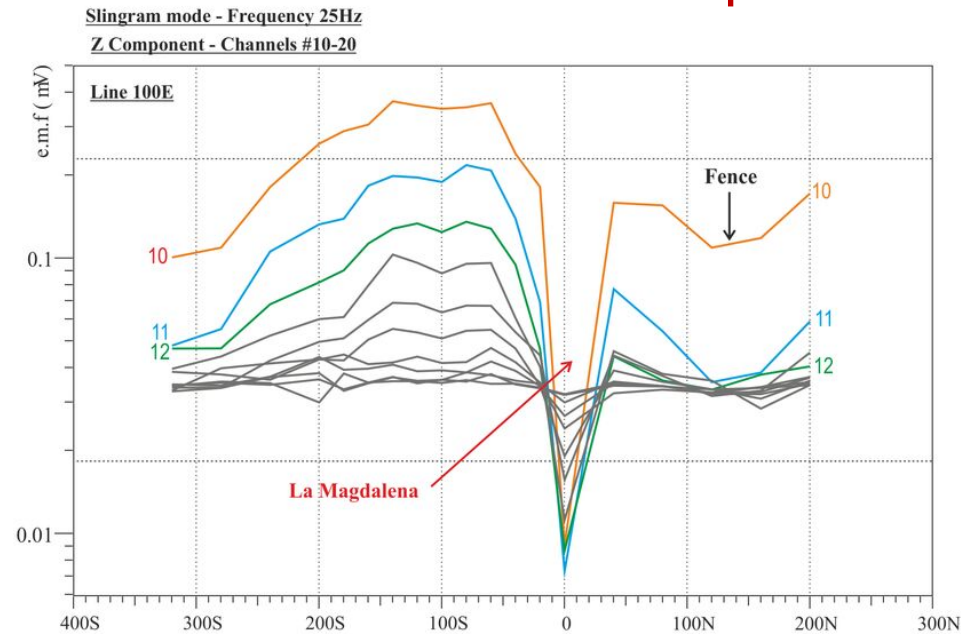
Results: Strong detectability. 147

Methodological Test: Slingram

- Ground based, moving loop: Slingram
- PROTEM induction coil
 - RX Equivalent area: 100 m²



Specification	Turam	Slingram
TX Loop size	700 m x 400 m	100 m x 100 m
TX-RX synchronization	Crystal	Ref. Cable
Current pulses	15.5 A	22 A
T/O time	295 μ s	75 μ s
Measured parameters	dBdt (z, x)	dBdt (z, x)
Base frequency	Hi: 25 Hz MD: 6.25 Hz	Hi: 25 Hz MD: 6.25 Hz
Measurement mode	Off time	Off time

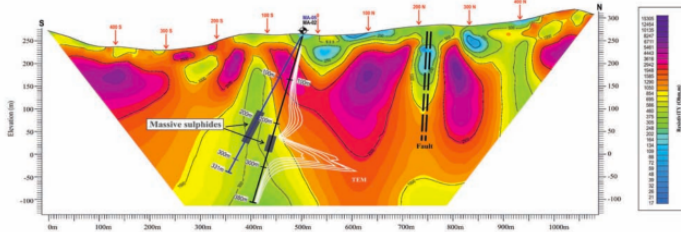


Characteristic plate-like conductor.
Dipping north

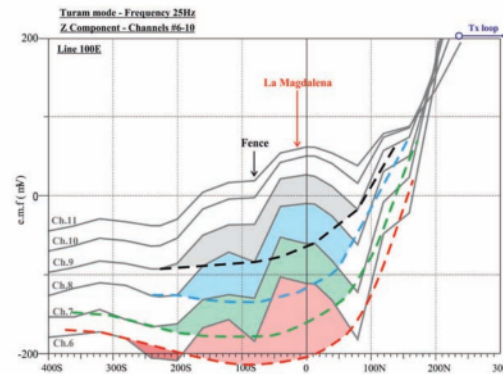
Results: Strong detectability. 148

Methodological Test: Final choice Turam

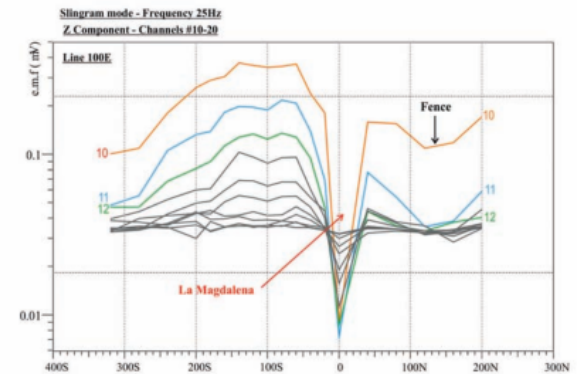
ERT: Inconclusive



Turam: Strong signal

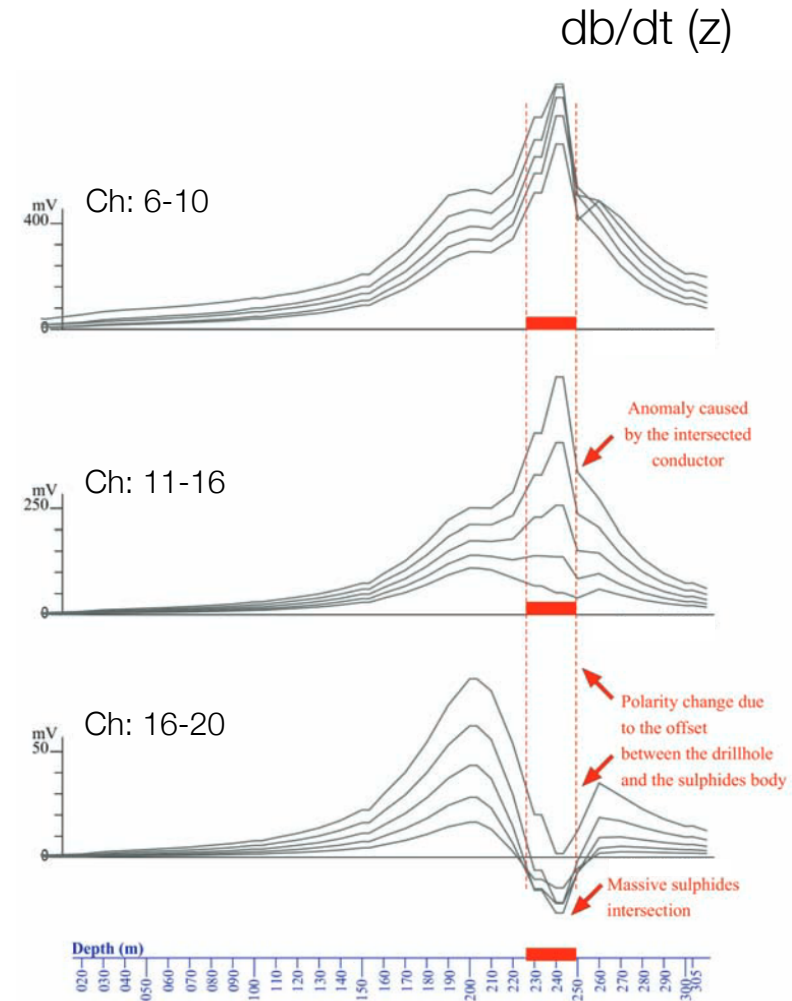
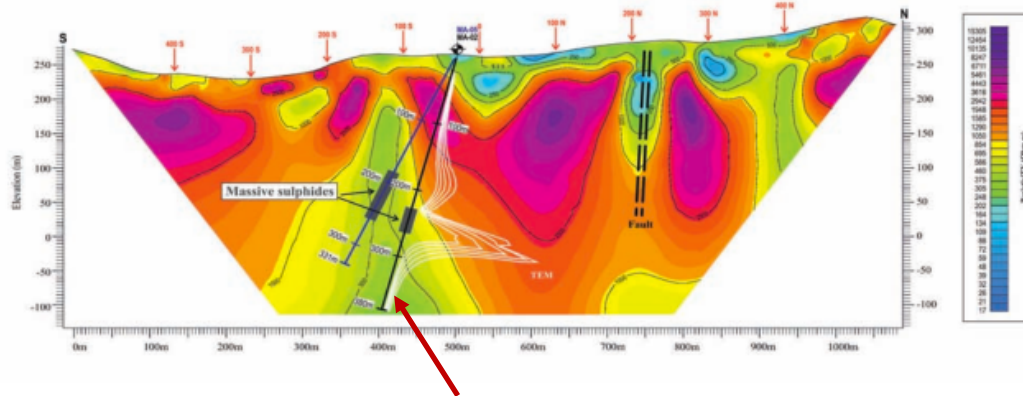


Slingram: Strong signal



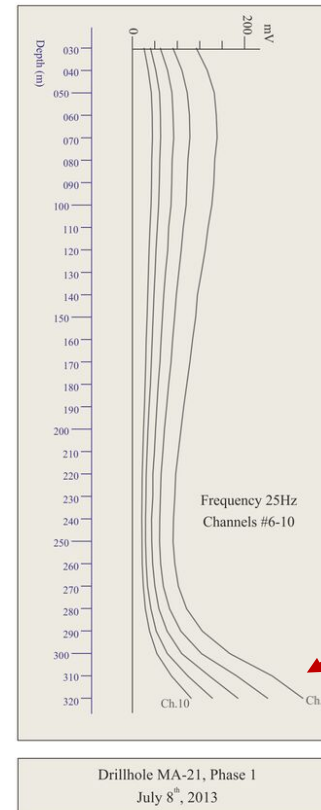
Borehole TDEM

- PROTEM system
 - TEM-67 transmitter
 - BH-43-3D probe (3-components)
 - Base Frequencies: Hi (25 Hz), MD (6.25 Hz)



Borehole TDEM: Discovery of Masa 2

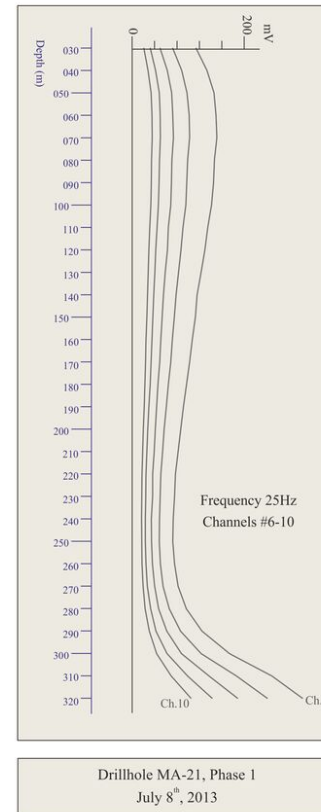
- Borehole TDEM carried out using multiple drillholes
- MA-21 drilled to 320m (Phase 1)
 - Did not intersect mineralization
 - Indicate an off-hole conductor



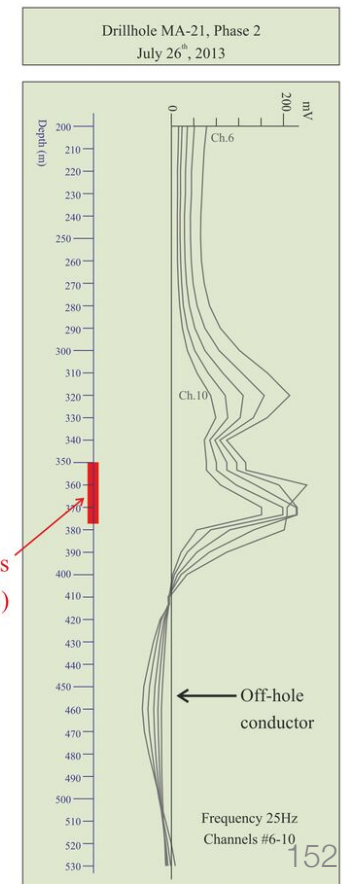
Possible off-hole conductor

Borehole TDEM: Discovery of Masa 2

- Borehole TDEM carried out using multiple drillholes
- MA-21 drilled to 320m (Phase 1)
 - Did not intersect mineralization
 - Indicate an off-hole conductor
- MA-21 drilled to 520m (Phase 2)
 - Mineralization 350-370m

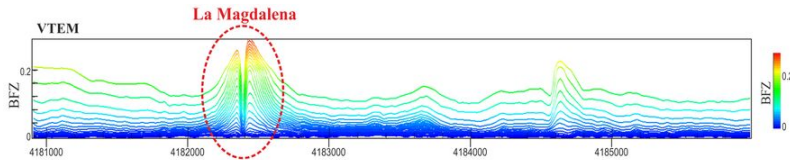


Massive sulphides
(Masa 2)

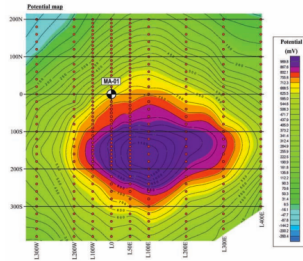


Synthesis

- VTEM: initial discovery



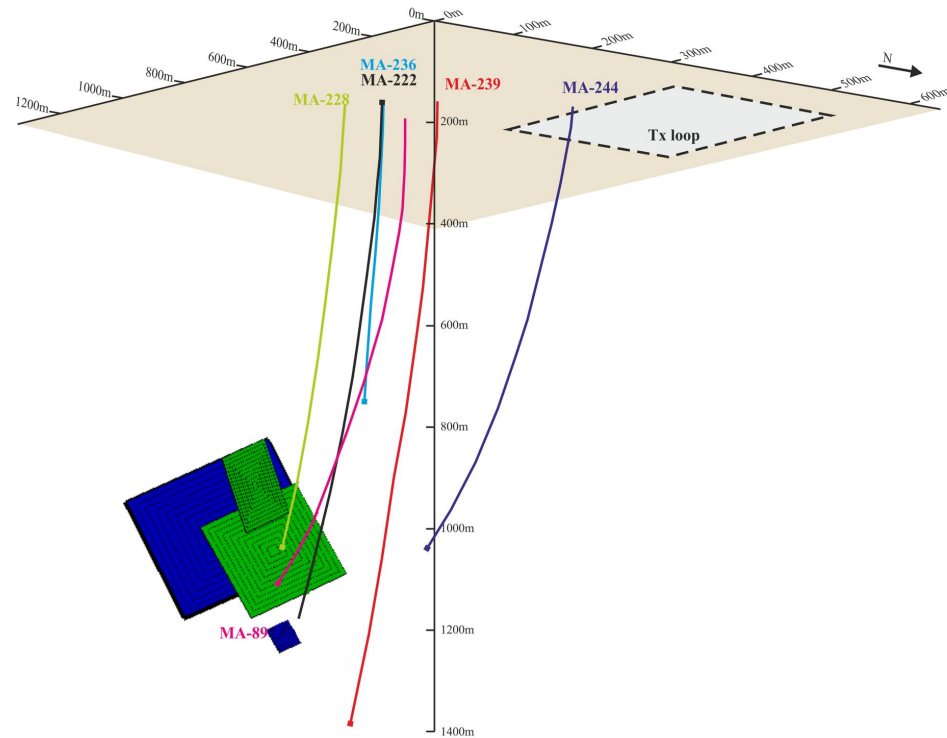
- Mise a la Masse: evaluation



- Ground surveys: methodological tests
 - ERT
 - Turam
 - Slingram

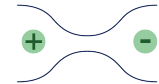
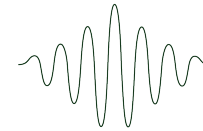
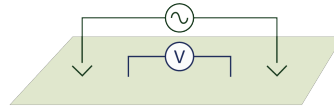
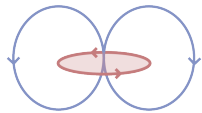


- Borehole TDEM: find off-hole conductors



End of Inductive Sources

Next up



DC Resistivity

EM
Fundamentals

Inductive
Sources

Grounded
Sources

Natural
Sources

GPR

Induced
Polarization

The
Future

Lunch: Play with apps