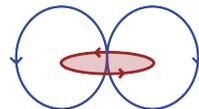
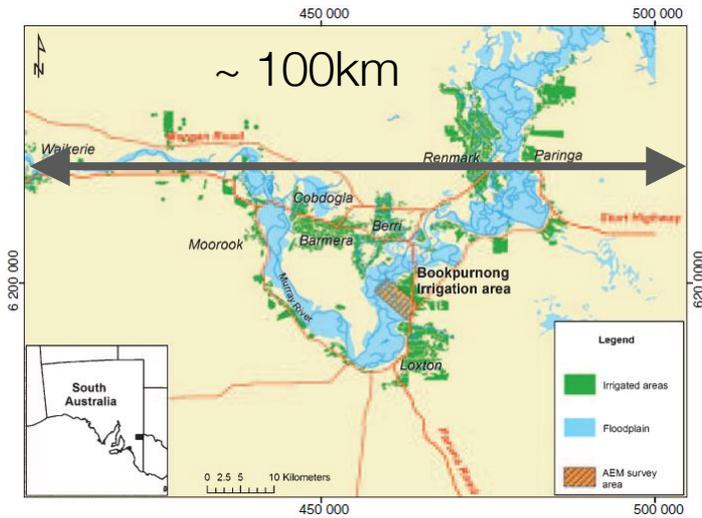


# EM: Inductive Sources

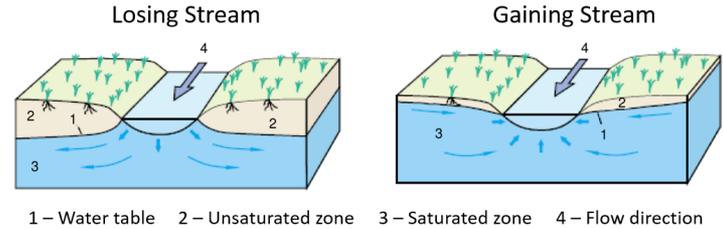


# Motivation

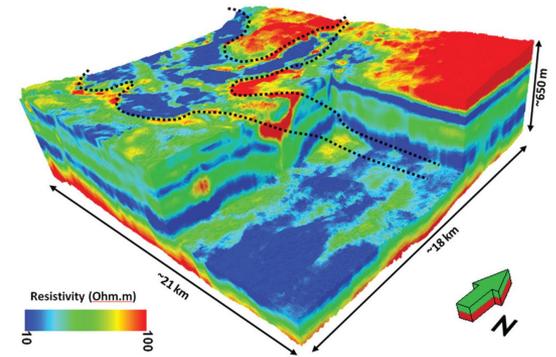
Large areas to be covered



Groundwater



High resolution near surface



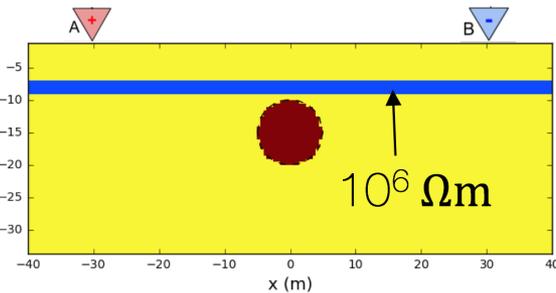
Rugged terrain



Minerals



Shielding problem



# Outline

## Setup

- Basic experiment
- Transmitters, Receivers

## Time Domain EM

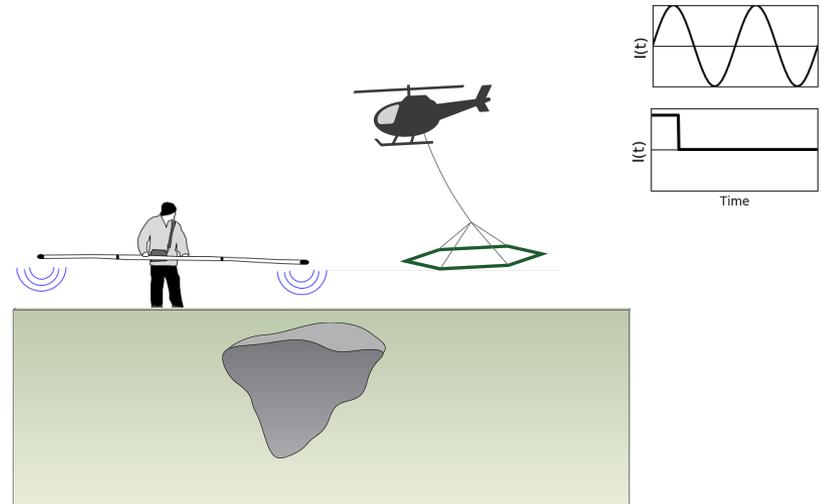
- Vertical Magnetic Dipole
- Propagation with Time
- Case History – Groundwater, Hydrocarbons

## Frequency Domain EM

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

# 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:**

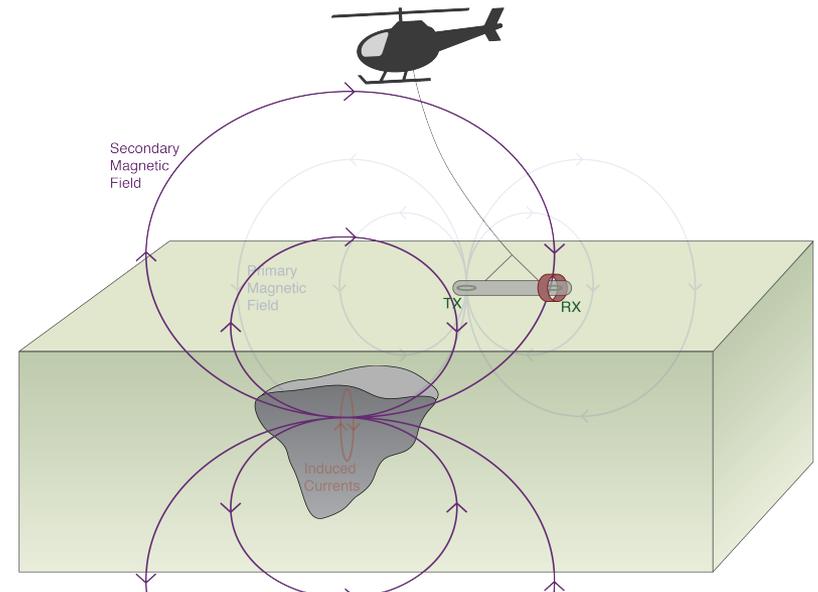
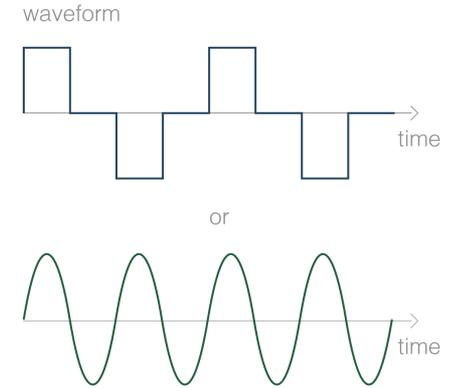
- Produces a primary magnetic field

- **Exciting the target:**

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

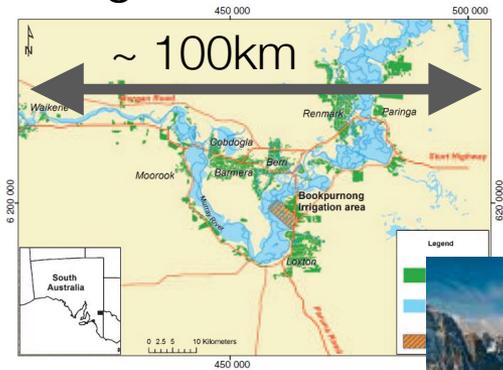
- **Receiver:**

- Induced currents produce secondary magnetic fields



# Transmitter

Large areas



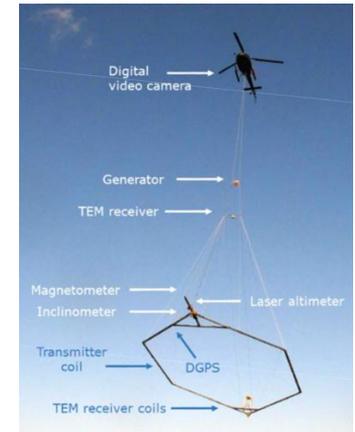
Rugged terrain



Airborne Survey

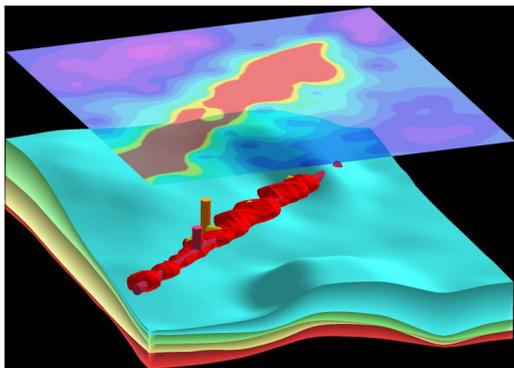


Resolve

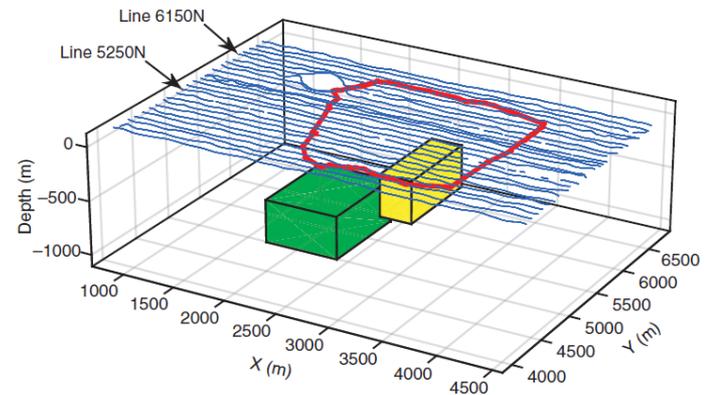


SkyTEM

Deep Targets

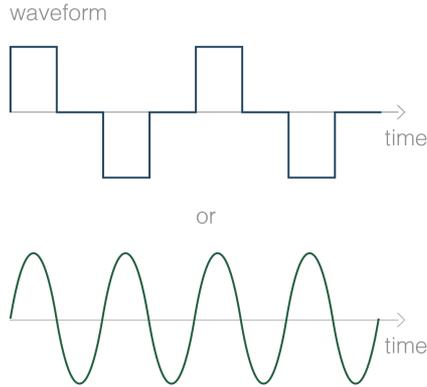


Large Loop



# Transmitter

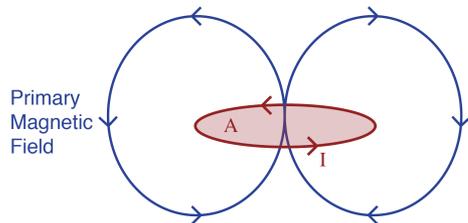
- Time or frequency?



- Key factor is moment

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

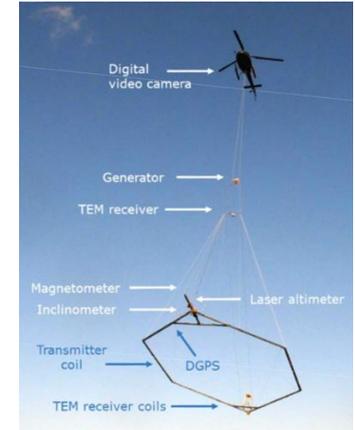
$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \left( \frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3} \right)$$



## Airborne Survey

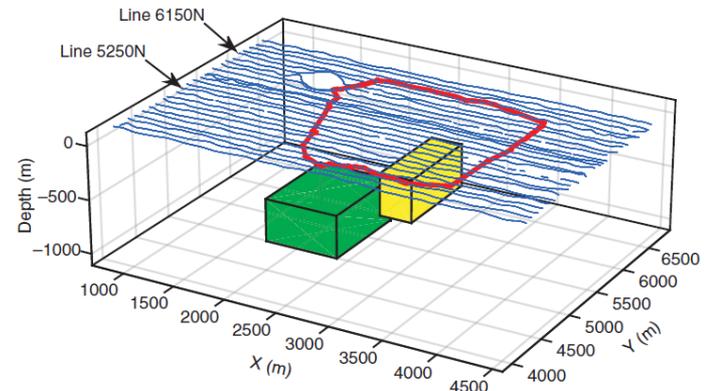


Resolve



SkyTEM

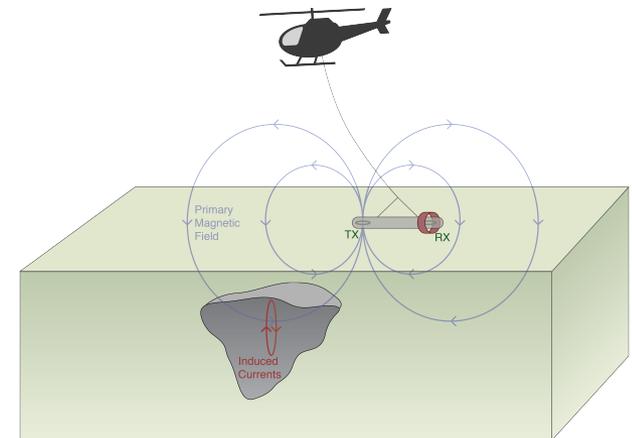
## Large Loop



# 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

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

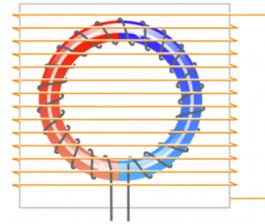


# Receiver and Data

## Magnetometer

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

$\mathbf{b}(t)$

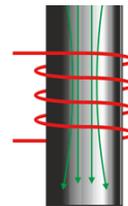


Fluxgate

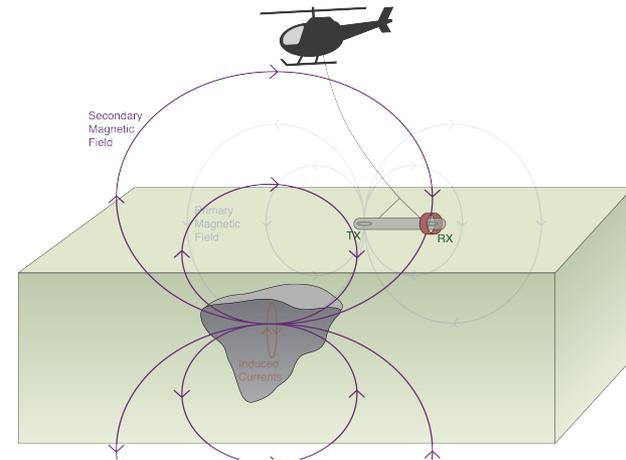
## Coil

- 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  $V_s/V_p$

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

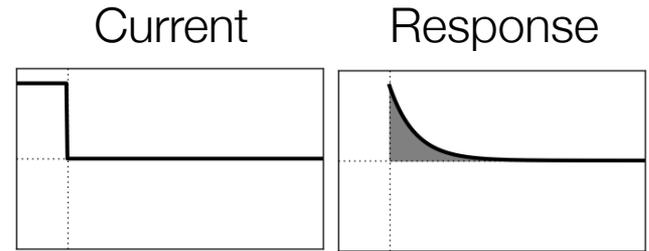


Coil

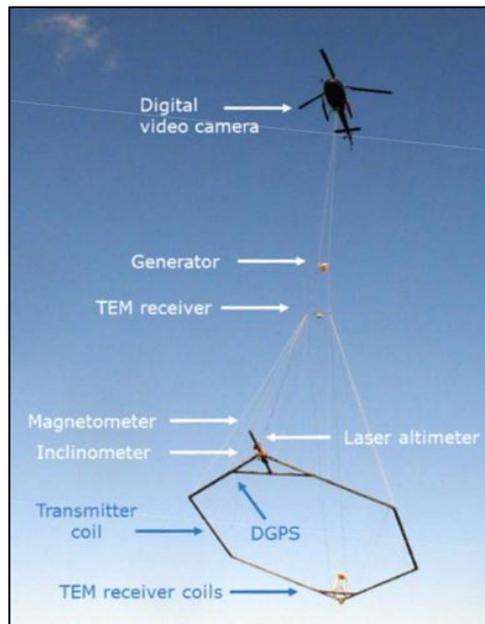


# Receiver: Time Domain

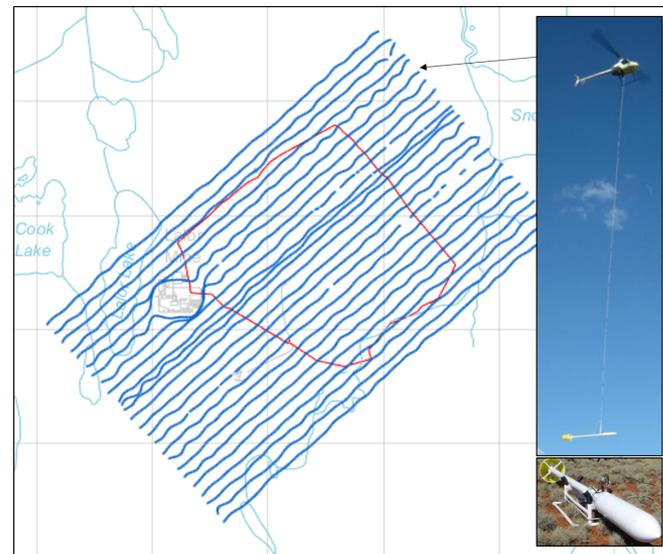
- Primary field has off-time
- Measure secondary fields
- Receivers can be mounted on transmitter loop or above it



SkyTEM

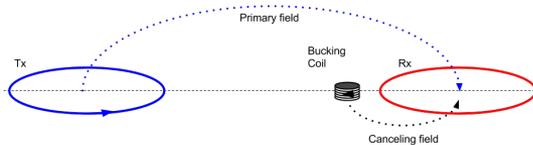


HeliSAM

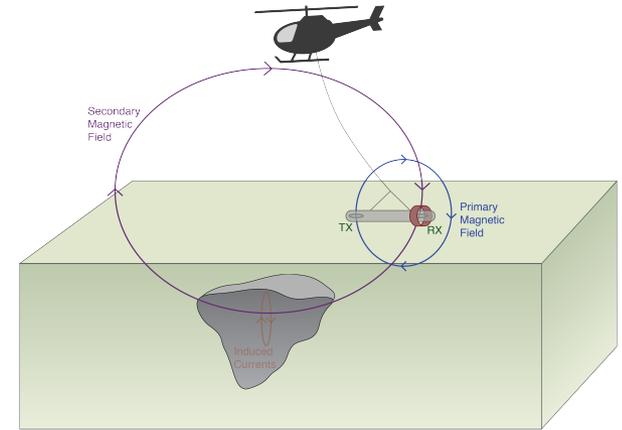


# Receiver: Frequency Domain

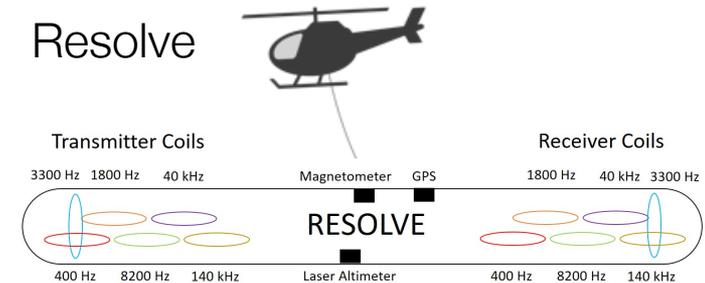
- Primary field
  - always “on”
  - large compared to secondary fields
- Primary removal
  - Compute and subtract
  - Bucking coil



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



Resolve

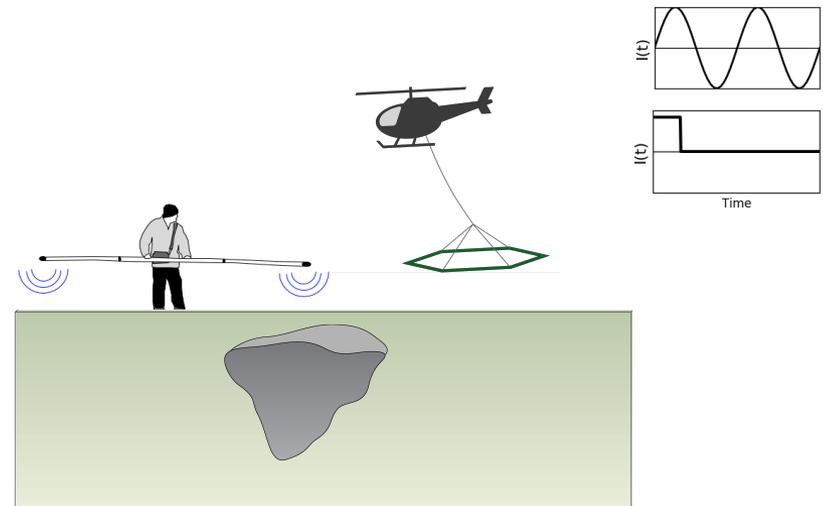


EM-31



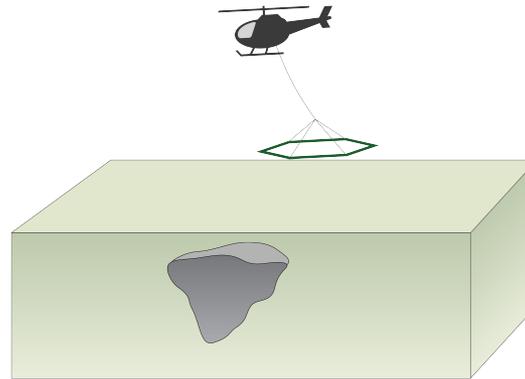
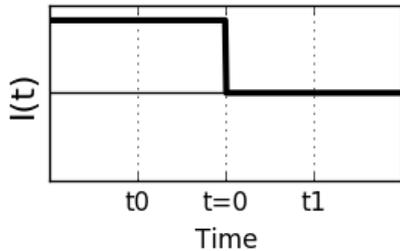
# Important questions

- 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
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- What is the “footprint” of the transmitter”
  - These are questions of **SURVEY DESIGN**

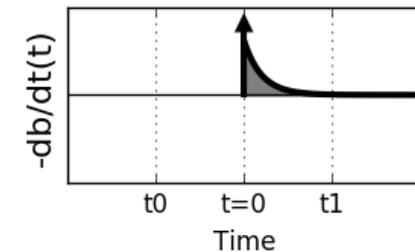
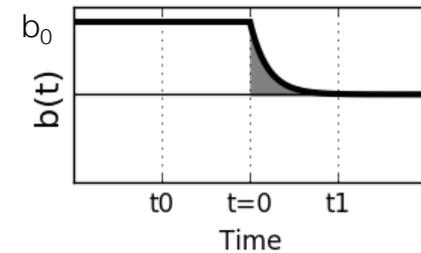


# EM with Inductive Sources: Time Domain

Transmitter current



Receiver

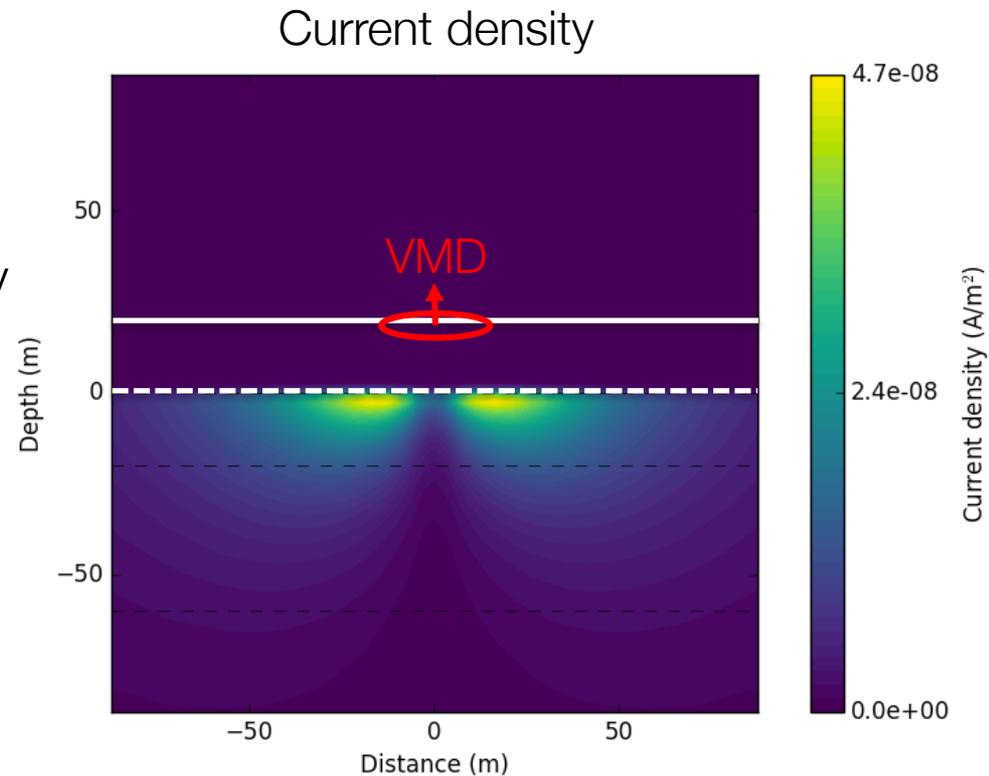


<b>time</b>	<b>b</b>	<b>db/dt</b>
$t < 0$	$b_0$	0
$t = 0$	$b_0$	$-b_0\delta(t)$
$t > 0$	secondary	secondary

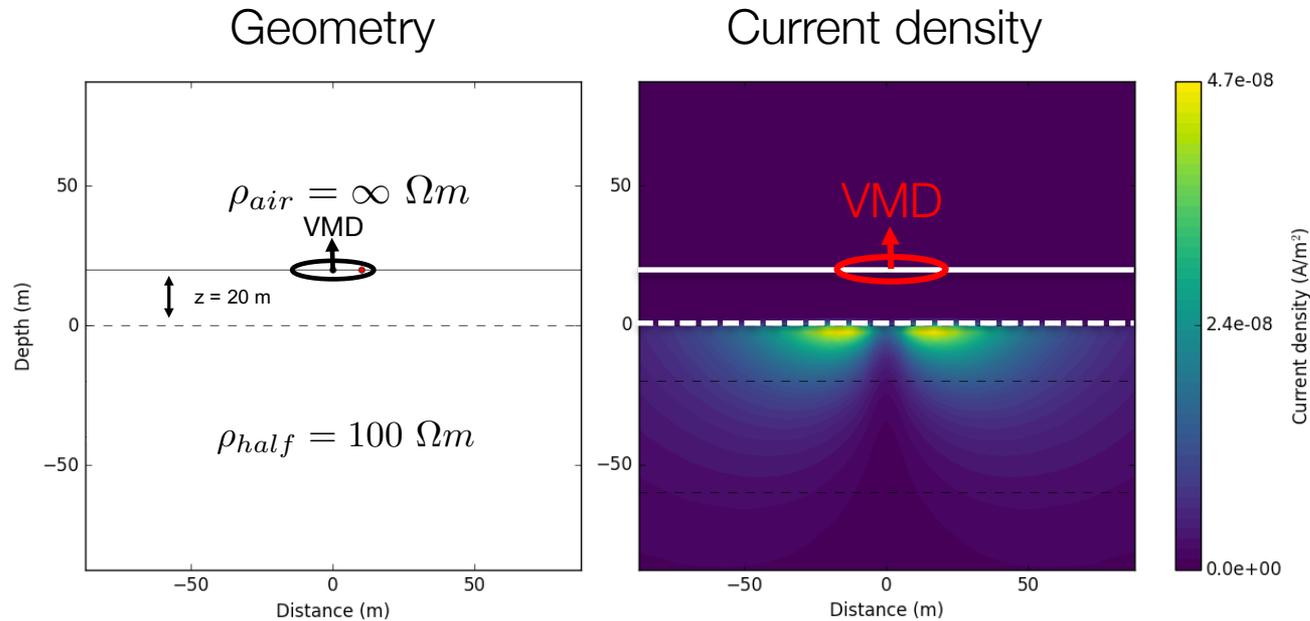
$\delta(t)$ : Dirac-delta function

# 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

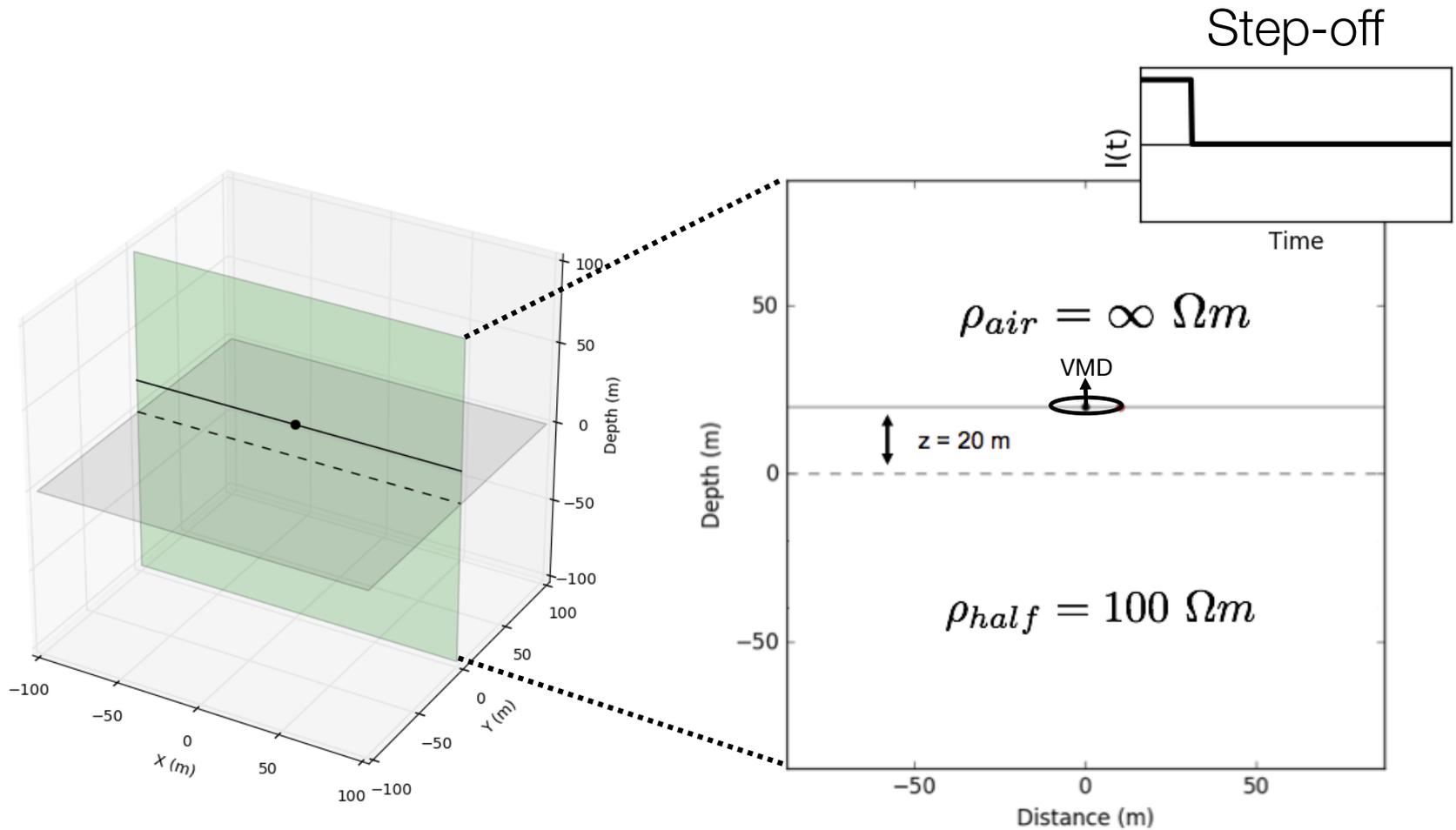


# Vertical Magnetic Dipole (VMD)



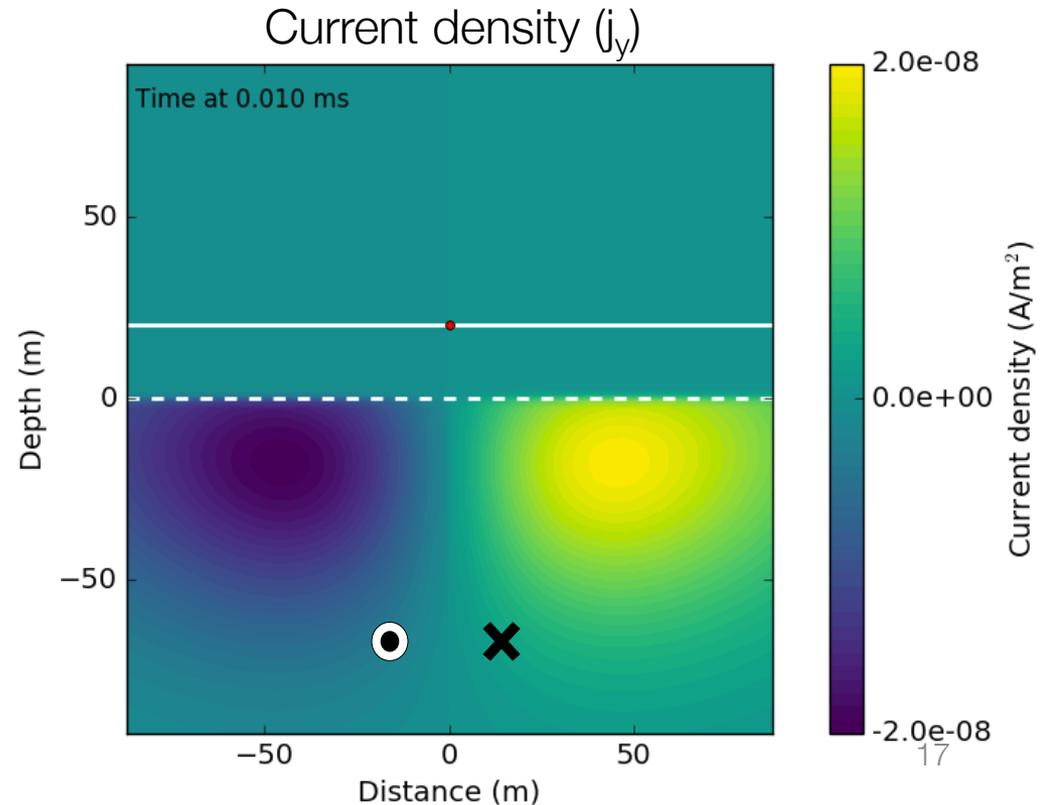
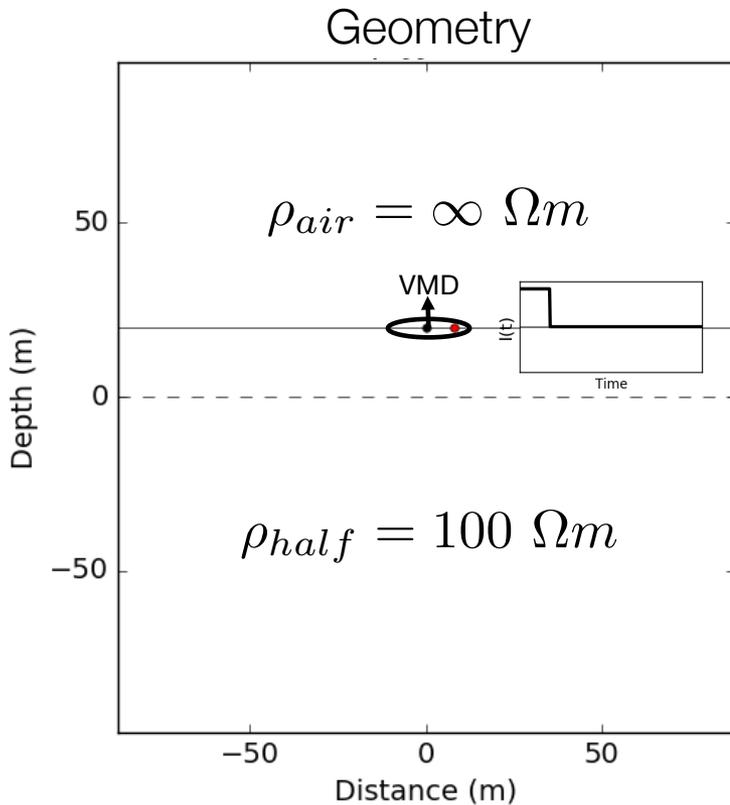
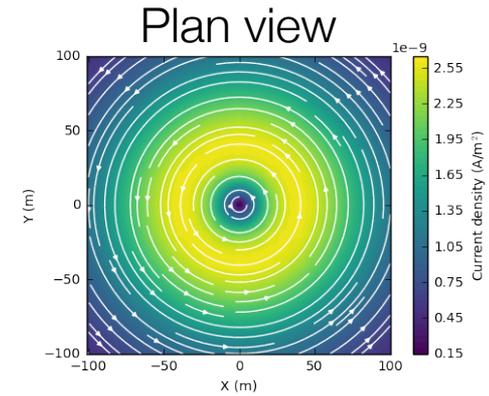
- Some questions
  - Where, and how strong, are the currents?
  - How do they depend upon the conductivity?
  - What do the resulting magnetic fields look like?

# Vertical Magnetic Dipole over a halfspace (TDEM)



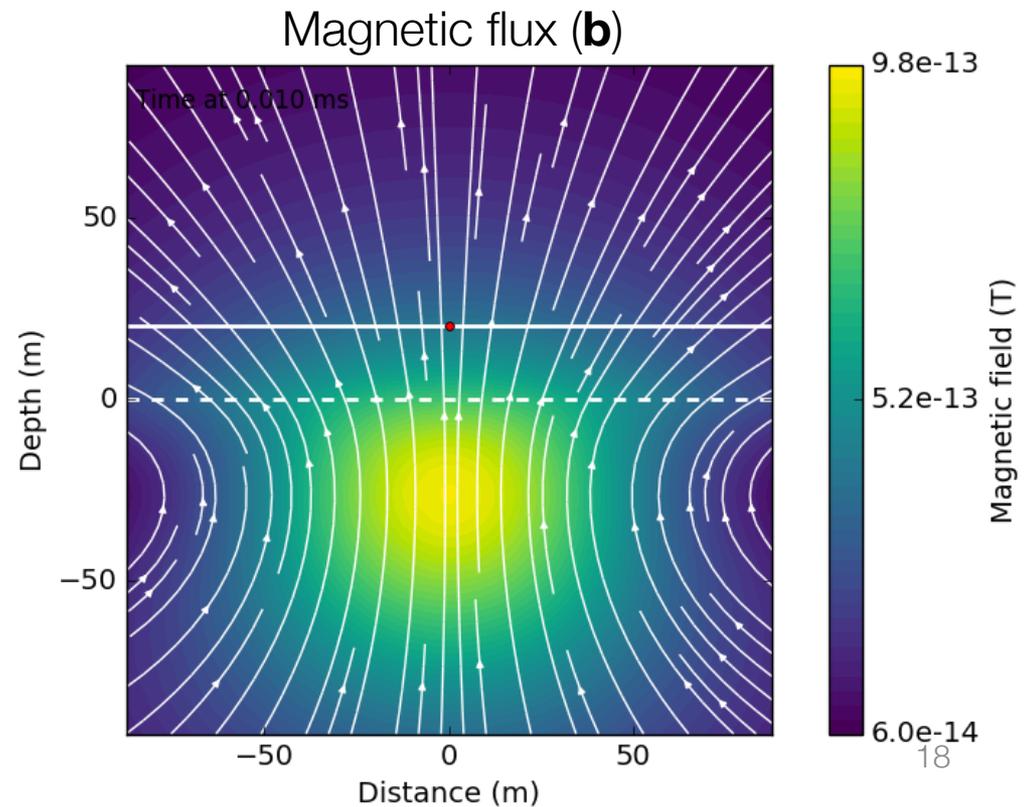
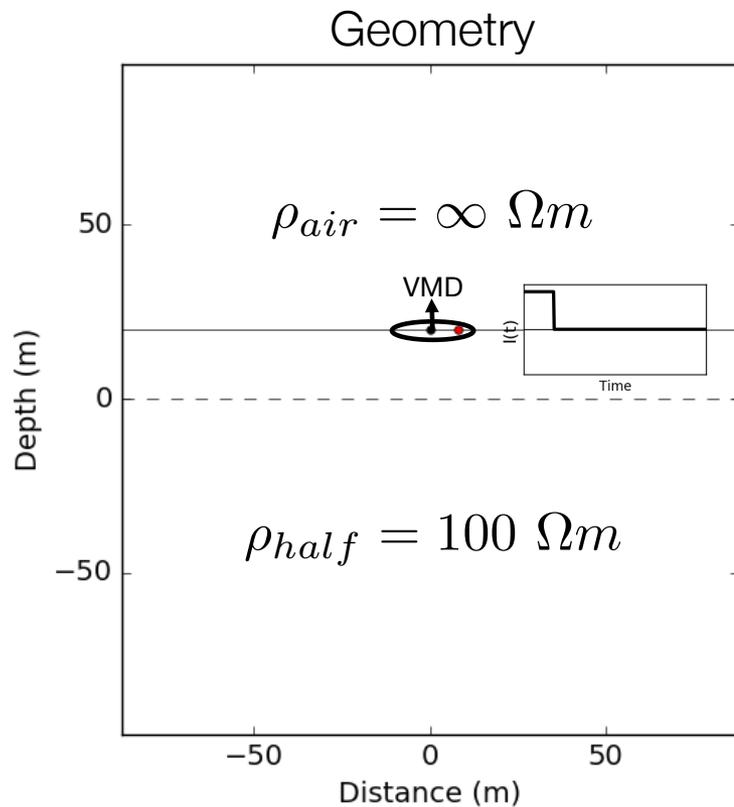
# Current Density

- Time: 0.01ms



# Magnetic flux density

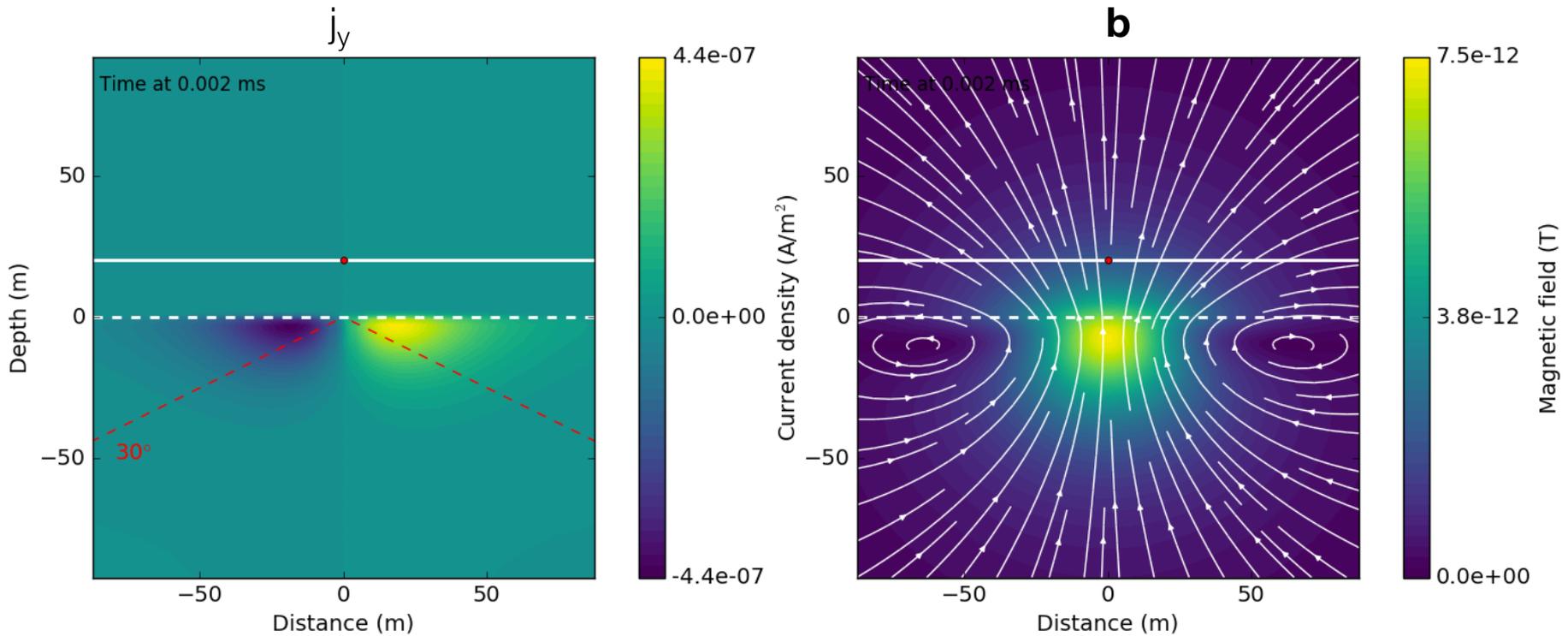
- Time: 0.01ms



# Propagation through time

- Time: 0.002ms
- diffusion distance = 18 m

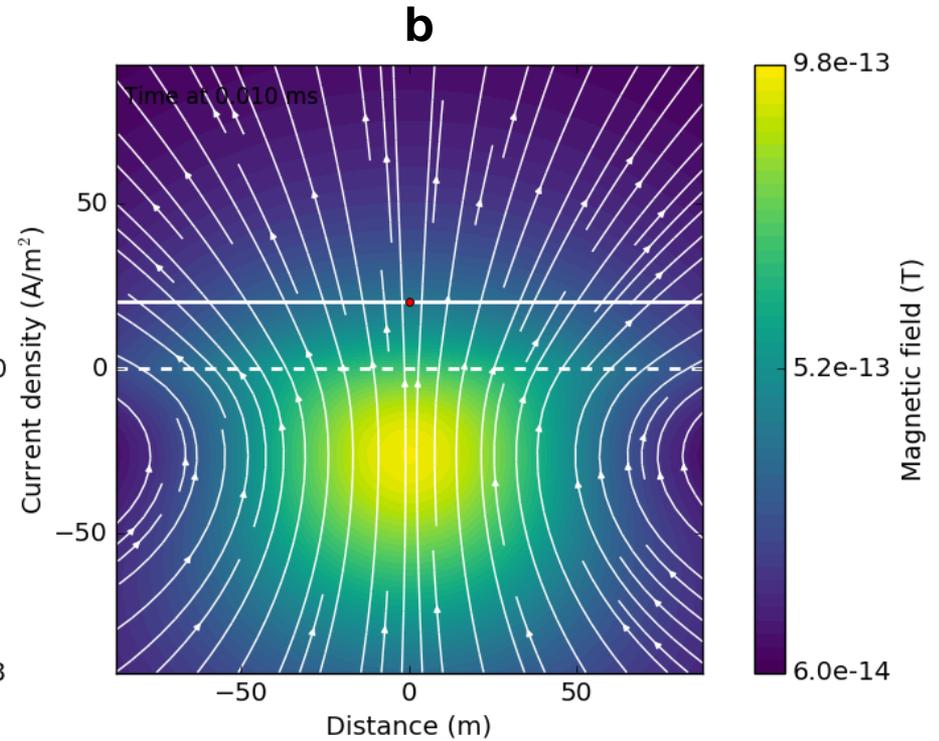
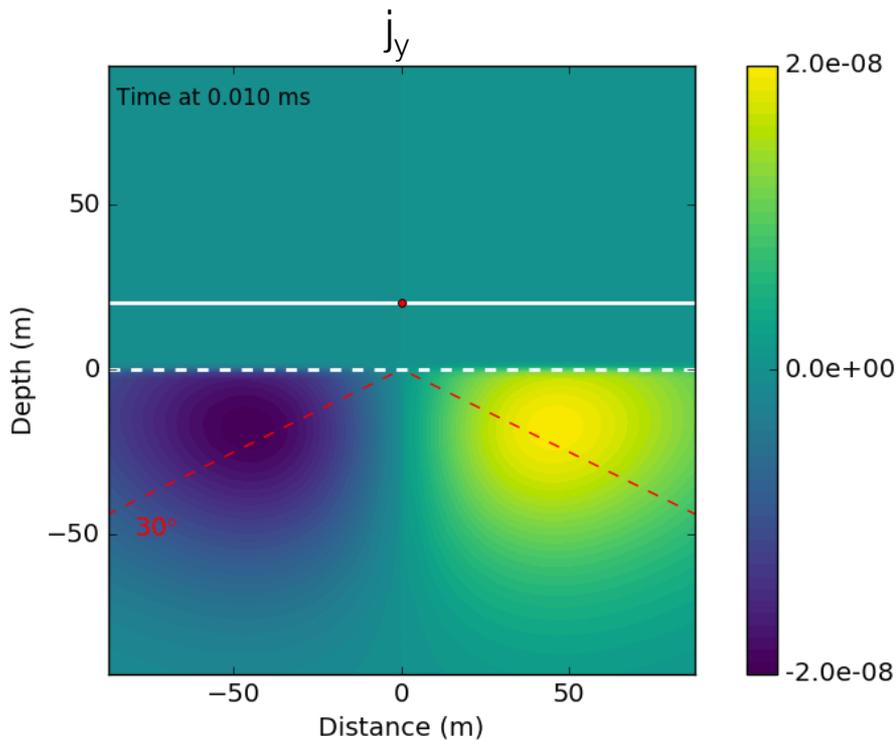
$$d = 1260\sqrt{t\rho}$$



# Propagation through time

- Time: 0.01ms
- diffusion distance = 38 m

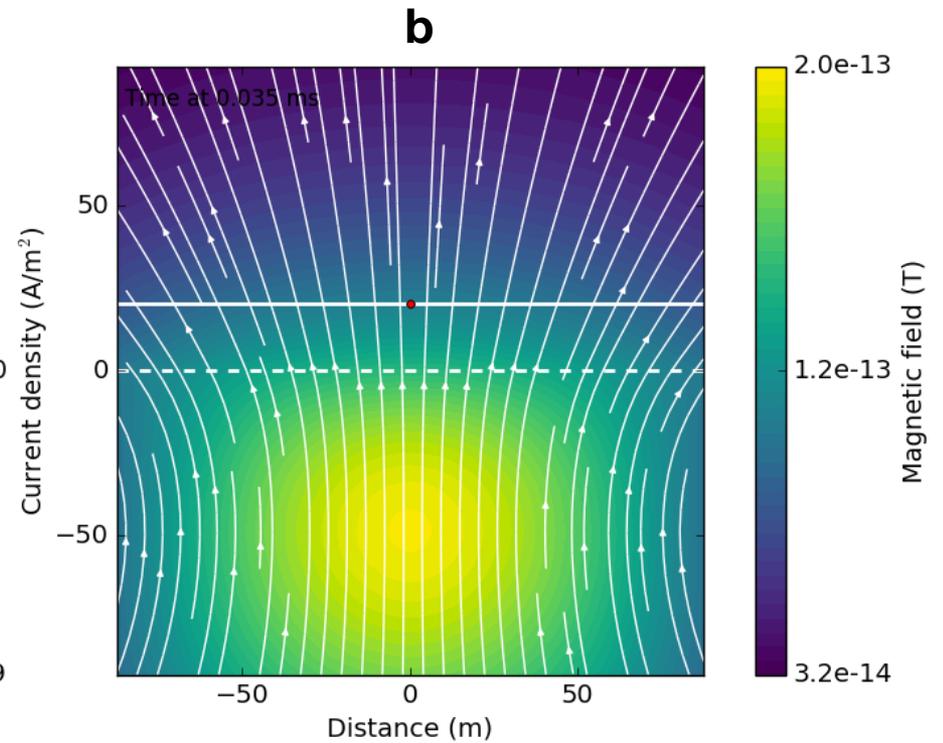
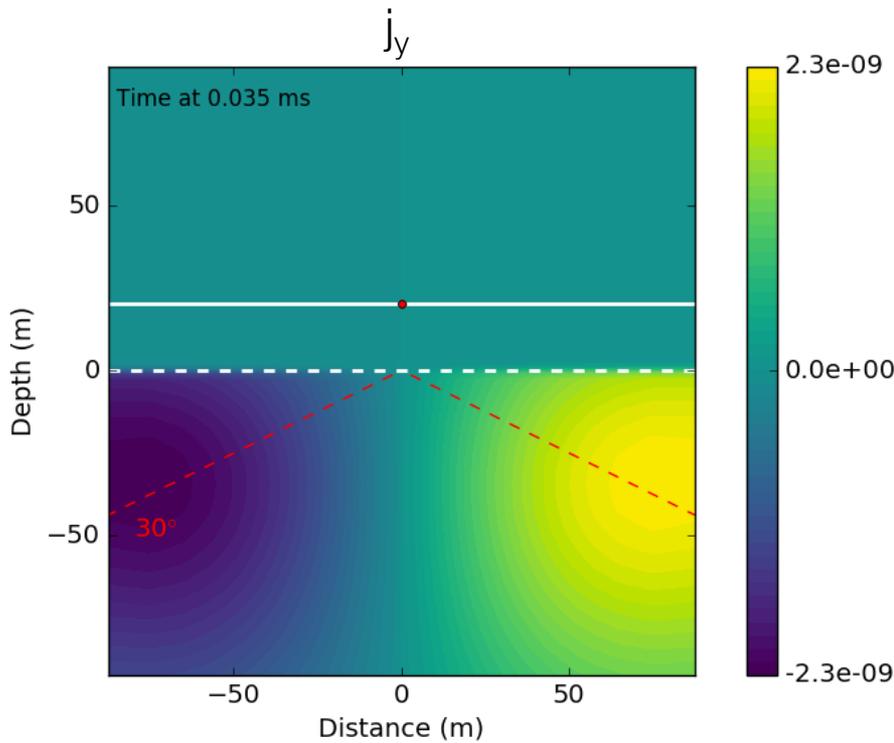
$$d = 1260\sqrt{t\rho}$$



# Propagation through time

- Time: 0.035ms
- diffusion distance = 75 m

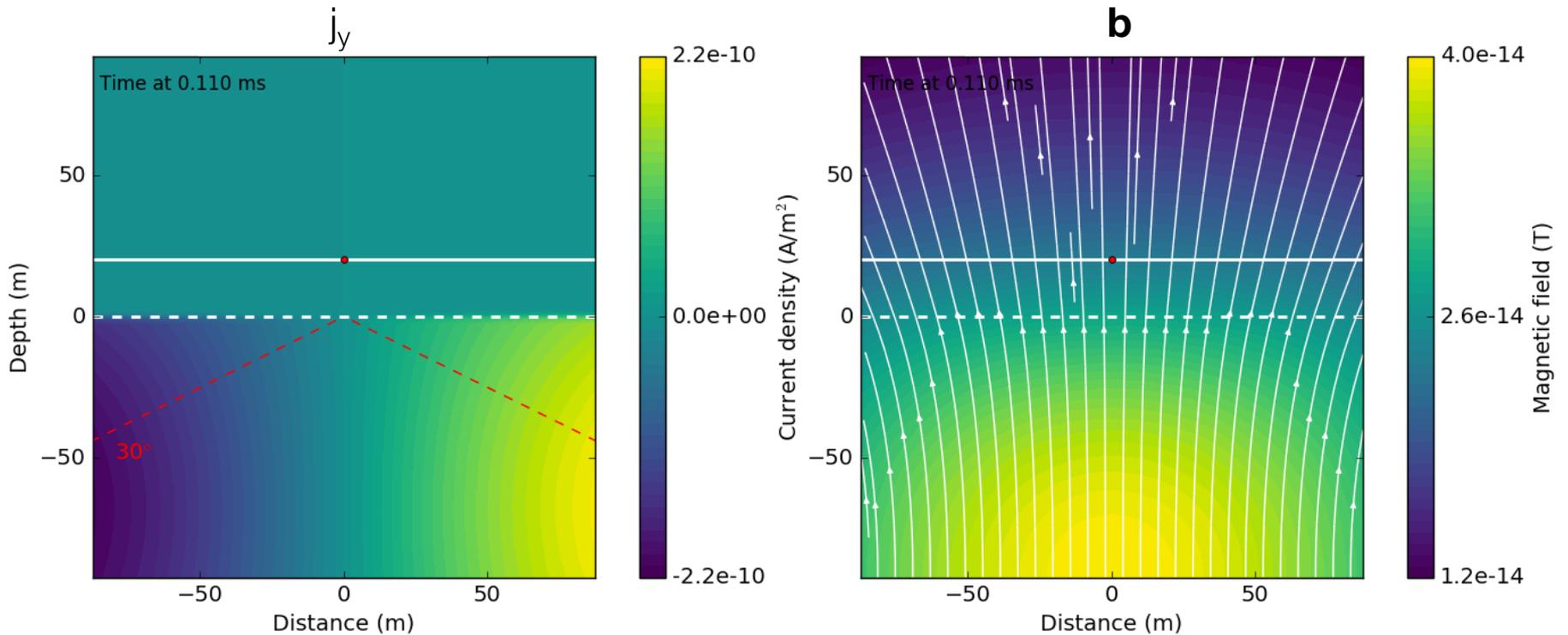
$$d = 1260\sqrt{t\rho}$$



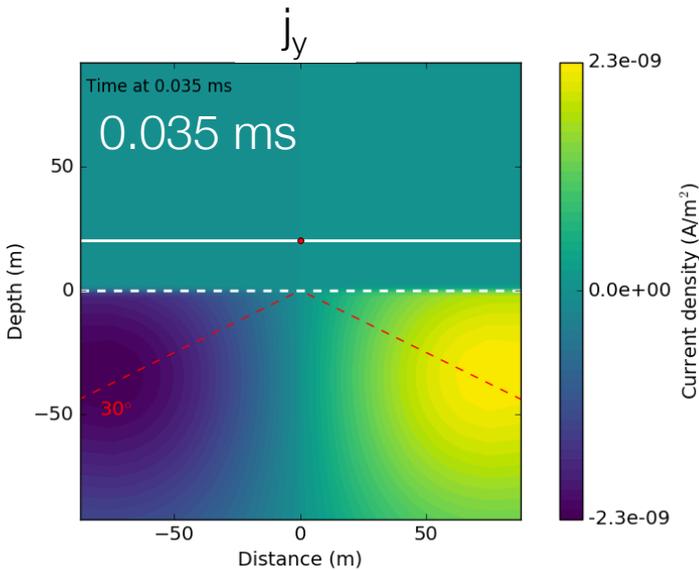
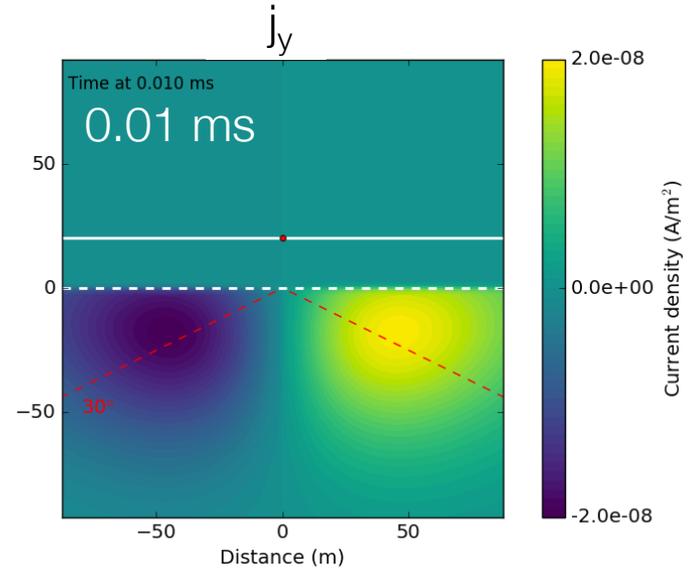
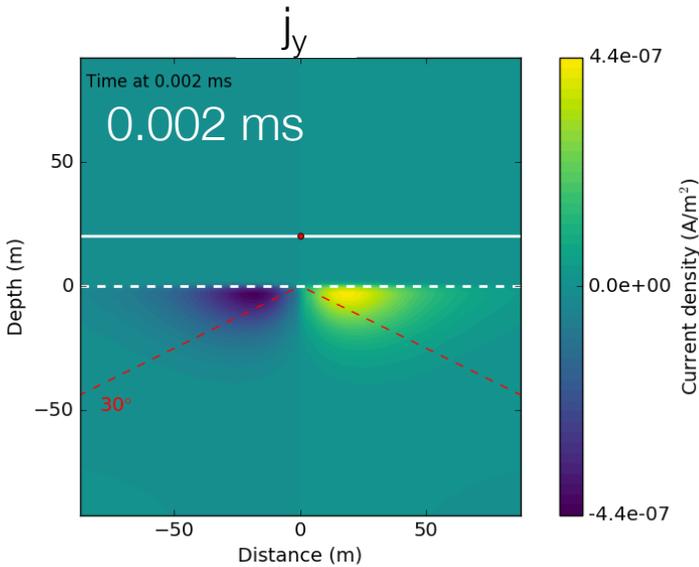
# Propagation through time

- Time: 0.110ms
- diffusion distance = 132 m

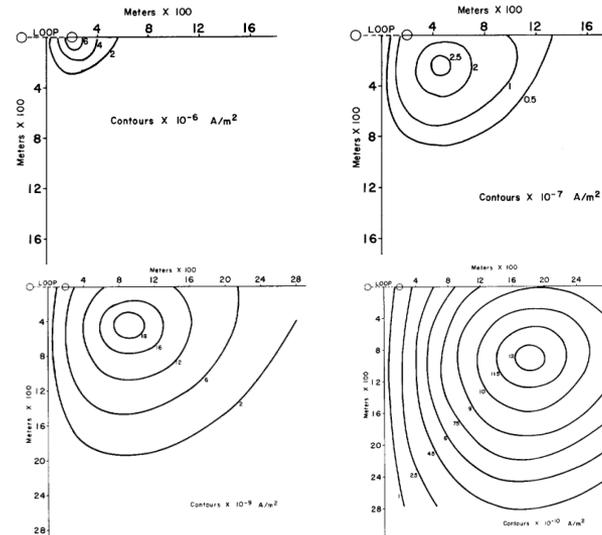
$$d = 1260\sqrt{t\rho}$$



# Summary: propagation through time



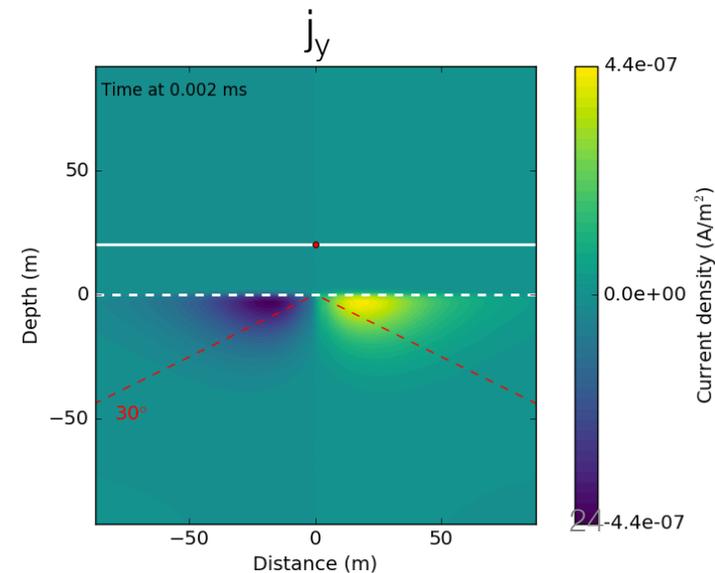
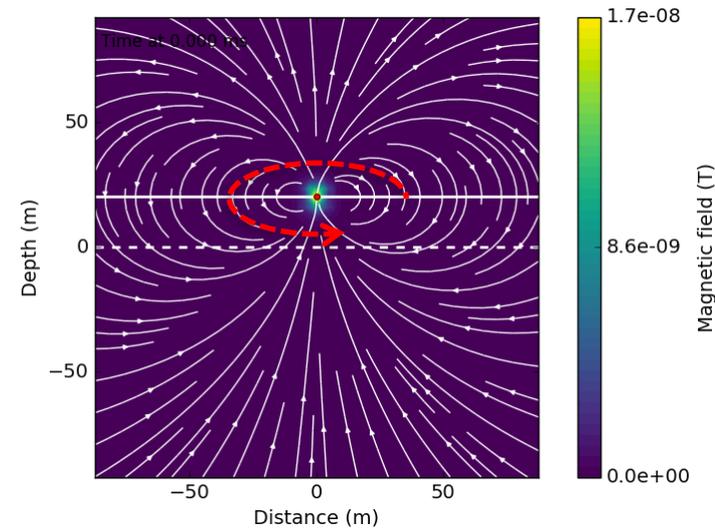
Nabighian (1979)



# 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

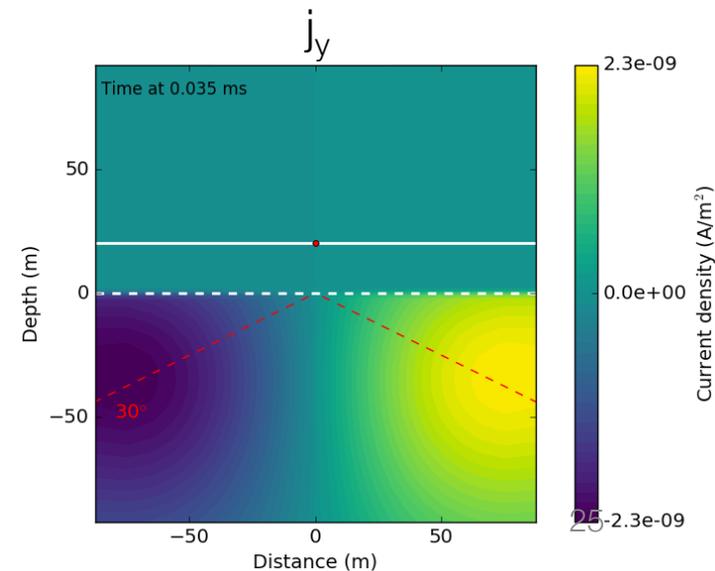
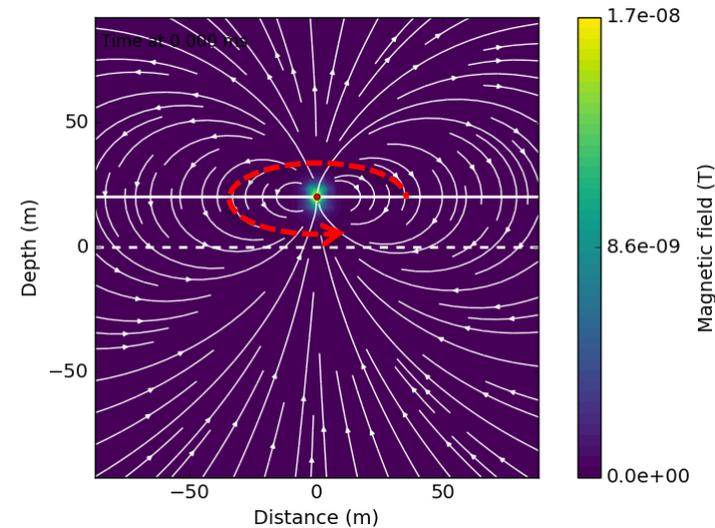
magnetic field (on-time)



# Important points

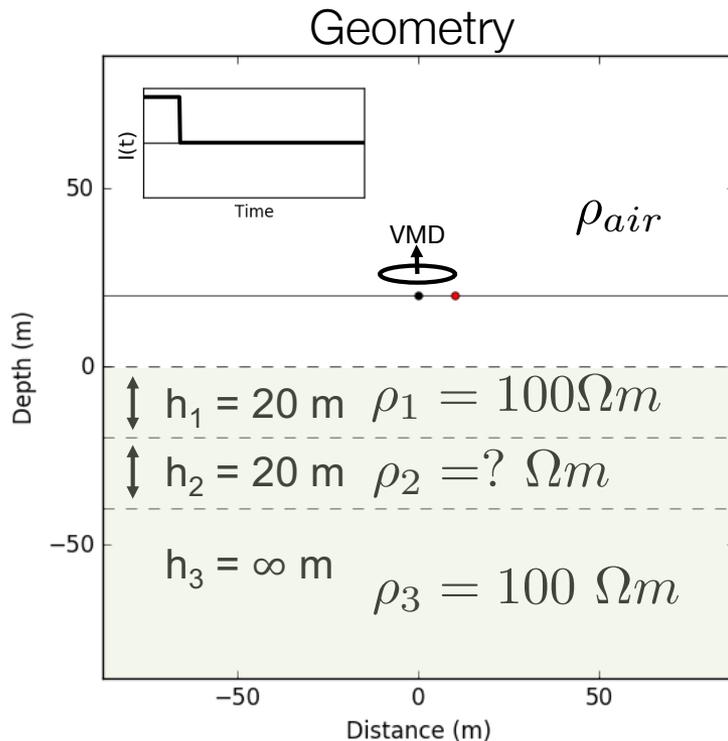
- Currents flow in same plane as transmitter currents
- Currents diffuse outward downward
- Each transmitter has a “footprint”
- Max resolution controlled by earliest time
- Depth of investigation controlled by latest time

magnetic field (on-time)



# Layered earth

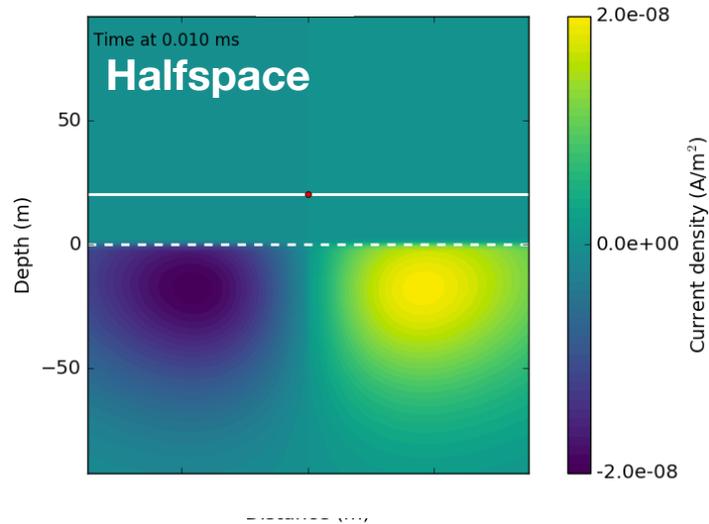
- 3 layers + air,
- $\rho_2$  varies



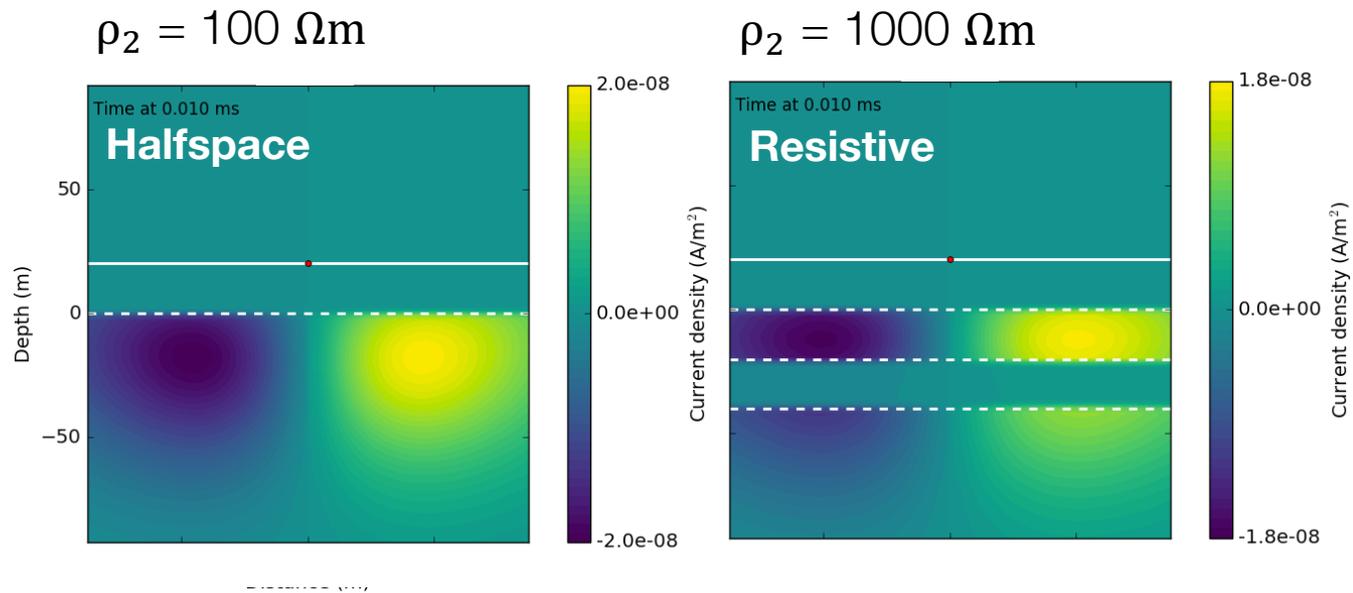
- Four different cases:
  - Halfspace
    - $\rho_2 = 100 \Omega m$
  - Resistive
    - $\rho_2 = 1000 \Omega m$
  - Conductive
    - $\rho_2 = 10 \Omega m$
  - Very conductive
    - $\rho_2 = 1 \Omega m$
- Fields
  - $j_y$  off-time
  - **b** off-time

# Layered earth currents ( $j_y$ )

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

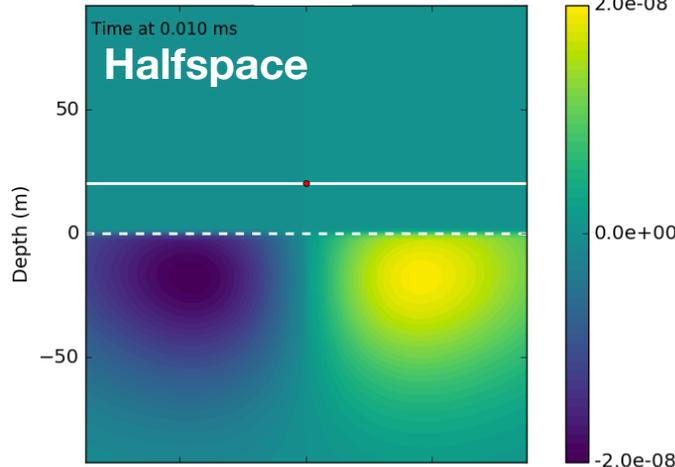


# Layered earth currents ( $j_y$ )

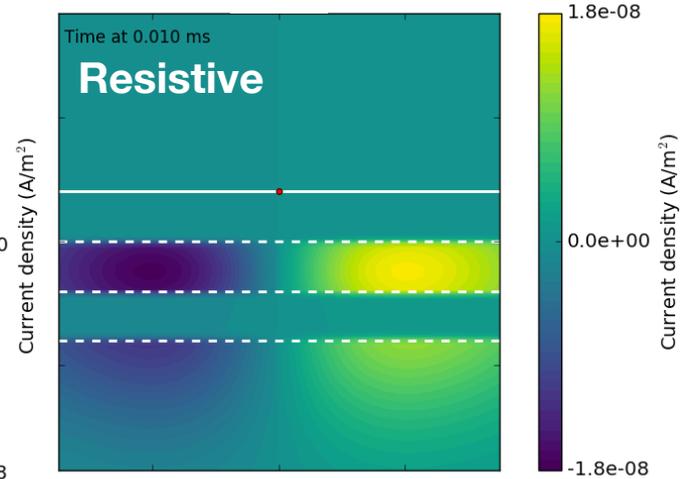


# Layered earth currents ( $j_y$ )

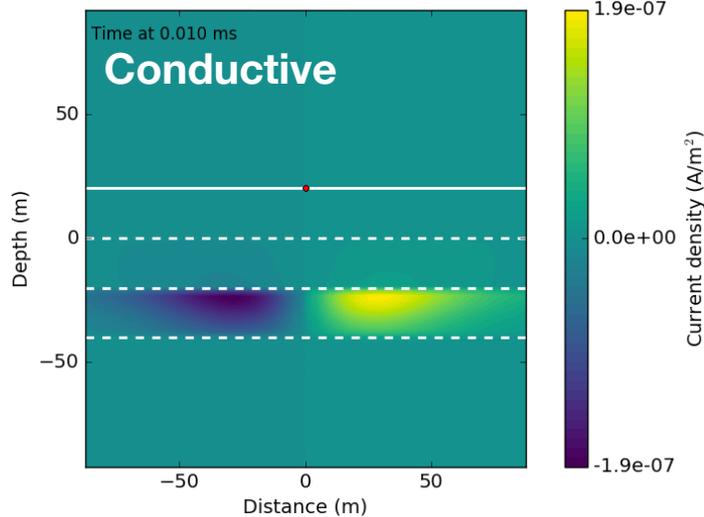
$\rho_2 = 100 \Omega\text{m}$



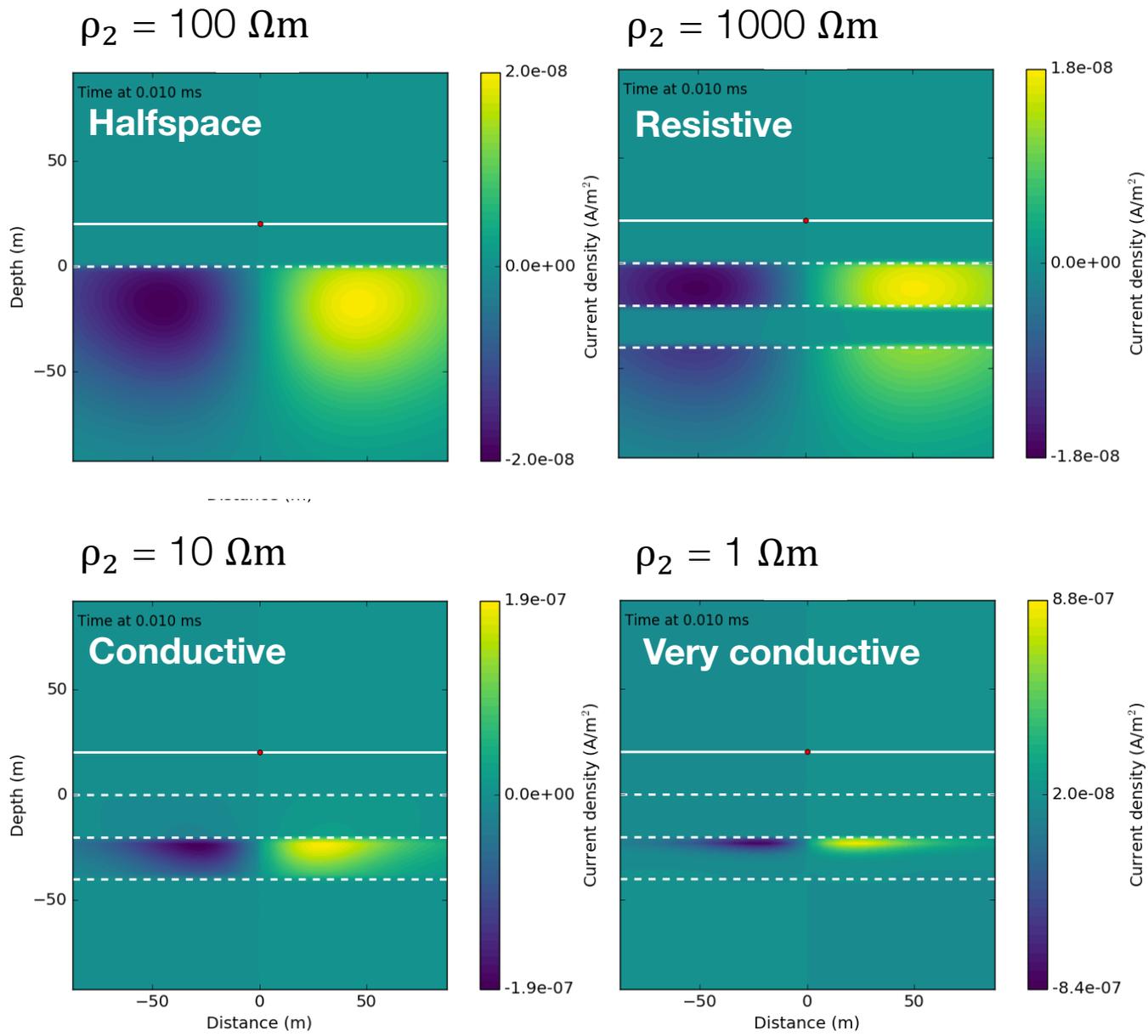
$\rho_2 = 1000 \Omega\text{m}$



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

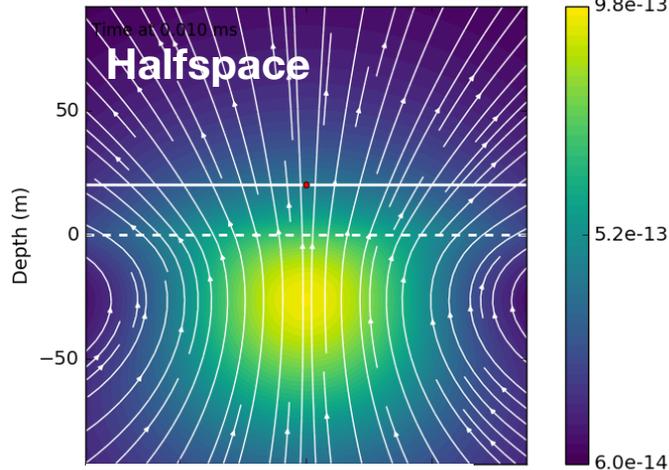


# Layered earth currents ( $j_y$ )

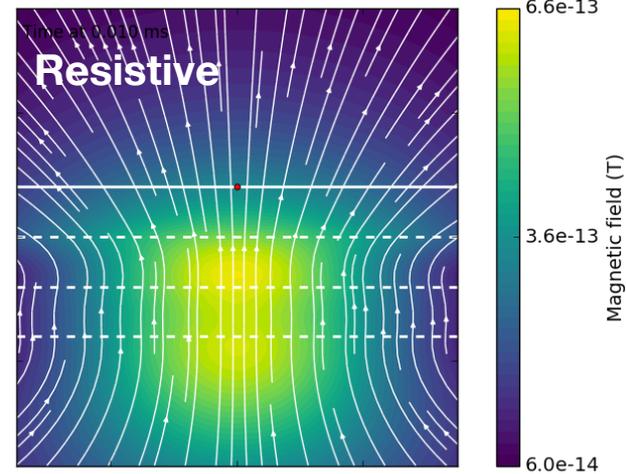


# Layered earth mag. fields (**b**)

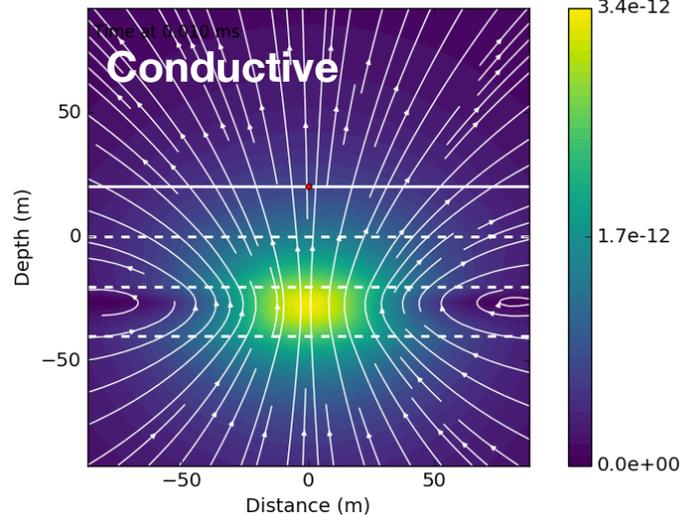
$\rho_2 = 100 \Omega\text{m}$



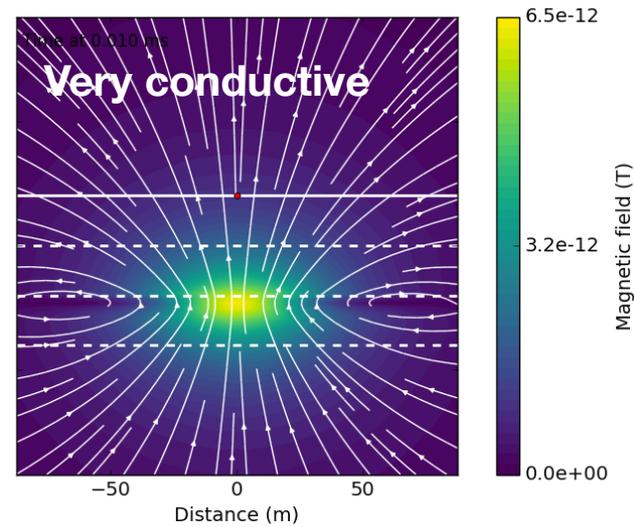
$\rho_2 = 1000 \Omega\text{m}$



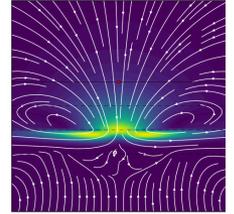
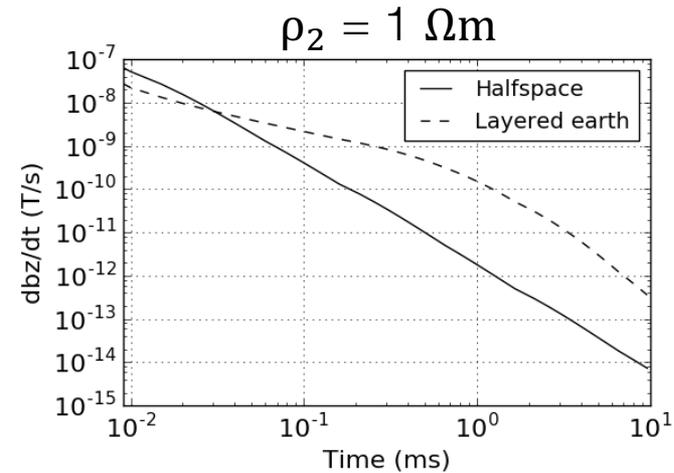
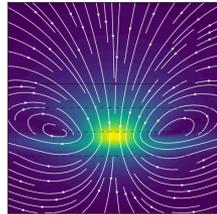
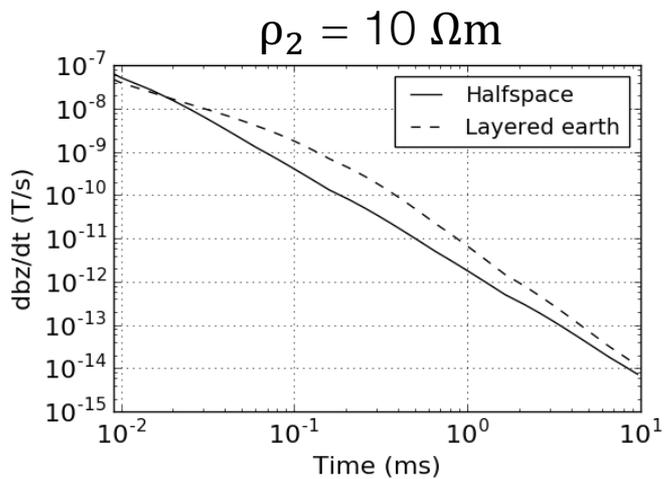
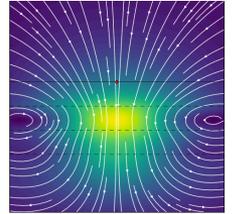
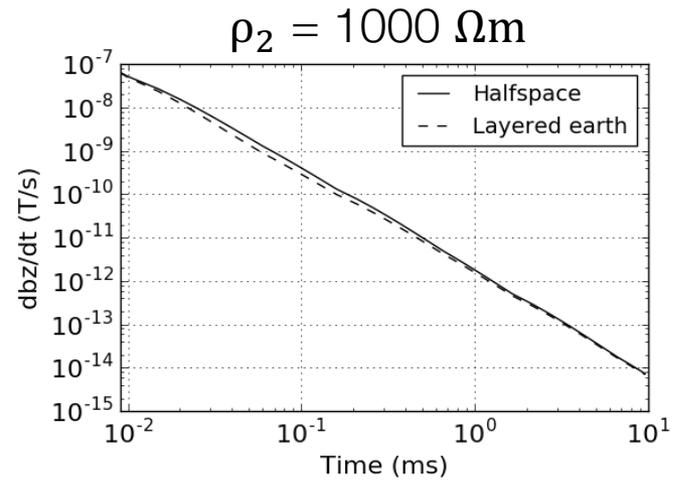
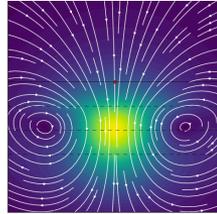
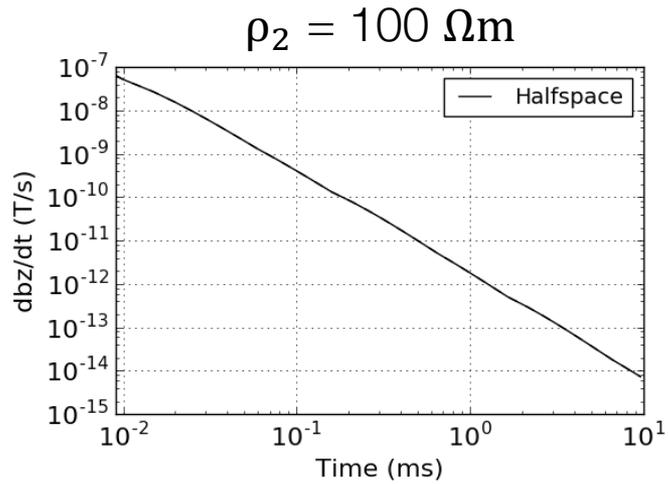
$\rho_2 = 10 \Omega\text{m}$



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



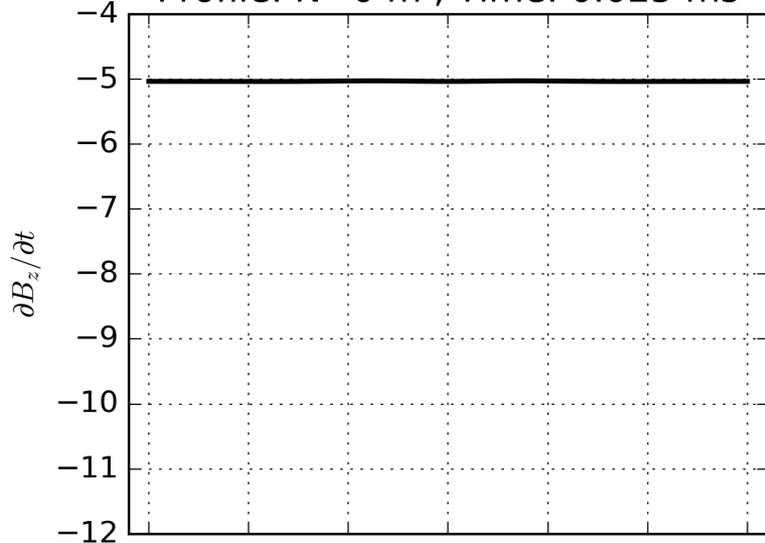
# $db_z/dt$ sounding curves



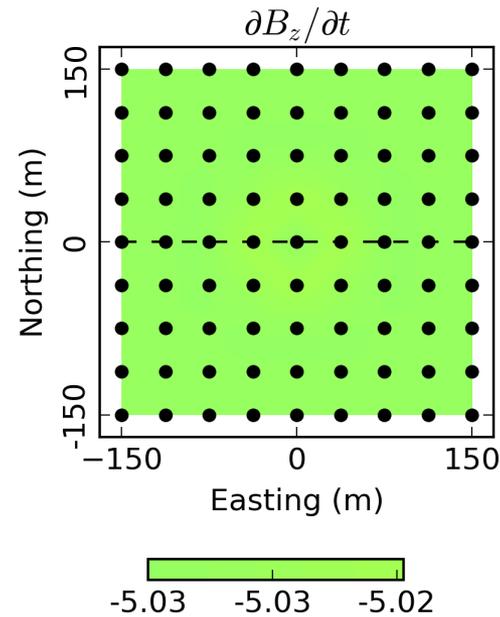
# Airborne example: conductive sphere

Data profile

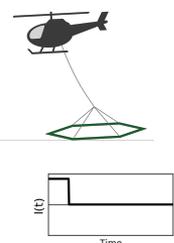
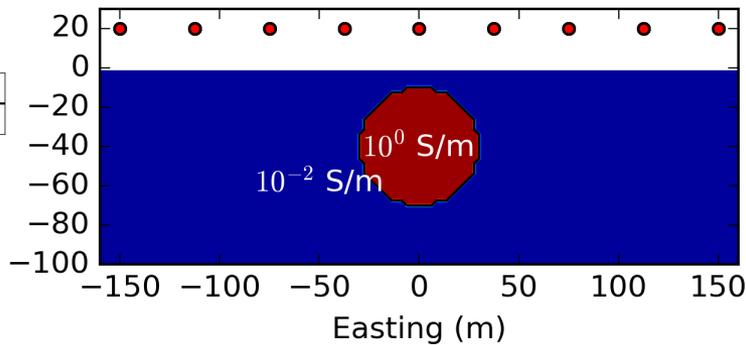
Profile: N=0 m , Time: 0.025 ms



Data map



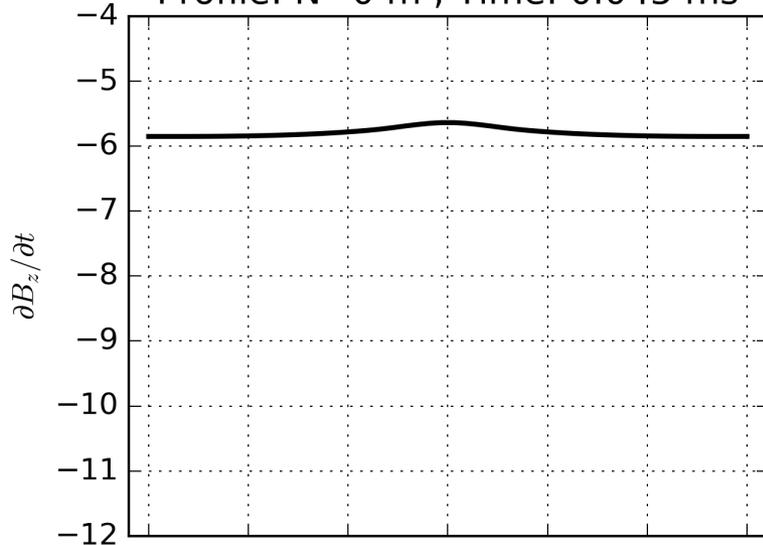
Conductivity



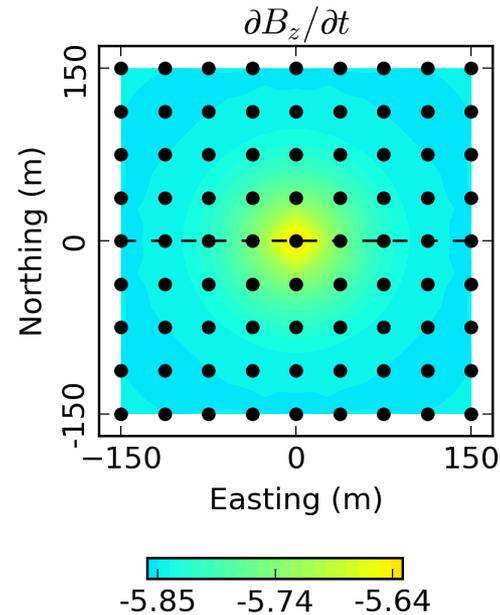
# Airborne example: conductive sphere

Data profile

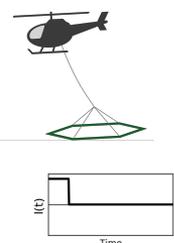
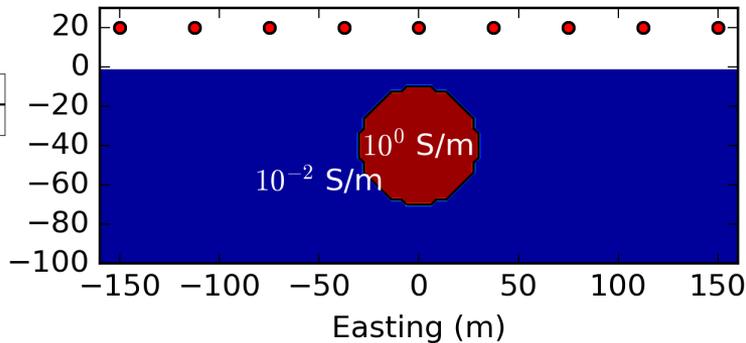
Profile: N=0 m , Time: 0.045 ms



Data map



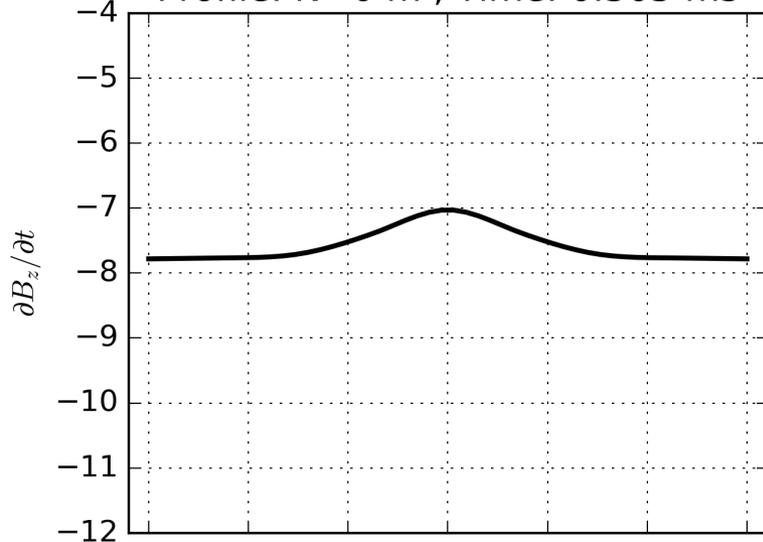
Conductivity



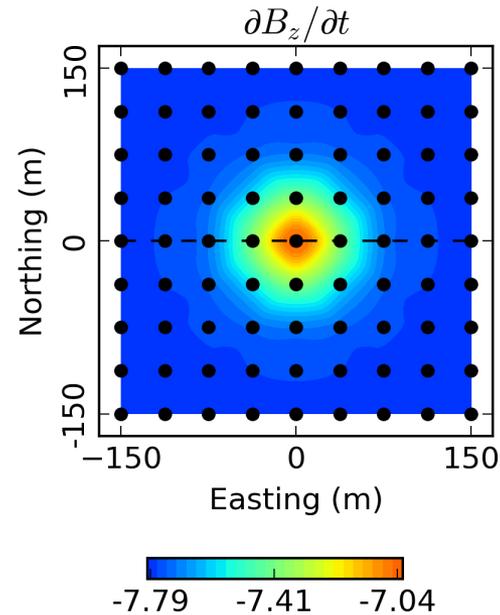
# Airborne example: conductive sphere

Data profile

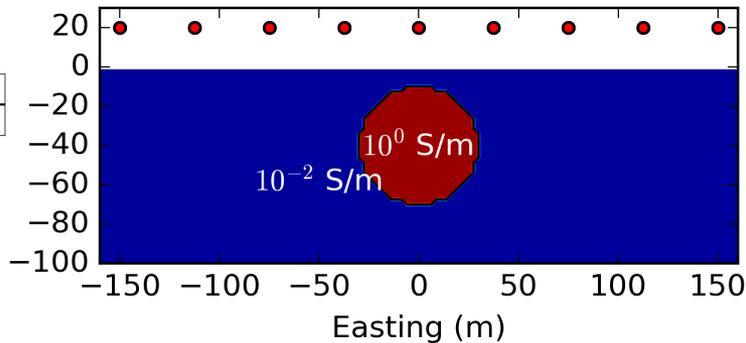
Profile: N=0 m , Time: 0.305 ms



Data map



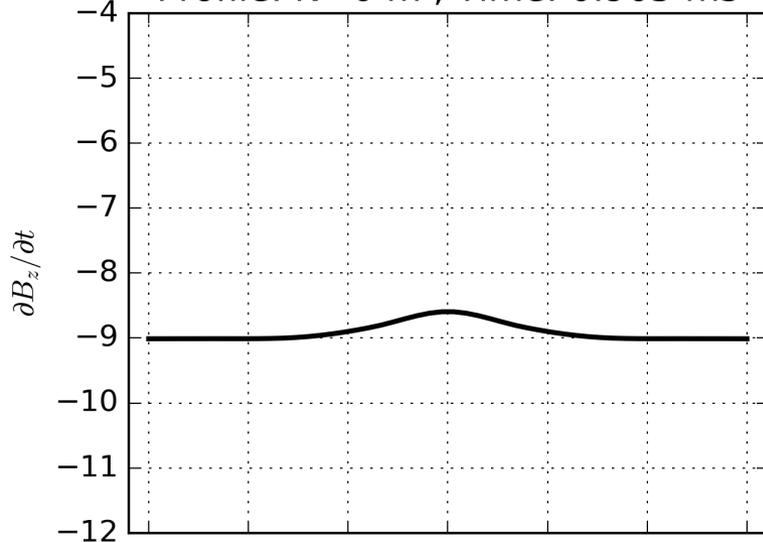
Conductivity



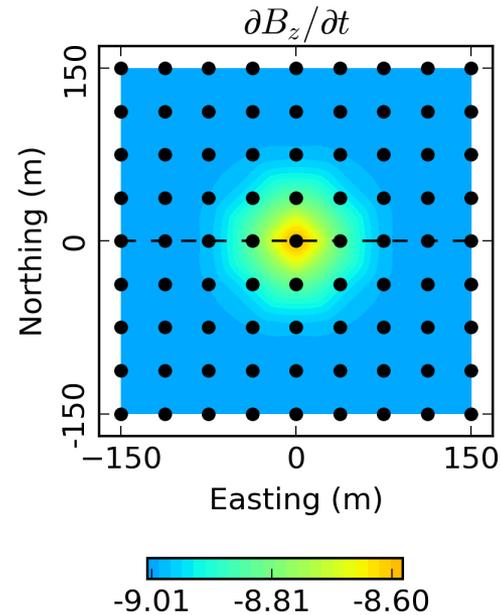
# Airborne example: conductive sphere

Data profile

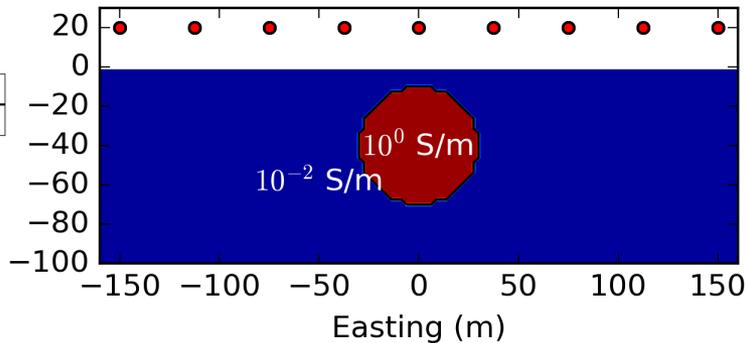
Profile: N=0 m , Time: 0.905 ms



Data map



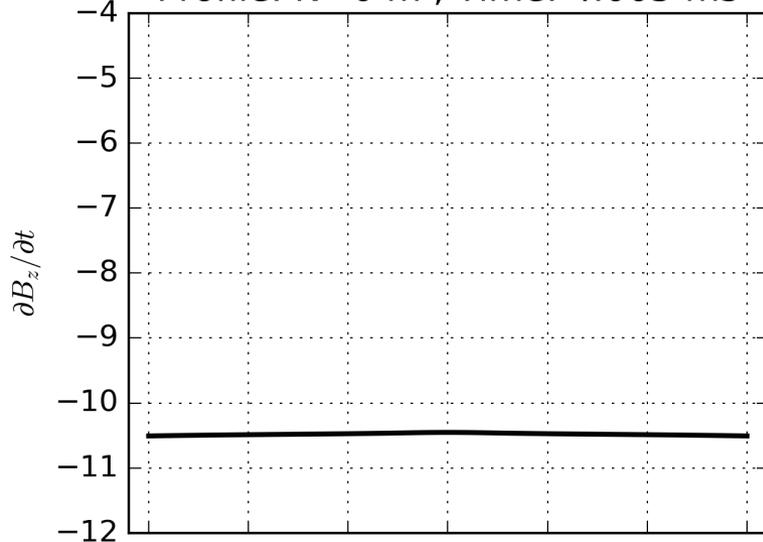
Conductivity



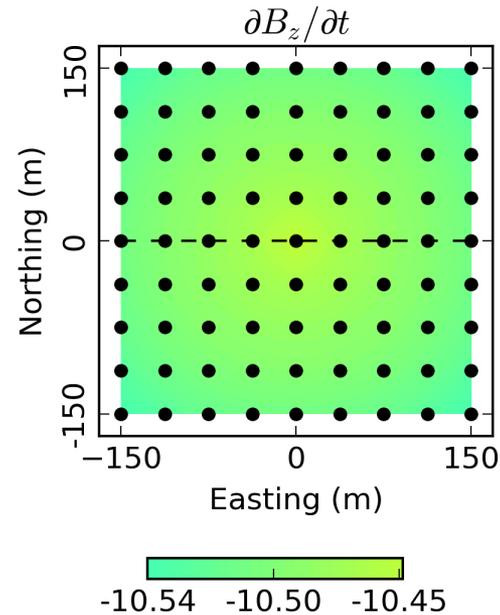
# Airborne example: conductive sphere

Data profile

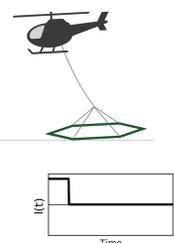
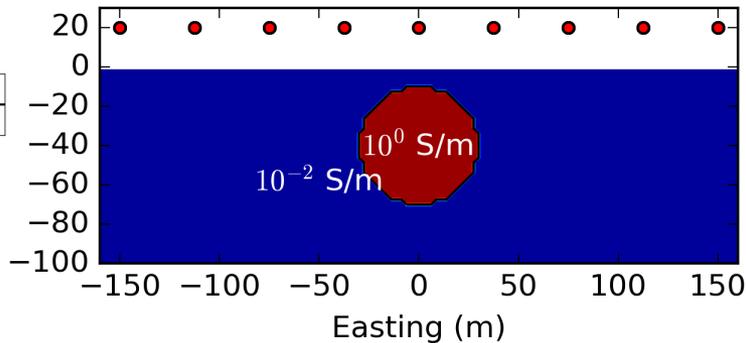
Profile: N=0 m , Time: 4.005 ms



Data map

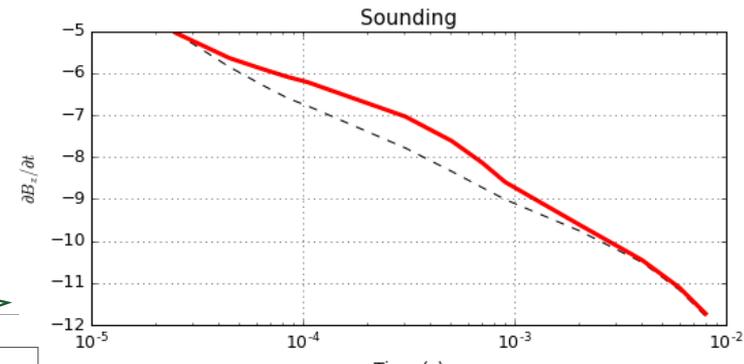
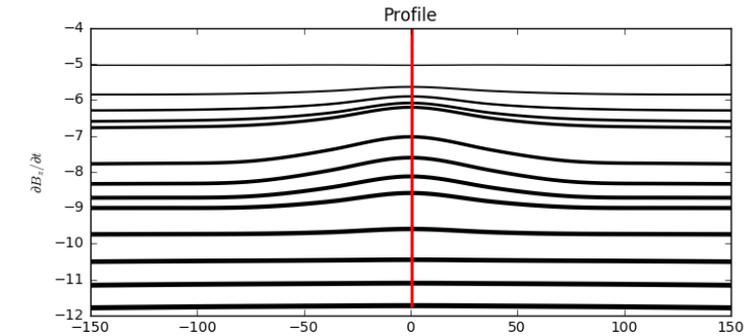


Conductivity

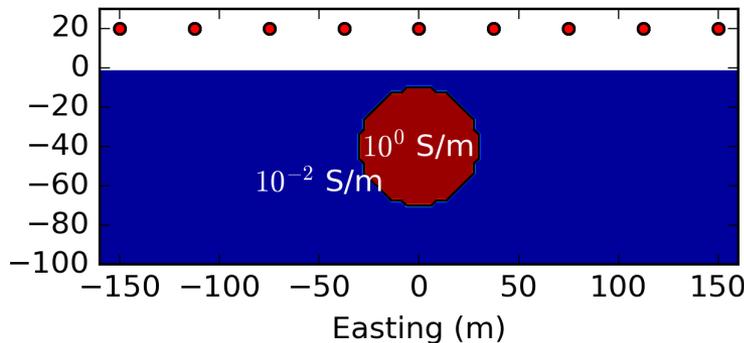


# Summary: airborne example

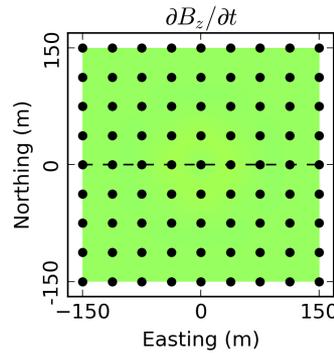
Data profile



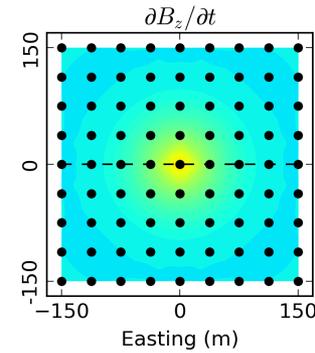
Conductivity



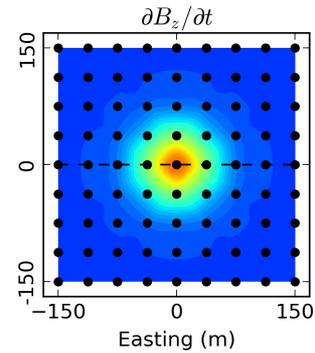
0.025 ms



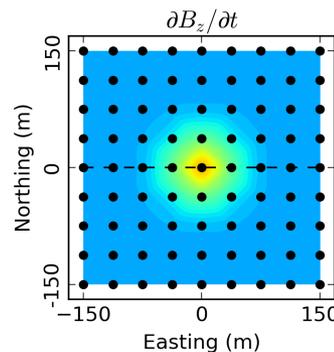
0.045 ms



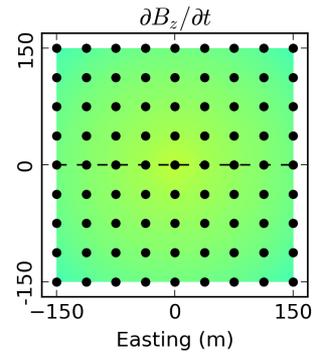
0.305 ms



0.905 ms

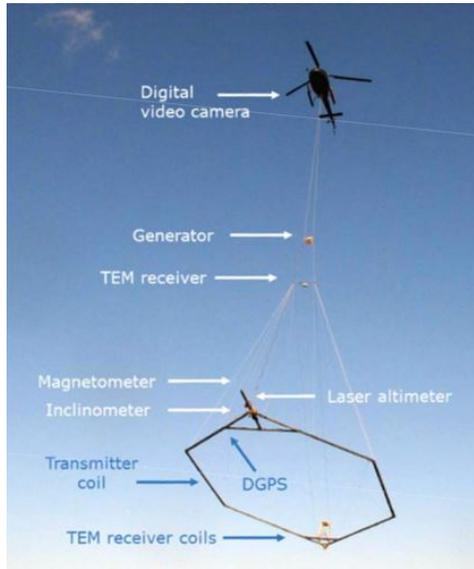


4.005 ms



# Some Airborne TDEM Systems

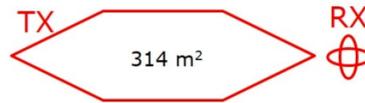
## SkyTEM (2006)



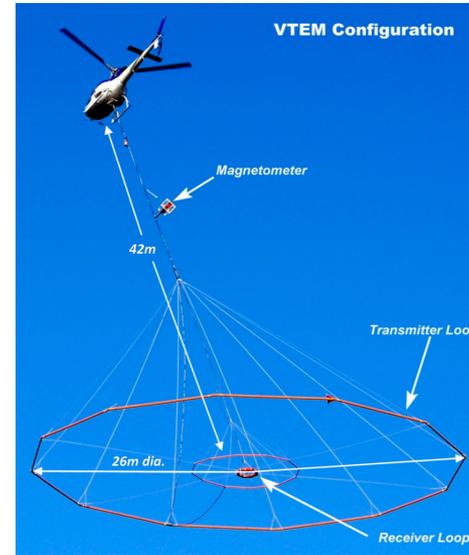
Area = 314 m<sup>2</sup>

Peak dipole moment:

- HM: 113040 NIA
- LM: 12560 NIA



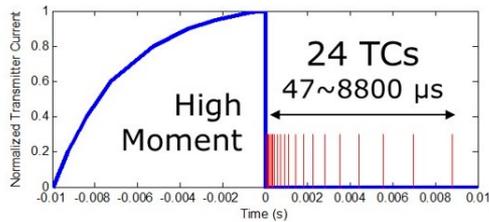
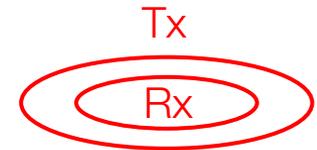
## VTEM (2007)



Area = 535 m<sup>2</sup>

Peak dipole moment:

- 503,100 NIA

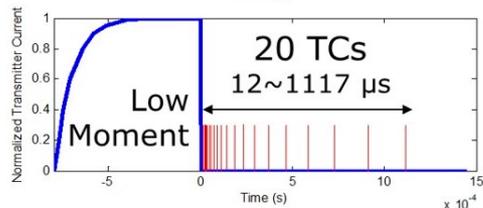


Peak current: 90 A

Turns: 4

On-time: 10 ms

Off-time: 10 ms

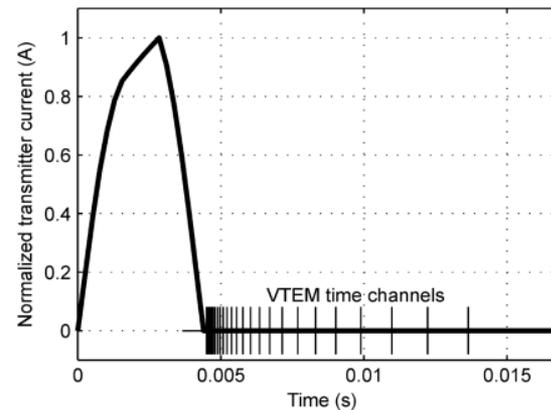


Peak current: 40 A

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, Minerals

Frequency Domain EM

Questions

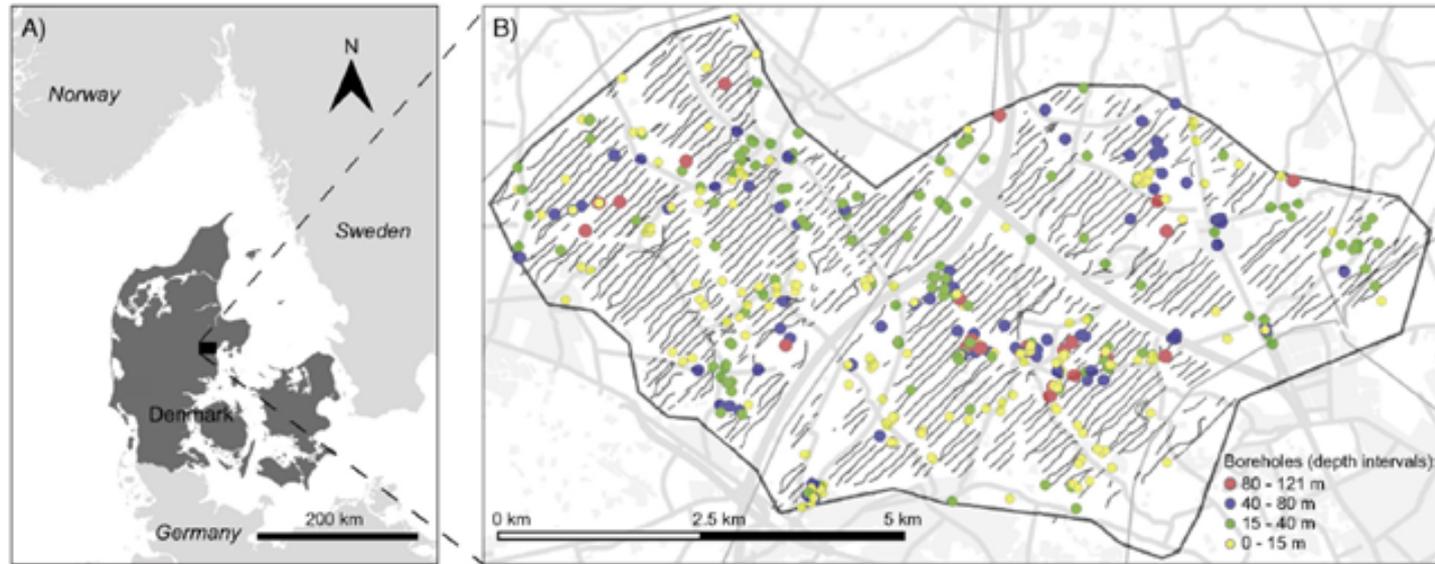
# Case History: Kasted

Vilhelmsen et al. (2016)

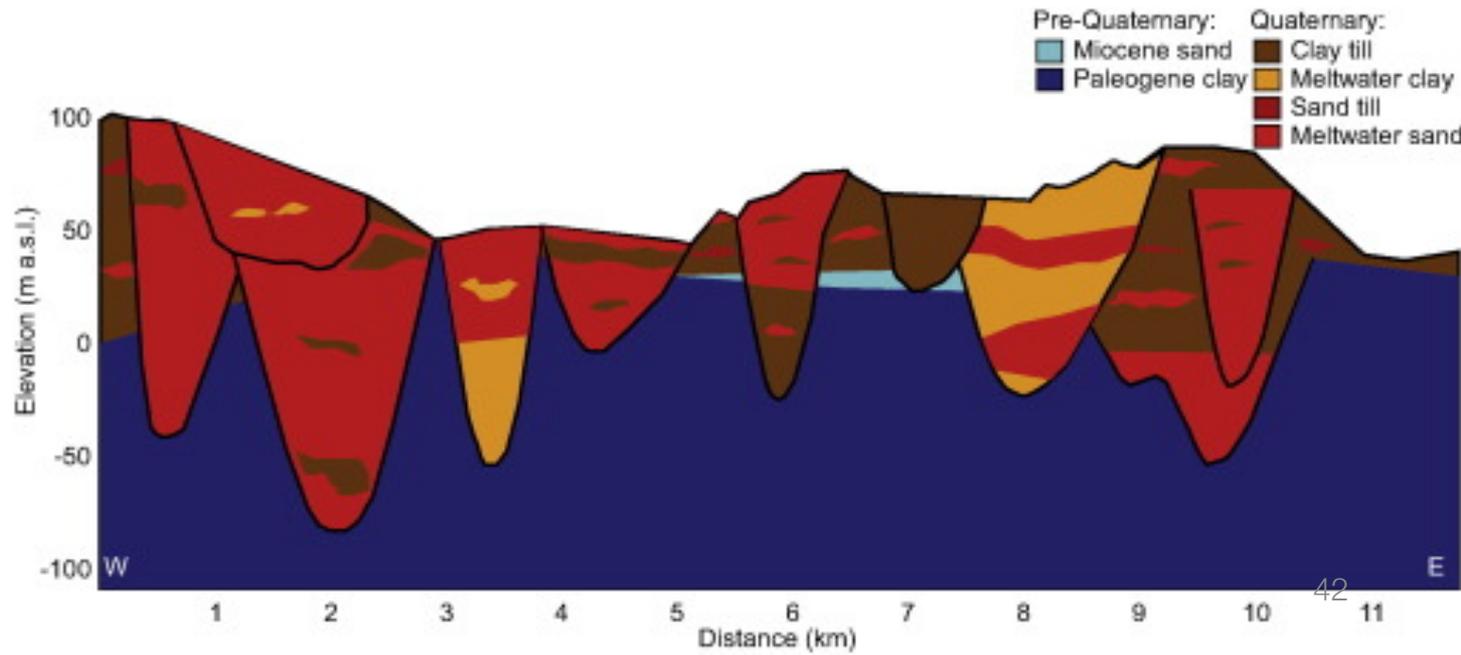
# Setup

A) Survey Area:  
Kasted, Denmark

B) Borehole locations

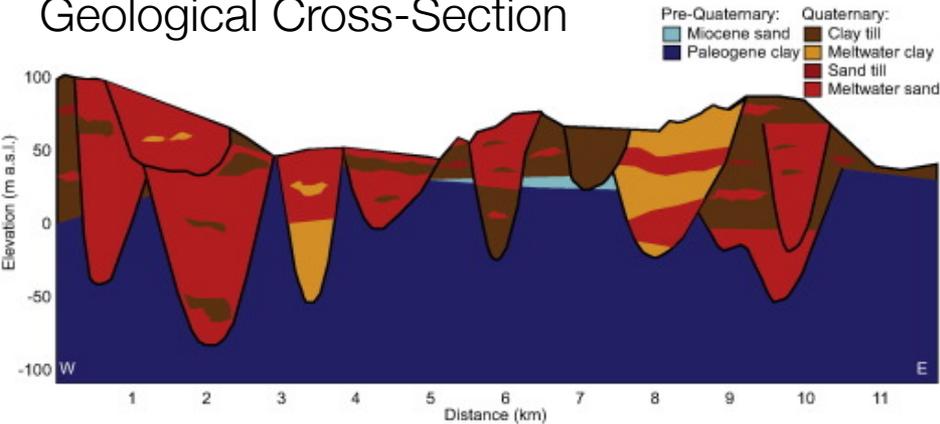


Local Geology:  
W-E cross-section



# Properties

Geological Cross-Section

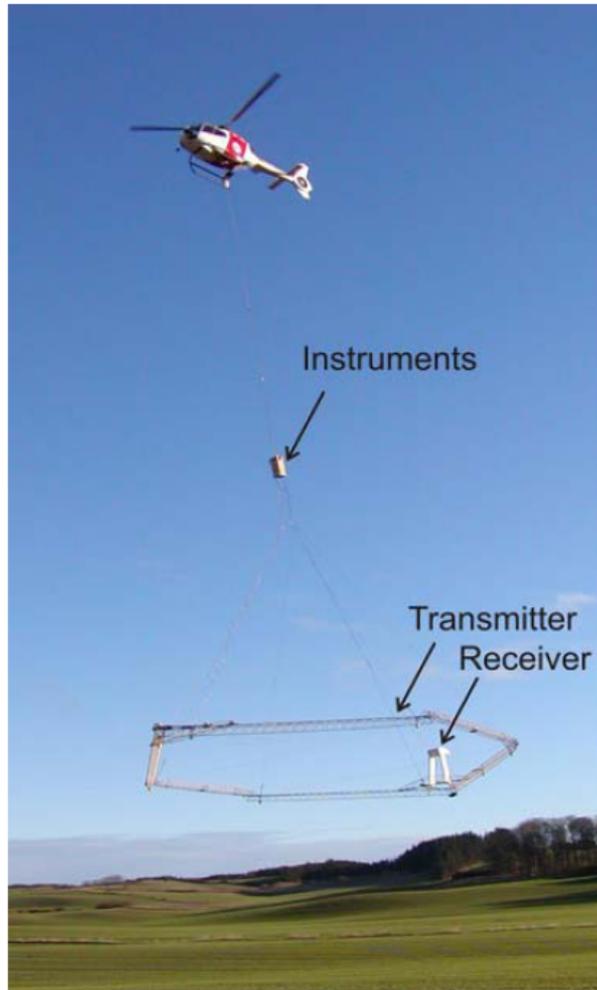


- Buried valleys with clays beneath
- Infill (water-bearing): coarse sand and gravel
- Clays are conductive (1-40  $\Omega m$ )
- Water-bearing sands and gravels are more resistive (>40  $\Omega m$ )

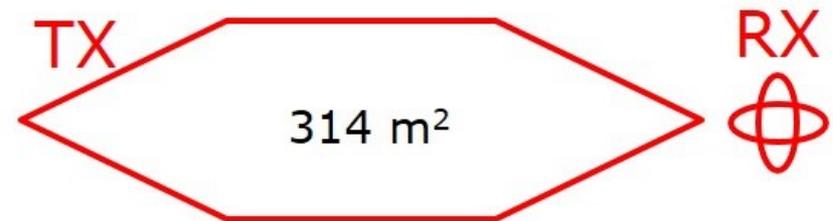
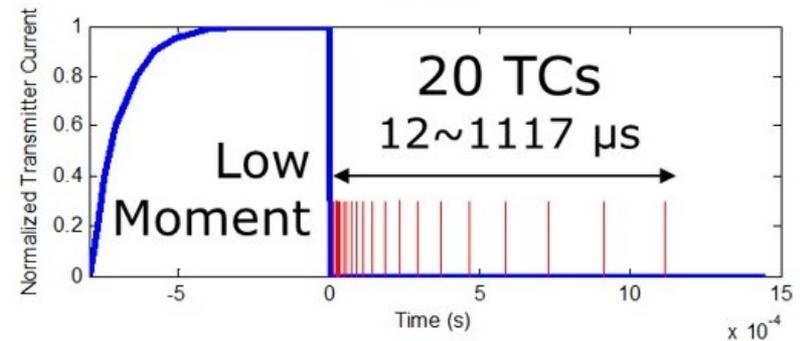
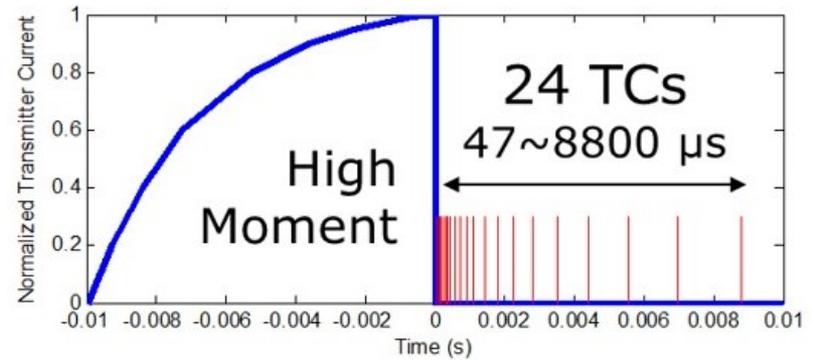
Geological Units	Resistivity ( $\Omega m$ )
Palaeogene Clay	1-10
Clay Till	25-60
Sand Till	>50
Meltwater Sand and Gravel	>60
Glaciolacustrine Clay	10-40
Miocene Silt and Sand	>40
Miocene Clay	10-40
Sand	>40
Clay	1-60

# Survey

## SkyTEM System



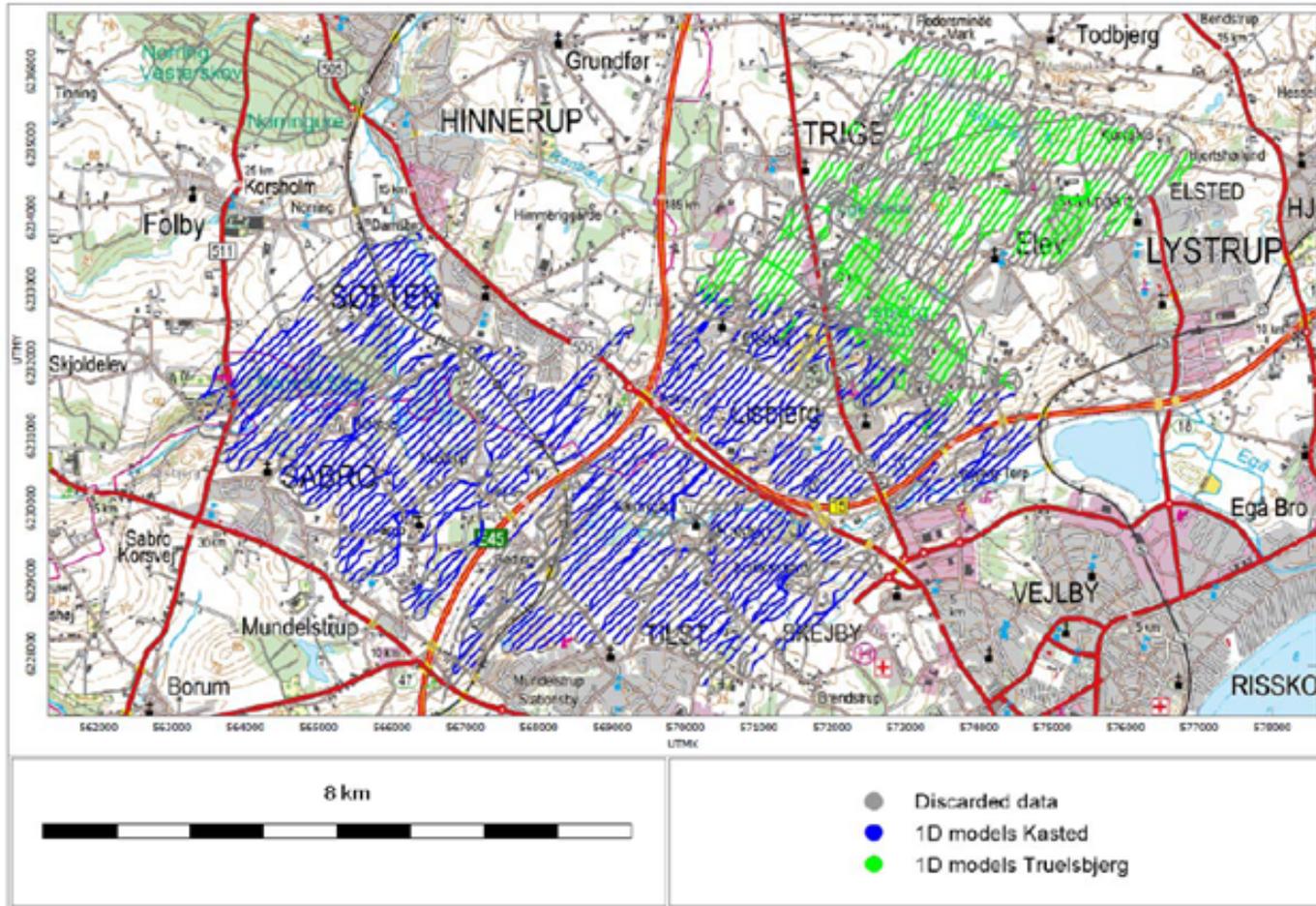
## System Configuration



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

# Data

Blue: data used for Kasted study

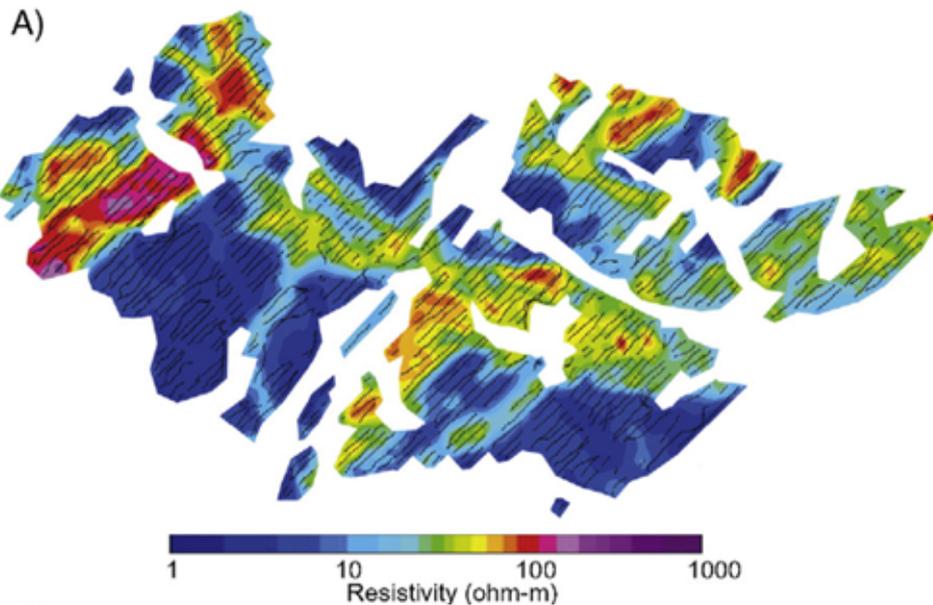


- 333 line km of data, 100 m line-spacing
- Data points with strong coupling to cultural noise were removed (~30%)

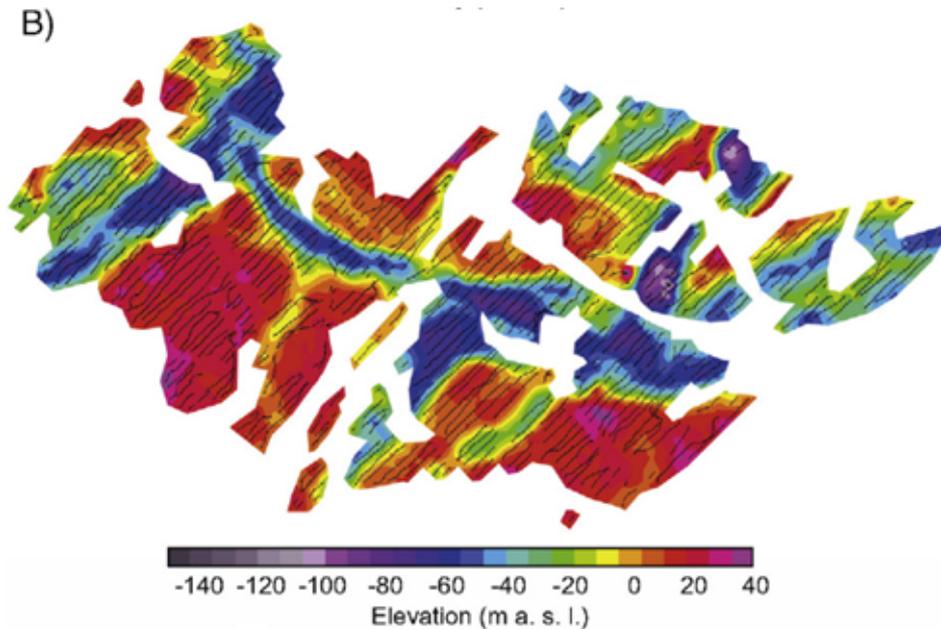
# Processing (inversion)

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

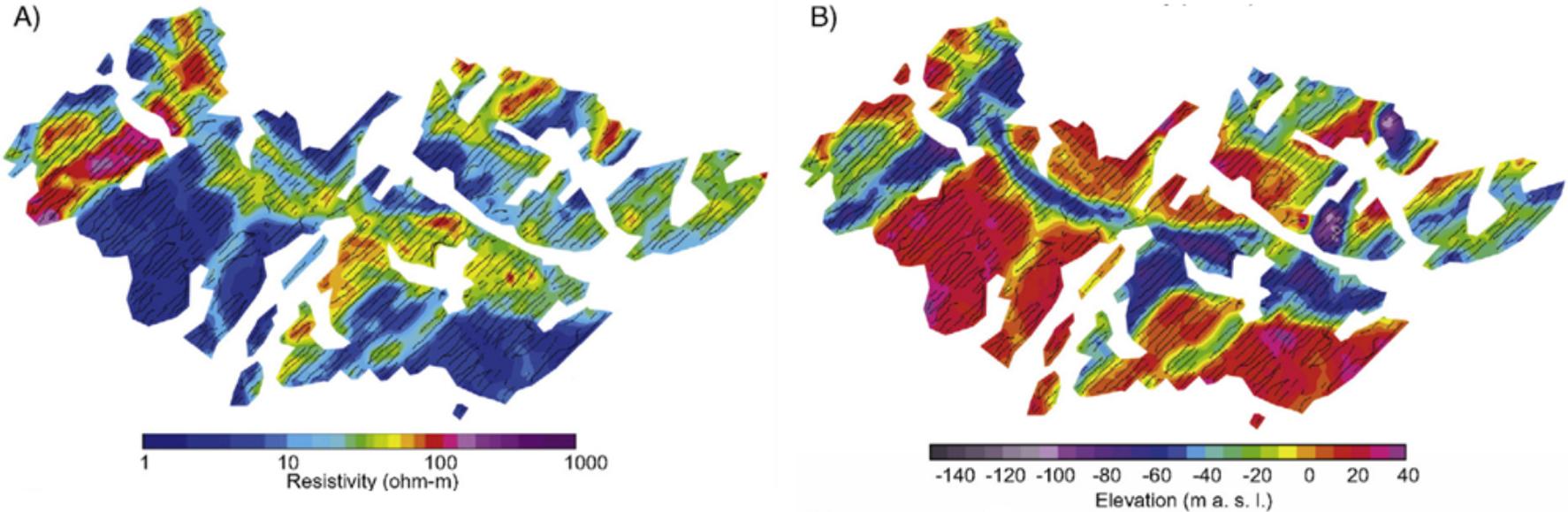
Depth slice 5 m above sea-level



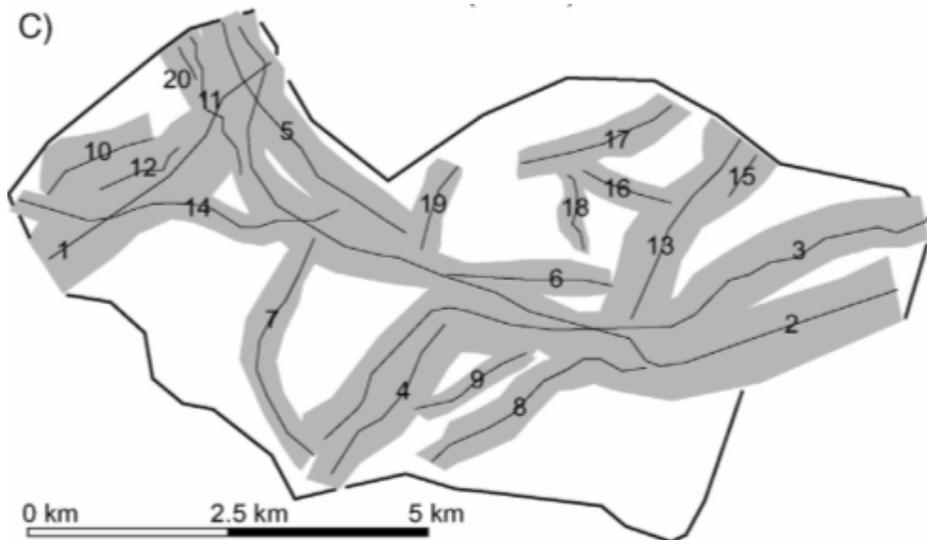
Approximate depth to the top of Paleogene clay layer



# Interpretation

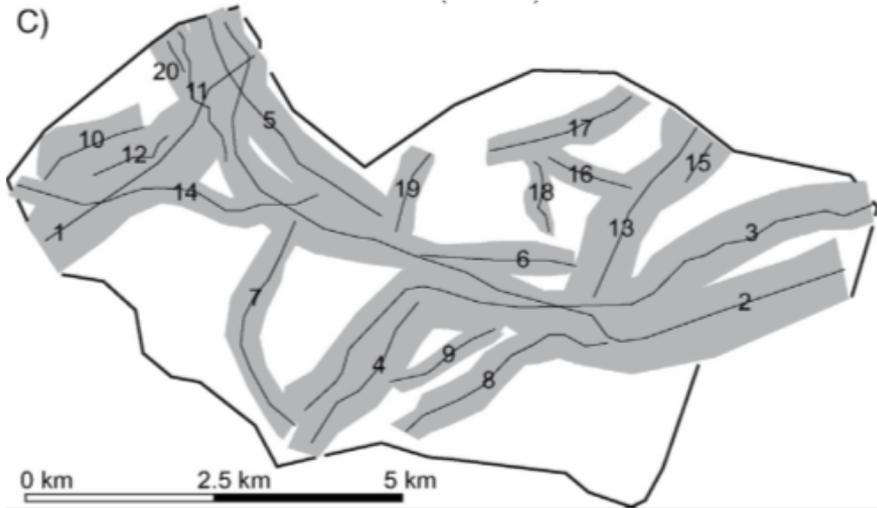


## Delineation of valley structures



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

# Synthesis

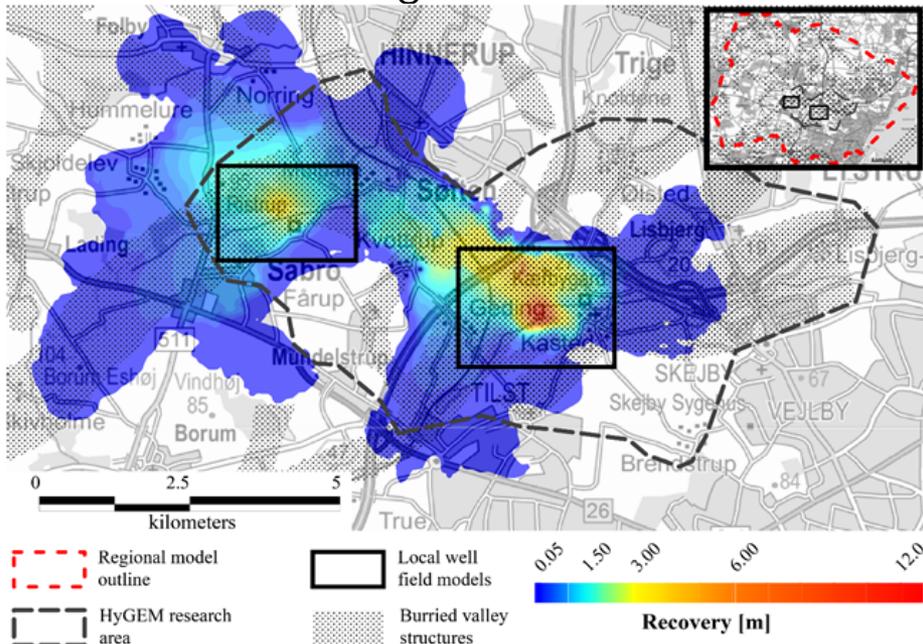


- 3D geologic model incorporated into MODFLOW-USG groundwater modeling tool

- Extracted water from 2 wells.

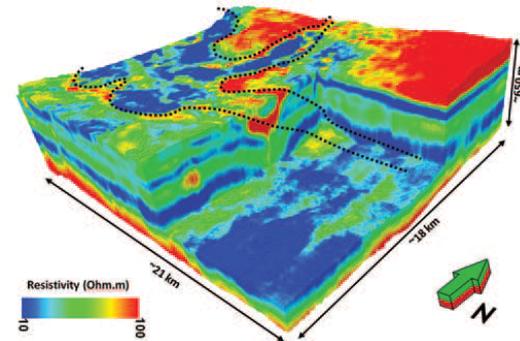
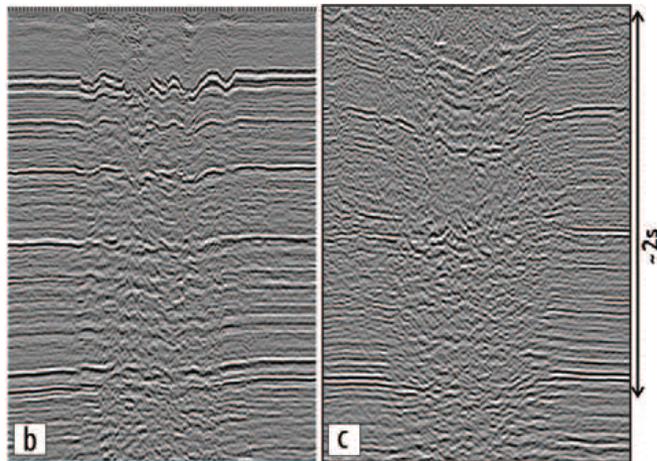
## MODFLOW-USG groundwater model

- Dewatering between the two wells correlated with the resistive valley structures



# Case History: Wadi Sahba

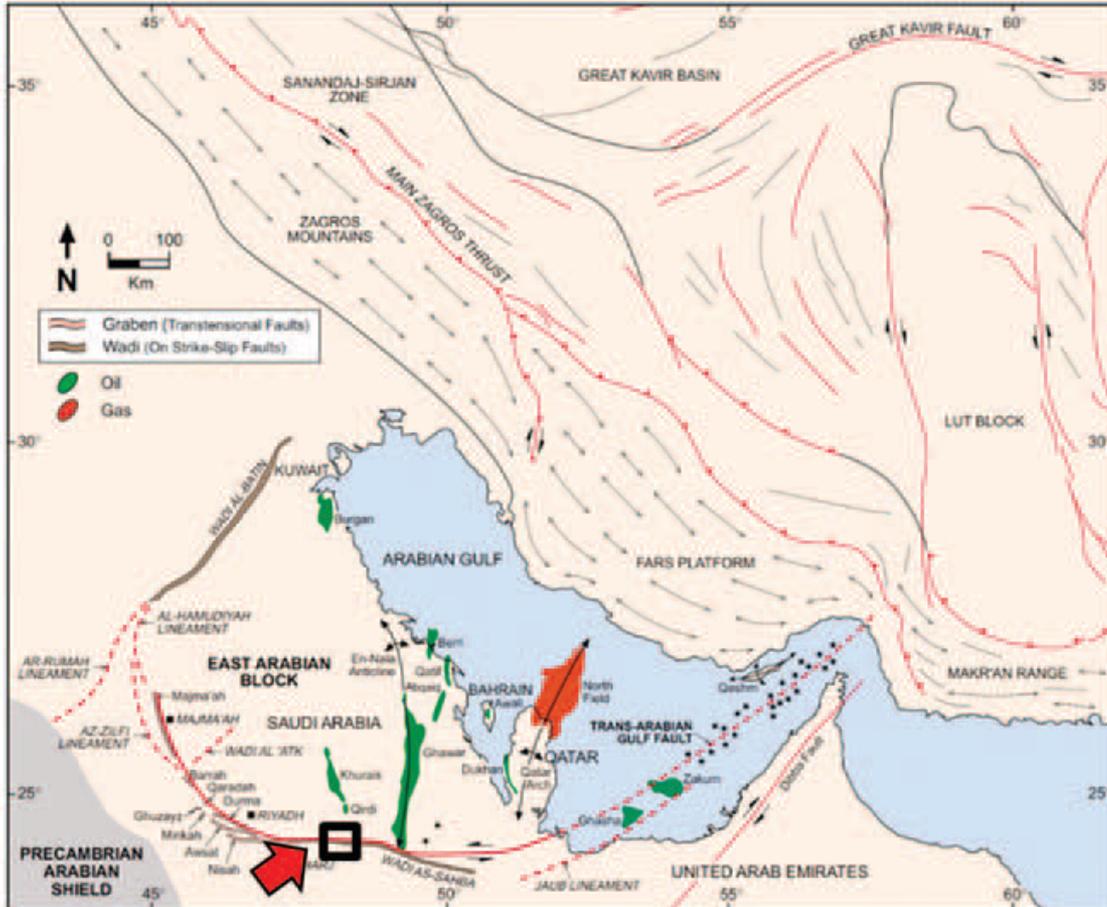
Colombo et al. 2016



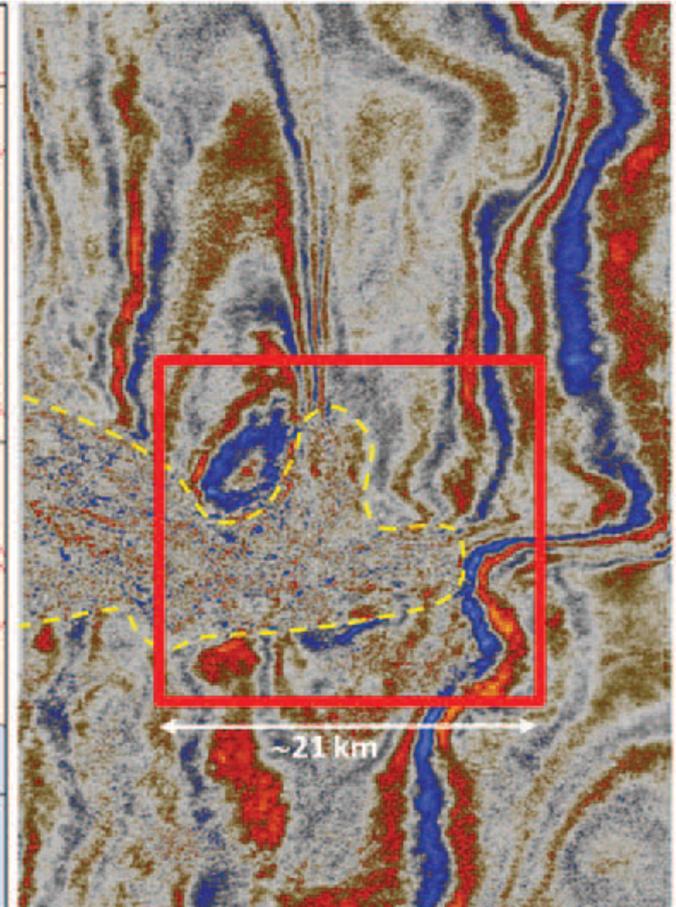
?

# Setup

Location of Wadi area, Saudi Arabia



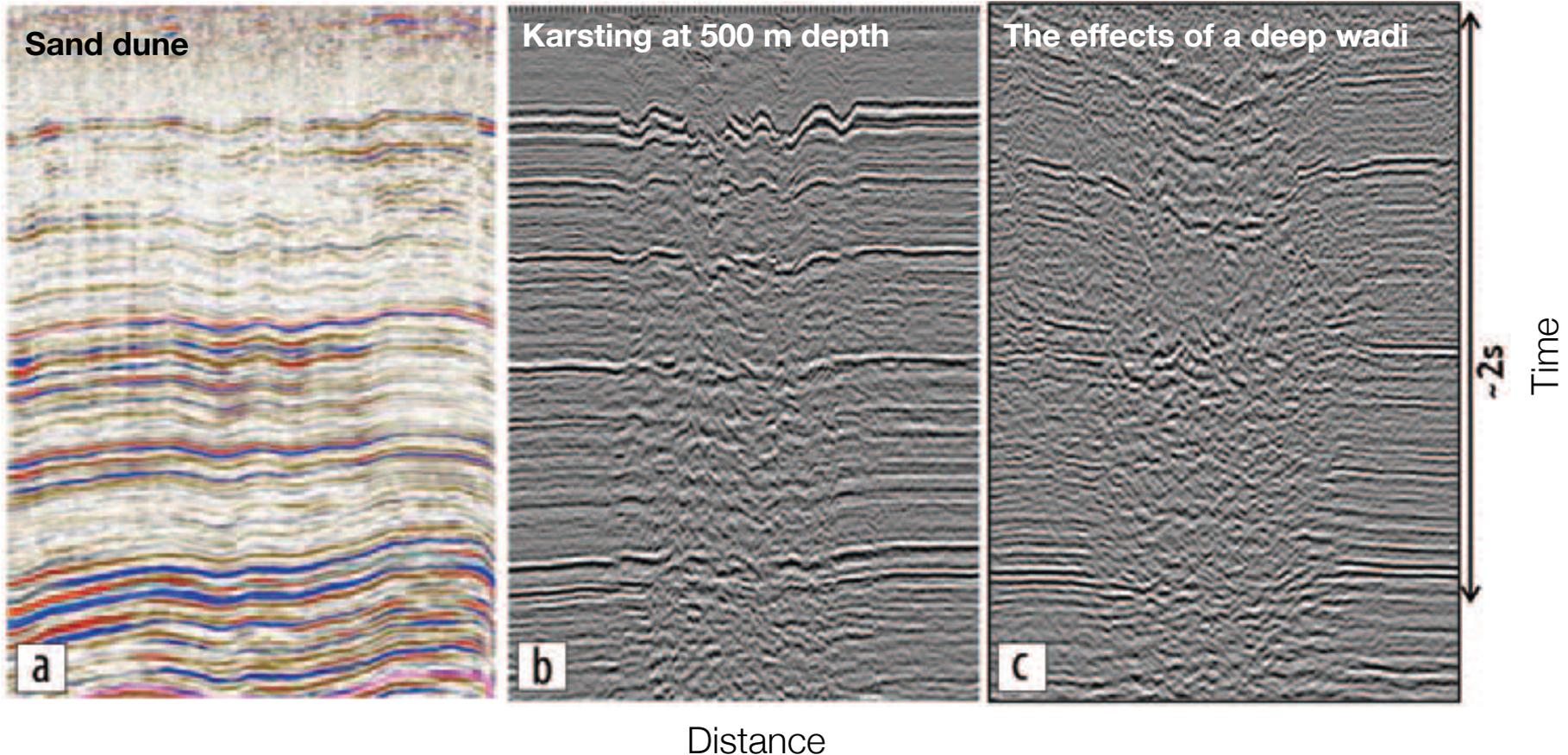
Seismic slice



- 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:

$$v_p = g(\phi)$$

$v_p$ : P-velocity

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

$\phi$ : porosity

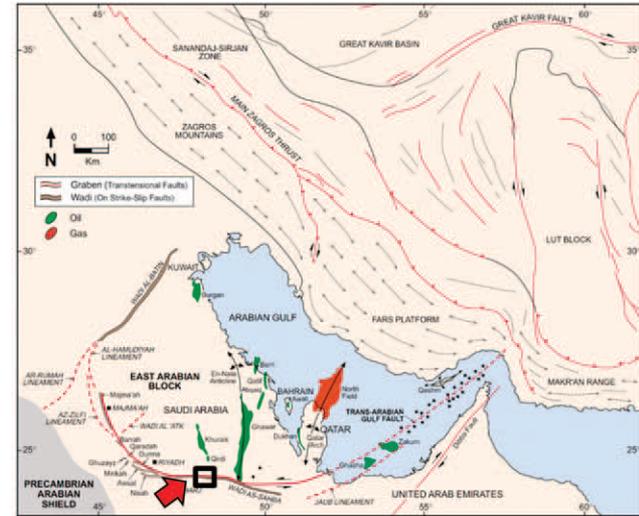
- Poor seismic data:

- 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

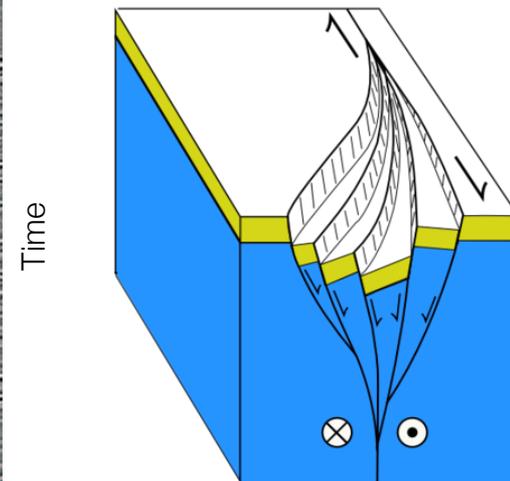


Seismic section



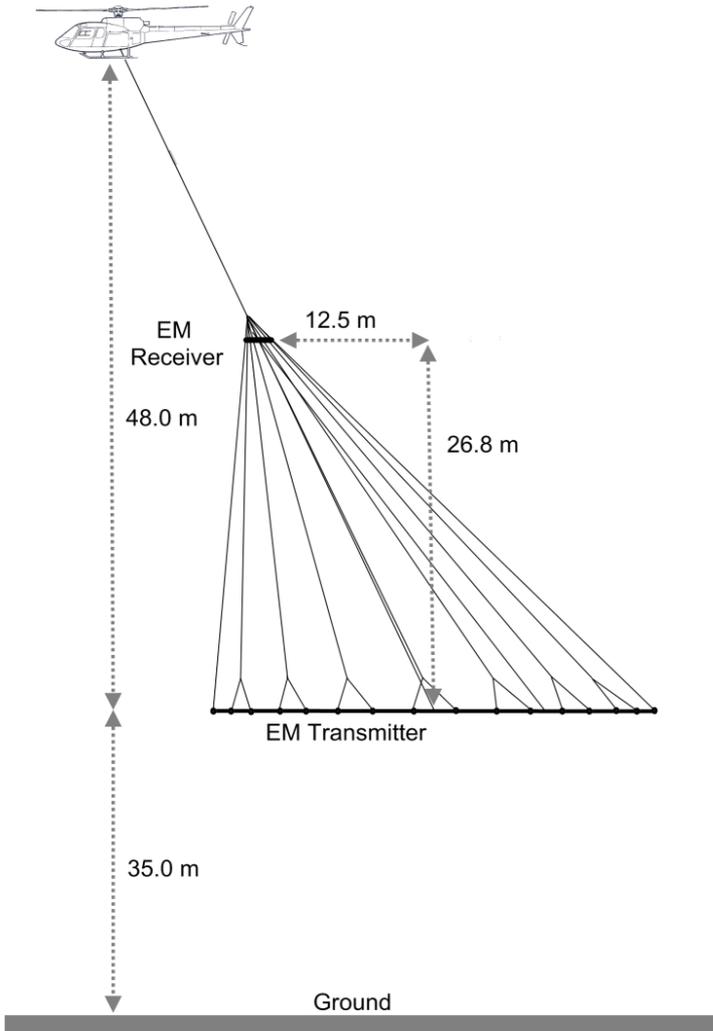
Distance

Flower faults

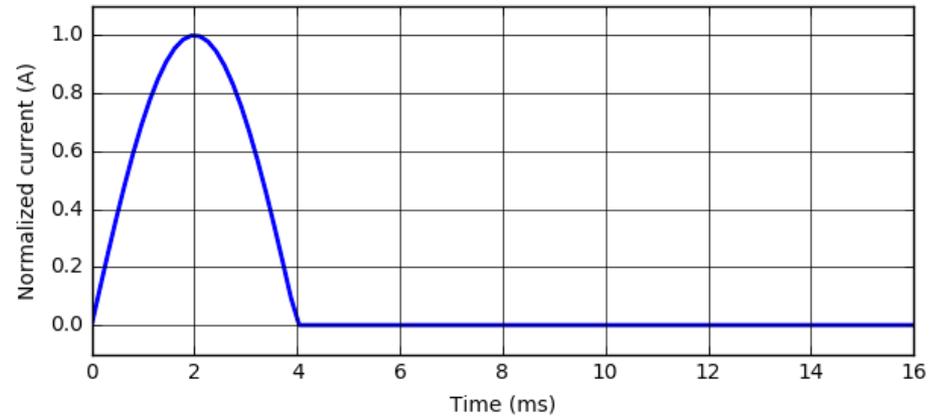


# Survey

## HELITEM

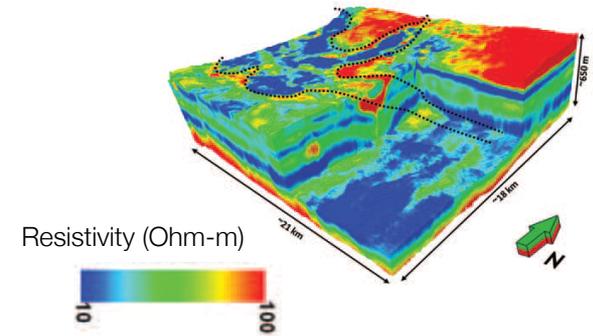


## System Configuration

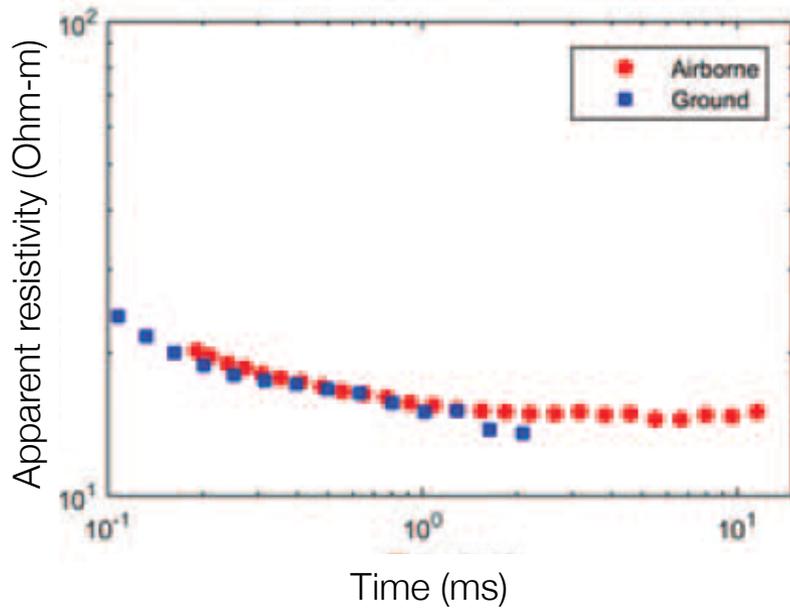


- Peak Tx current: 1200 A
- Dipole moment:  $1.7 \times 10^6$  A-m<sup>2</sup>
- Stacked TEM curve spacing: ~2.7 m
- Total soundings: ~1.6 million

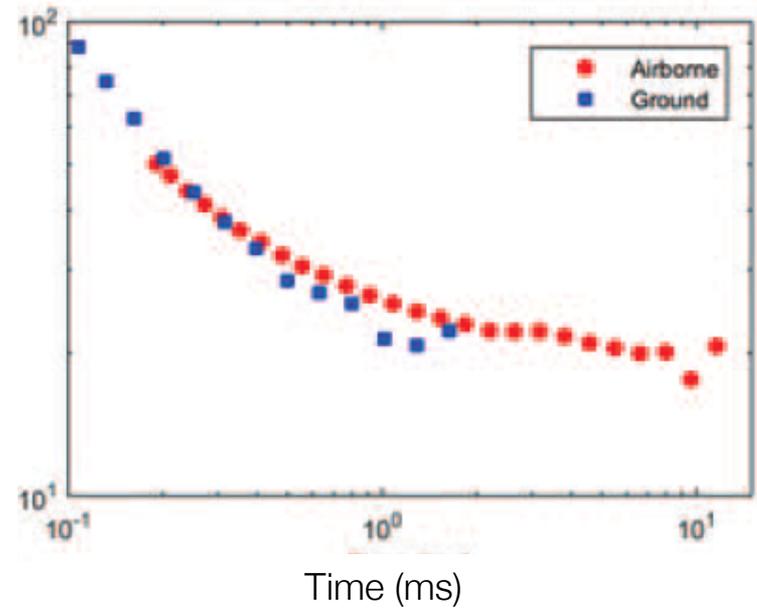
# Comparisons: airborne and ground EM



Conductive area

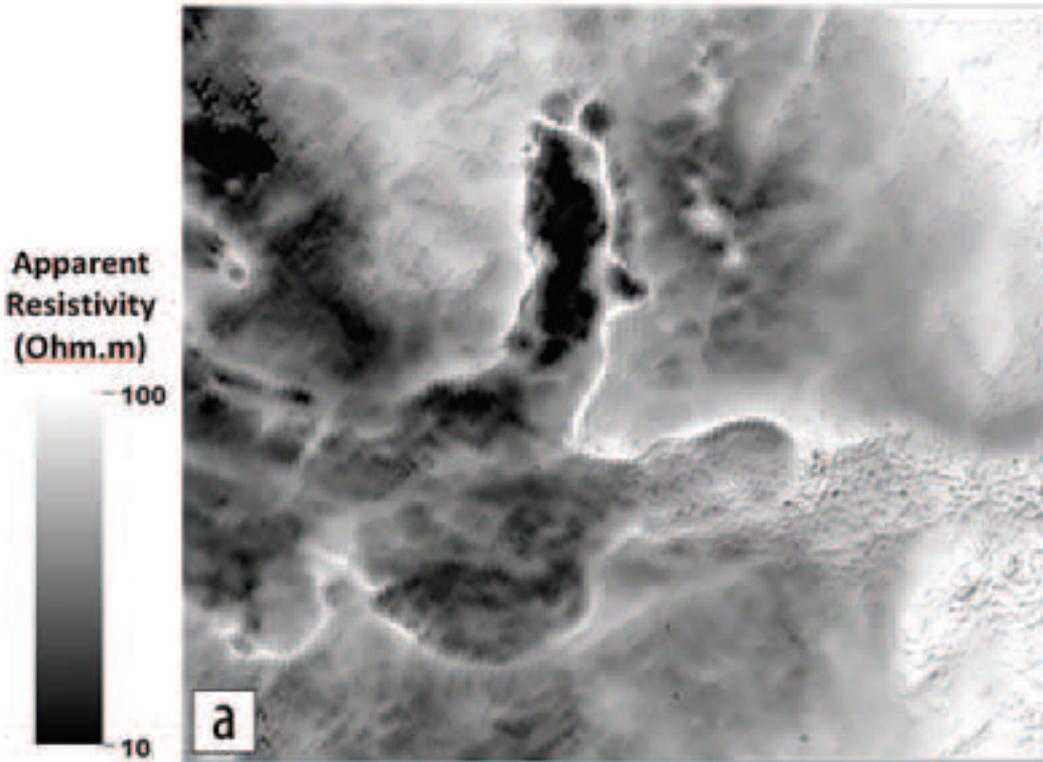


Resistive area



# EM data

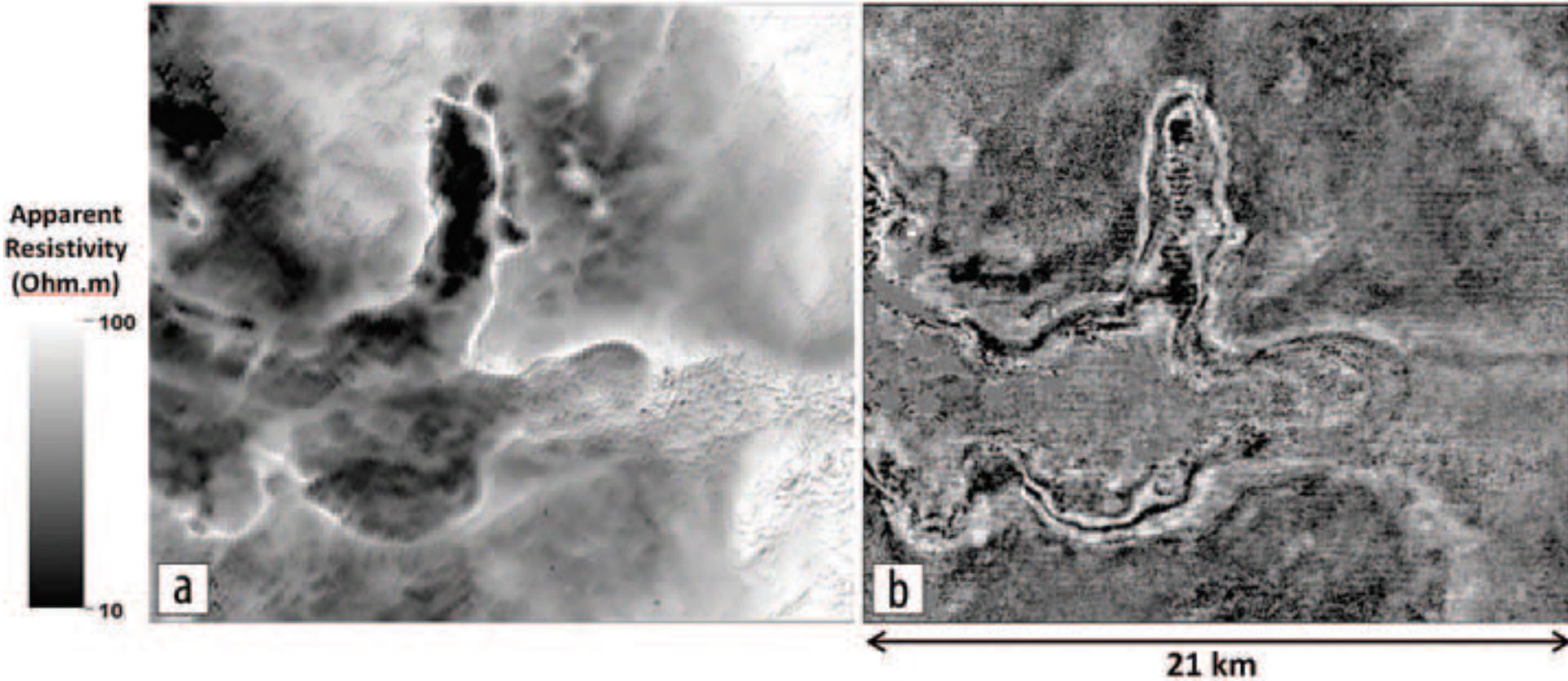
Apparent resistivity map



# Comparison: EM and Seismic data

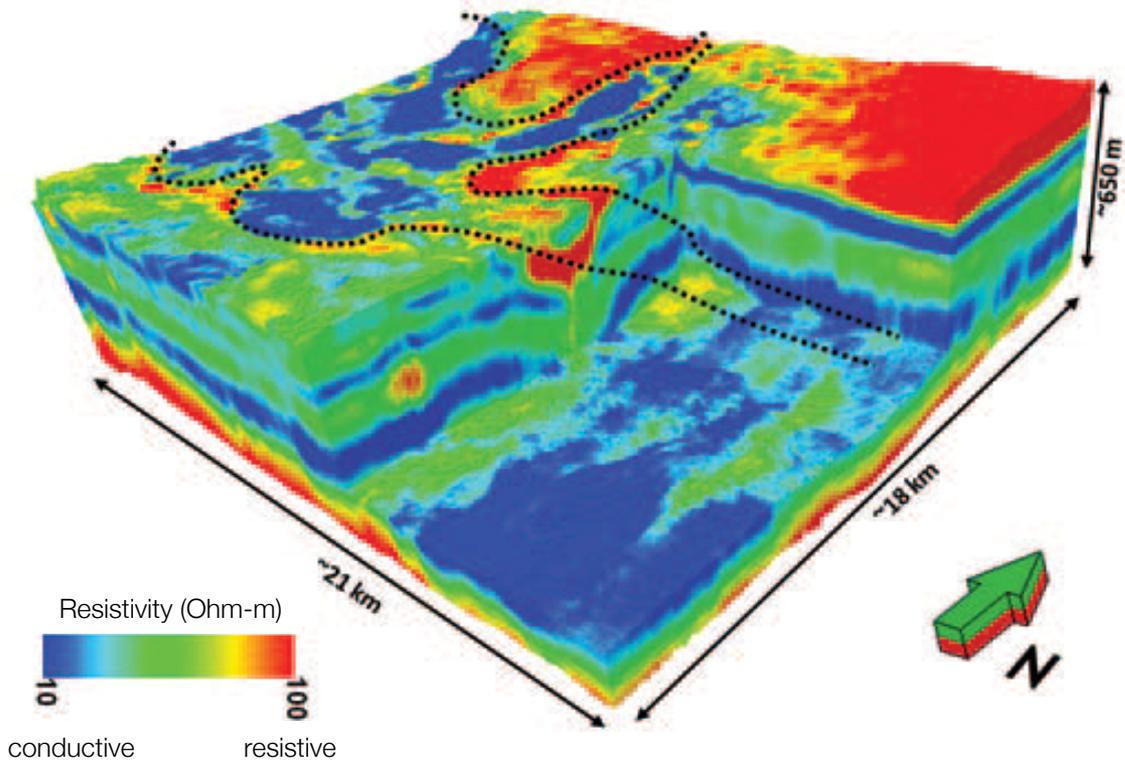
Apparent resistivity map

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 ( $\sigma$ ): high to low

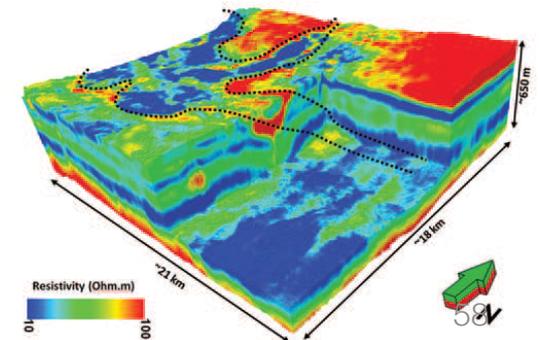
$$v_p = g(\phi) \quad \phi: \text{porosity}$$
$$\sigma = f(\phi)$$

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

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

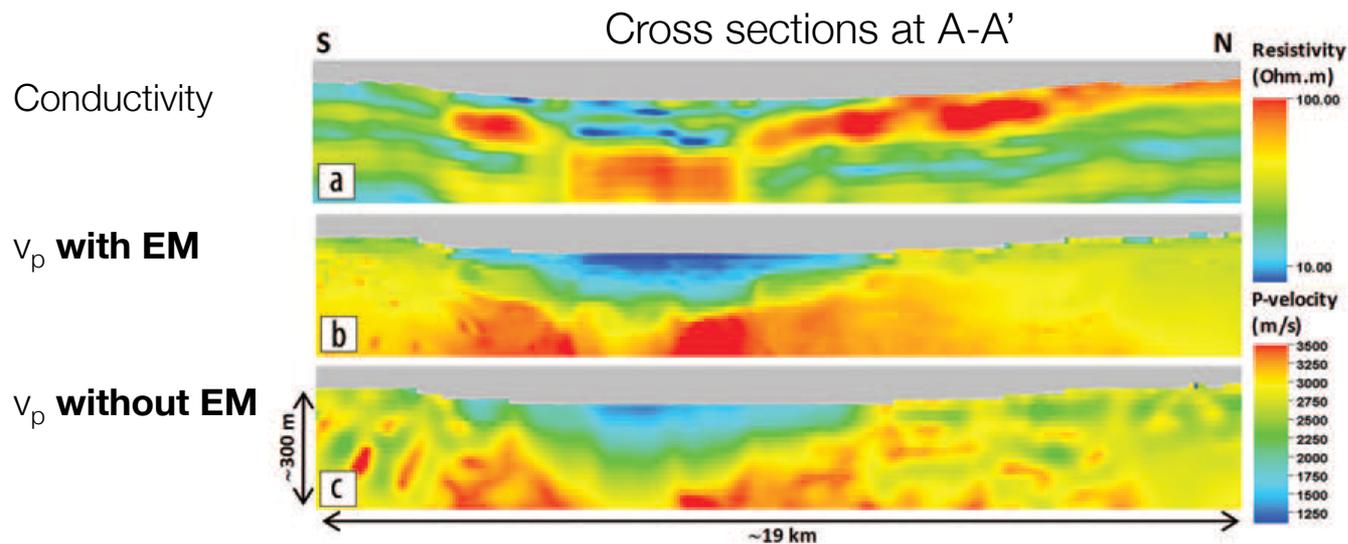
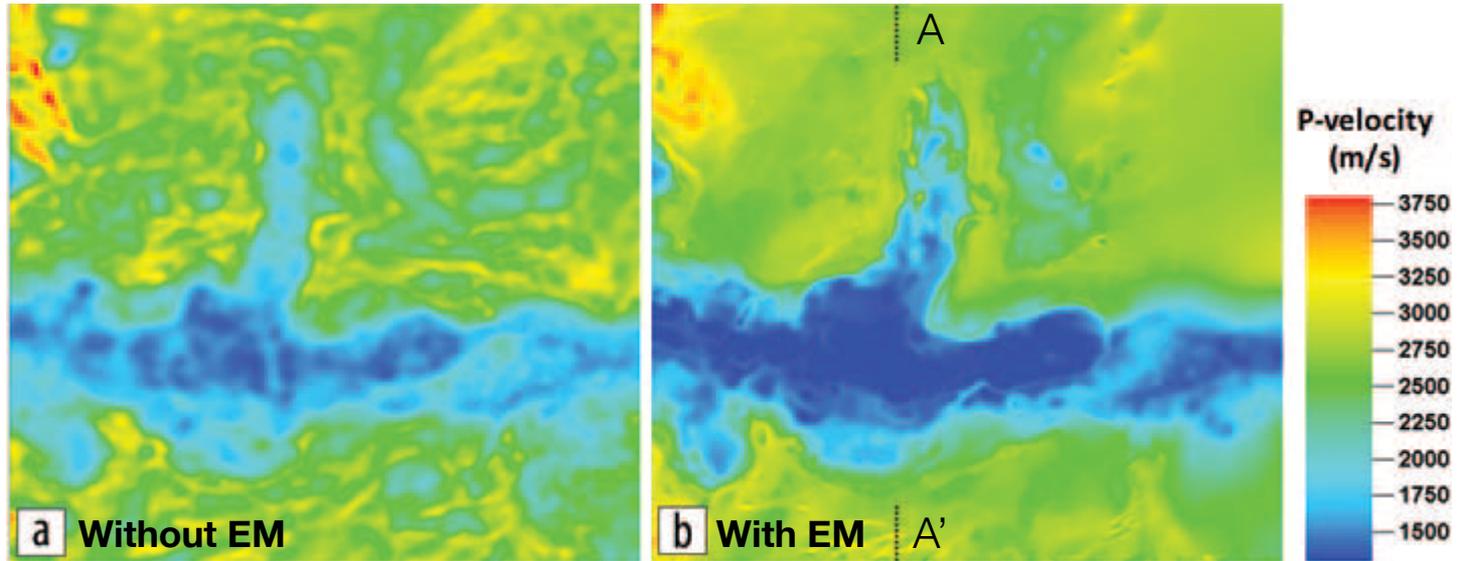
$$\|\nabla \mathbf{m}_s \times \nabla \mathbf{m}_\sigma\|_2^2$$

Gallardo and Meju, 2004



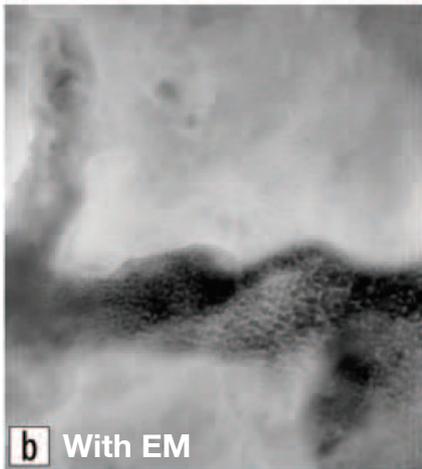
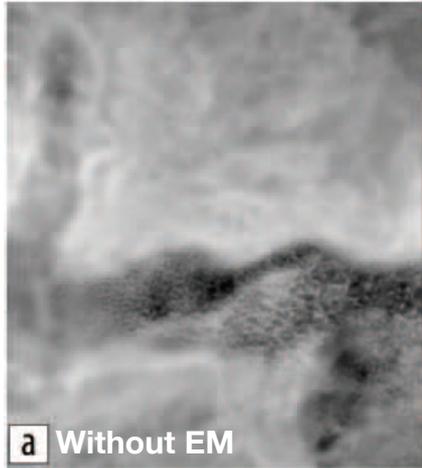
# Cooperative inversion: Seismic + EM

$V_p$  depth slices at 340 m below sea level

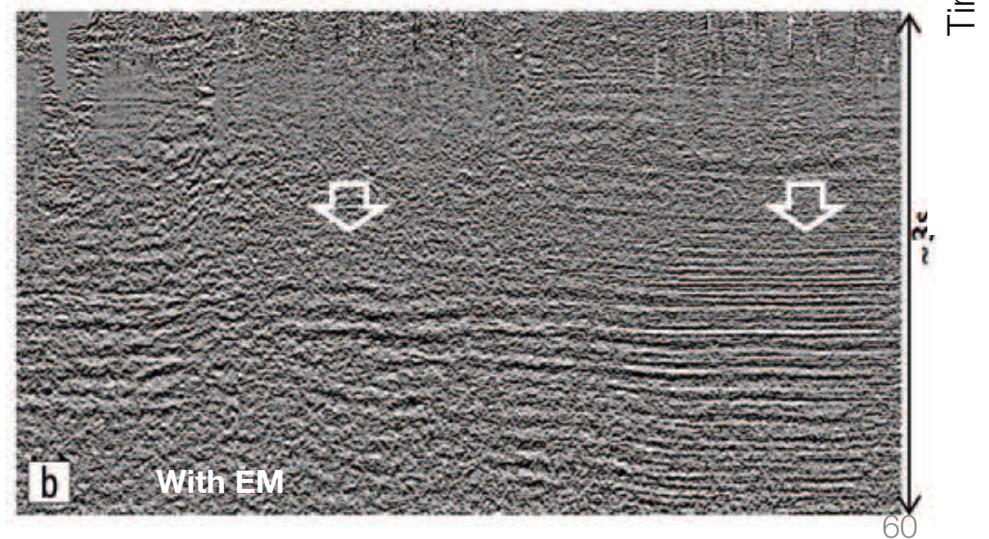
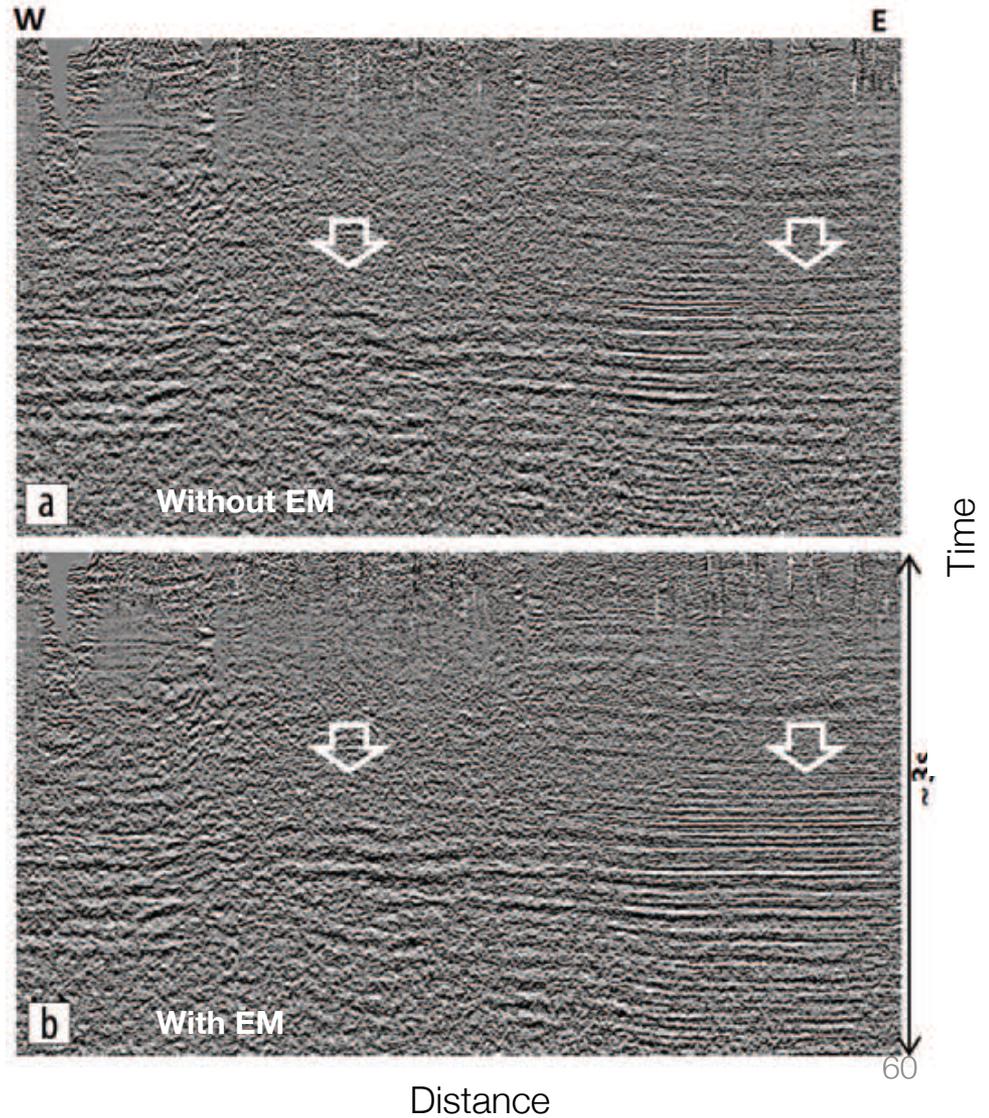


# Static correction

Estimated statics on plan map



Static corrected sections

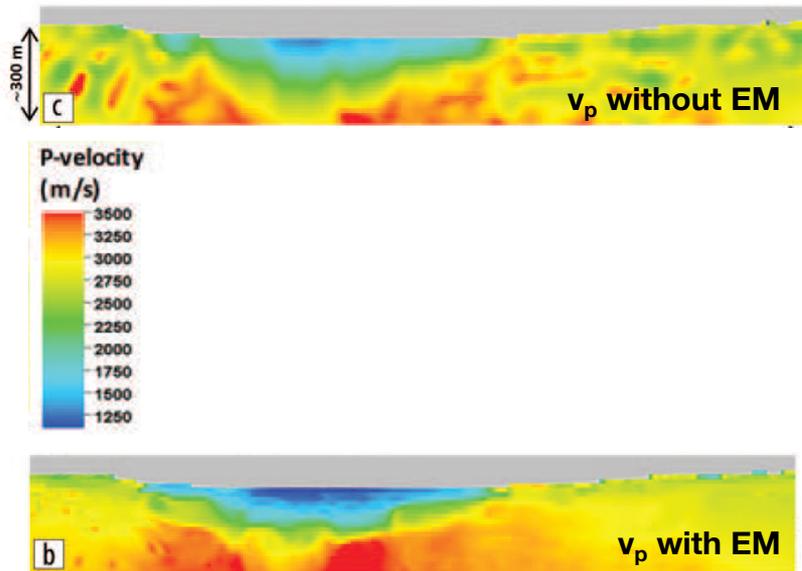


Distance

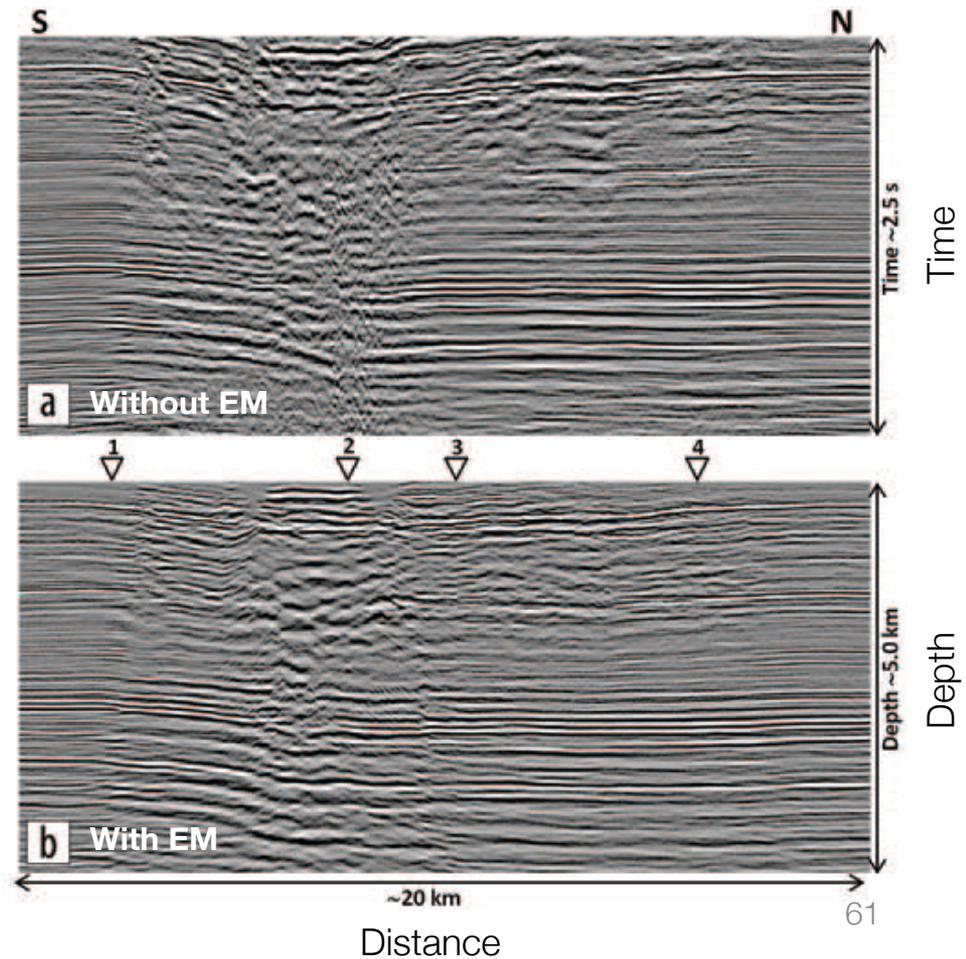
# Pre-stack depth migration

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

$v_p$  cross sections at A-A'

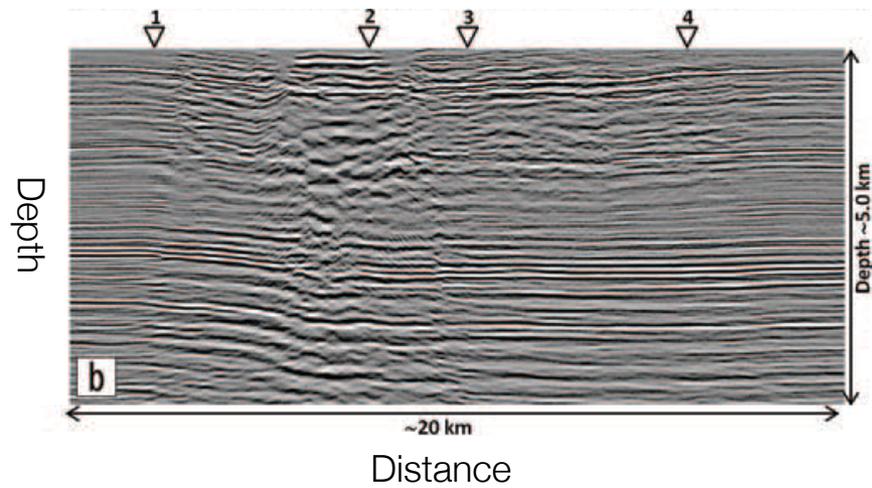


Cross sections at A-A'

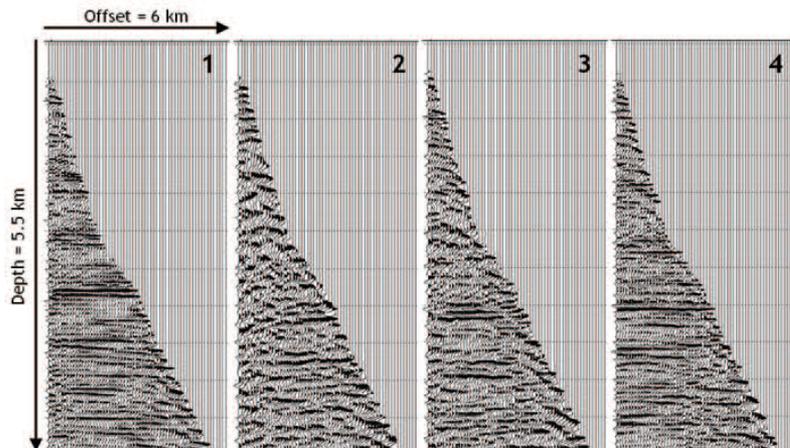


# Interpretation and Synthesis

Depth section at A-A'

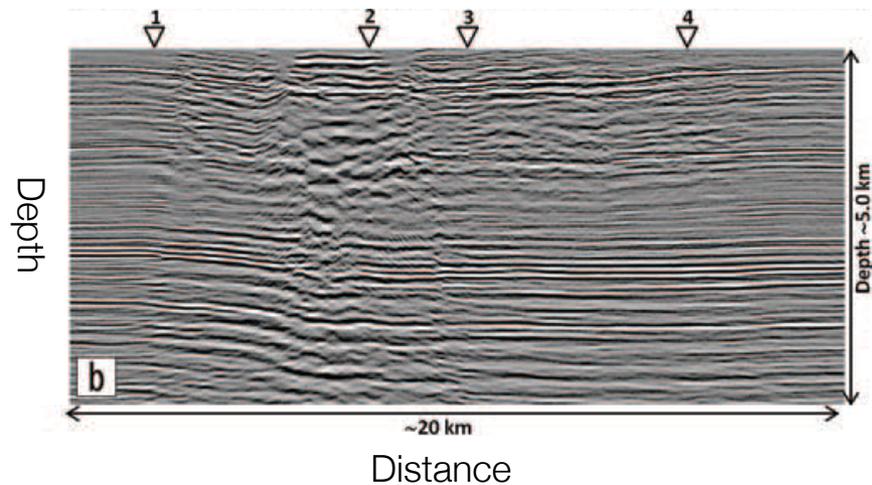


Common image gathers

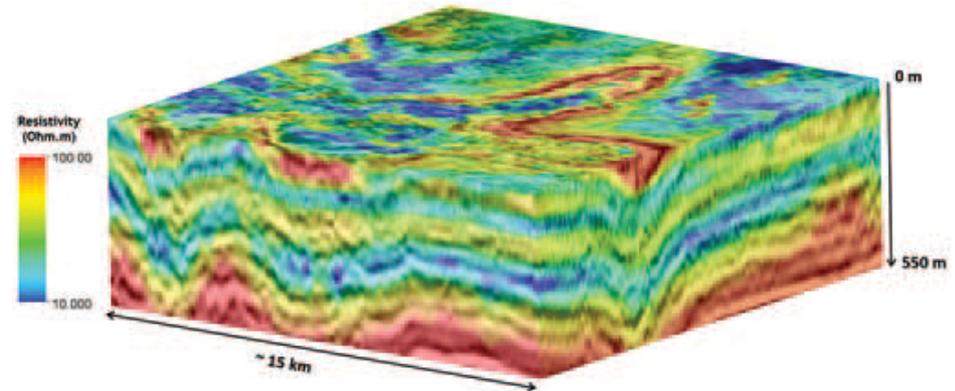


# Interpretation and Synthesis

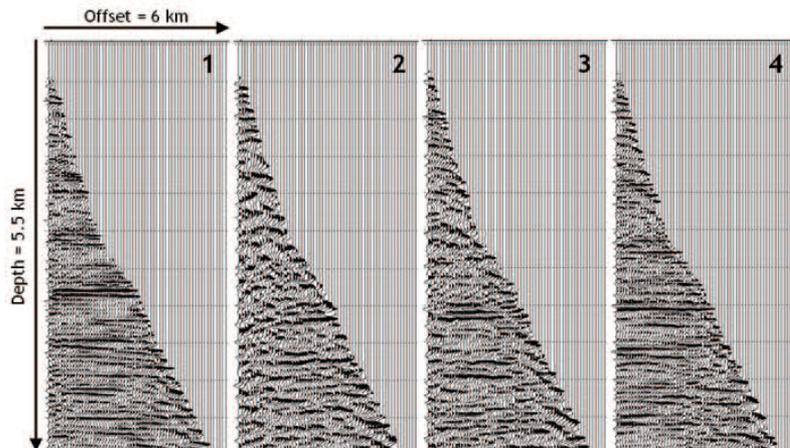
Depth section at A-A'



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

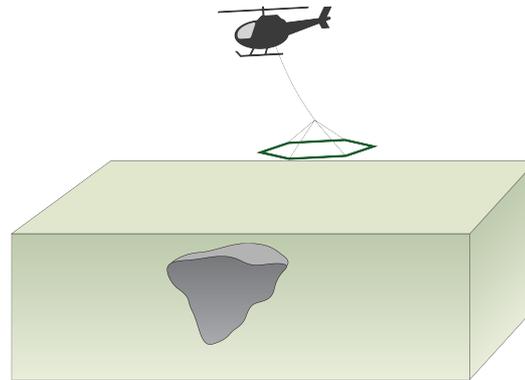
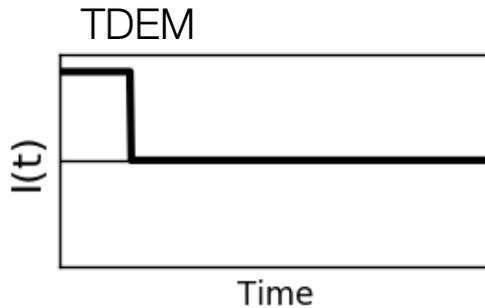
## Frequency Domain EM

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

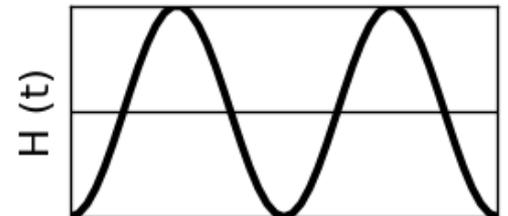
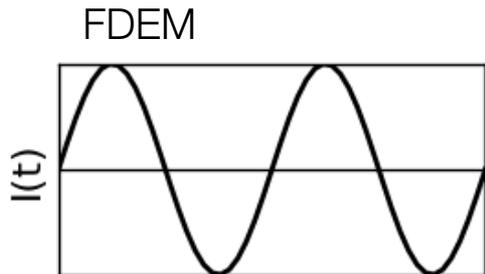
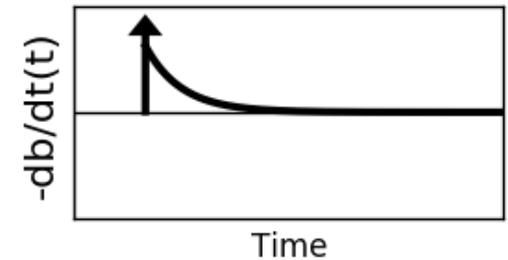
# EM with Inductive Sources

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

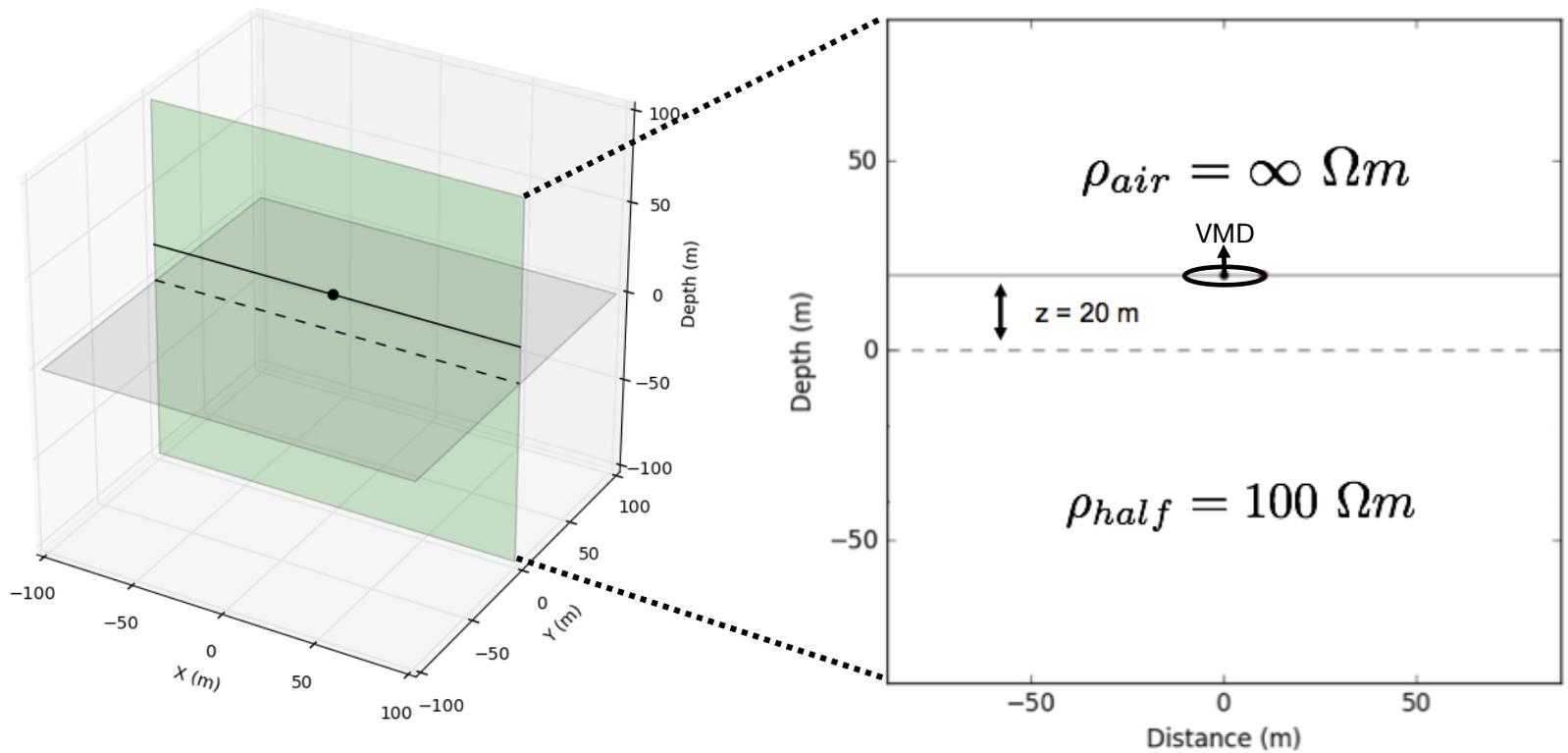
Transmitter current



Receiver

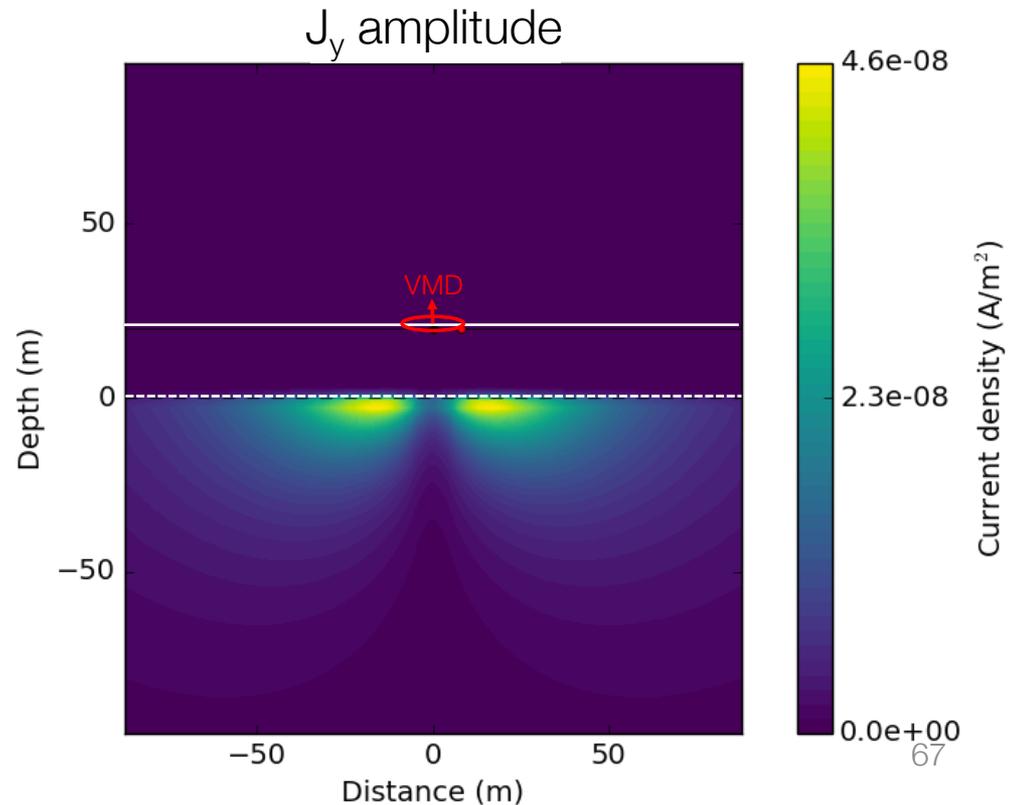
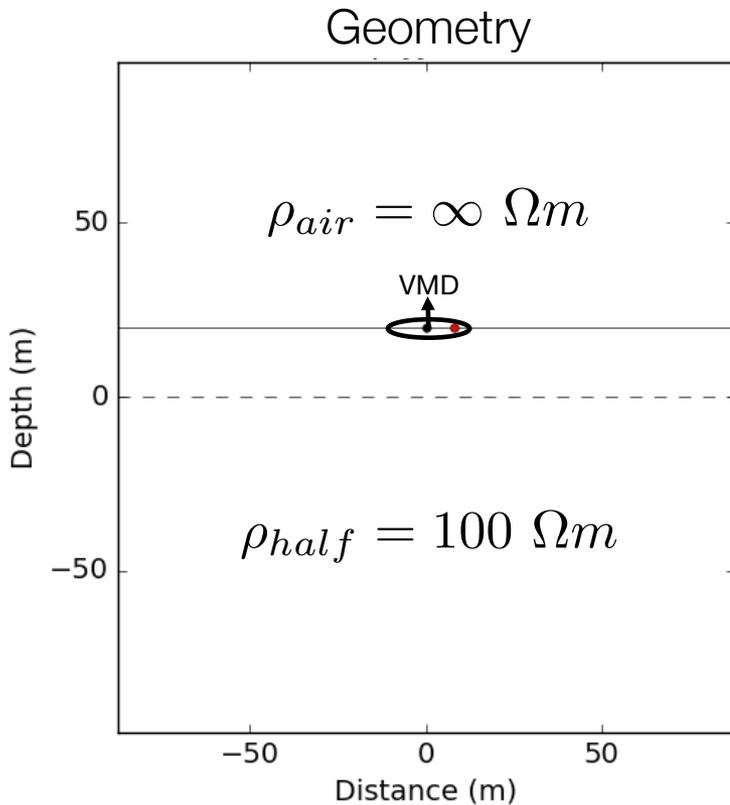
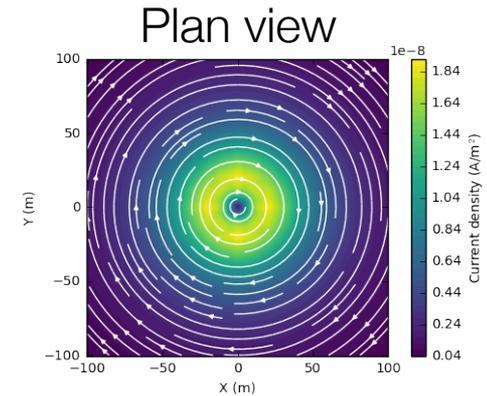


# Vertical Magnetic Dipole over a halfspace (FDEM)



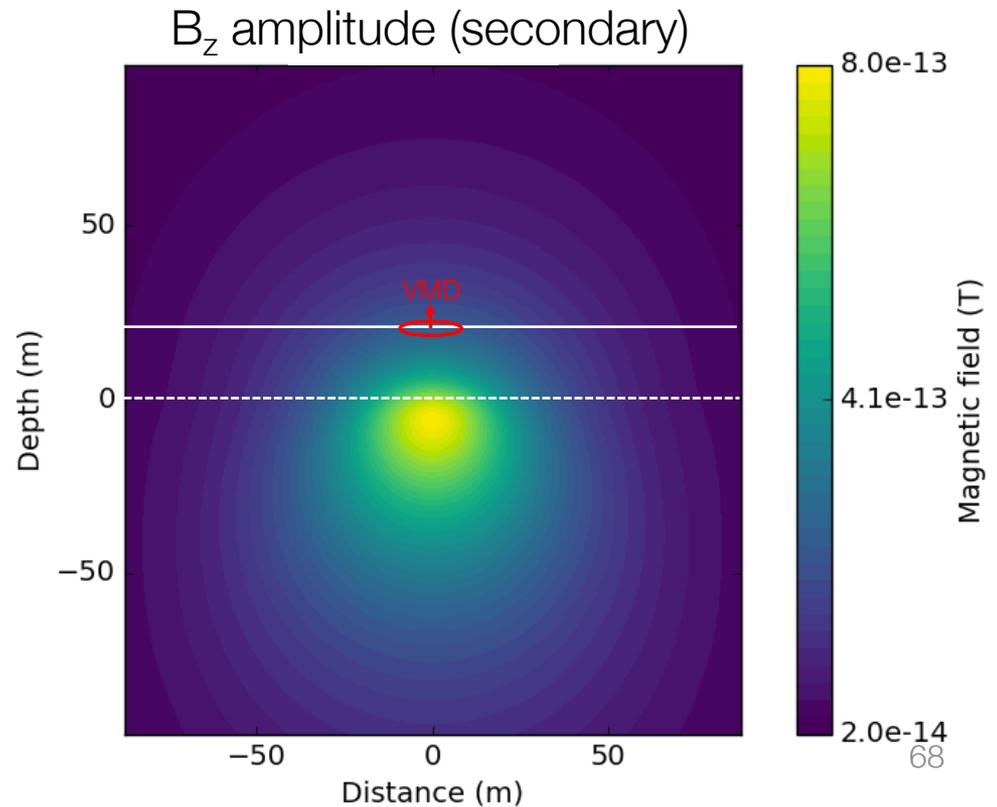
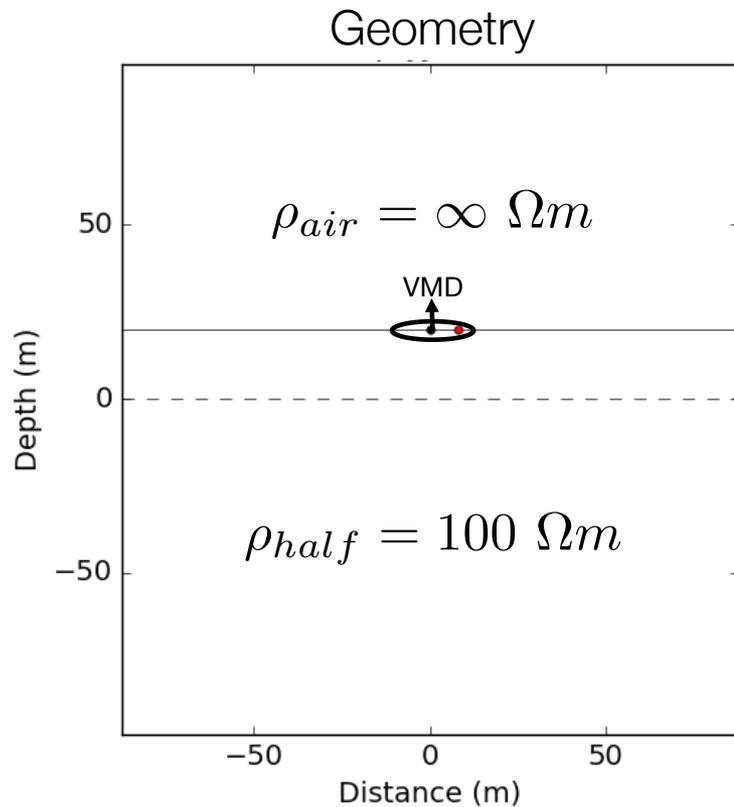
# Current Density

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



# Secondary Magnetic Flux Density

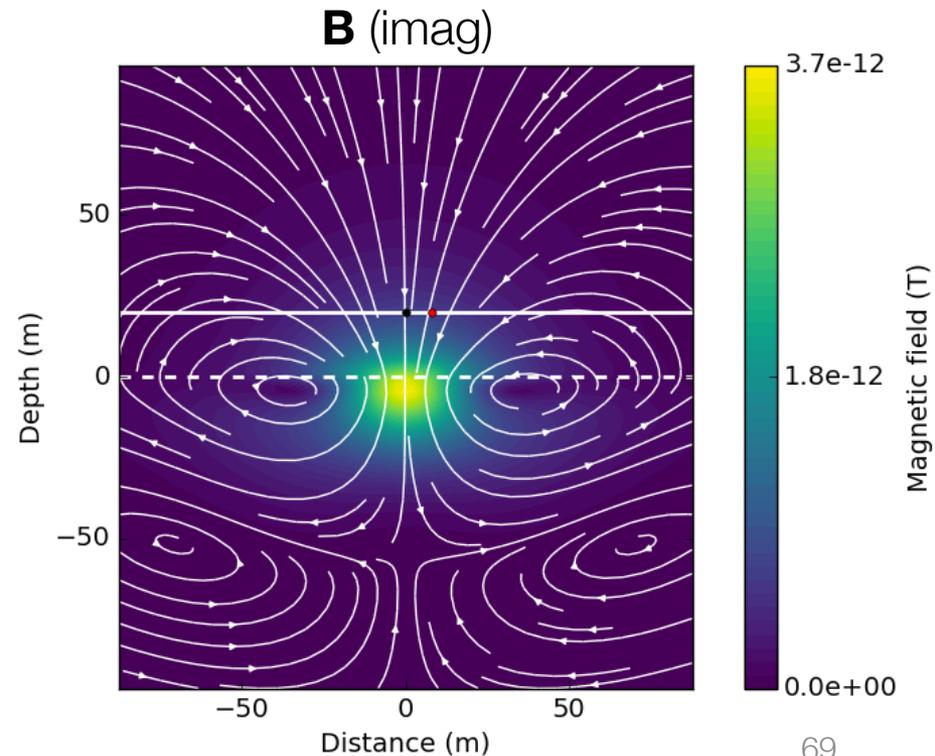
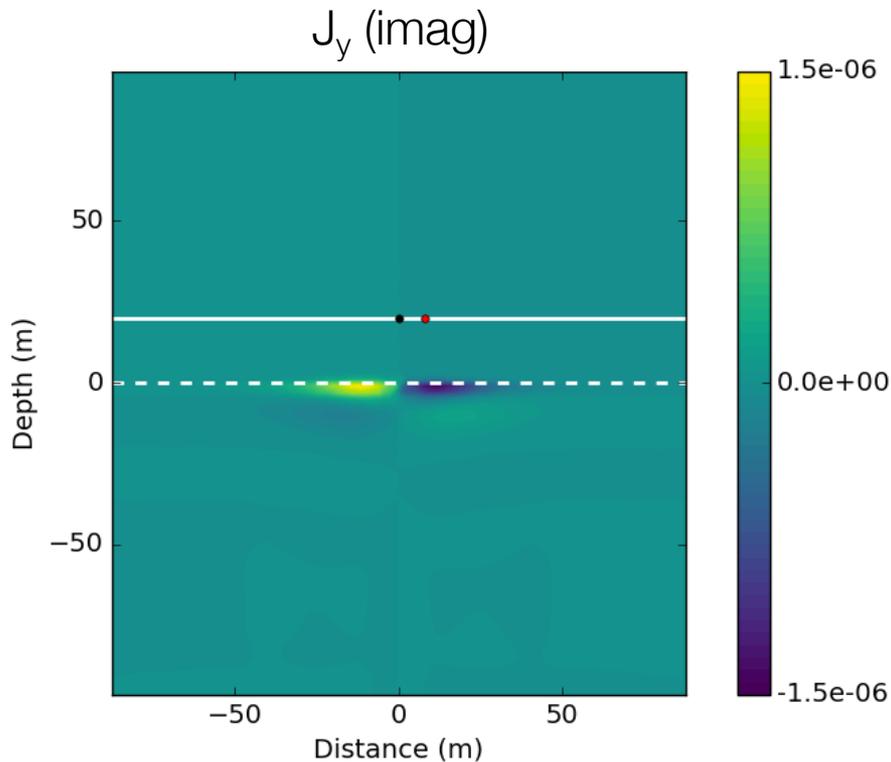
- Frequency = 10 kHz



# Effects of Frequency

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

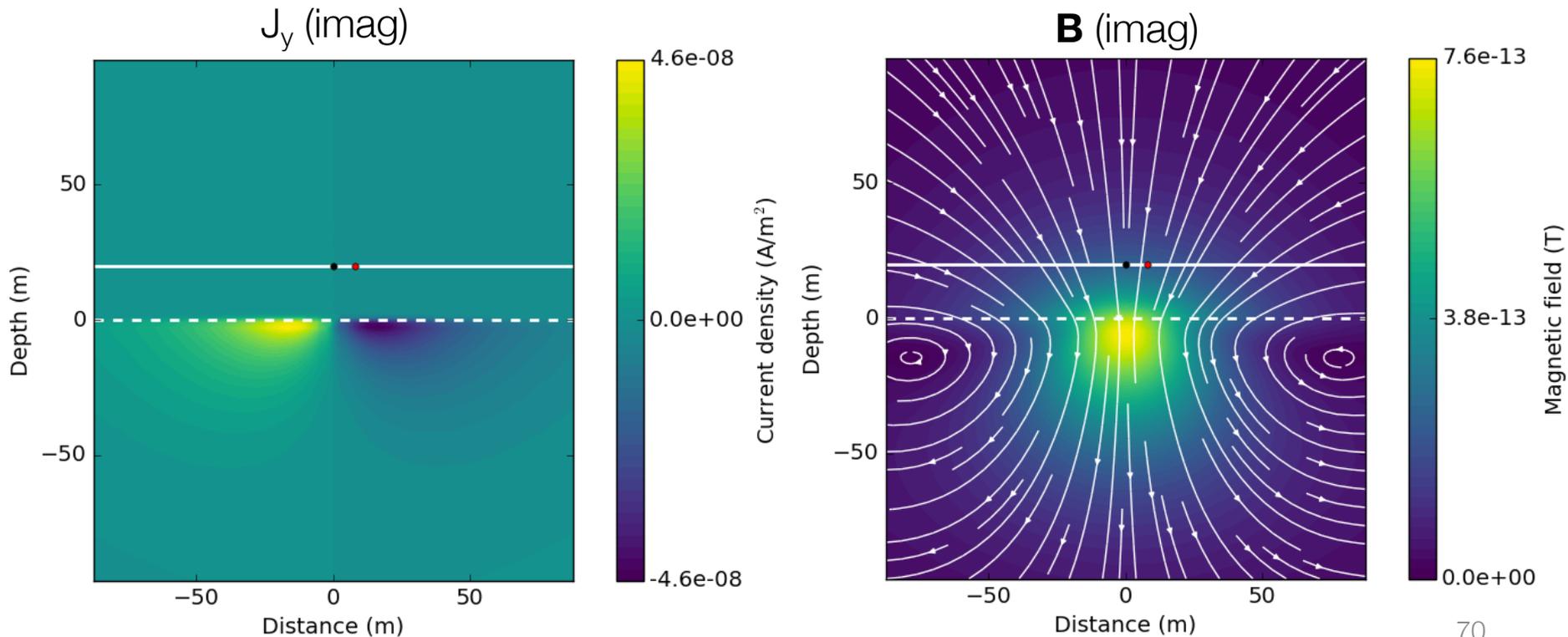
$$\delta = 503 \sqrt{\frac{\rho}{f}}$$



# Effects of Frequency

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

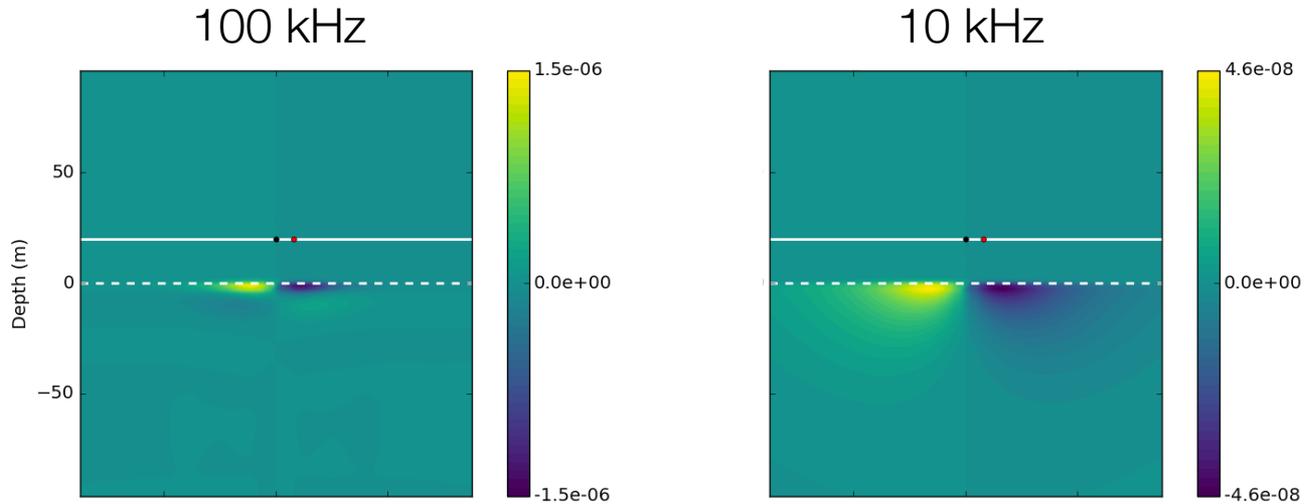
$$\delta = 503 \sqrt{\frac{\rho}{f}}$$



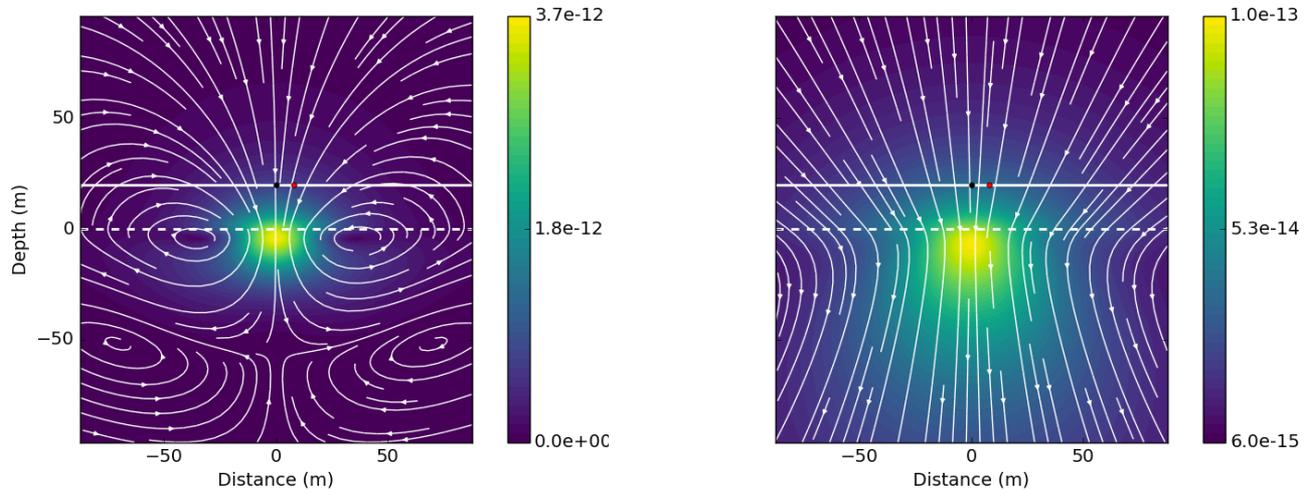
$$\delta = 503 \sqrt{\frac{\rho}{f}}$$

# Summary: Effects of Frequency

$J_y$  imag.

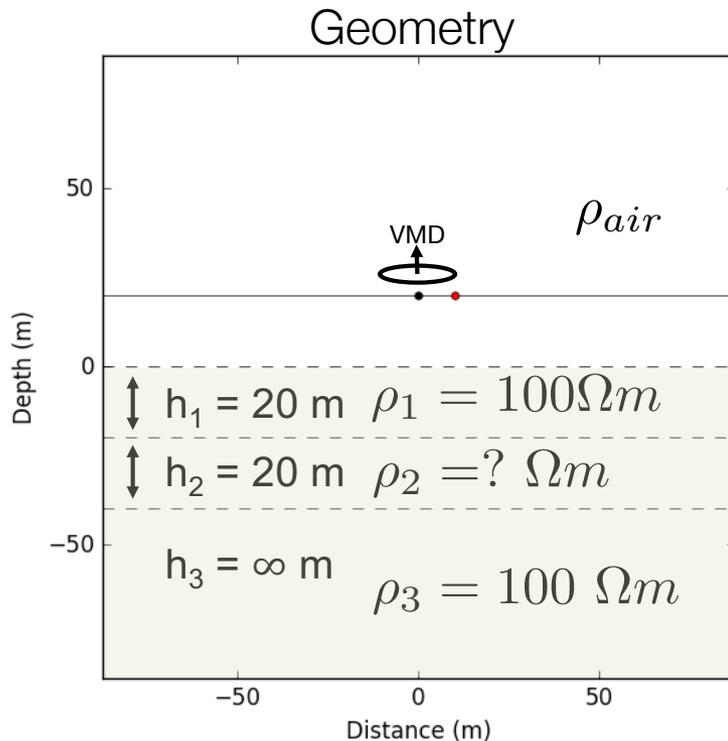


$\mathbf{B}$  imag.



# Layered earth

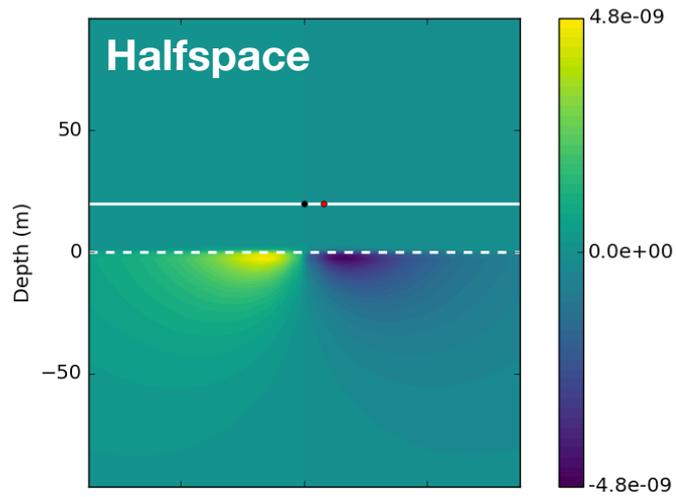
- 3 layers + air,
- $\rho_2$  varies



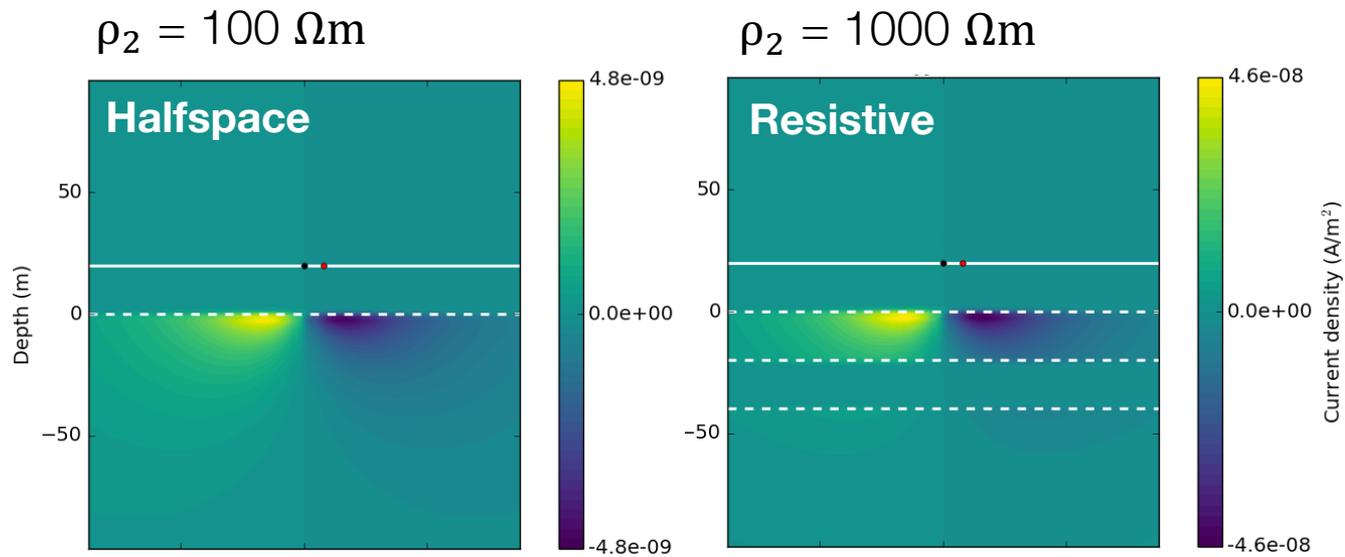
- Four different cases:
  - Halfspace
    - $\rho_2 = 100 \Omega m$
  - Resistive
    - $\rho_2 = 1000 \Omega m$
  - Conductive
    - $\rho_2 = 10 \Omega m$
  - Very conductive
    - $\rho_2 = 1 \Omega m$
- Fields
  - $J_y$  imag
  - Secondary **B** imag

# Current density ( $J_y$ imag)

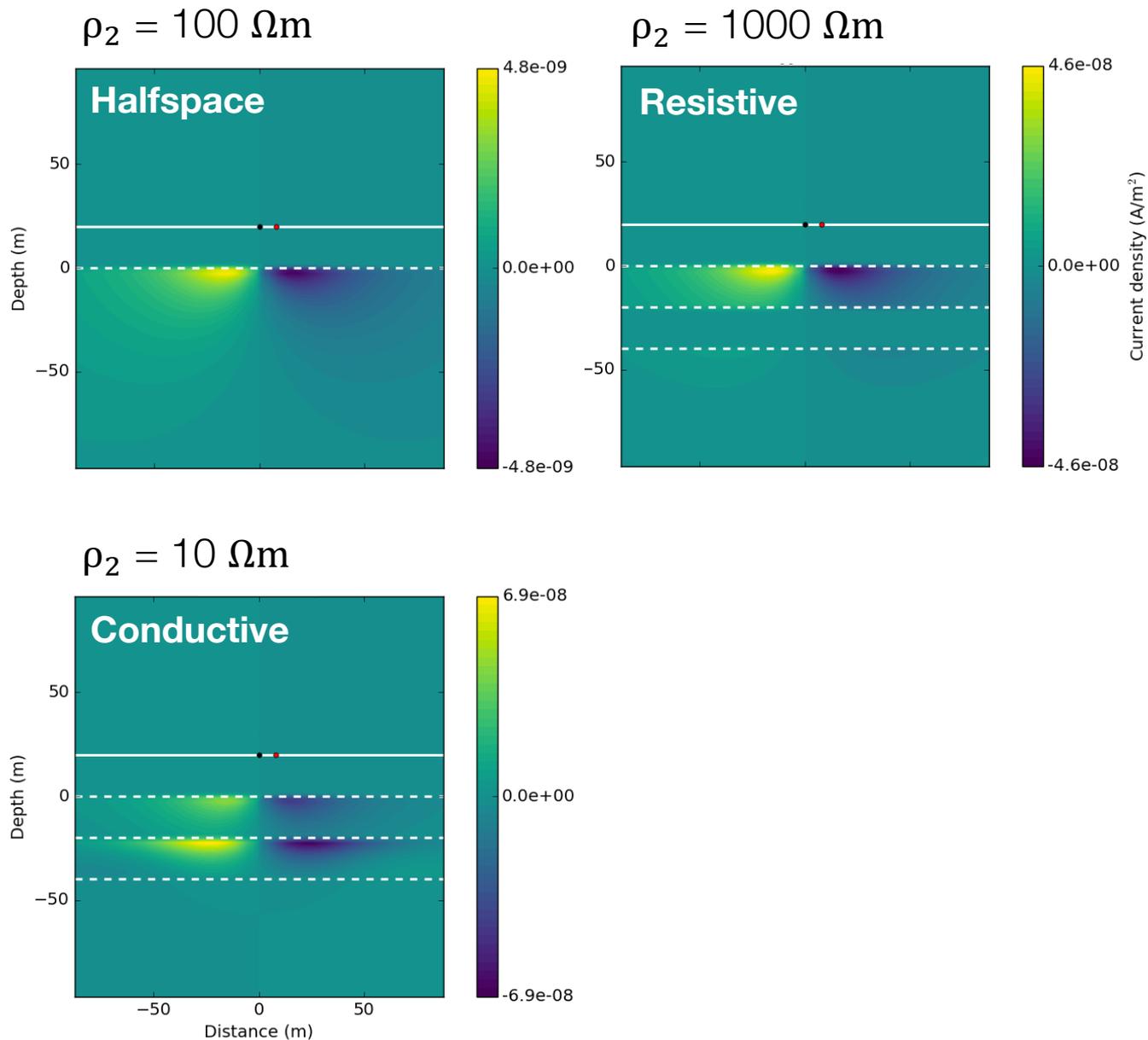
$\rho_2 = 100 \Omega\text{m}$



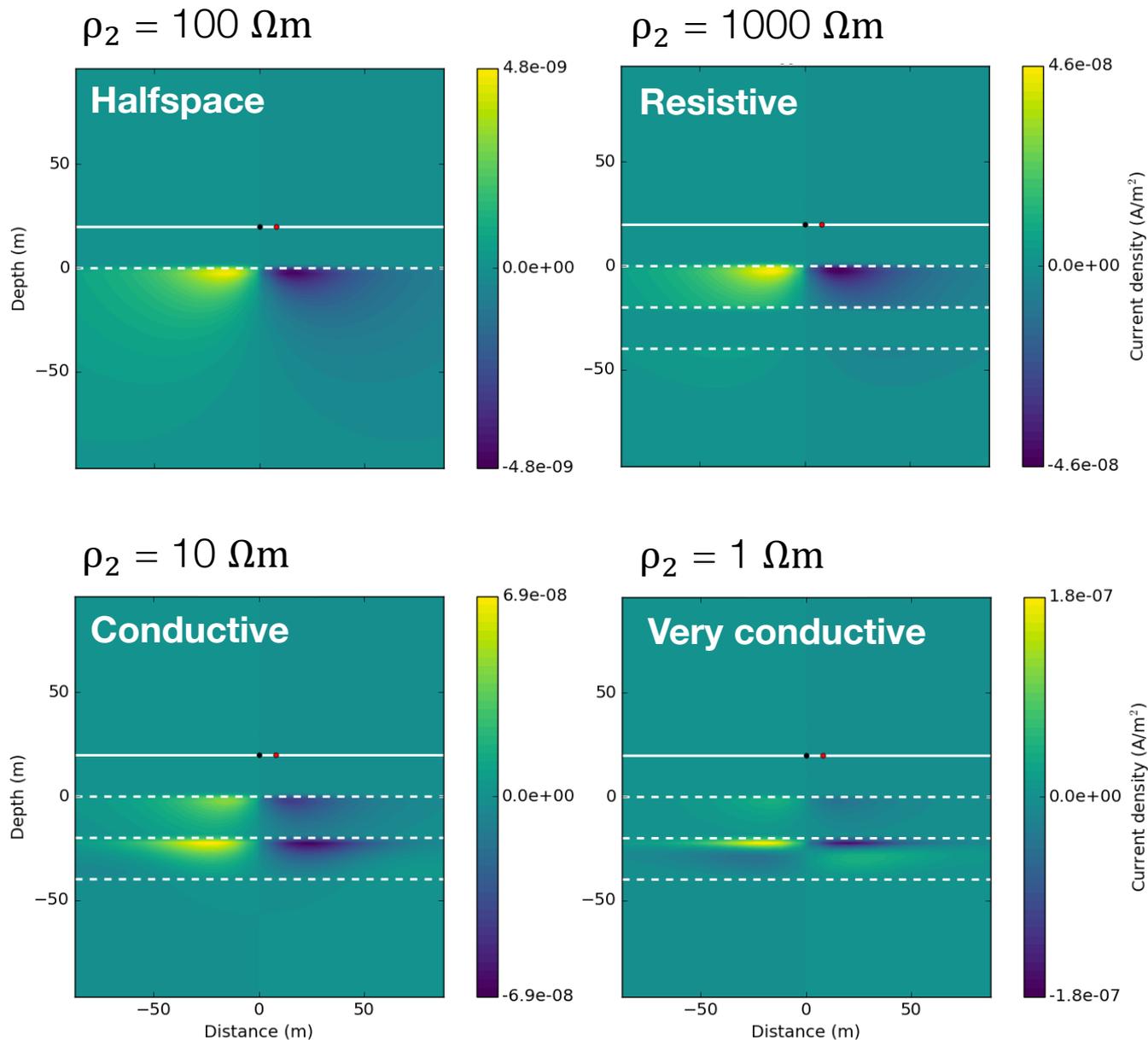
# Current density ( $J_y$ imag)



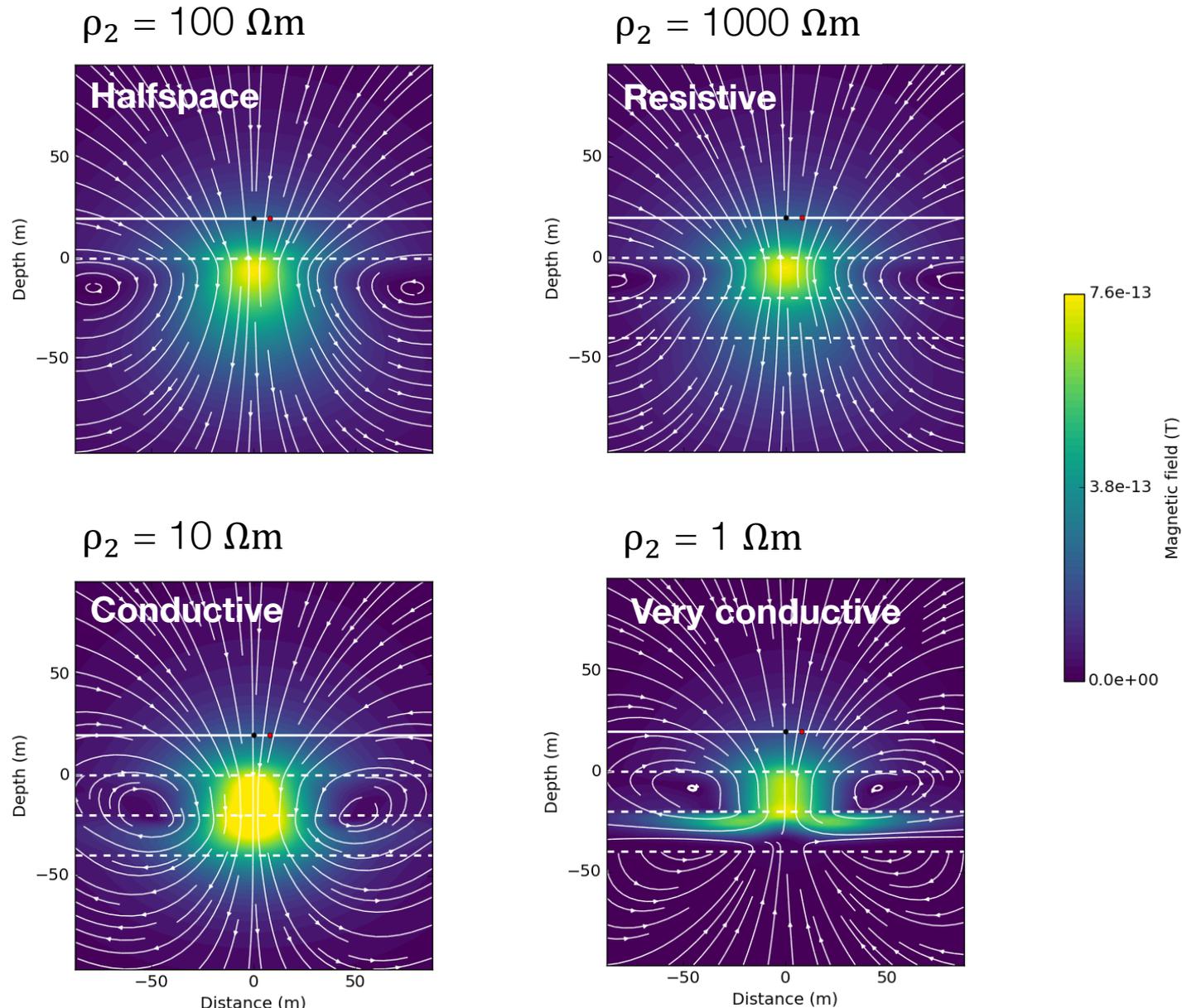
# Current density ( $J_y$ imag)



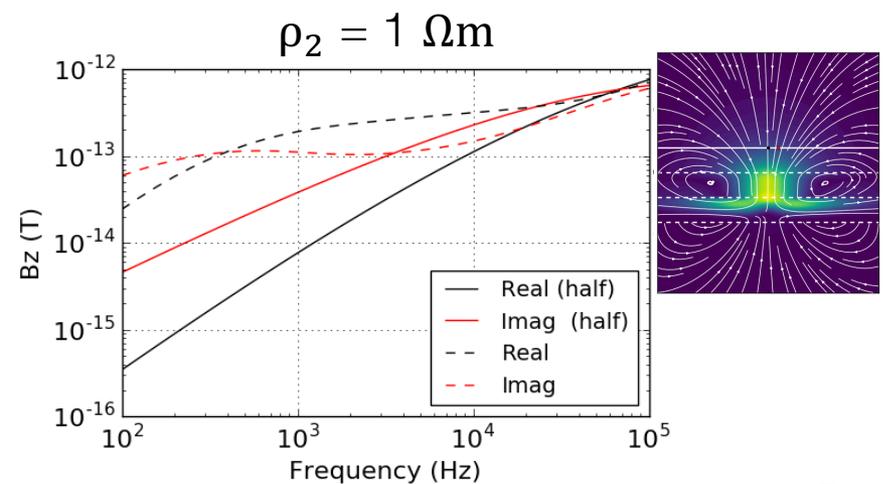
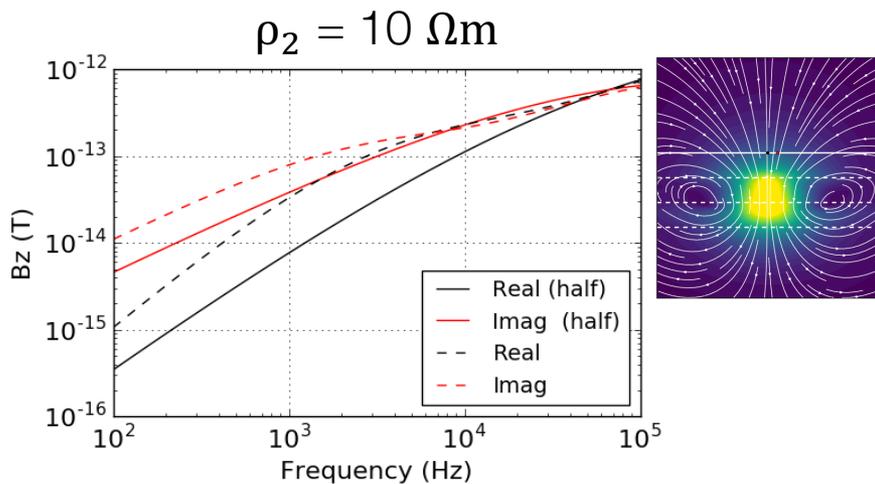
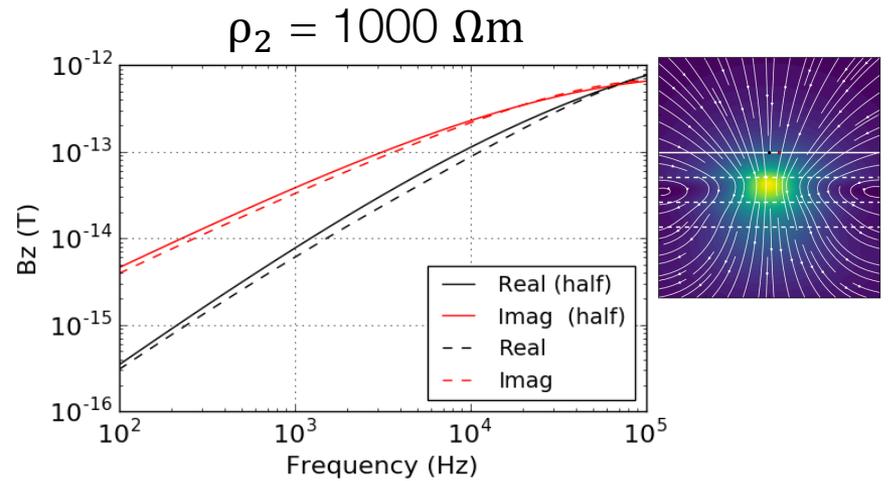
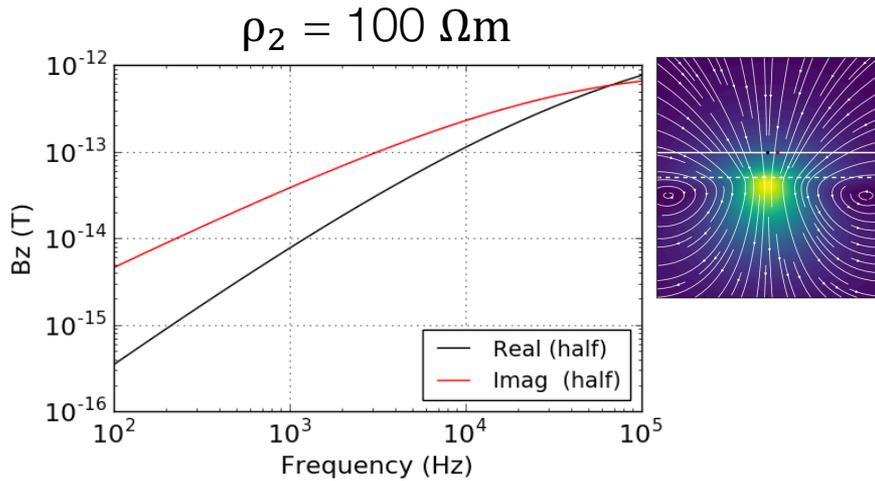
# Current density ( $J_y$ imag)



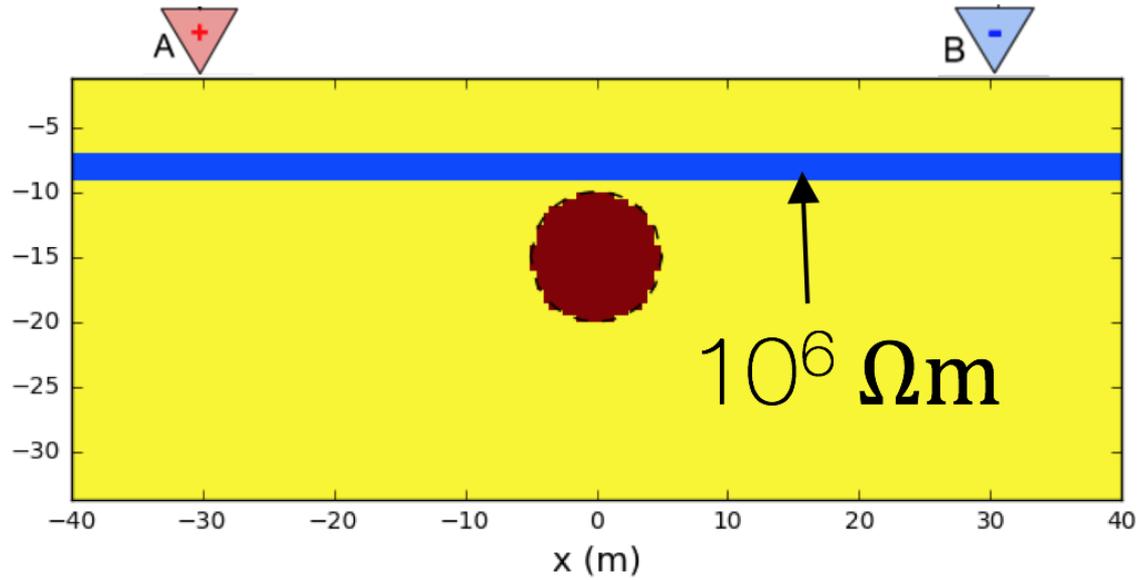
# Magnetic flux density (**B** imag)



# $B_z$ sounding curves

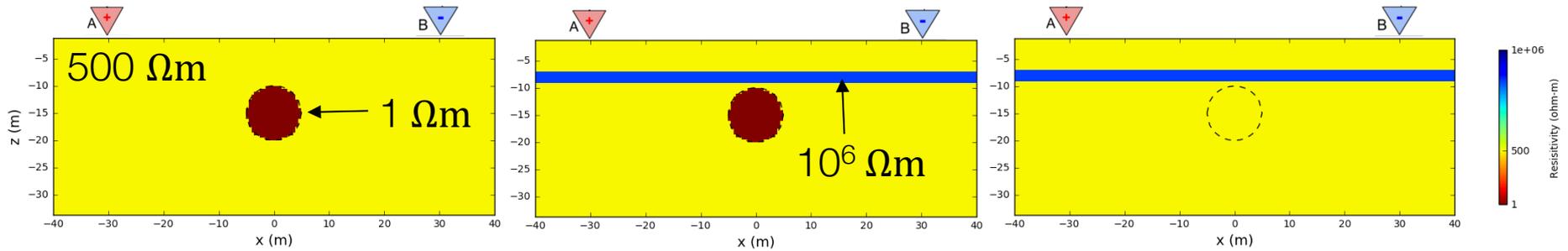


# Back to the “shielding” problem

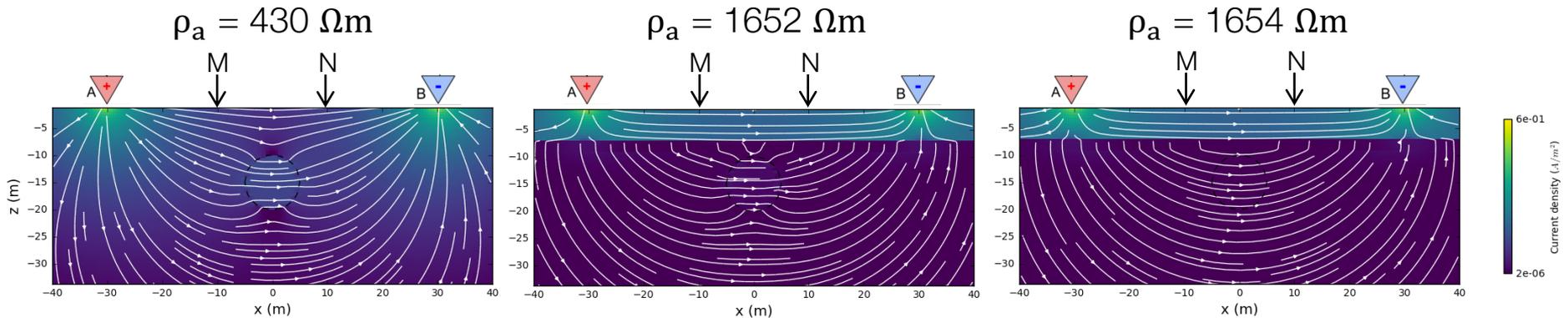


# Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)

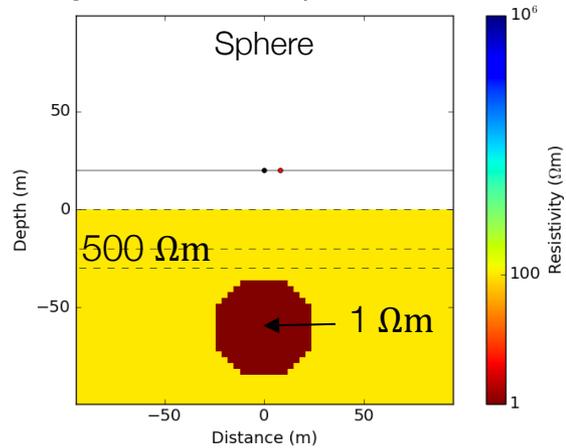


Currents and measured data at MN

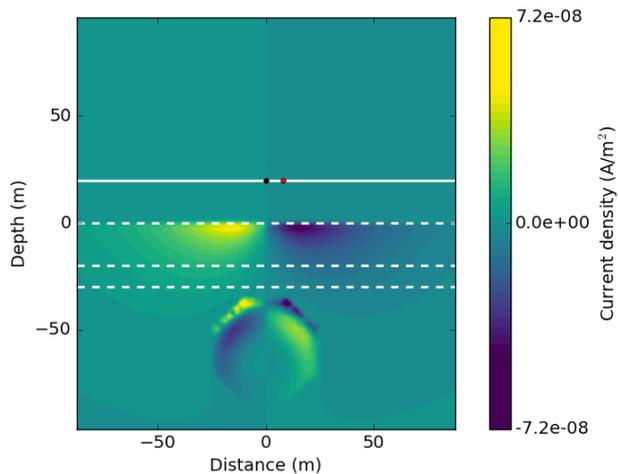


# Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

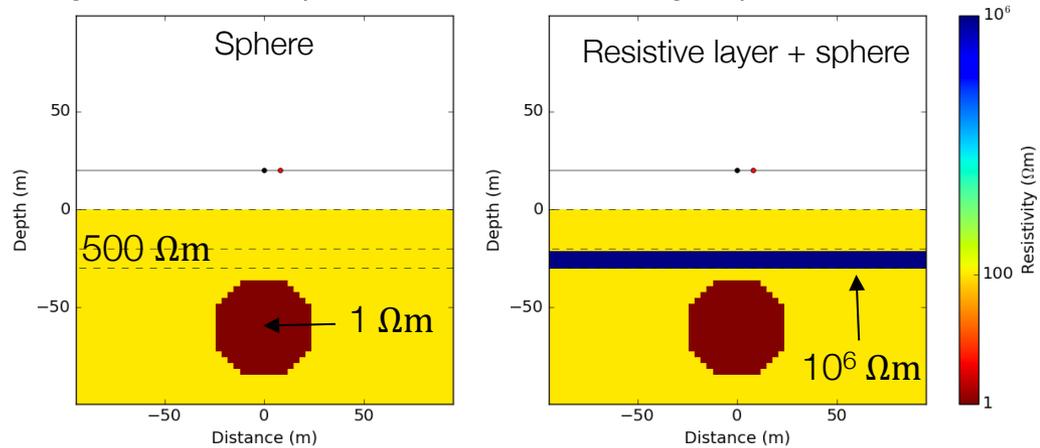


Currents ( $J_y$  imag)

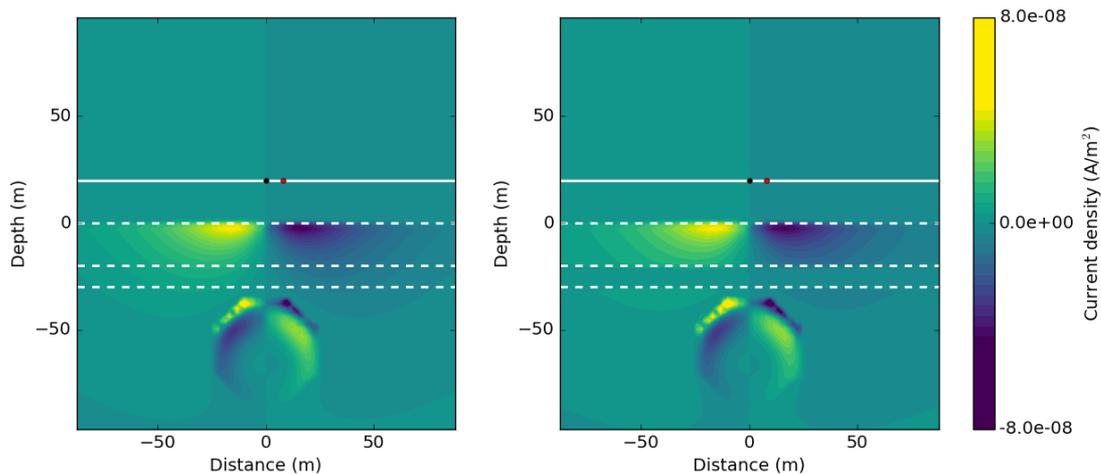


# Shielding: EM with resistive layer

## Resistivity models (thin **resistive** layer)

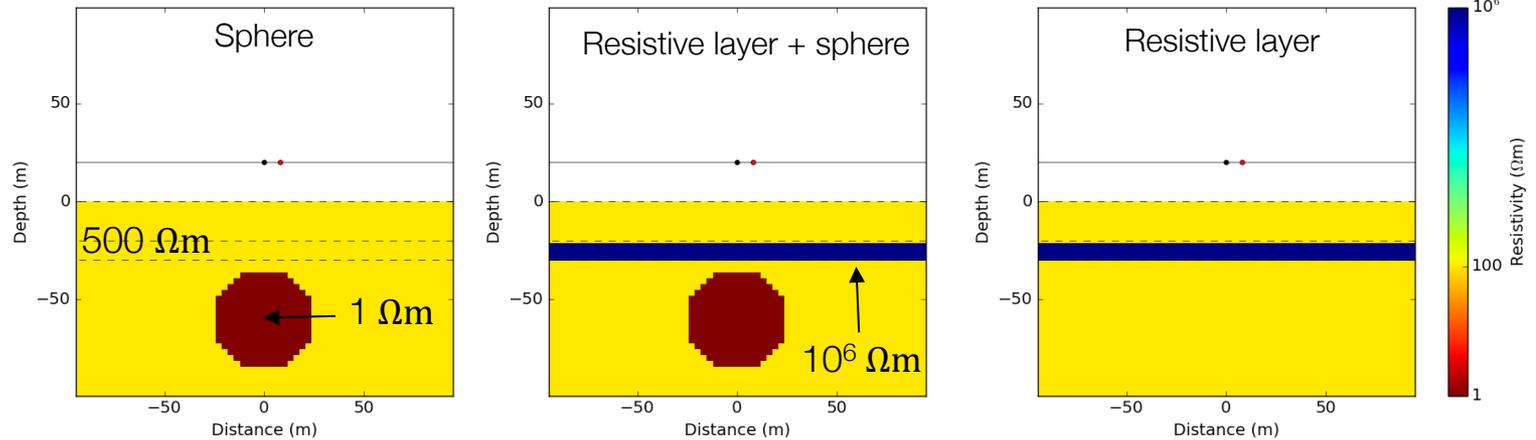


## Currents ( $J_y$ imag)

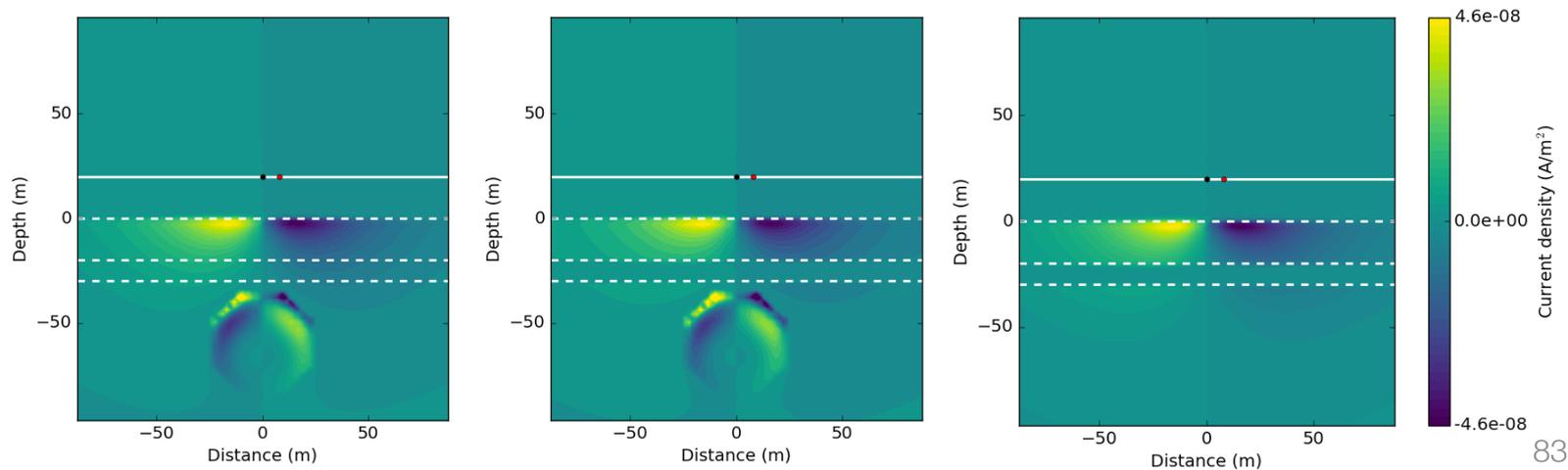


# Shielding: EM with resistive layer

## Resistivity models (thin **resistive** layer)

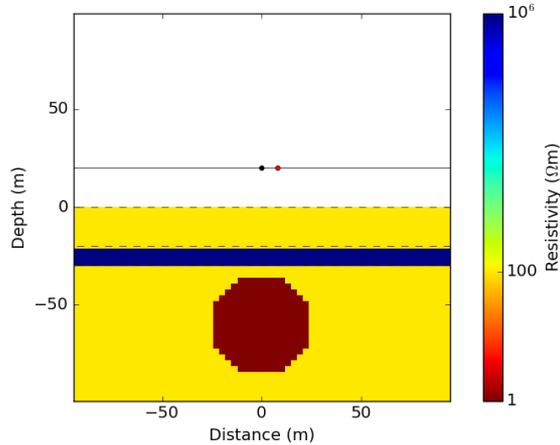


## Currents ( $J_y$ imag)

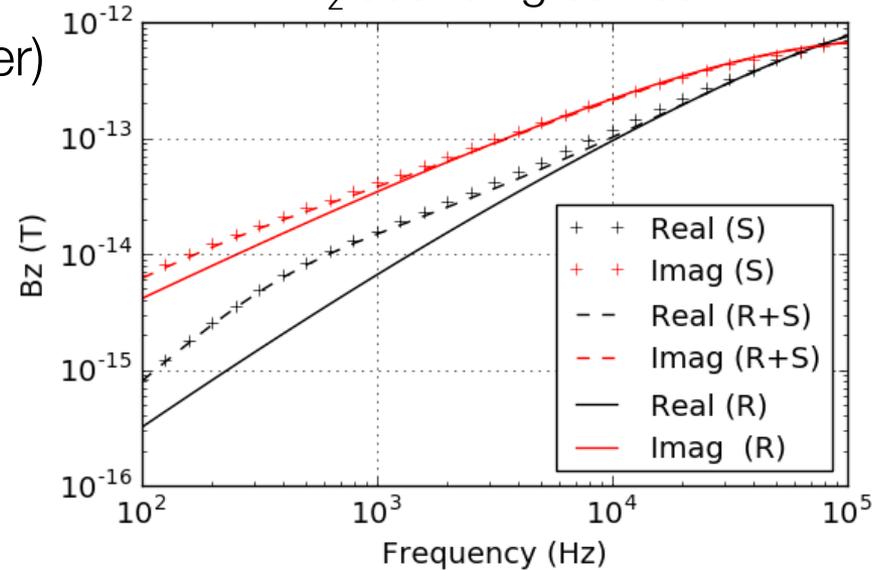


# Shielding: EM with resistive layer

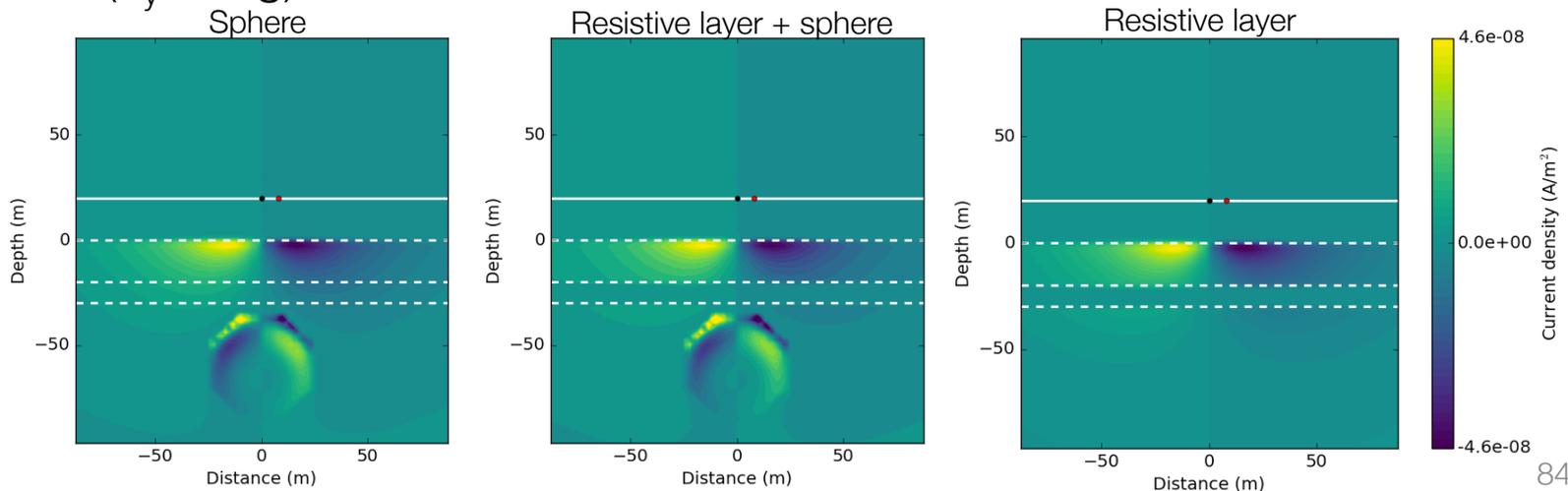
Resistivity models (thin **resistive** layer)



$B_z$  sounding curves

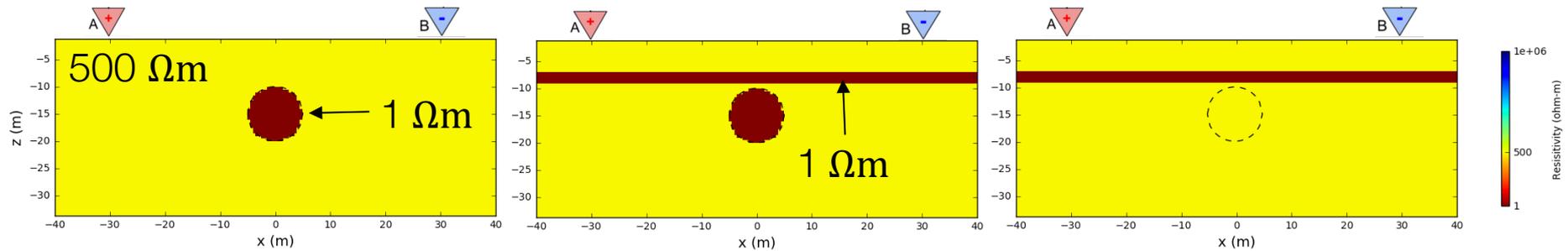


Currents ( $J_y$  imag)

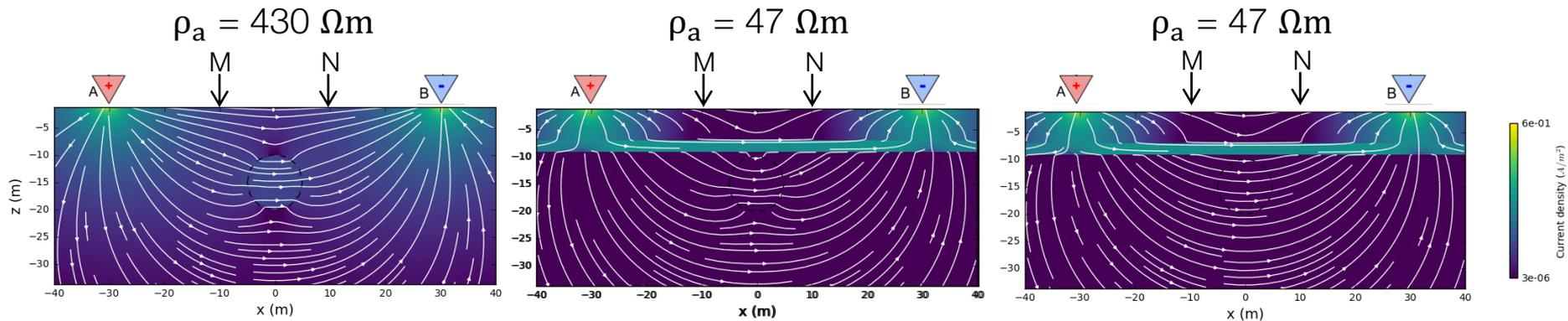


# Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)

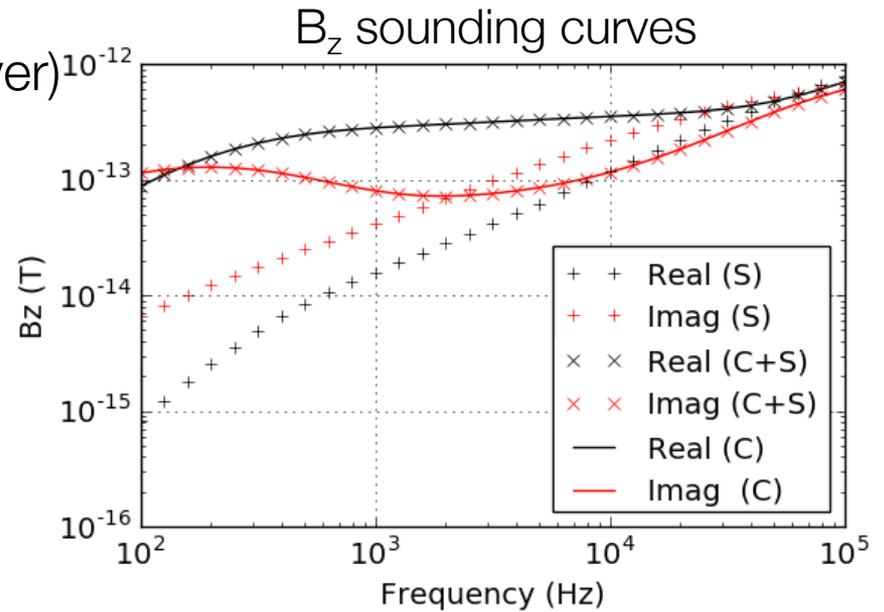
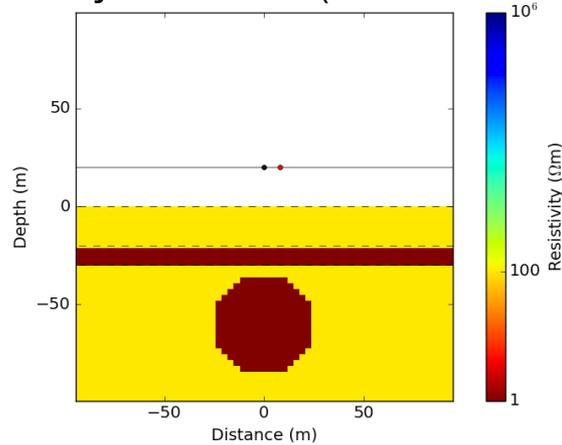


Currents and measured data at MN

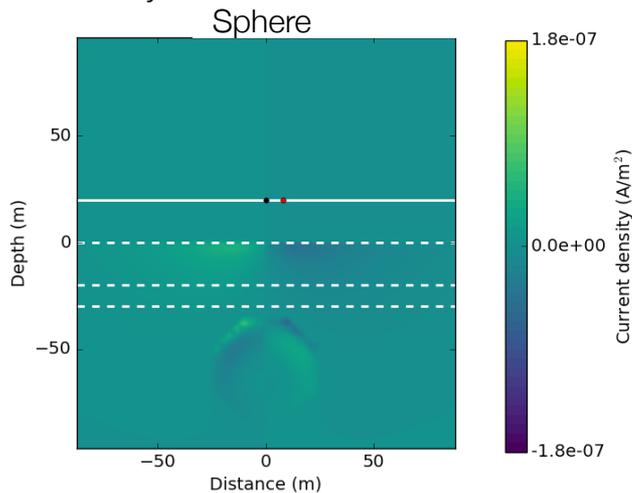


# Shielding: EM with conductive layer

Resistivity models (thin **conductive** layer)

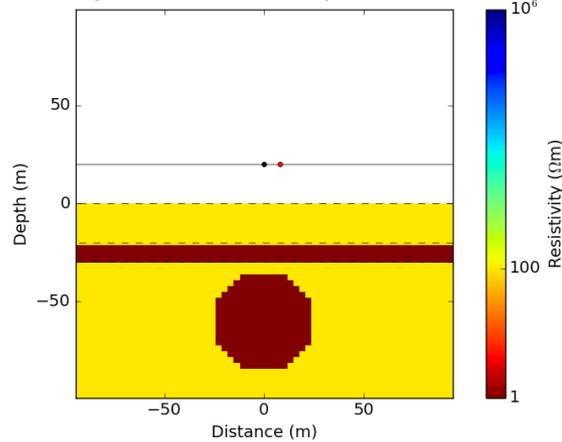


Currents ( $J_y$  imag)

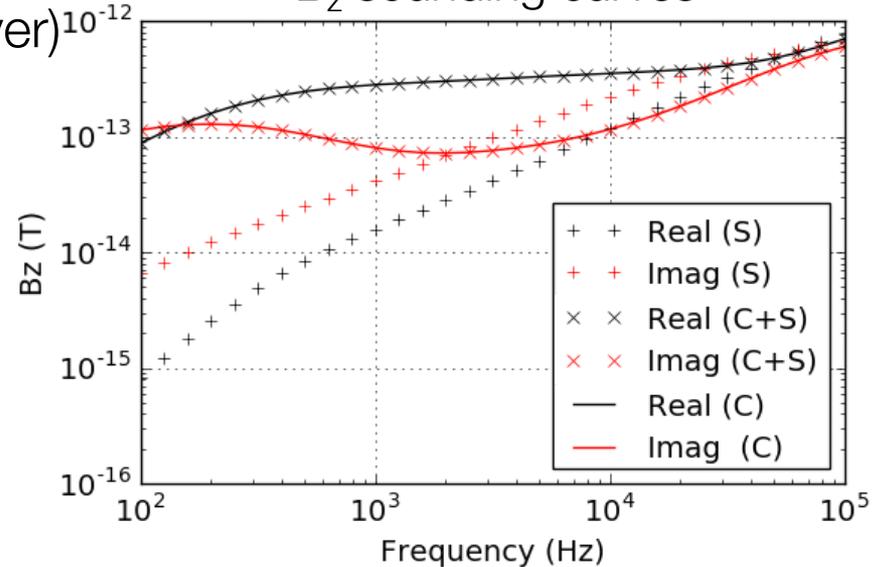


# Shielding: EM with conductive layer

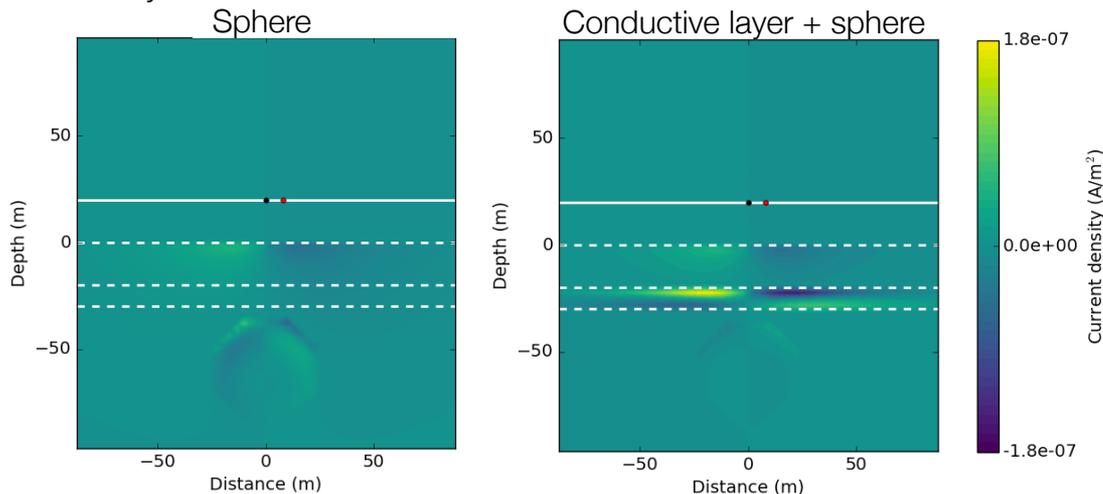
Resistivity models (thin **conductive** layer)



$B_z$  sounding curves

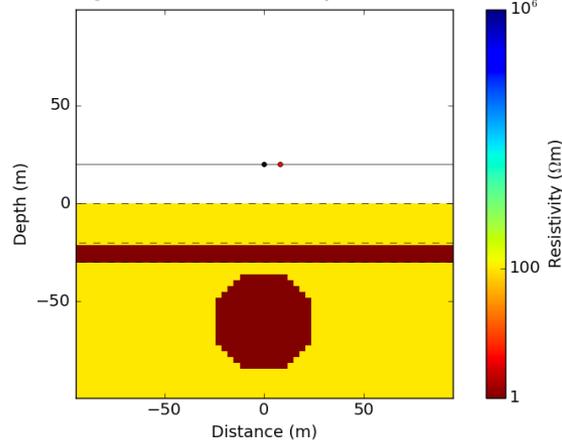


Currents ( $J_y$  imag)

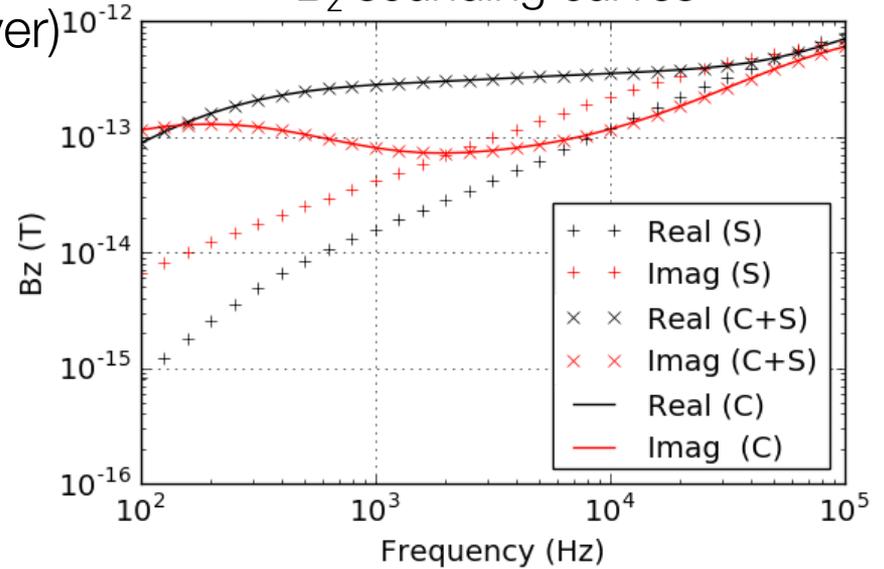


# Shielding: EM with conductive layer

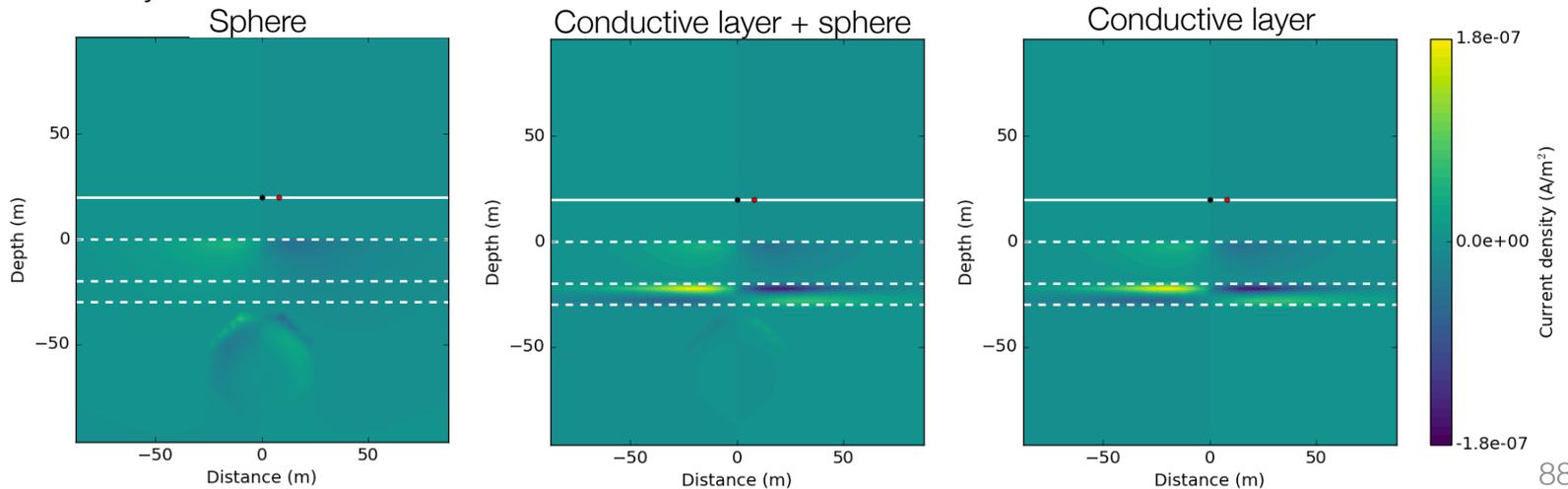
Resistivity models (thin **conductive** layer)



$B_z$  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, Landslides

## Questions

# Case History: Bookpurnong

Viezzoli et al., 2009

Setup

Bookpurnong  
Irrigation Area

Murray River  
Floodplain

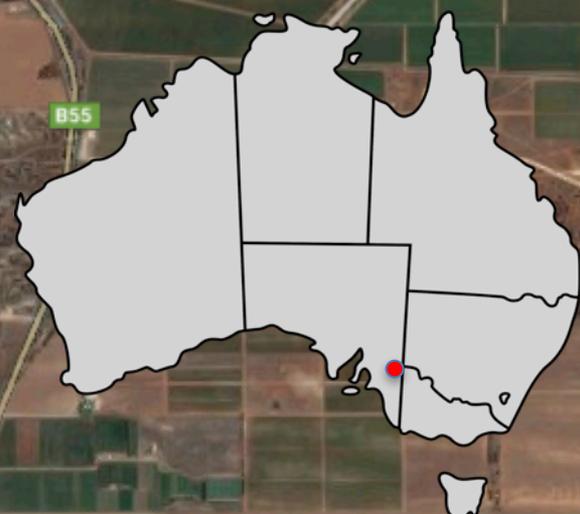
1 km

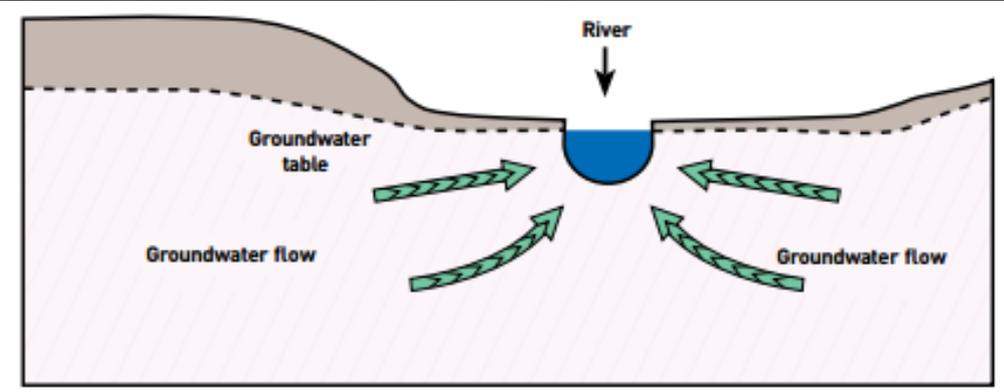
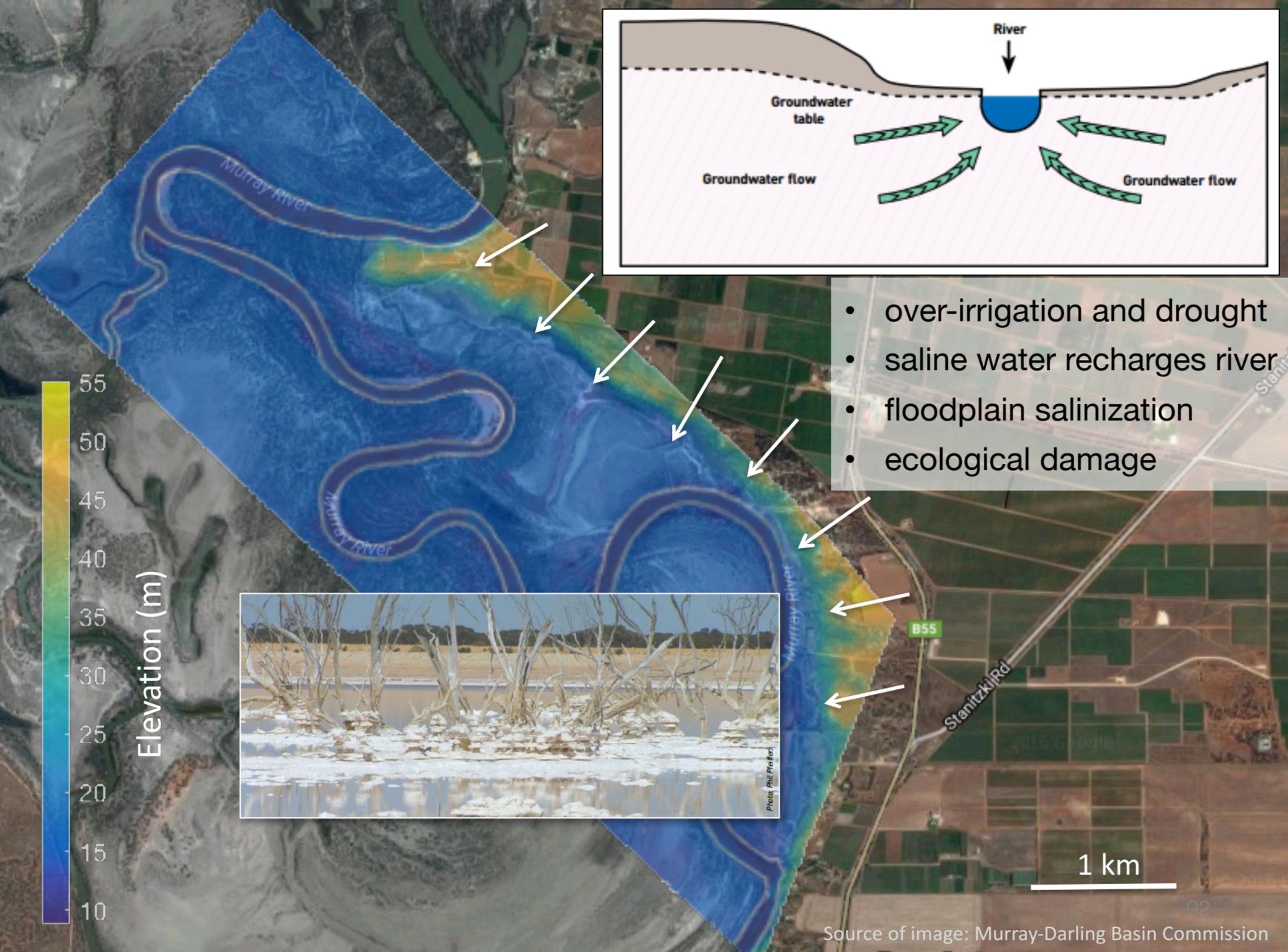
B55

Bookpurnong

Staniford

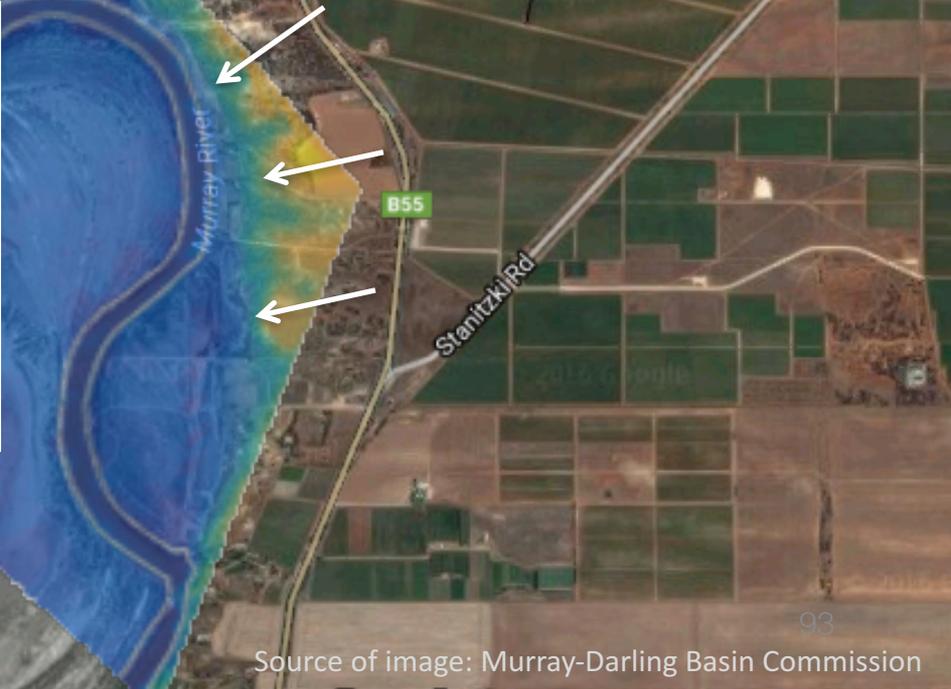
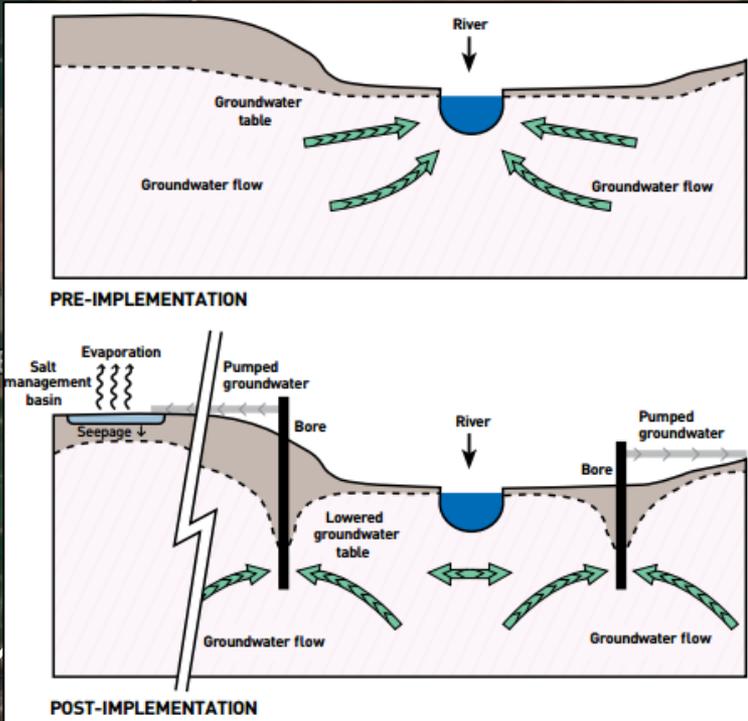
B55

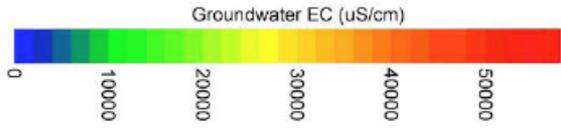
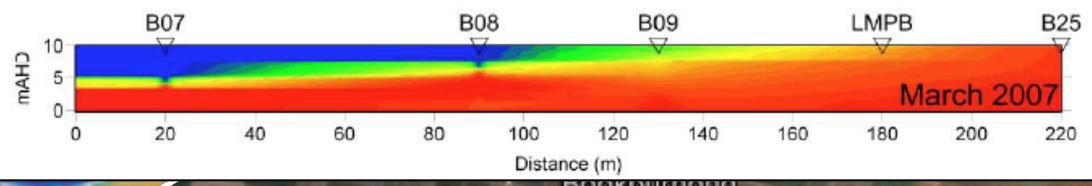
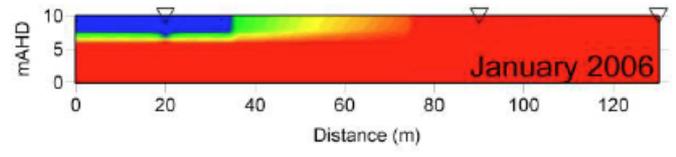
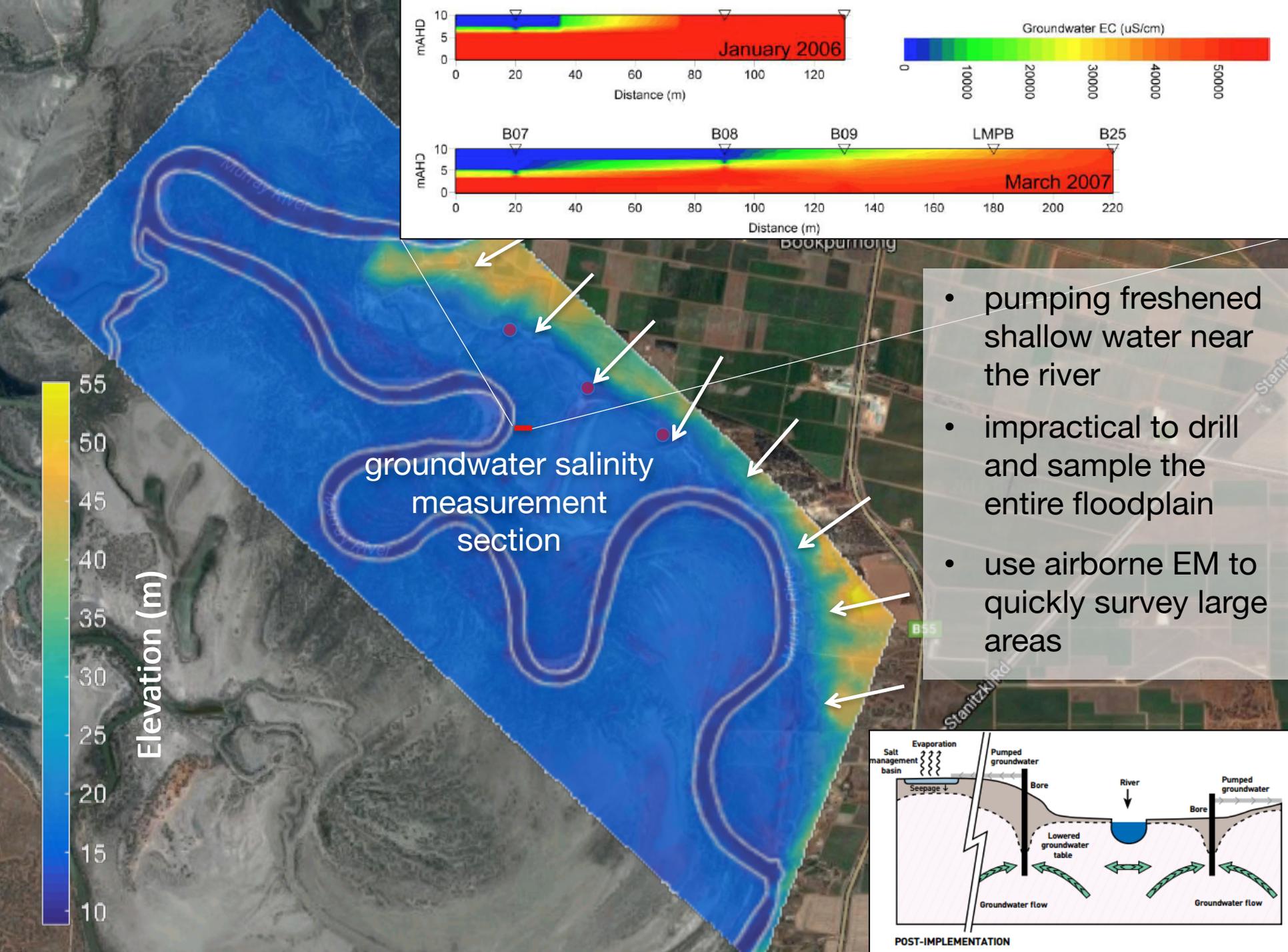




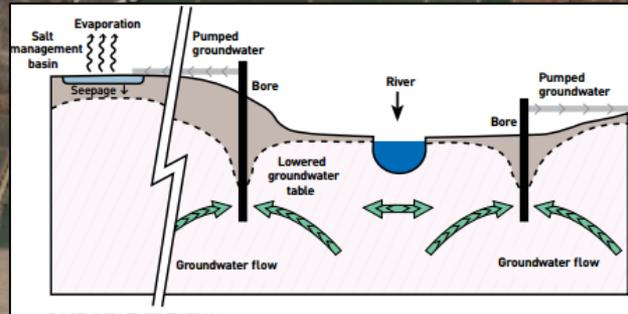
- over-irrigation and drought
- saline water recharges river
- floodplain salinization
- ecological damage





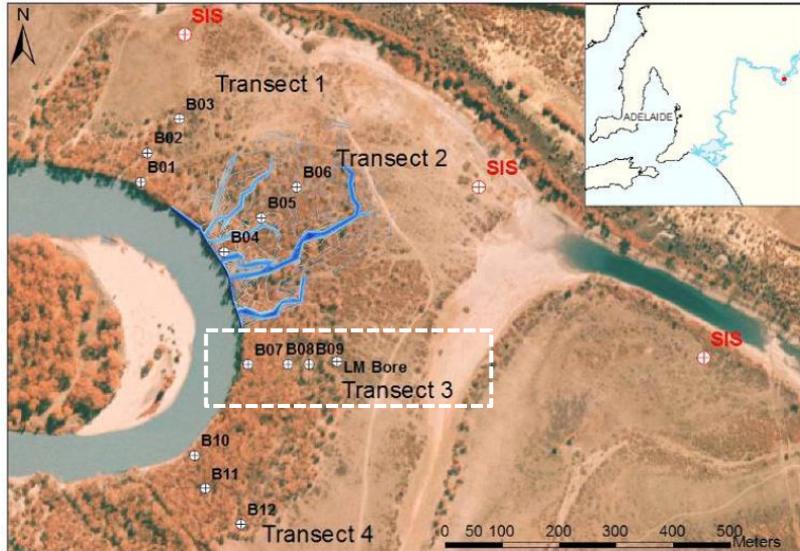


- pumping freshened shallow water near the river
- impractical to drill and sample the entire floodplain
- use airborne EM to quickly survey large areas



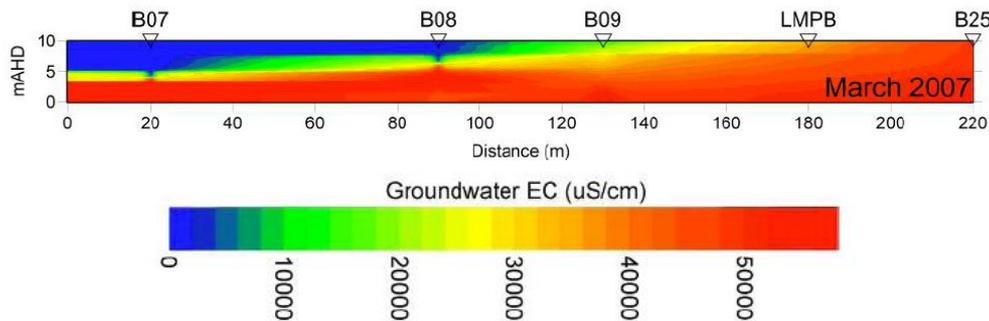
# Properties

Location map for salinity measurements



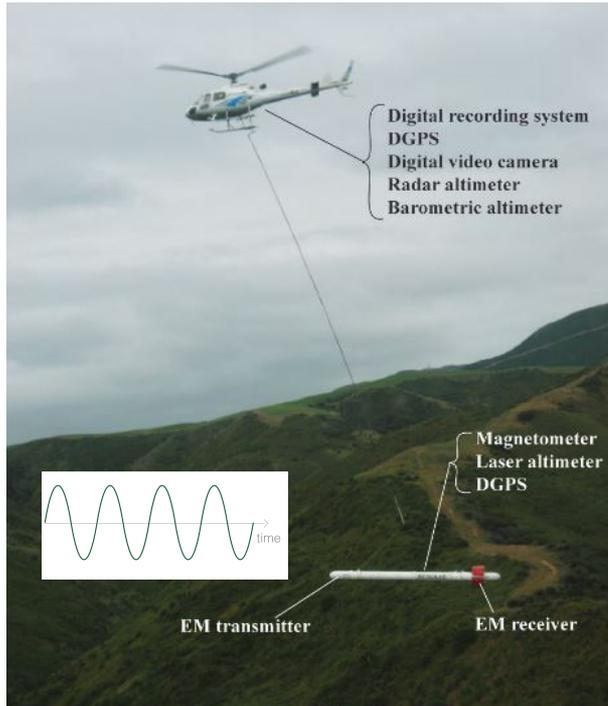
Unit	Conductivity
Saline water	High, 3 - 5 S/m
Fresh water	Low, 0.01 S/m

Conductivity from salinity measurements



# Survey

Resolve system (2008)



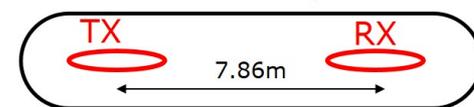
Flight lines



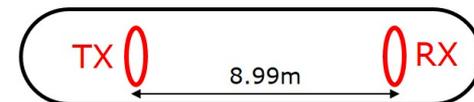
Horizontal Co-planar (HCP) frequencies:  
 - 382, 1822, 7970, 35920 and 130100 Hz

Vertical Co-axial (VCA) frequencies:  
 - 3258 Hz

Horizontal Co-planar



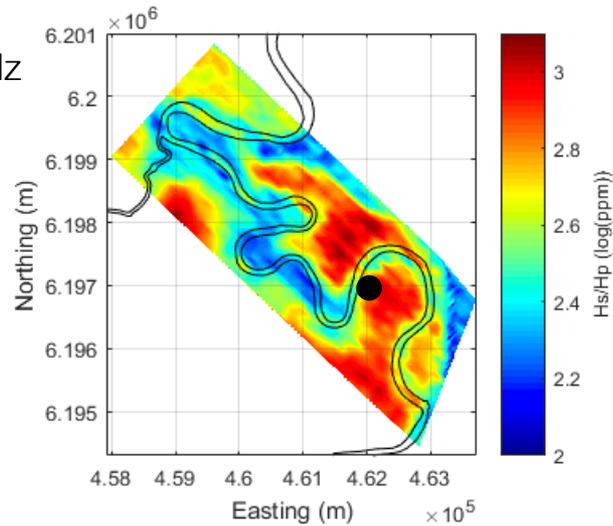
Vertical Co-axial



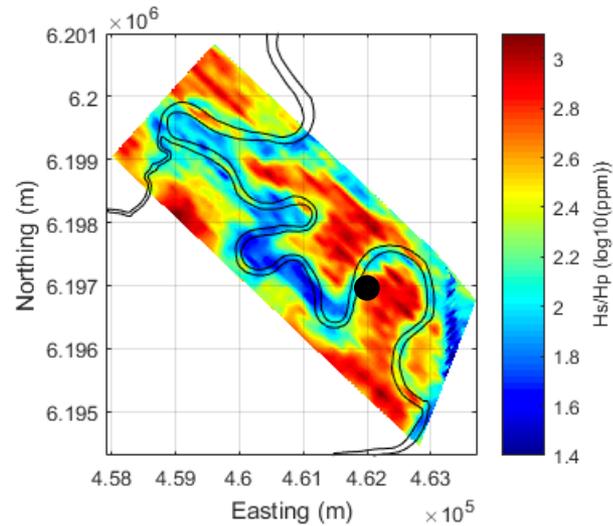
# Horizontal Co-planar (HCP) data

In-Phase (Real)

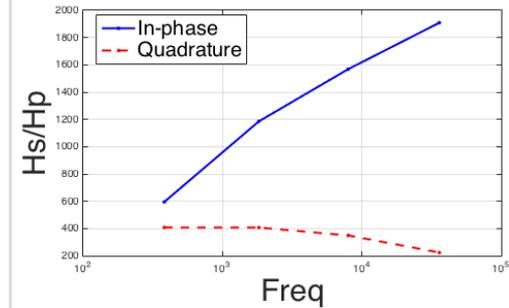
382 Hz



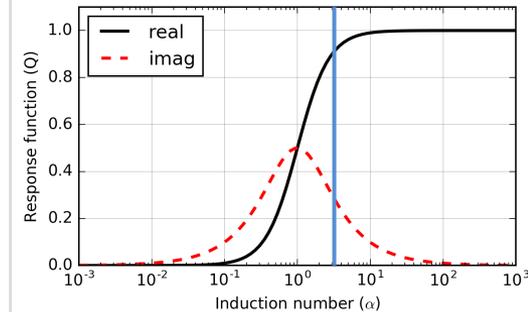
Quadrature (Imaginary)



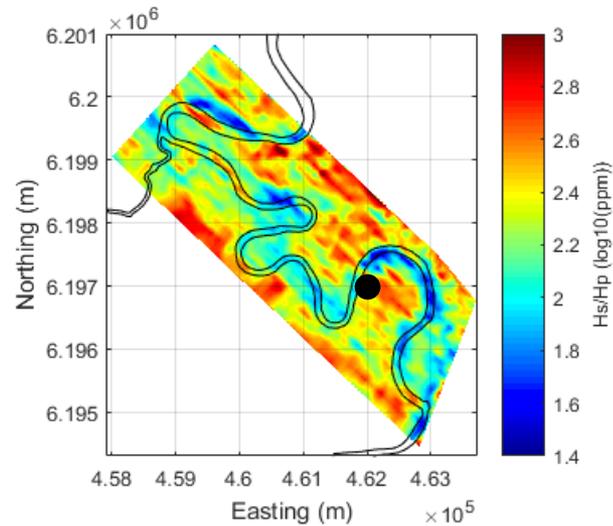
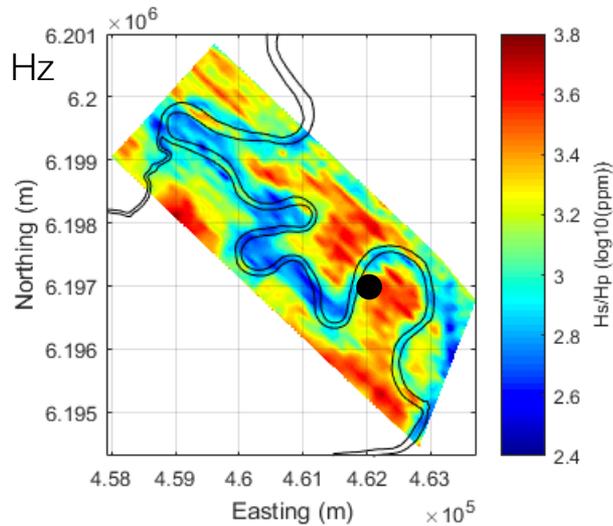
Sounding curve



Response curve

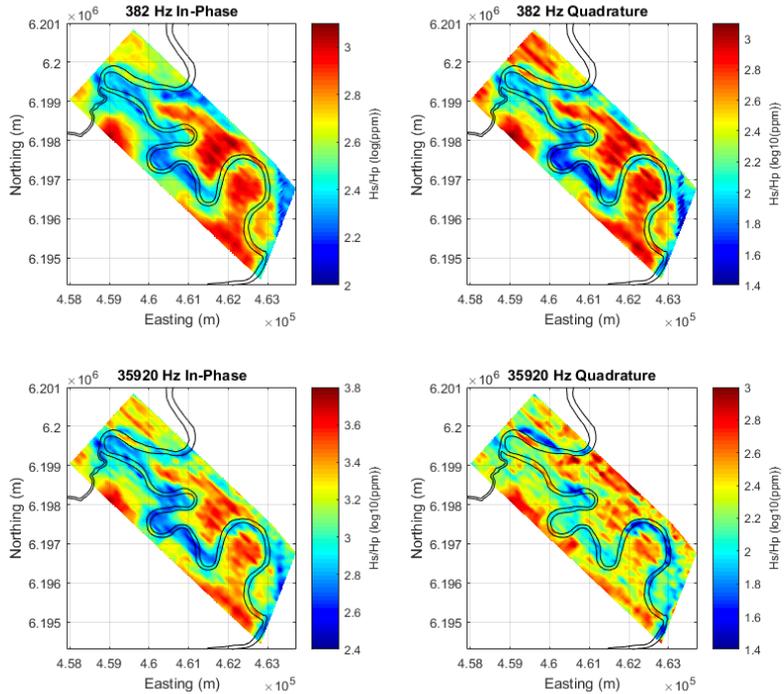


35920 Hz

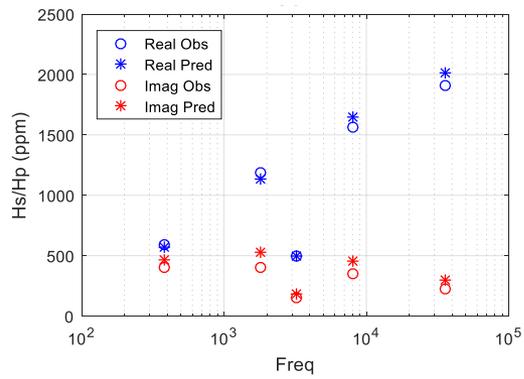


# Processing: 1D inversion

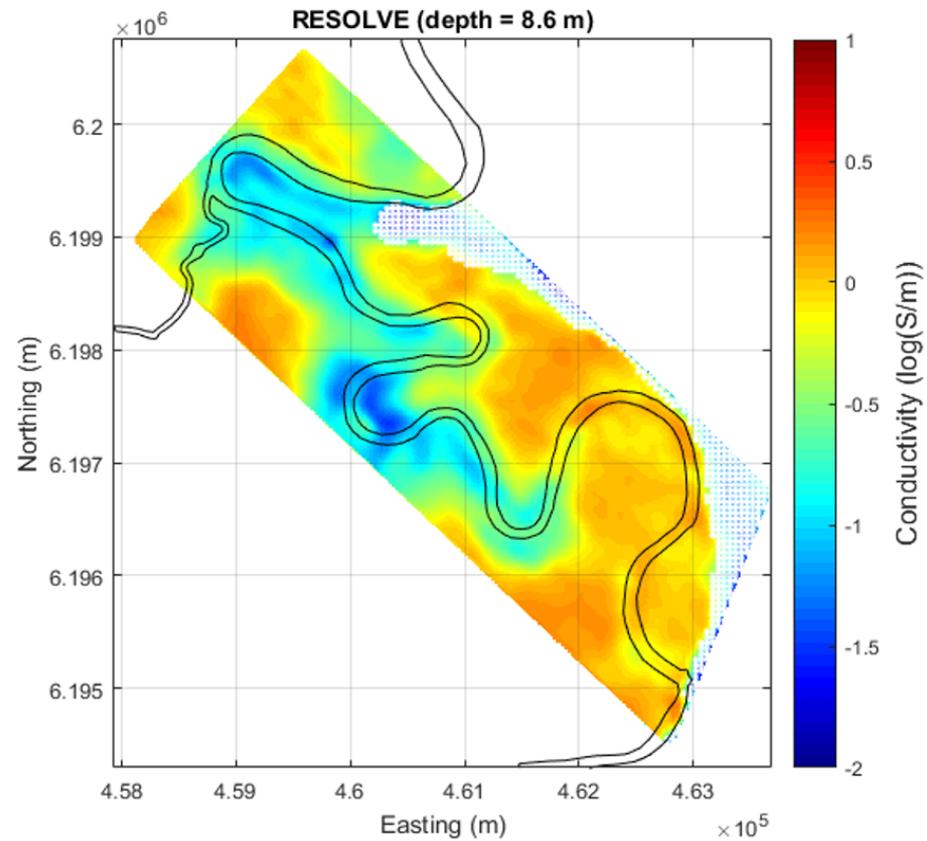
## Data



## Data fit

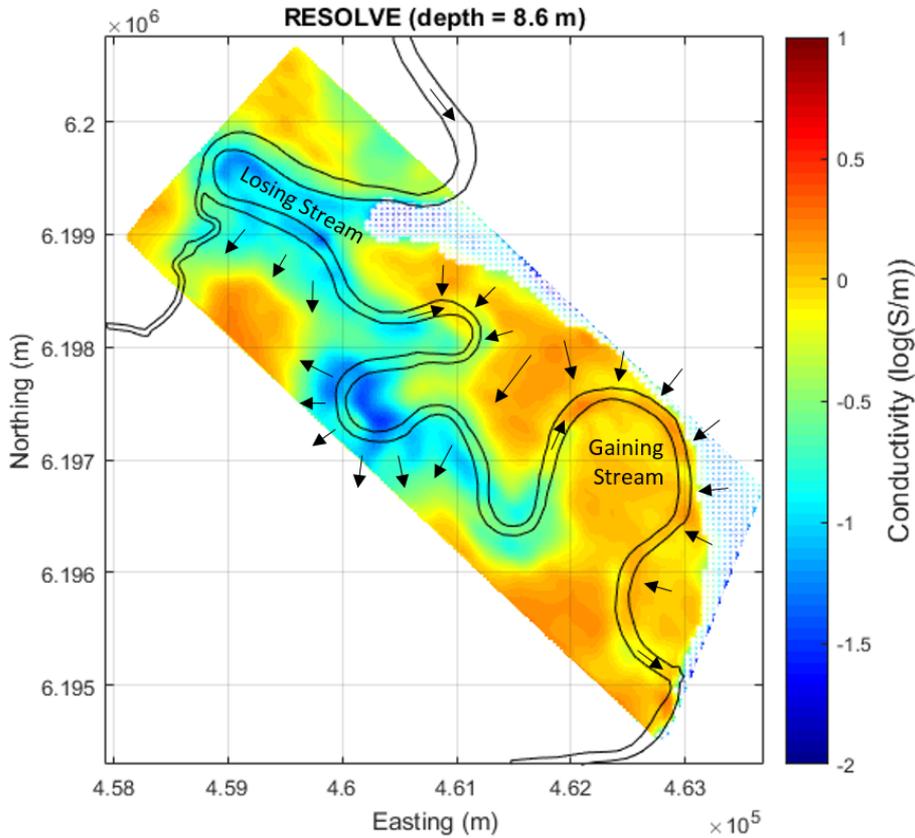


## Conductivity model (stitched)

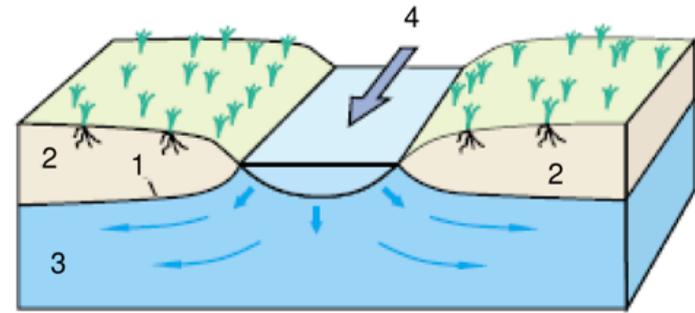


# Interpretation

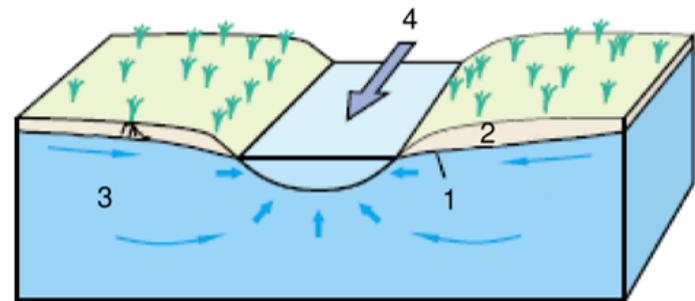
Conductivity model (stitched)



Losing Stream



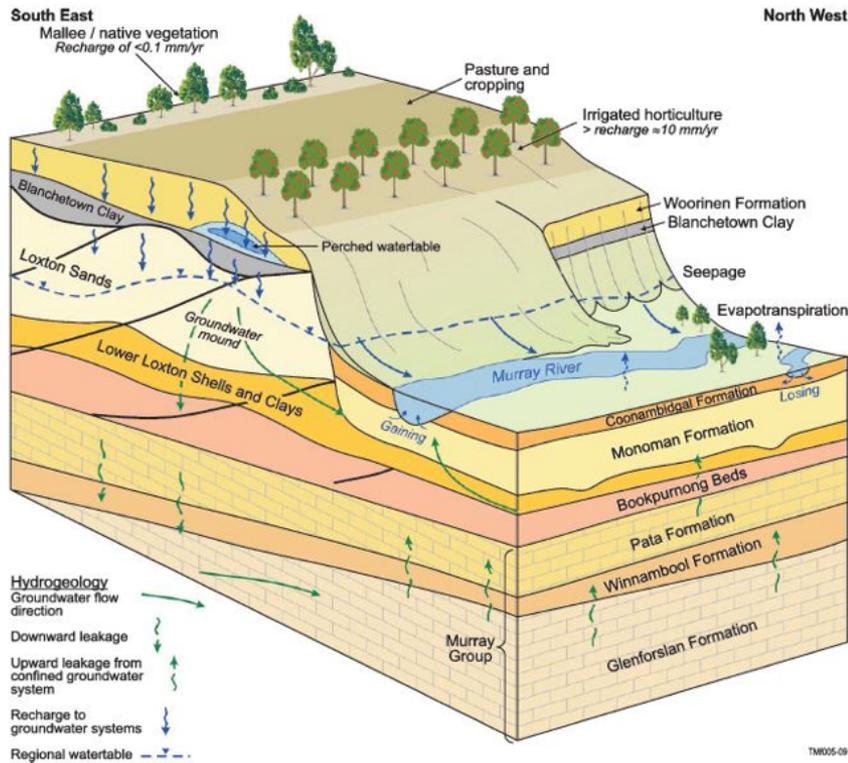
Gaining Stream



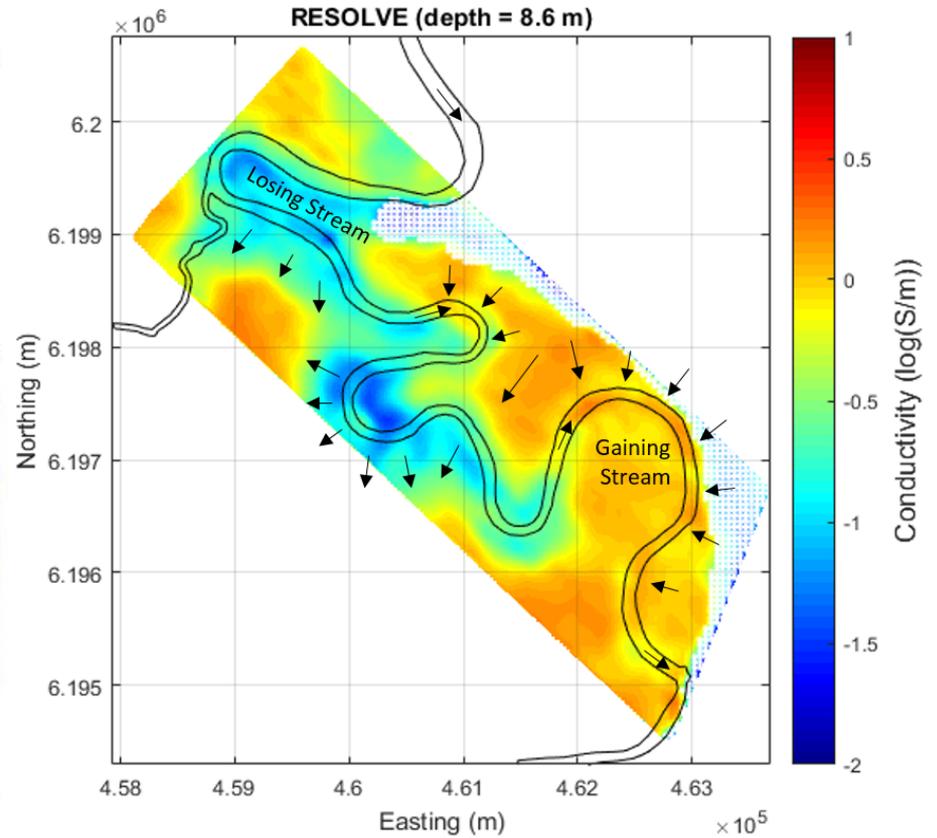
- 1 – Water table
- 2 – Unsaturated zone
- 3 – Saturated zone
- 4 – Flow direction

# Synthesis

## Hydrological model



## Conductivity model (stitched)



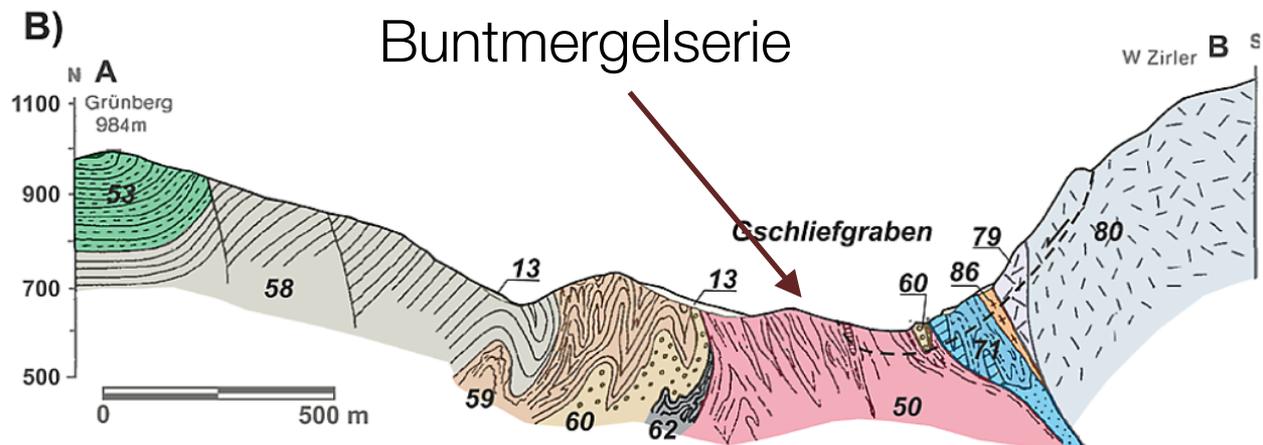
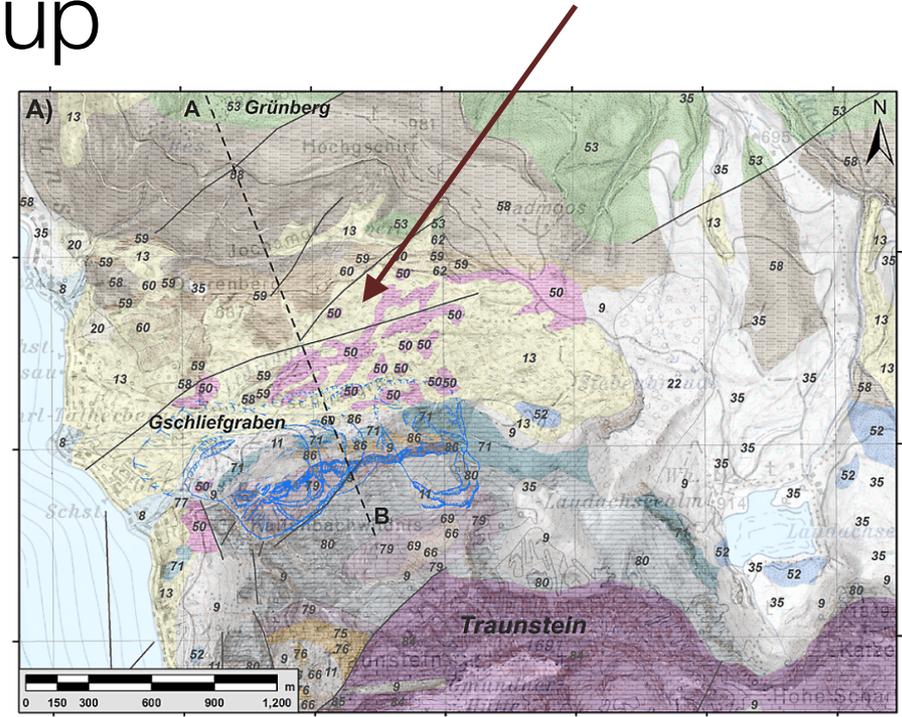
# Case History: Airborne geophysical mapping for landslide investigation

Supper et al., 2013



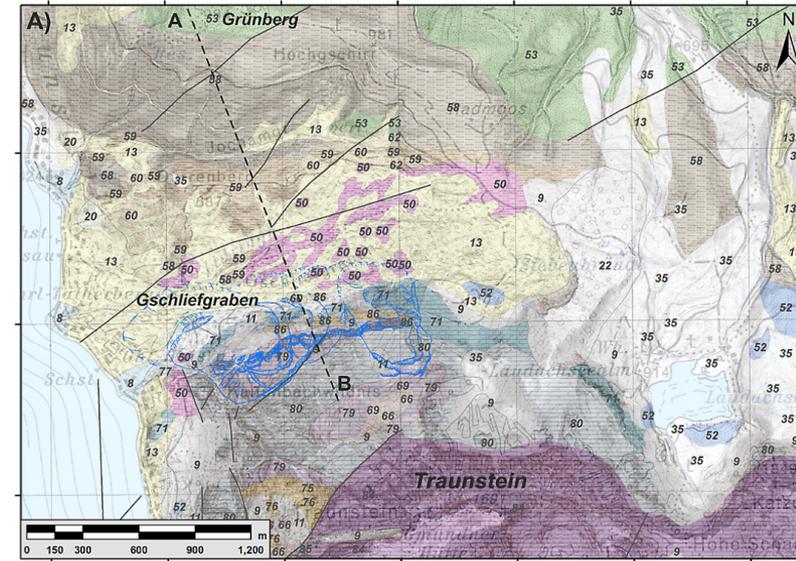
# Setup

- Gschlifgraben 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

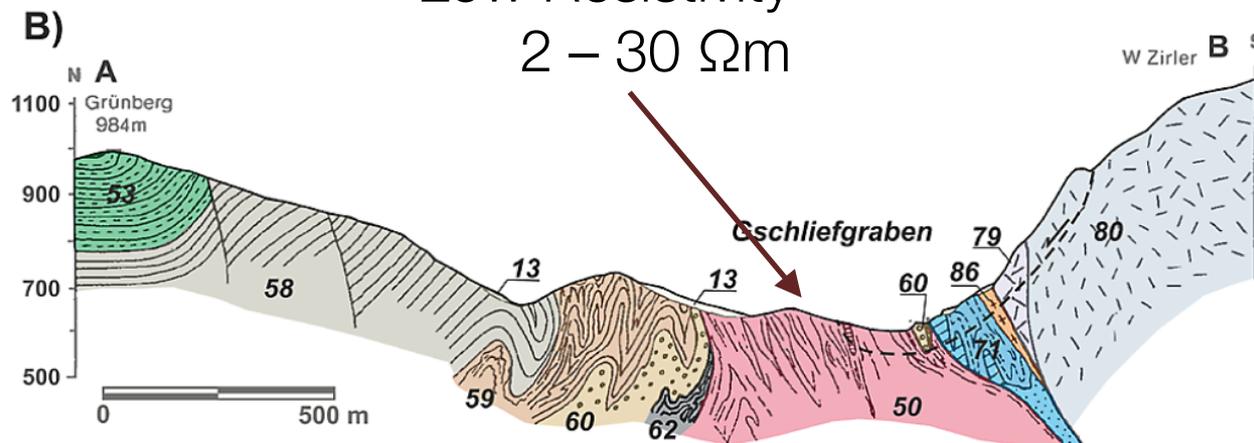


# Properties

Deformed variegated marl, claystone, ... (target unit)	2 – 30 $\Omega\text{m}$
Claystone, marl	50 – 100 $\Omega\text{m}$
Intermediate Sandstone	> 150 $\Omega\text{m}$

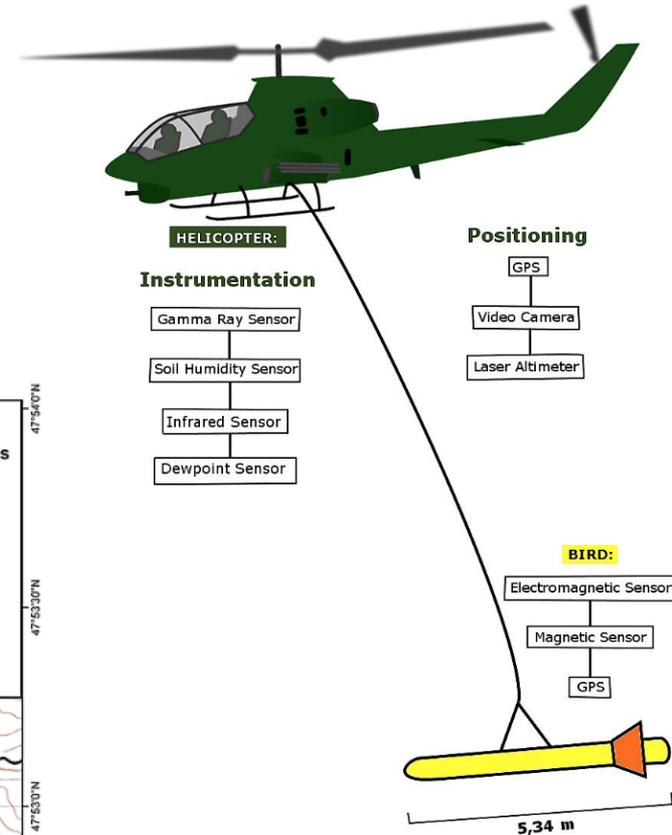
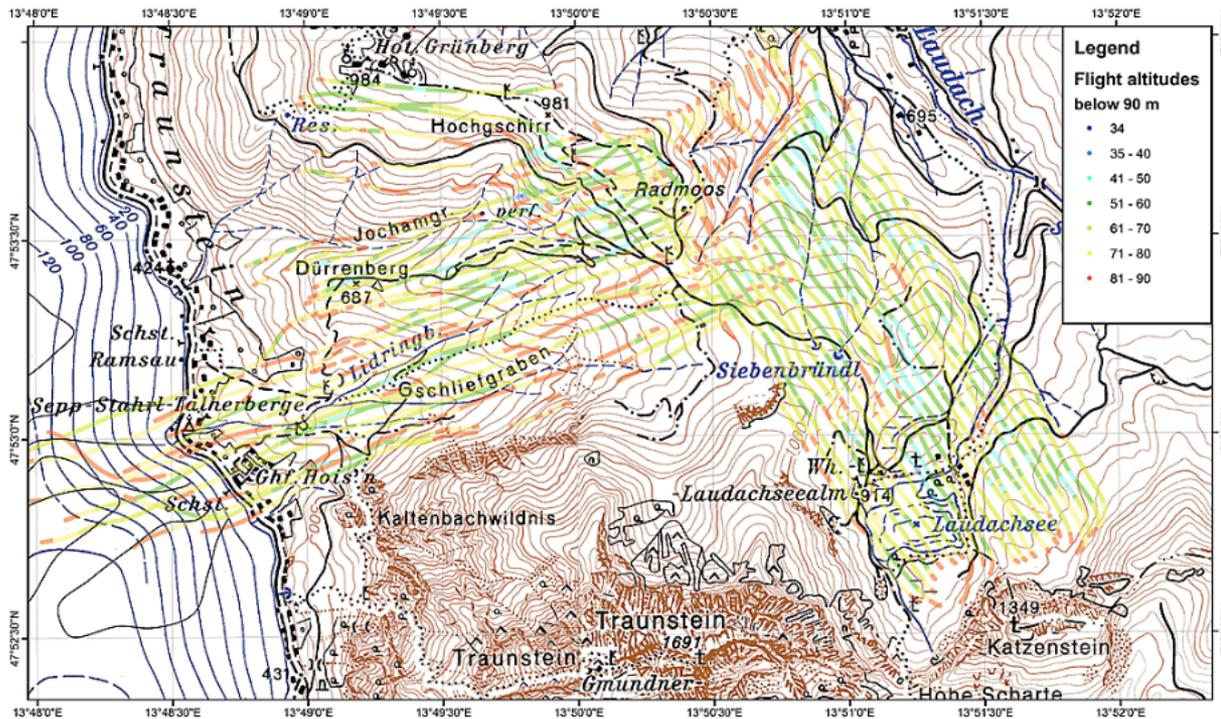


Buntmergelserie  
Low Resistivity  
2 – 30  $\Omega\text{m}$



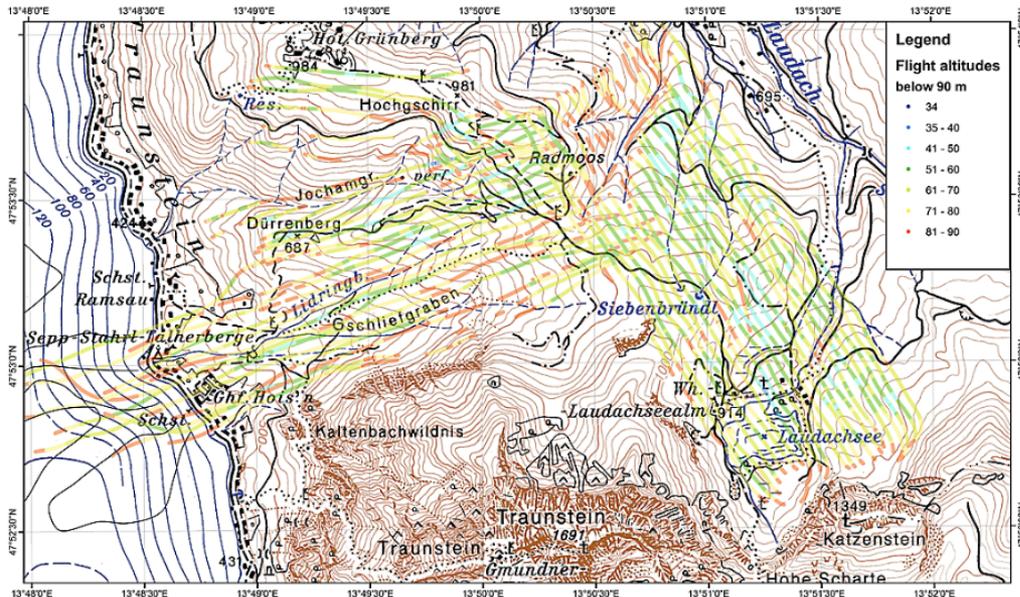
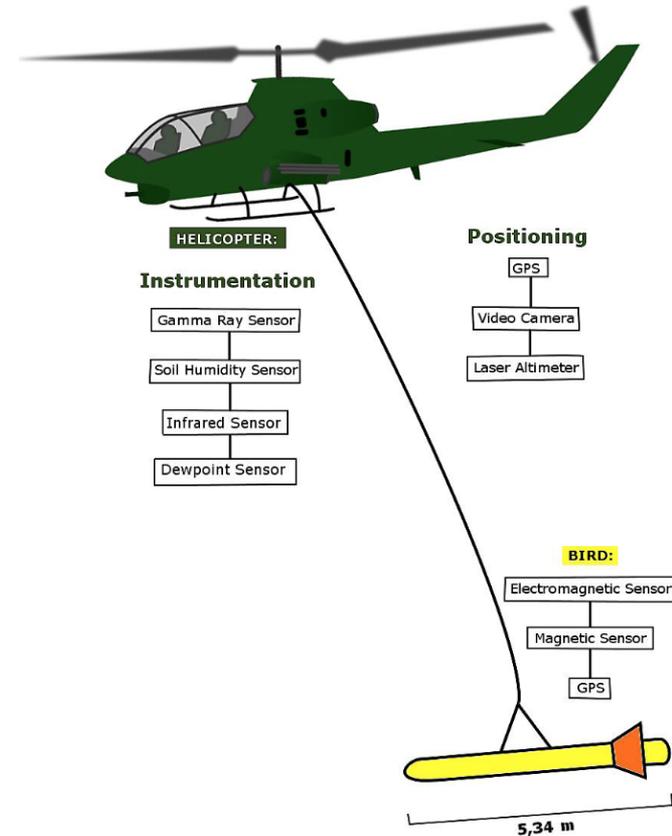
# Survey

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



# Survey: Airborne EM

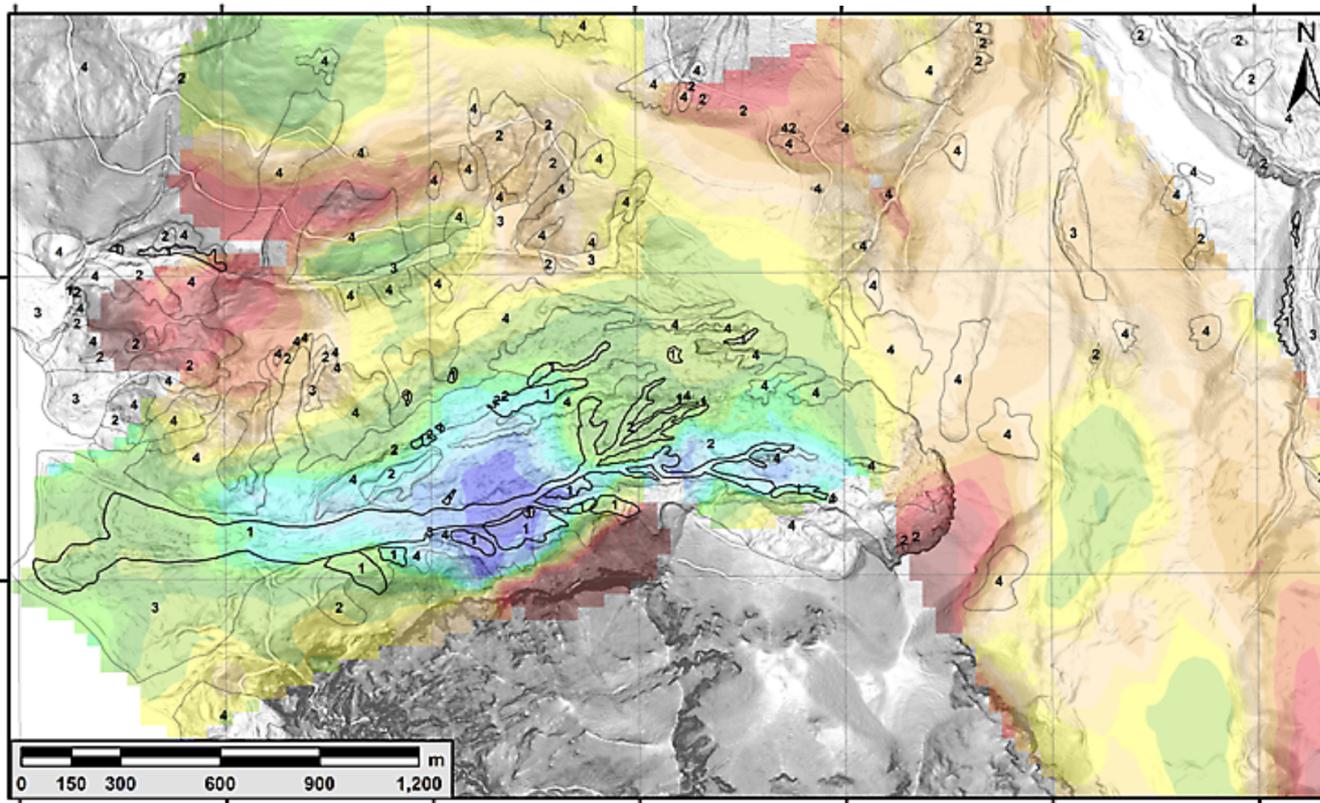
- Frequency domain system
  - Frequencies: 340 Hz, 3200 Hz, 7190 Hz and 28 850 Hz
- Sensor height needs to be  $< 90$  m
- Rough topography  $\rightarrow$  flown only uphill (2x flight time)



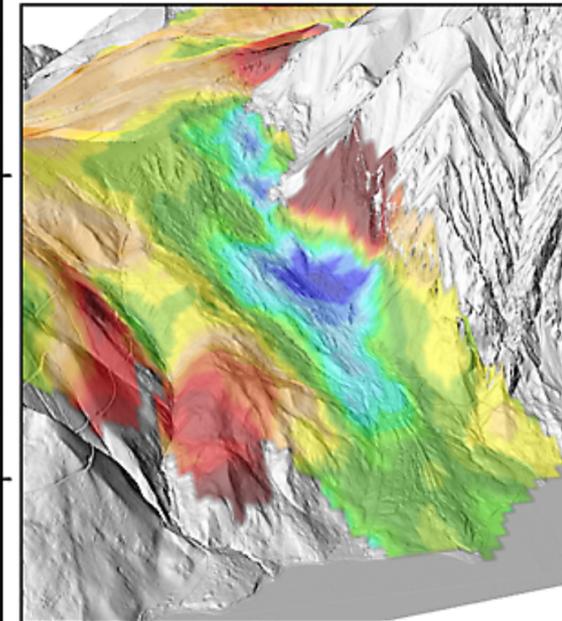
# Data & Processing

- Data inverted in 1D

resistivity 0 – 2m below surface



3D view



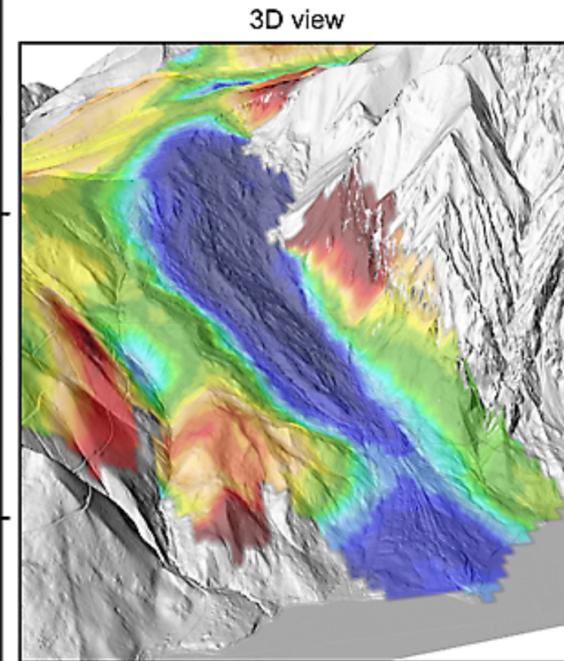
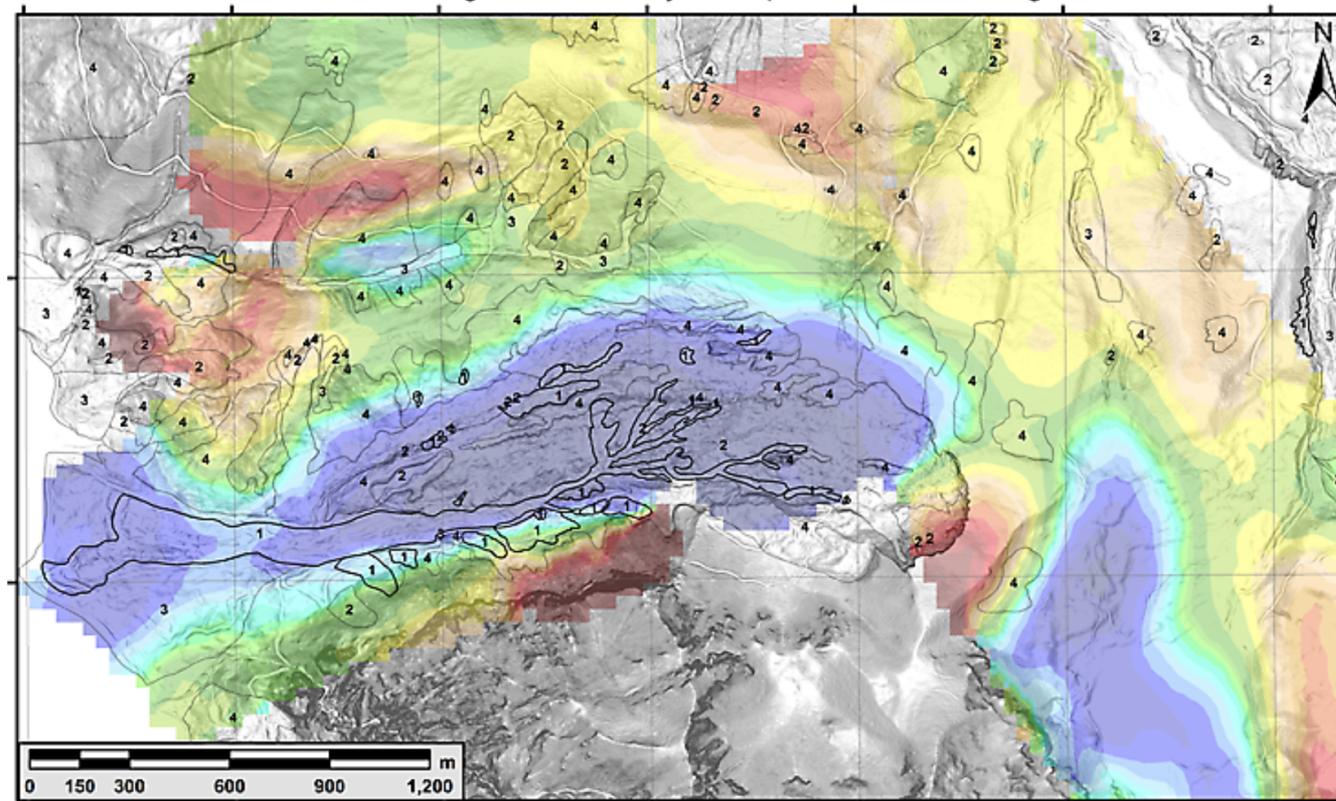
Legend:		Resistivity [Ohmm]:			
2.5 - 5	25.1 - 30	50.1 - 55	120.1 - 135	250.1 - 300	
5.1 - 10	30.1 - 35	55.1 - 60	135.1 - 150	300.1 - 350	
10.1 - 15	35.1 - 40	60.1 - 75	150.1 - 175	350.1 - 500	
15.1 - 20	40.1 - 45	75.1 - 100	175.1 - 200	500.1 - 750	
20.1 - 25	45.1 - 50	100.1 - 120	200.1 - 250	750.1 -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



## Legend:

### Resistivity [Ohmm]:

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

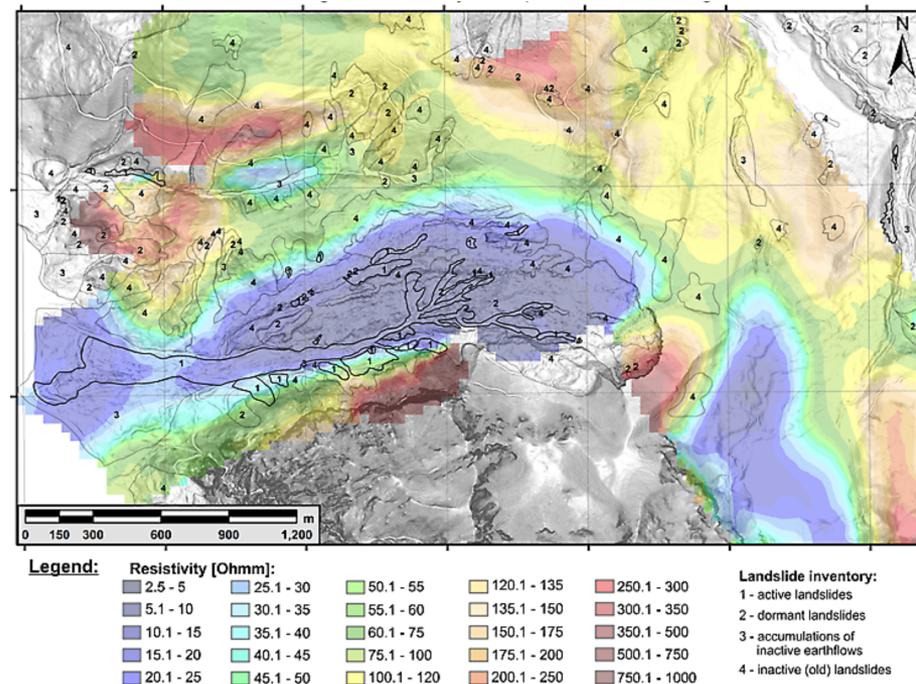
### Landslide inventory:

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

# Interpretation

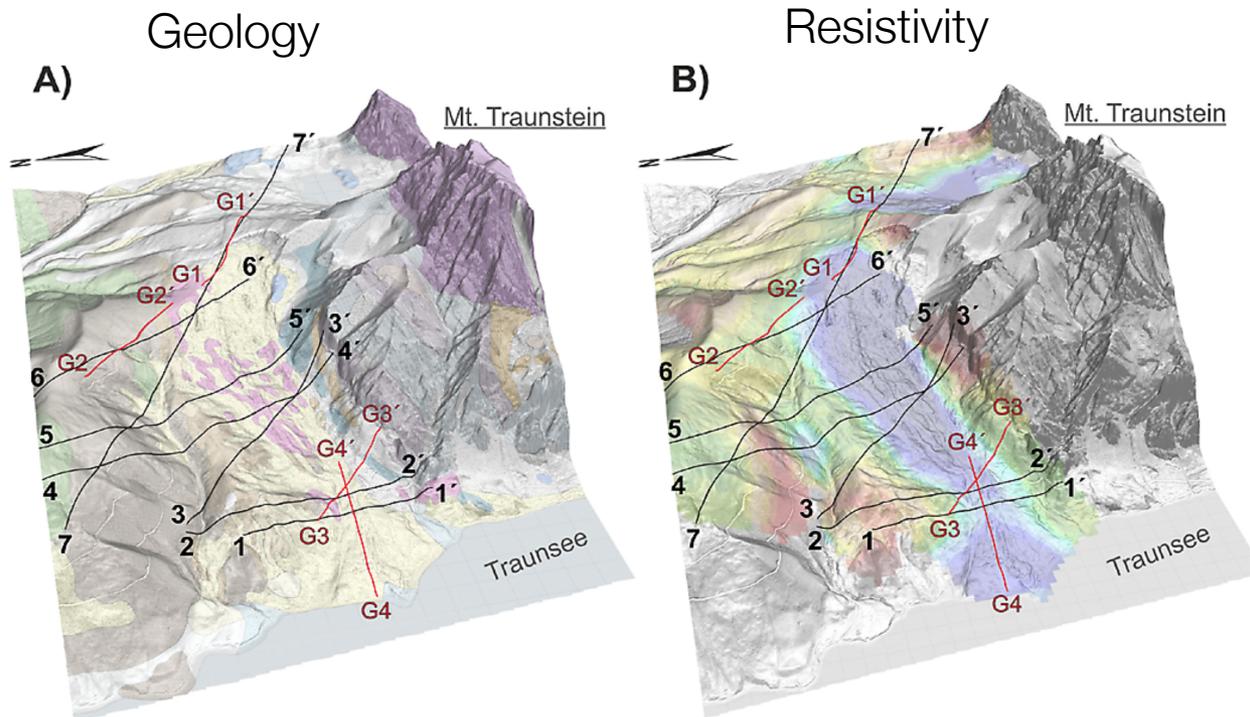
- 2 – 30  $\Omega\text{m}$  contour delineates the Buntmergelserie
  - landslide inventory map shows recent landslides are associated with Buntmergelserie
  - Low resistivities show this is most incompetent unit
- Buntmergelserie: highly tectonised
  - Anti-synclinal fold
  - Strongly west-east dipping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

resistivity 20m below surface



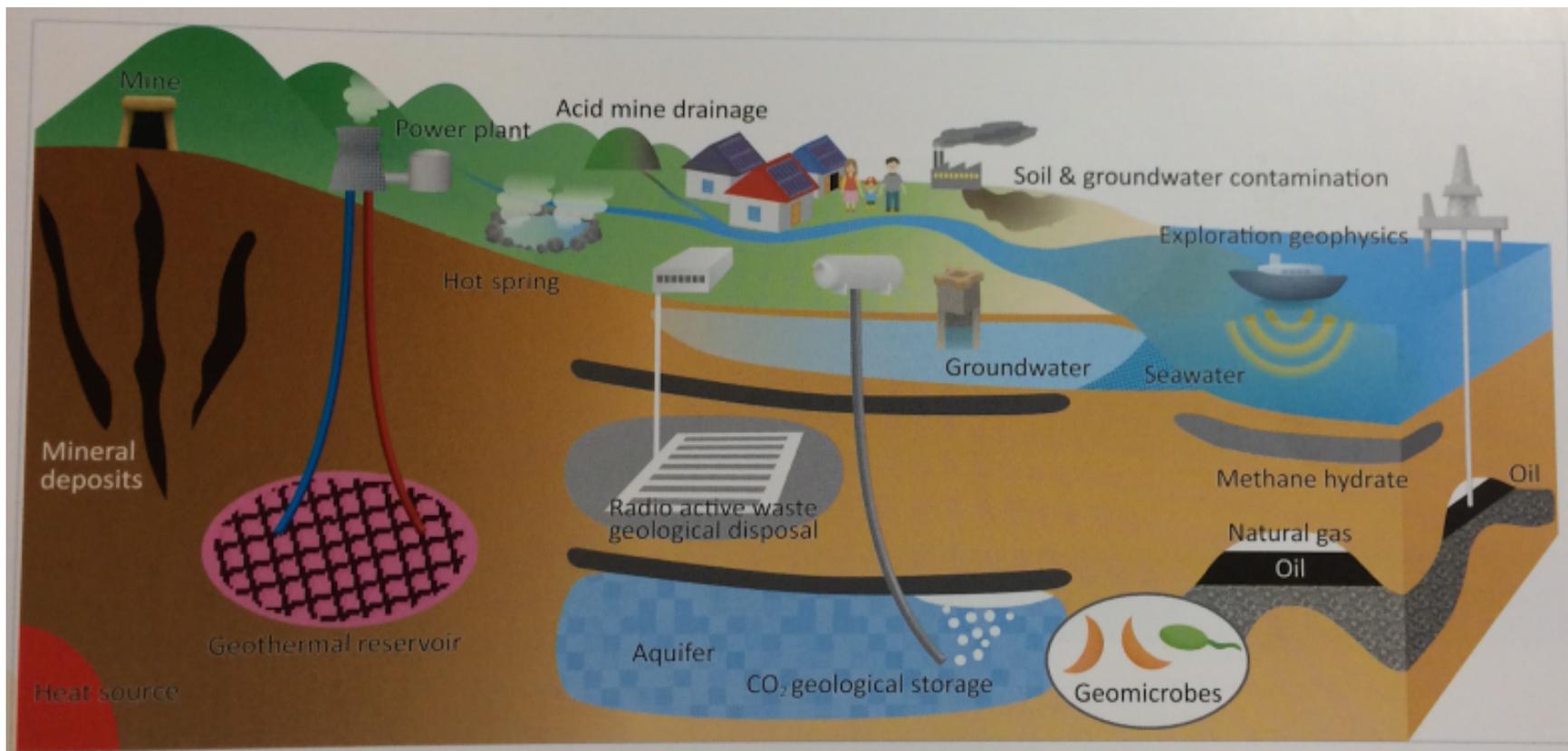
# Synthesis

- 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 Gschlifgraben area



An example from DISC Tokyo

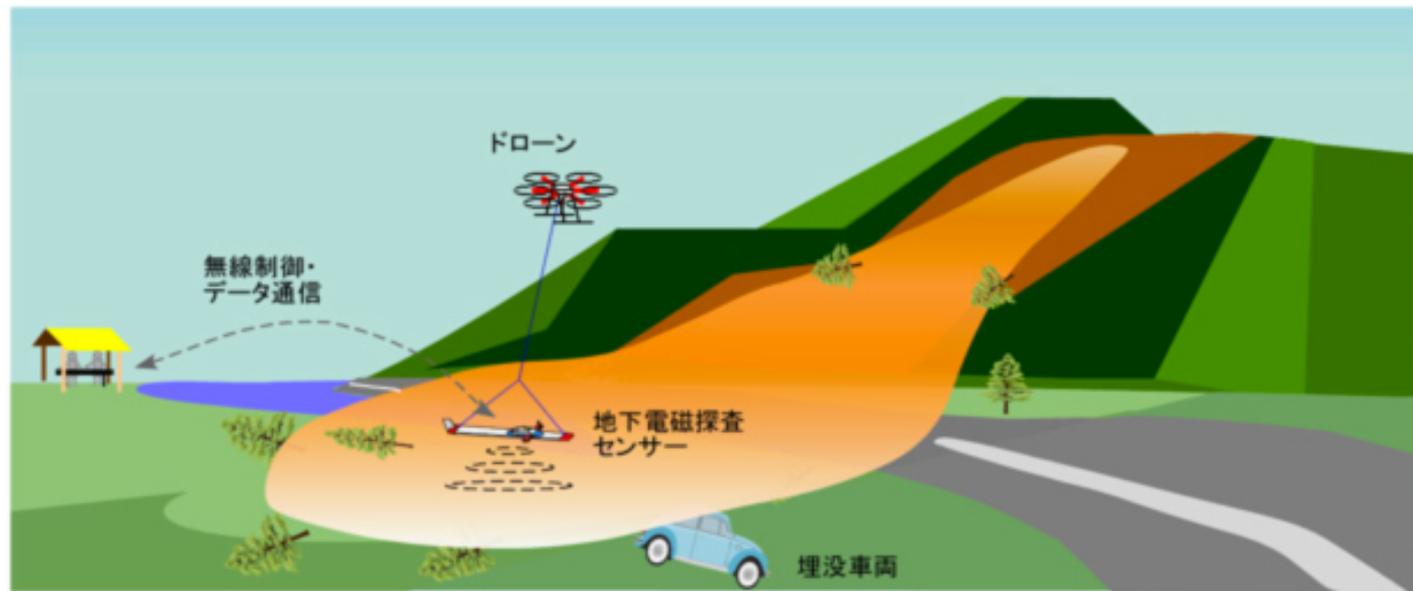
# DISC Tokyo...



# EM Geophysics using Drone Technology: AIST

## Setup:

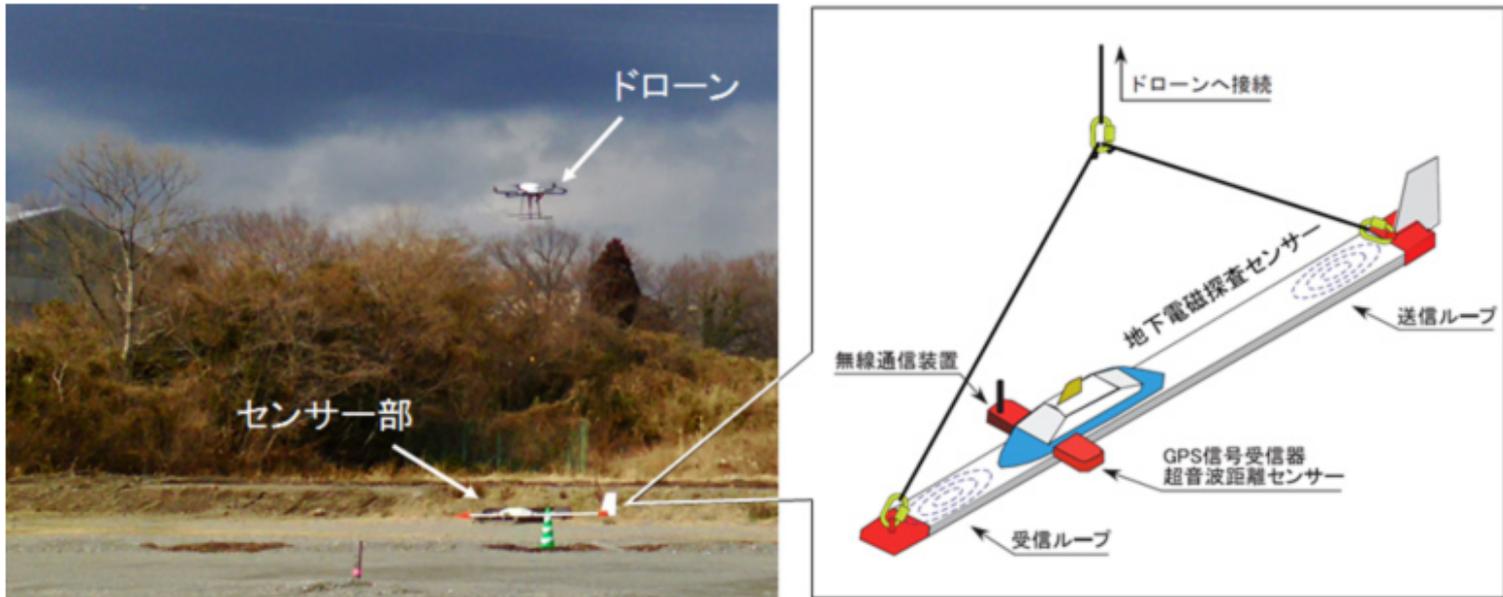
- Develop FDEM system for a drone
- Application: near surface geophysics problems
- Example: find automobiles buried in a landslide



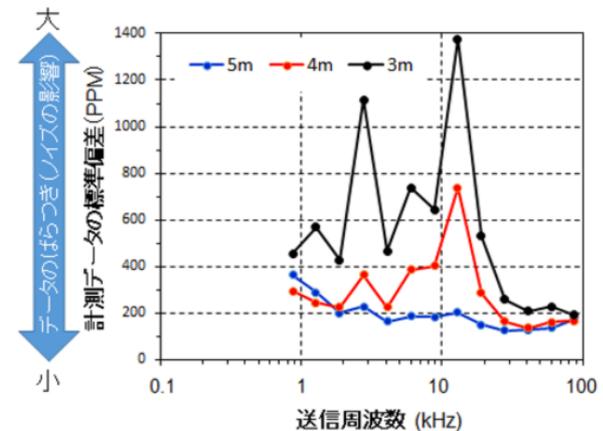
Exploration image of buried vehicles at the site of sediment-related disasters by developed system

# Survey equipment

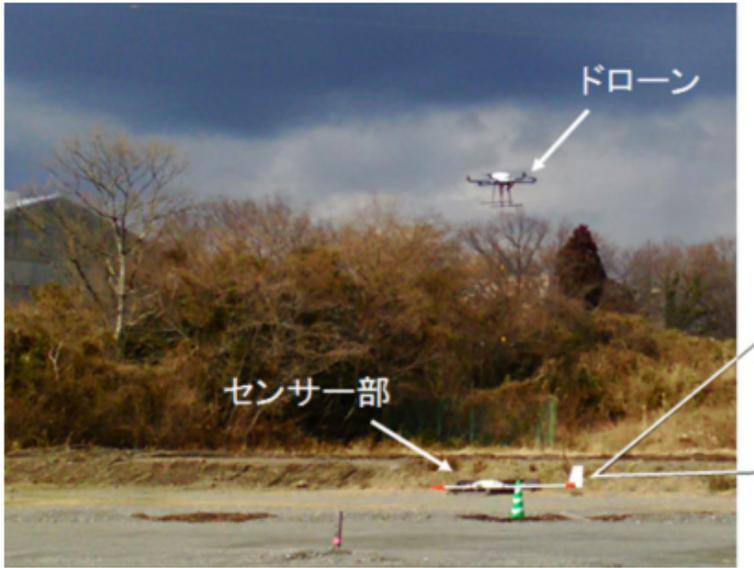
## Drone EM system



- 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

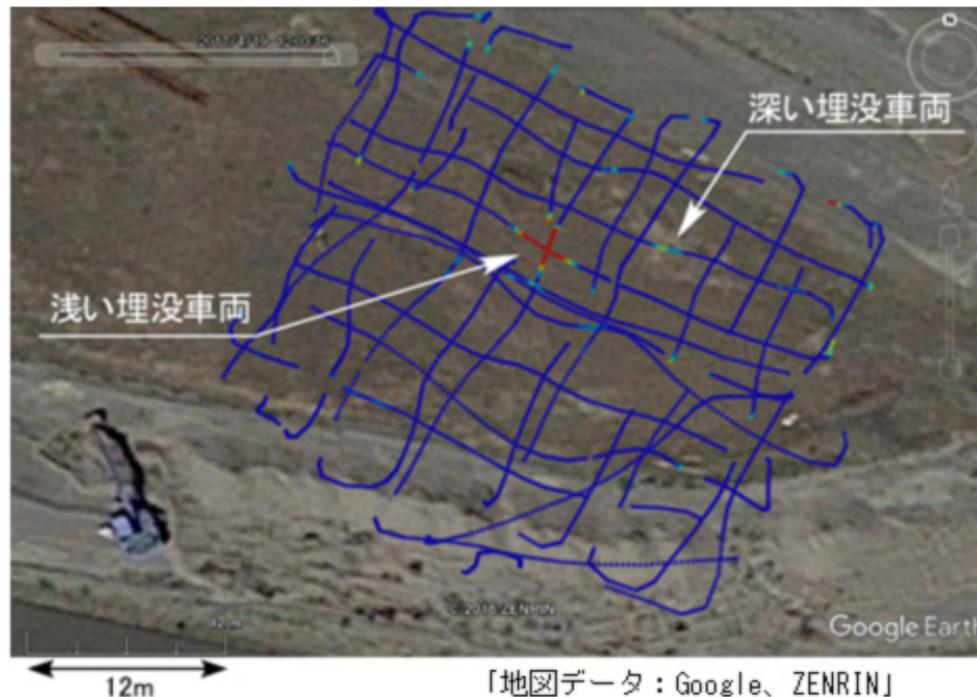


Fig. 6 Exploration data by precision drone navigation measurement (measurement frequency 60 kHz)

# End of Inductive Sources

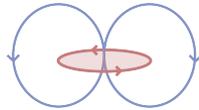
Next up



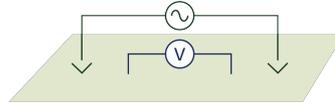
DC Resistivity



EM  
Fundamentals



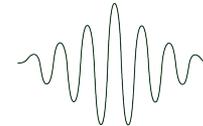
Inductive  
Sources



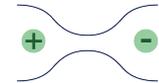
Grounded  
Sources



Natural  
Sources



GPR



Induced  
Polarization



The  
Future

Lunch: Play with apps

# Additional Material

- Tutorial on UXO
- Case Histories:
  - Pole Mountain (UXO)
  - Lalore (Minerals)
  - West Plains (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



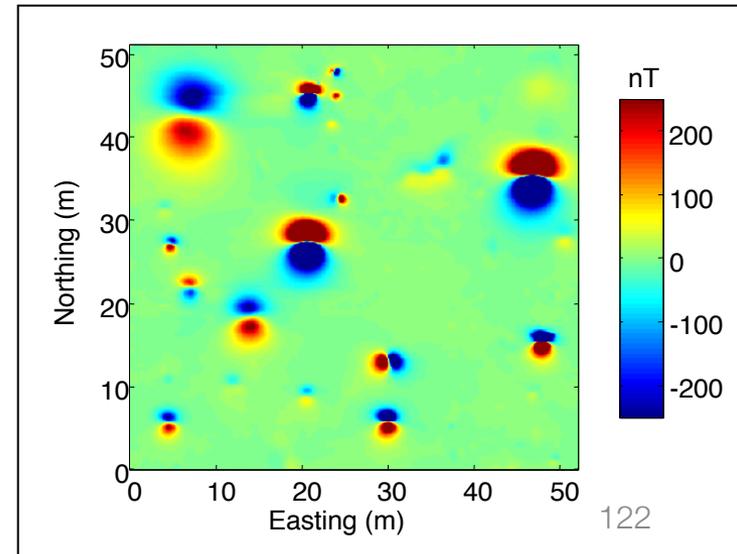
Ferrex



- Digital data
- Look for magnetic dipoles



TM4



# Magnetic Survey: Dig Anomalies



**76mm**

# 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

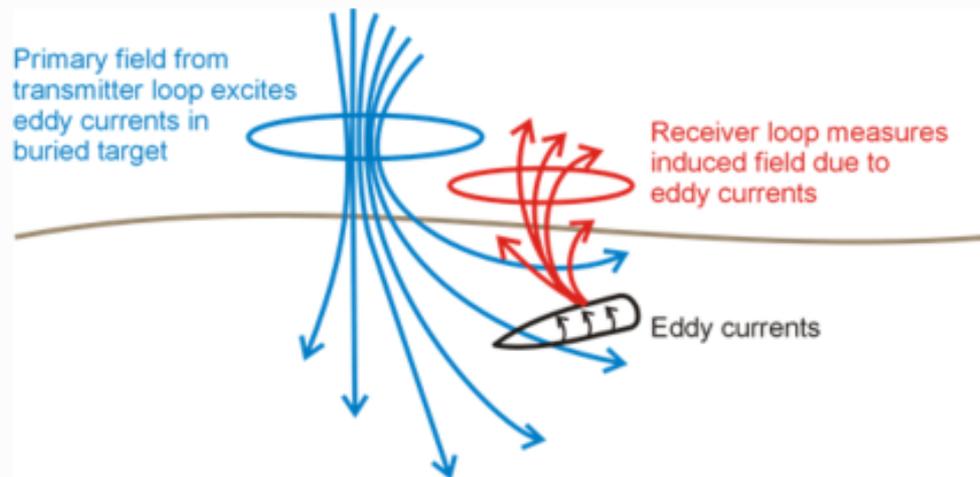
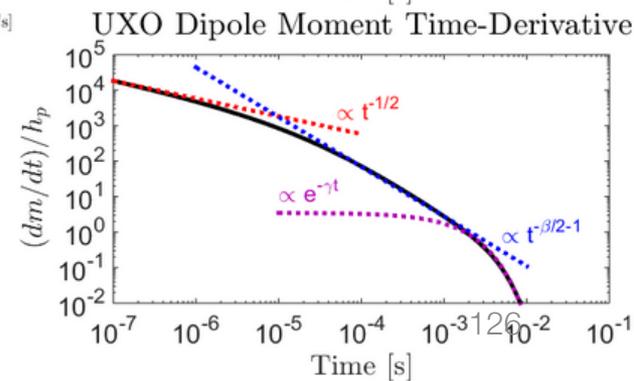
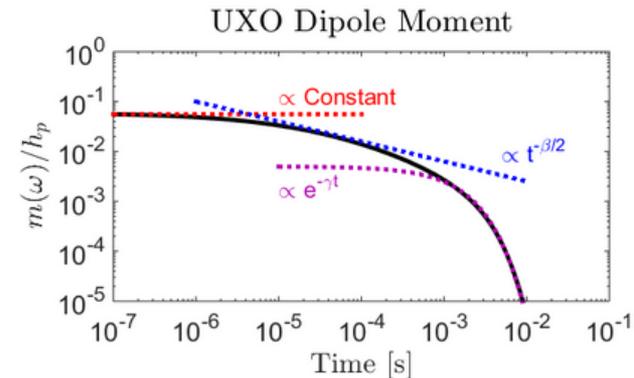
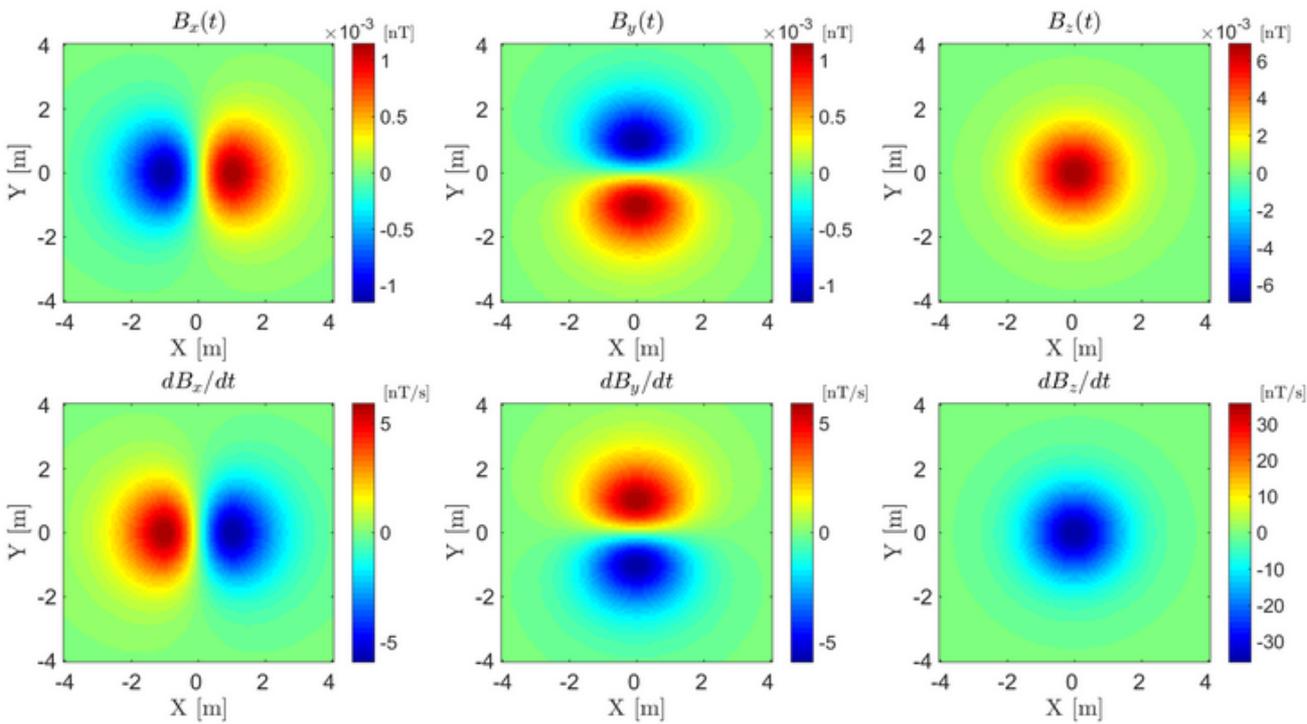


Fig. 260 Electromagnetic induction (EMI) survey for UXO location.



# 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:

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

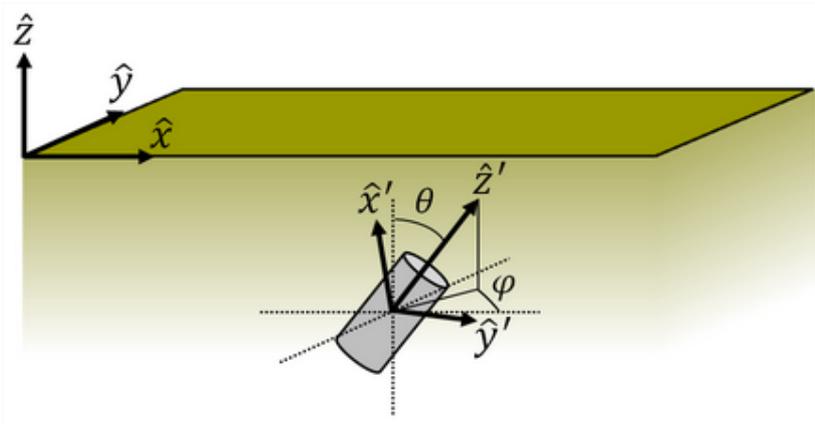
- $\mathbf{m}(t)$  is dipole moment (decays with time)
- $\mathbf{m}(t)$  depends on:
  - Orientation of the inducing field
  - The polarization tensor

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

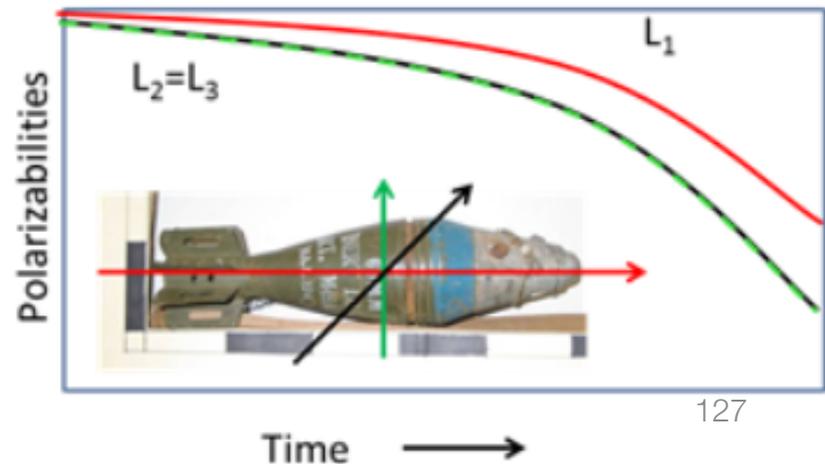
- The polarization tensor  $\mathbf{L}$ :

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

Field and UXO coordinate systems

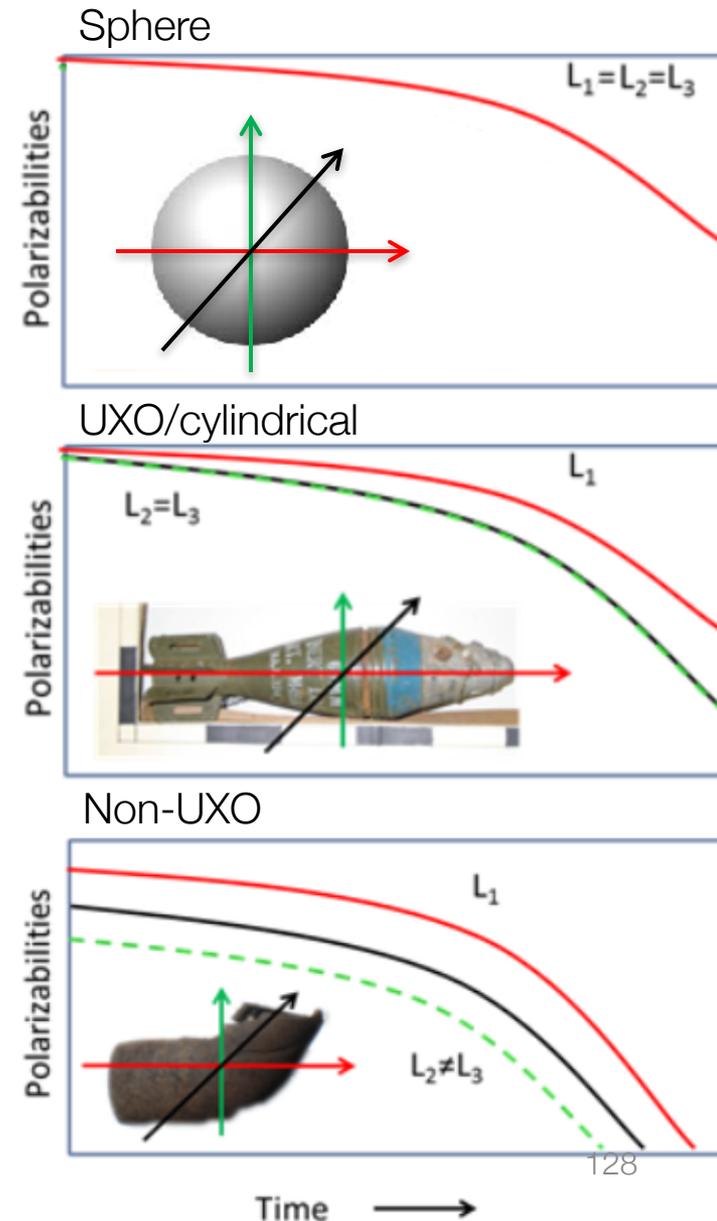


Primary (L1) and secondary (L2,L3) polarizations for UXO



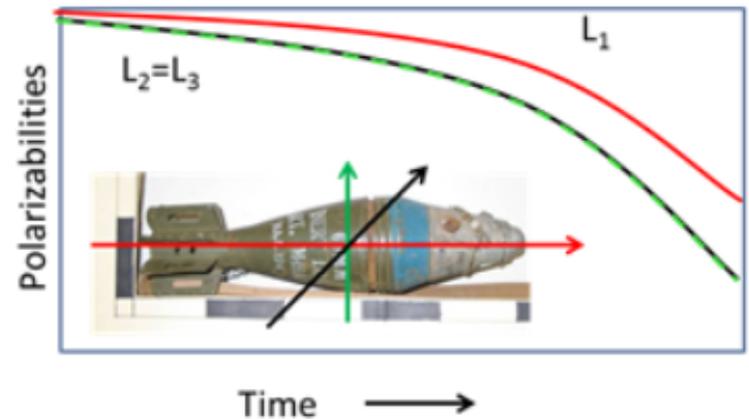
# Objects and Polarization Tensors

- 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

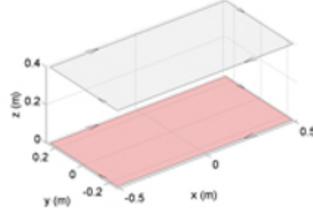


To carry out inversion for polarization tensor need data:

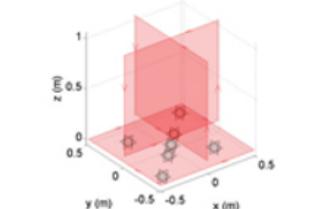
- multiple transmitters (orientations)
- multiple components of data

# Common Systems

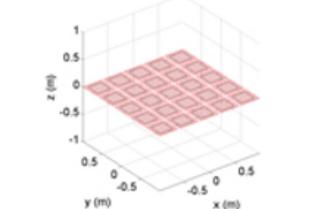
EM-61

Sensor	Geometry	Time channels
<b>EM-61</b> 		$t_{min} = 0.2 \text{ ms}$ $t_{max} = 1.5 \text{ ms}$ $N = 4$

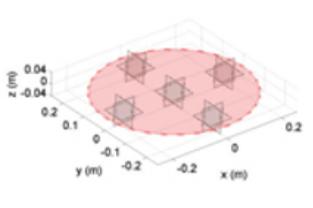
MetalMapper

<b>MetalMapper</b> 		$t_{min} = 0.1 \text{ ms}$ $t_{max} = 10 \text{ ms}$ $N = 42$
---	--	---

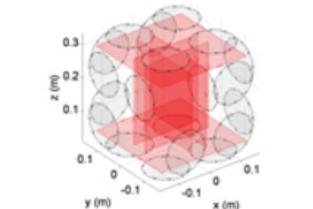
TEMTADS

<b>TEMTADS</b> 		$t_{min} = 0.1 \text{ ms}$ $t_{max} = 20 \text{ ms}$ $N = 115$
---	--	--

MPV

<b>MPV</b> 		$t_{min} = 0.1 \text{ ms}$ $t_{max} = 20 \text{ ms}$ $N = 32$
--	---	---

BUD

<b>BUD</b> 		$t_{min} = 0.1 \text{ ms}$ $t_{max} = 1.5 \text{ ms}$ $N = 45$
---	--	--

# 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

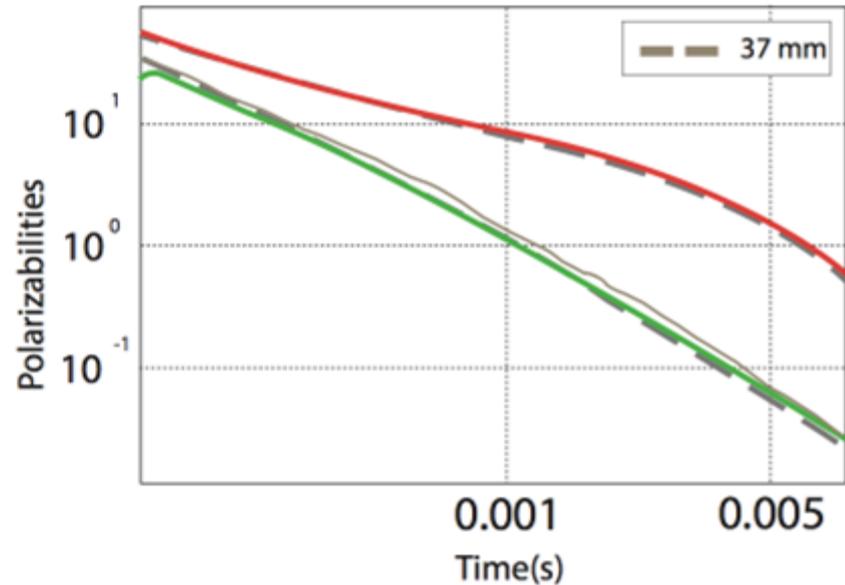
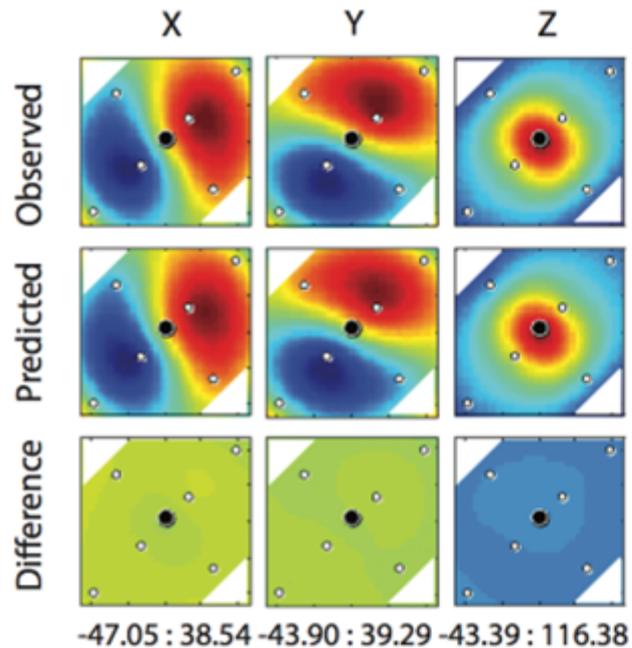
- To recover polarization tensor, target must be polarized from as many angles as possible.
- May require multiple passes with single transmitter or use of multi-transmitter system.

## Time Channels

- Sufficient time-channels required to characterize decay behaviour.



# Example: Metal Mapper Data

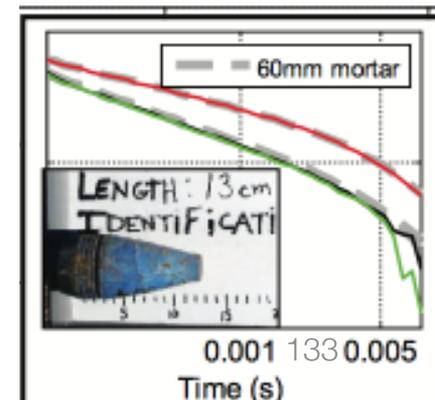
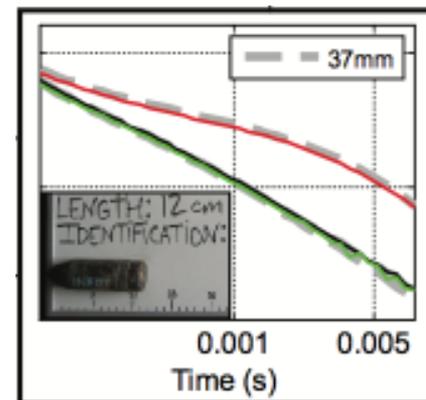
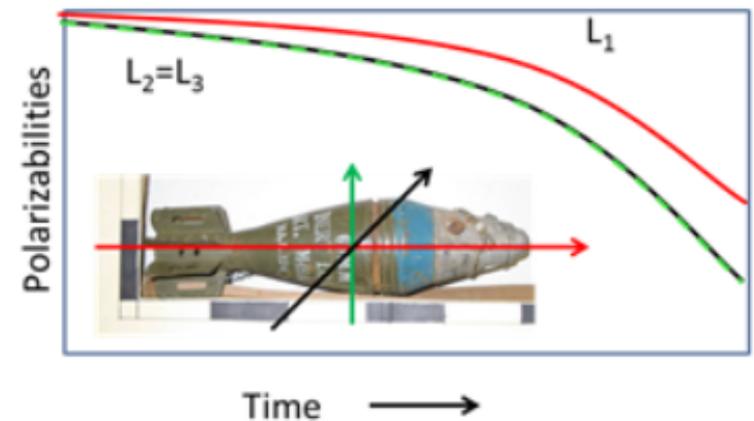
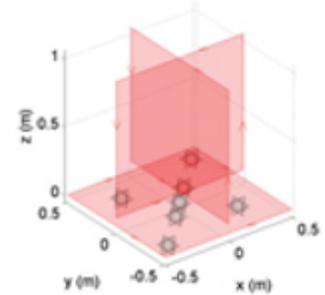


- Polarizations indicate a cylindrical object
- Predicted data using recovered polarization tensor fits the observed data
- Recovered polarizations match those of a 37 mm projectile

# Summary

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

MetalMapper



# Field Example: Pole Mountain

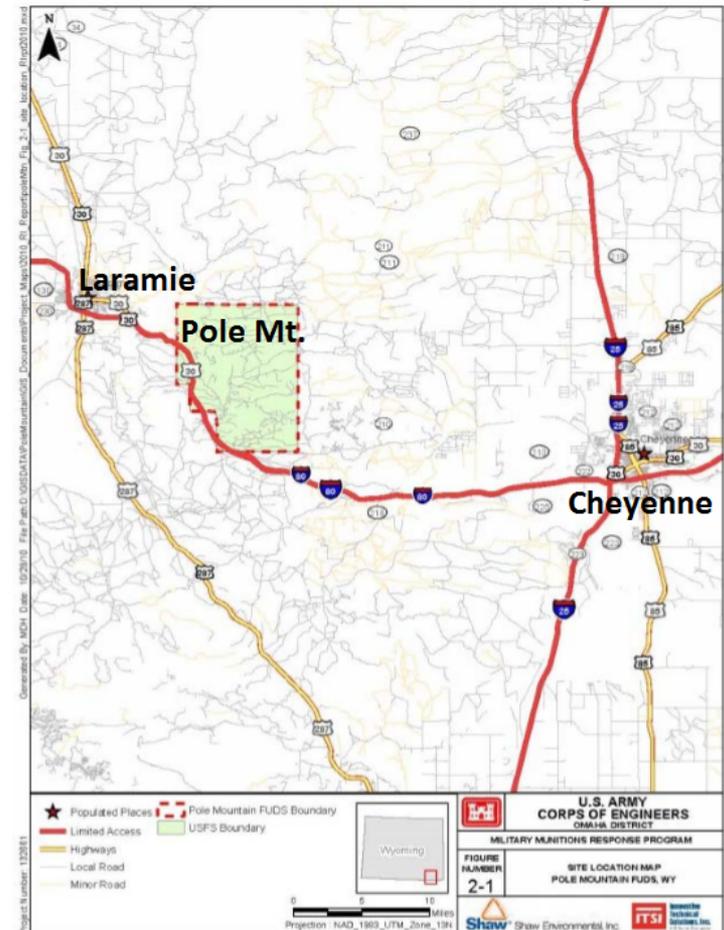
## History

- 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)

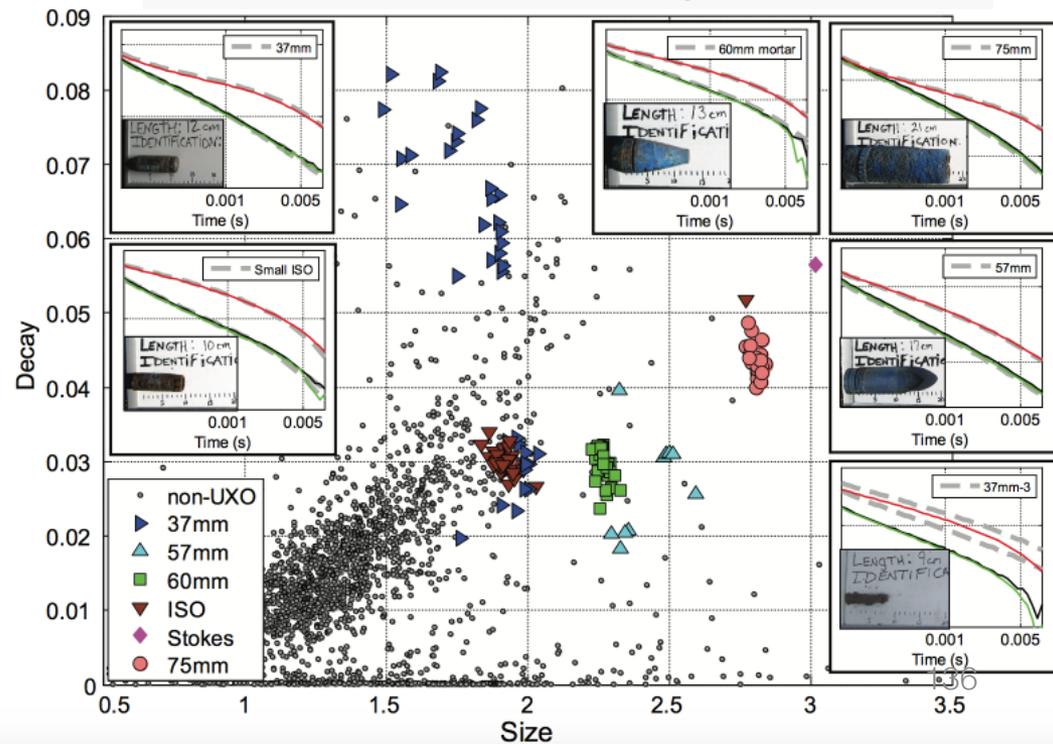
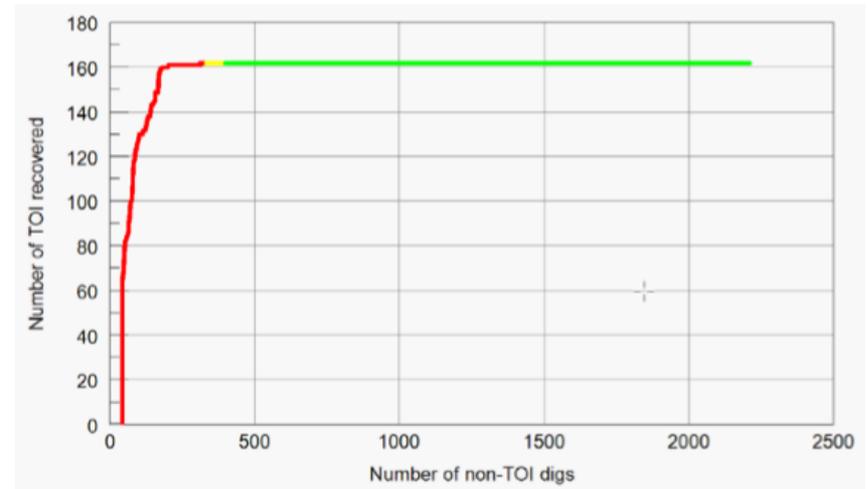


Metal Mapper (cued interrogation)



# 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.



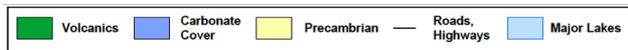
# Case History: HeliSAM at Lalore

Yang & Oldenburg, 2016

# Setup

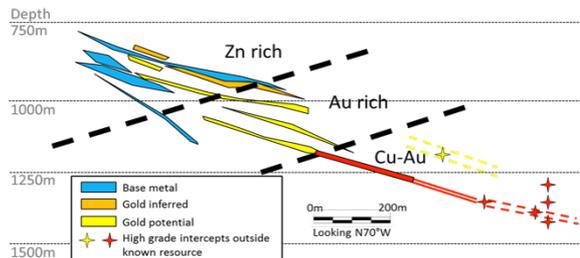
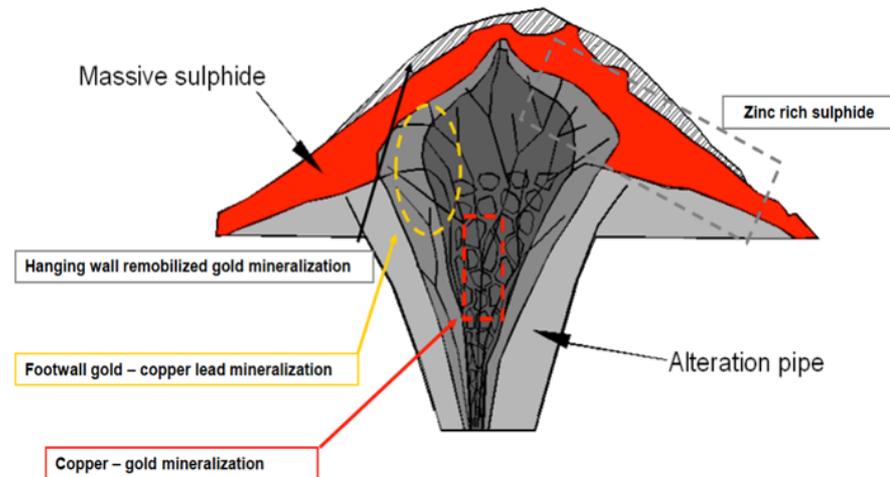
## Geological framework

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



HUBBAY  
MINERALS INC

## Typical cross-section

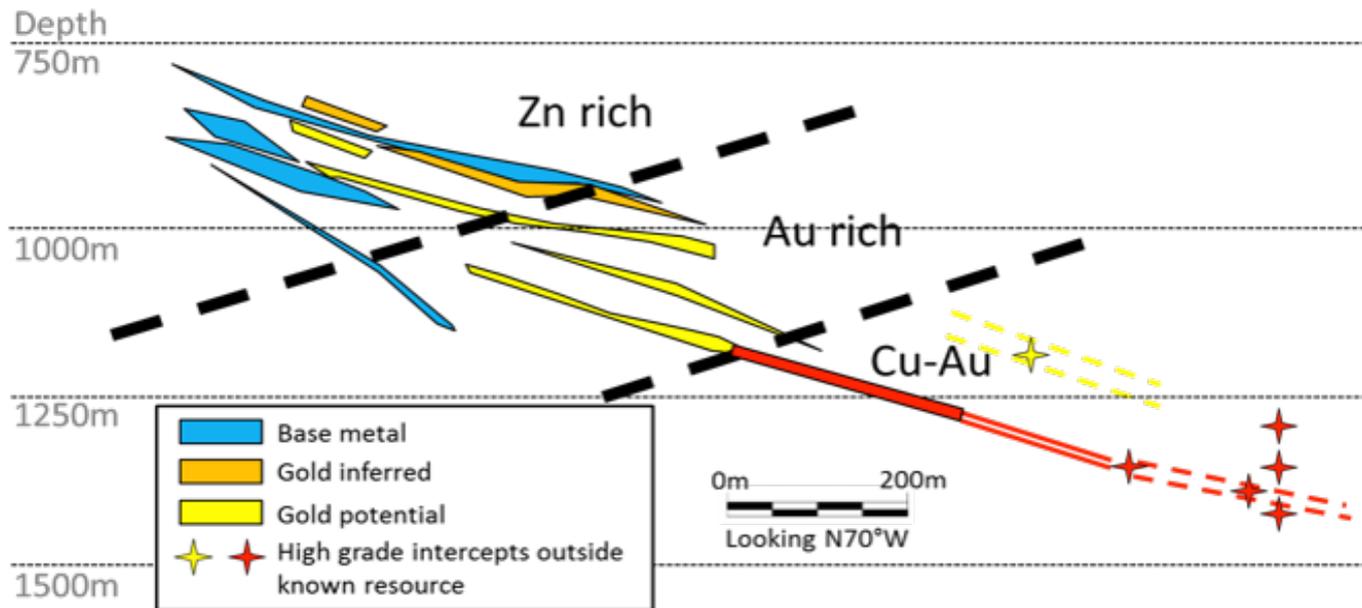


## Goal:

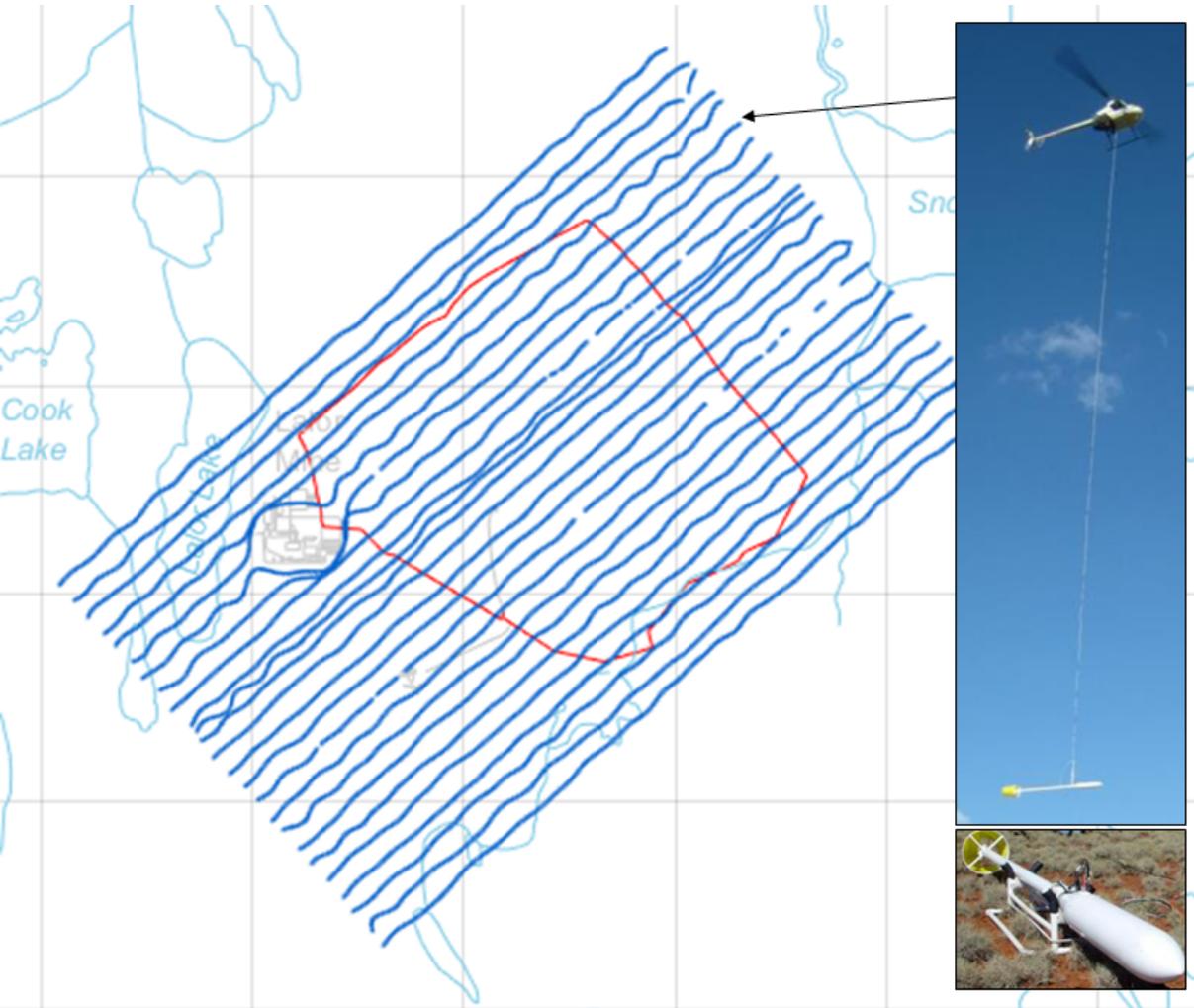
- Find deposits
- TDEM to find deeper off-hole targets

# Properties

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

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

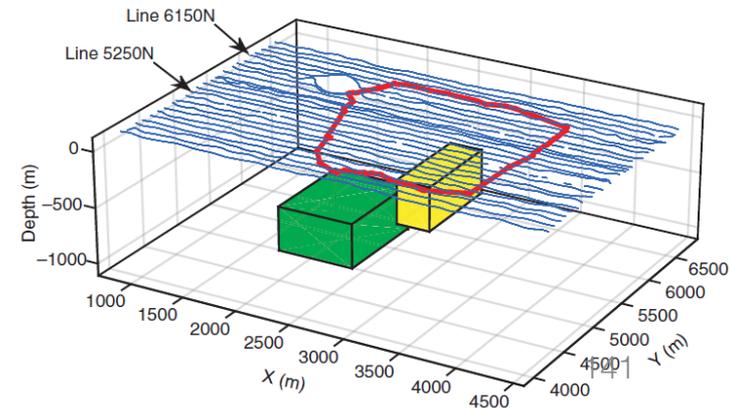
earth's magnetic field      anomalous earth's field      induced EM field

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

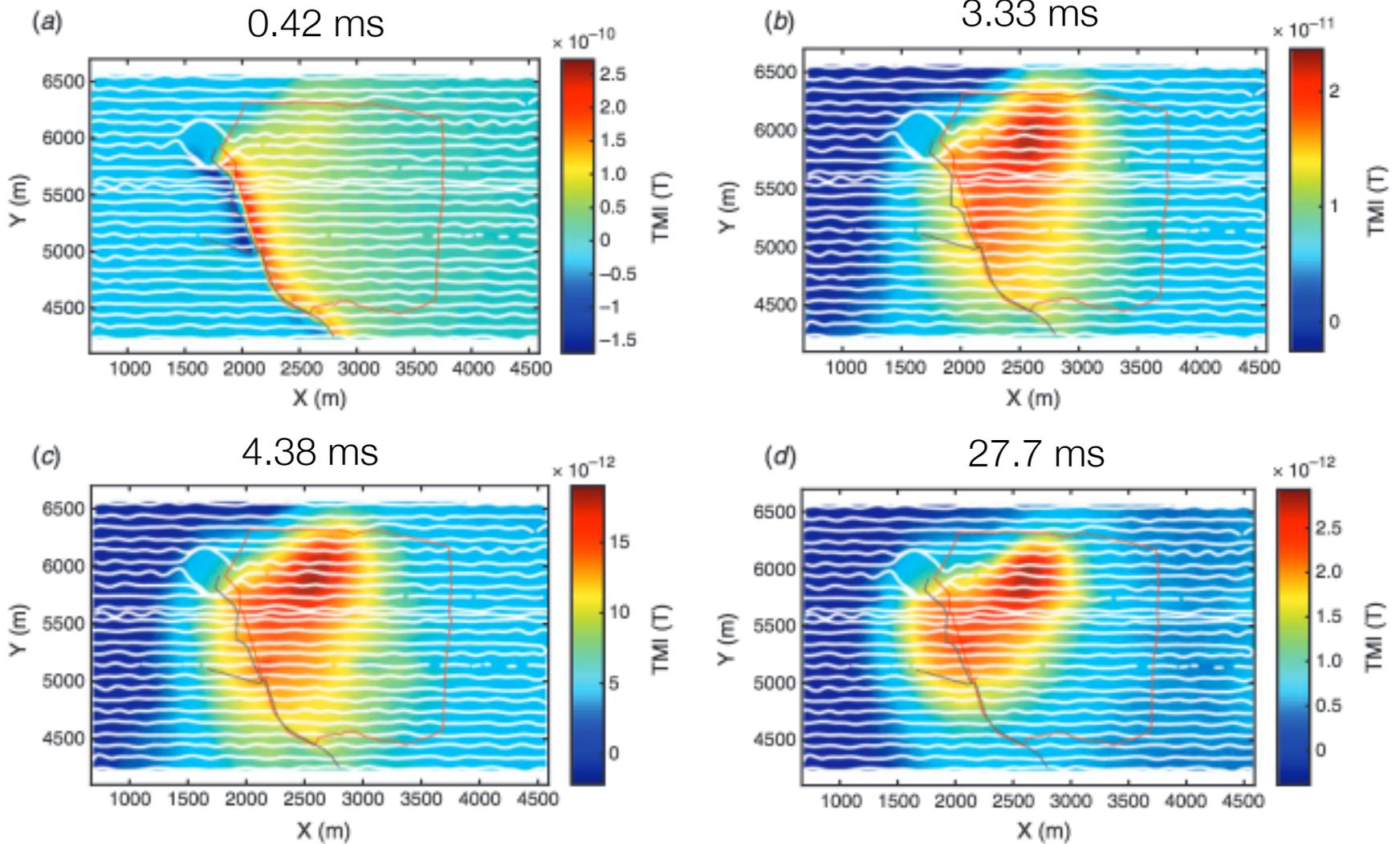
$$\begin{aligned}\Delta|\mathbf{B}| &= |\mathbf{B}_0 + \mathbf{B}_a + \mathbf{B}_{em}| - |\mathbf{B}_0| \\ &\approx (\mathbf{B}_a + \mathbf{B}_{em}) \cdot \hat{\mathbf{B}}_0\end{aligned}$$

- Change polarity on TX
- Subtract to obtain HeliSAM data

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

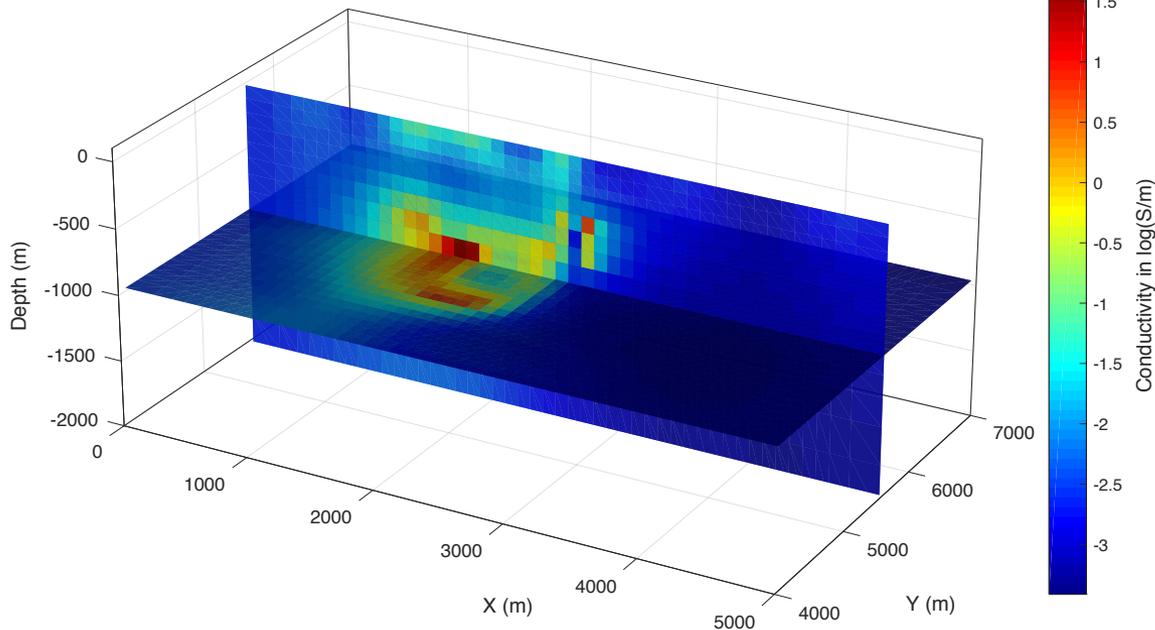
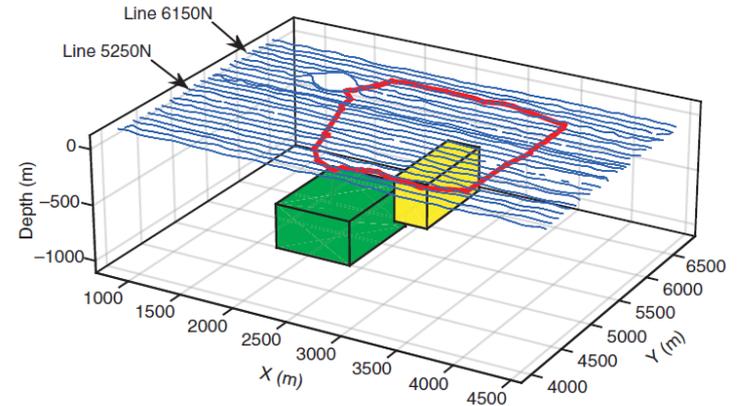


# Data



# Processing: Inversion of Late Time Data

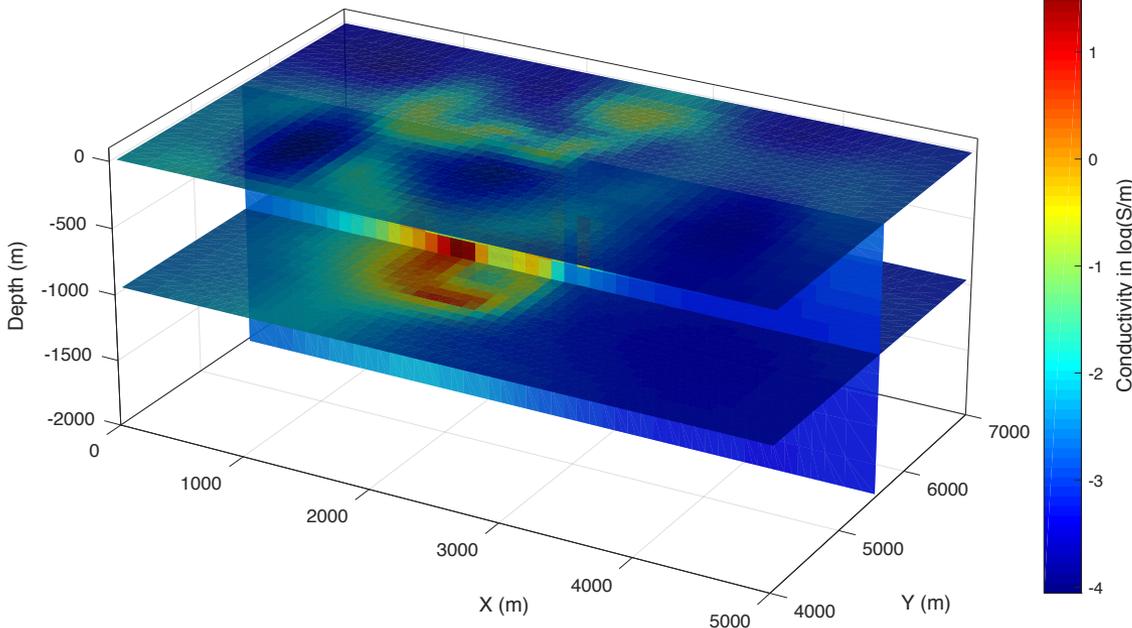
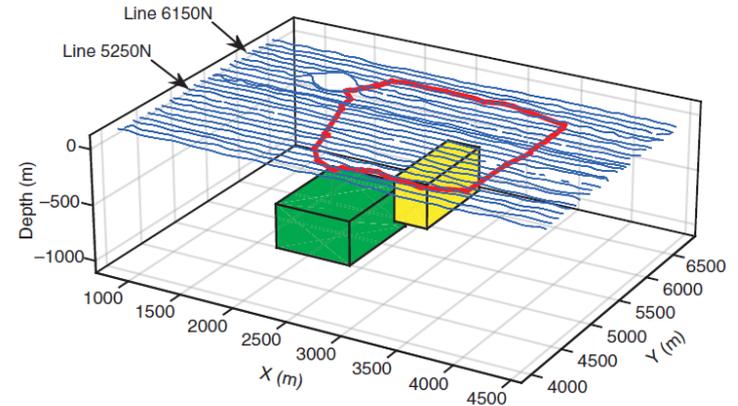
- Discard early time data
  - Contaminated by infrastructure
- Invert Time Ch 8-16 (4.44-28 ms)
- Inversion needs a “warm start”
  - Maxwell used to generate 2 prisms



- Image deep structure

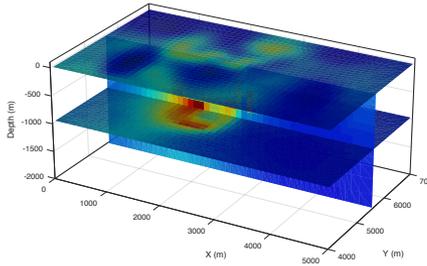
# Processing: Inversion of Late Time Data

- 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



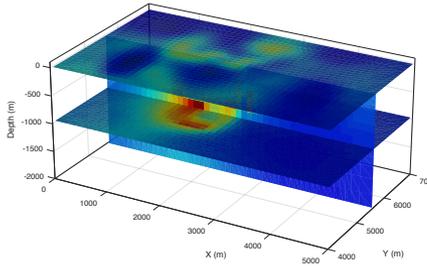
- Image deep structure
- See near surface conductive features

# Processing: Inversion of Early Time Data



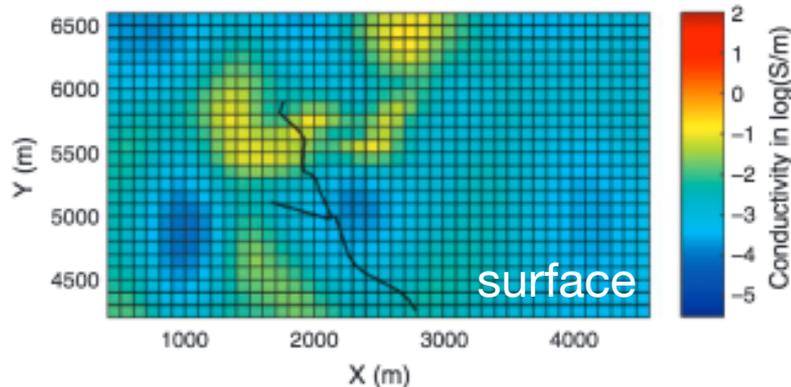
- Late-time inversion sees deep structure
- Some conductive features near surface
- **What is the effect of throwing away the early time data?**

# Processing: Inversion of Early Time Data



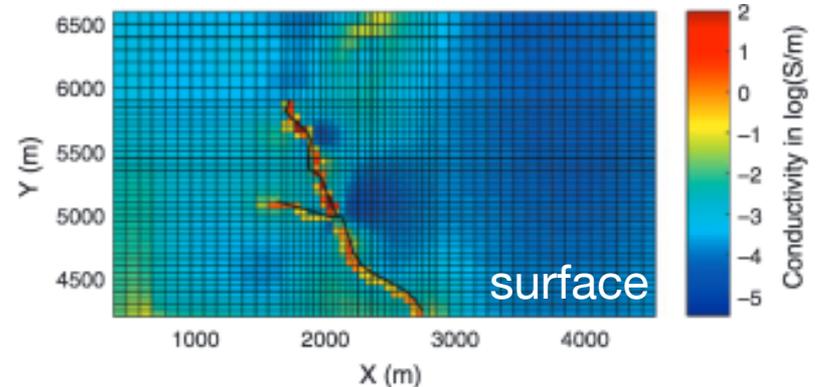
- Late-time inversion sees deep structure
- Some conductive features near surface
- **What is the effect of throwing away the early time data?**

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]

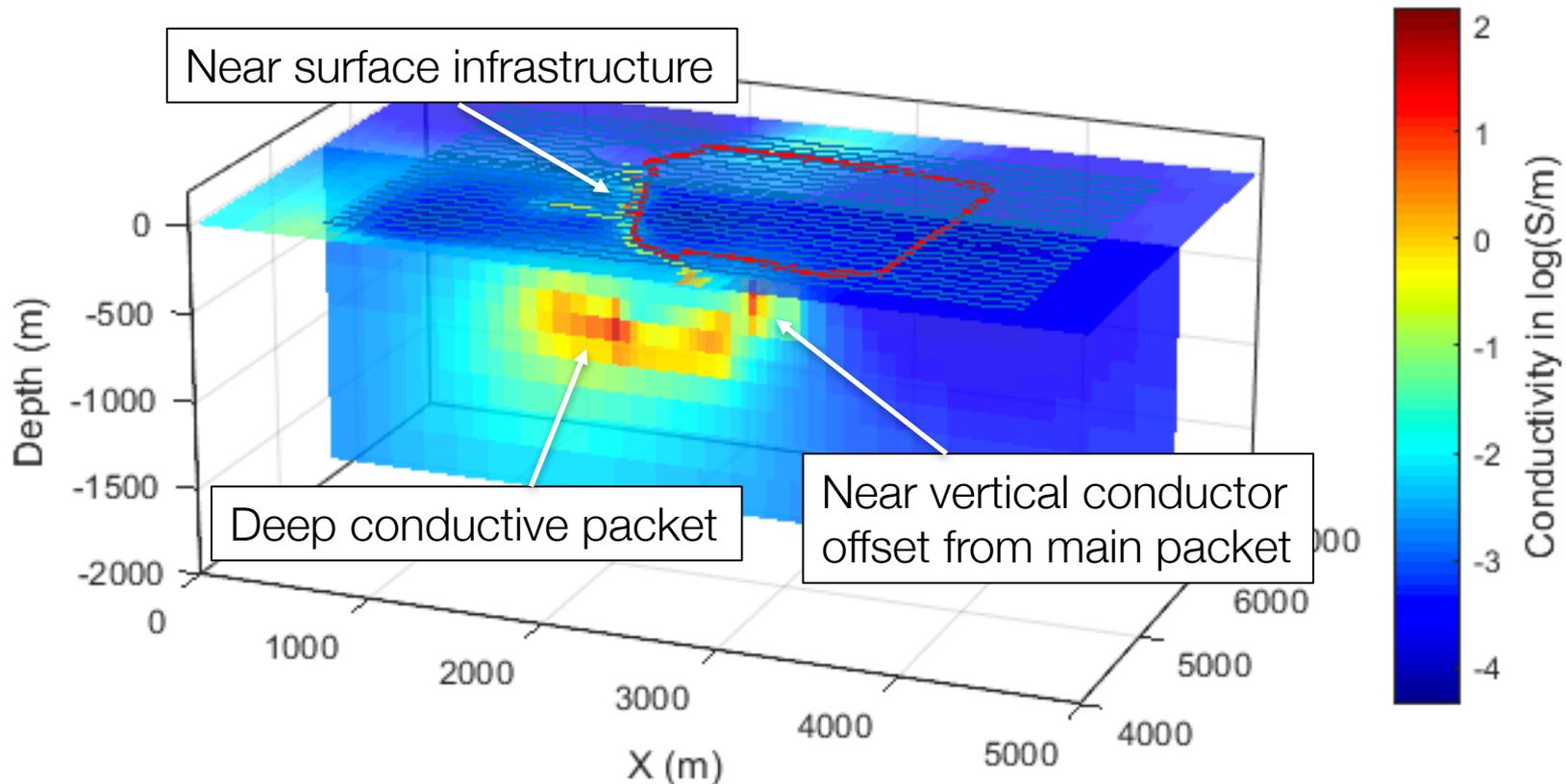


- information about infrastructure and near-surface conductivity

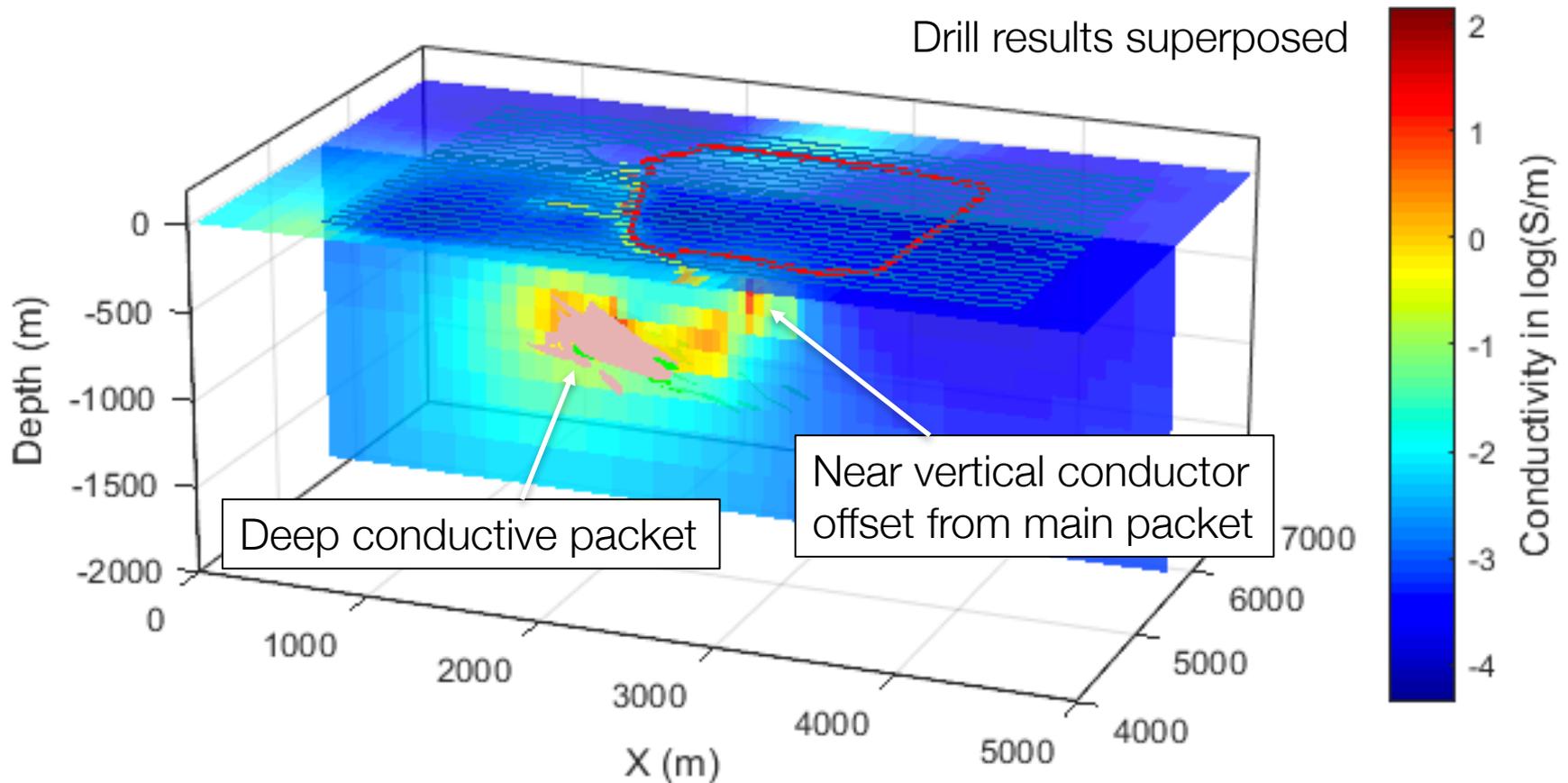
# Processing: Inversion of all time channels

Starting and reference model:

- High conductivity from early time inversion
- Two conductive blocks

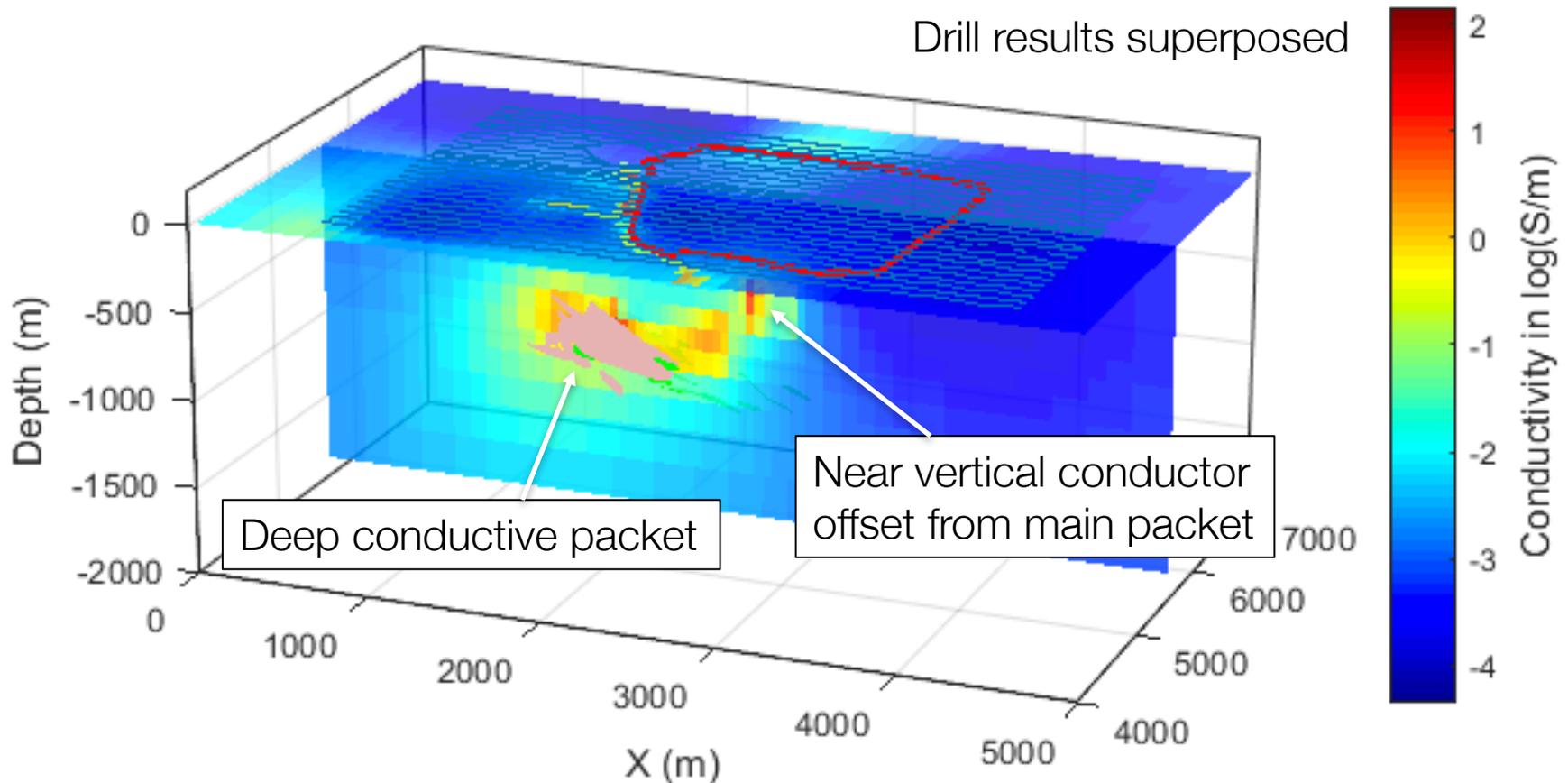


# Synthesis



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

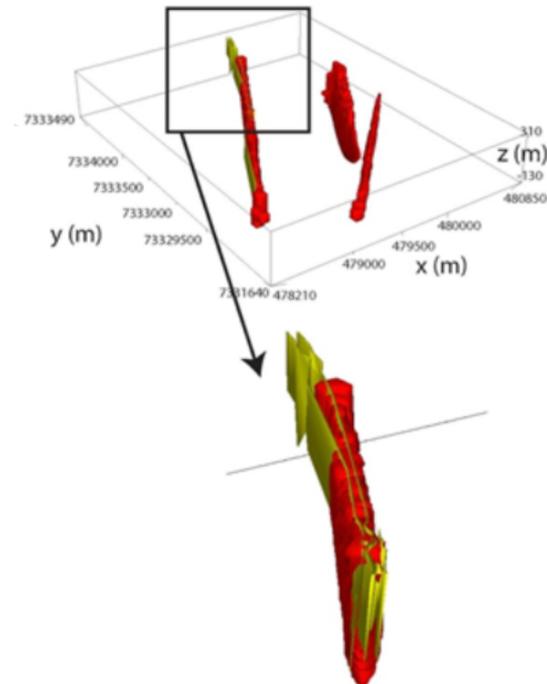
# Takeaways



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

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

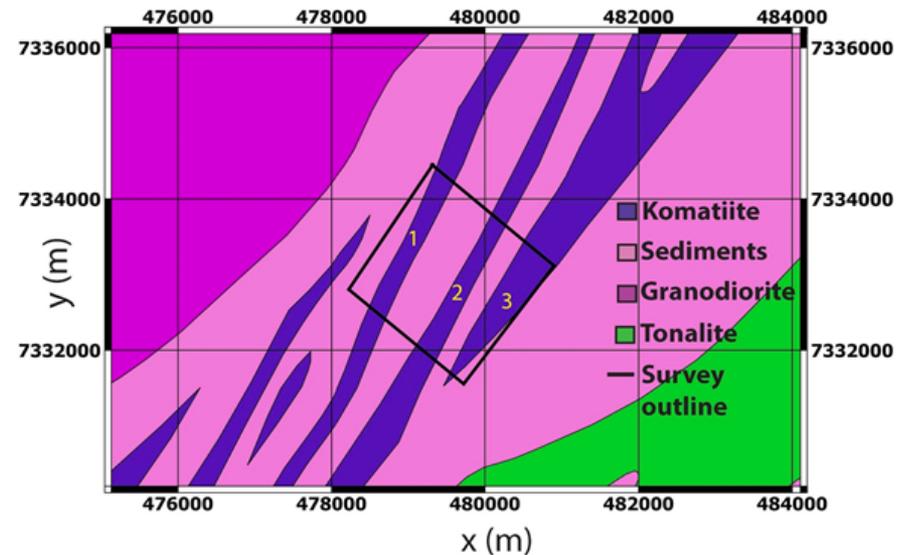
McMillan et al, 2014



# Setup



Geology map

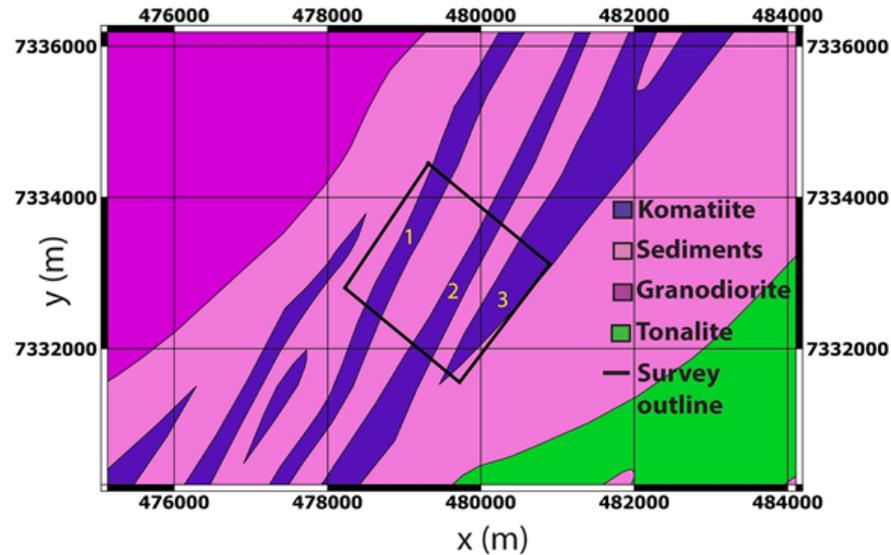


- Ultramafic komatiite units
  - steeply dipping
  - gold mineralization
- Area covered by thin layer of glacial material (outcrops scarce)
- Geology map from regional mag. survey
  - Low resolution; No dip information about the komatiite units

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

# Properties

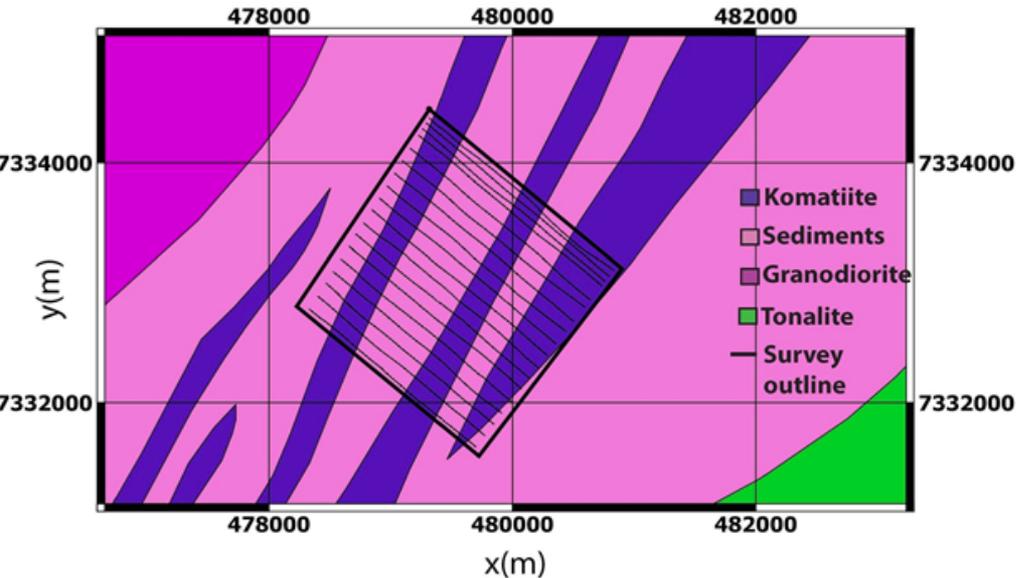
Geology map



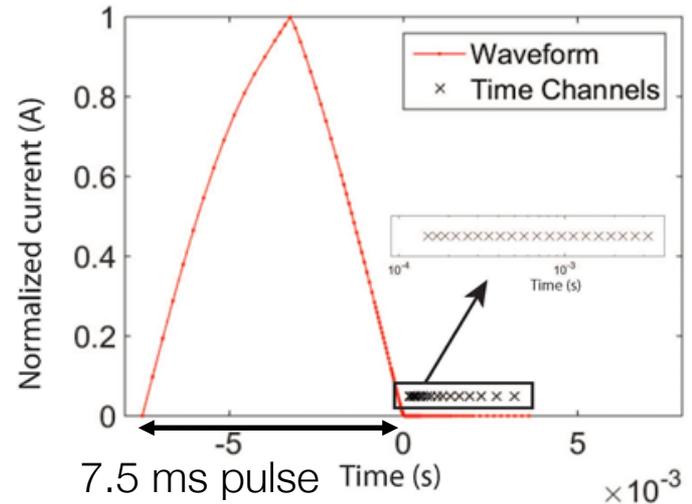
Units	Conductivity	Susceptibility
Komatiite	High	Moderate
Sediments	Moderate	Low
Granodiorite	Low	Low-Moderate
Tonalite	Low	Low-Moderate

# Survey: VTEM

Survey lines



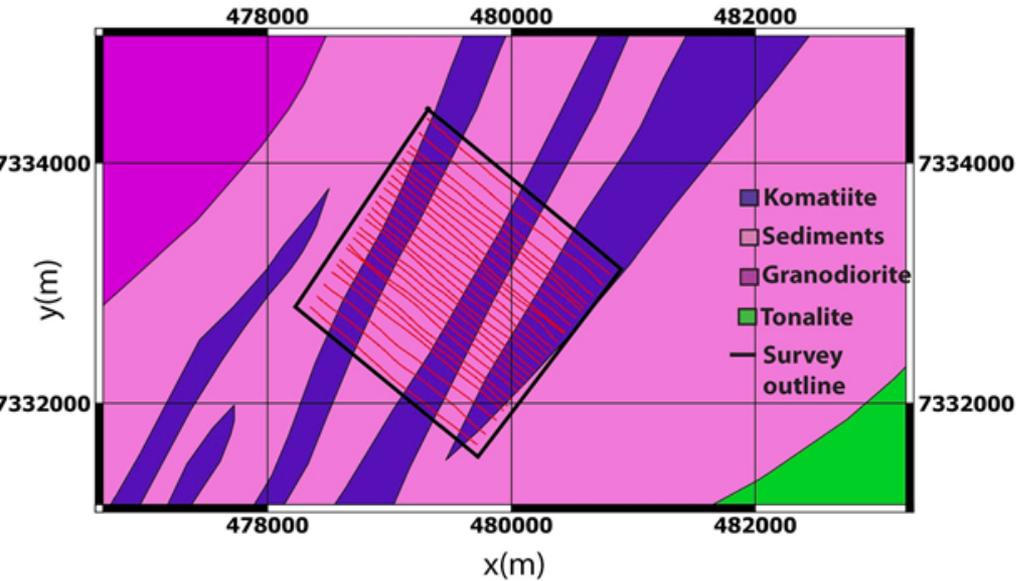
Current waveform



- 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  $\mu$ s)

# Survey: RESOLVE

Survey lines

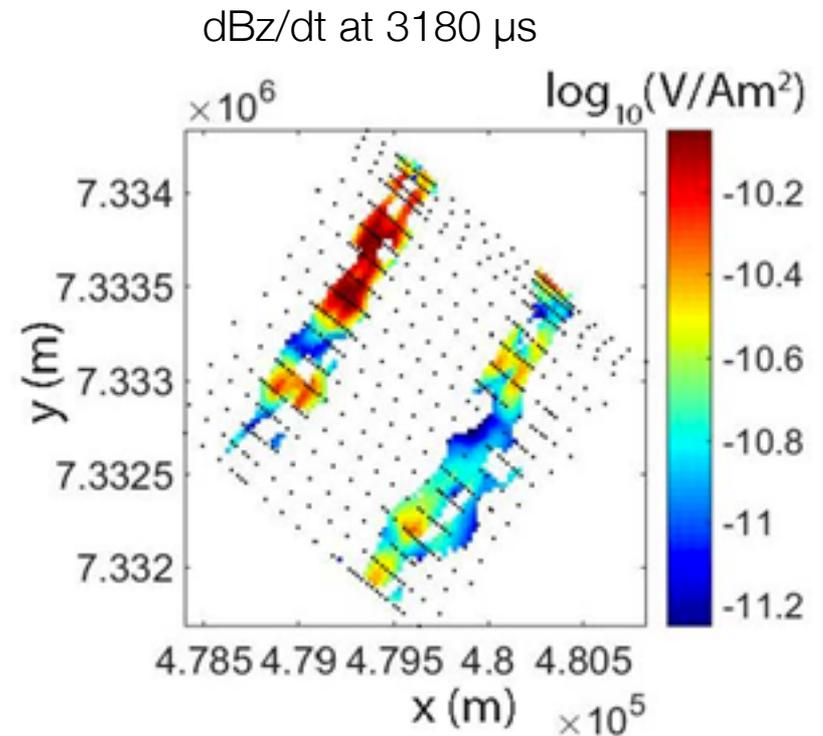
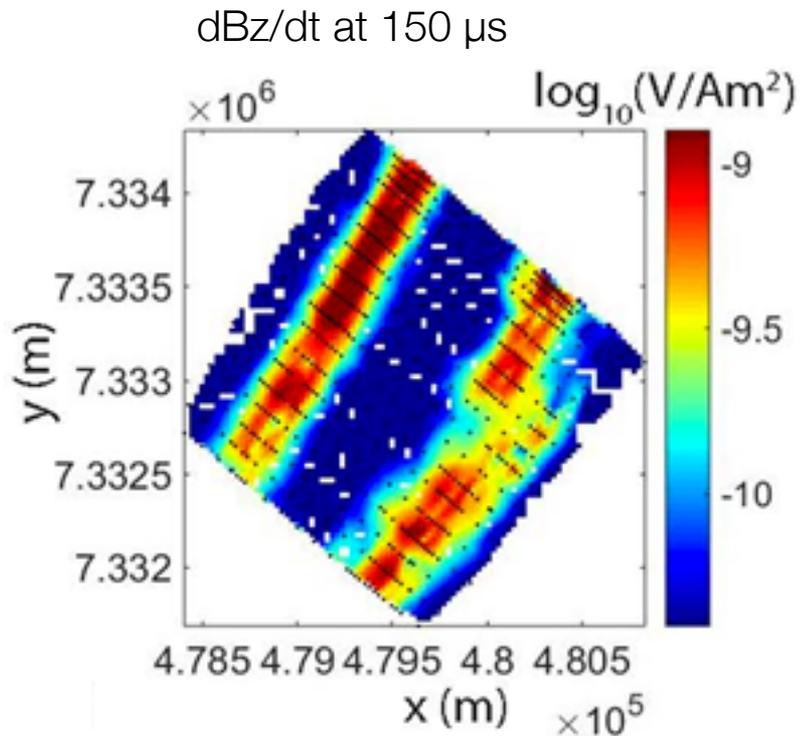


System



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

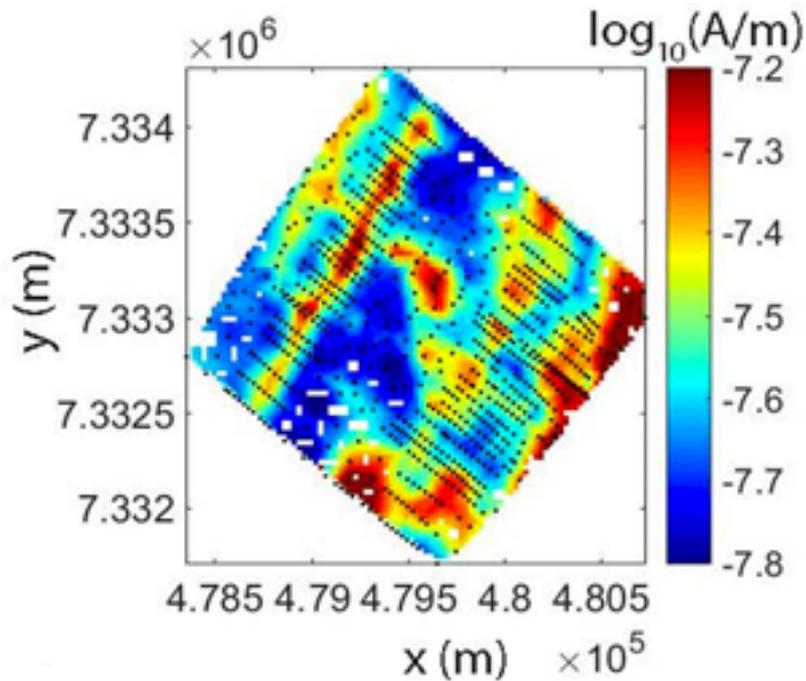
# Data: VTEM



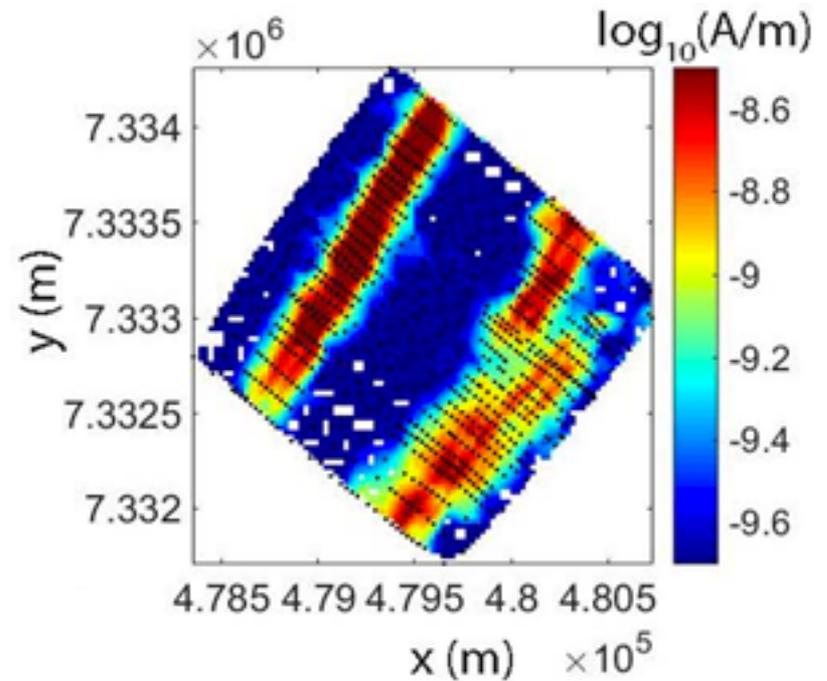
- At 150  $\mu\text{s}$ : strong conductivity anomalies
- Noise level:  $5 \times 10^{-12}$   $\text{V}/\text{Am}^2$  (values below blanked-out)

# Data: RESOLVE

Bz Imaginary at 115,000 Hz



Bz Imaginary at 385 Hz

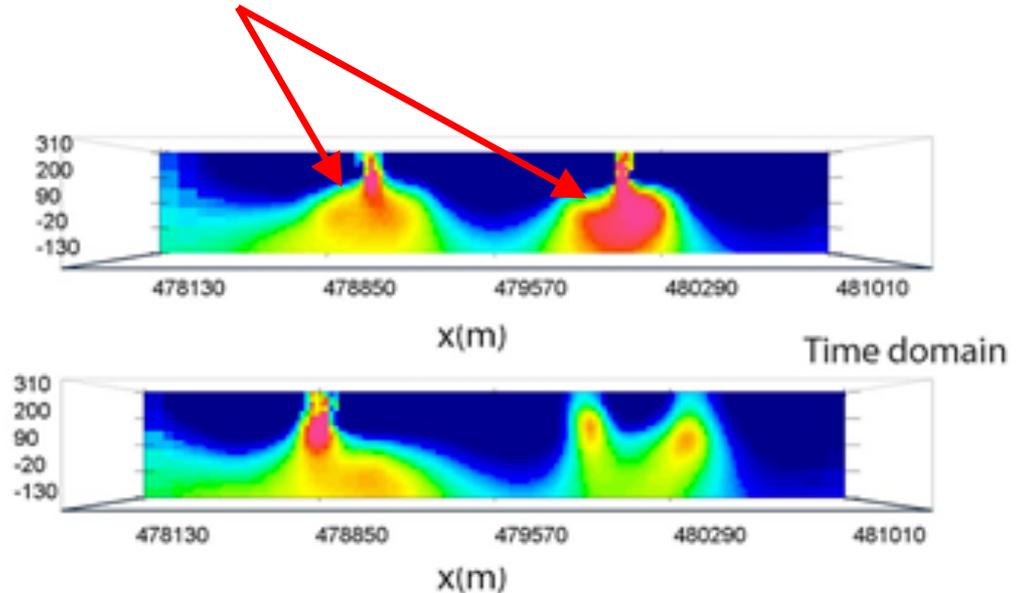
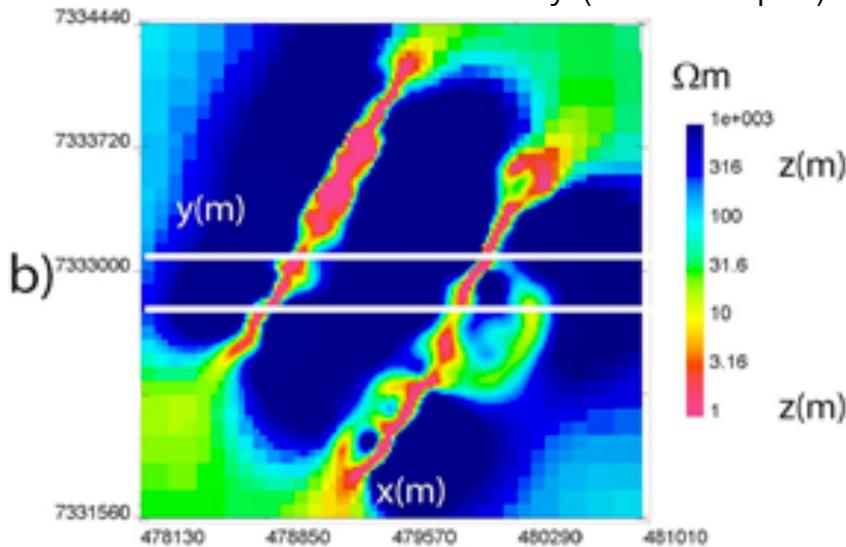


- 115,000 Hz data contains near-surface information
- 385 Hz data similar to the VTEM data at 150  $\mu s$

# Processing: VTEM

- Voxel inversion
  - Starting model: 1000  $\Omega\text{m}$
- Image conductors
- Smooth regularization blurs conductors at depth

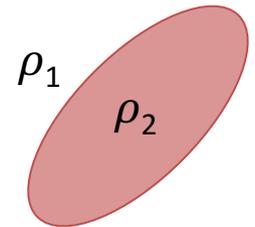
Recovered conductivity (190m depth)



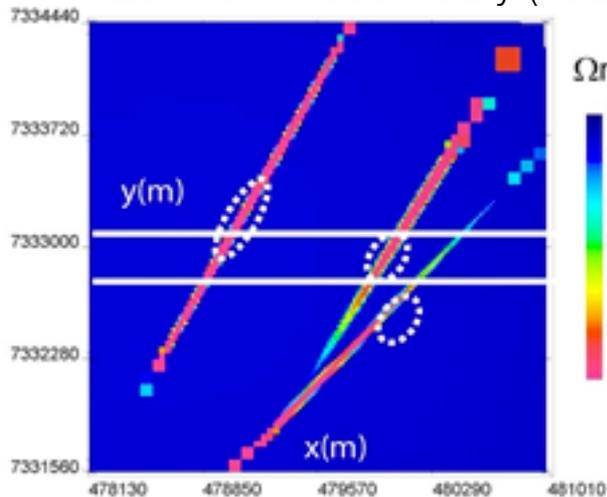
How do we image thin, dipping conductors in 3D?

# Processing: VTEM

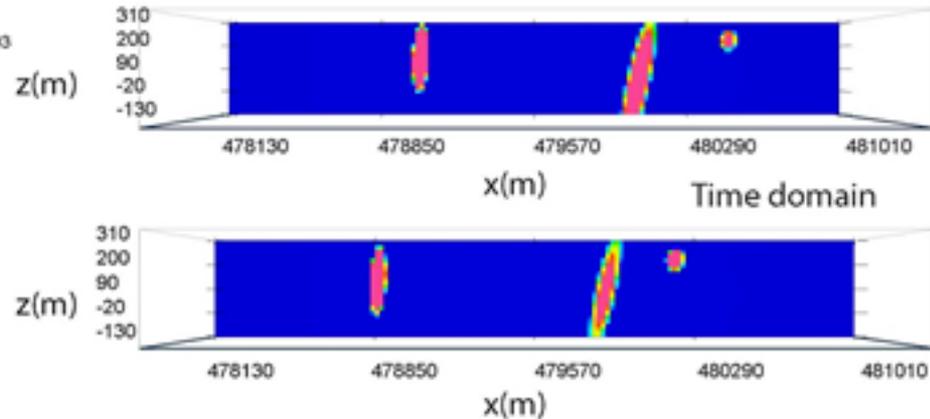
- Parametric inversion
  - Parameterize dipping conductors as Gaussian ellipsoids
  - Invert for:
    - Resistivity: background and ellipsoid
    - Shape and location of ellipsoid



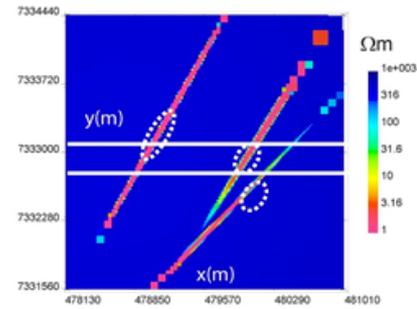
Recovered conductivity (190m depth)



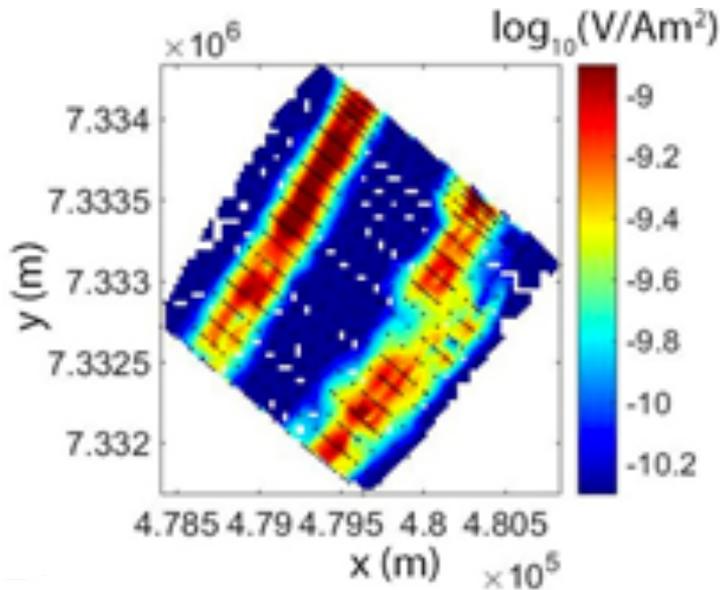
Dashed lines: Initial guess



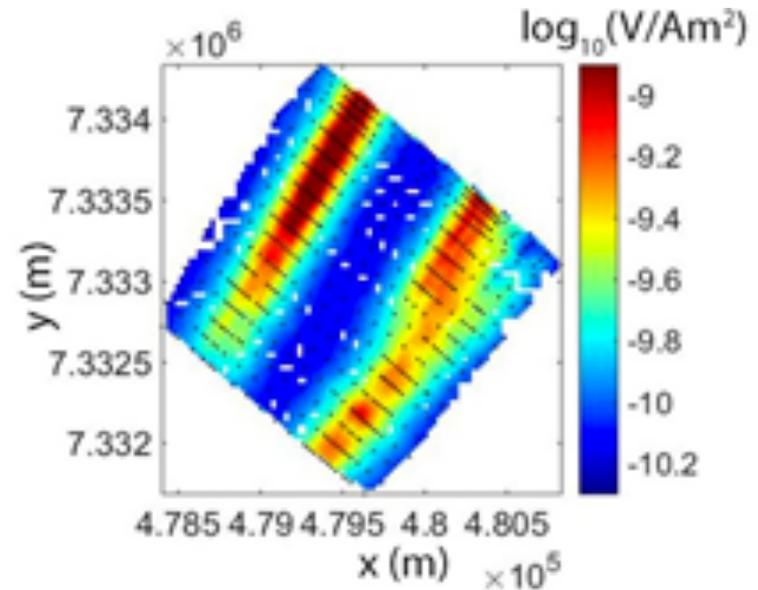
# Processing: VTEM



Observed dBz/dt at 150 $\mu$ s



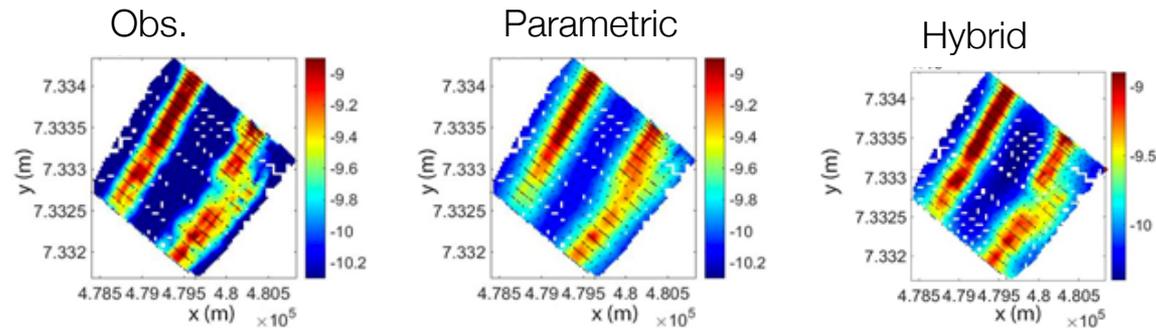
Predicted dBz/dt at 150  $\mu$ s



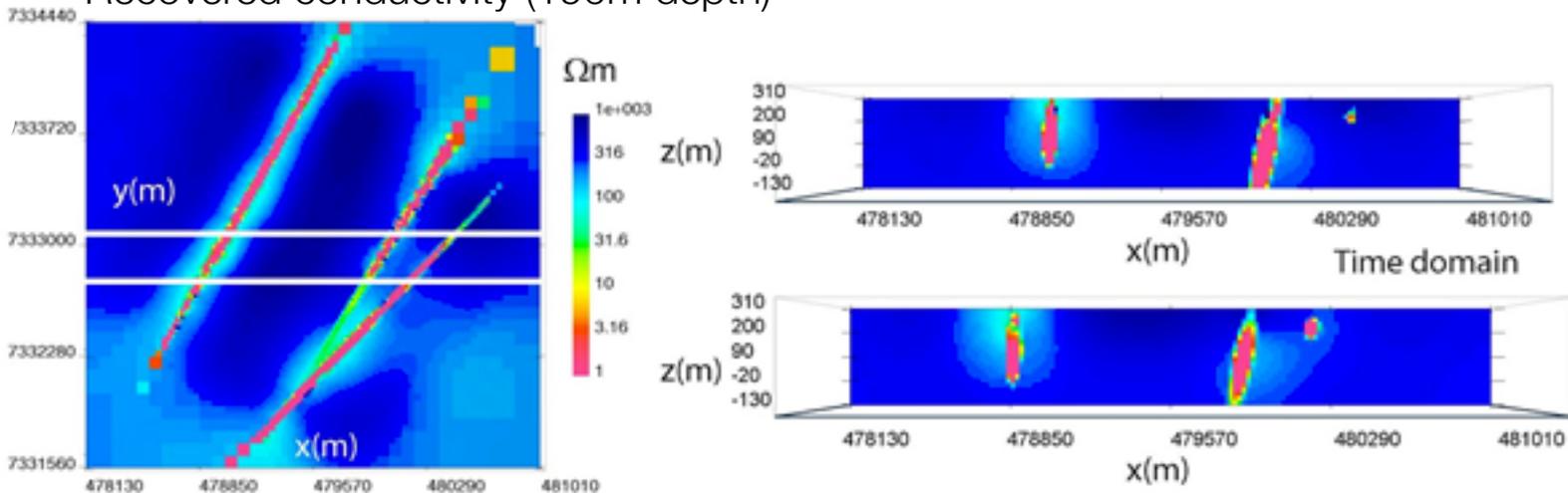
Parametric inversion too simple to explain heterogeneous earth

# Processing: Hybrid Inversion

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



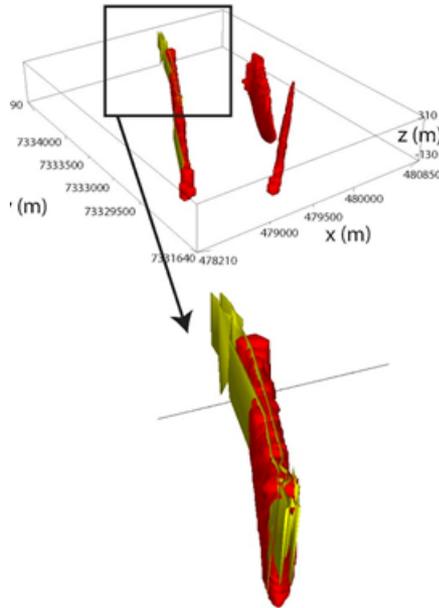
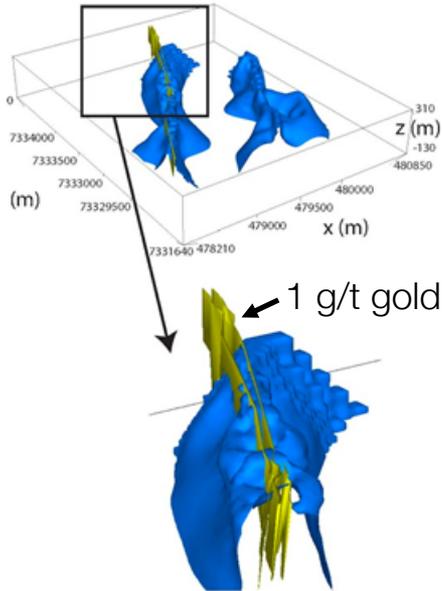
Recovered conductivity (190m depth)



# Interpretation: VTEM

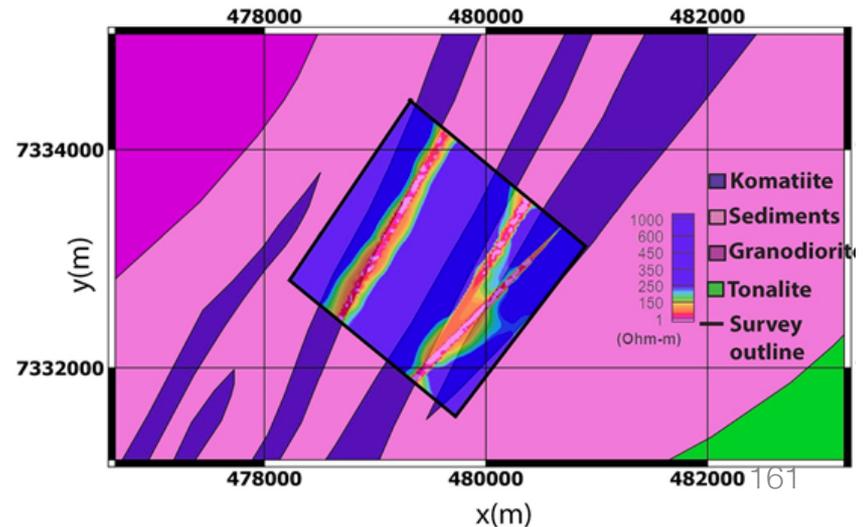
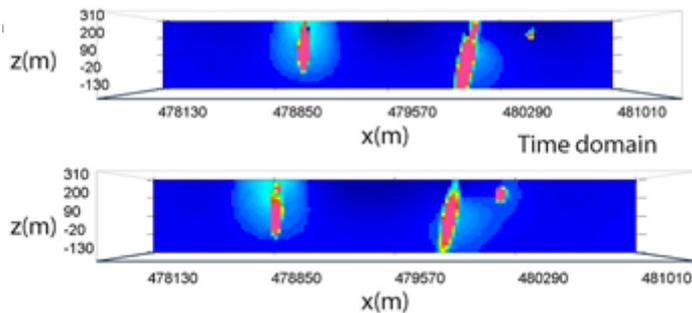
Voxel inversion cut-off ( $30 \Omega\text{m}$ )

Hybrid inversion cut-off ( $30 \Omega\text{m}$ )



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

Hybrid inversion: vertical sections

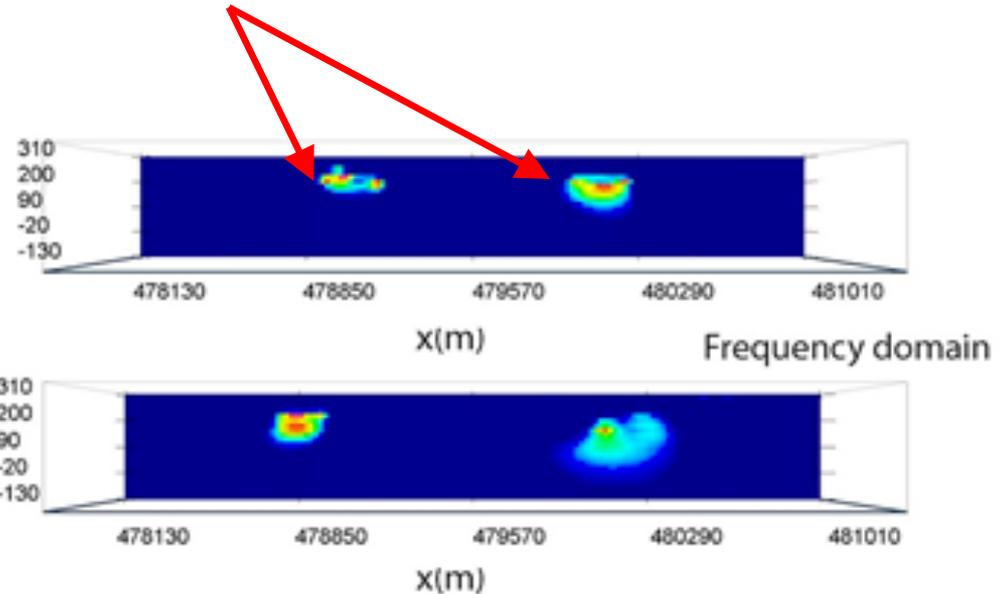
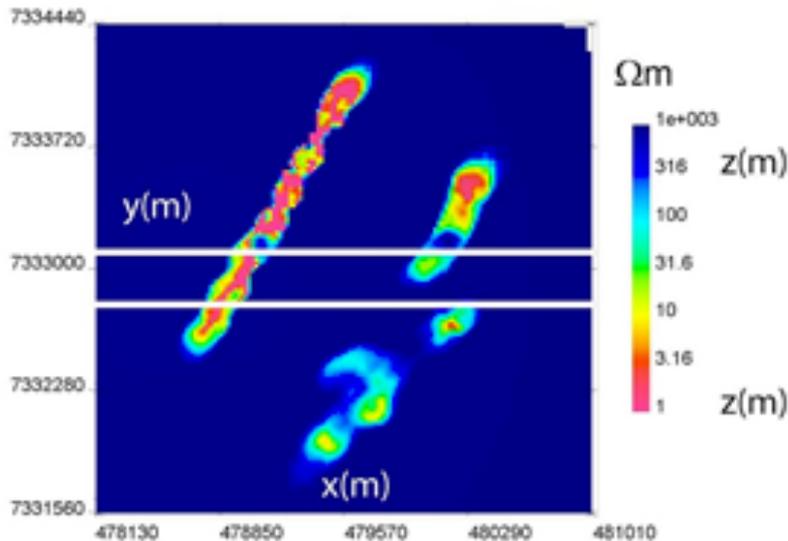


# Processing: RESOLVE

- Voxel inversion
  - Starting model: 1000  $\Omega\text{m}$

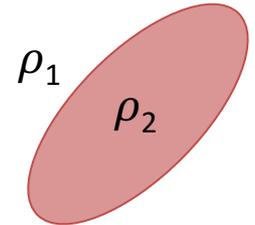
- Image conductors
- Smooth regularization blurs thin conductors

Recovered conductivity (190m depth)

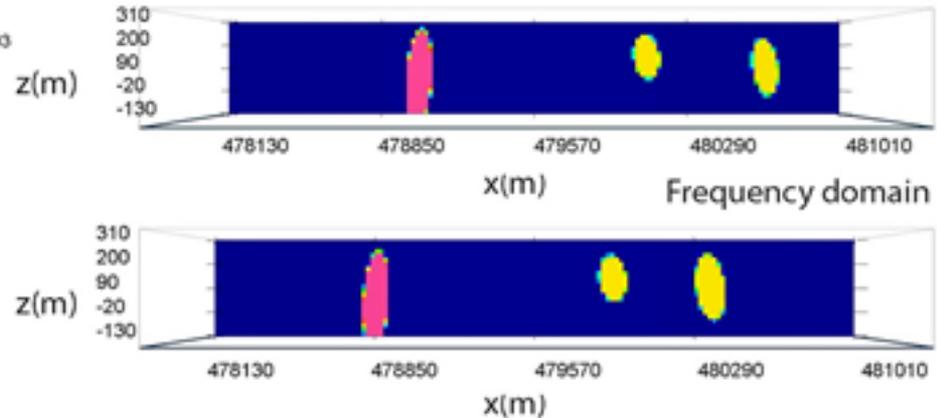
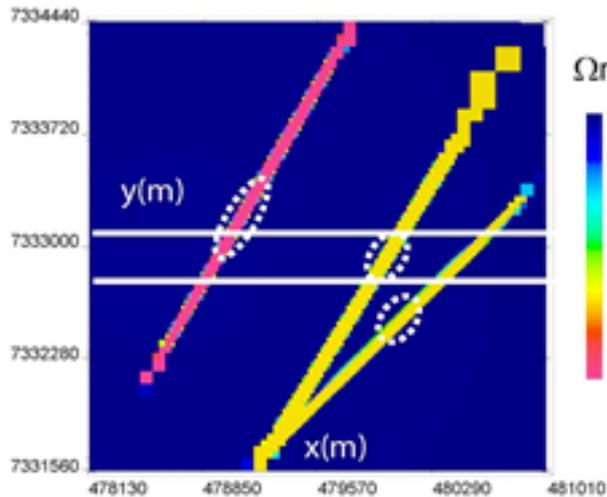


# Processing: RESOLVE

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

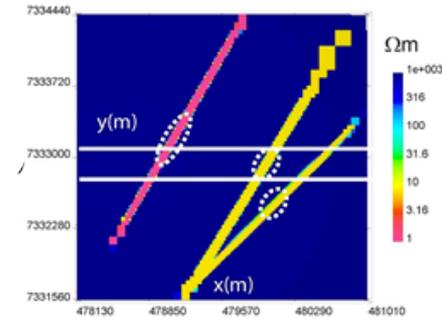


Recovered conductivity (190m depth)

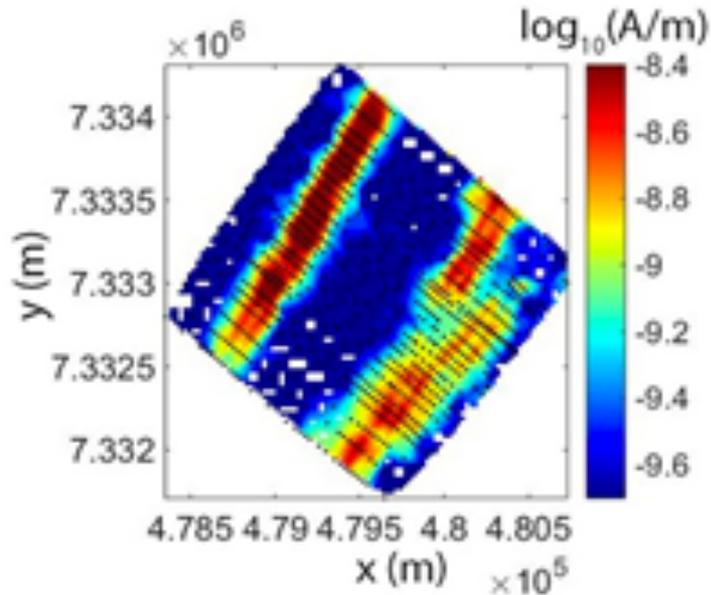


Dashed lines: Initial guess

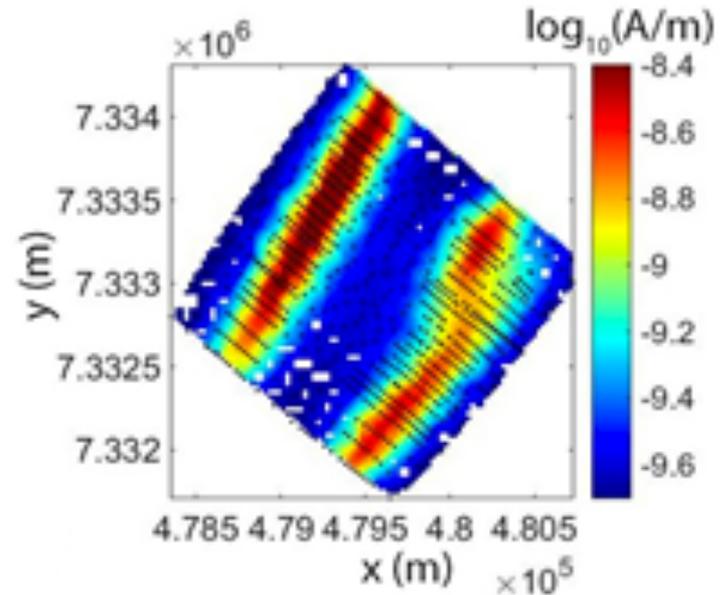
# Processing: RESOLVE



Observed Bz Imag at 385 Hz



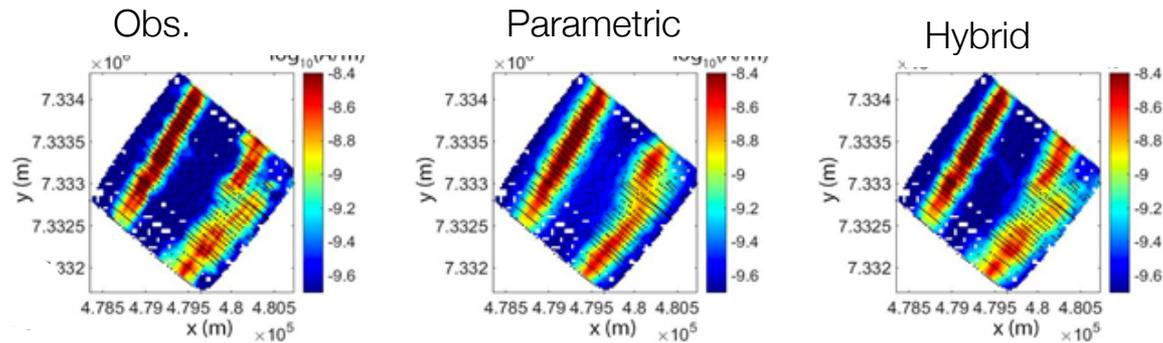
Predicted Bz Imag at 385 Hz



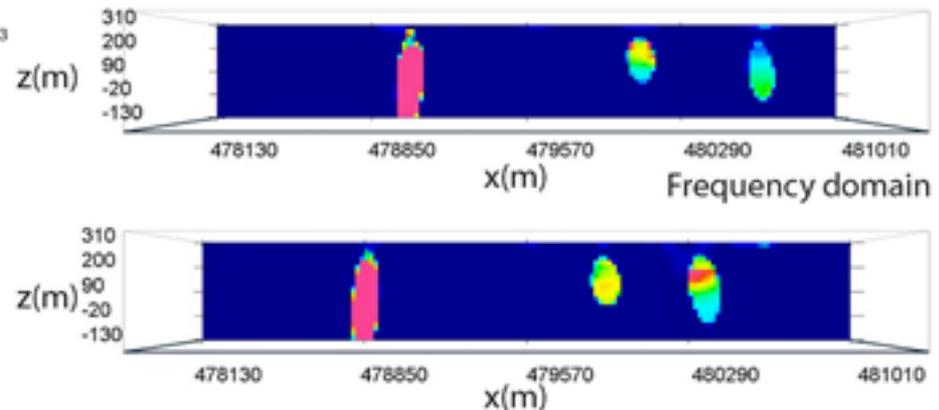
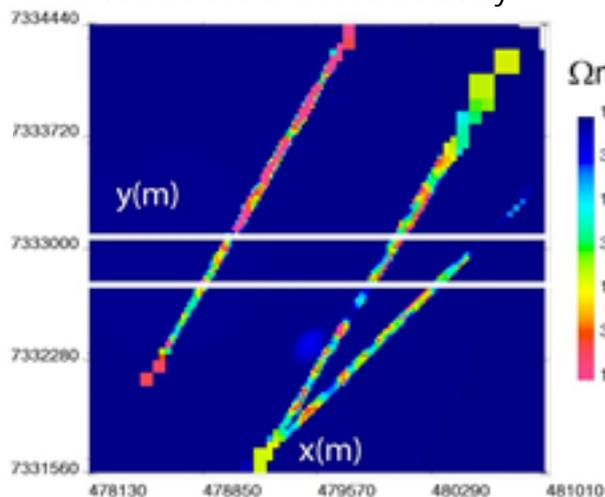
Parametric inversion too simple to explain heterogeneous earth

# Processing: Hybrid Inversion

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

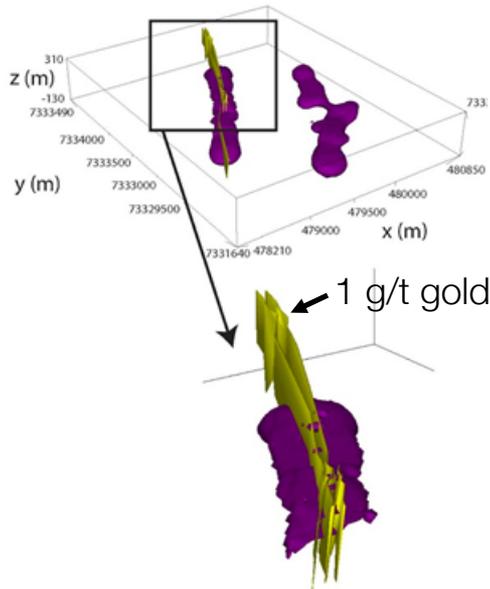


Recovered conductivity

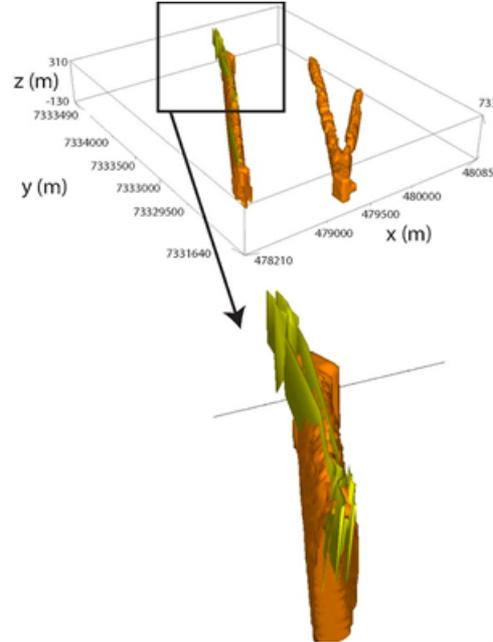


# Interpretation: RESOLVE

Voxel inversion cut-off ( $30 \Omega\text{m}$ )

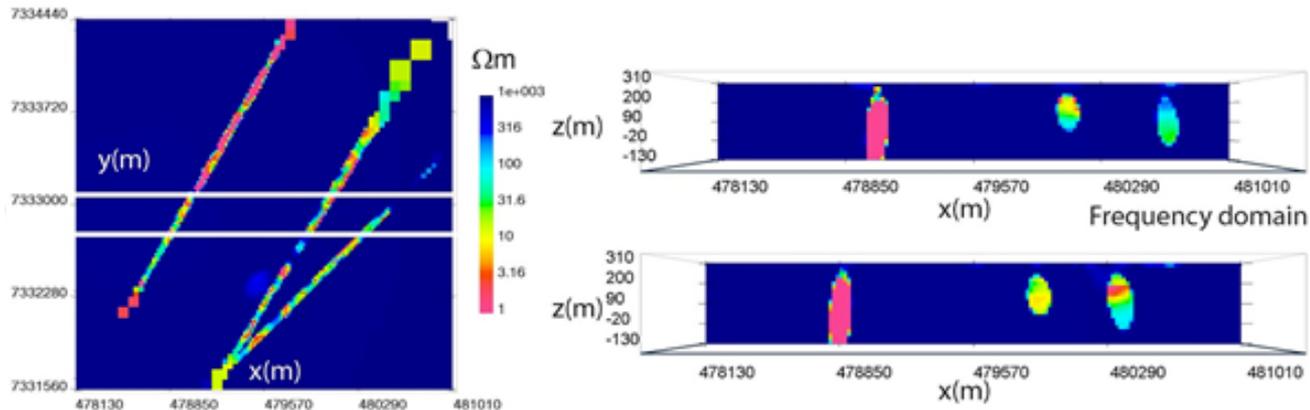


Hybrid inversion cut-off ( $30 \Omega\text{m}$ )



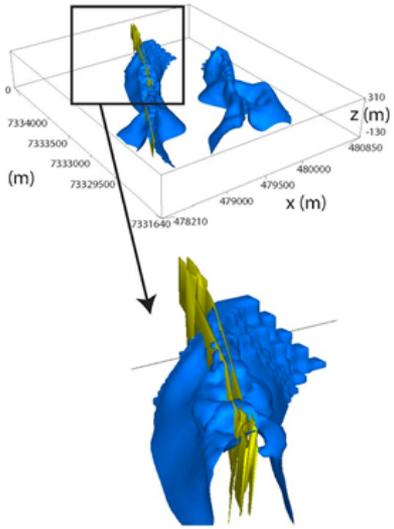
- Voxel inversion: blurs thin conductors
- Hybrid inversion
  - Dips recovered
  - Tighter boundary of the komatiite
  - Good agreement with gold grade

Hybrid inversion

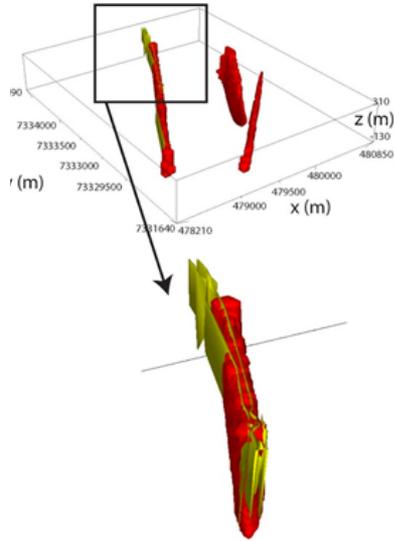


# Synthesis

VTEM

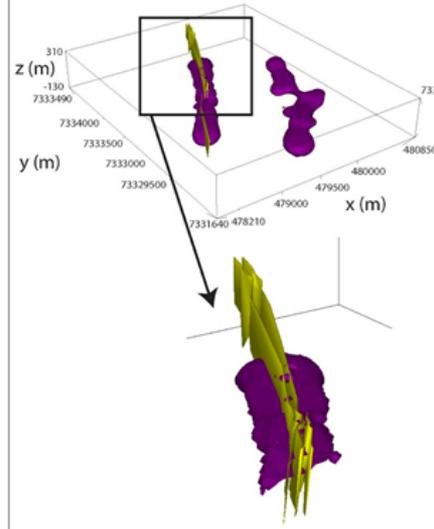


voxel

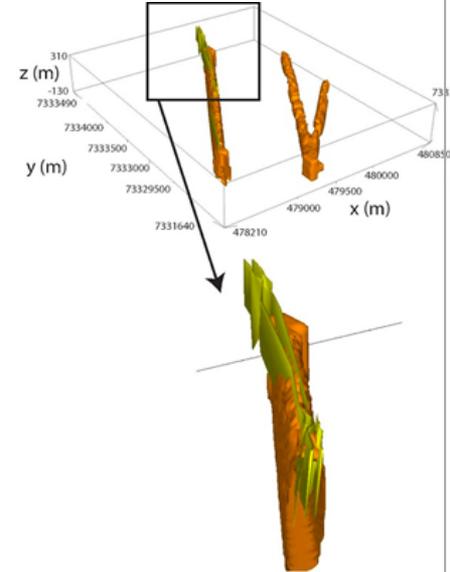


hybrid

RESOLVE



voxel



hybrid

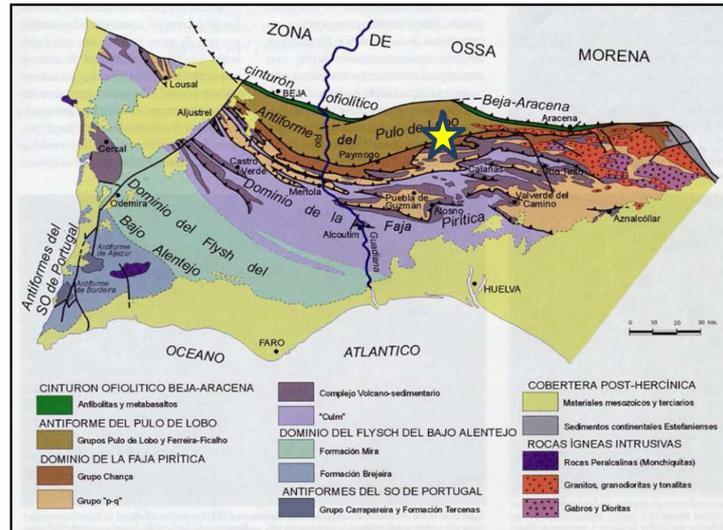
- TDEM and FDEM survey sensitive to conductors
- Hybrid inversion beneficial for imaging thin, dipping conductors

# Case History: La Magdalena

Granda et al., 2016

# Setup

## Geological setting

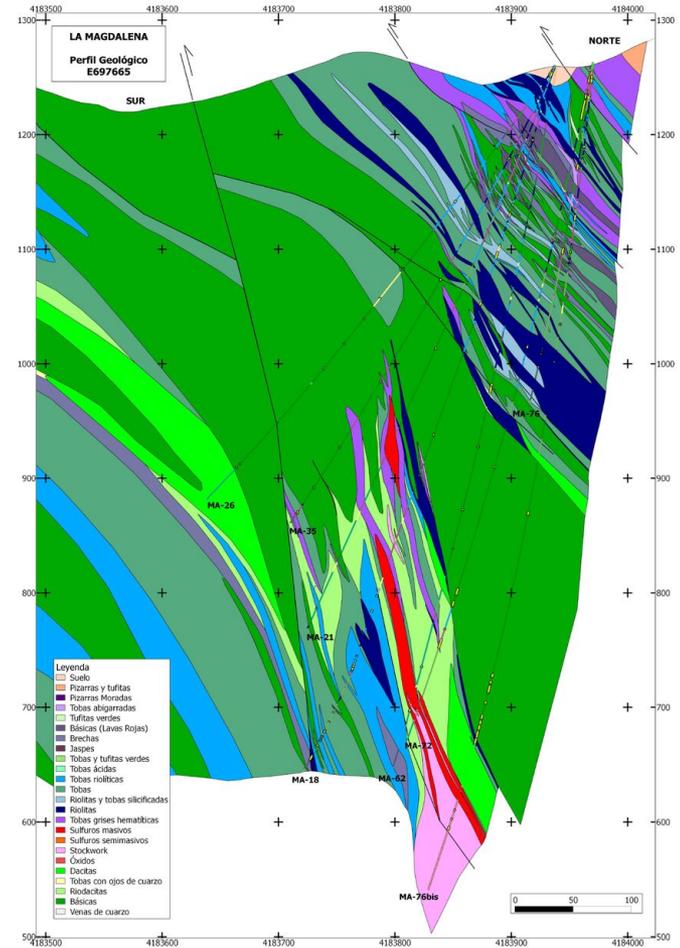


- Volcano-Sedimentary (VS) mineralization
- Thin, steeply dipping veins

**Goal:** Find deposits

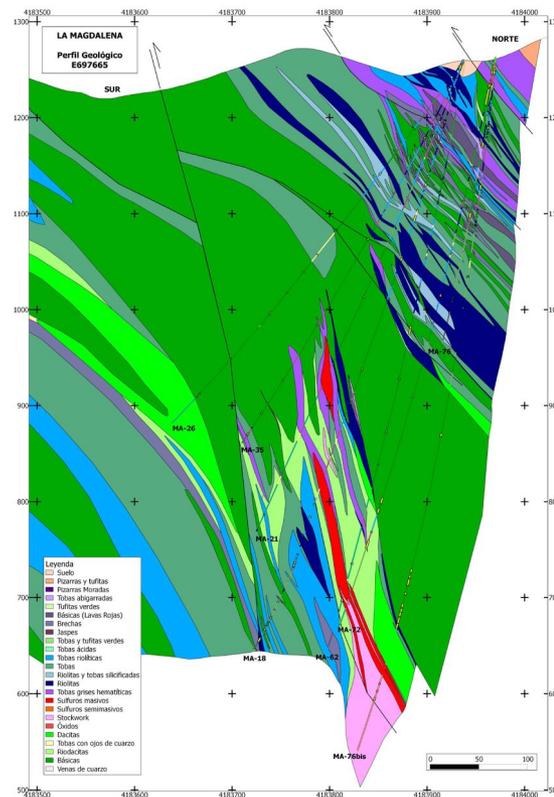
- Use borehole TDEM to find deeper, off-hole targets

## 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

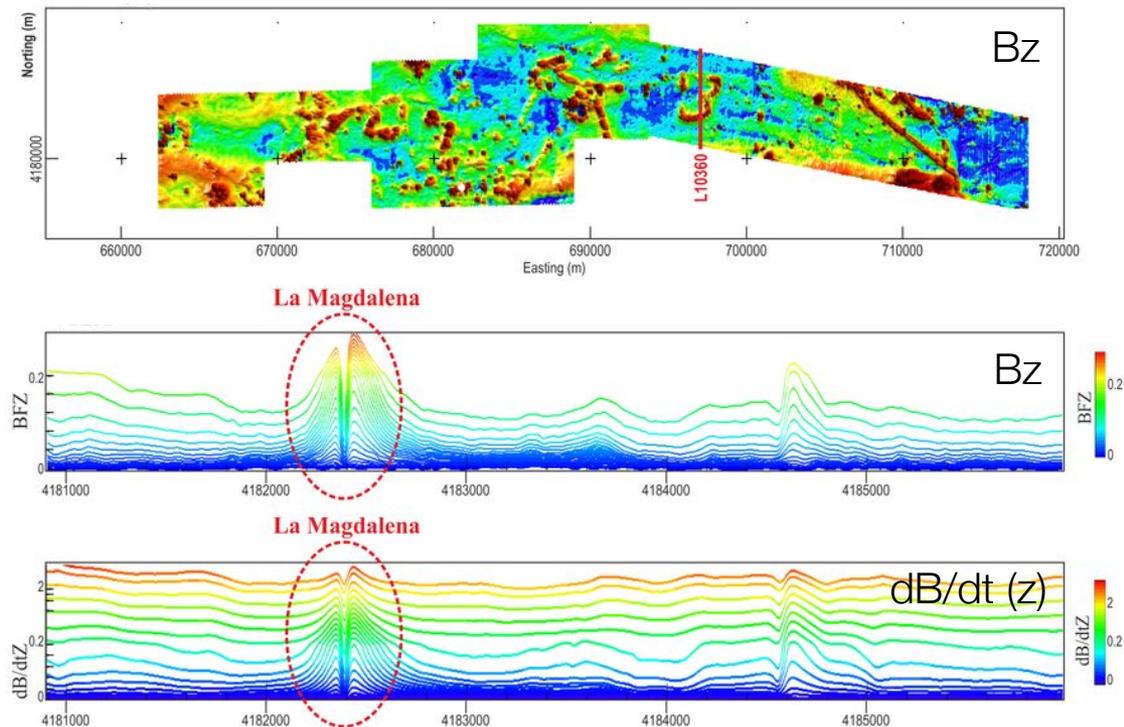
Goal	Survey	Detail
Find potential targets	VTEM	350 km <sup>2</sup>
Evaluate continuity of mineralization	Mise-a-la-Masse	Single current in ore body
Methodological Tests	ERT	Pole-dipole along a single line
	Surface TEM: Turam configuration	
	Surface TEM: Slingram configuration	
Find off-hole conductors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

# Initial Discovery: VTEM

- VTEM airborne survey
  - 350 km<sup>2</sup> area
  - N-S lines, 100m - 200m spacing
  - Measure:
    - dB/dt (x, z)
    - Bz, Bx
    - Mag.

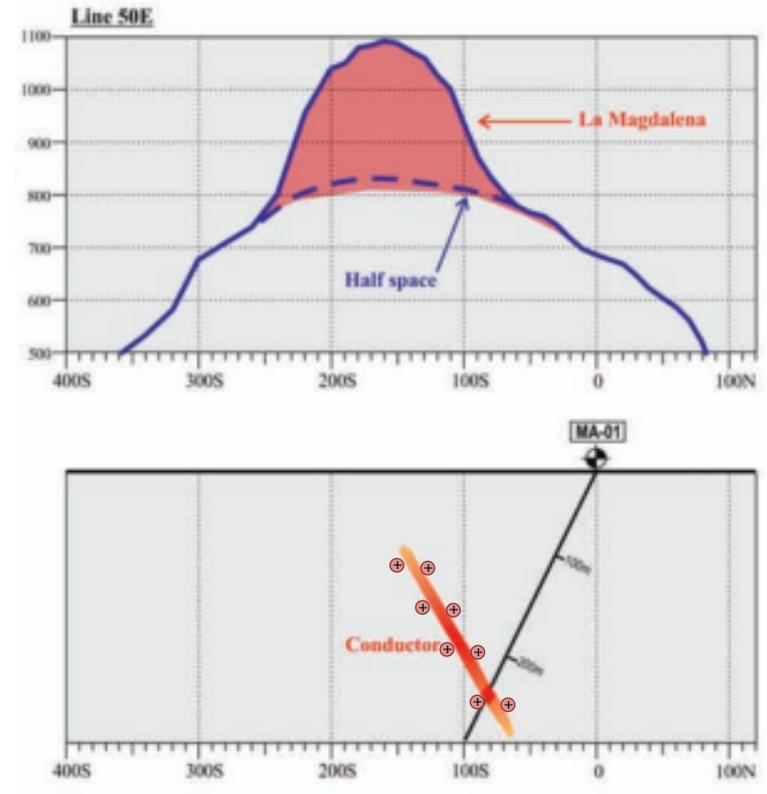
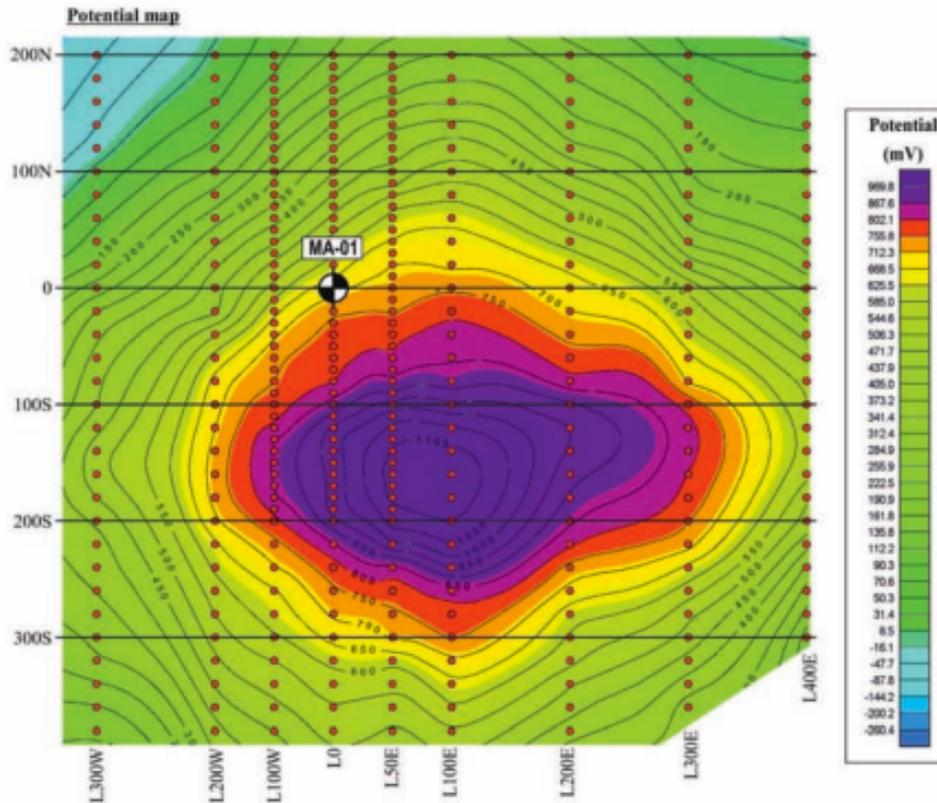
## Survey Parameters

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



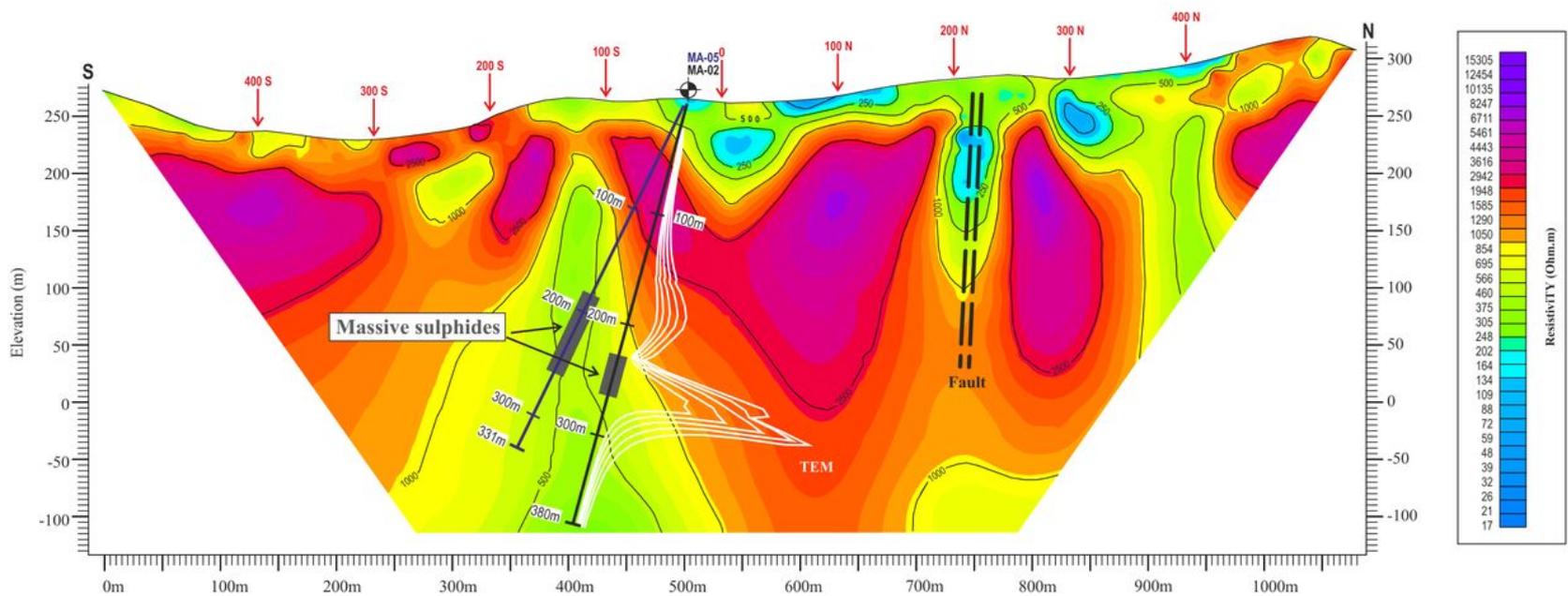
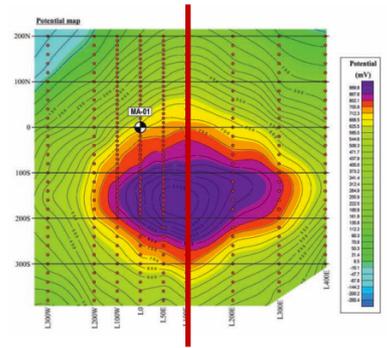
# Evaluation: Mise-a-la-masse

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



# Methodological Test: ERT

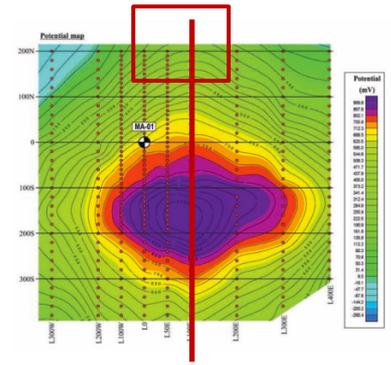
- Pole-dipole
  - $a = 20\text{m}$  and  $n = 40$



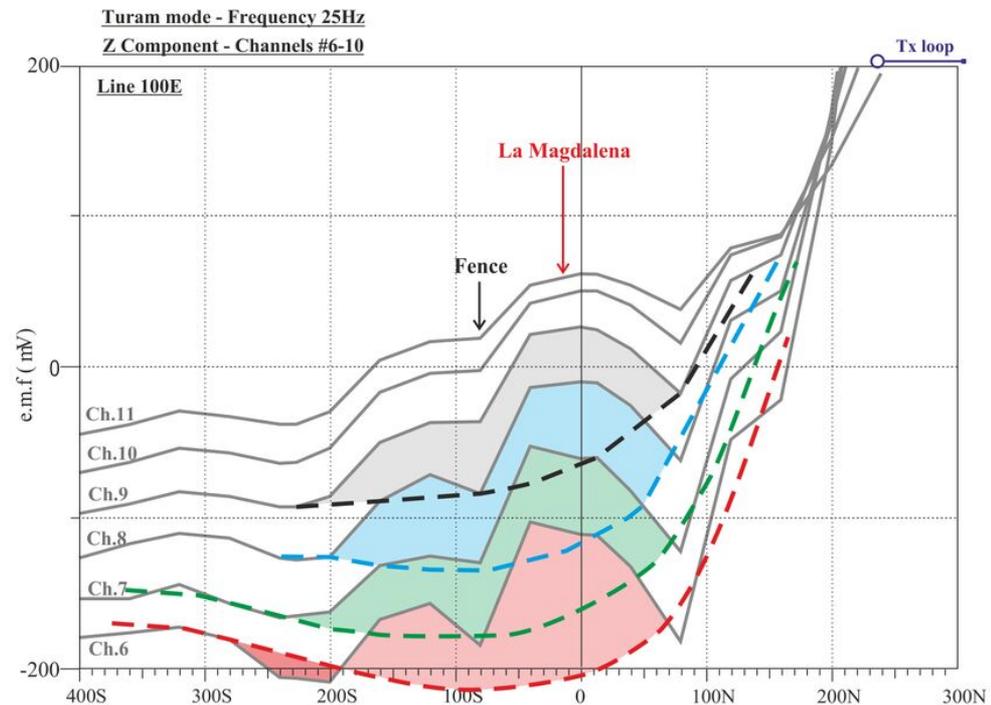
Results: found a moderately low resistivity region, not as low as anticipated 174

# Methodological Test: Turam

- Ground based, fixed loop: Turam
- PROTEM induction coil
  - RX Equivalent area: 100 m<sup>2</sup>
- TX located several hundred meters north of mineralization
  - (ensure good EM coupling)



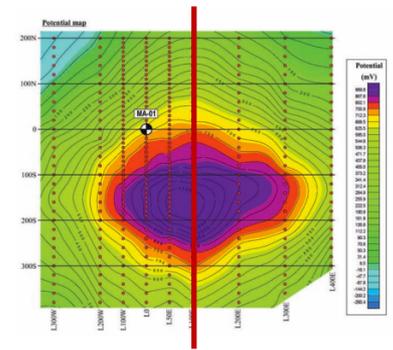
Specification	Turam
TX Loop size	700 m x 400 m
TX-RX synchronization	Crystal
Current pulses	15.5 A
T/O time	295 $\mu$ s
Measured parameters	dBdt (z, x)
Base frequency	Hi: 25 Hz MD: 6.25 Hz
Measurement mode	Off time



Results: Strong detectability. 175

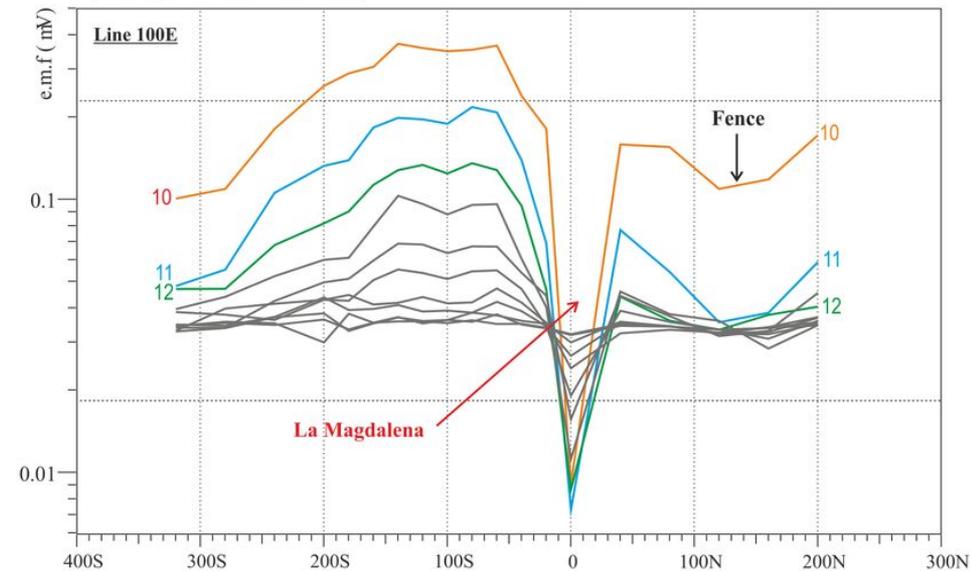
# Methodological Test: Slingram

- Ground based, moving loop: Slingram
- PROTEM induction coil
  - RX Equivalent area: 100 m<sup>2</sup>



**Slingram mode - Frequency 25Hz**

**Z Component - Channels #10-20**



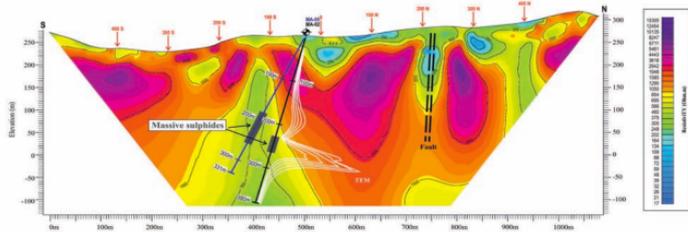
Characteristic plate-like conductor.  
Dipping north

Results: Strong detectability. 176

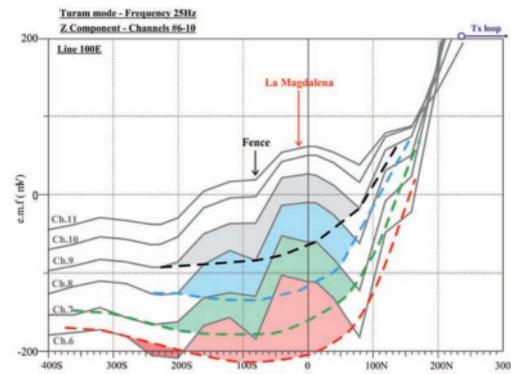
Specification	Turam	Slingram
TX Loop size	700 m x 400 m	100 m x 100 m
TX-RX synchronization	Crystal	Ref. Cable
Current pulses	15.5 A	22 A
T/O time	295 $\mu$ s	75 $\mu$ s
Measured parameters	dBdt (z, x)	dBdt (z, x)
Base frequency	Hi: 25 Hz MD: 6.25 Hz	Hi: 25 Hz MD: 6.25 Hz
Measurement mode	Off time	Off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

# Methodological Test: Final choice Turam

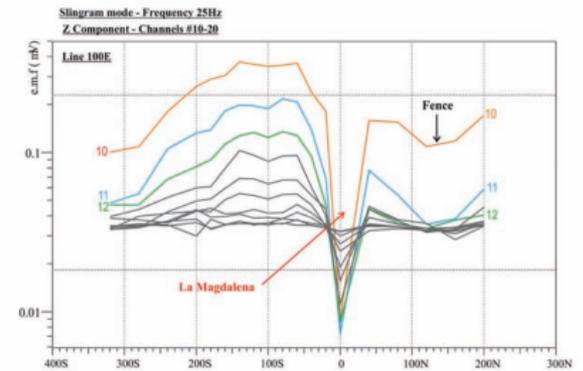
ERT: Inconclusive



Turam: Strong signal

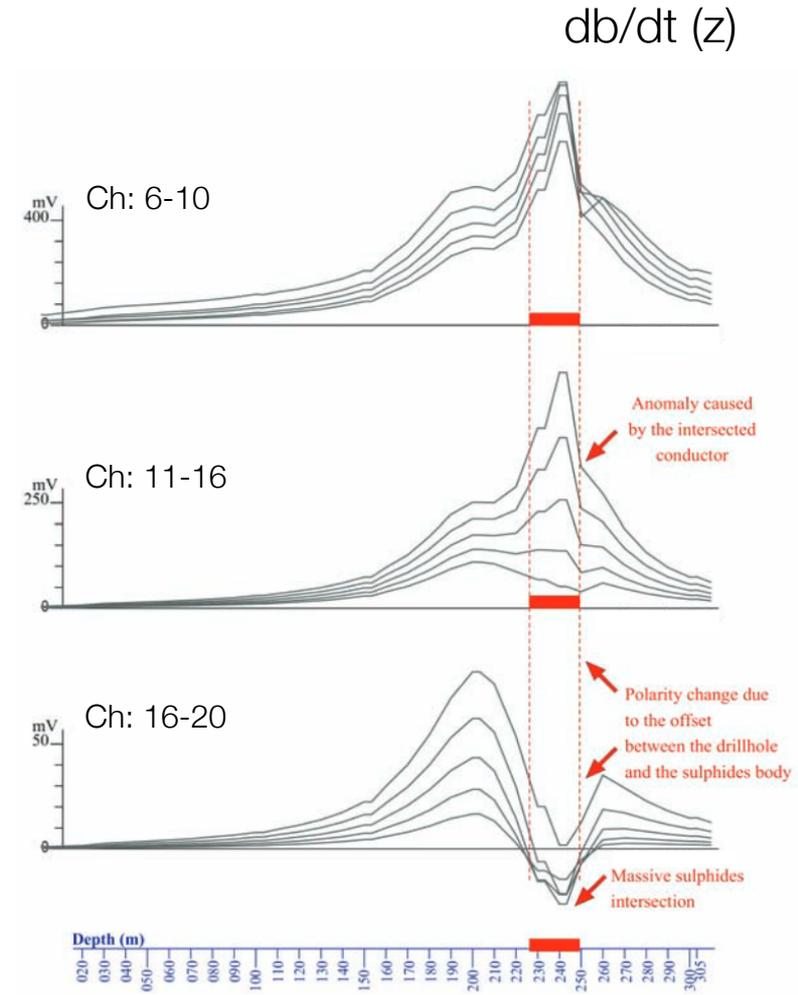
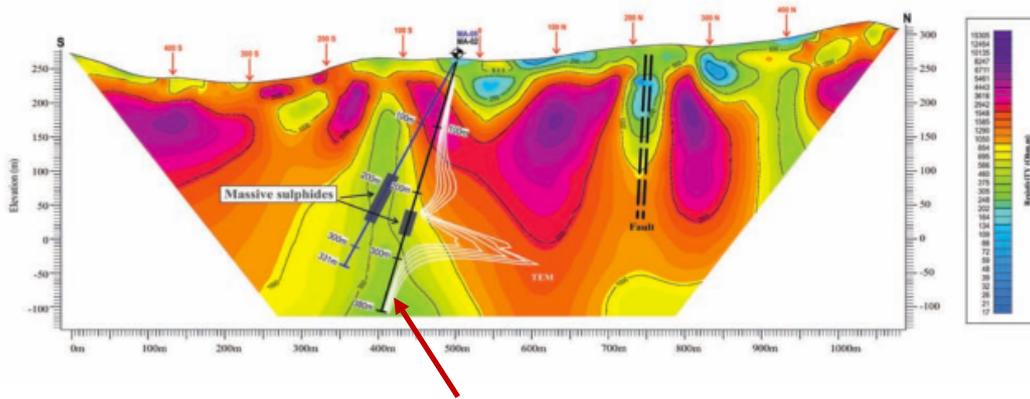


Slingram: Strong signal



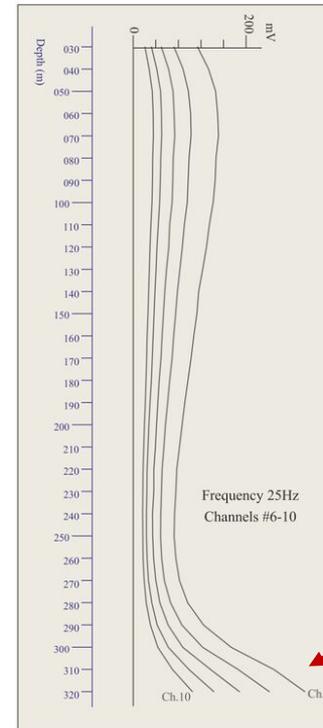
# Borehole TDEM

- 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

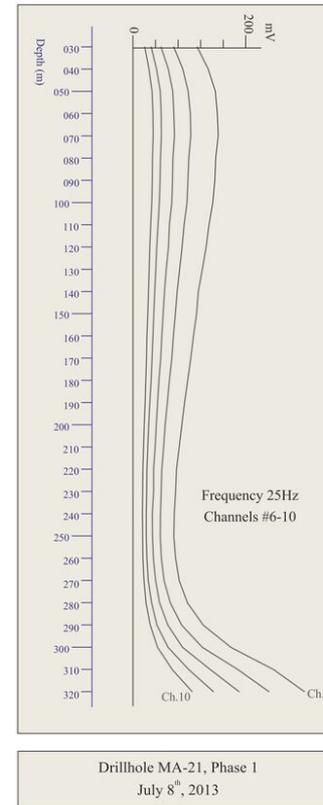
- Borehole TDEM carried out using multiple drillholes
- MA-21 drilled to 320m (Phase 1)
  - Did not intersect mineralization
  - Indicate an off-hole conductor



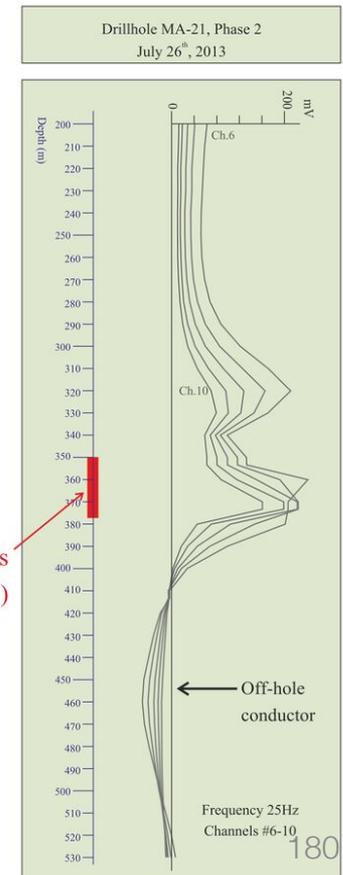
Drillhole MA-21, Phase 1  
July 8<sup>th</sup>, 2013

# 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

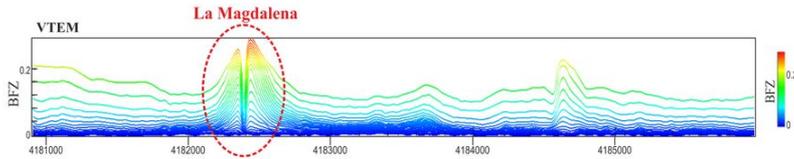


Massive sulphides  
(Masa 2)

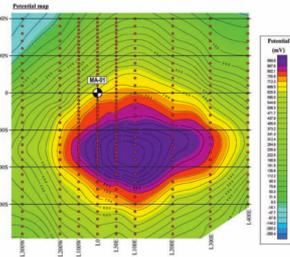


# Synthesis

- VTEM: initial discovery



- Mise a la Masse: evaluation

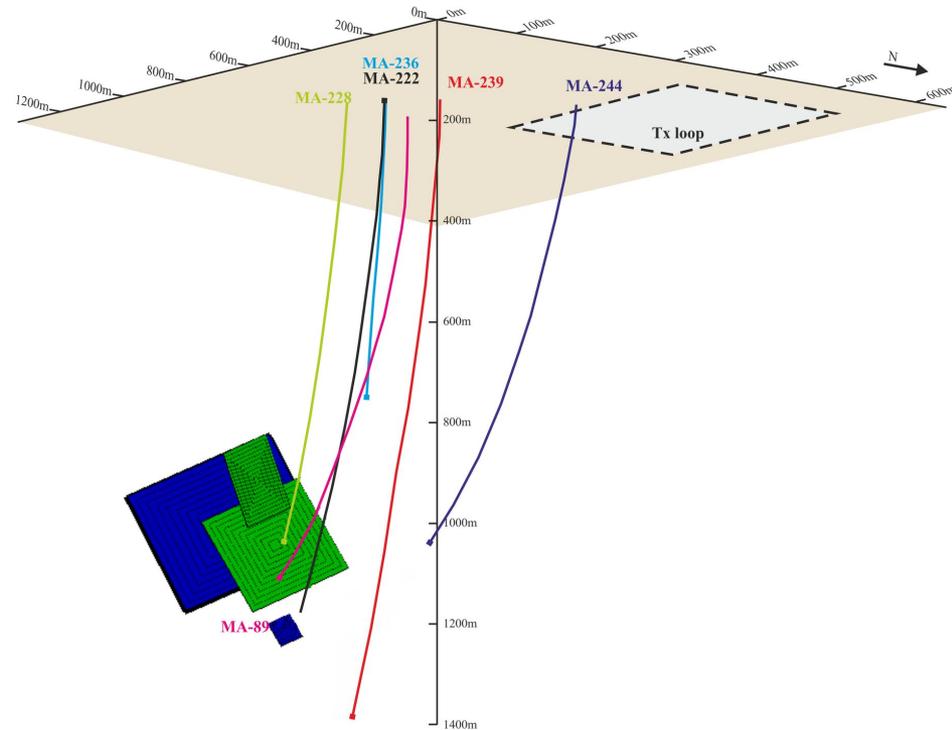


- Ground surveys: methodological tests

- ERT
- Turam
- Slingram



- Borehole TDEM: find off-hole conductors



# End of Inductive Sources

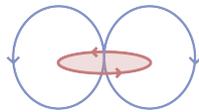
Next up



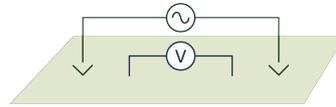
DC Resistivity



EM  
Fundamentals



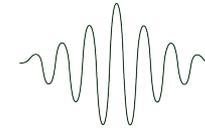
Inductive  
Sources



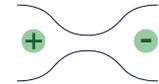
Grounded  
Sources



Natural  
Sources



GPR



Induced  
Polarization



The  
Future

Lunch: Play with apps