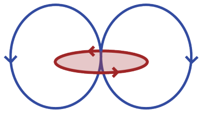
EM: Inductive Sources

DISC

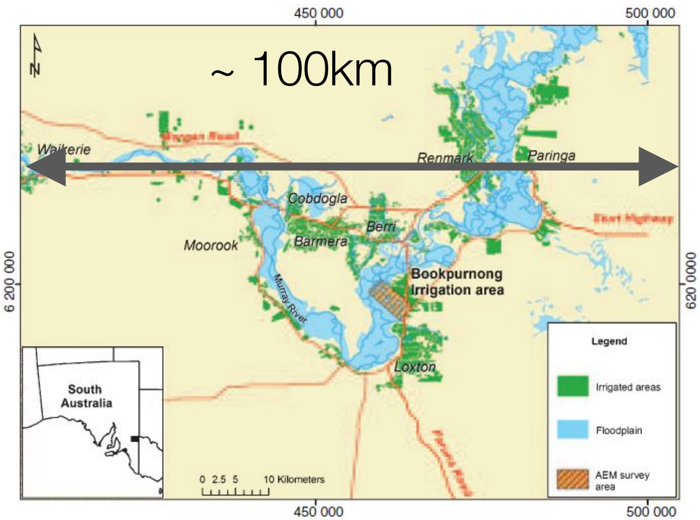
2017

Electromagnetics
Fundamentals and Applications

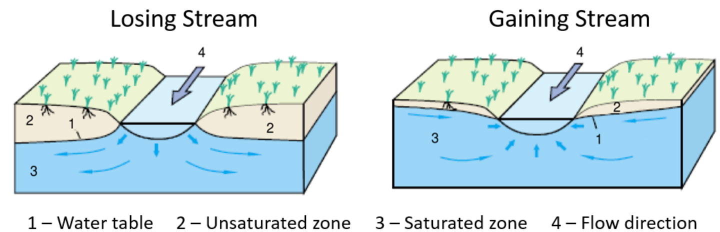


Motivation

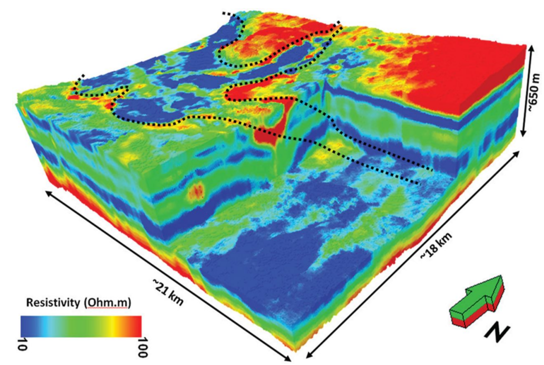
Large areas to be covered



Groundwater



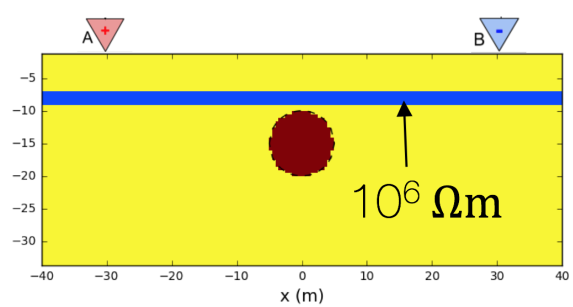
High resolution near surface



Rugged terrain

Minerals

Shielding problem



Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

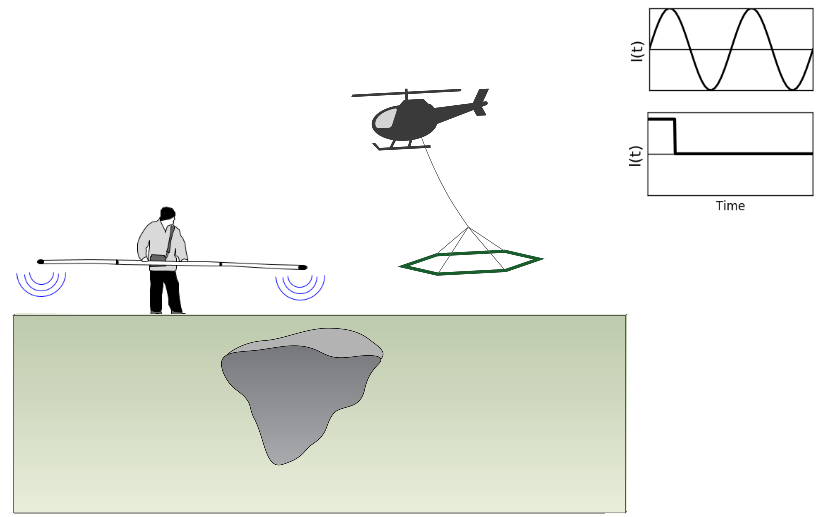
- Vertical Magnetic Dipole
- Propagation with Time
- Case History – Groundwater, Hydrocarbons

Frequency Domain EM

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

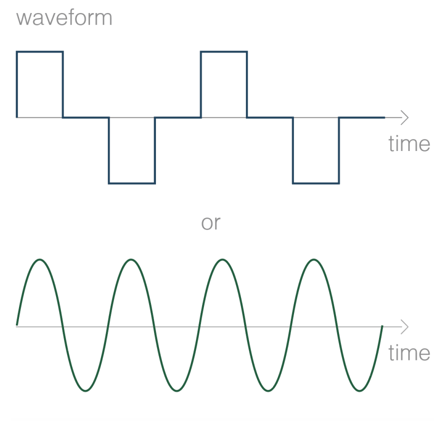
Important questions

- What is the target?
  - at the surface? At depth?. 1D, 2D, 3D?
- Transmitter
  - Location: surface? in the air?
  - Waveform: frequency or time?
  - “Size” and orientation?
- Exciting the target
  - Conductivity of the target and host
  - Geometry of the target (Coupling)
- Receiver and data
  - What fields to measure?
  - What instrument?

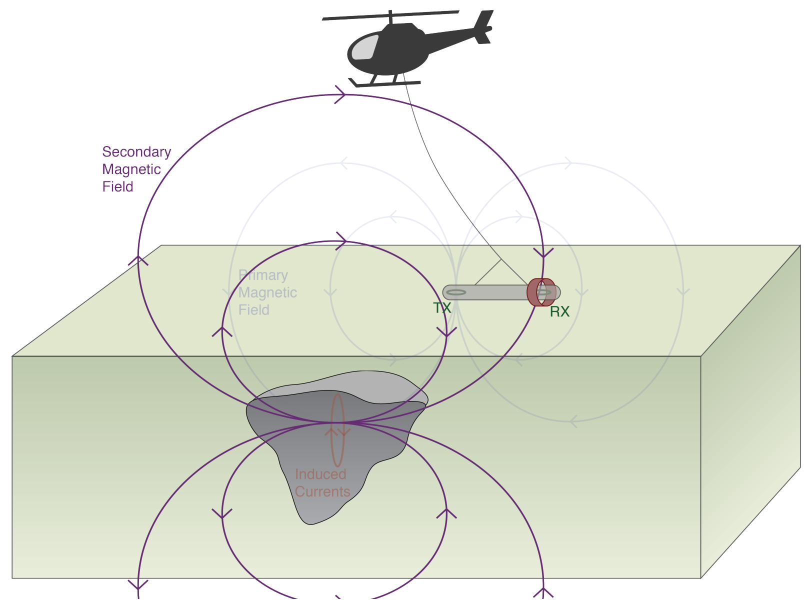


- Where to collect data? How many? How accurate?
- What is depth of investigation?
- What is the “footprint” of the transmitter”
  - These are questions of **SURVEY DESIGN**

Basic Experiment

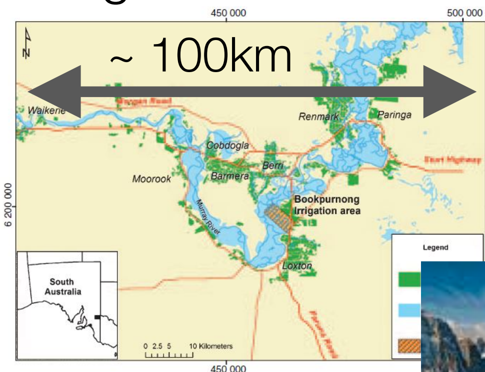


- **Transmitter:**
  - Produces a primary magnetic field
- **Exciting the target:**
  - Time varying magnetic fields generate electric fields everywhere
  - Producing currents in conductors
- **Receiver:**
  - Induced currents produce secondary magnetic fields



Transmitter

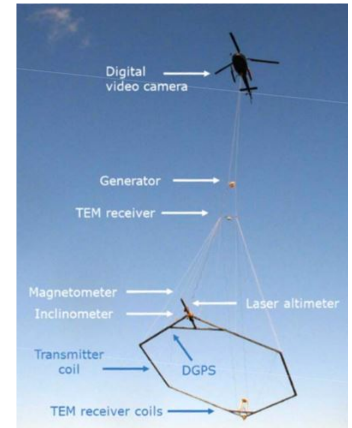
Large areas



Rugged terrain

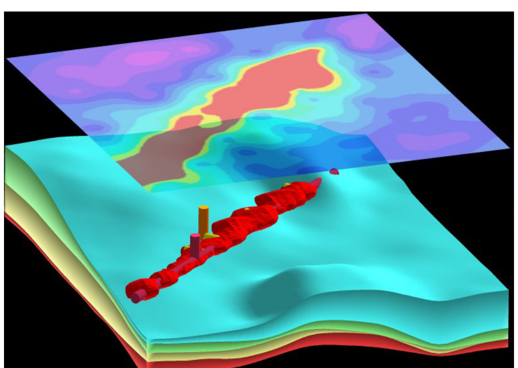
Airborne Survey

Resolve

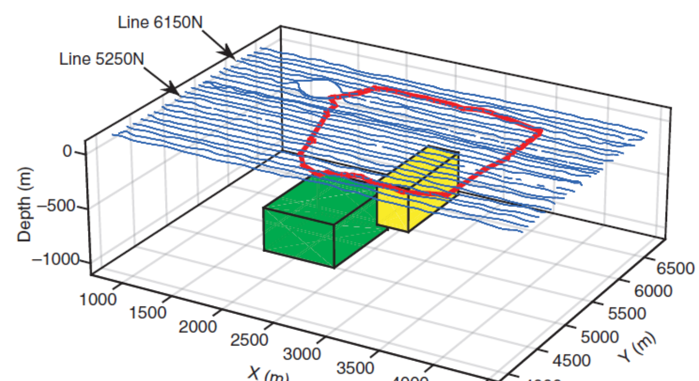


SkyTEM

Deep Targets

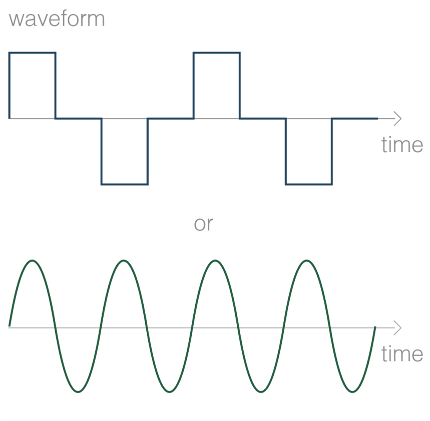


Large Loop



Transmitter

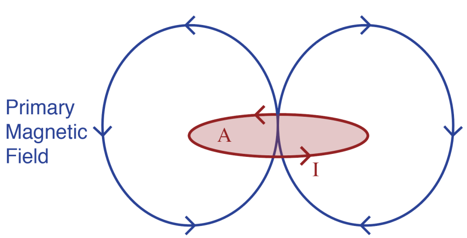
- Time or frequency?



- Key factor is moment

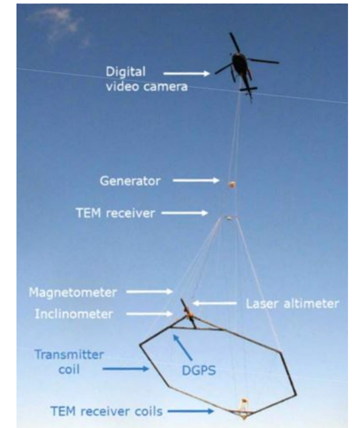
$$m = I \text{ (current) } A \text{ (area) } N \text{ (\# of turns)}$$

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



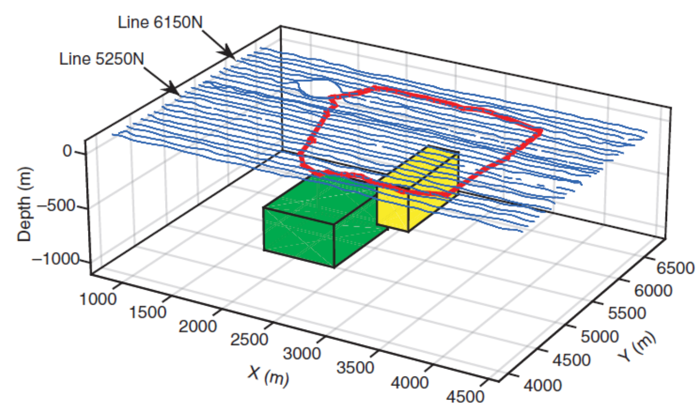
Airborne Survey

Resolve



SkyTEM

Large Loop

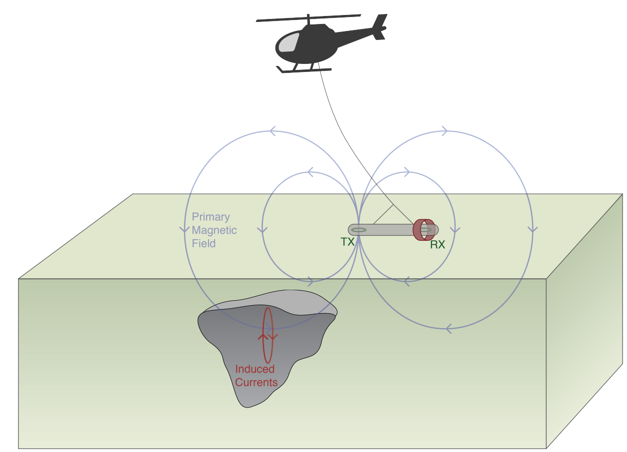


Exciting the target

- Primary field from a loop

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

- 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

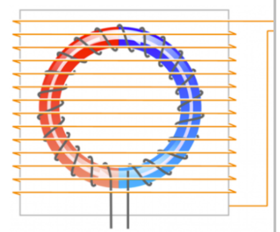


Receiver and Data

Magnetometer

$$\mathbf{b}(t)$$

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

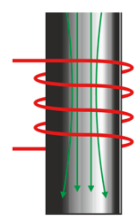


Fluxgate

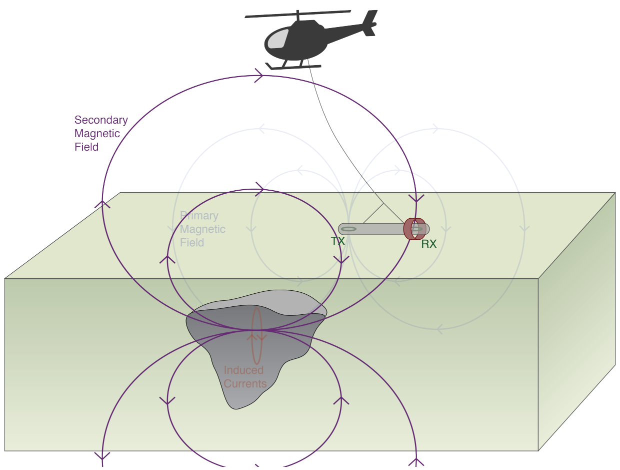
Coil

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

- Measures:
  - Voltage
  - Single component that depends on coil orientation
    - Coupling matters
- eg. airborne frequency domain.
  - ratio of Hs/Hp is the same as Vs/Vp



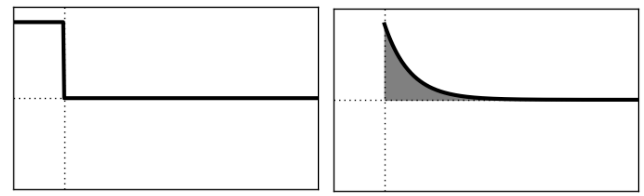
Coil



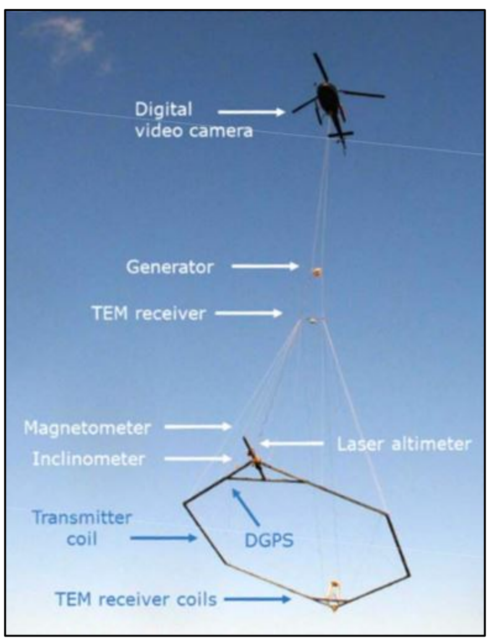
Receiver: Time Domain

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

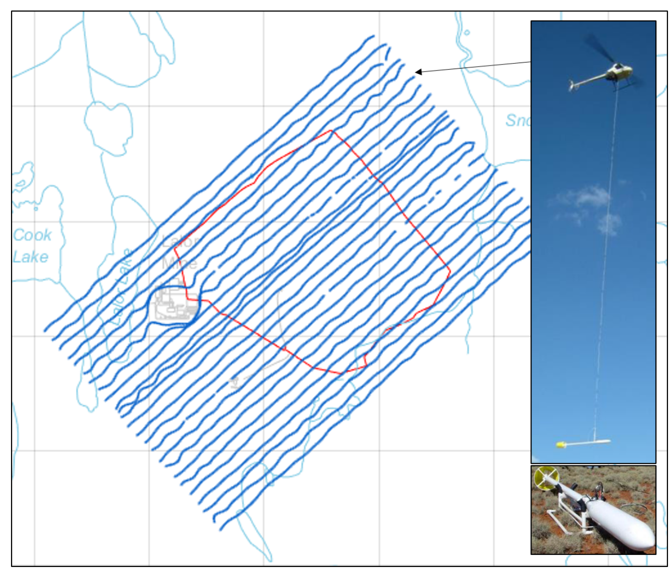
Current Response



SkyTEM

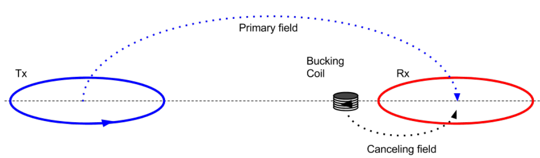


HeliSAM

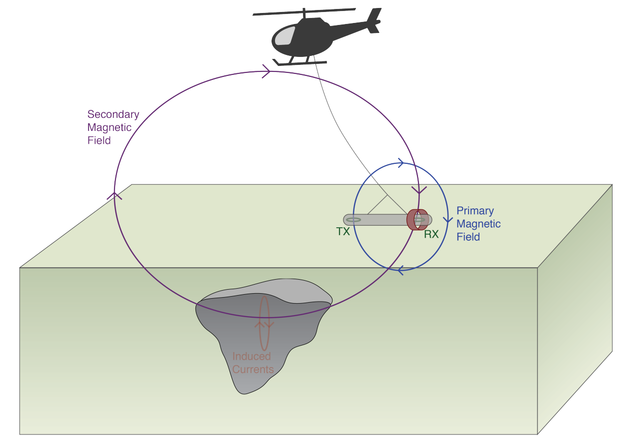


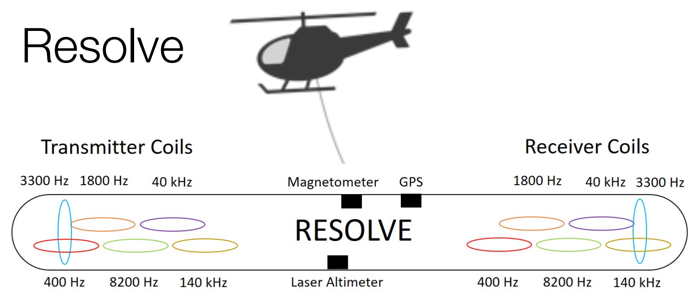
Receiver: Frequency Domain

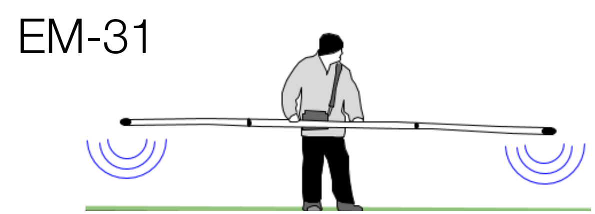
- Primary field
  - always “on”
  - large compared to secondary fields
- Primary removal
  - Compute and subtract
  - Bucking coil



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







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- Transmitter
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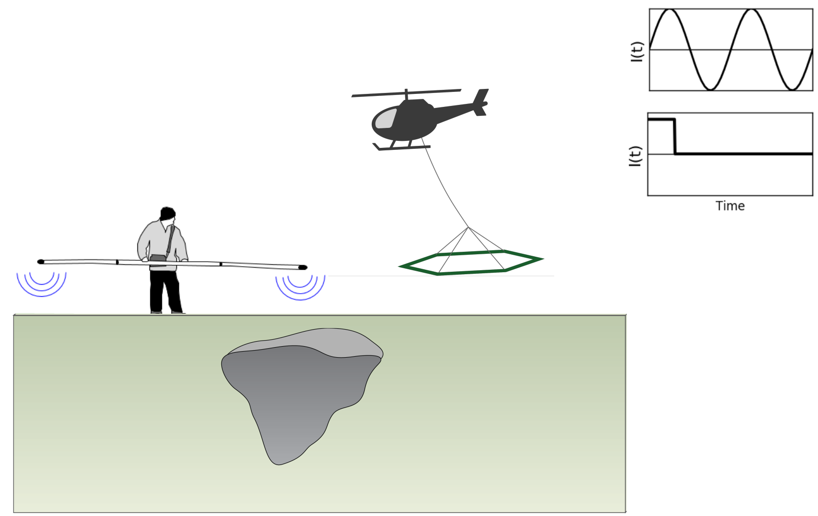

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- What is the "footprint" of the transmitter"
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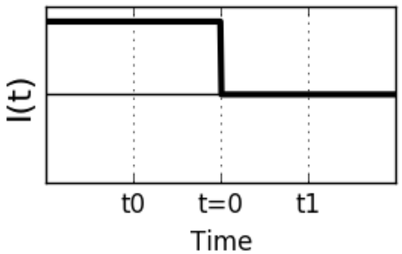
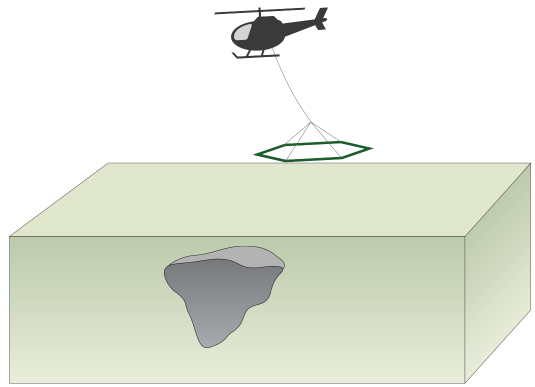
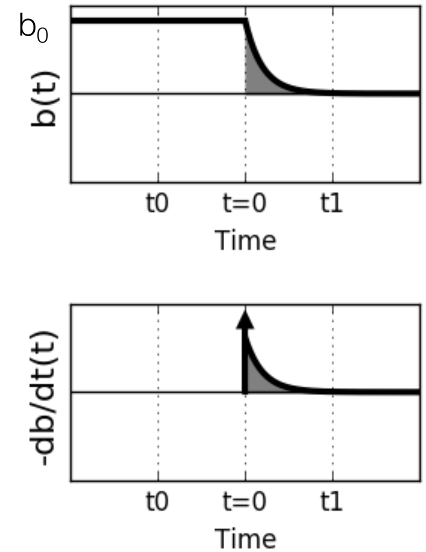
EM with Inductive Sources: Time Domain

Transmitter current





Receiver



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

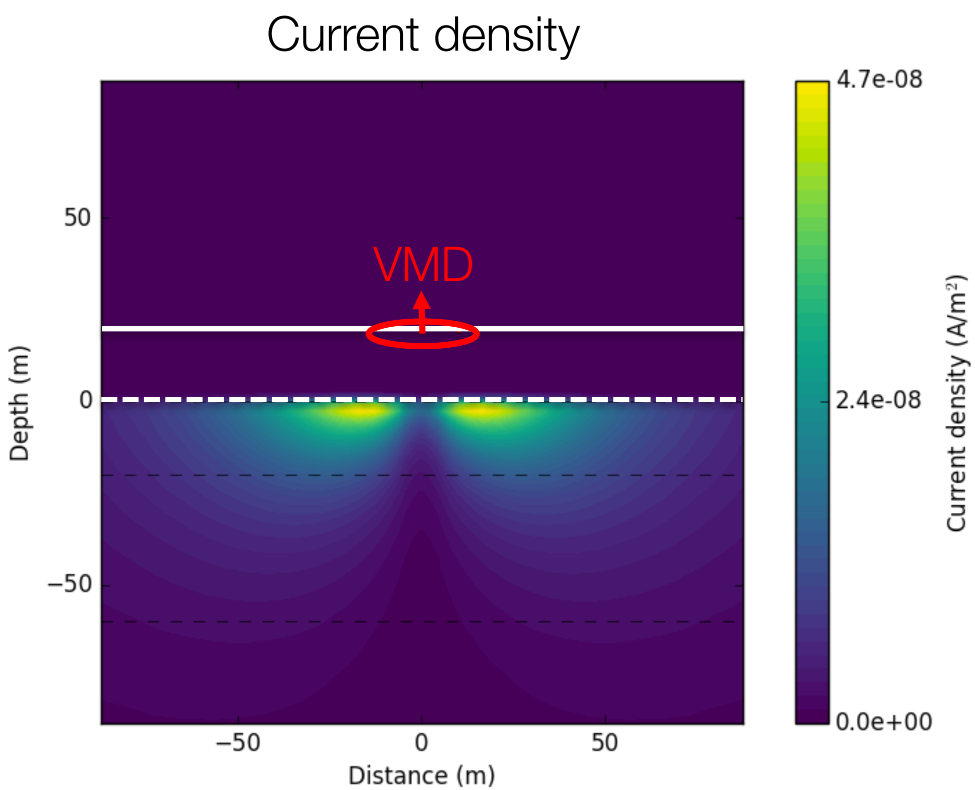
$\delta(t)$: Dirac-delta function

Footprint of Airborne EM system

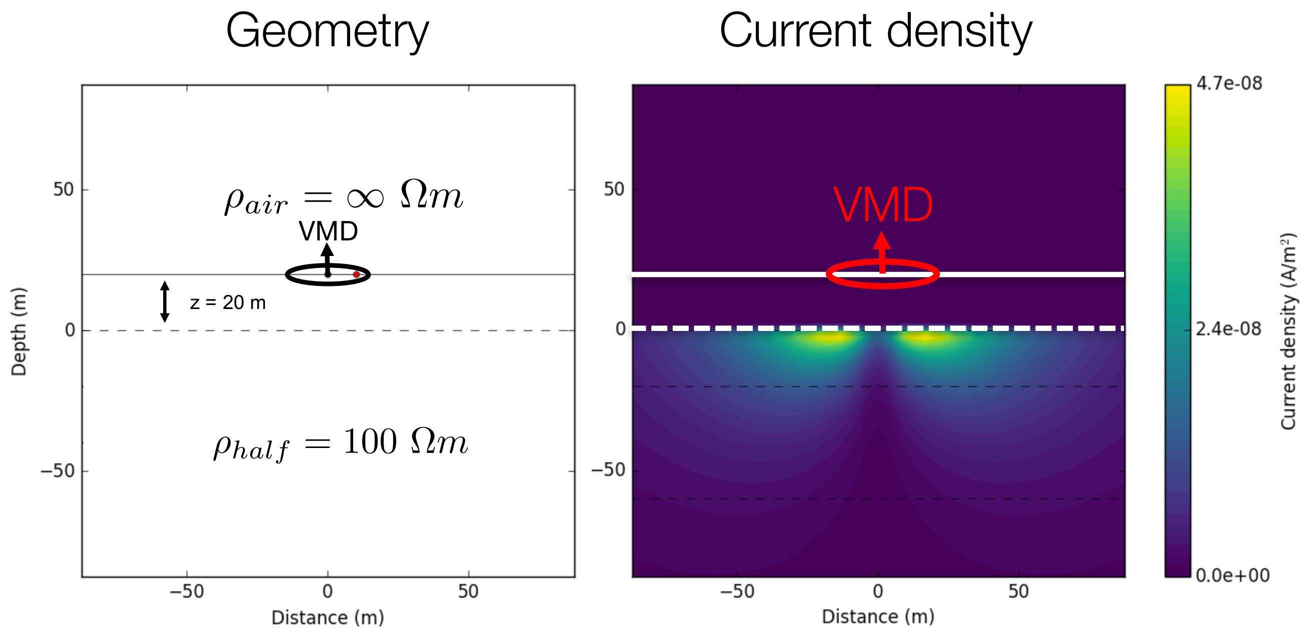
- What volume of earth is "seen" by the airborne system?
  - Where are the currents?

- Currents depend on
  - Transmitter
  - Waveform: time or frequency
  - Background conductivity

- Simple case: loop source over homogeneous earth

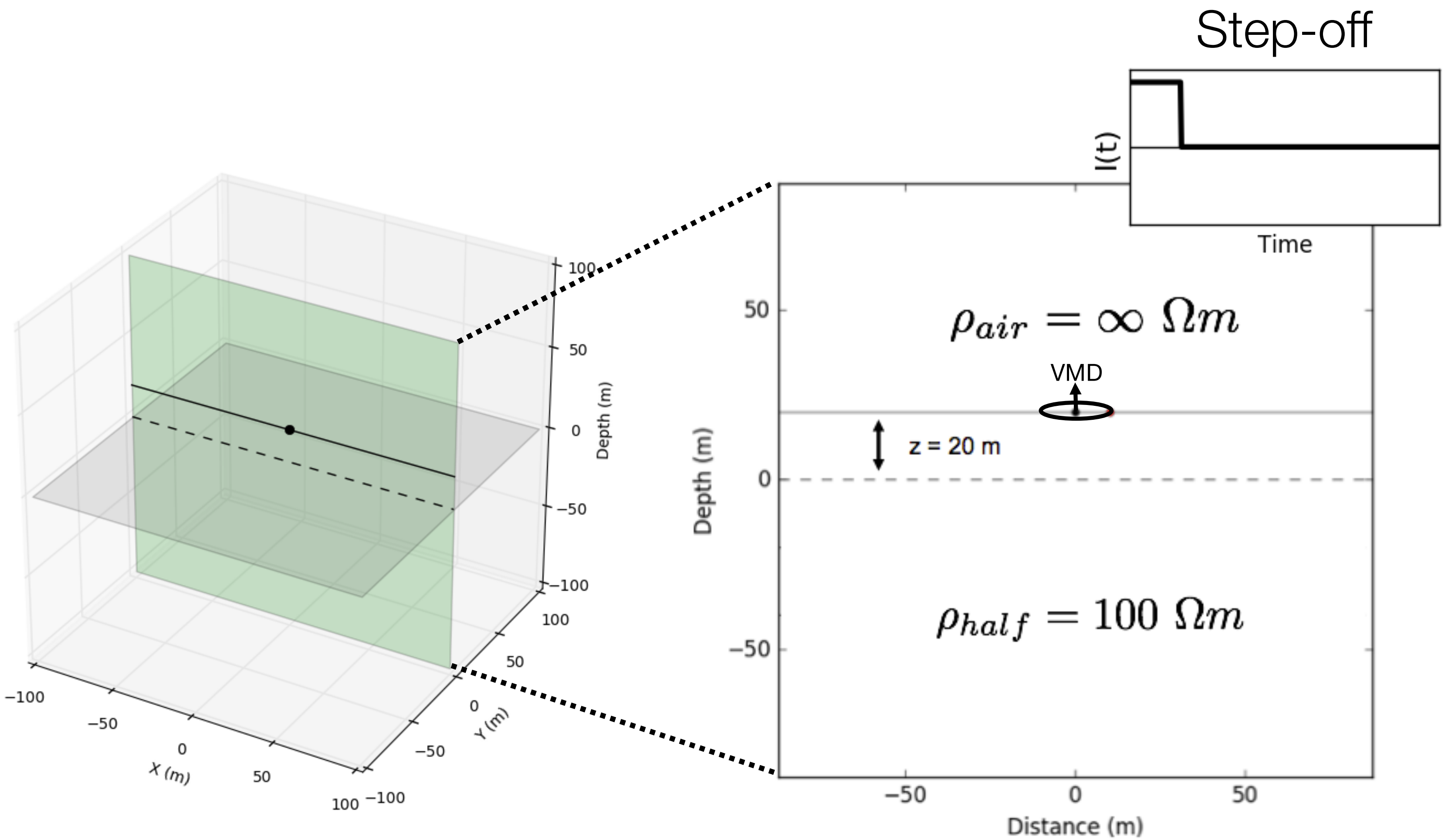


Vertical Magnetic Dipole (VMD)



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

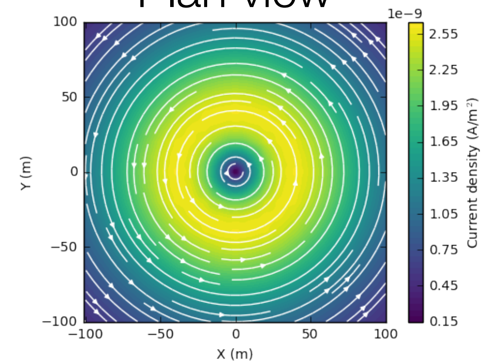
Vertical Magnetic Dipole over a halfspace (TDEM)



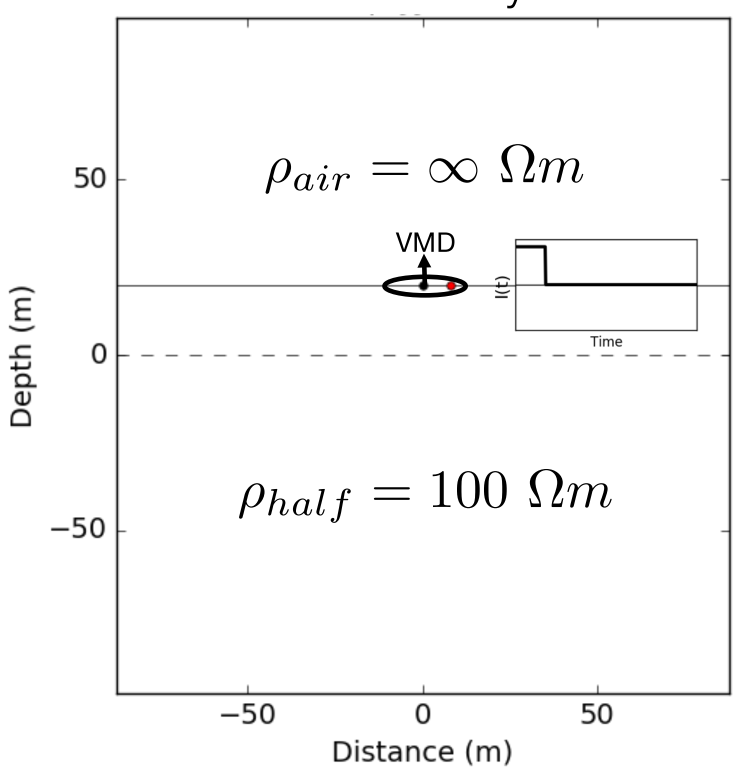
Current Density

- Time: 0.01ms

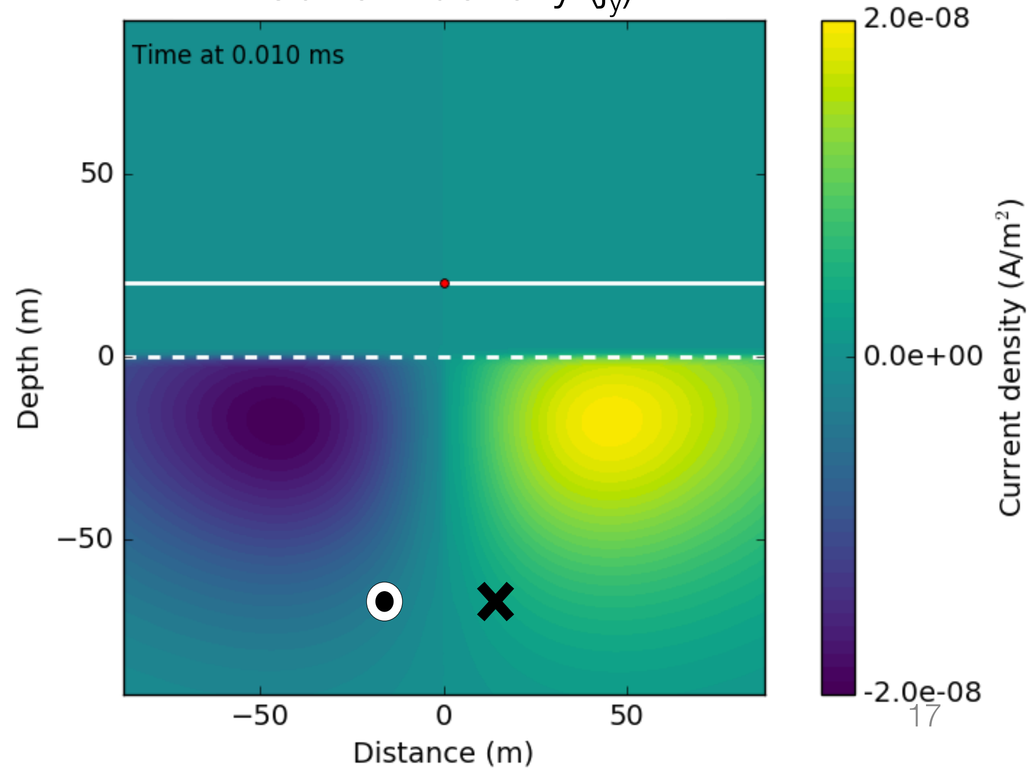
Plan view



Geometry

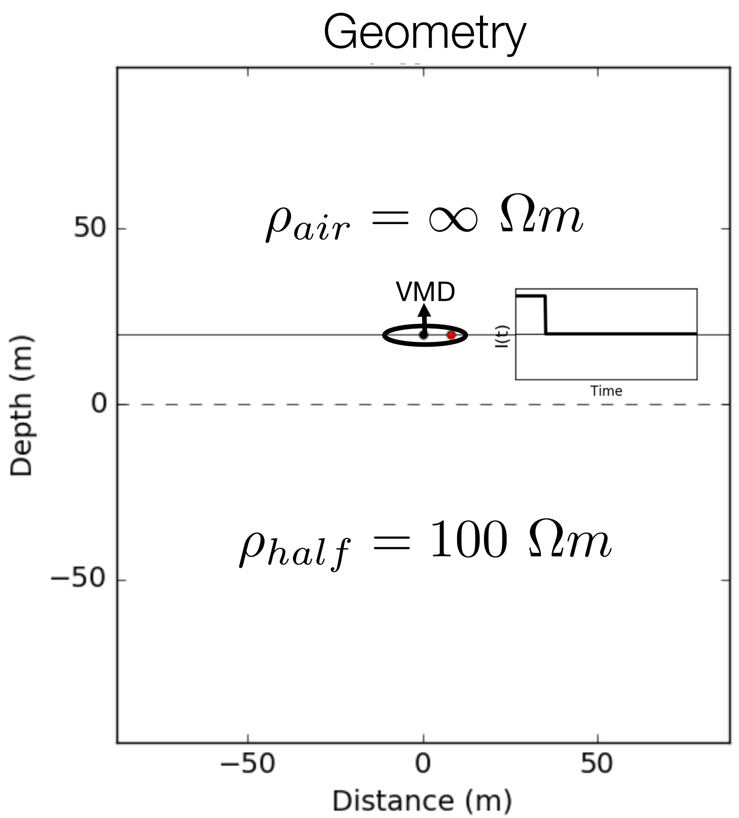


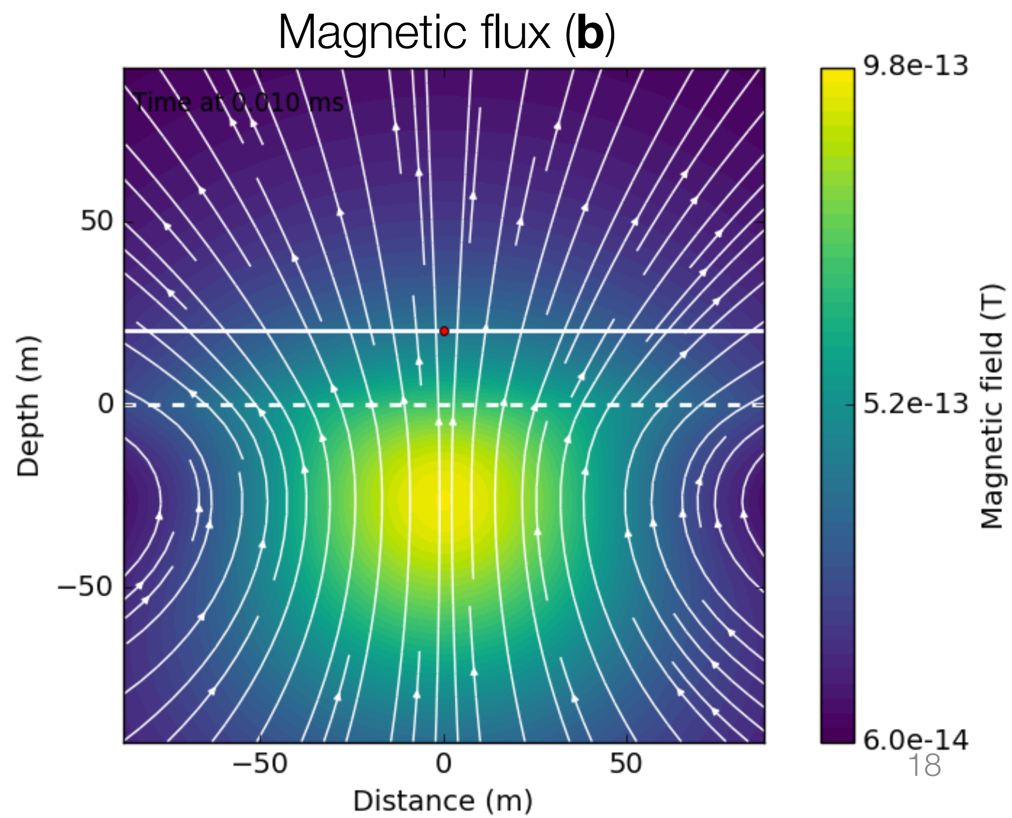
Current density (j_y)



Magnetic flux density

- Time: 0.01ms

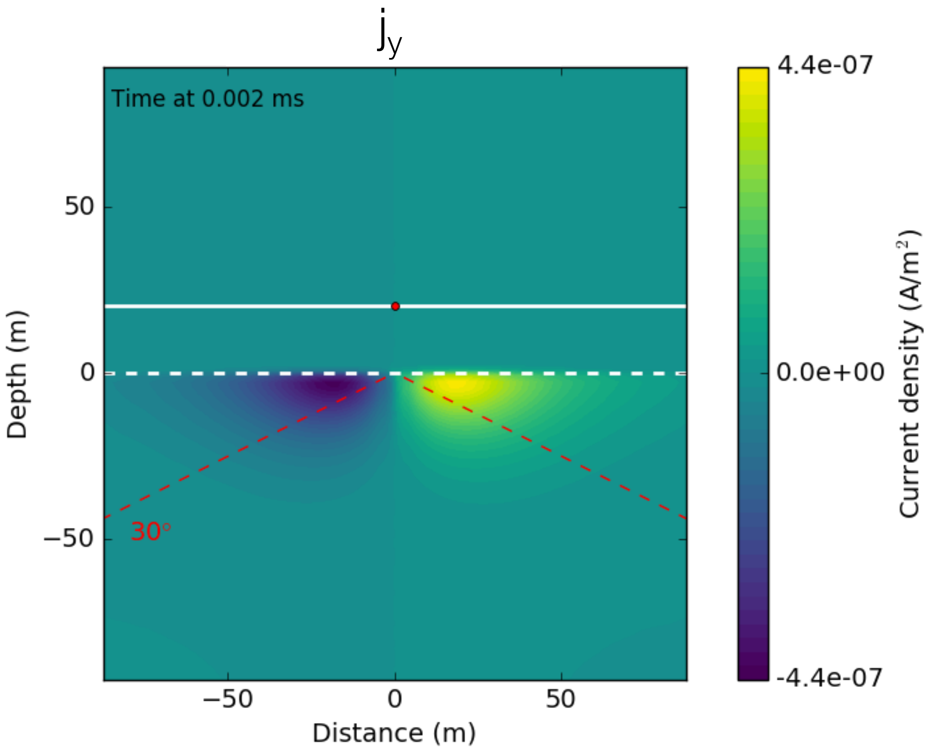


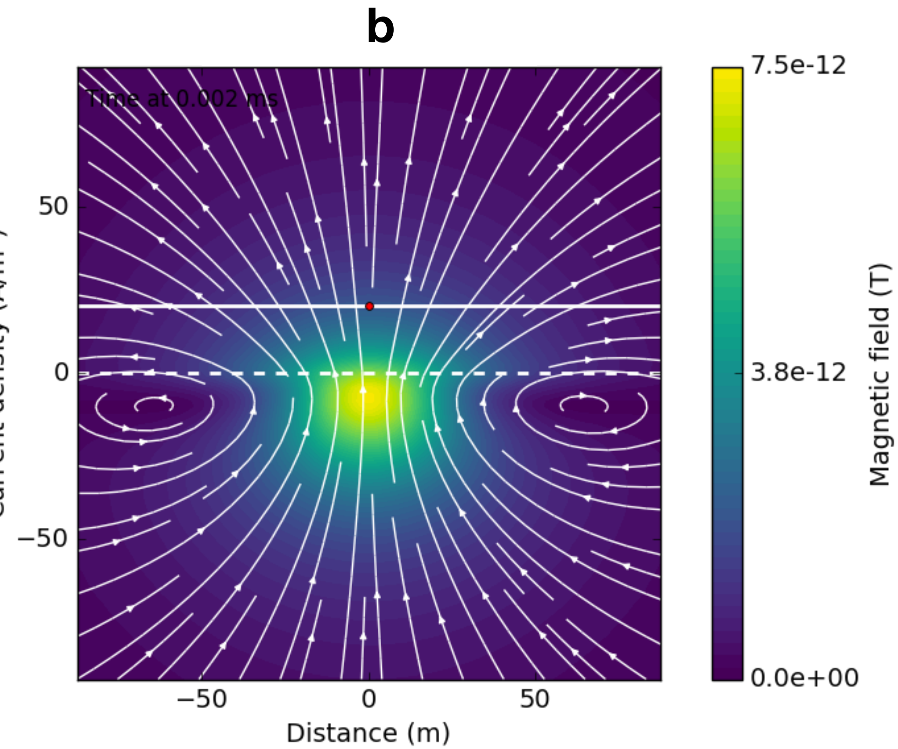


Propagation through time

- Time: 0.002ms
- diffusion distance = 18 m

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

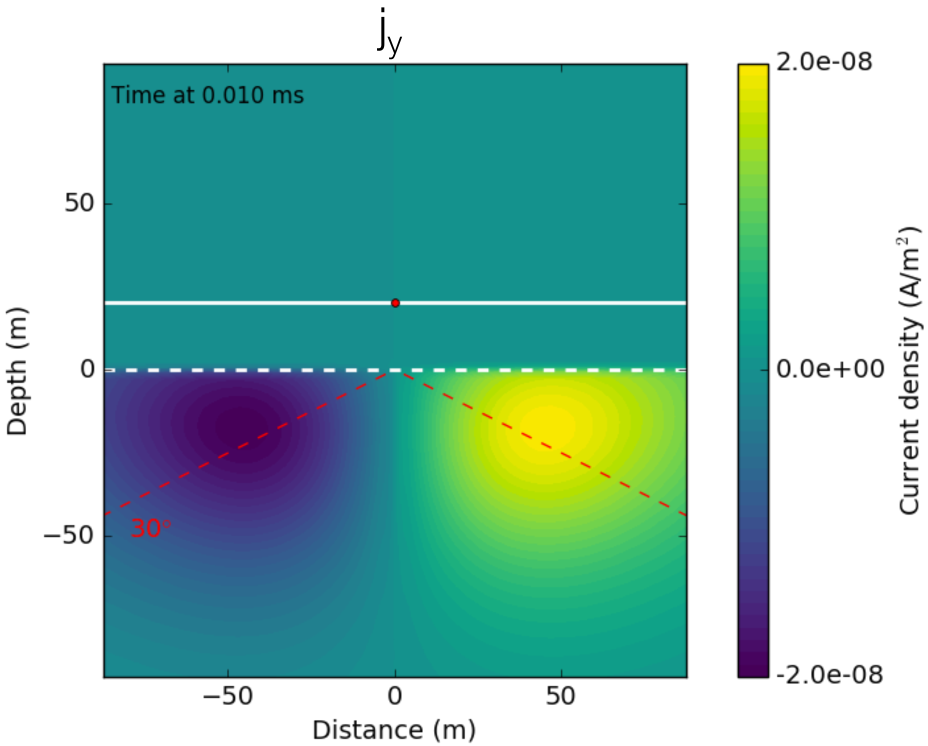


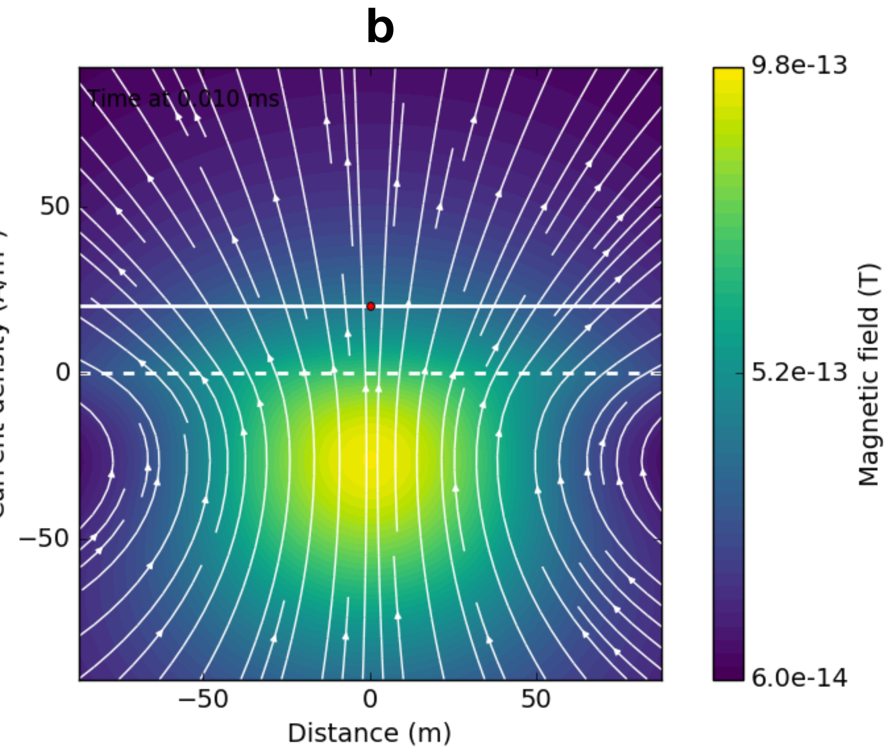


Propagation through time

- Time: 0.01ms
- diffusion distance = 38 m

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

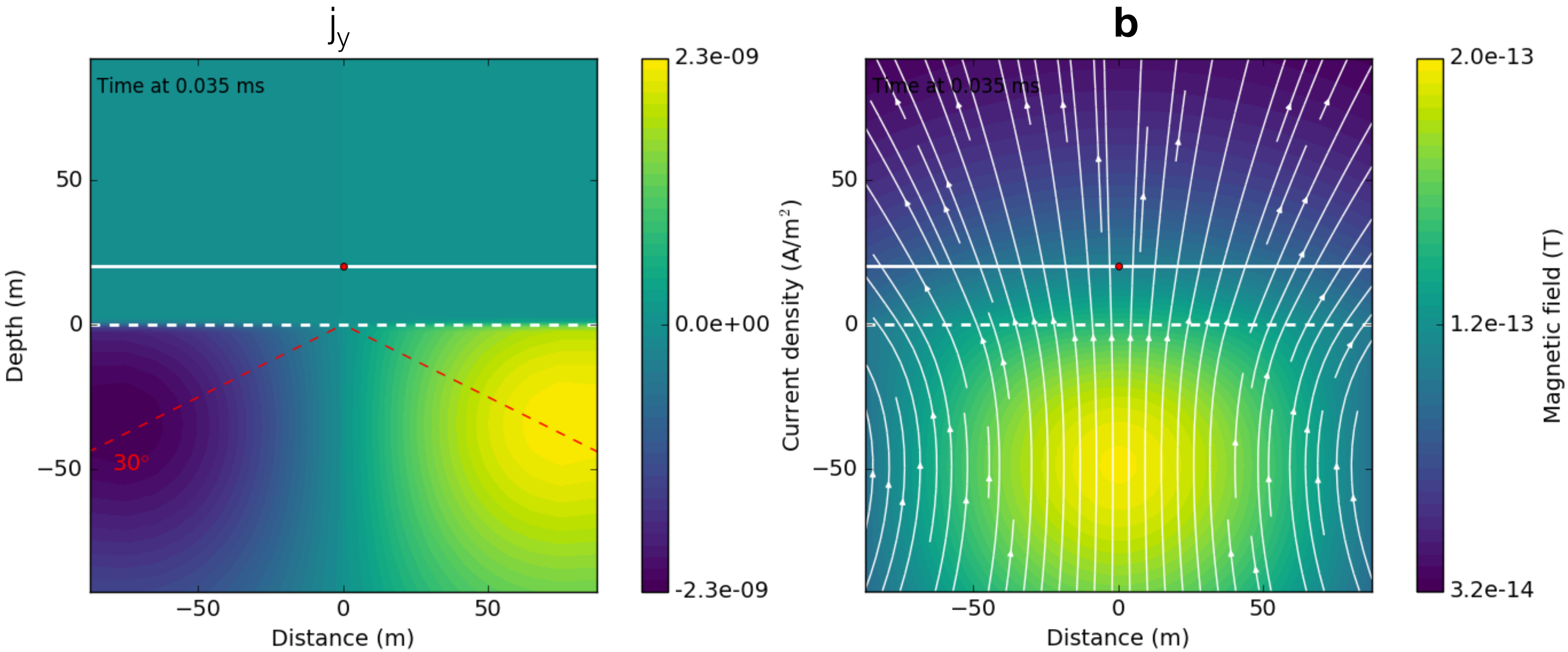




Propagation through time

- Time: 0.035ms
- diffusion distance = 75 m

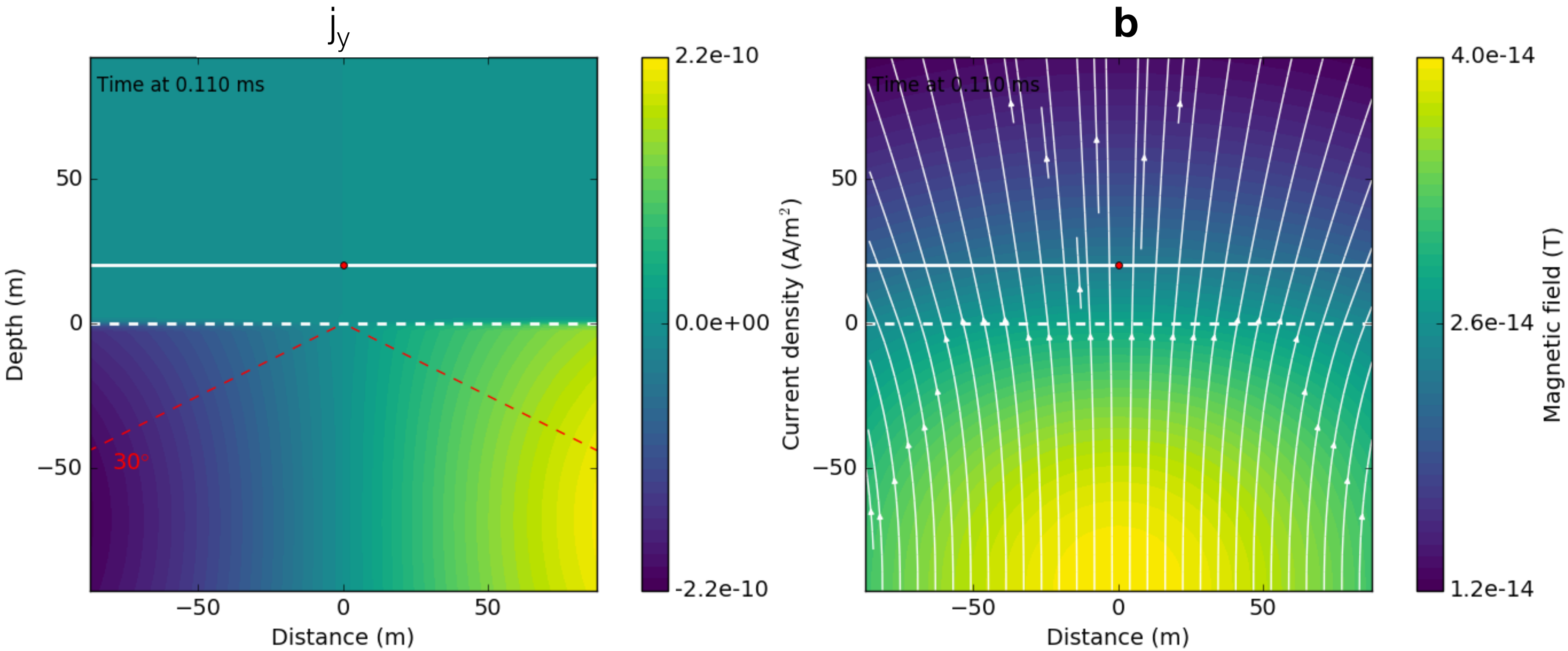
$$d = 1260\sqrt{t\rho}$$



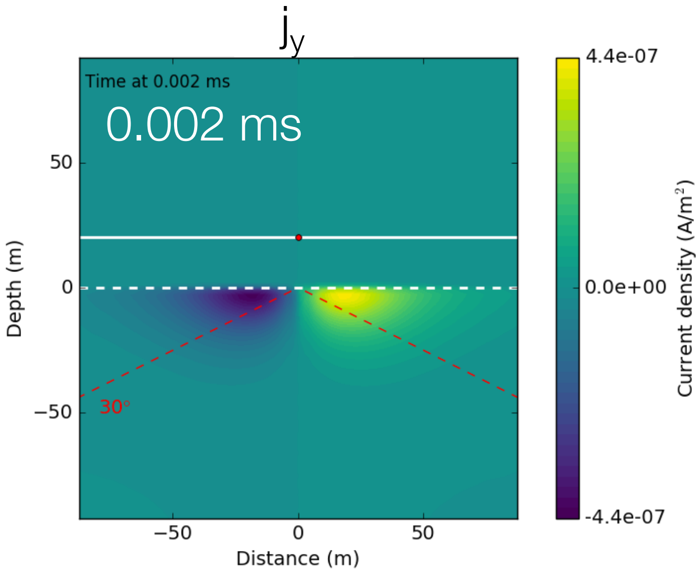
Propagation through time

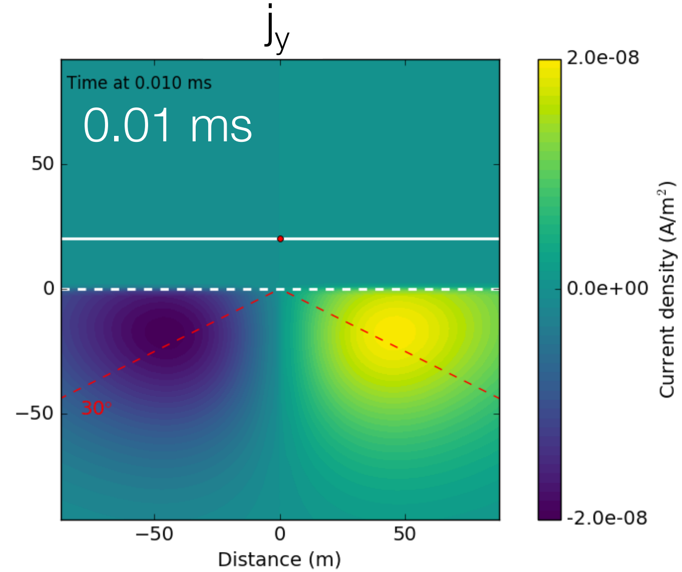
- Time: 0.110ms
- diffusion distance = 132 m

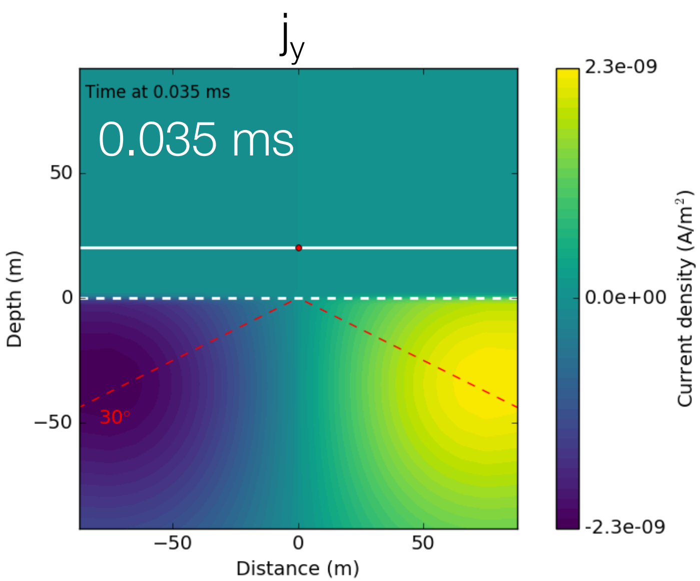
$$d = 1260\sqrt{t\rho}$$



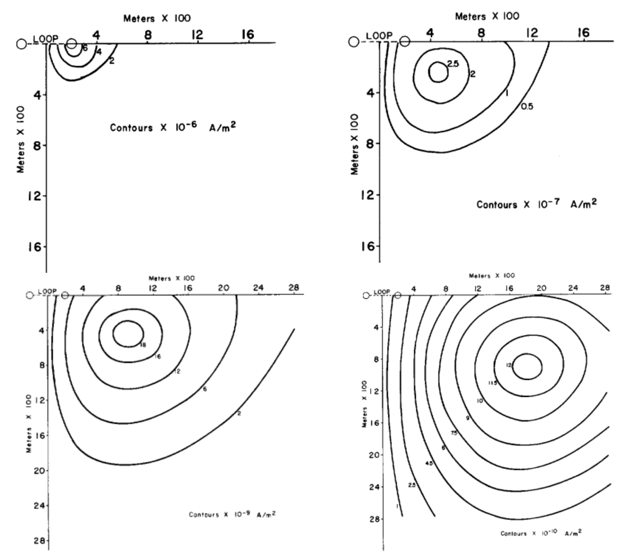
Summary: propagation through time







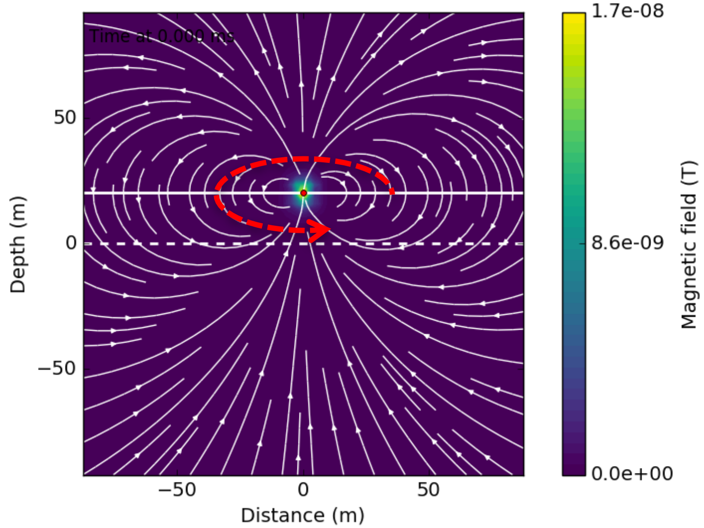
Nabighian (1979)



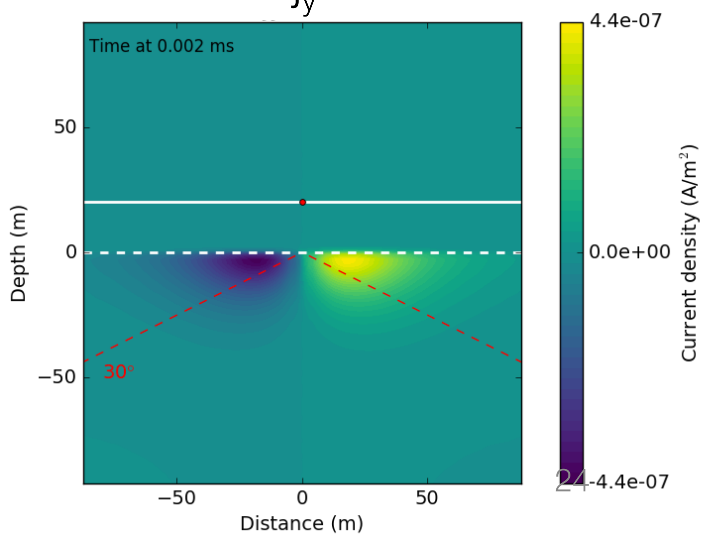
Important points

- 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)



j_y



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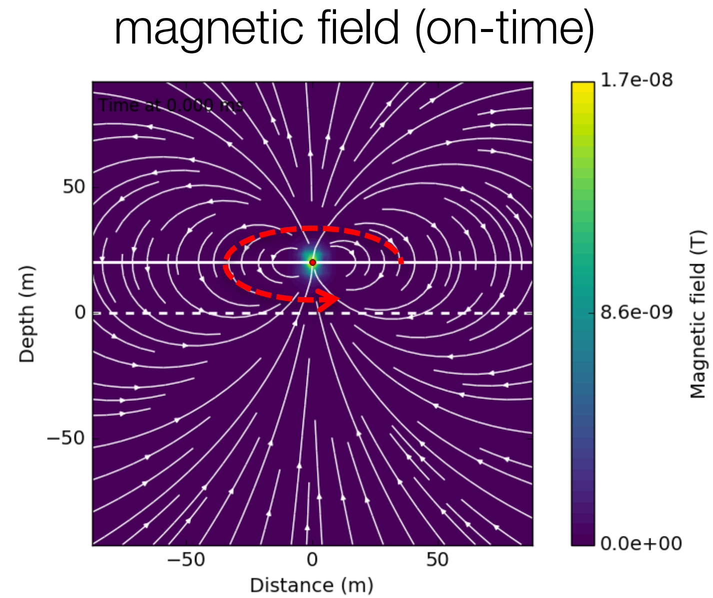
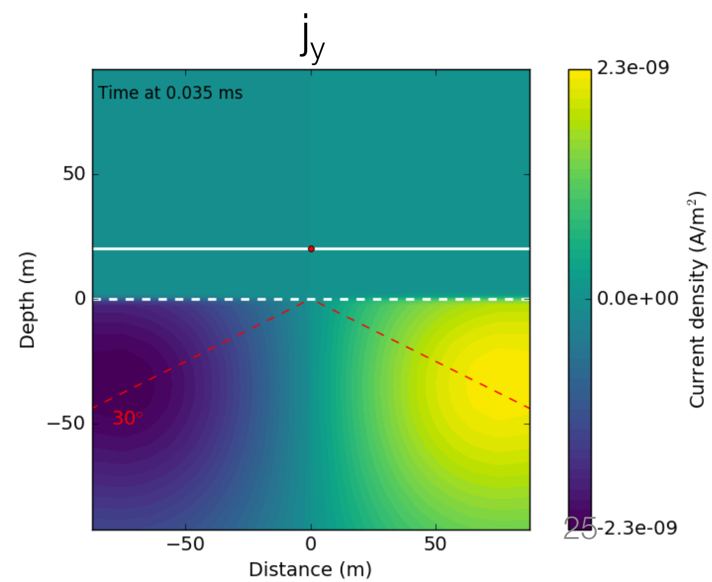
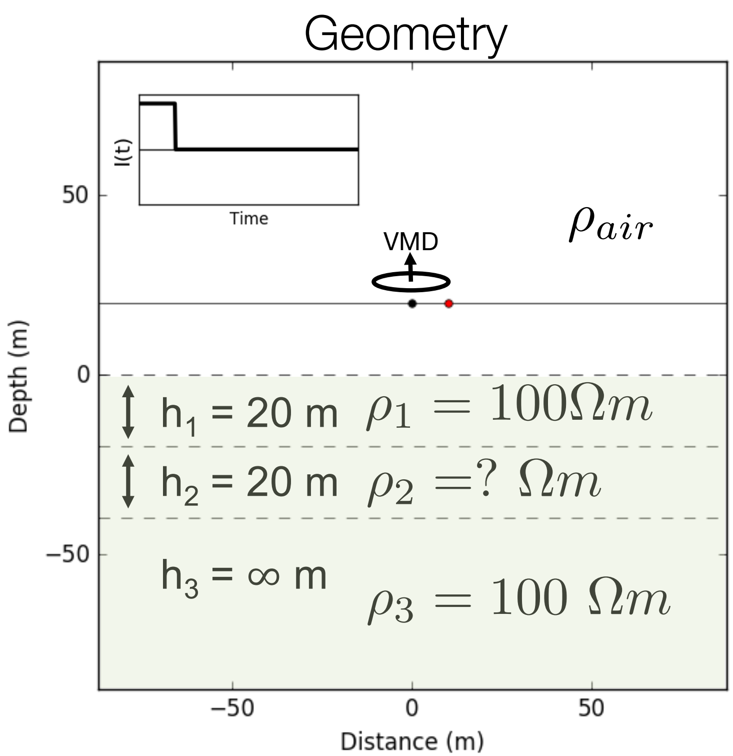




Layered earth

- 3 layers + air,
- ρ_2 varies

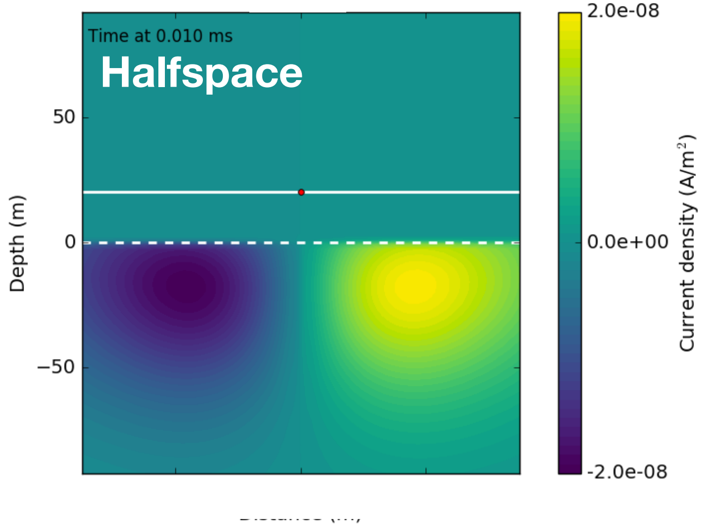


- Four different cases:
  - Halfspace
    $\rho_2 = 100 \ \Omega\text{m}$
  - Resistive
    $\rho_2 = 1000 \ \Omega\text{m}$
  - Conductive
    $\rho_2 = 10 \ \Omega\text{m}$
  - Very conductive
    $\rho_2 = 1 \ \Omega\text{m}$

- Fields
  - j_y off-time
  - **b** off-time

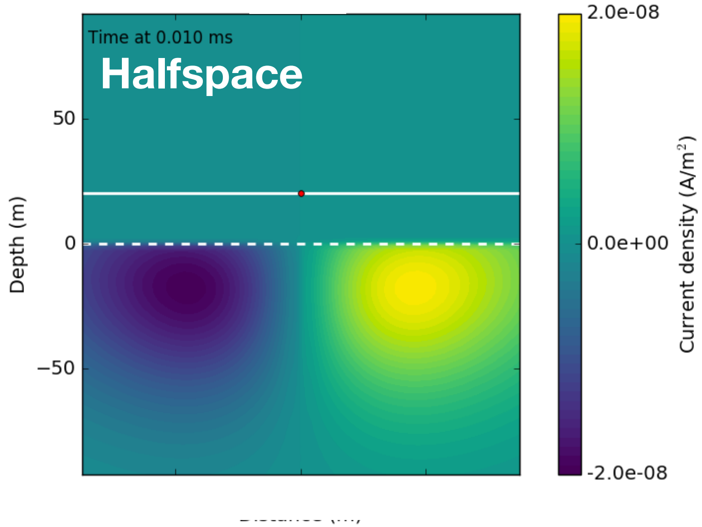
Layered earth currents (j_y)

$\rho_2 = 100\ \Omega m$

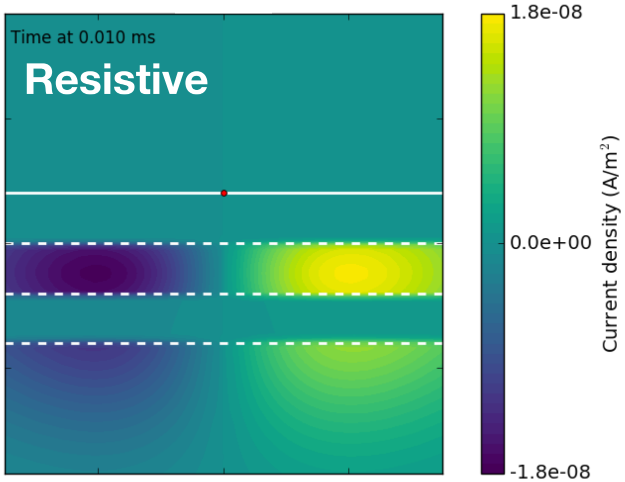


Layered earth currents (j_y)

ρ_2 = 100 Ωm

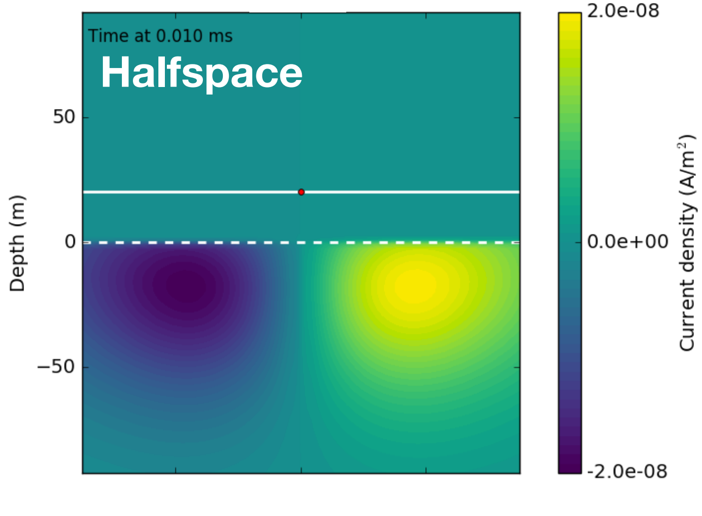


ρ_2 = 1000 Ωm

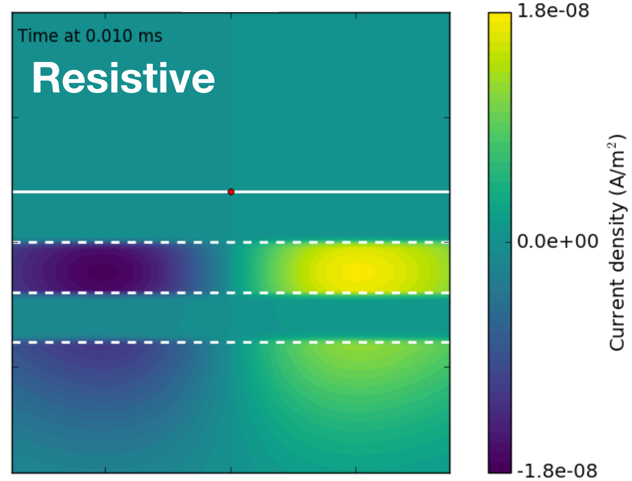


Layered earth currents (j_y)

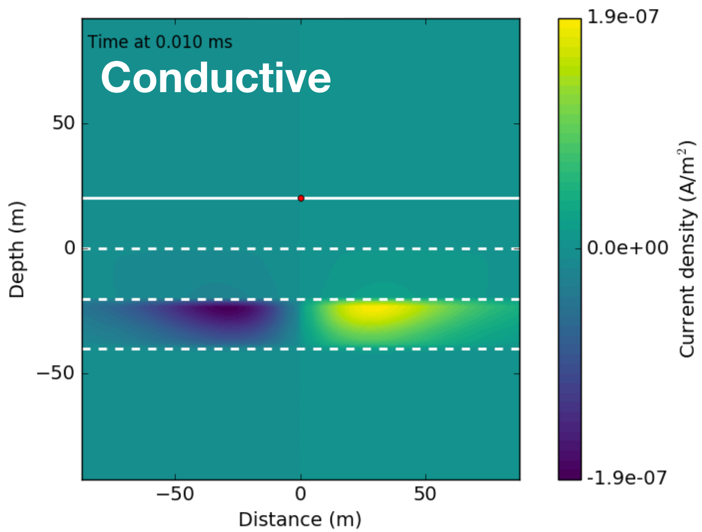
$\rho_2 = 100\ \Omega m$



$\rho_2 = 1000\ \Omega m$

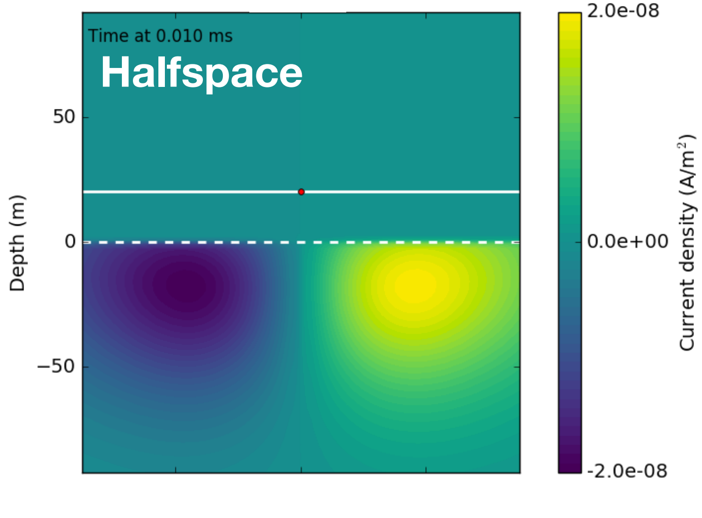


$\rho_2 = 10\ \Omega m$

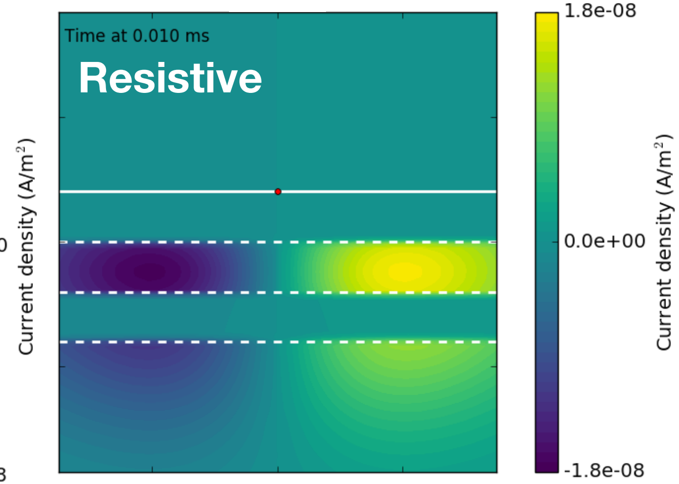


Layered earth currents (j_y)

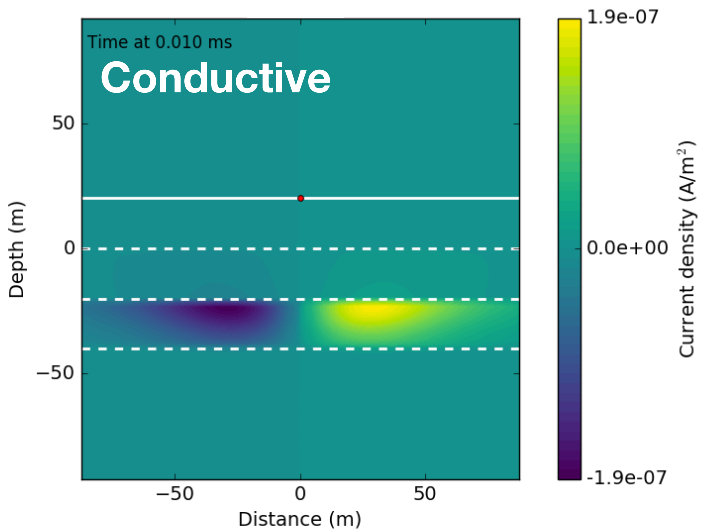
$\rho_2 = 100\ \Omega m$



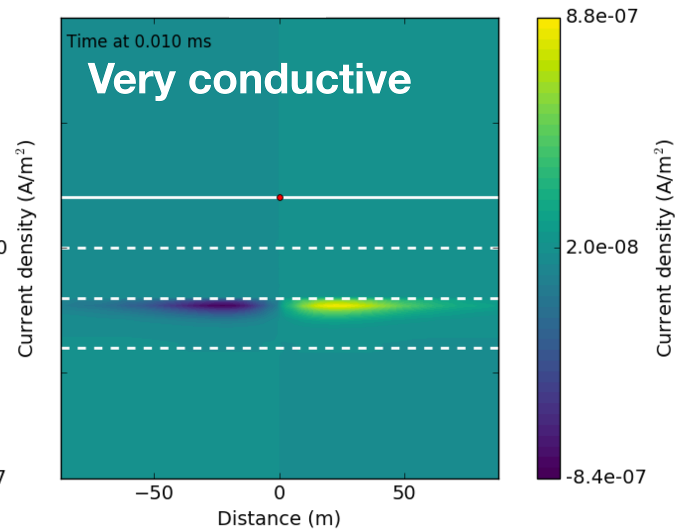
$\rho_2 = 1000\ \Omega m$



$\rho_2 = 10\ \Omega m$

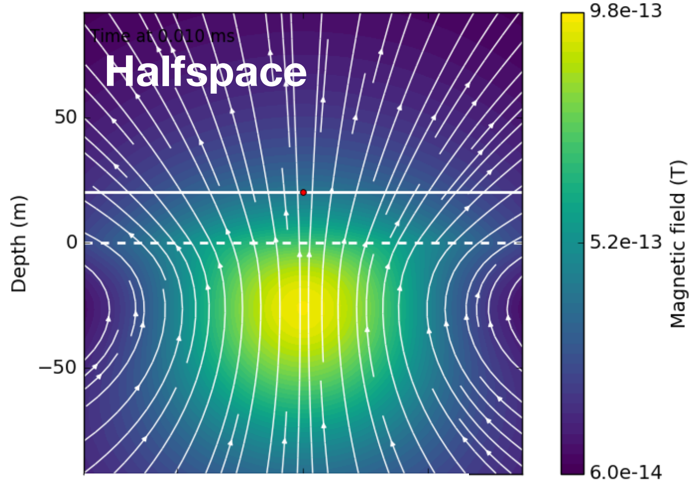


$\rho_2 = 1\ \Omega m$

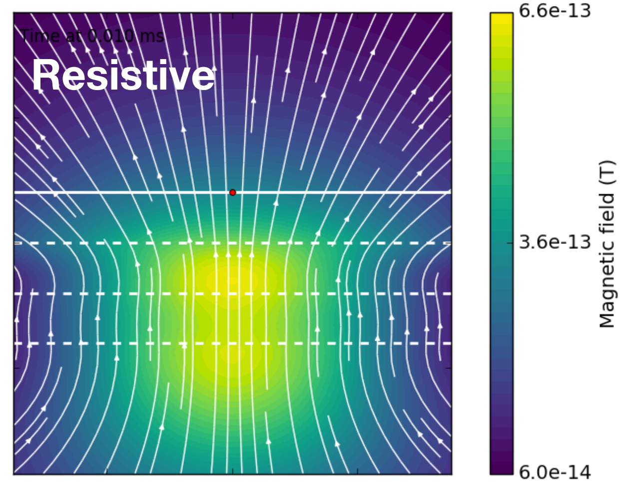


Layered earth mag. fields (**b**)

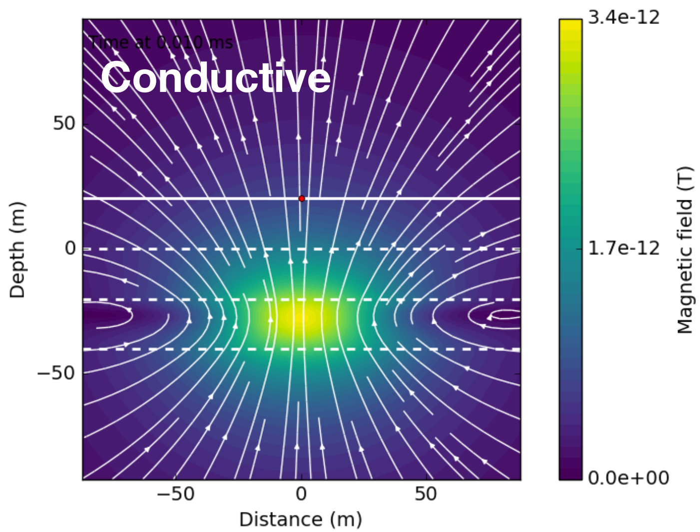
ρ_2 = 100 Ωm



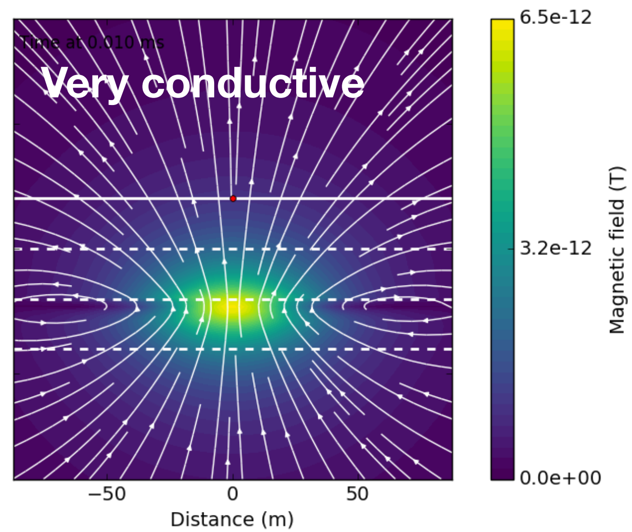
ρ_2 = 1000 Ωm



ρ_2 = 10 Ωm

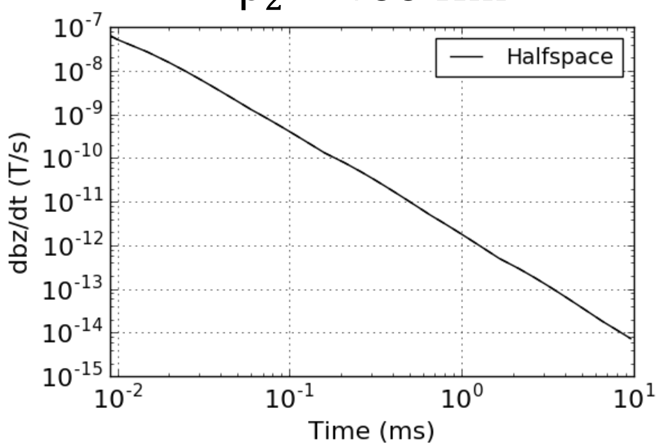


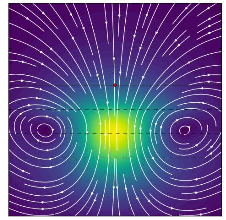
ρ_2 = 1 Ωm



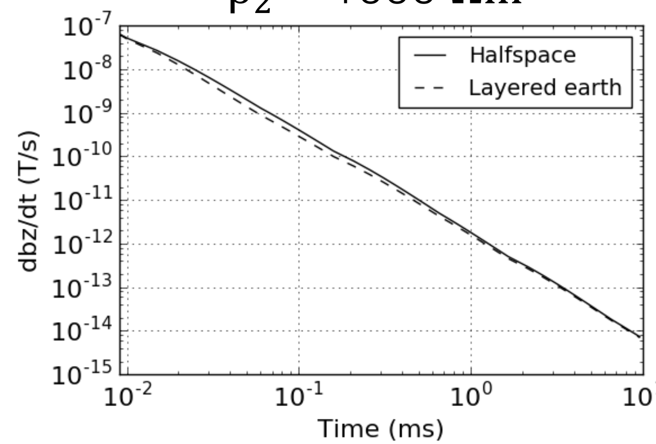
db_z/dt sounding curves

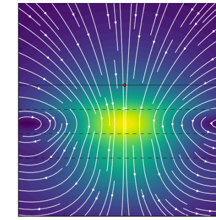
ρ_2 = 100 Ωm



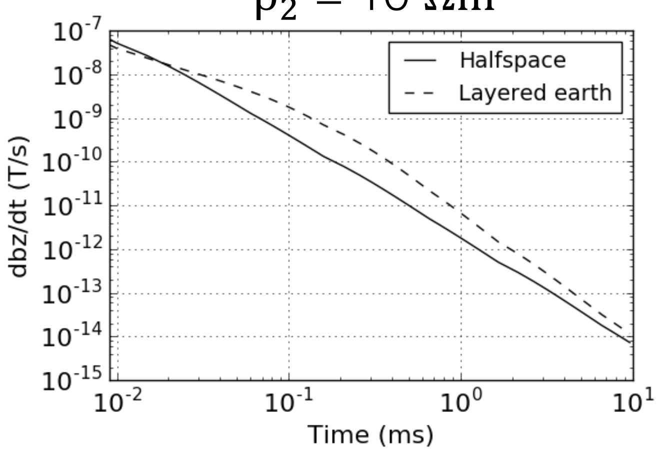


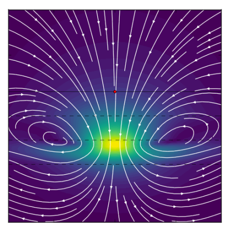
ρ_2 = 1000 Ωm



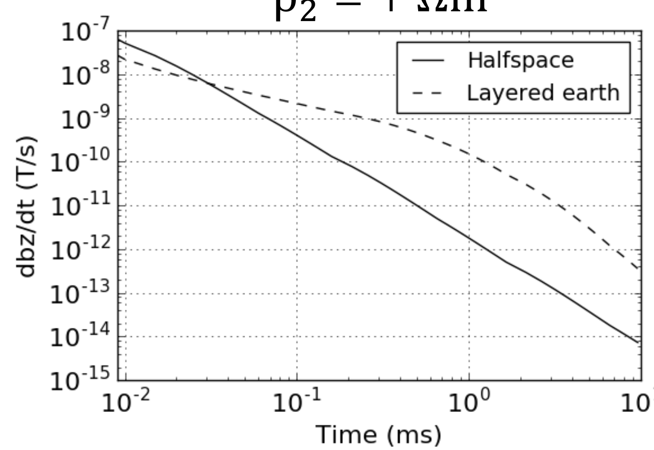


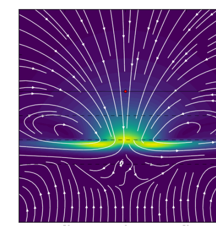
ρ_2 = 10 Ωm





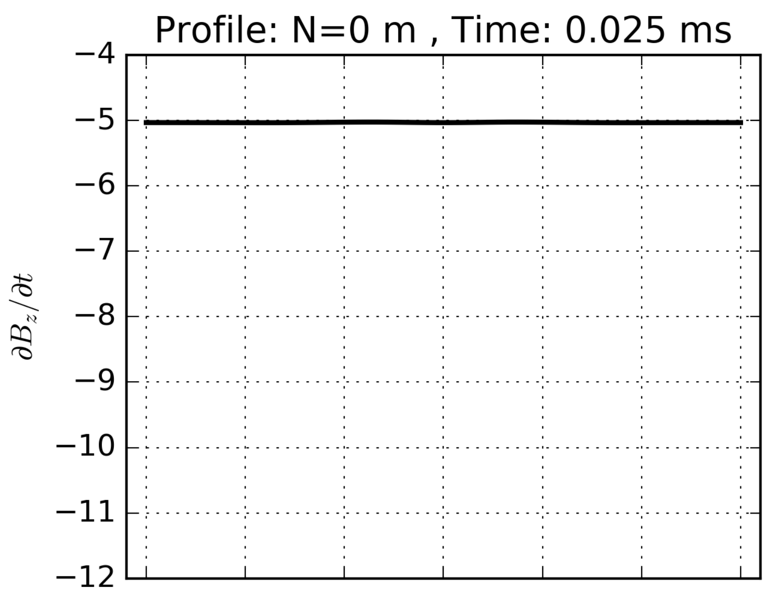
ρ_2 = 1 Ωm



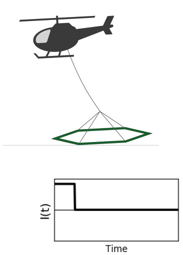


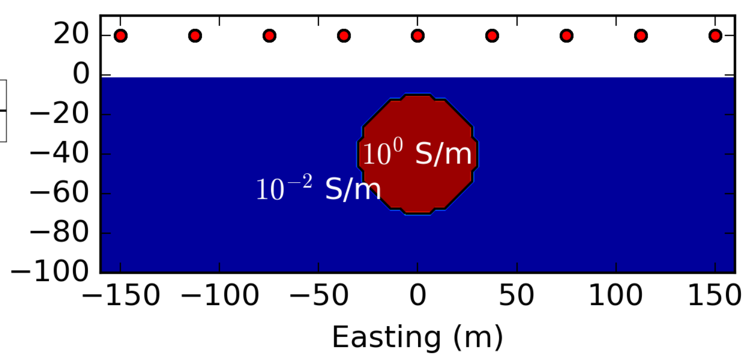
Airborne example: conductive sphere

Data profile

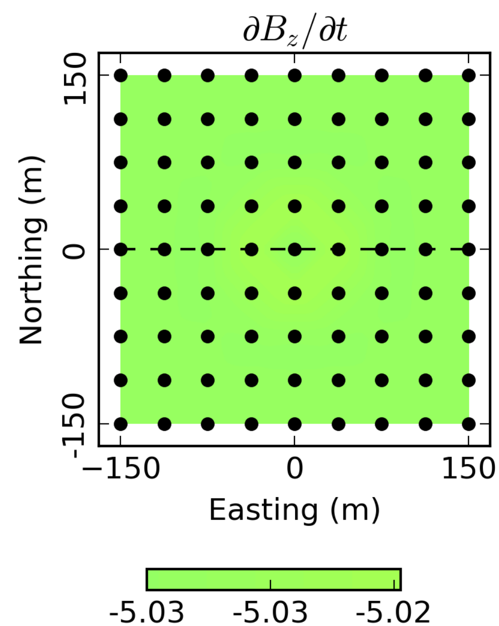


Conductivity



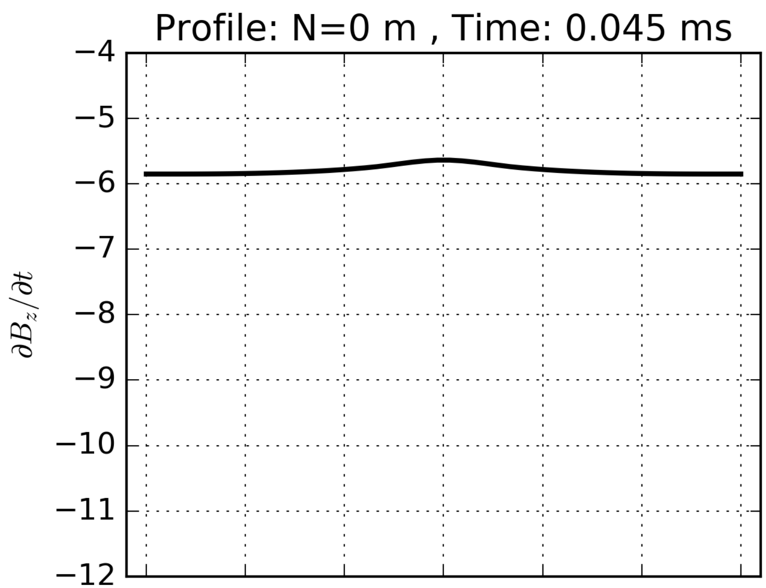


Data map

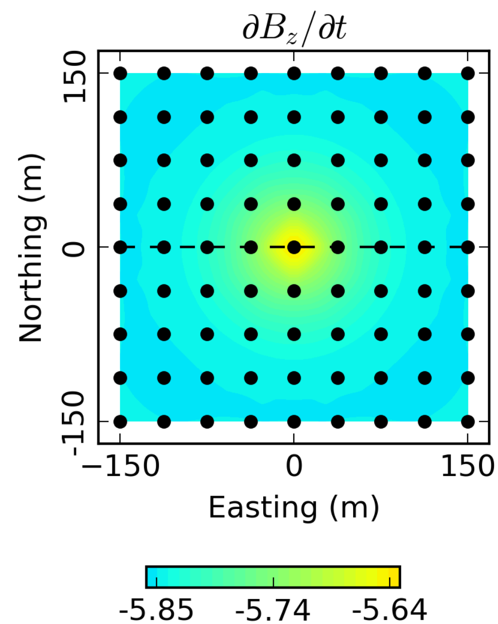


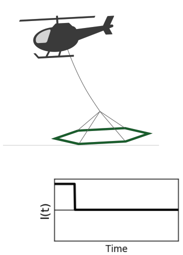
Airborne example: conductive sphere

Data profile

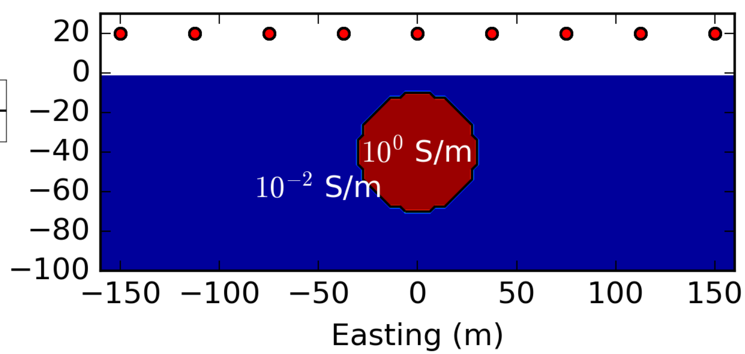


Data map



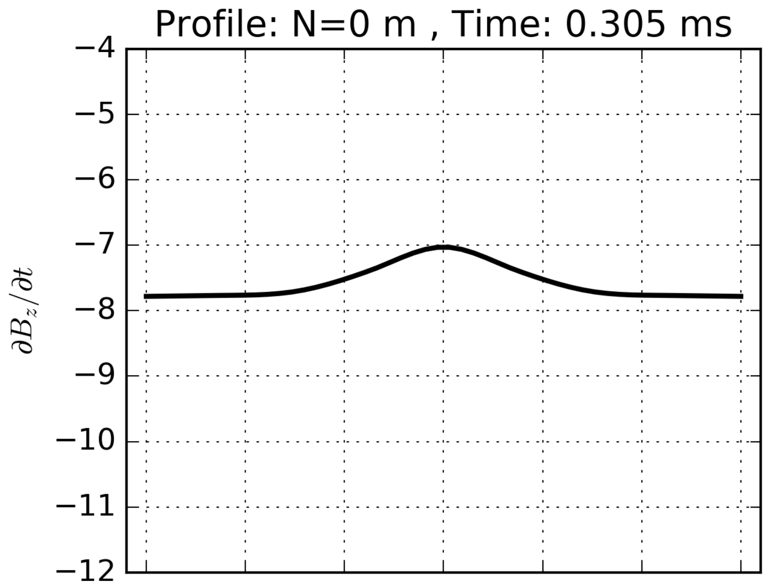


Conductivity

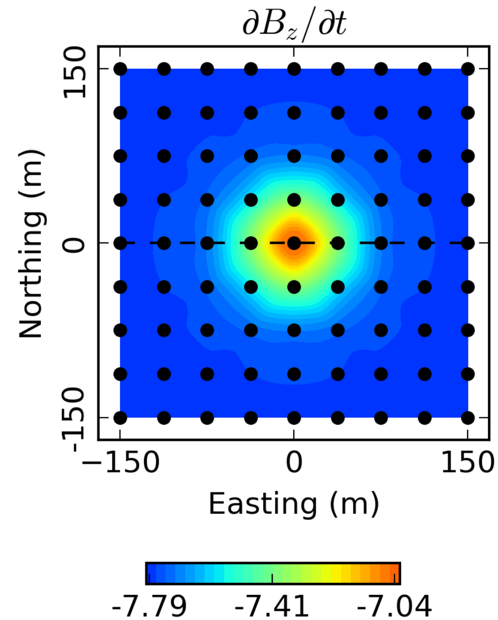


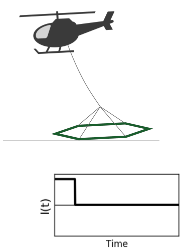
Airborne example: conductive sphere

Data profile

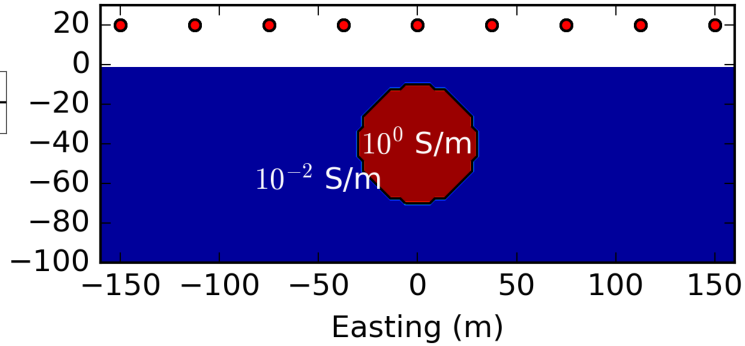


Data map



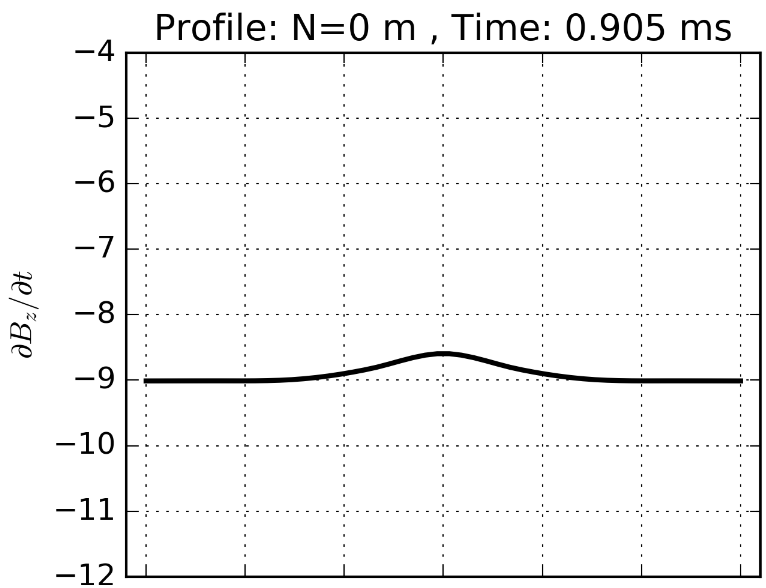


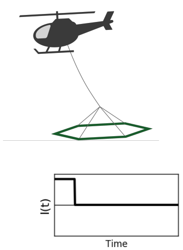
Conductivity



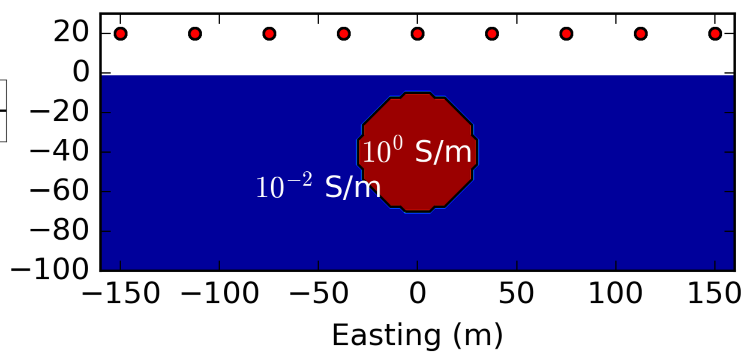
Airborne example: conductive sphere

Data profile

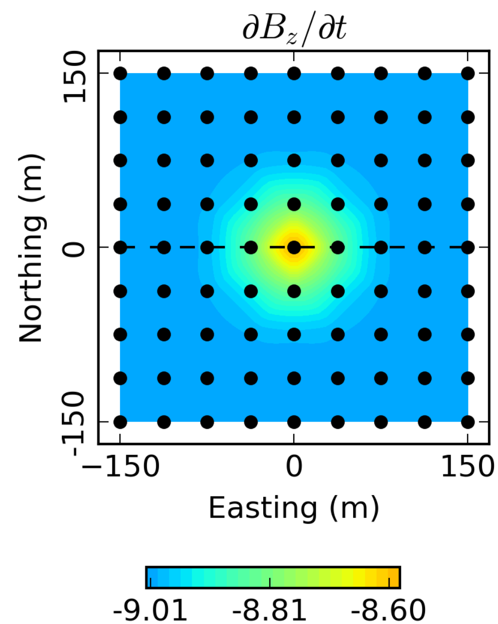




Conductivity

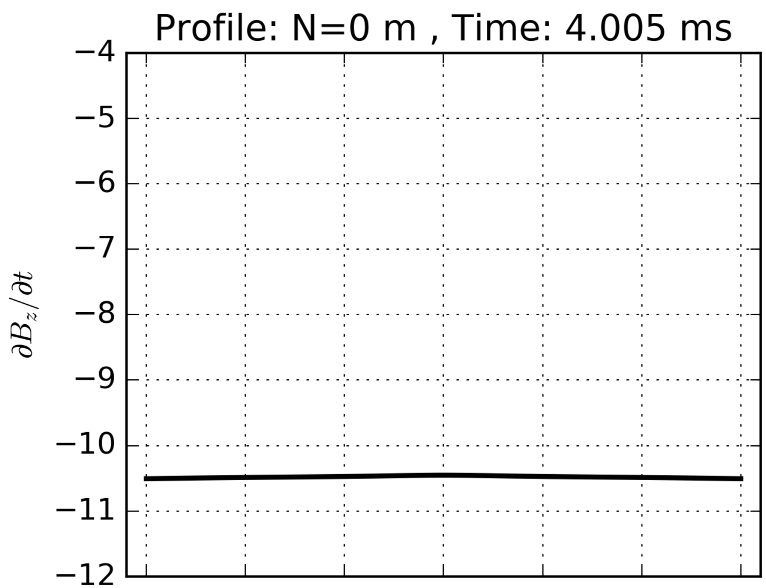


Data map

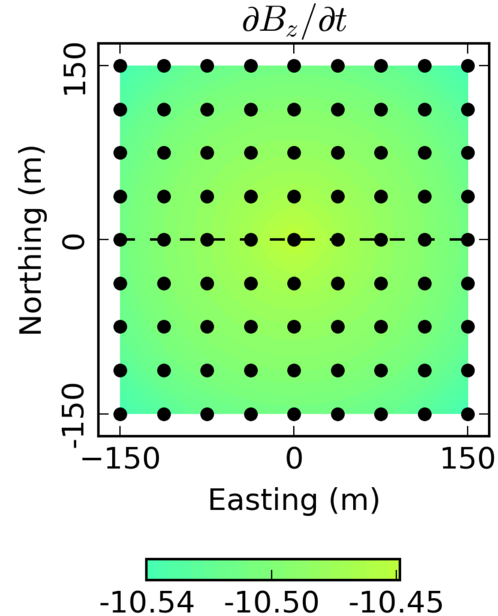


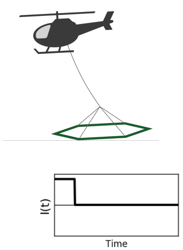
Airborne example: conductive sphere

Data profile

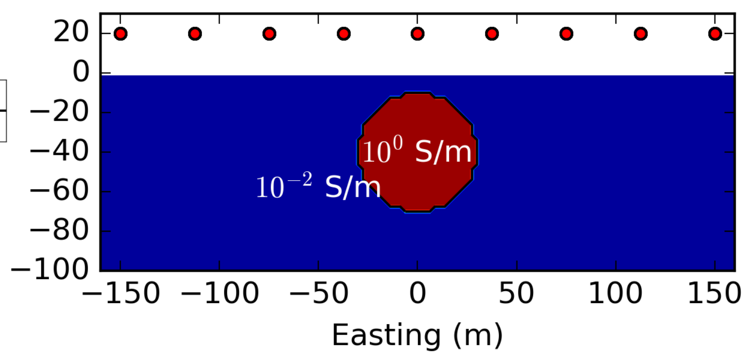


Data map



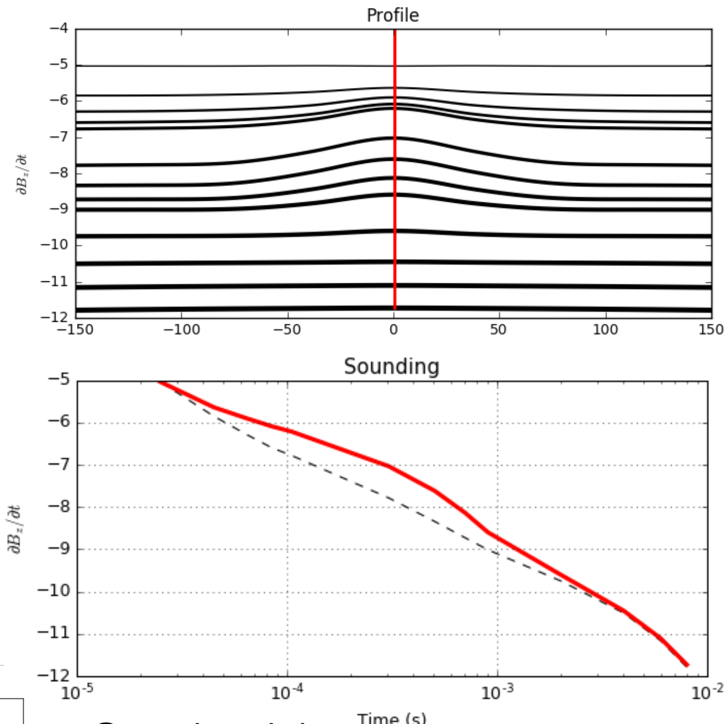


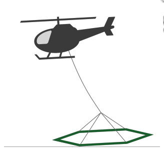
Conductivity

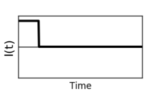


Summary: airborne example

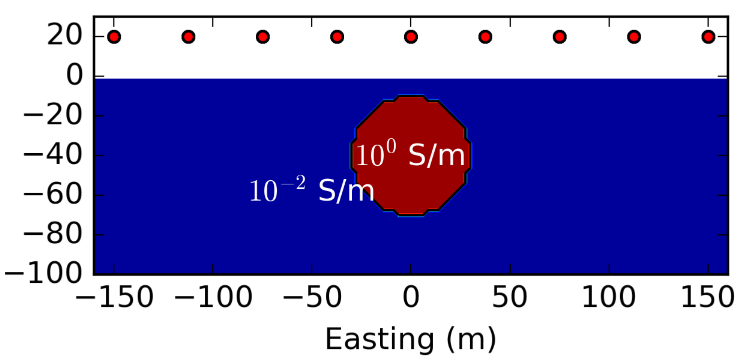
Data profile



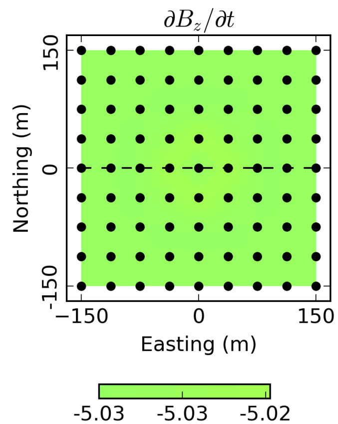




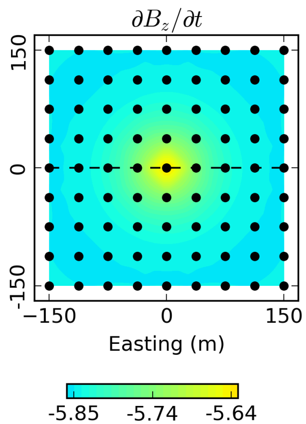
Conductivity



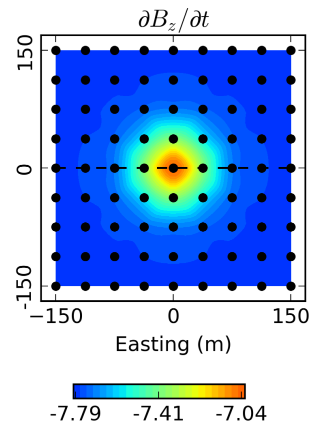
0.025 ms



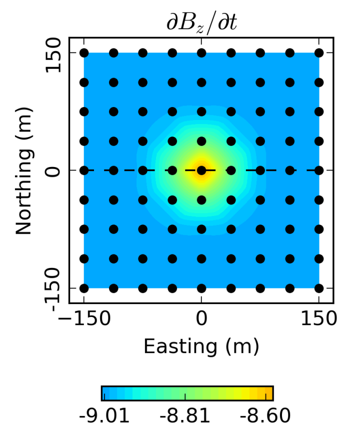
0.045 ms



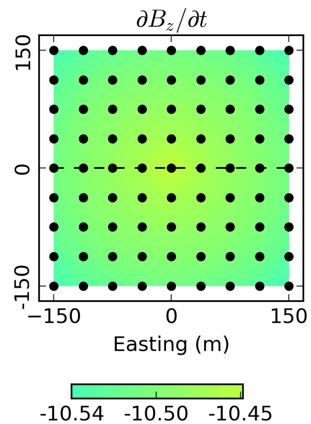
0.305 ms



0.905 ms

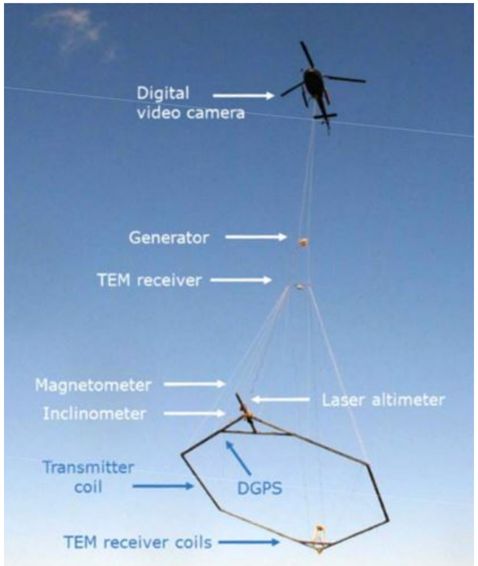


4.005 ms



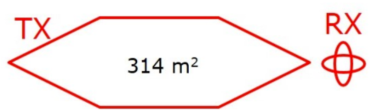
Some Airborne TDEM Systems

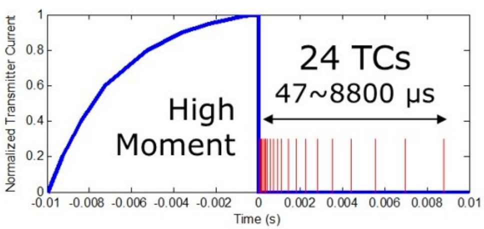
SkyTEM (2006)



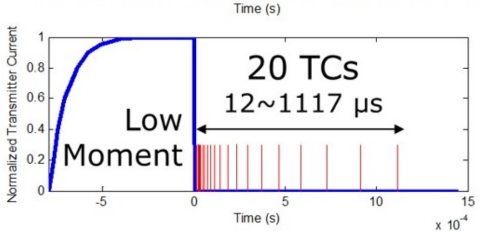
Area = 314 m^2

Peak dipole moment:
- HM: 113040 NIA
- LM: 12560 NIA



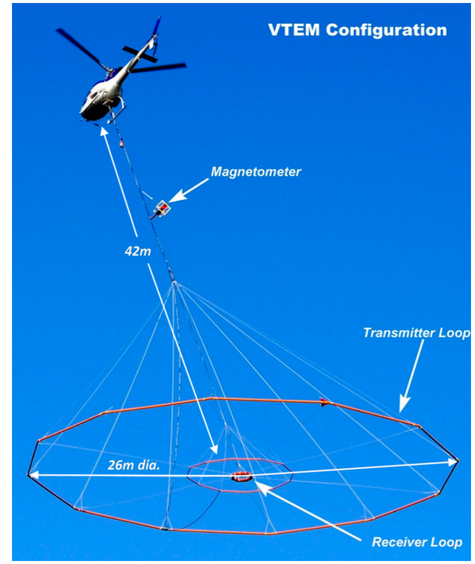


Peak current: 90 A
Turns: 4
On-time: 10 ms
Off-time: 10 ms



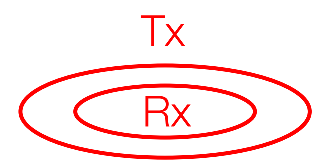
Peak current: 40 A
Turns: 1
On-time: 0.8 ms
Off-time: 1.45 ms

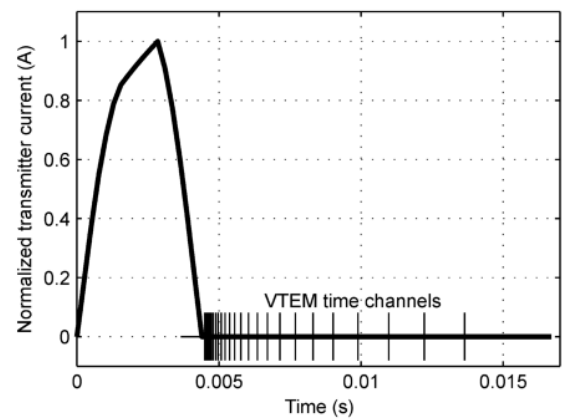
VTEM (2007)



Area = 535 m^2

Peak dipole moment:
- 503,100 NIA





Peak current: 235 A
Turns: 4
On-time: 4.5 ms
Off-time: 9.1 ms

Outline

Setup

Time Domain EM

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

Frequency Domain EM

Questions

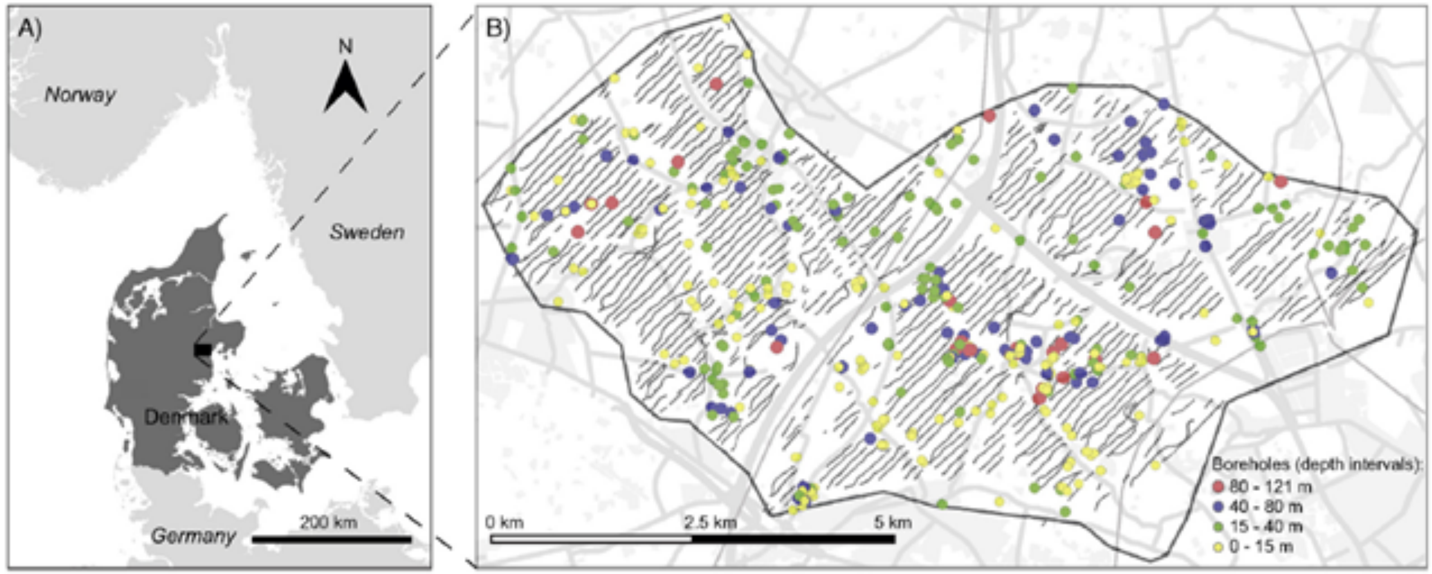
Case History: Kasted

Vilhelmsen et al. (2016)

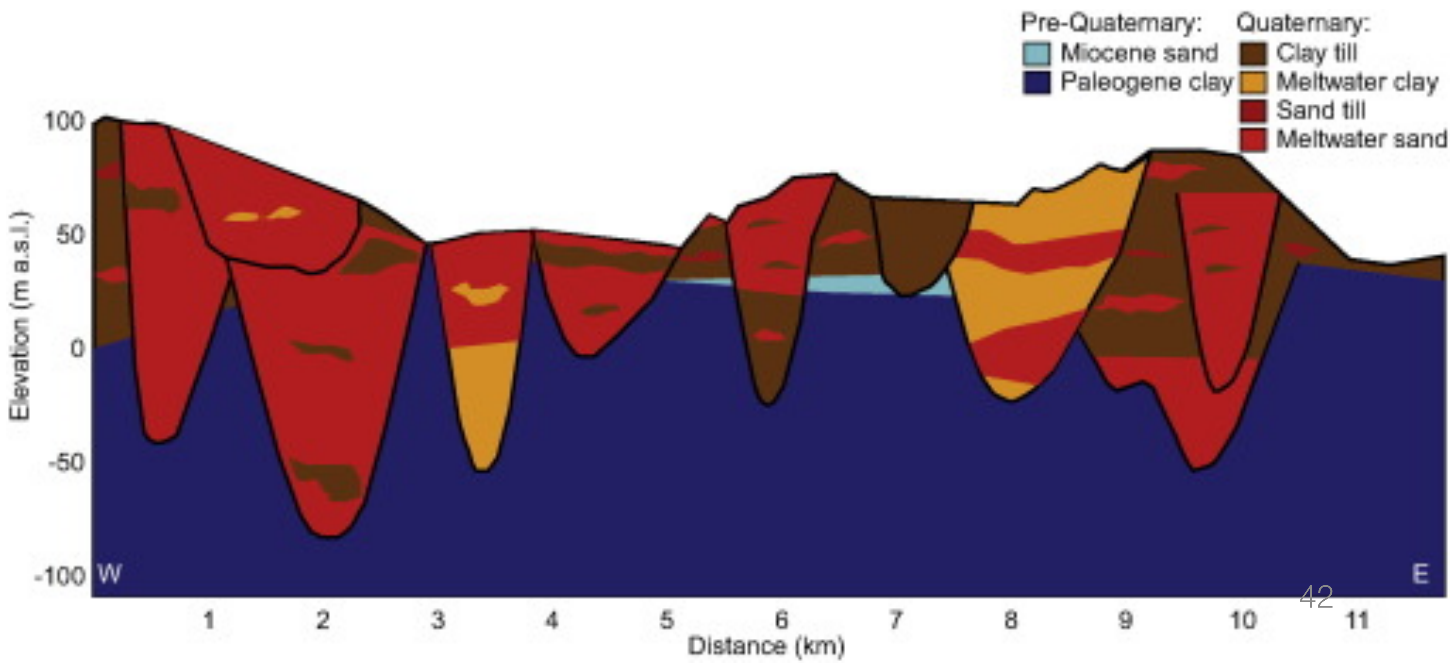
Setup

A) Survey Area: Kasted, Demark

B) Borehole locations

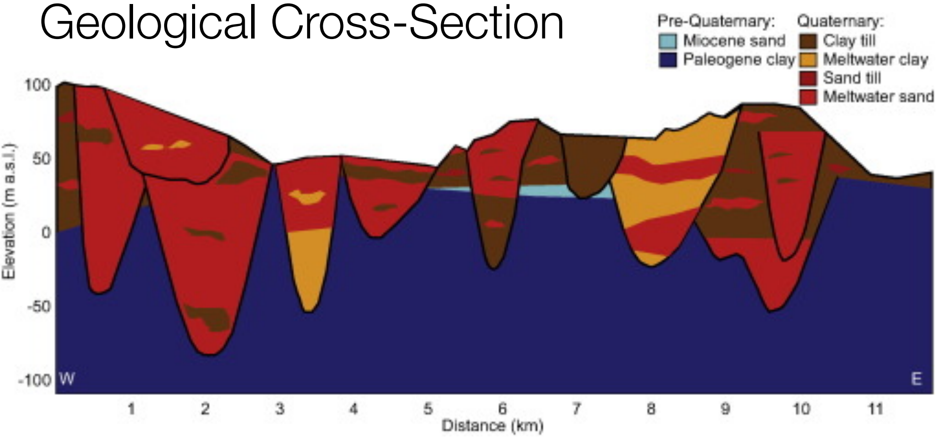


Local Geology: W-E cross-section



Properties

Geological Cross-Section

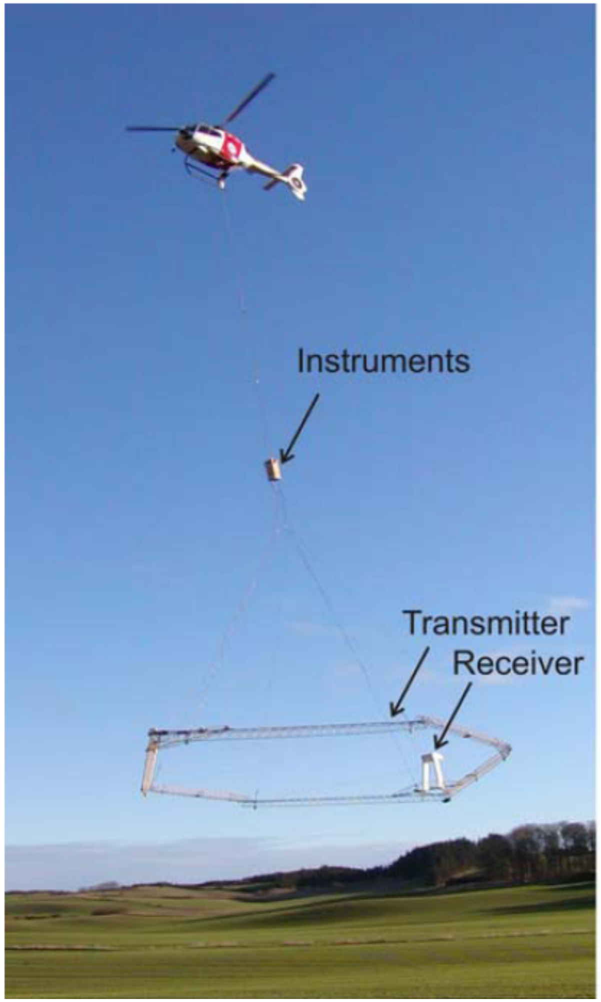


Geological Units	Resistivity (Ωm)
Palaeogene Clay	1-10
Clay Till	25-60
Sand Till	>50
Meltwater Sand and Gravel	>60
Glaciolacustrine Clay	10-40
Miocene Silt and Sand	>40
Miocene Clay	10-40
Sand	>40
Clay	1-60

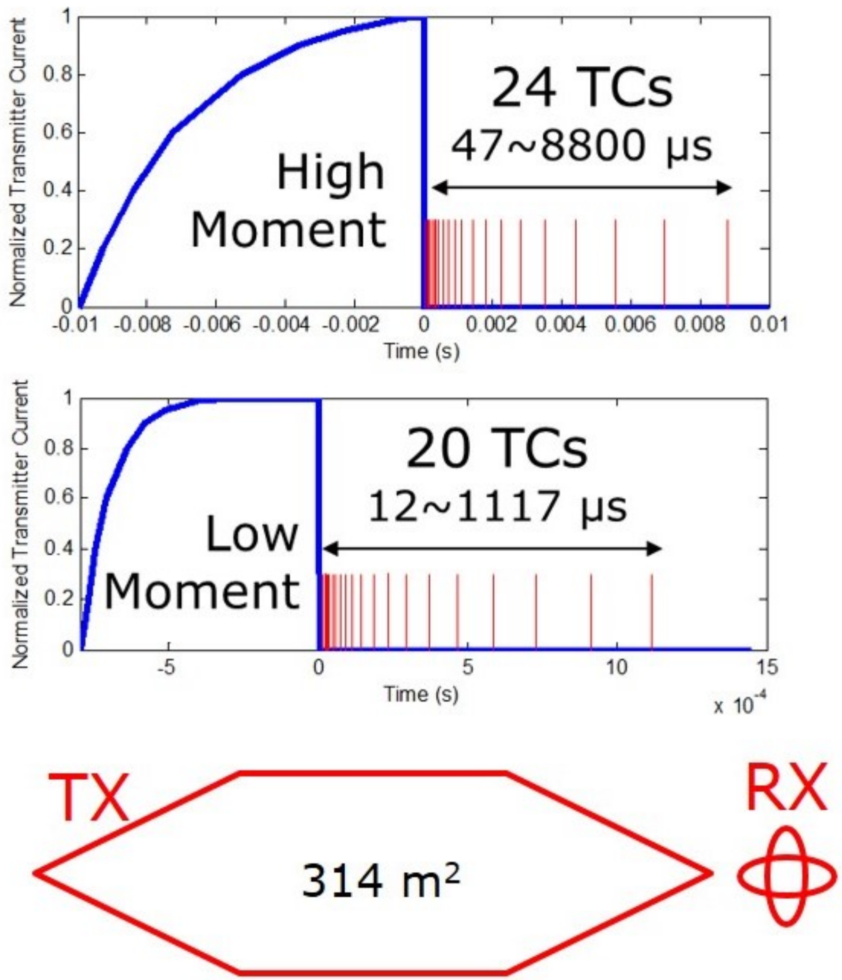
- Buried valleys with clays beneath
- Infill (water-bearing): coarse sand and gravel
- Clays are conductive (1-40 Ωm)
- Water-bearing sands and gravels are more resistive (>40 Ωm)

Survey

SkyTEM System



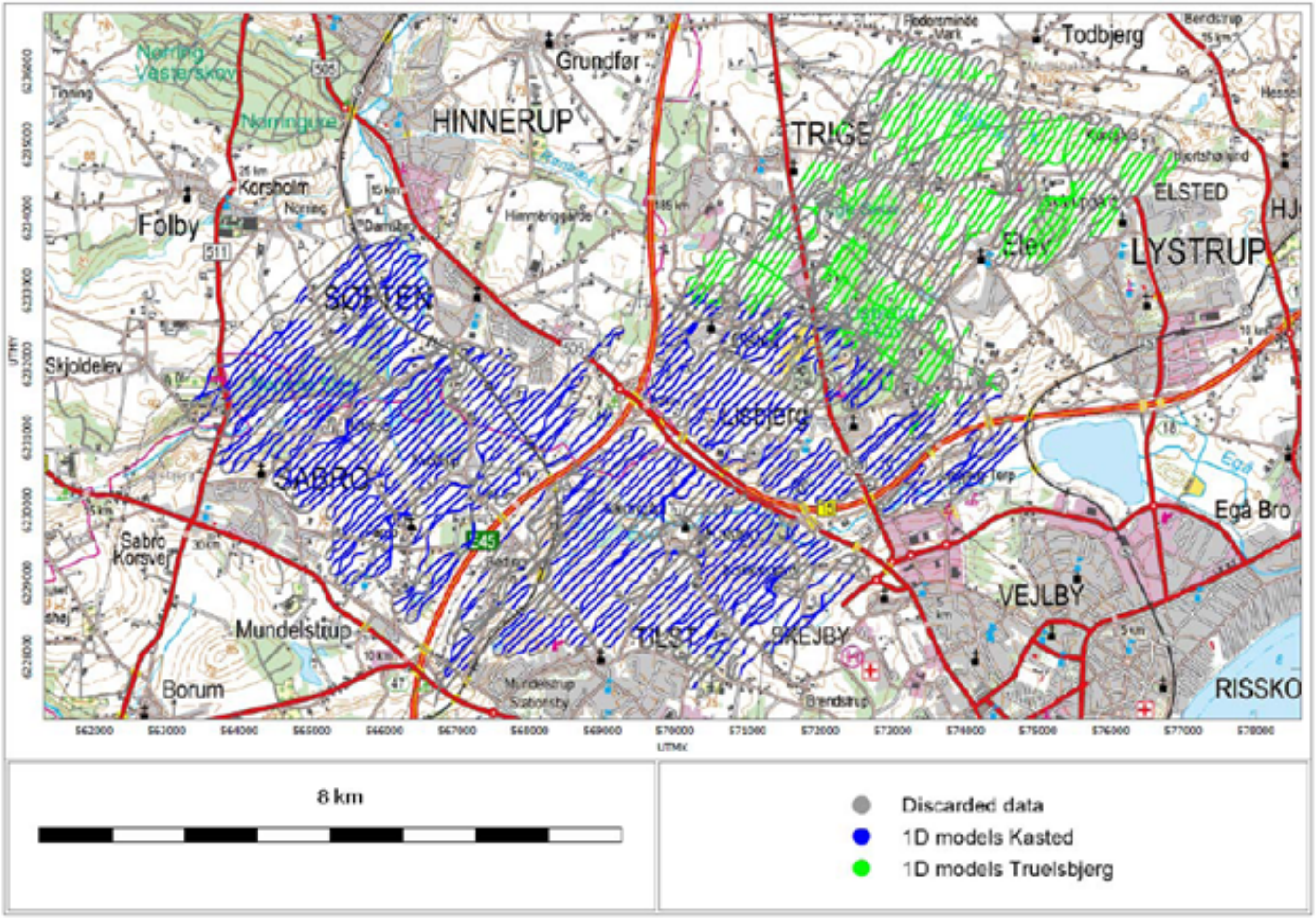
System Configuration



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

Data

Blue: data used for Kasted study



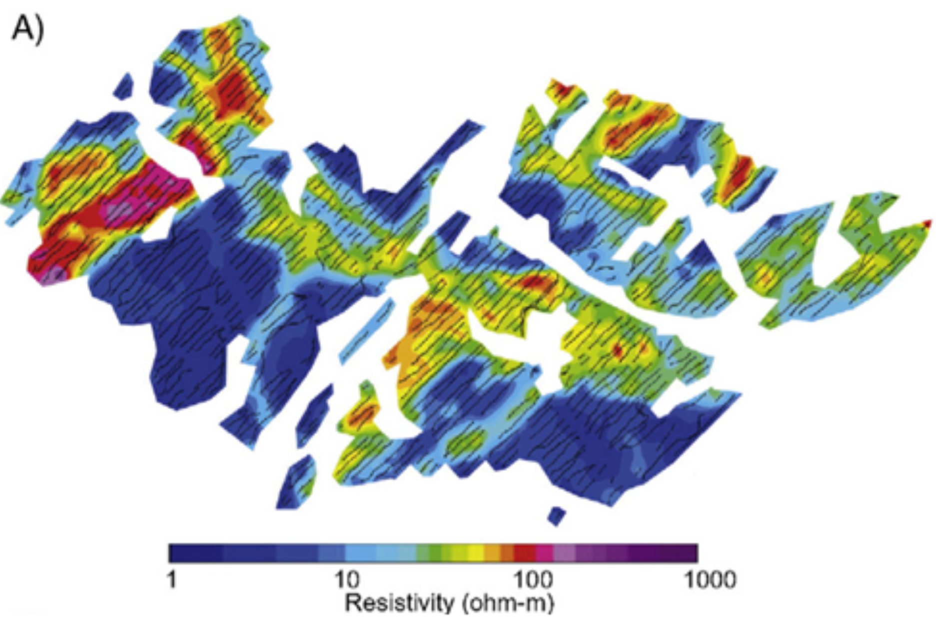
- 333 line km of data, 100 m line-spacing
- Data points with strong coupling to cultural noise were removed (~30%)

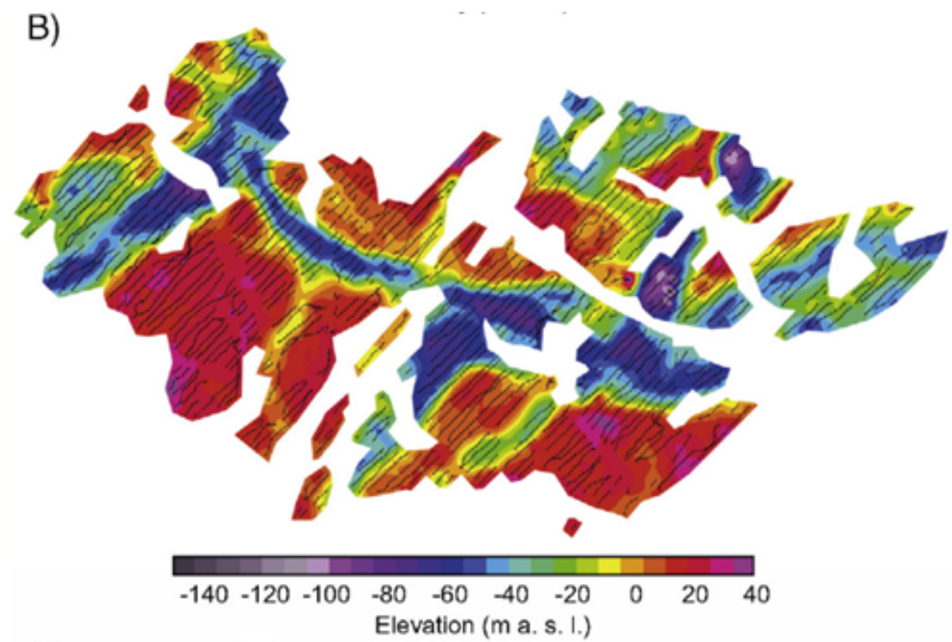
Processing (inversion)

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

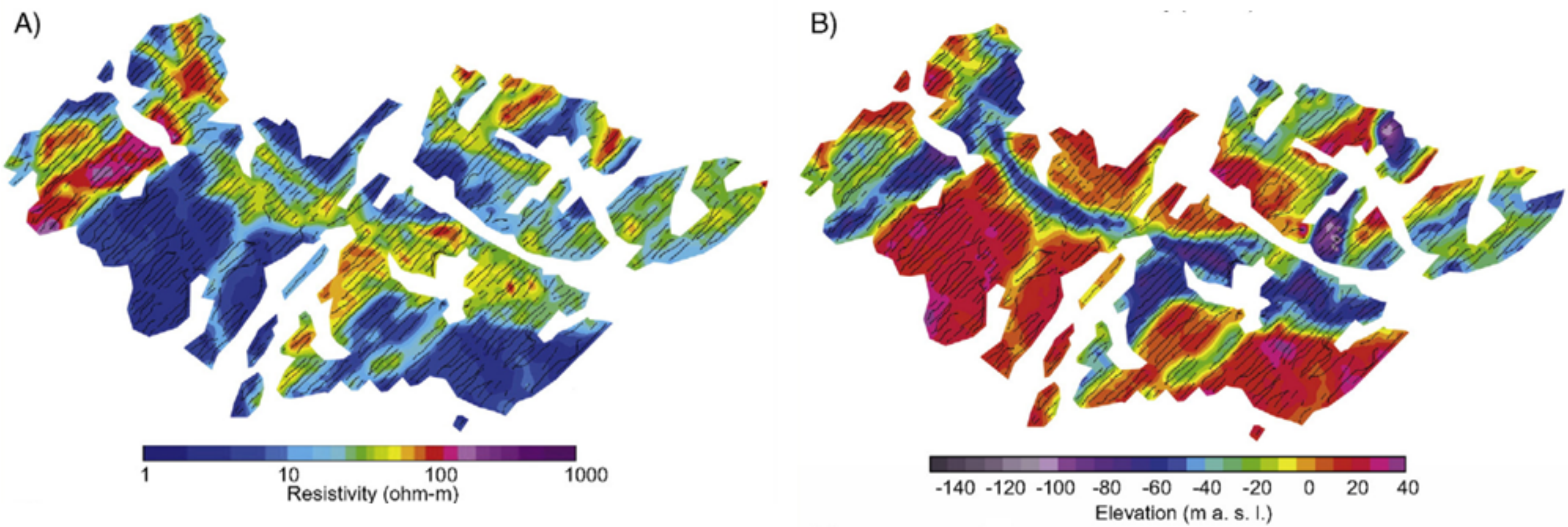
Depth slice 5 m above sea-level

Approximate depth to the top of Paleogene clay layer

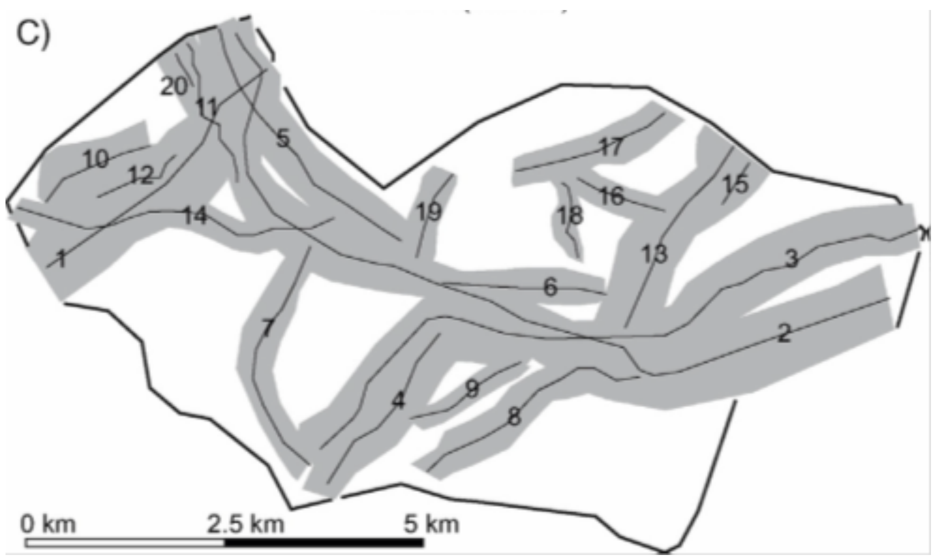




Interpretation

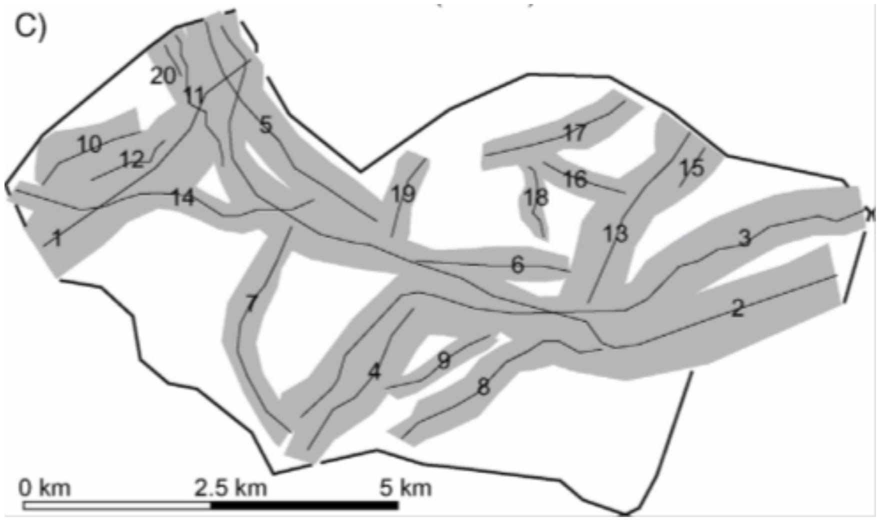


Delineation of valley structures

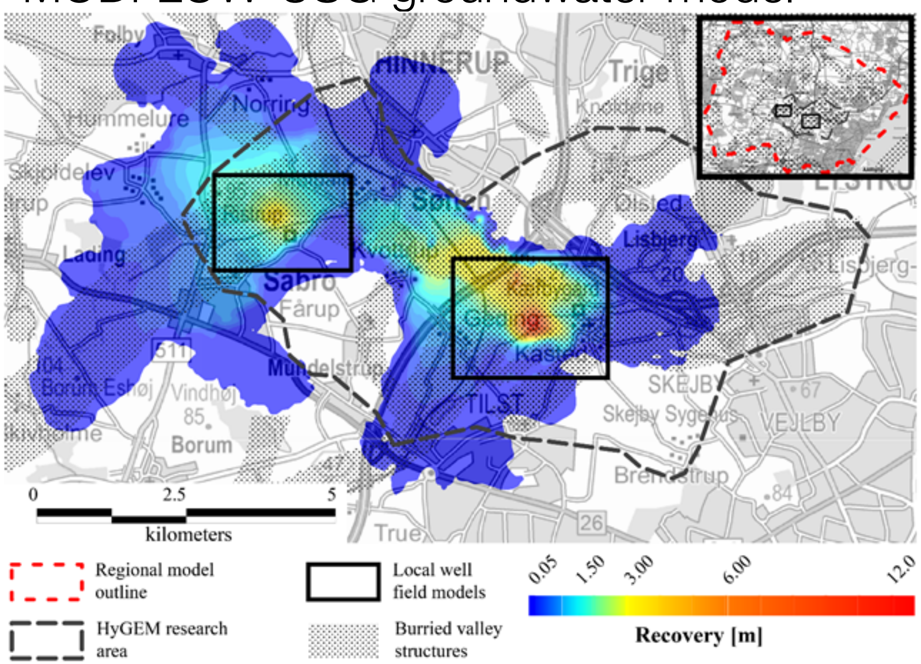


- Inversion results used to construct geological model.
- Delineated 20 buried and cross-cutting valley structures.

Synthesis



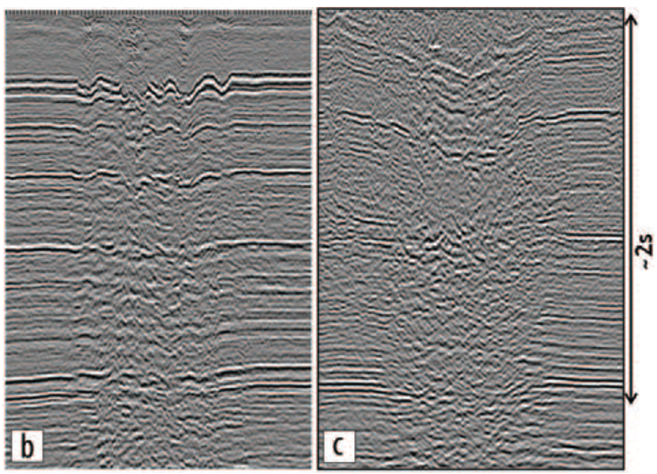
MODFLOW-USG groundwater model

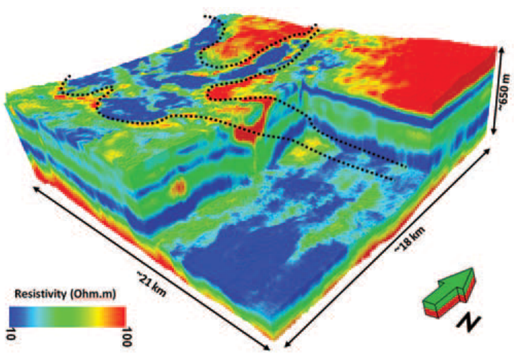


- 3D geologic model incorporated into MODFLOW-USG groundwater modeling tool
- Extracted water from 2 wells.
- Downdraw between the two wells correlated with the resistive valley structures

Case History: Wadi Sahba

Colombo et al. 2016

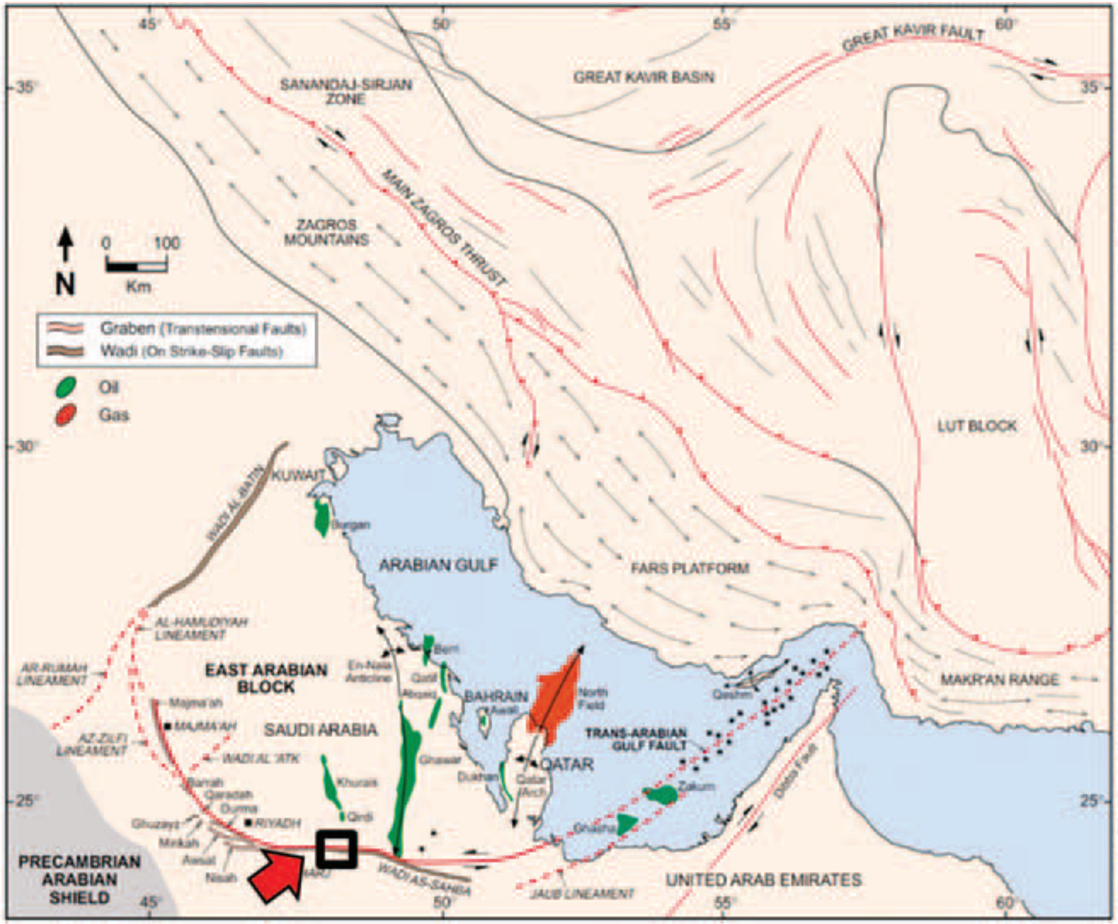




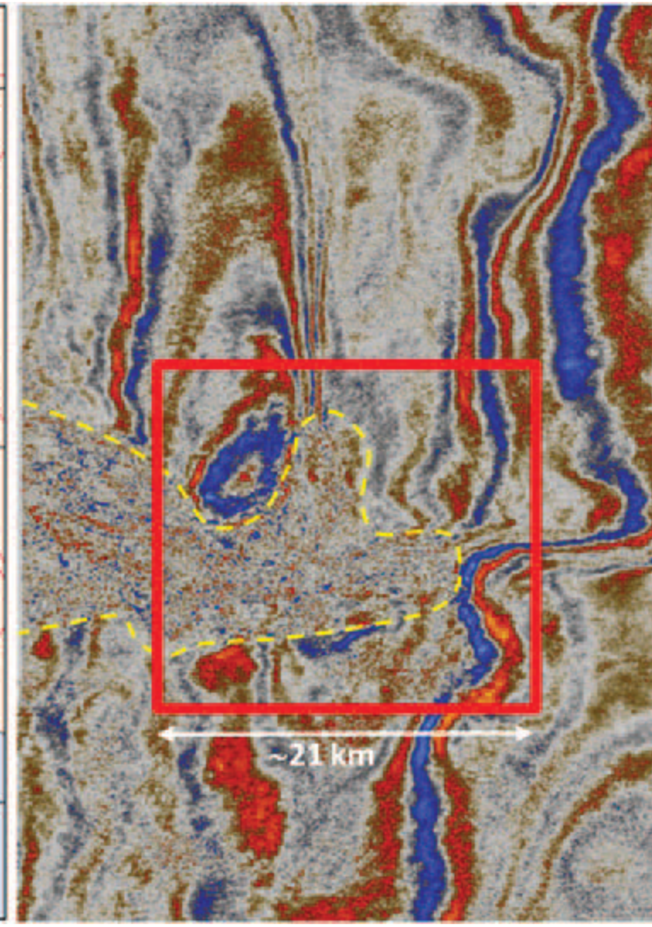
?

Setup

Location of Wadi area, Saudi Arabia



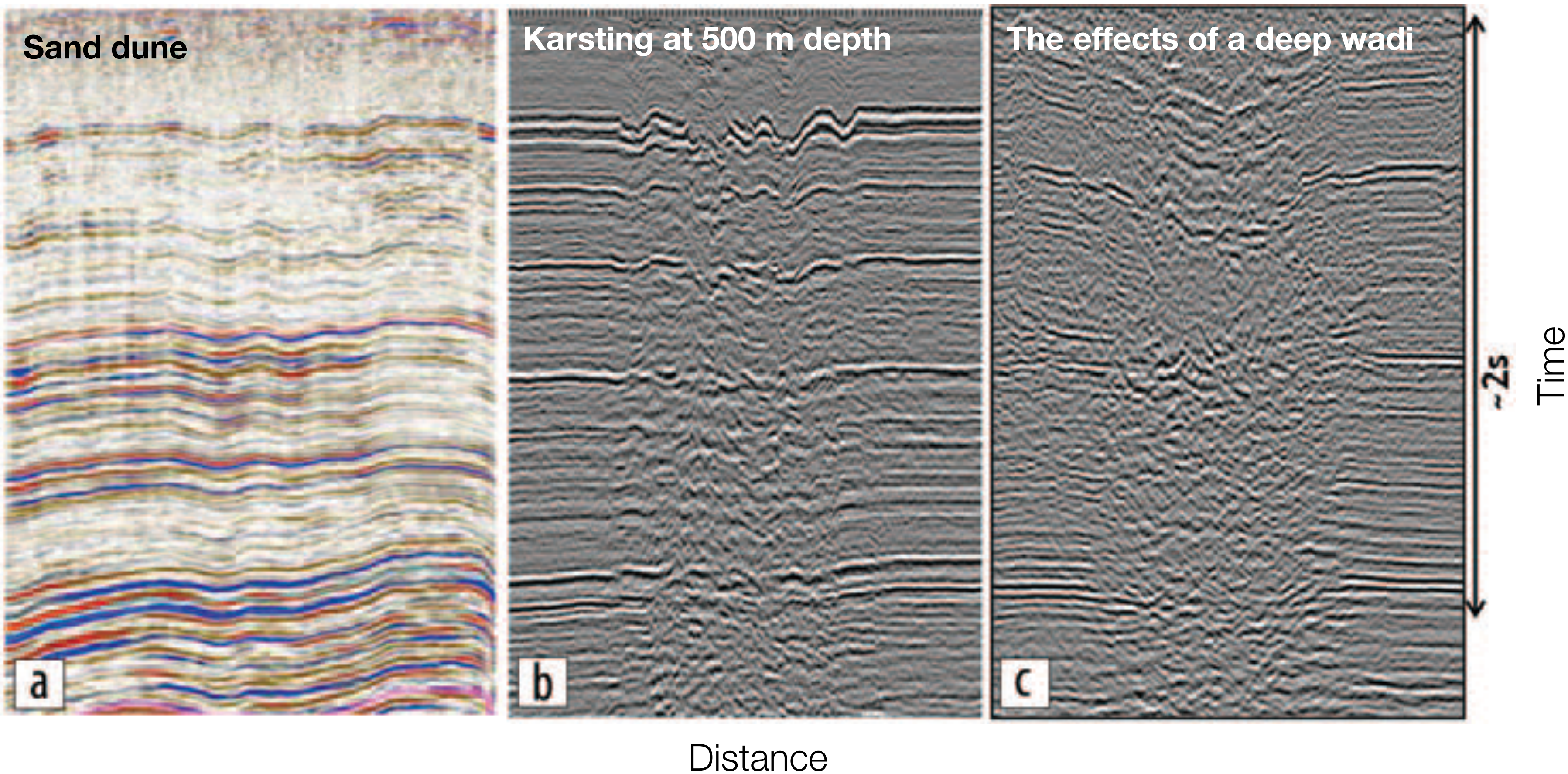
Seismic slice



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

Challenges for processing seismic data

Example seismic sections



- Strong effects from near surface anomalies even after static corrections

Properties

- P-velocity and conductivity:

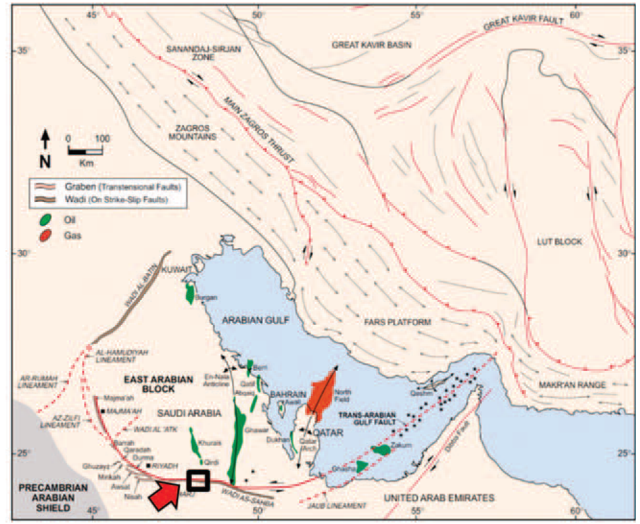
$$v_p = g(\phi)$$
$$\sigma = f(\phi)$$

v_p: P-velocity
ϕ: porosity

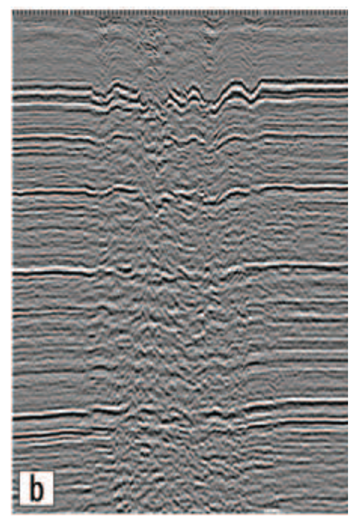
- Poor seismic data:
  - strong scattering effects probably caused by flower faults
  - velocity inversions (high to low v_p)

- From previous multi-physics analyses:
  - strong structural similarity between the inverted resistivity, and the existing seismic results

Geologic map



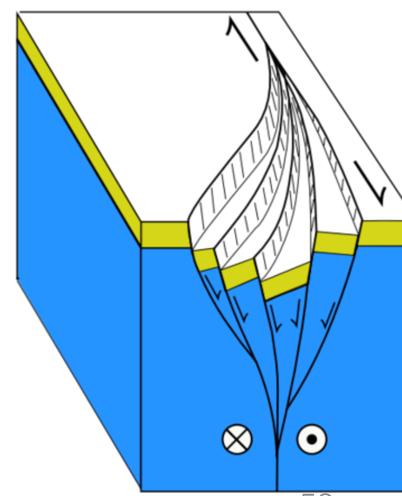
Seismic section



Time

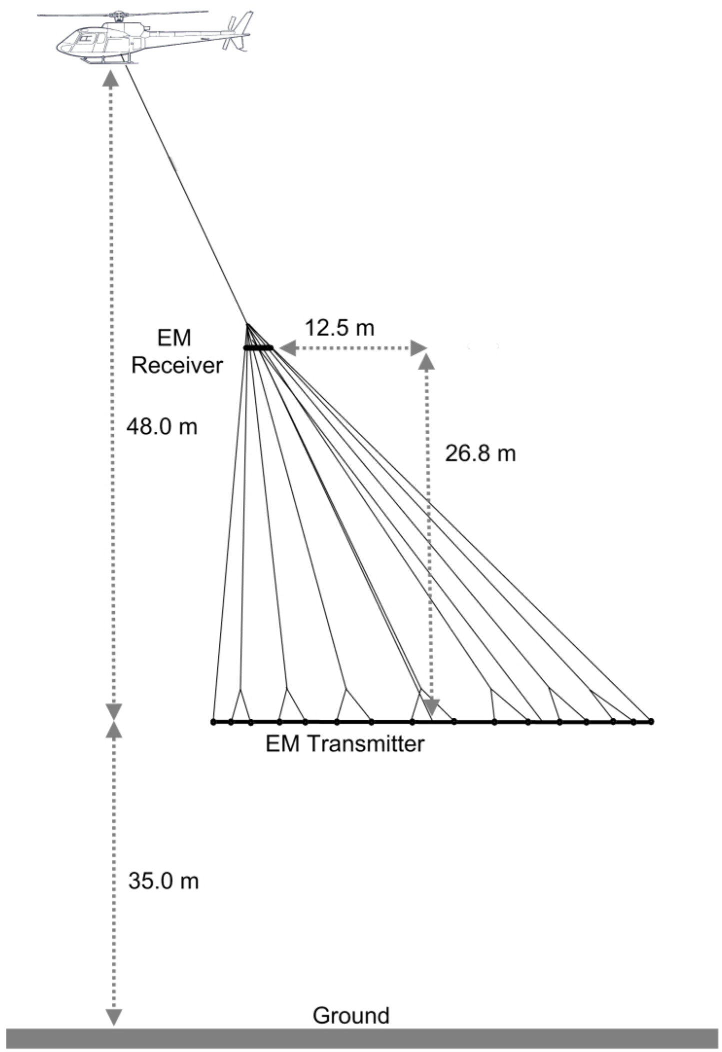
Distance

Flower faults

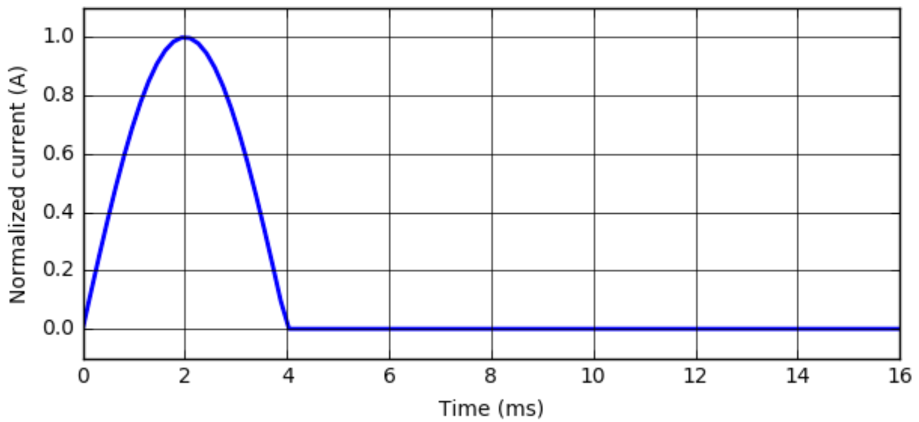


Survey

HELITEM

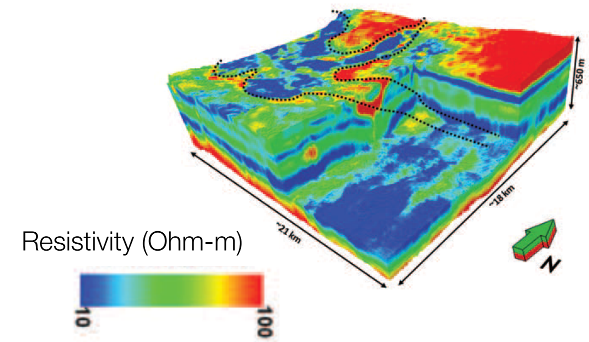


System Configuration

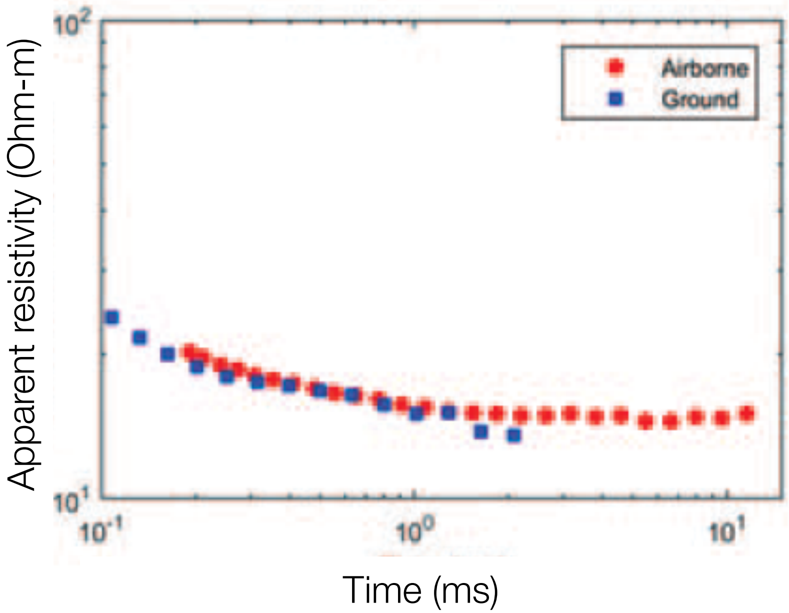


- Peak Tx current: 1200 A
- Dipole moment: 1.7×10^6 A-m^2
- Stacked TEM curve spacing: ~2.7 m
- Total soundings: ~1.6 million

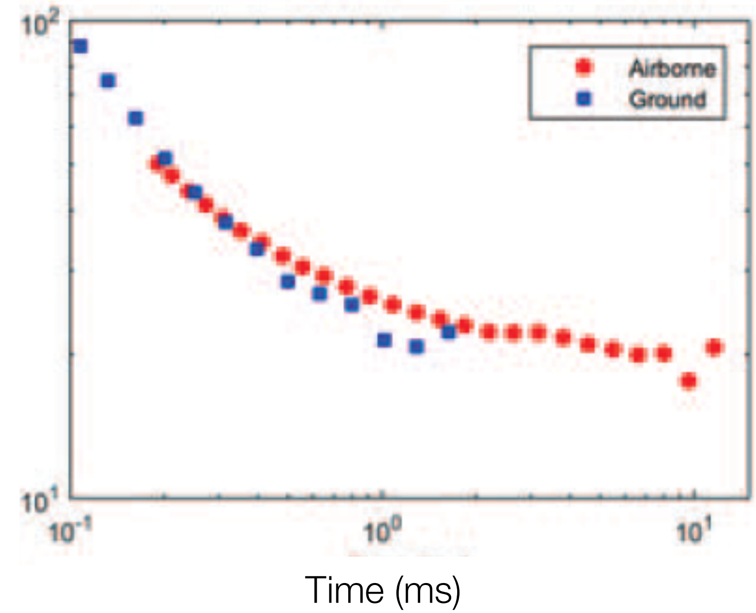
Comparisons: airborne and ground EM



Conductive area

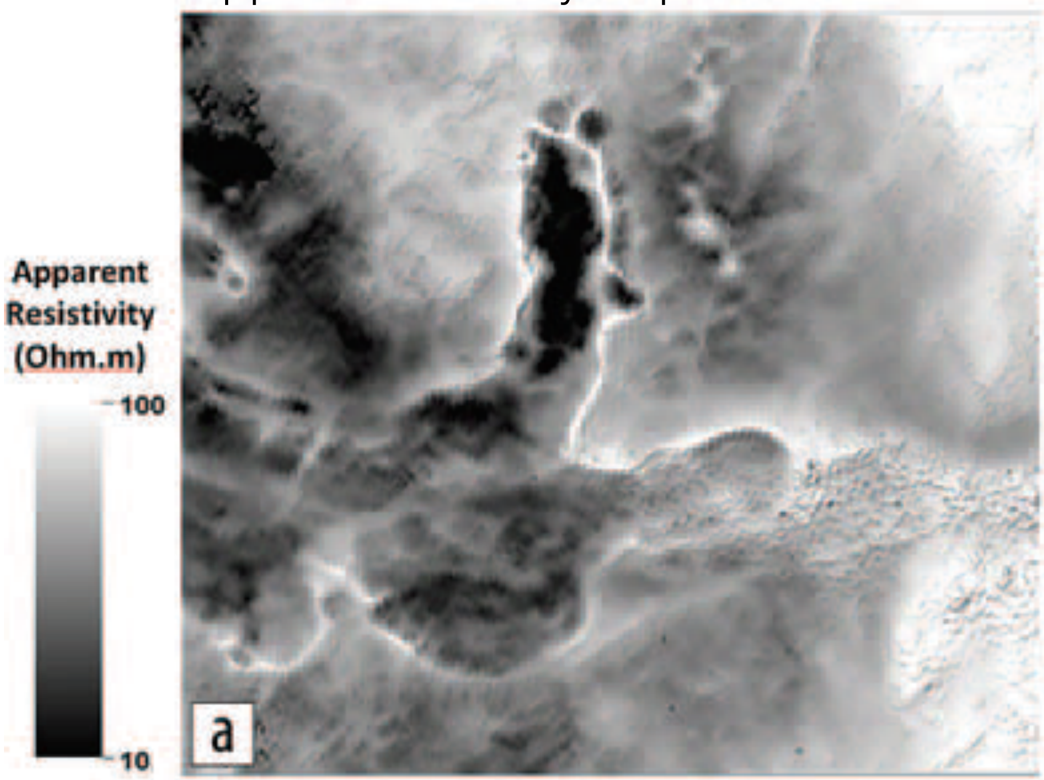


Resistive area

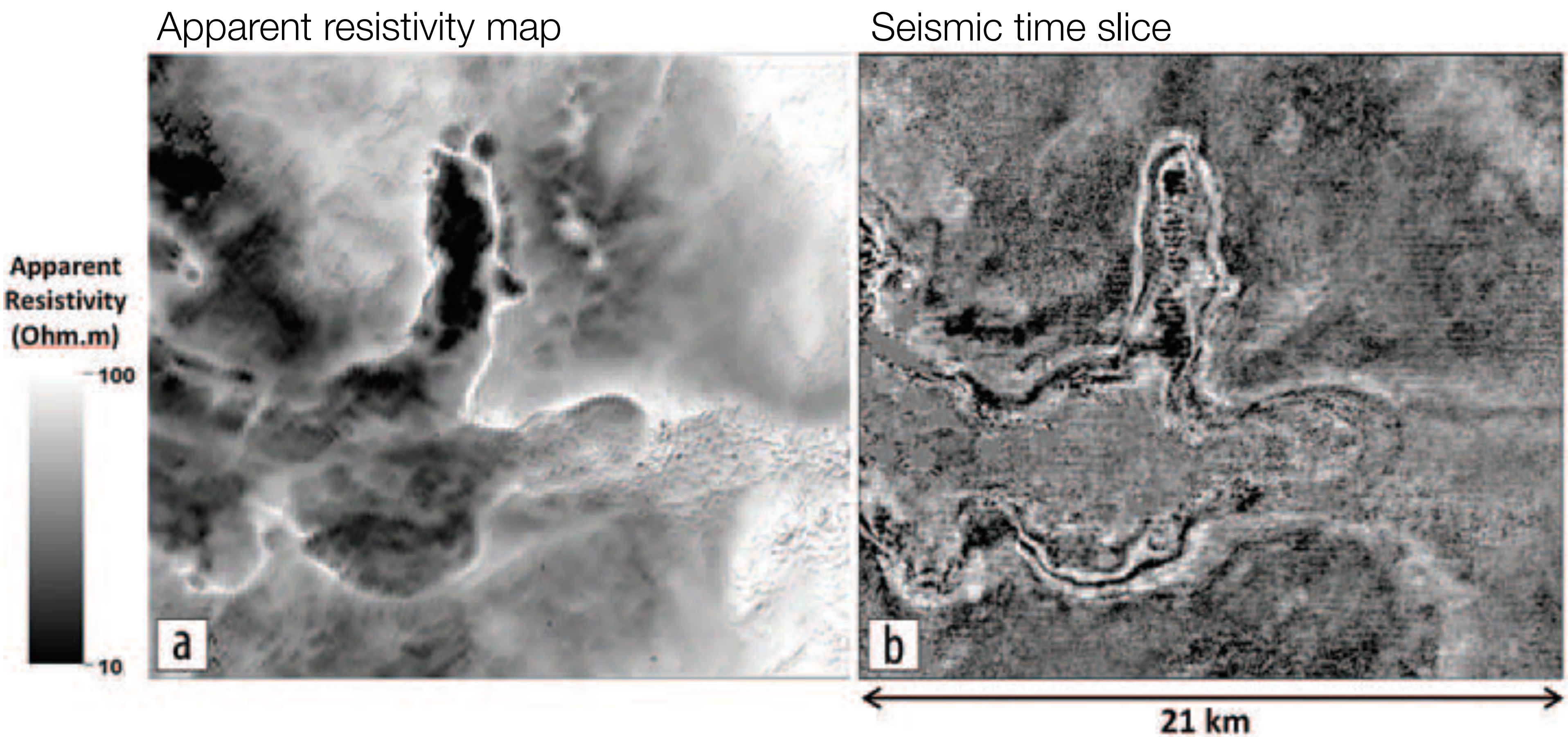


EM data

Apparent resistivity map

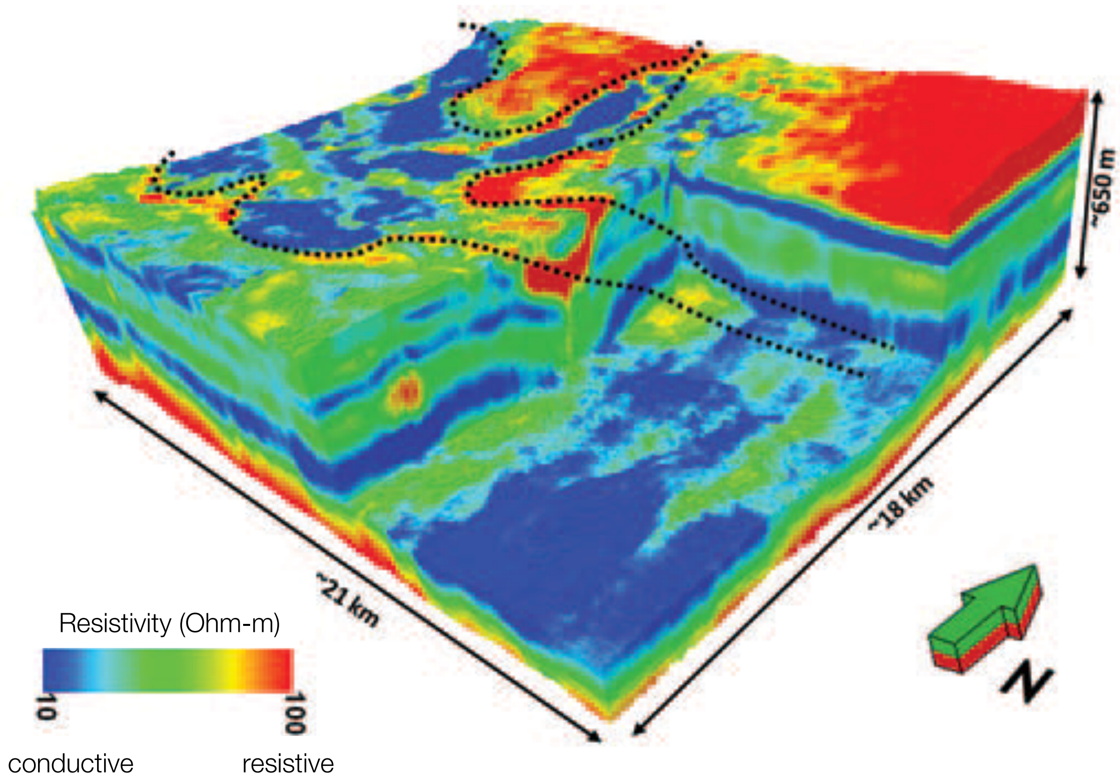


Comparison: EM and Seismic data



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 ($\boldsymbol{\sigma}$): high to low

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

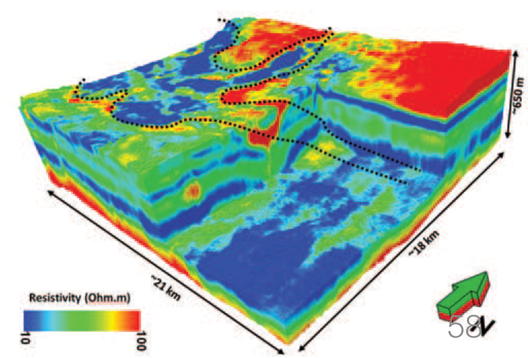
ϕ: porosity

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

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

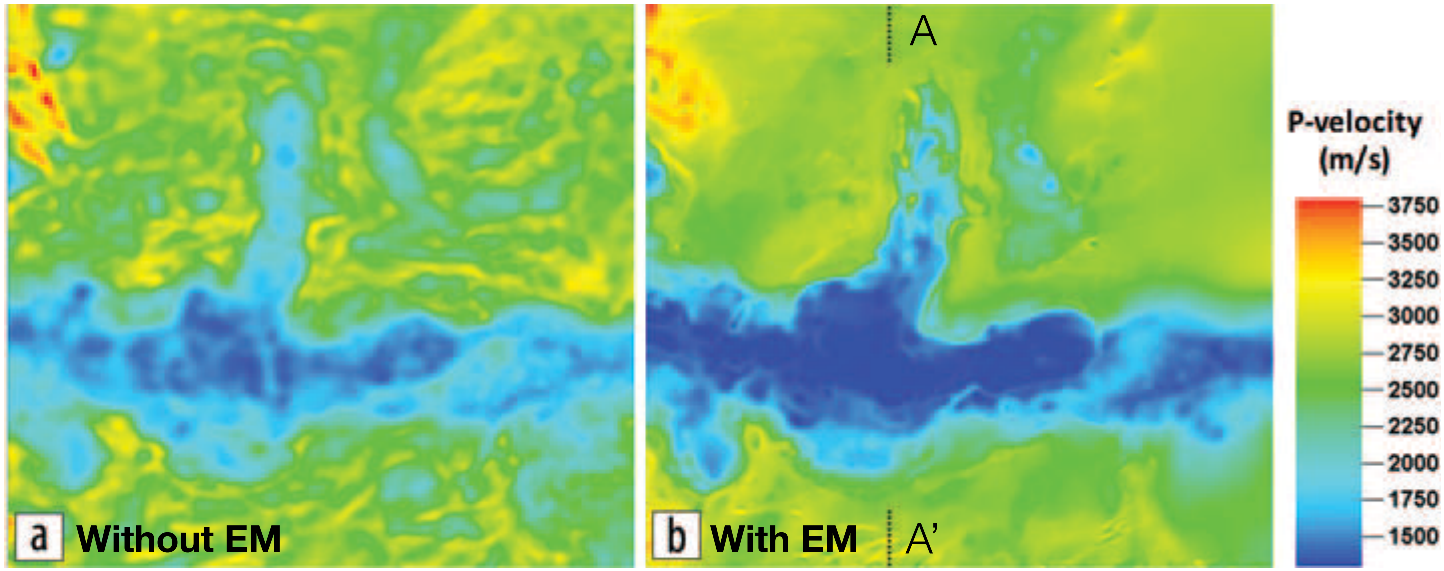
$$||\nabla \mathbf{m_s} \times \nabla \mathbf{m}_\sigma||_2^2$$

Gallardo and Meju, 2004



Cooperative inversion: Seismic + EM

V_p depth slices at 340 m below sea level

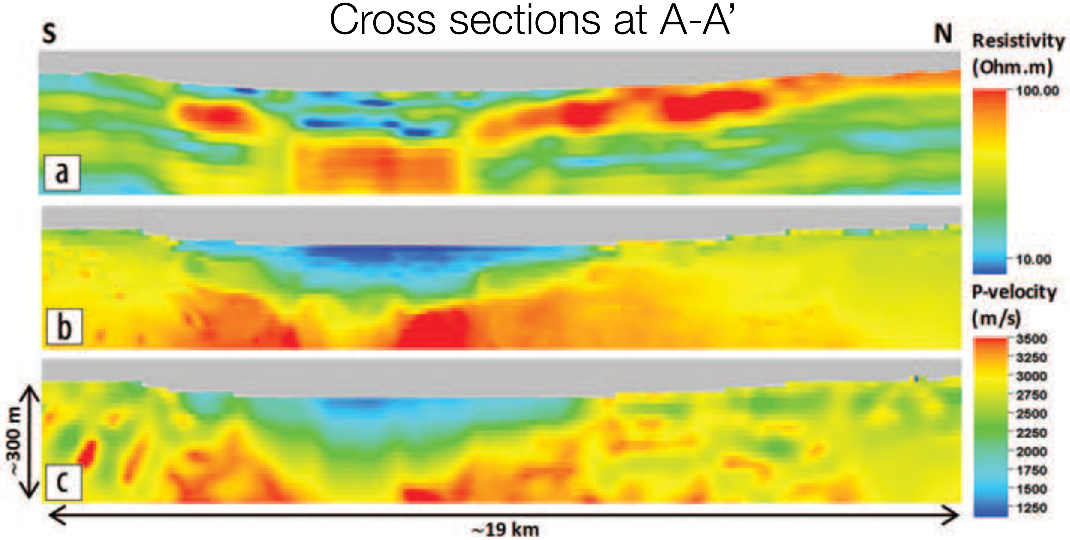


Cross sections at A-A'

Conductivity

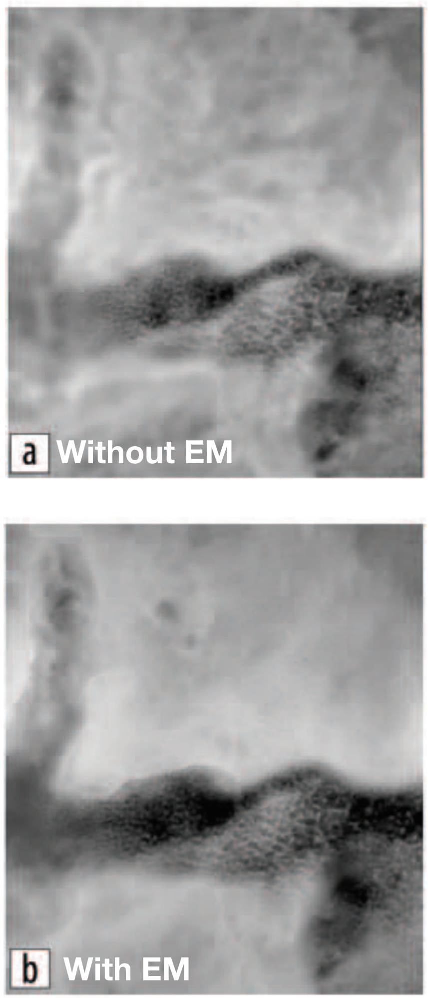
v_p **with EM**

v_p **without EM**

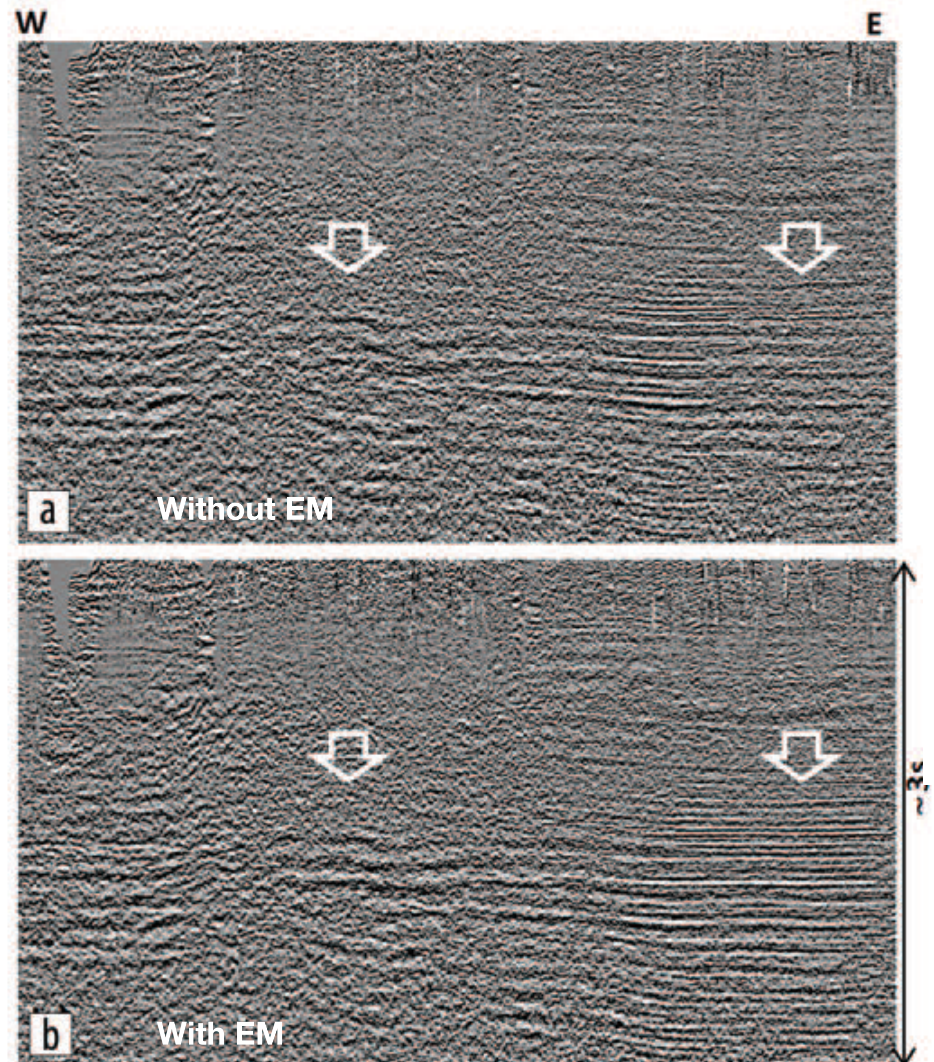


Static correction

Estimated statics on plan map



Static corrected sections



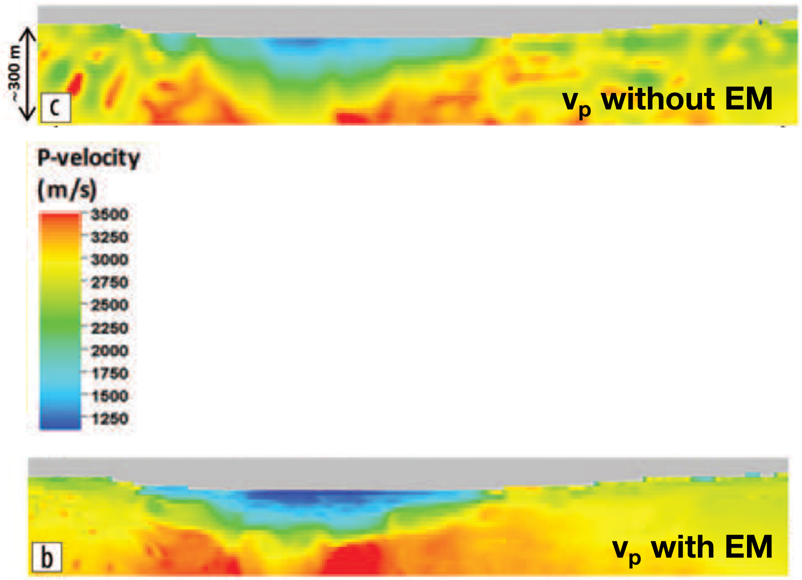
Time

Distance

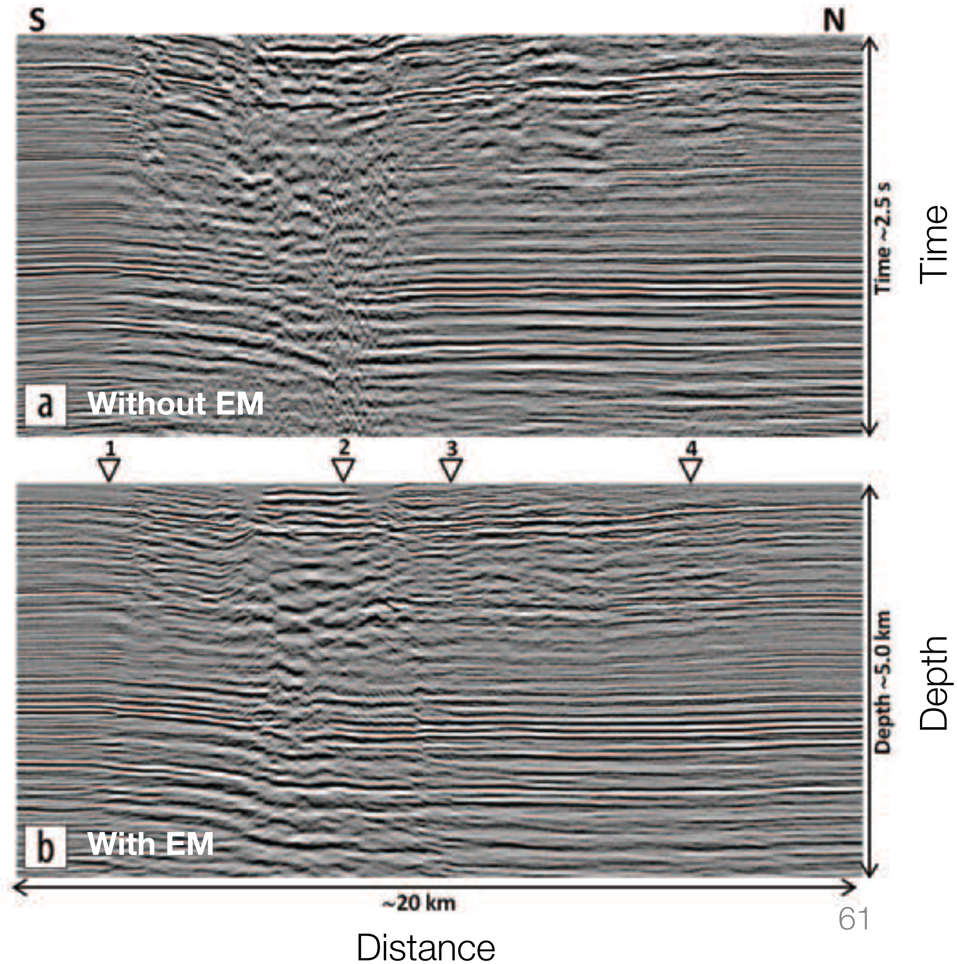
Pre-stack depth migration

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

v_p cross sections at A-A'



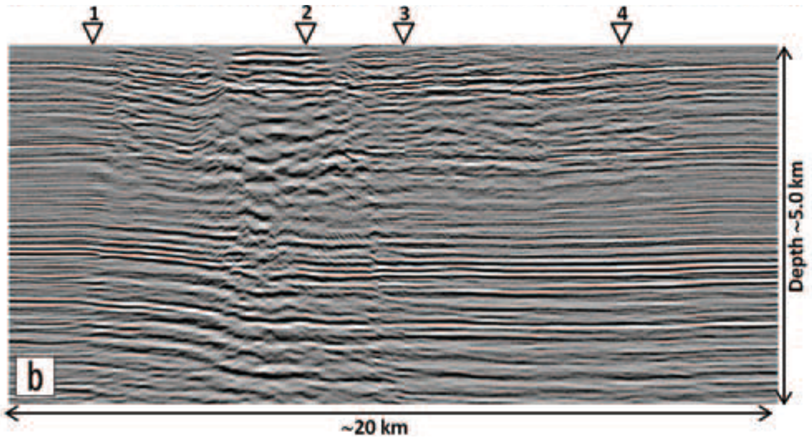
Cross sections at A-A'



Interpretation and Synthesis

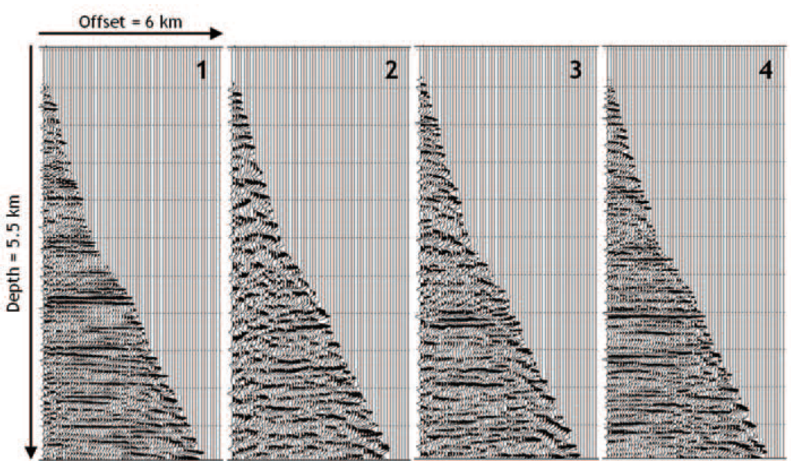
Depth section at A-A’

Depth



Distance

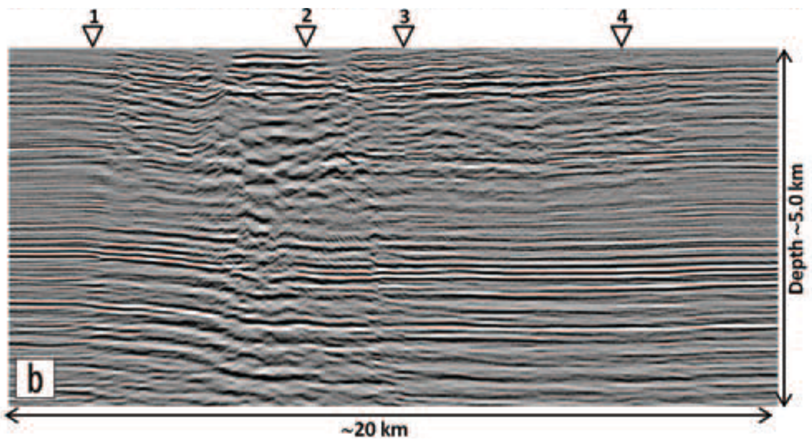
Common image gathers



Interpretation and Synthesis

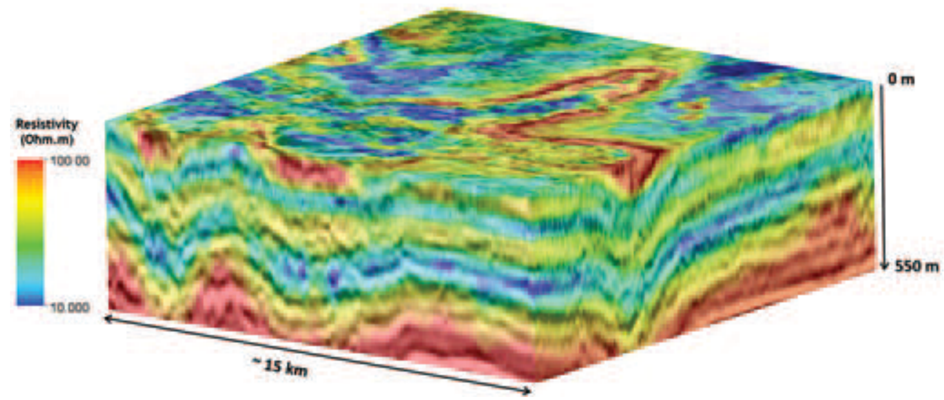
Depth section at A-A'

Depth

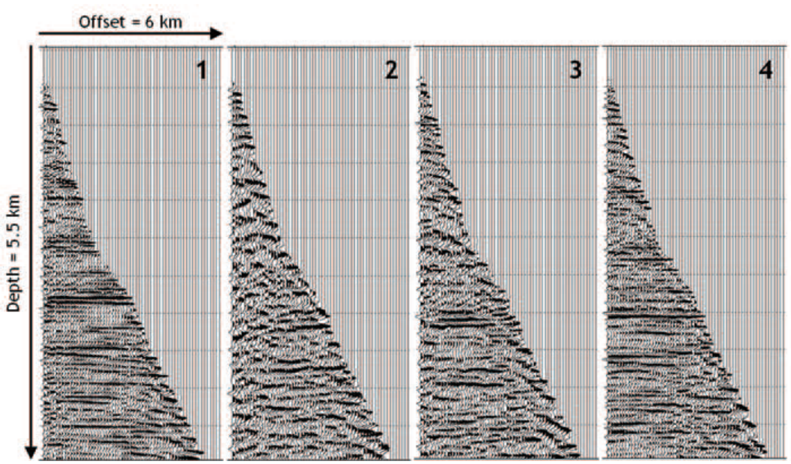


Distance

3D prestack depth migration co-rendered with EM



Common image gathers



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

Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Case History

Frequency Domain EM

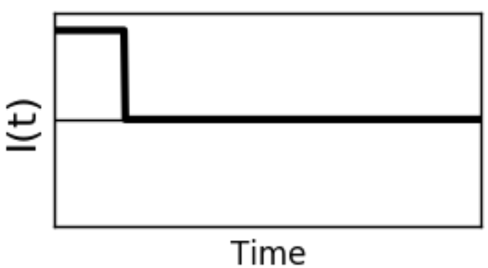
- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Ground water

EM with Inductive Sources

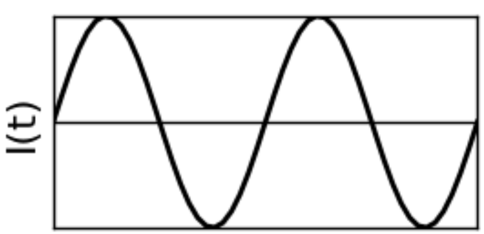
- Induction principles are the same for
  - TDEM: Time domain EM
  - FDEM: Frequency domain EM

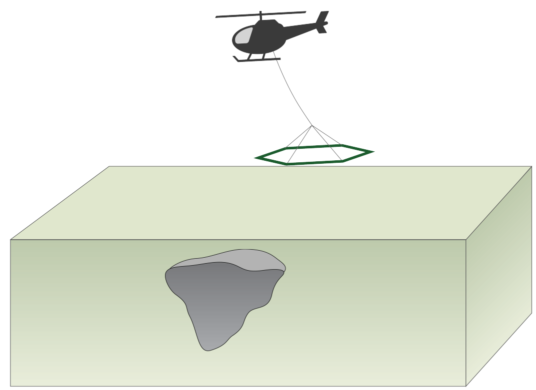
Transmitter current

TDEM

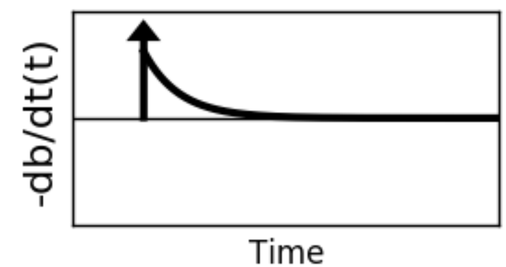


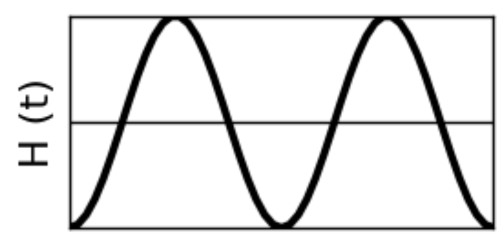
FDEM



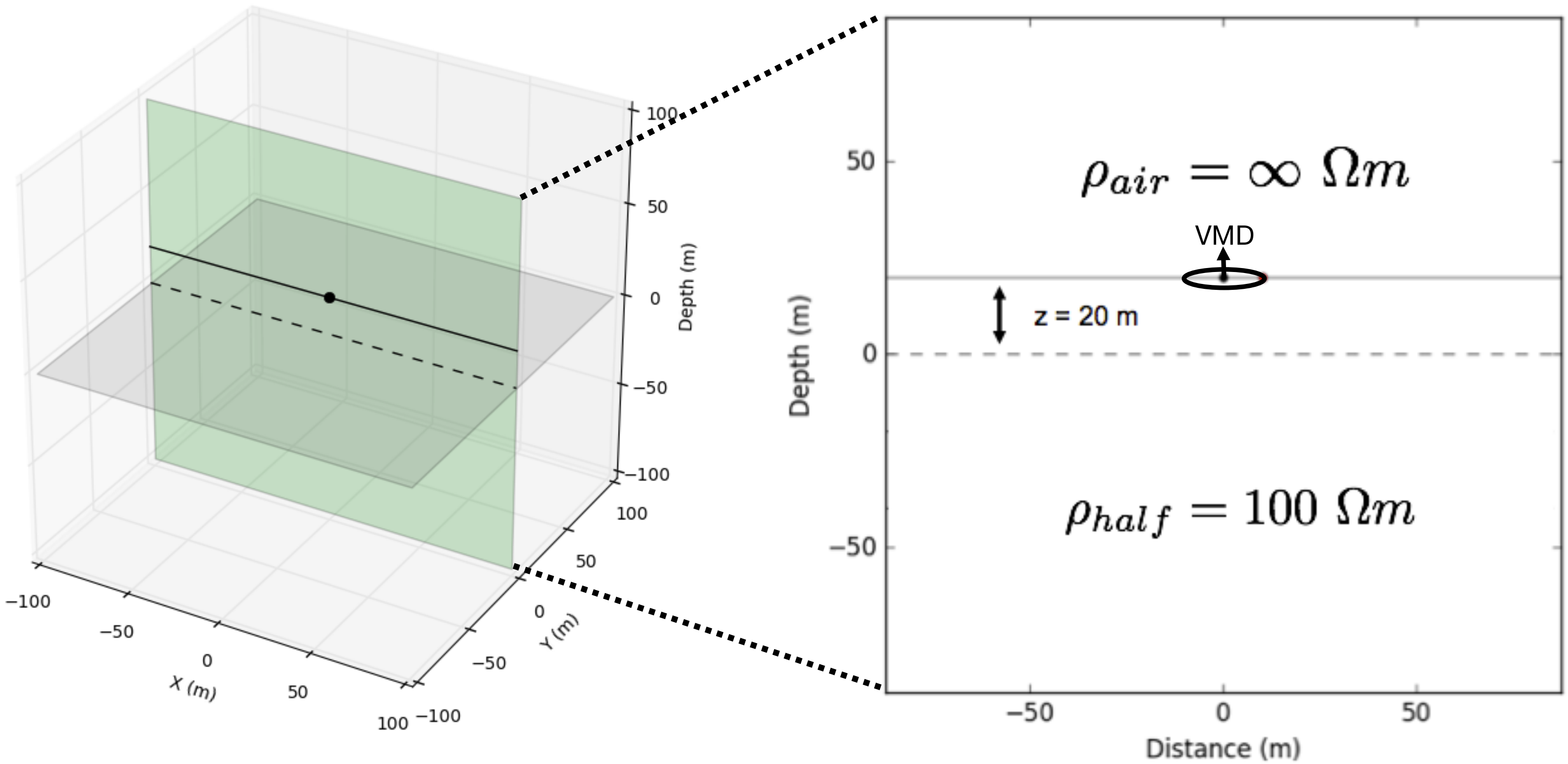


Receiver



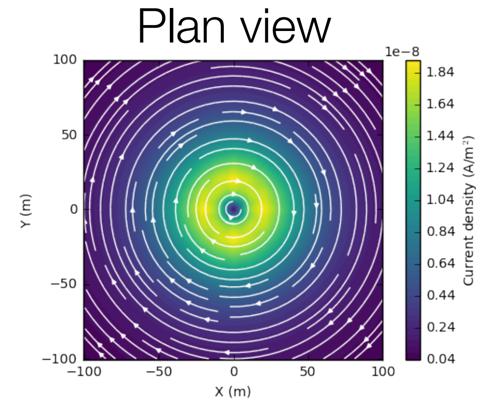


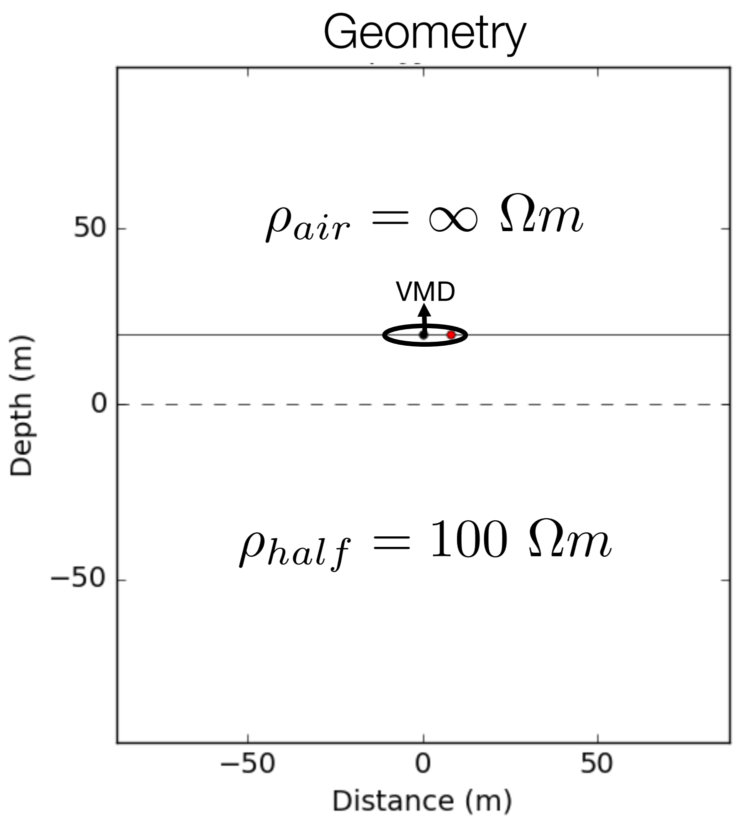
Vertical Magnetic Dipole over a halfspace (FDEM)

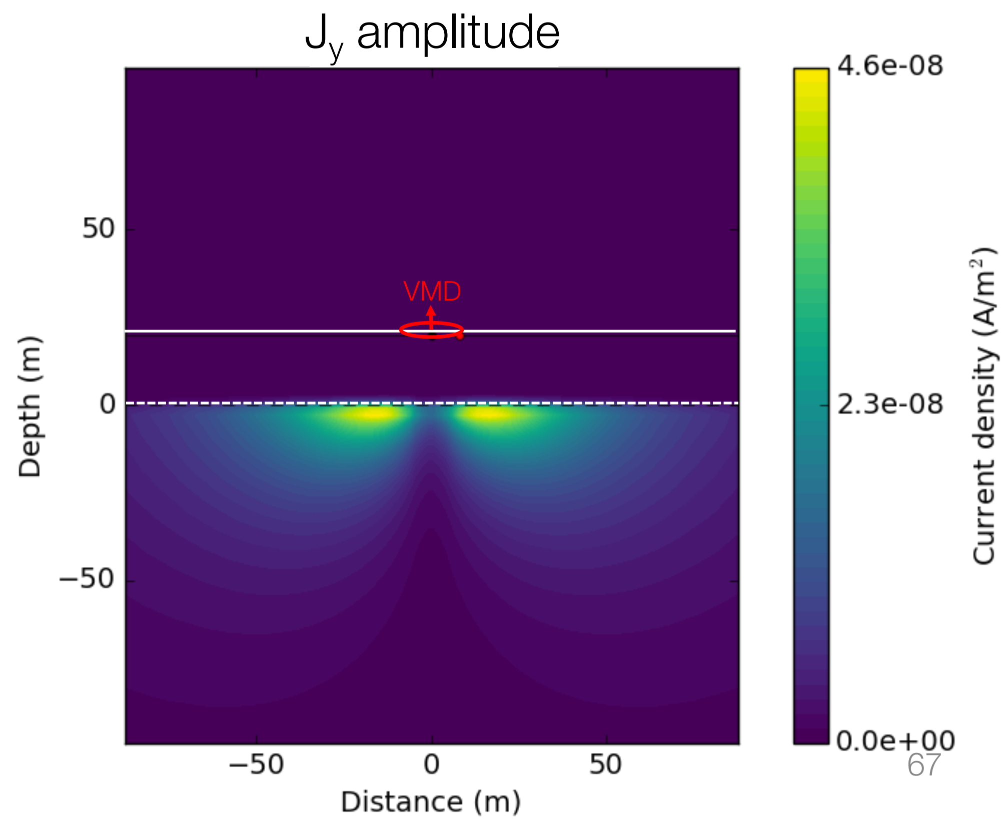


Current Density

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

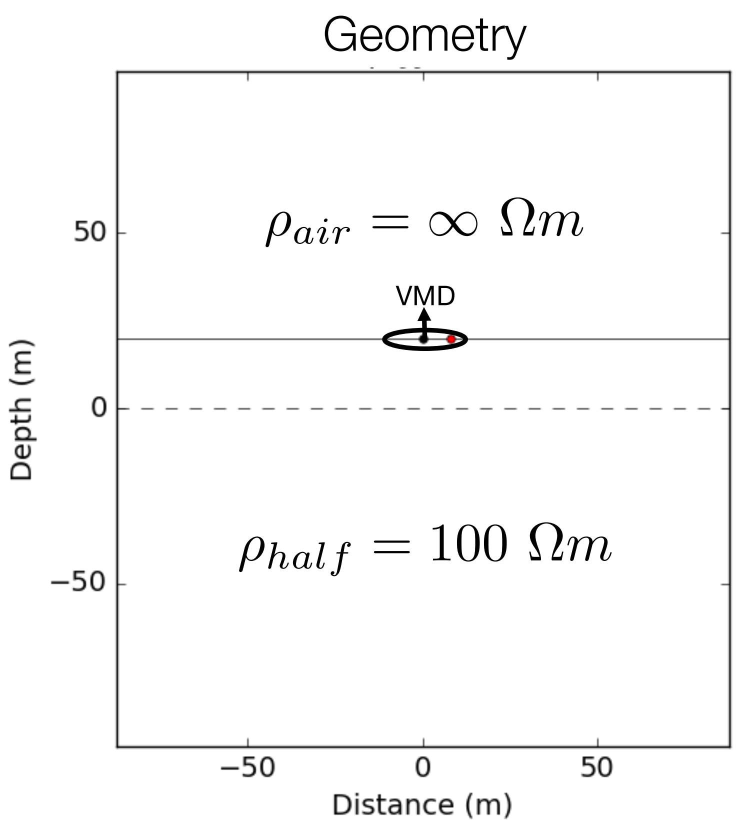


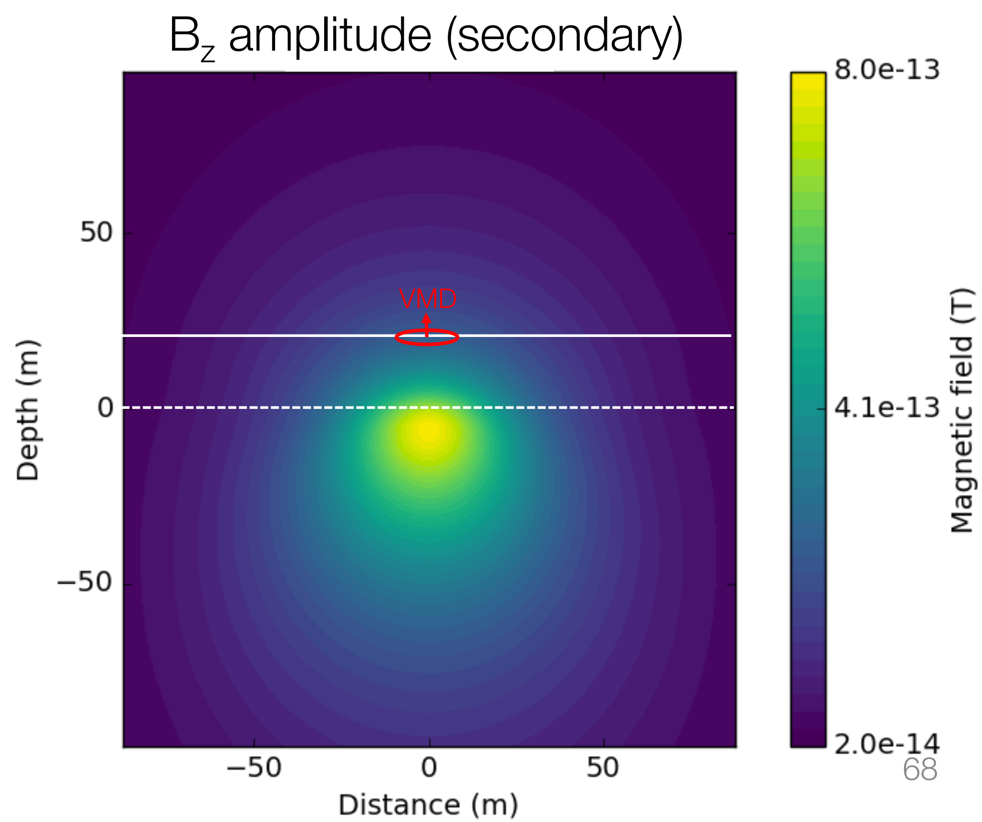




Secondary Magnetic Flux Density

- Frequency = 10 kHz

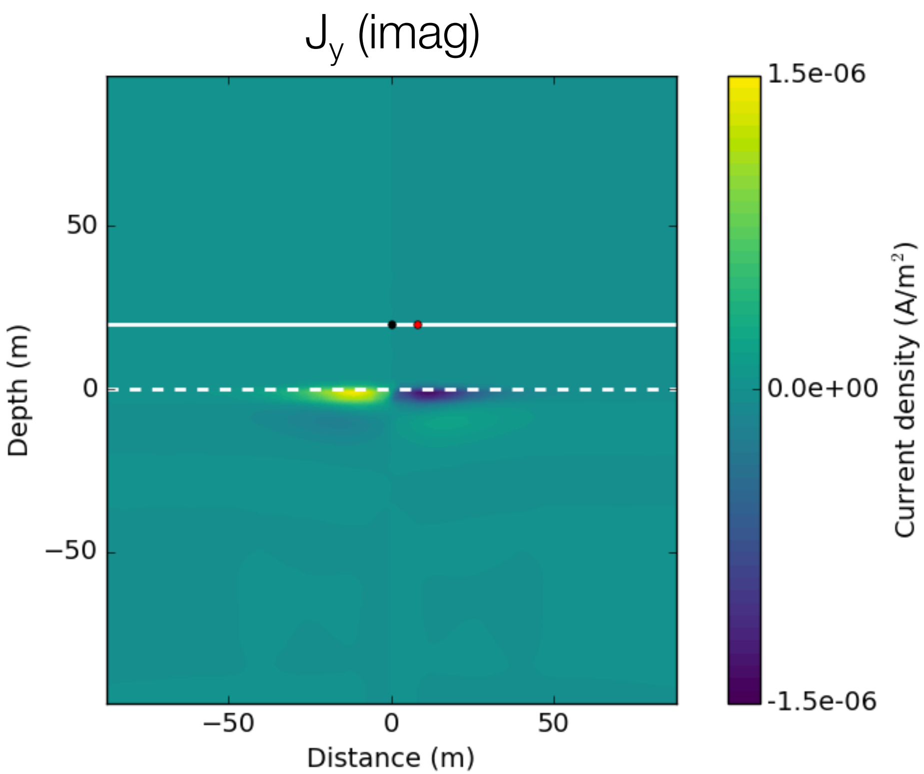


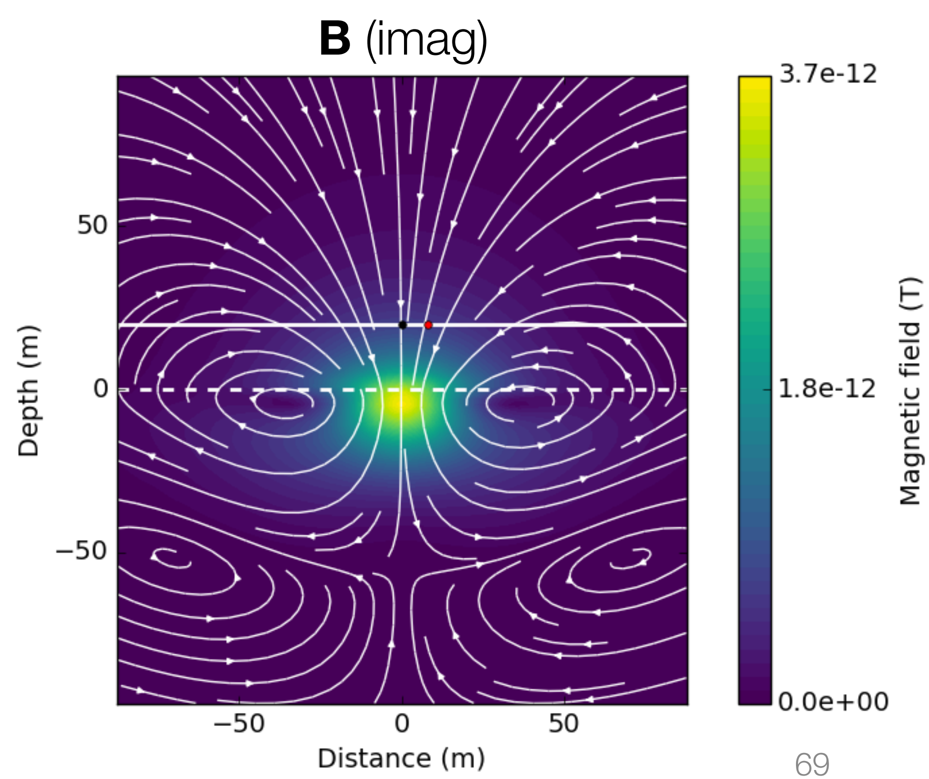


Effects of Frequency

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

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



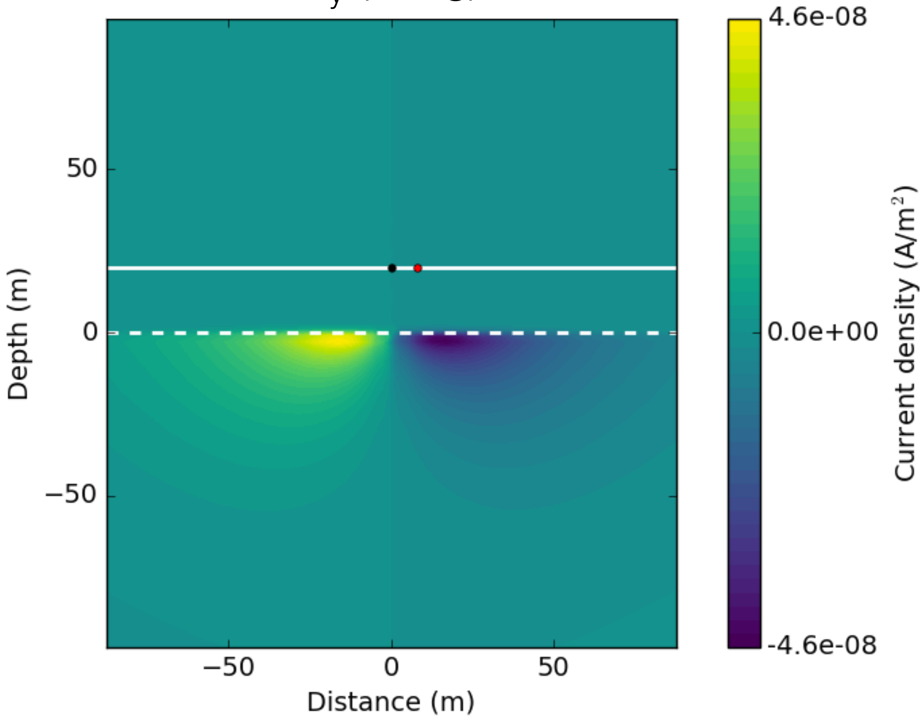


Effects of Frequency

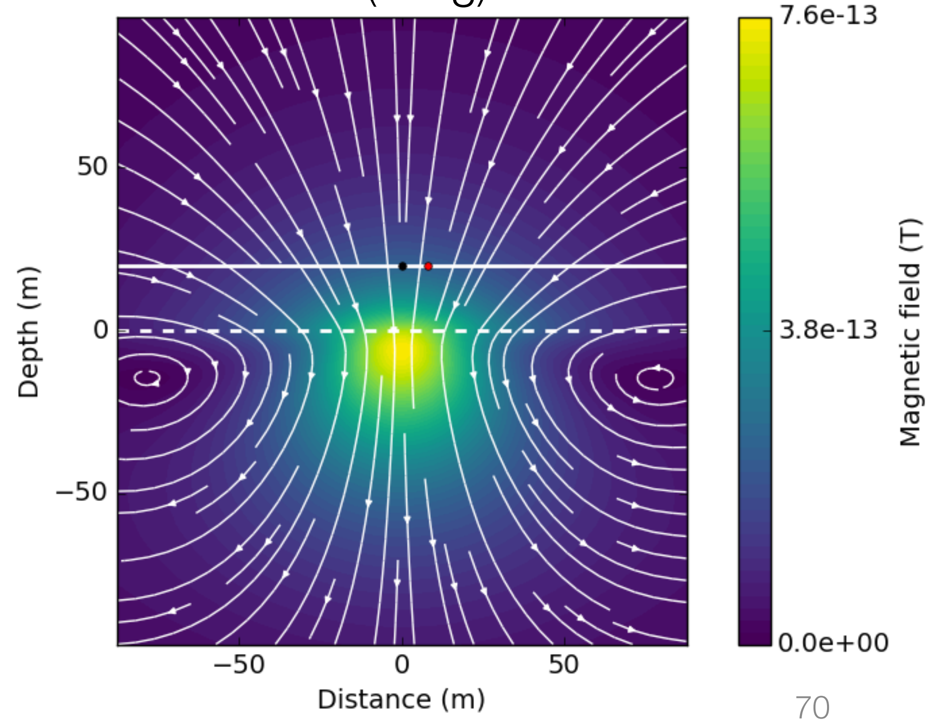
- Frequency at 10 kHz
- Skin depth = 50 m
- Currents diffusing downward and outward

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

J_y (imag)

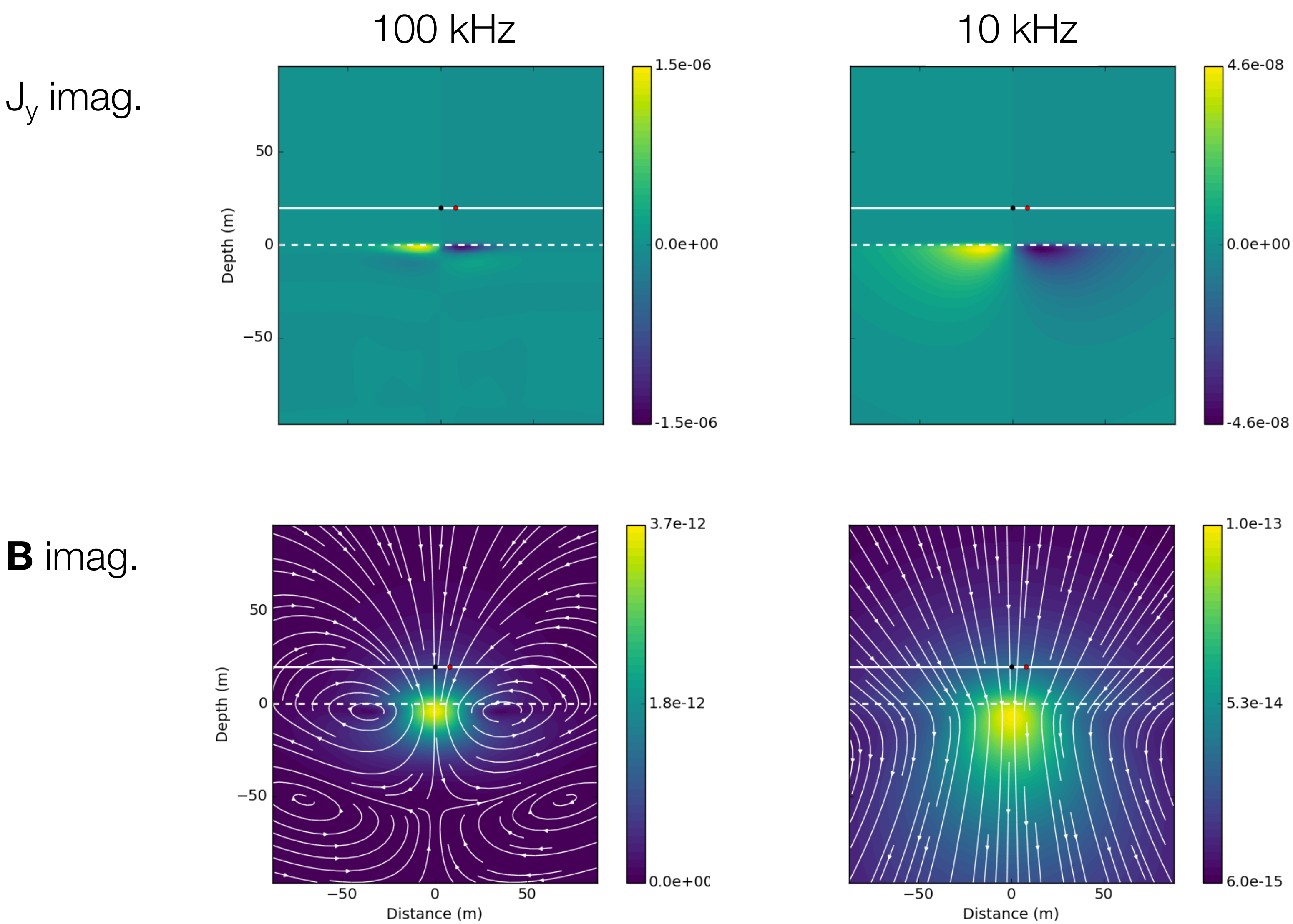


B (imag)



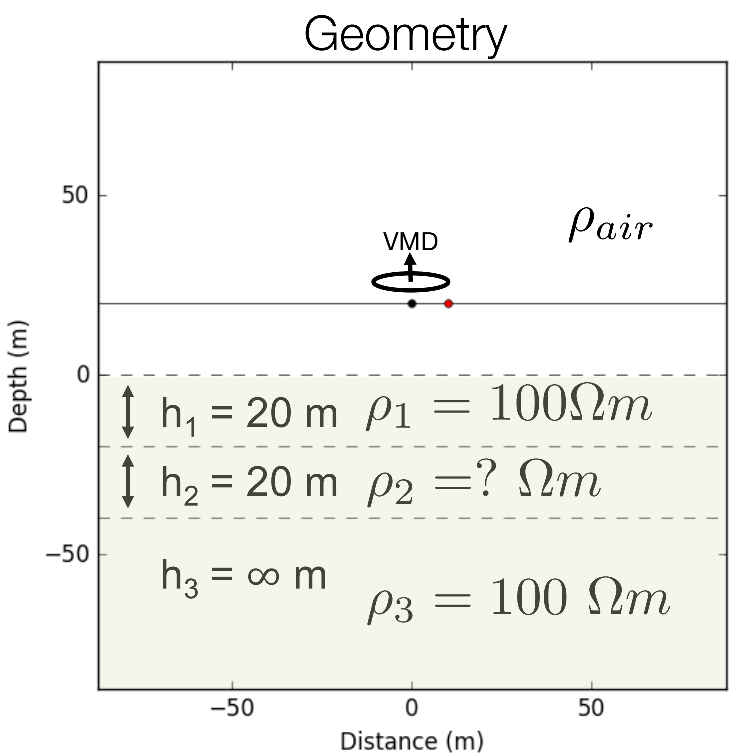
Summary: Effects of Frequency

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



Layered earth

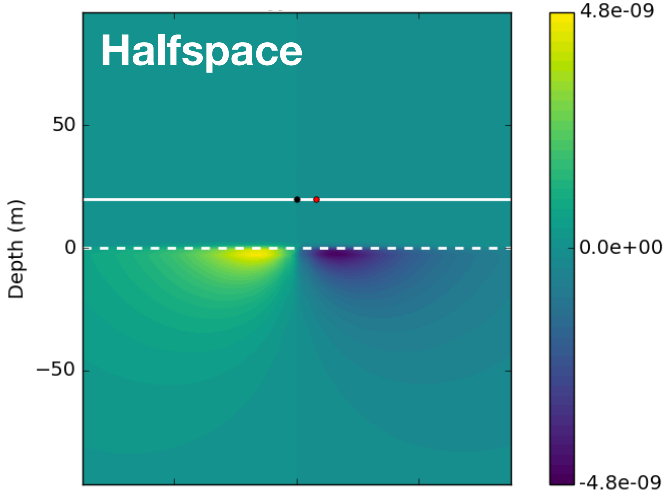
- 3 layers + air,
- ρ_2 varies



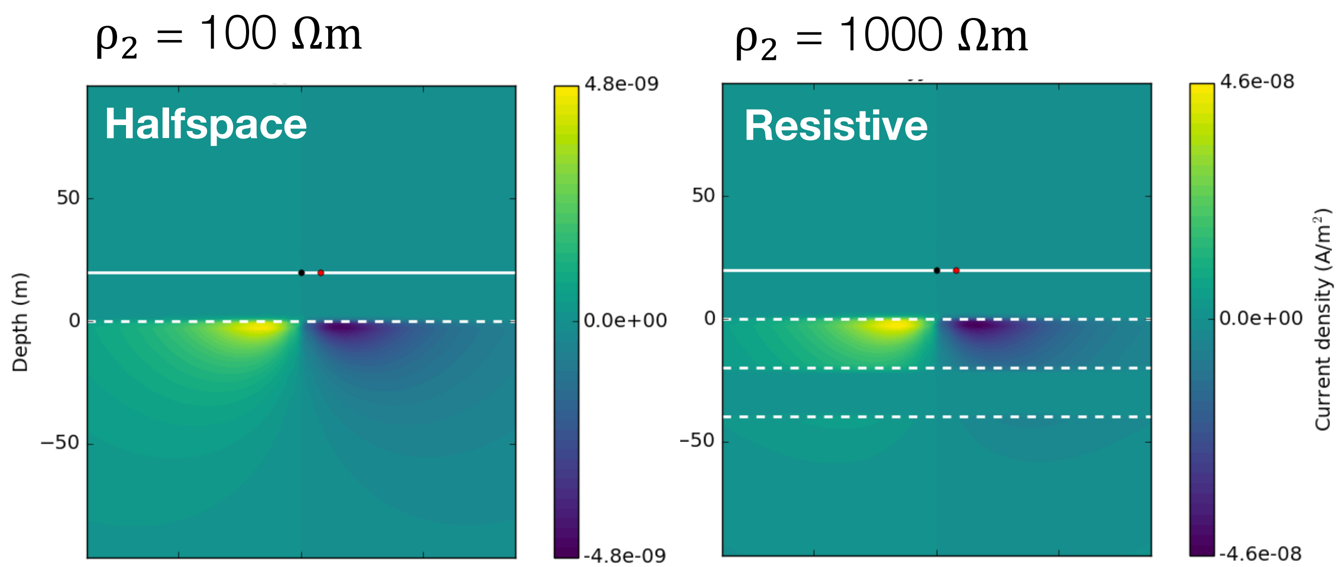
- Four different cases:
  - Halfspace
    $\rho_2 = 100\ \Omega \mathrm{m}$
  - Resistive
    $\rho_2 = 1000\ \Omega \mathrm{m}$
  - Conductive
    $\rho_2 = 10\ \Omega \mathrm{m}$
  - Very conductive
    $\rho_2 = 1\ \Omega \mathrm{m}$
- Fields
  - J_y imag
  - Secondary **B** imag

Current density (J_y imag)

$\rho_2 = 100\ \Omega m$

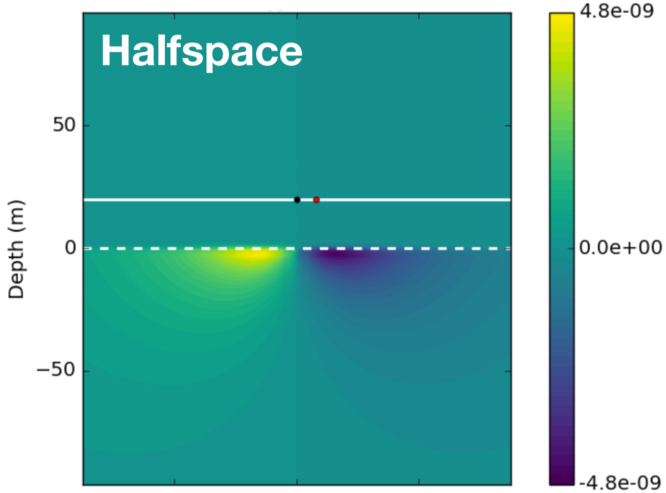


Current density (J_y imag)

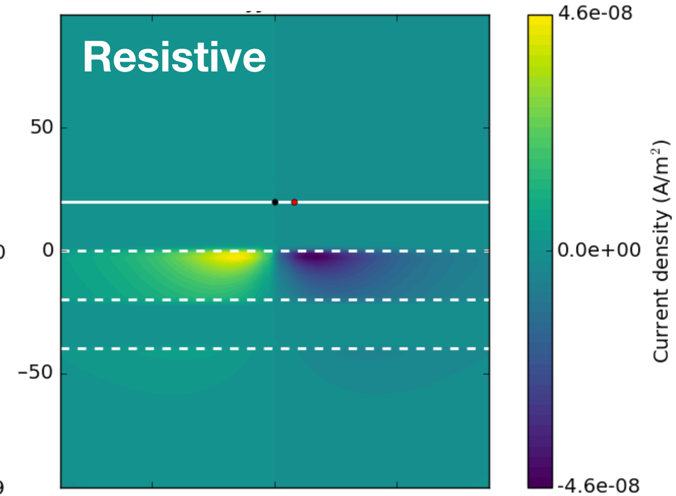


Current density (J_y imag)

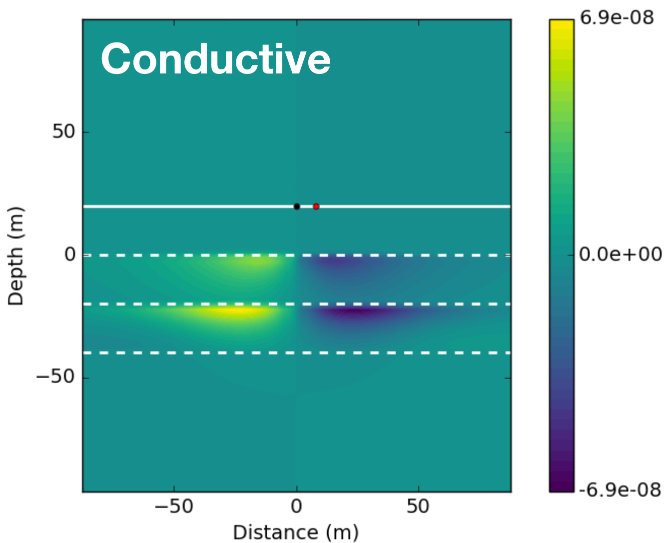
$\rho_2 = 100\ \Omega\text{m}$



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

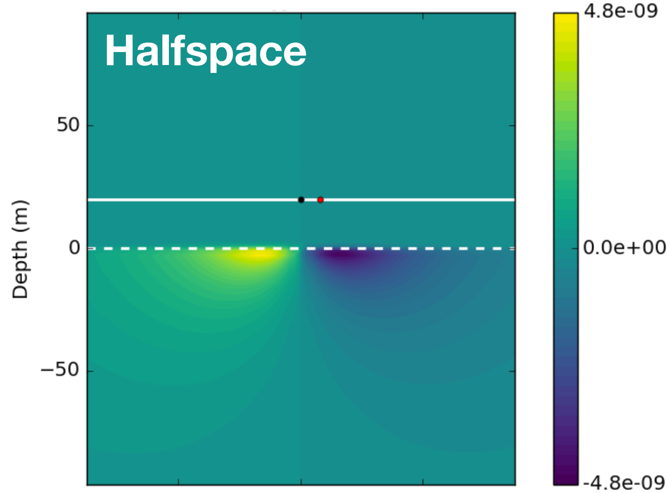


$\rho_2 = 10\ \Omega\text{m}$

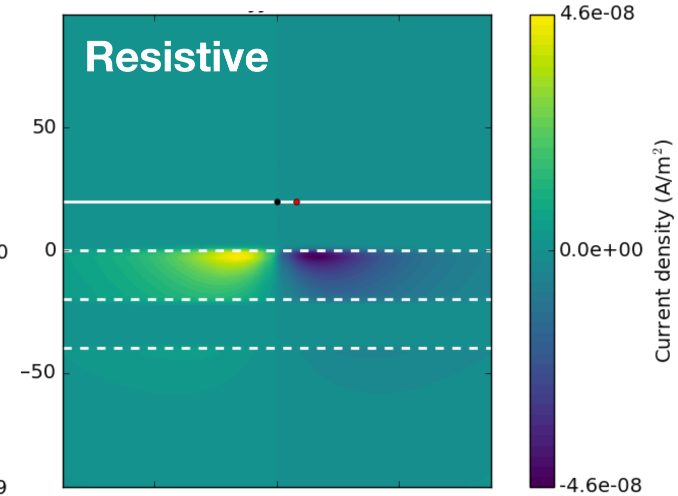


Current density (J_y imag)

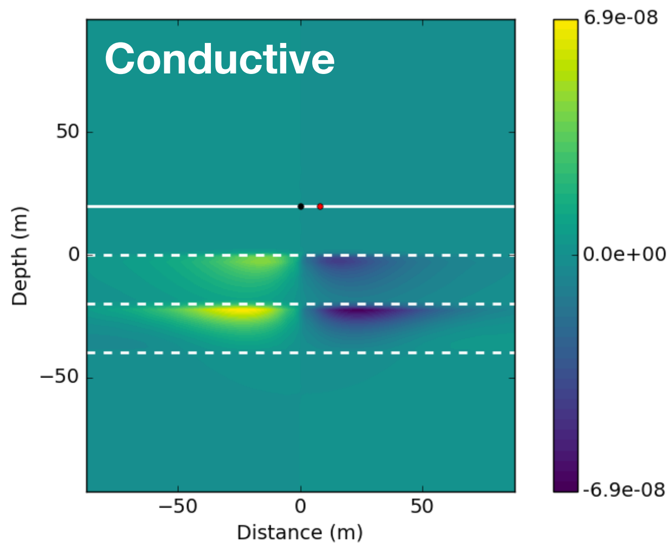
ρ_2 = 100 Ωm



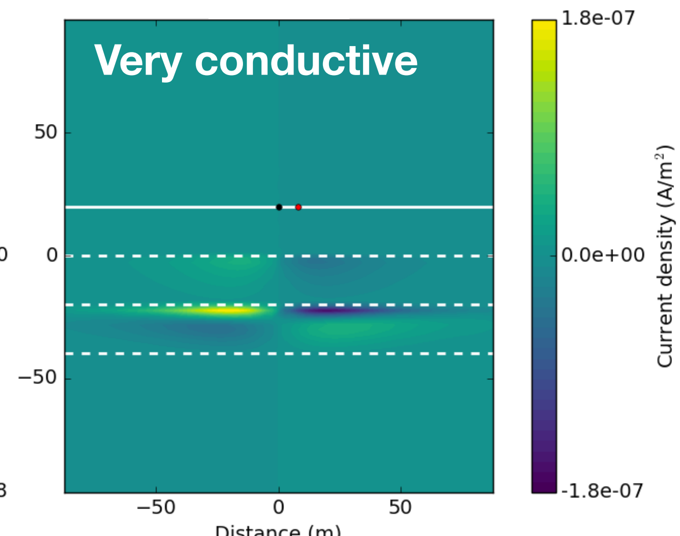
ρ_2 = 1000 Ωm



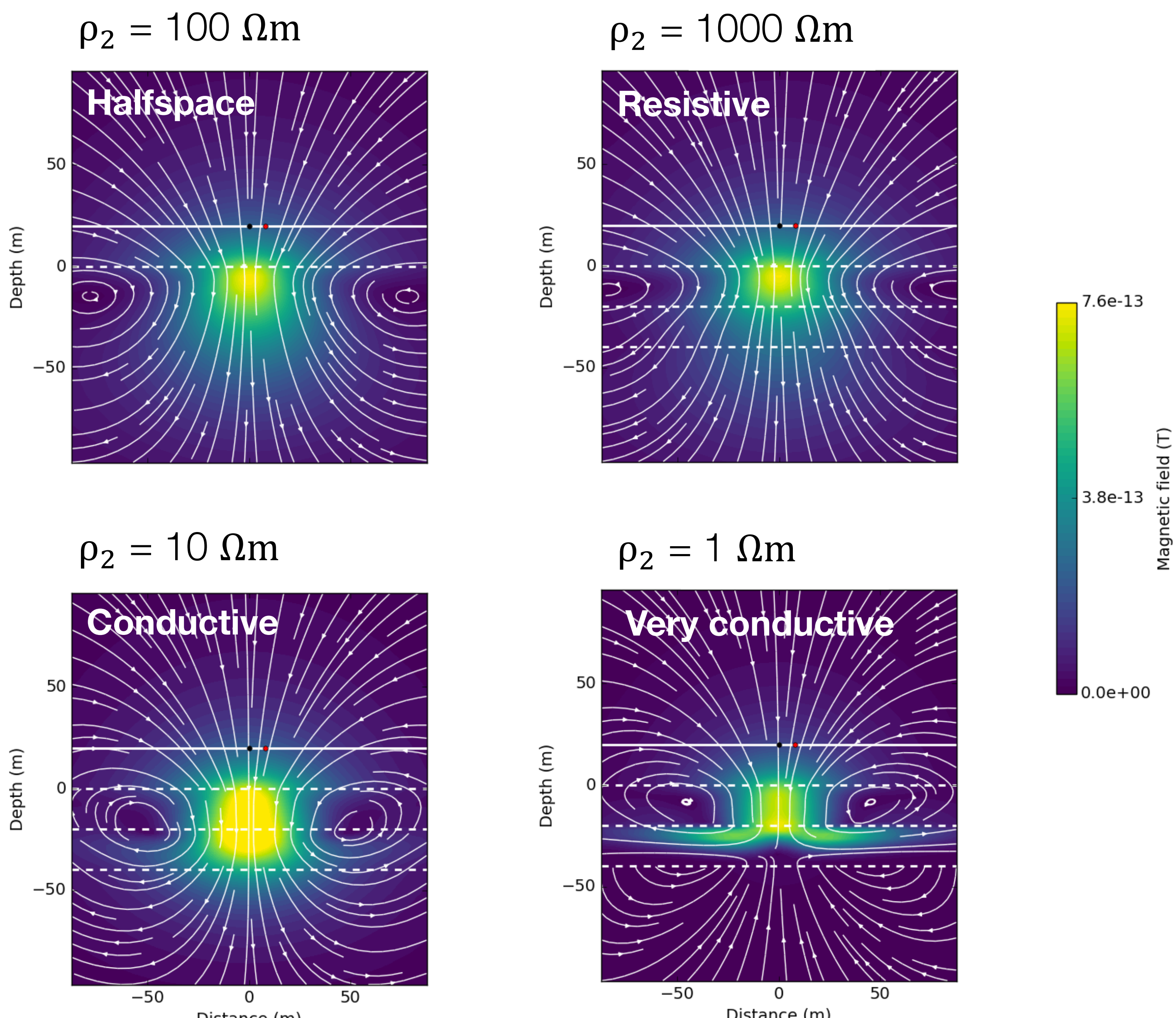
ρ_2 = 10 Ωm



ρ_2 = 1 Ωm

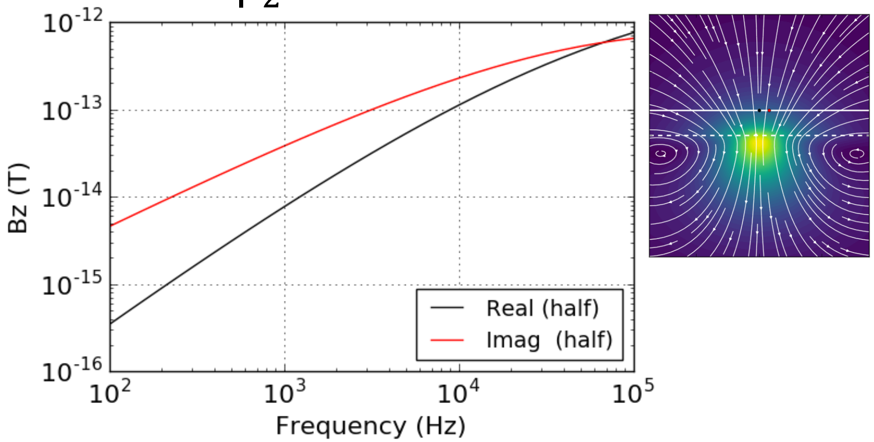


Magnetic flux density (**B** imag)

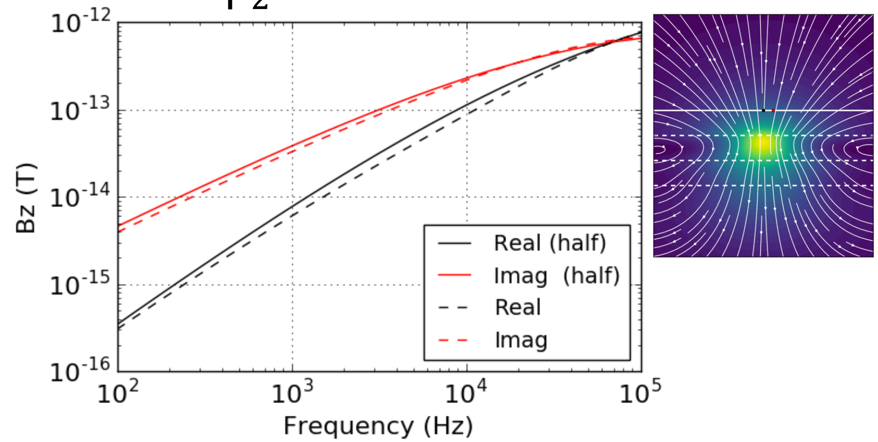


B_z sounding curves

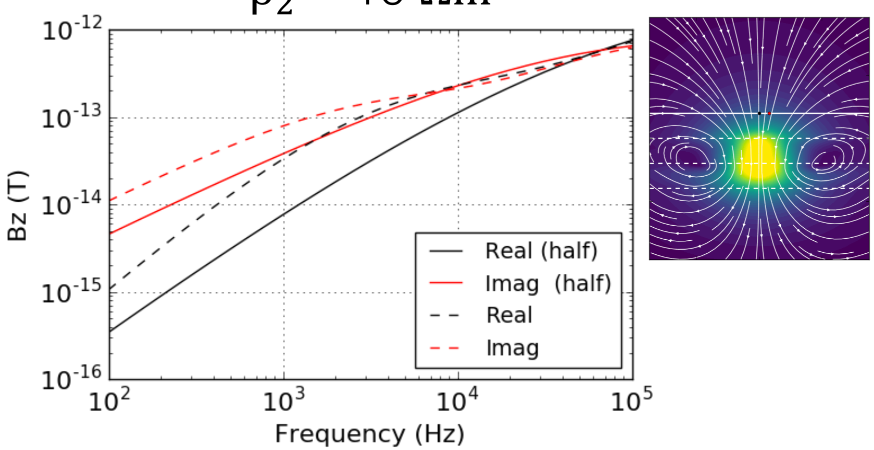
$\rho_2 = 100\ \Omega m$



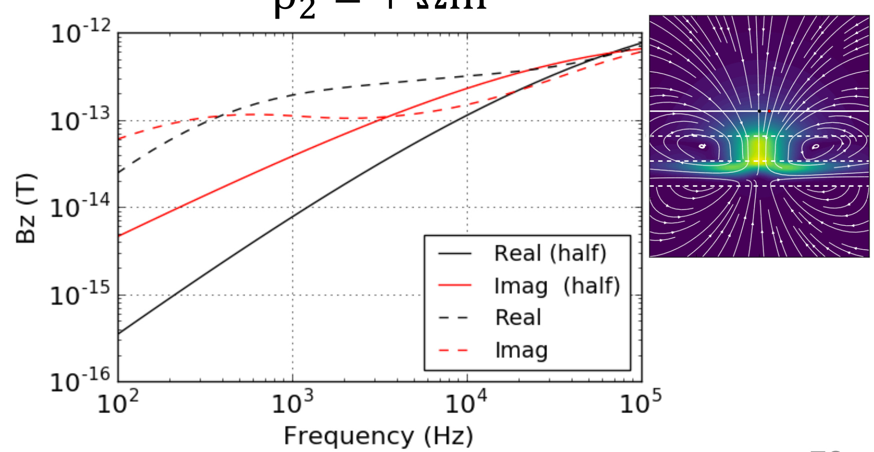
$\rho_2 = 1000\ \Omega m$



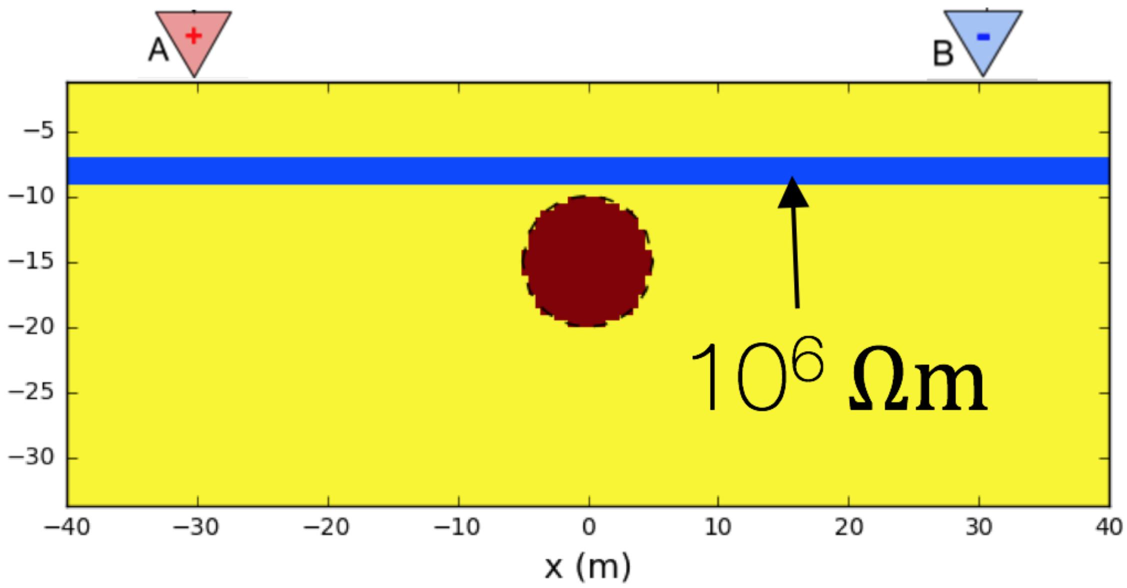
$\rho_2 = 10\ \Omega m$



$\rho_2 = 1\ \Omega m$

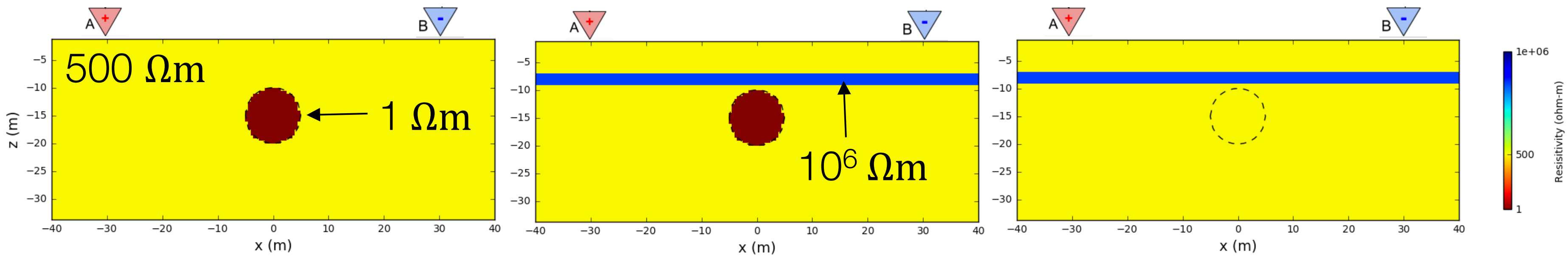


Back to the “shielding” problem



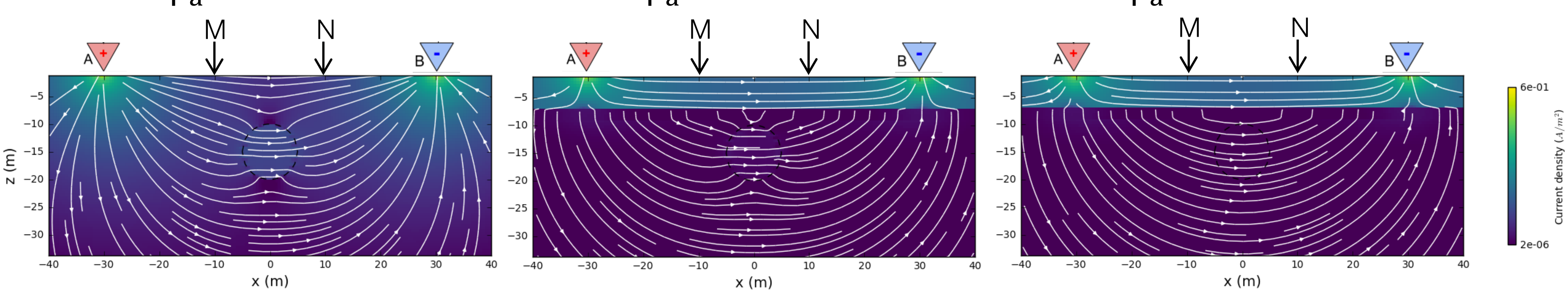
Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



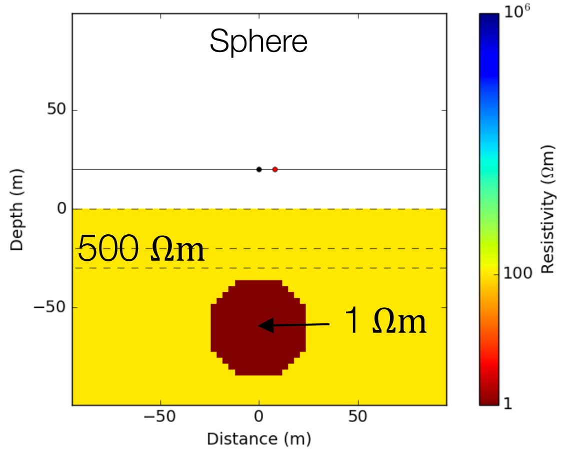
Currents and measured data at MN

ρ_a = 430 Ωm ρ_a = 1652 Ωm ρ_a = 1654 Ωm

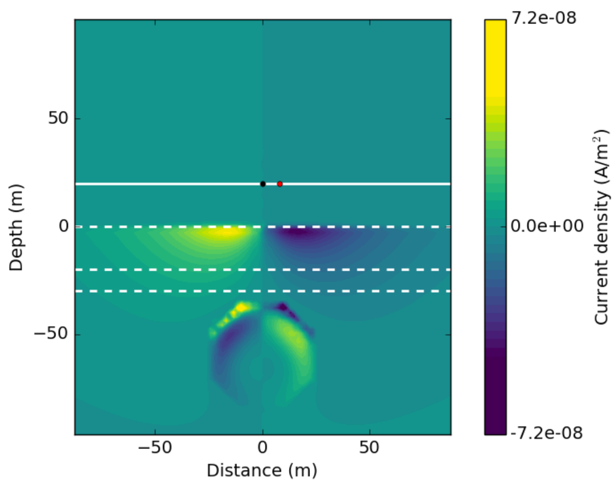


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

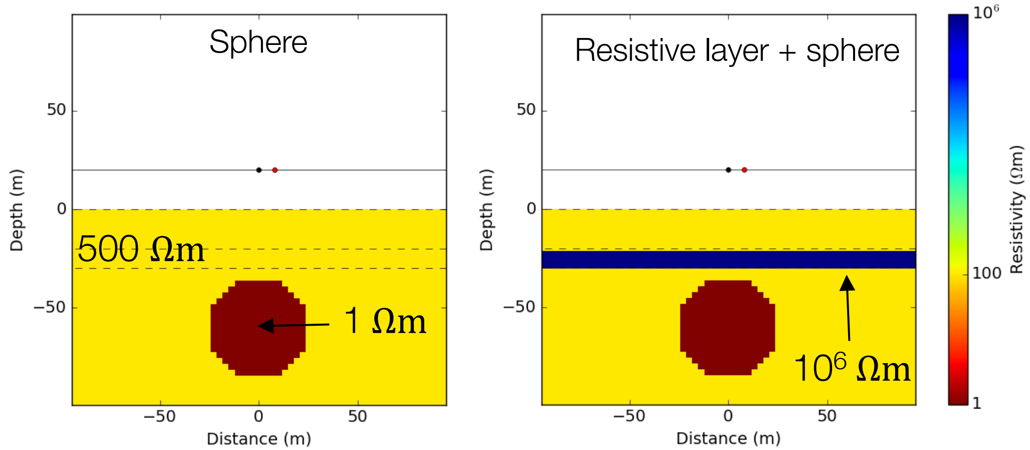


Currents (J_y imag)

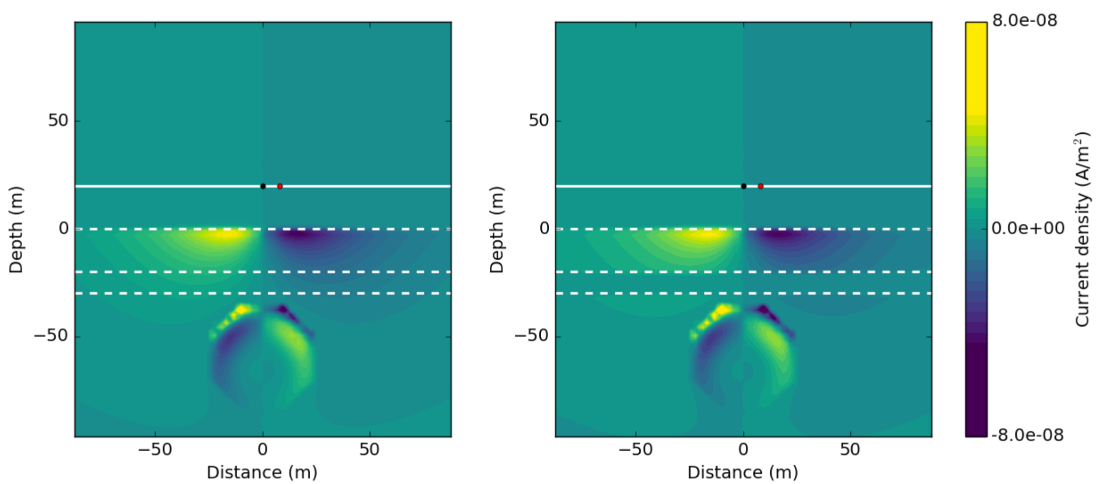


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

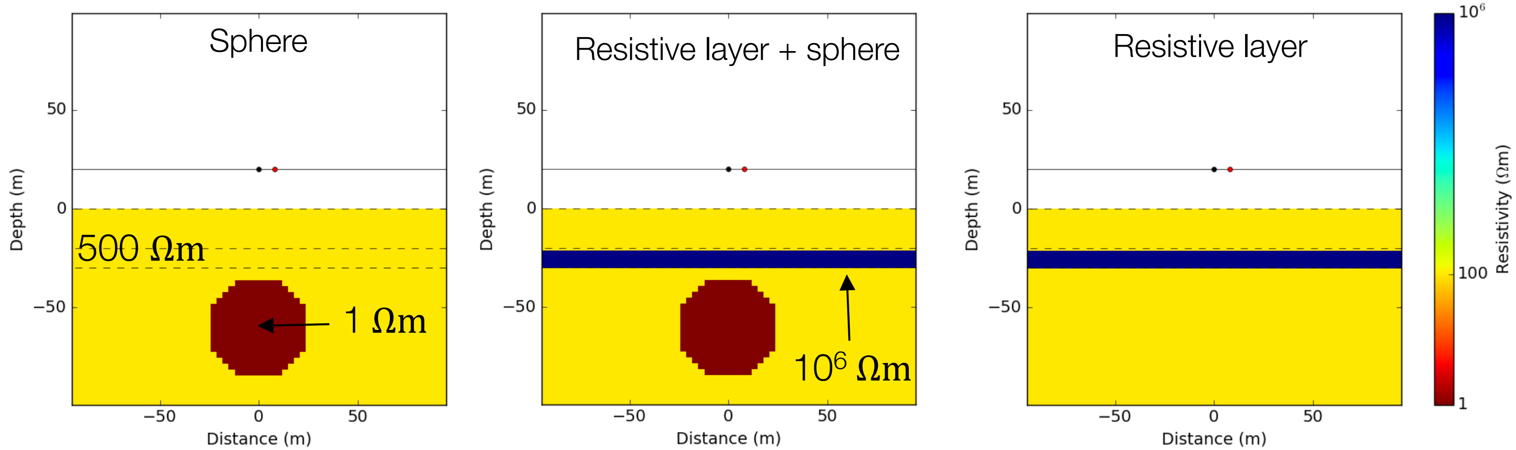


Currents (J_y imag)

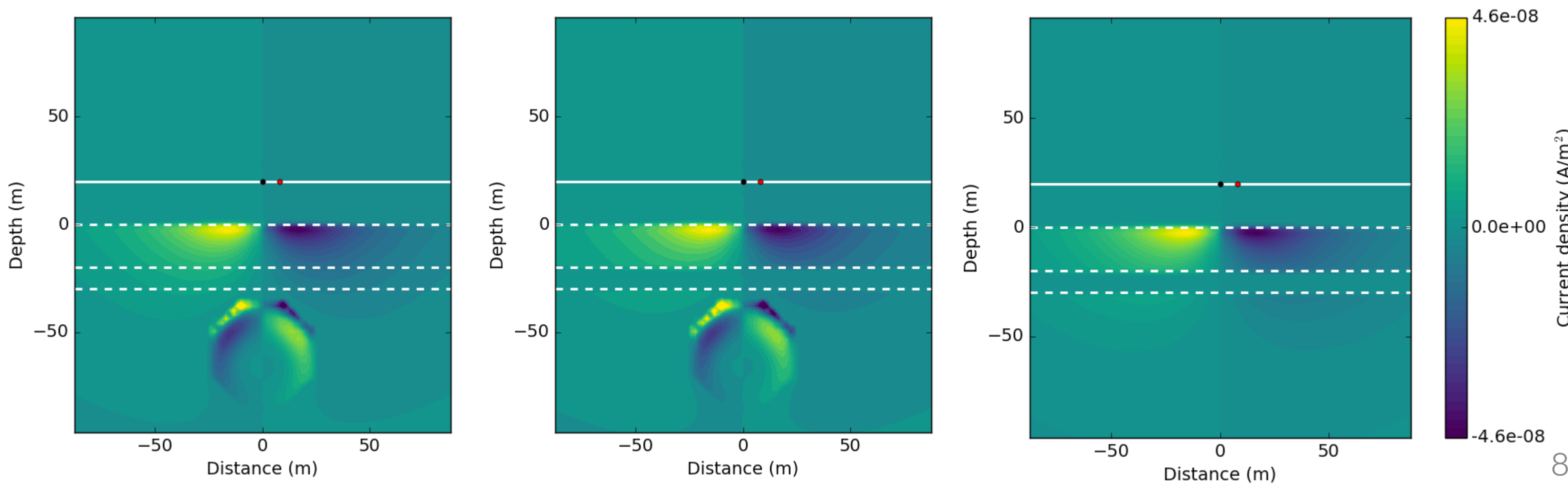


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

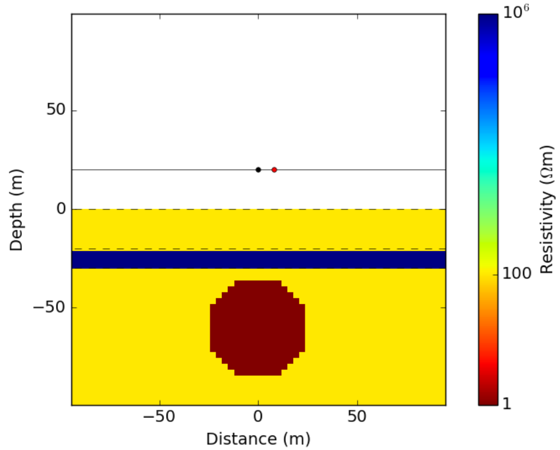


Currents (J_y imag)

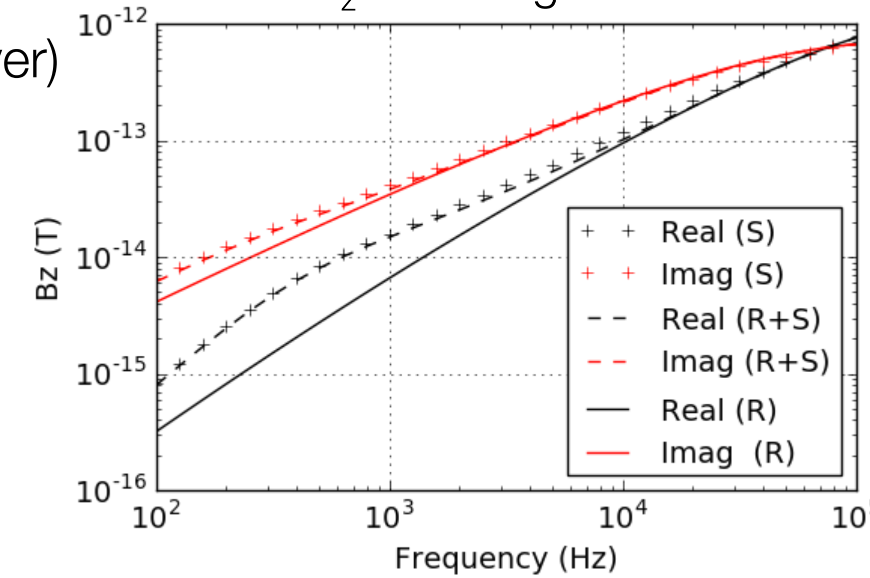


Shielding: EM with resistive layer

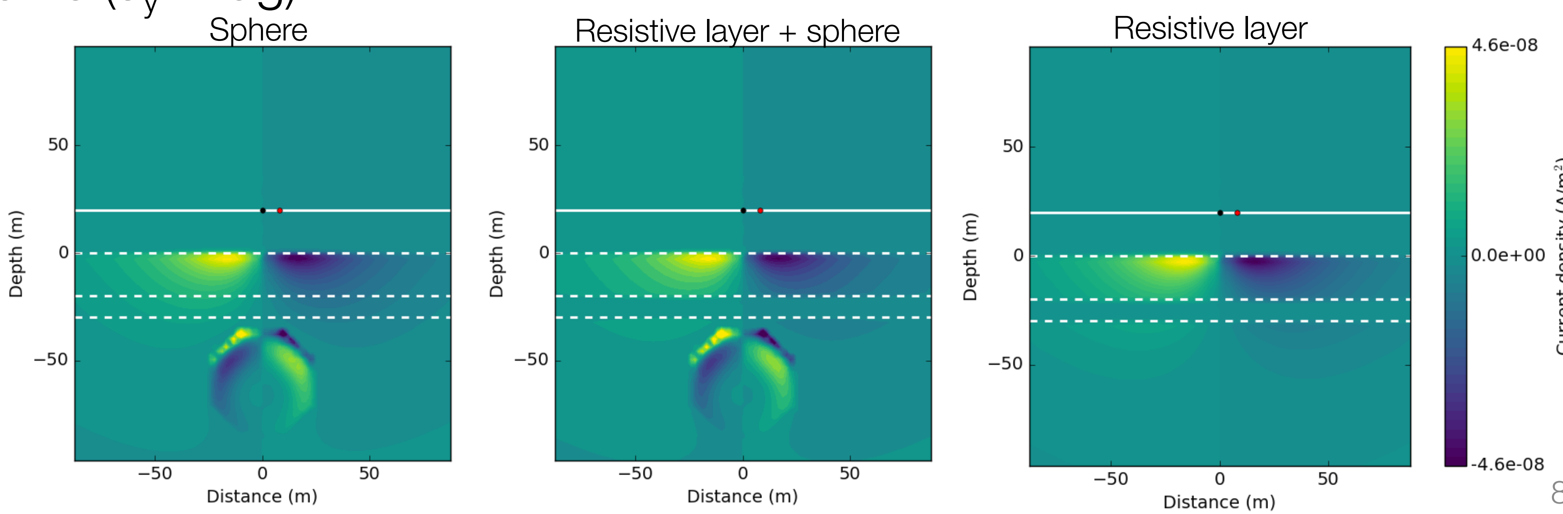
Resistivity models (thin **resistive** layer)



B_z sounding curves

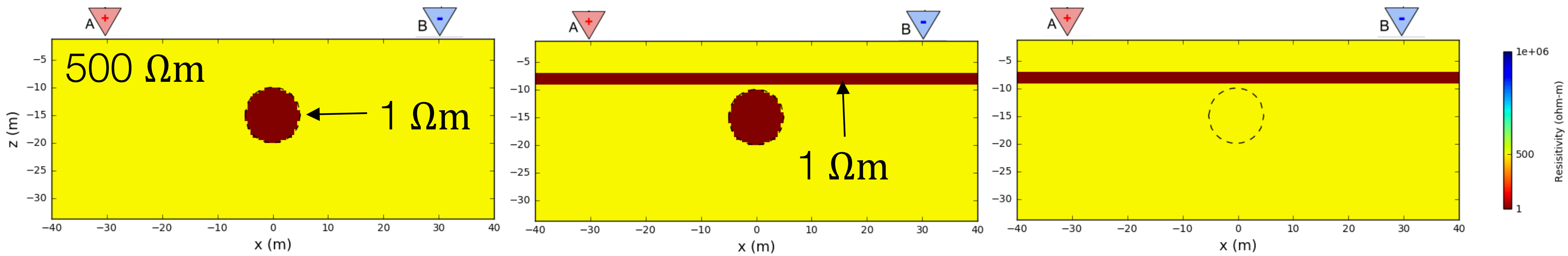


Currents (J_y imag)

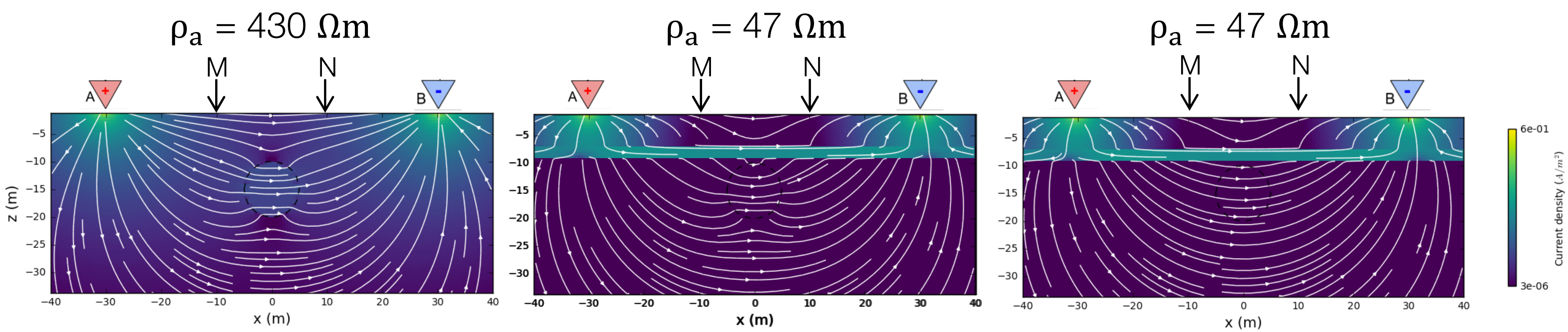


Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)

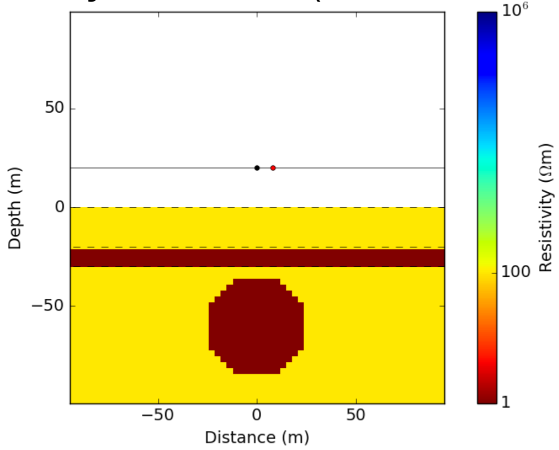


Currents and measured data at MN

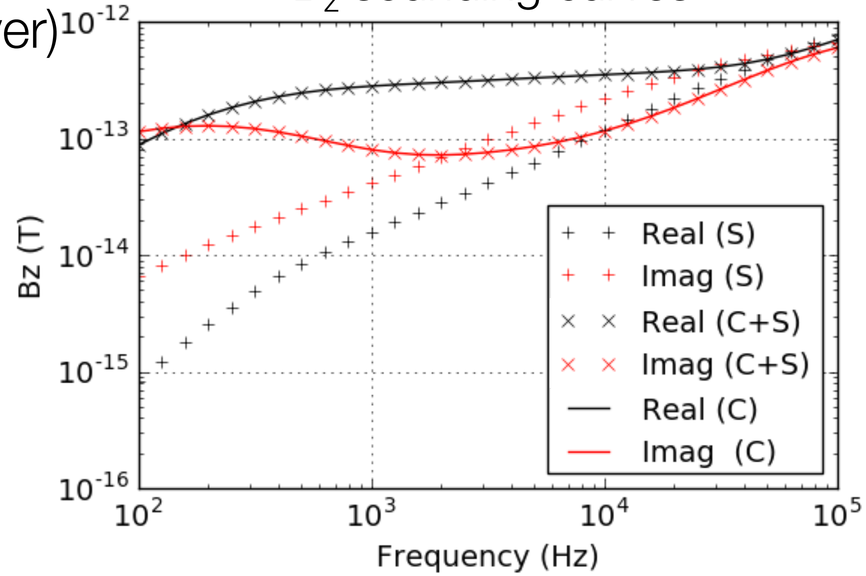


Shielding: EM with conductive layer

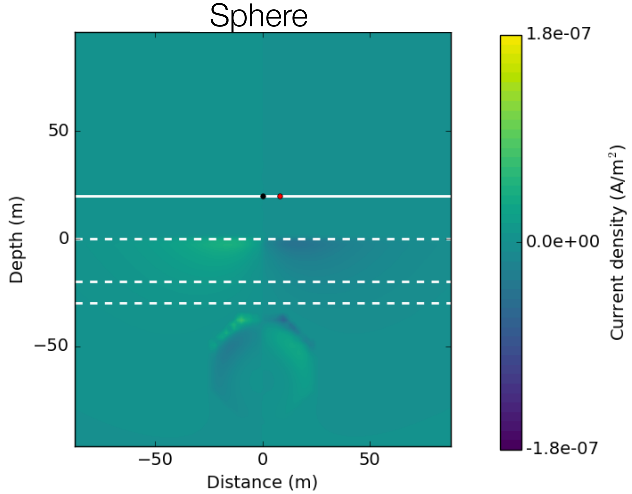
Resistivity models (thin **conductive** layer)



B_z sounding curves

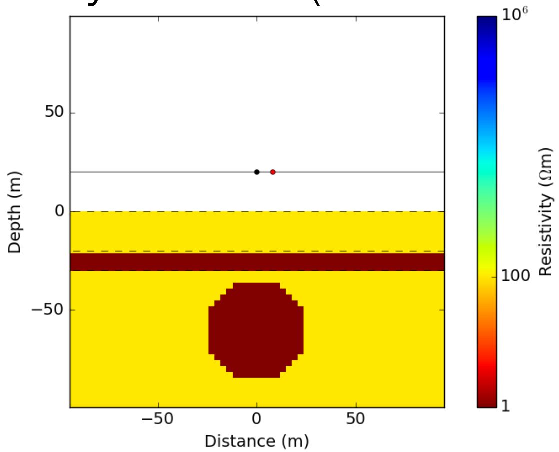


Currents (J_y imag)

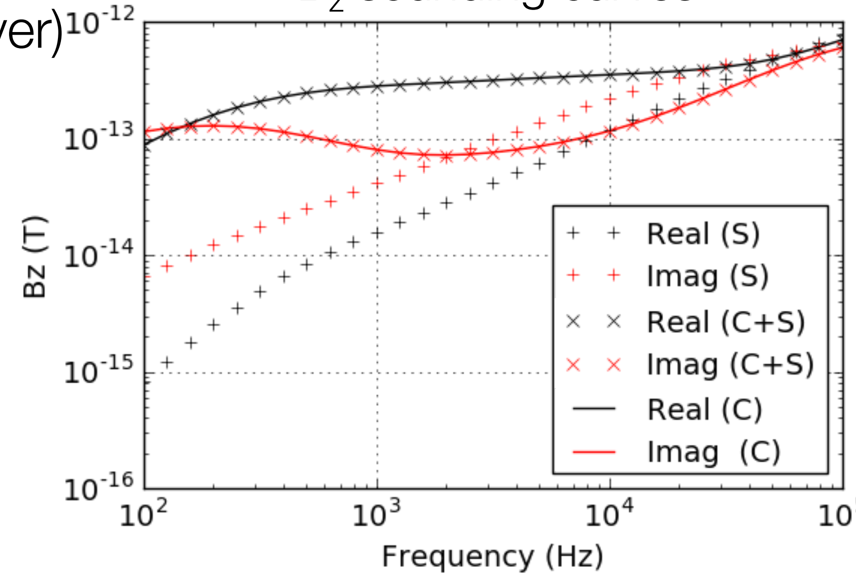


Shielding: EM with conductive layer

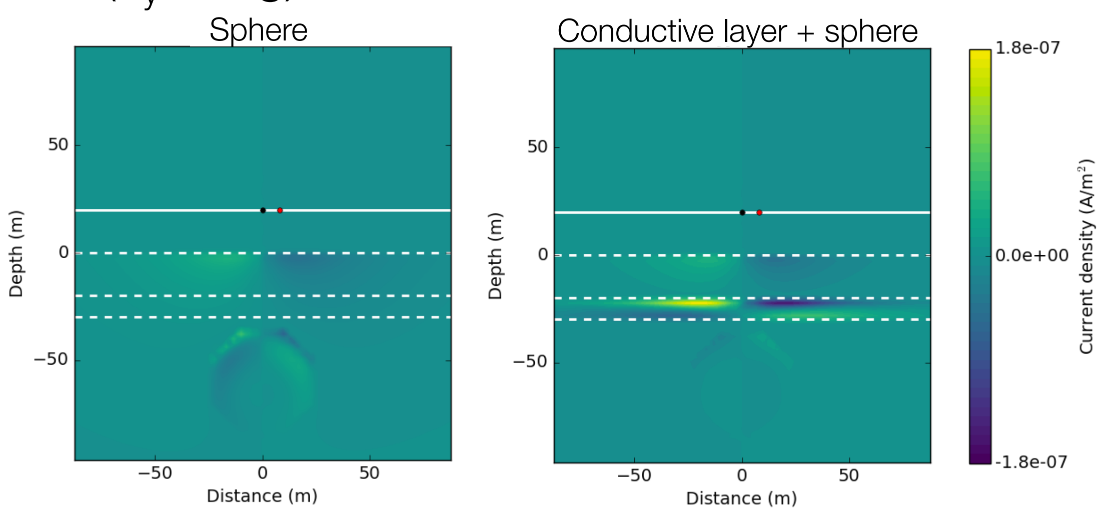
Resistivity models (thin **conductive** layer)



B_z sounding curves

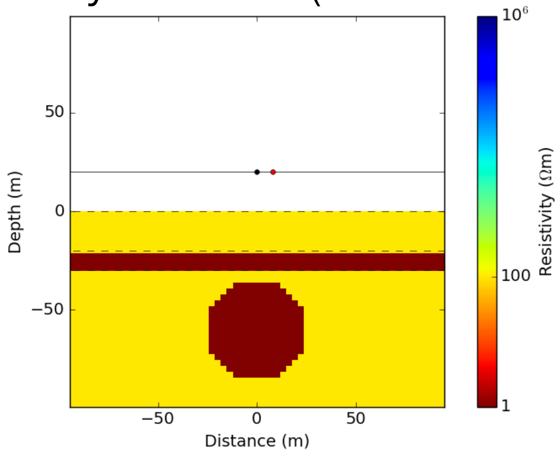


Currents (J_y imag)

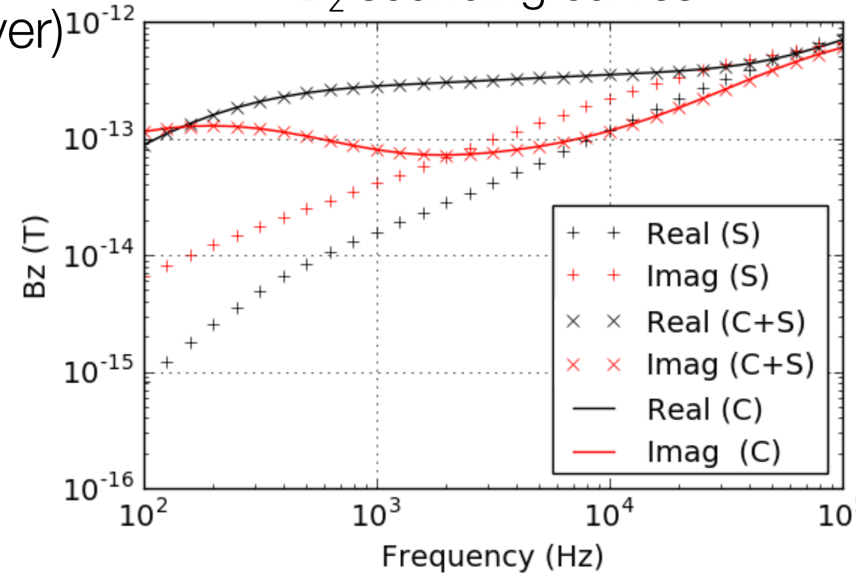


Shielding: EM with conductive layer

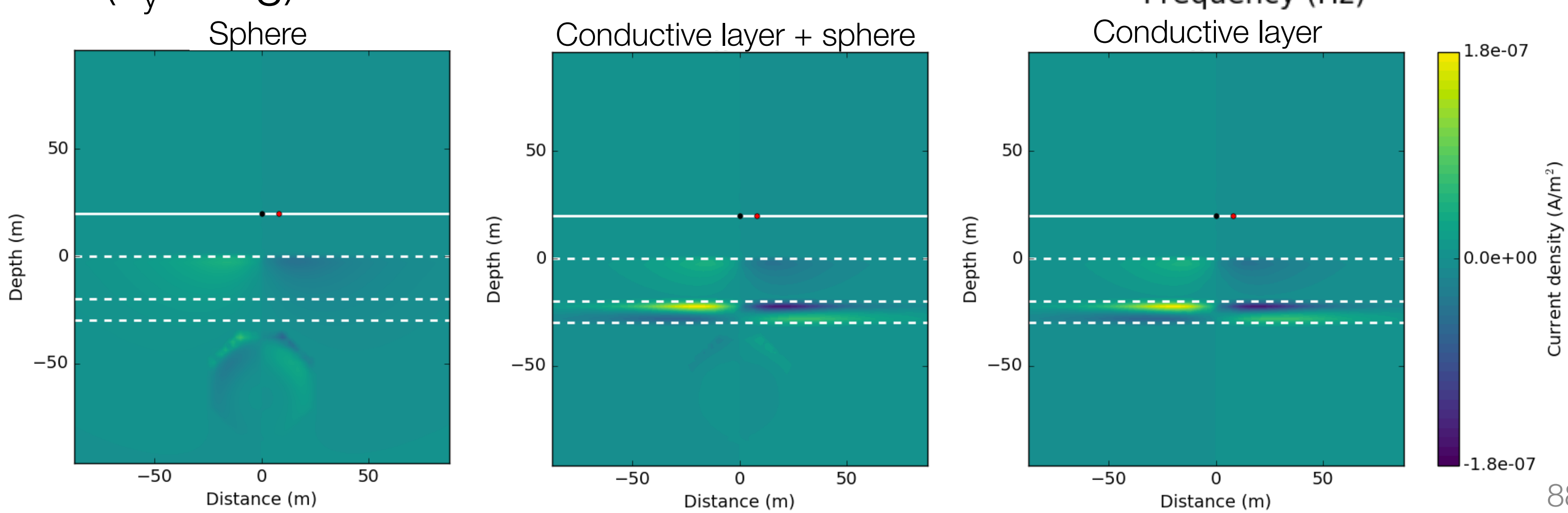
Resistivity models (thin **conductive** layer)



B_z sounding curves



Currents (J_y imag)



Outline

Setup

- Basic experiment
- Transmitters, Receivers

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Case History

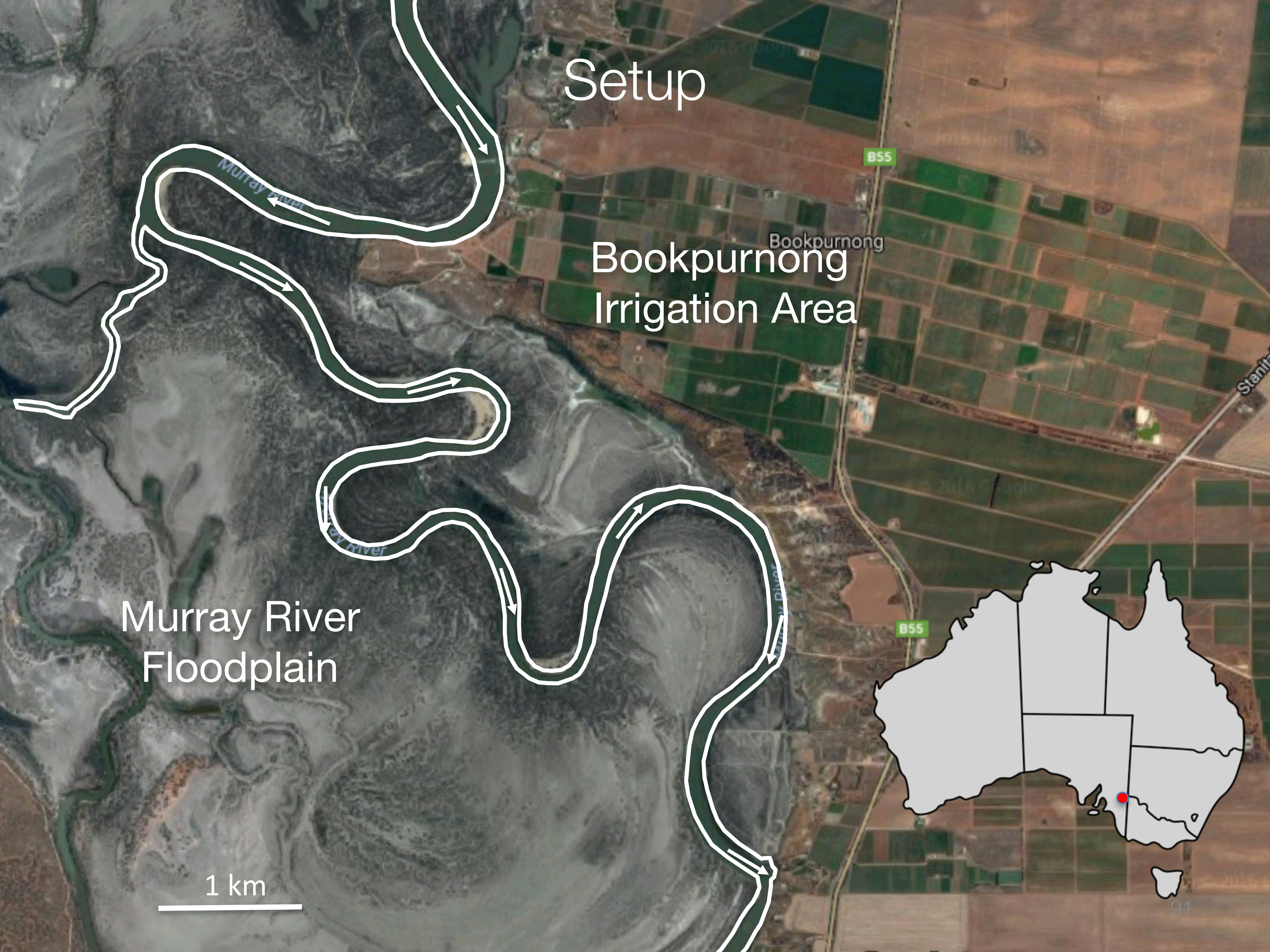
Frequency Domain EM

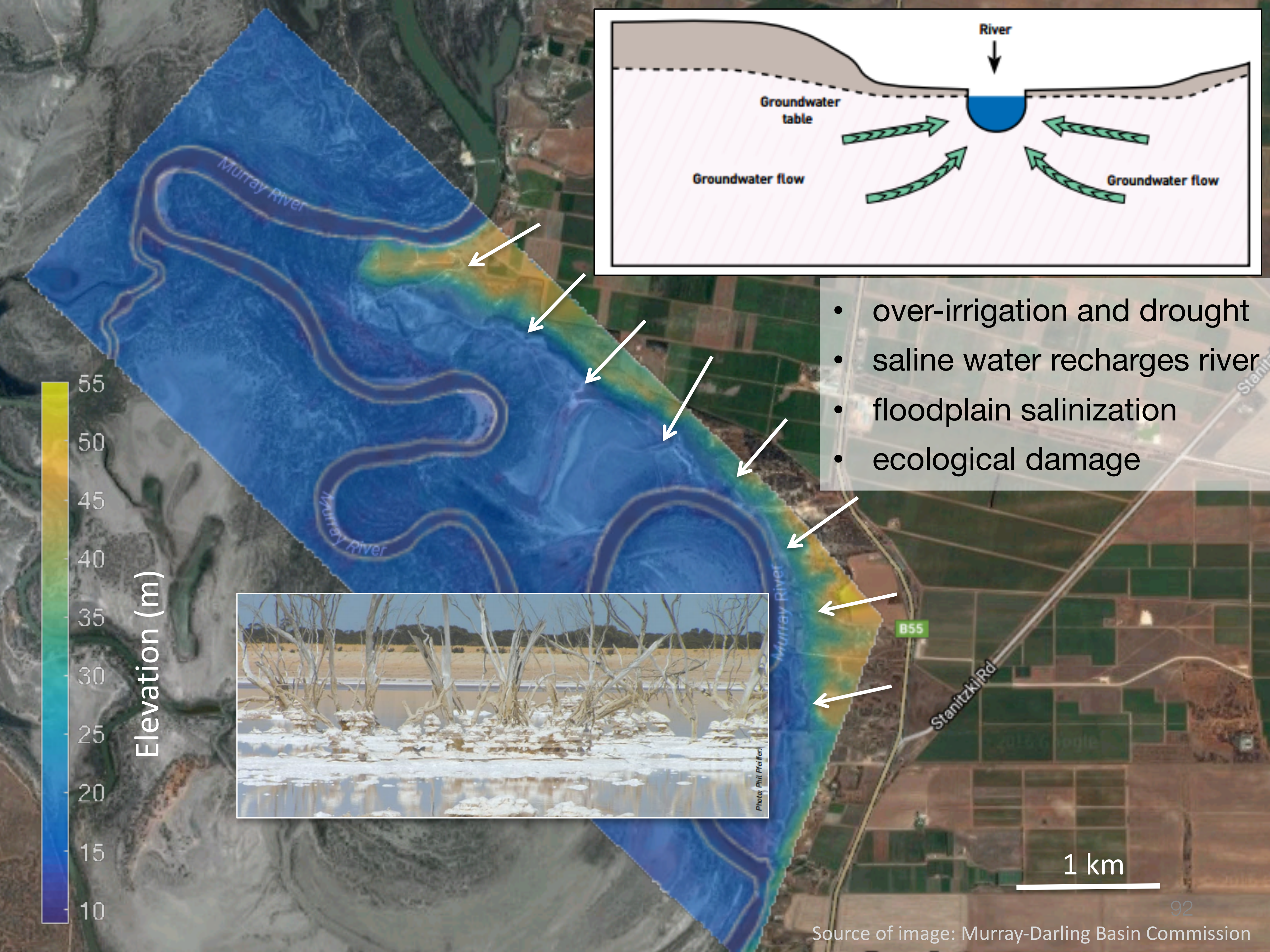
- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Groundwater

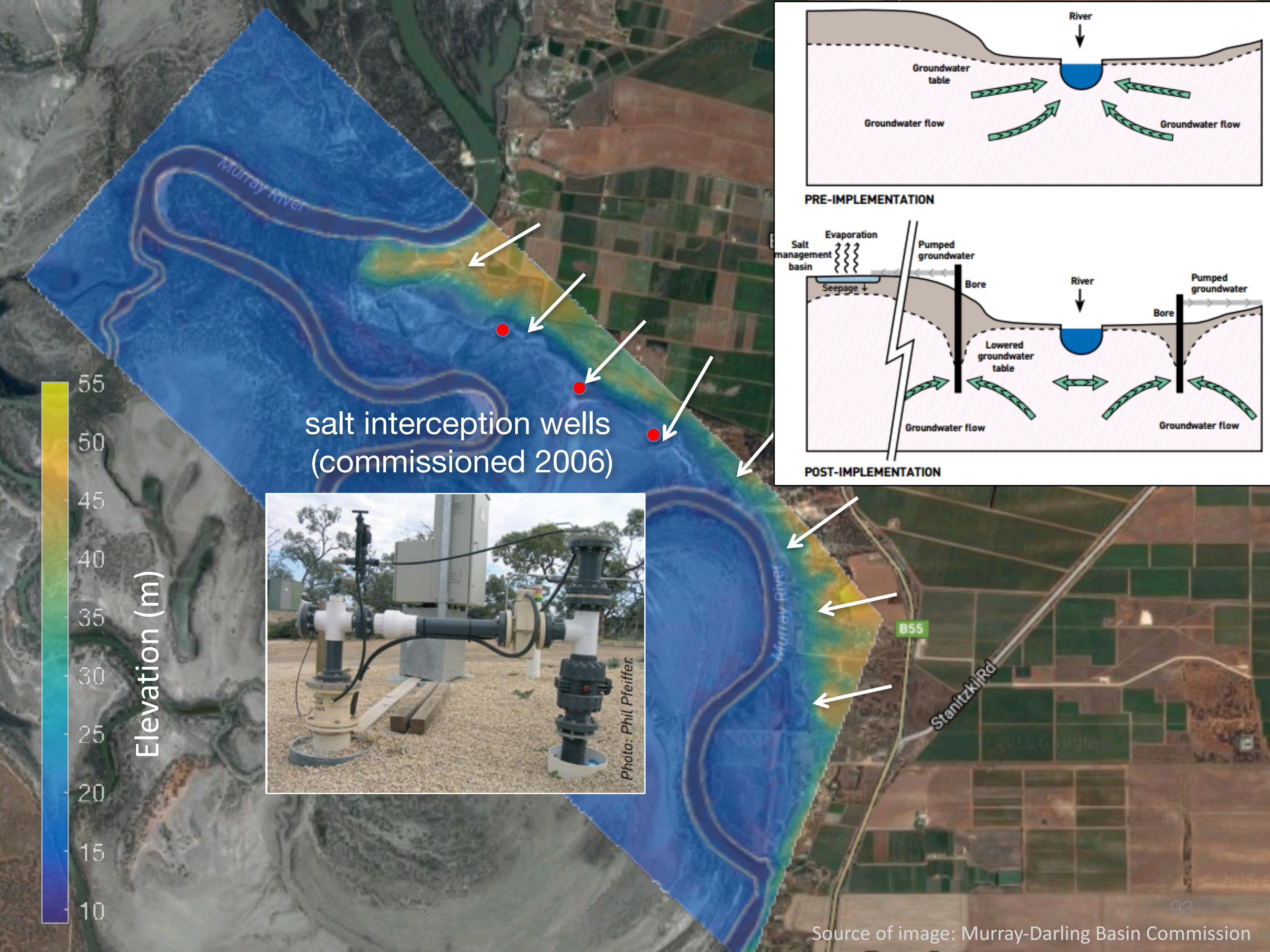
Questions

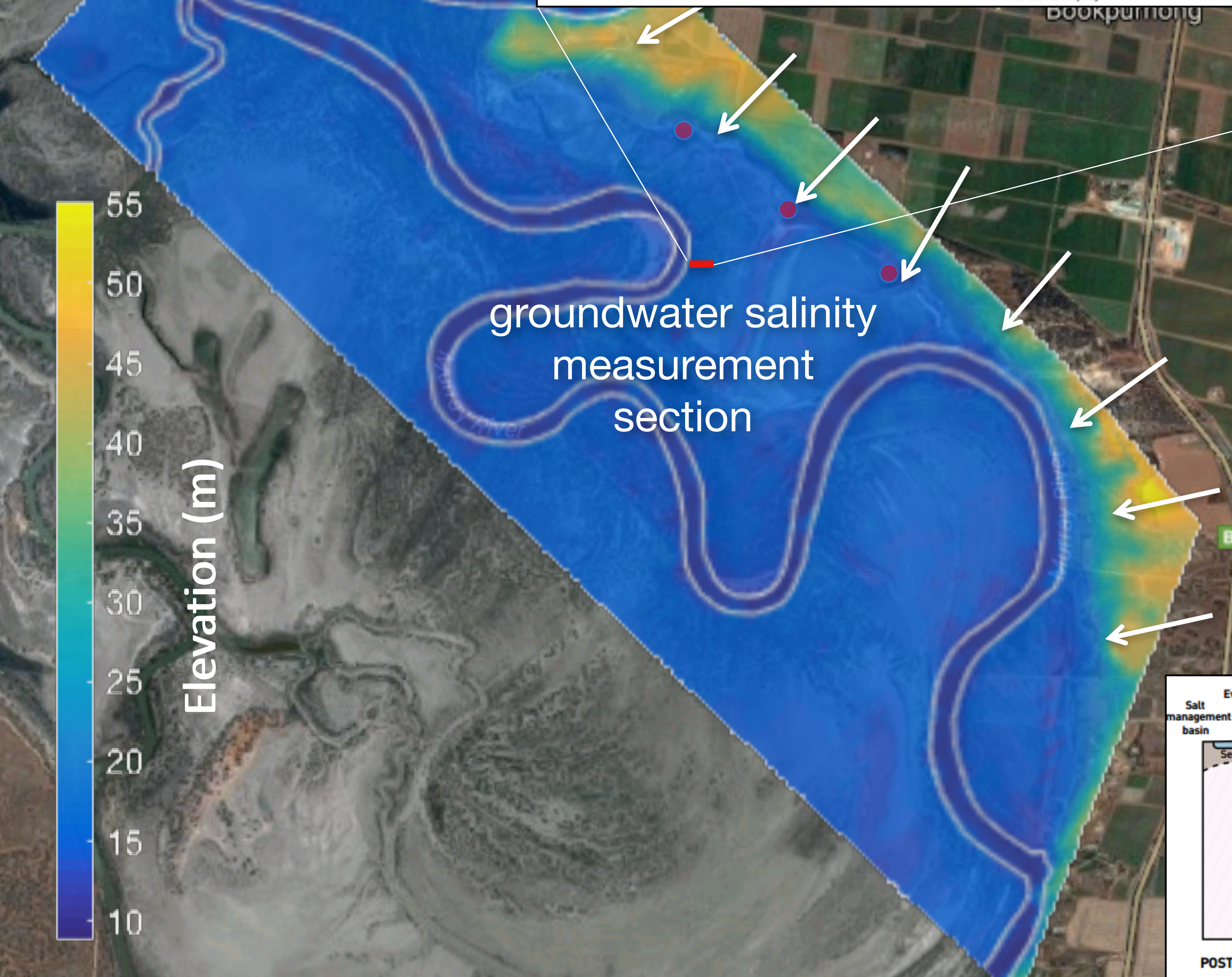
Case History: Bookpurnong

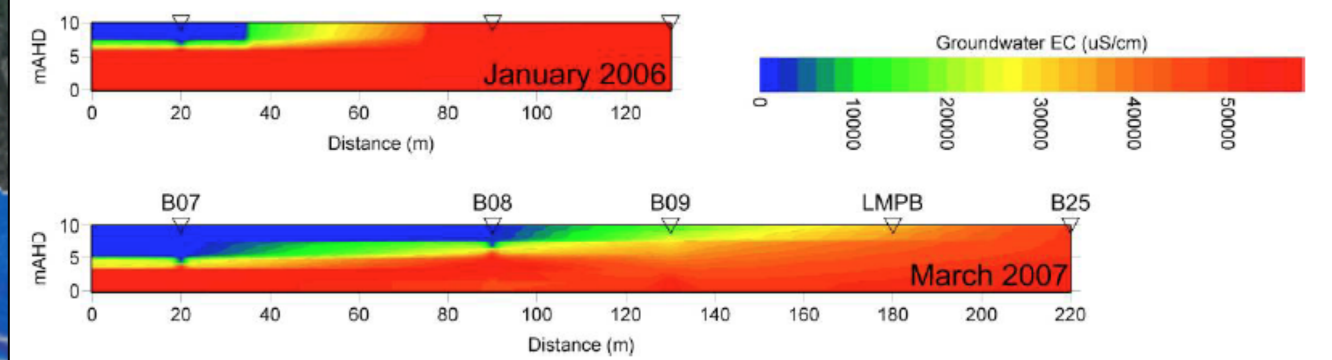
Viezzoli et al., 2009


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

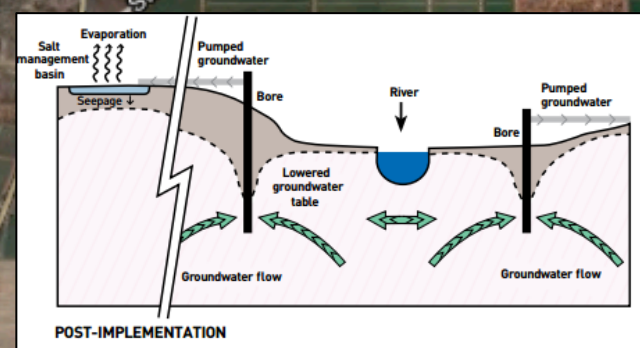

River
Groundwater table
Groundwater flow
Groundwater flow
• over-irrigation and drought
• saline water recharges river
• floodplain salinization
• ecological damage
Murray River
Murray River
Murray River
Elevation (m)
55
50
45
40
35
30
25
20
15
10
B55
Stanitzki Rd
1 km
Photo: Phil Pfeffer
Source of image: Murray-Darling Basin Commission


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



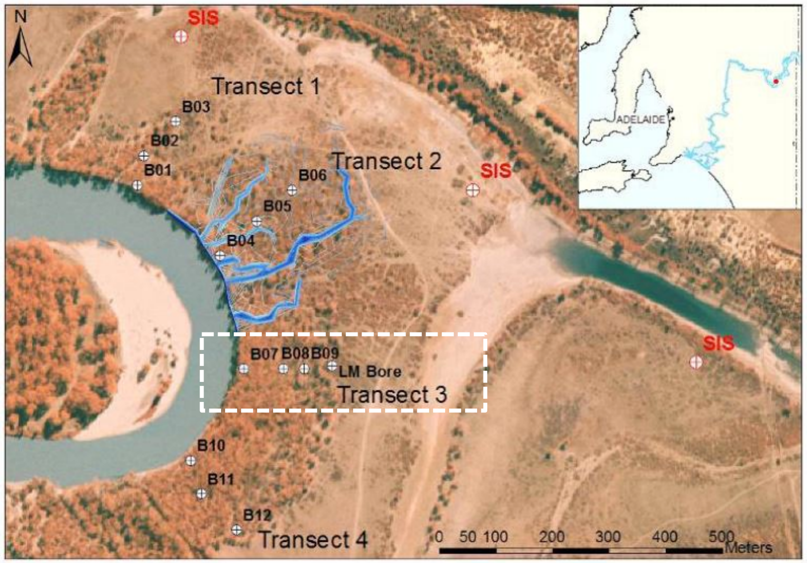


- pumping freshened shallow water near the river
- impractical to drill and sample the entire floodplain
- use airborne EM to quickly survey large areas



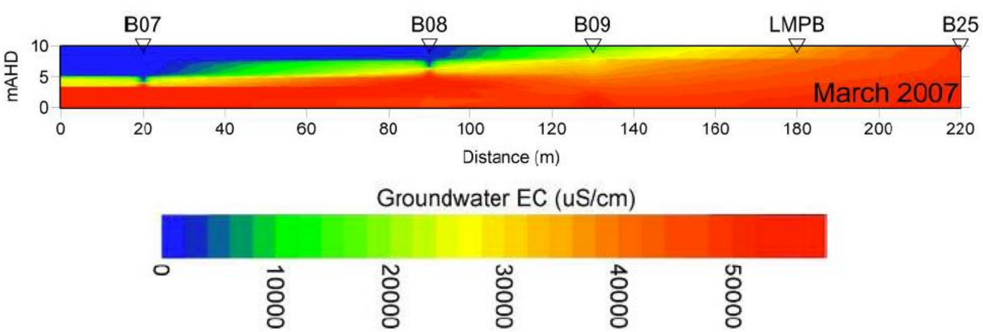
Properties

Location map for salinity measurements



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

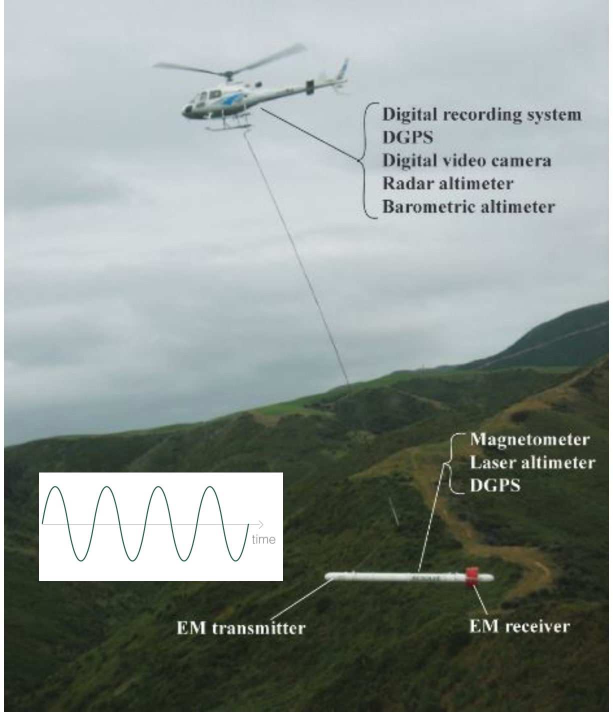
Conductivity from salinity measurements



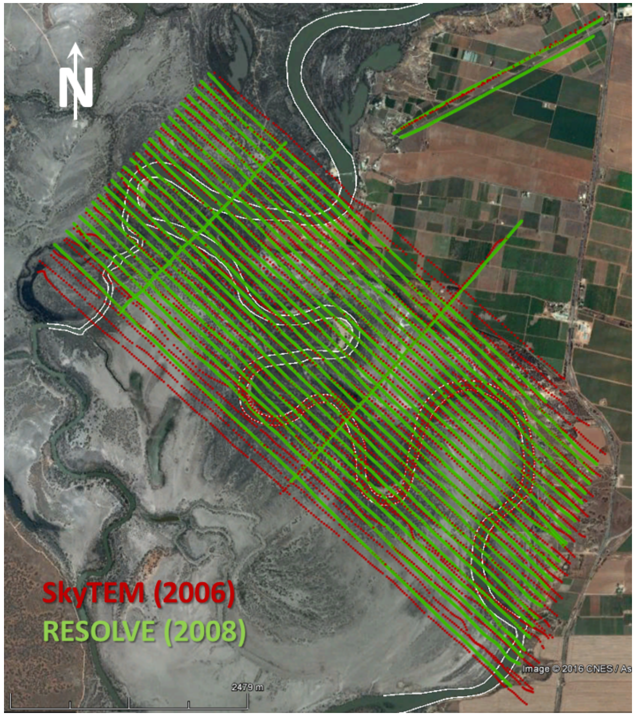
Holland et. al., 2008.

Survey

Resolve system (2008)

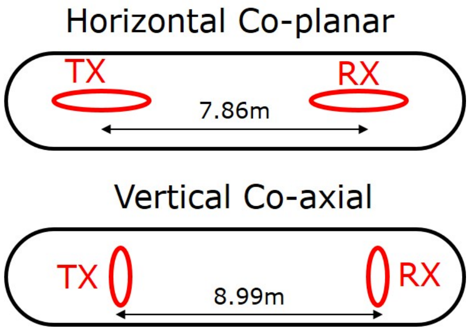


Flight lines



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

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

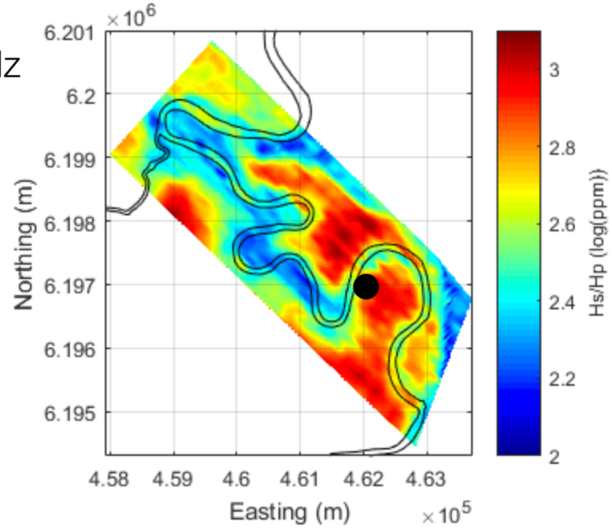


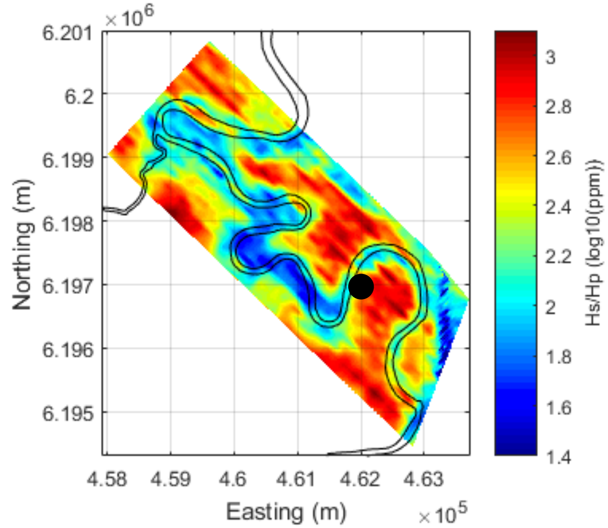
Horizontal Co-planar (HCP) data

In-Phase (Real)

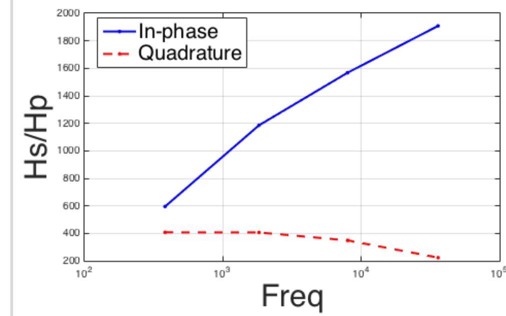
Quadrature (Imaginary)

382 Hz

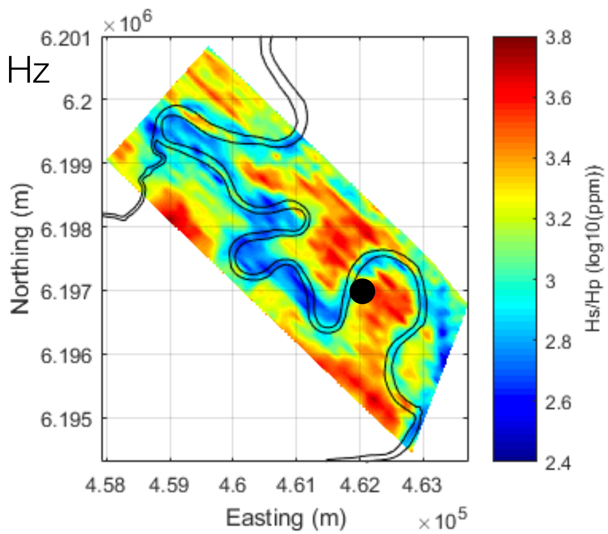


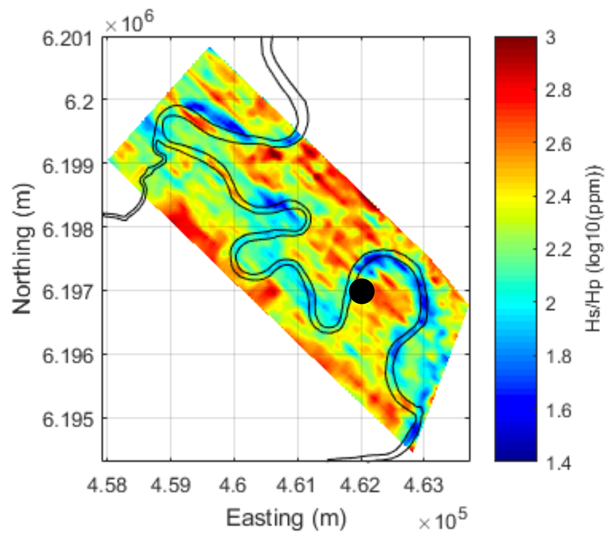


Sounding curve

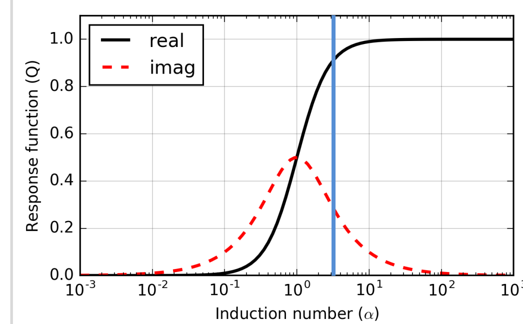


35920 Hz



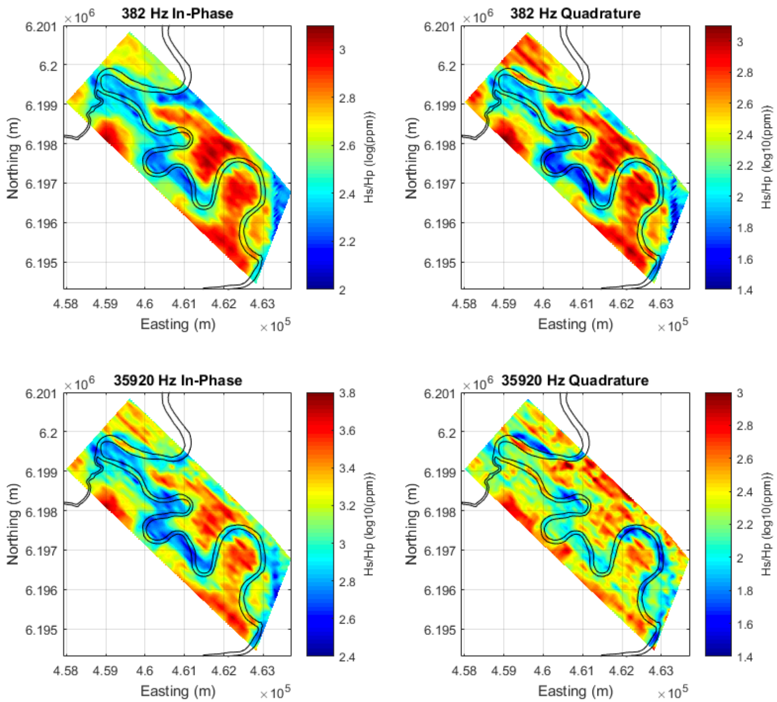


Response curve

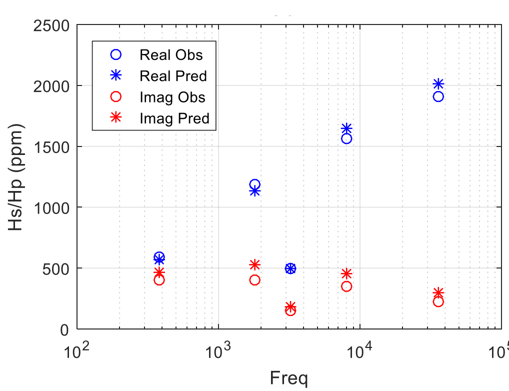


Processing: 1D inversion

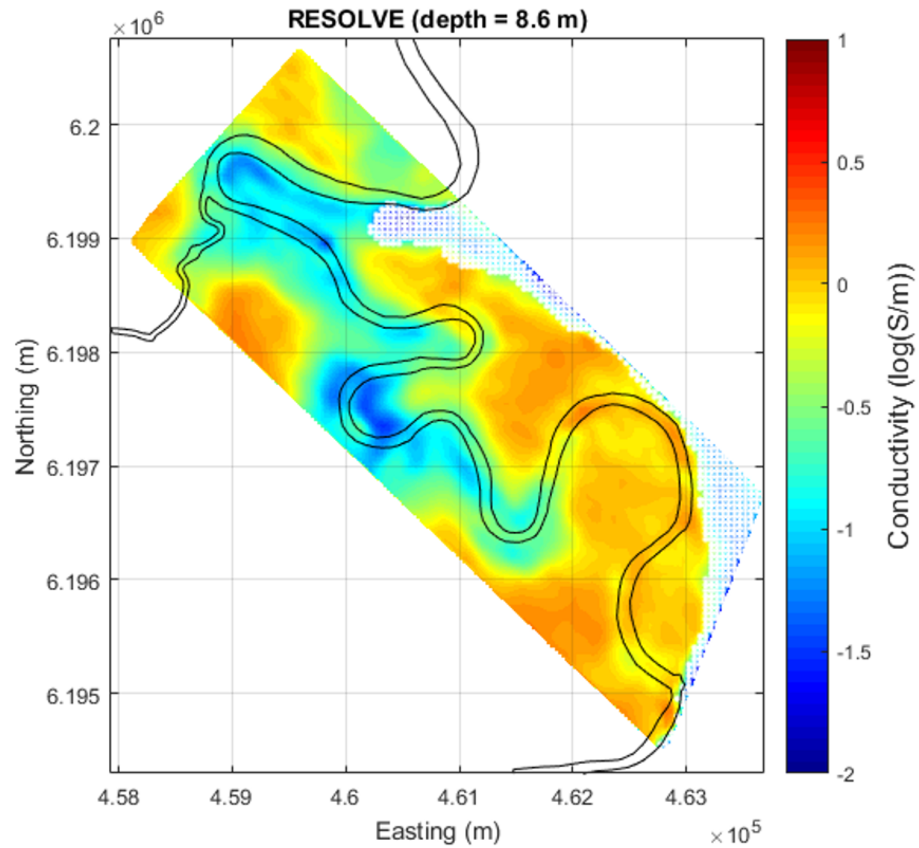
Data



Data fit

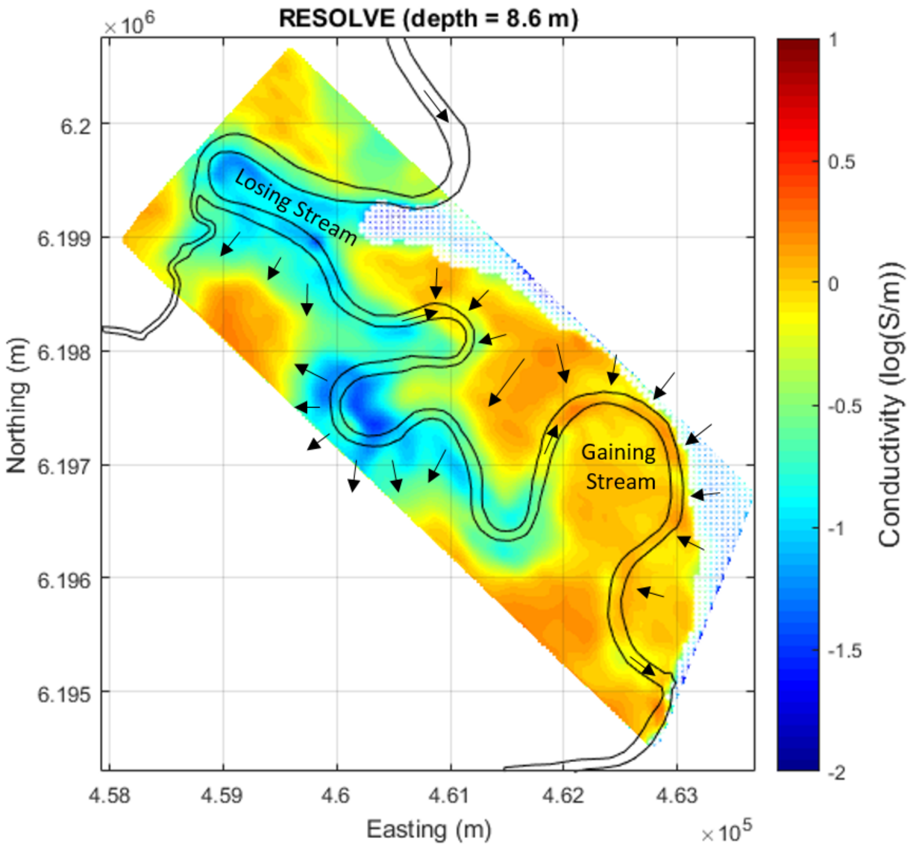


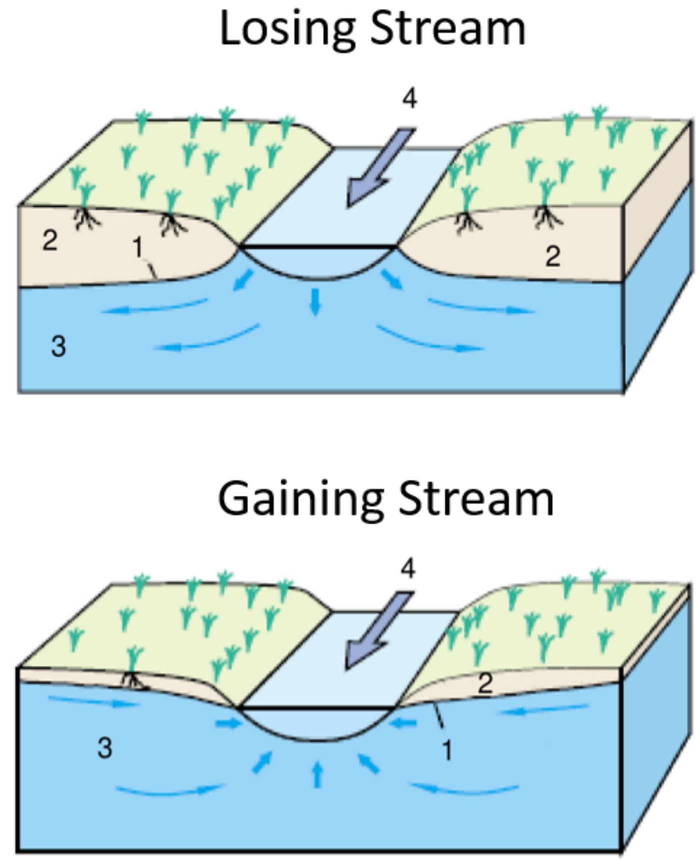
Conductivity model (stitched)



Interpretation

Conductivity model (stitched)



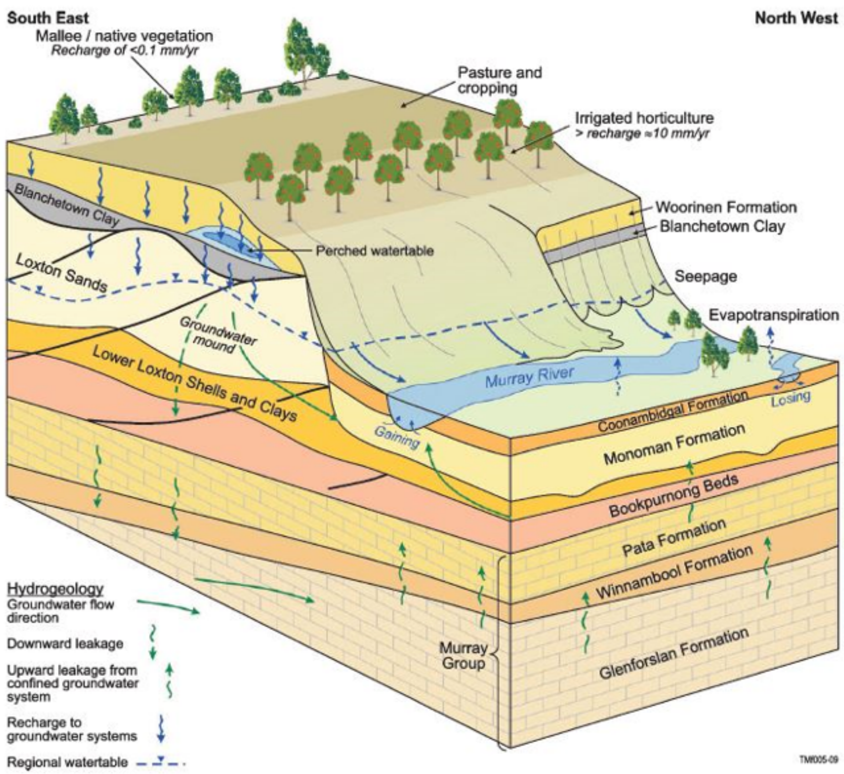


1 – Water table 2 – Unsaturated zone

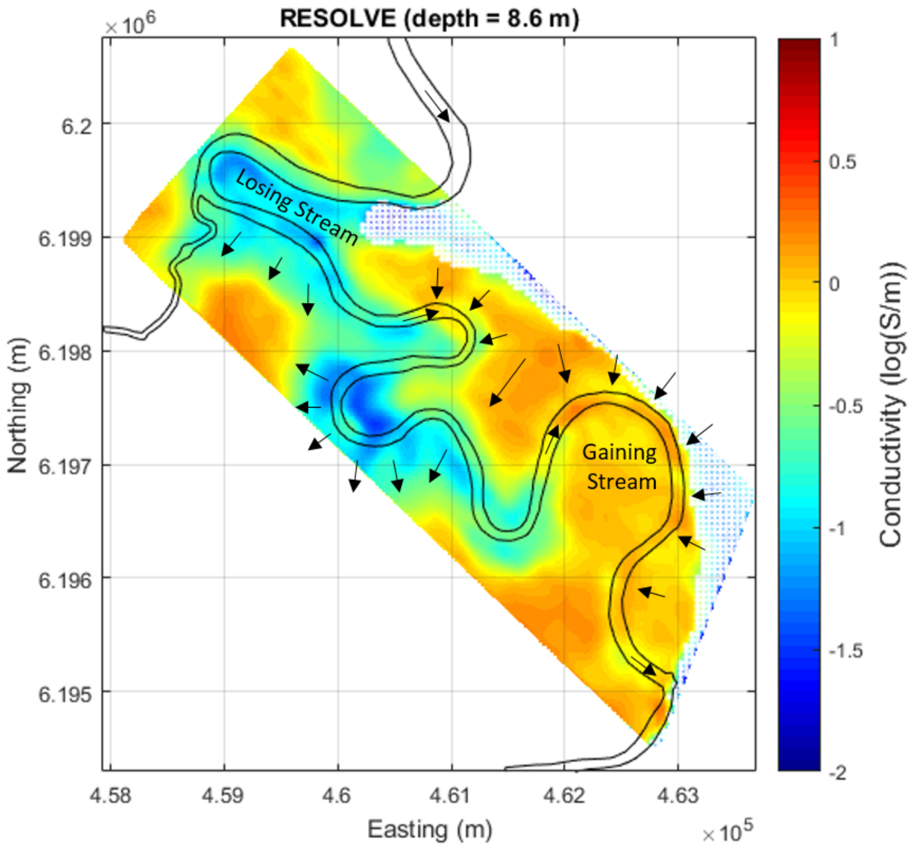
3 – Saturated zone 4 – Flow direction

Synthesis

Hydrological model

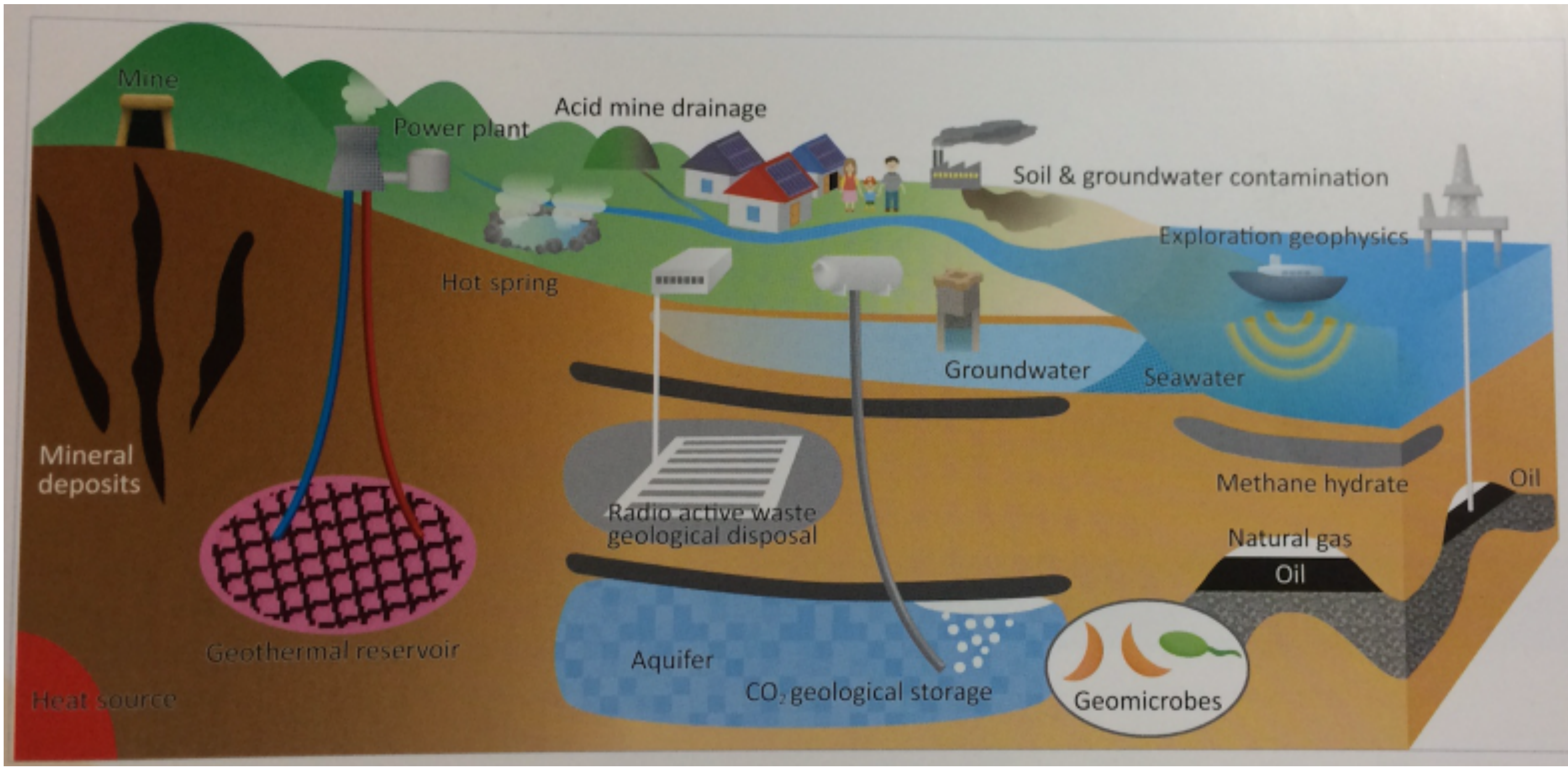


Conductivity model (stitched)



An example from DISC Tokyo

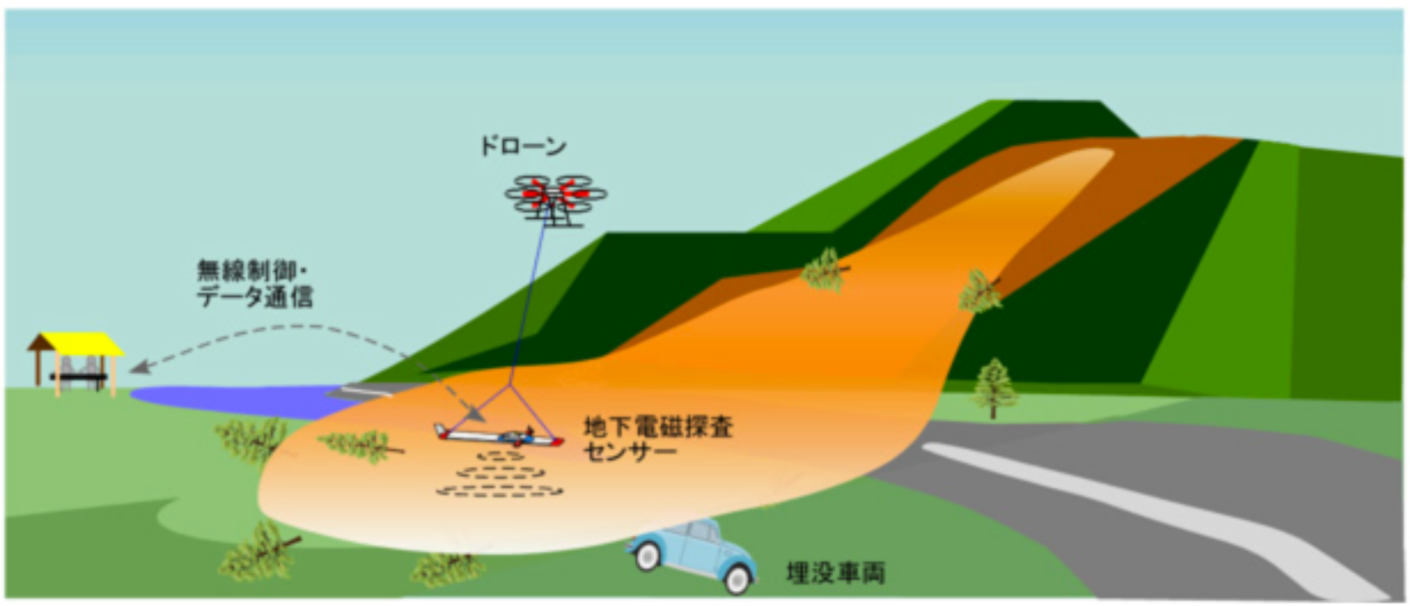
DISC Tokyo…


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

EM Geophysics using Drone Technology: AIST

Setup:

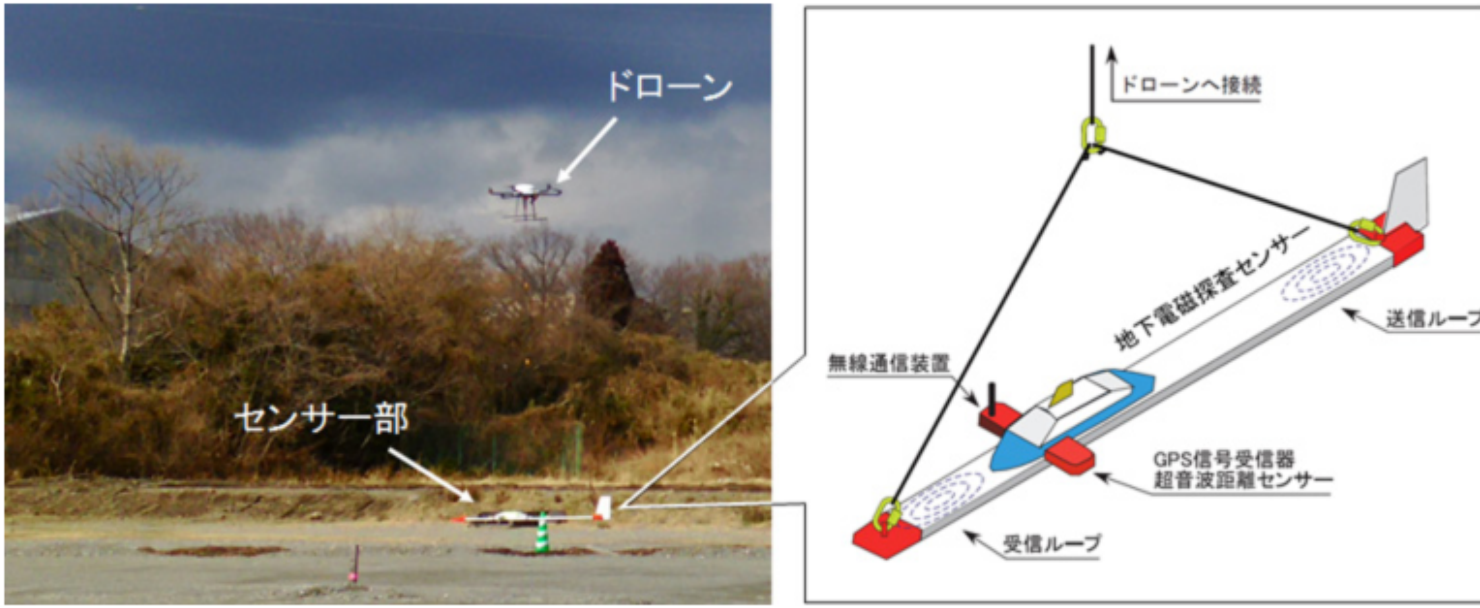
- Develop FDEM system for a drone
- Application: near surface geophysics problems
- Example: find automobiles buried in a landslide



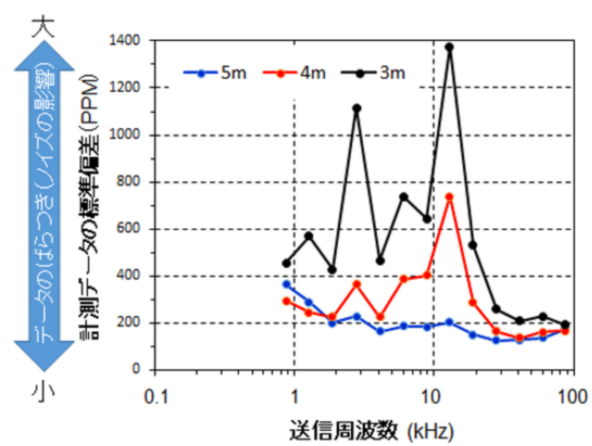
Exploration image of buried vehicles at the site of sediment-related disasters by developed system

Survey equipment

Drone EM system



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



Data acquisition

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

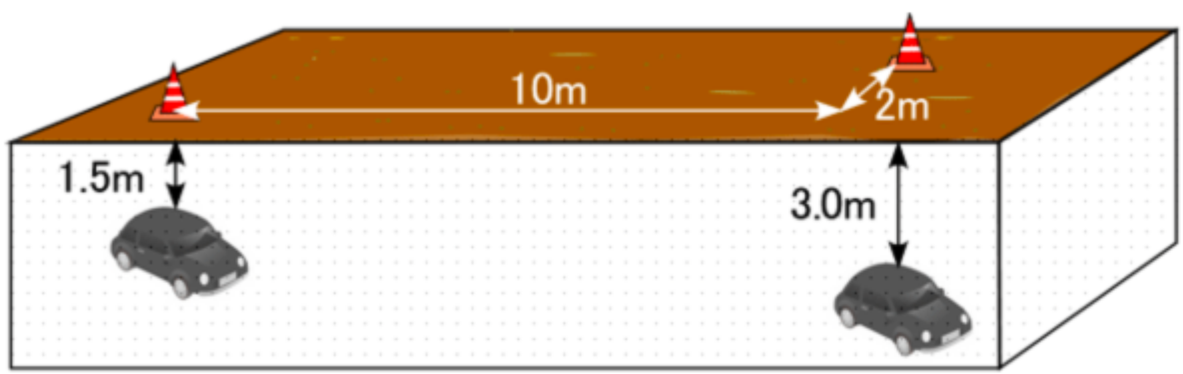


Fig. 4 Arrangement of the burial vehicle experiment site of the construction laboratory site
Two buried mini vehicles are buried in the ground of 1.5 m depth and 3.0 m depth, respectively.

Data and interpretation

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

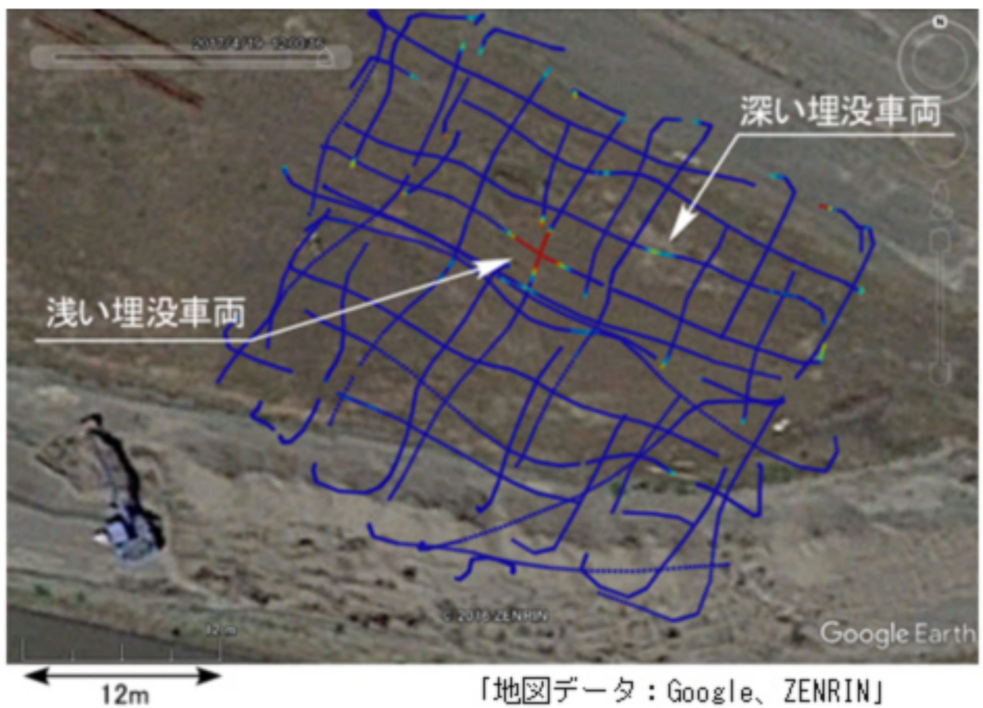


Fig. 6 Exploration data by precision drone navigation measurement (measurement frequency 60 kHz)

Additional Material

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

http://www.nohowinc.com/

http://www.centennialofflight.gov

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

Various Types of UXO

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

How do we find UXO?

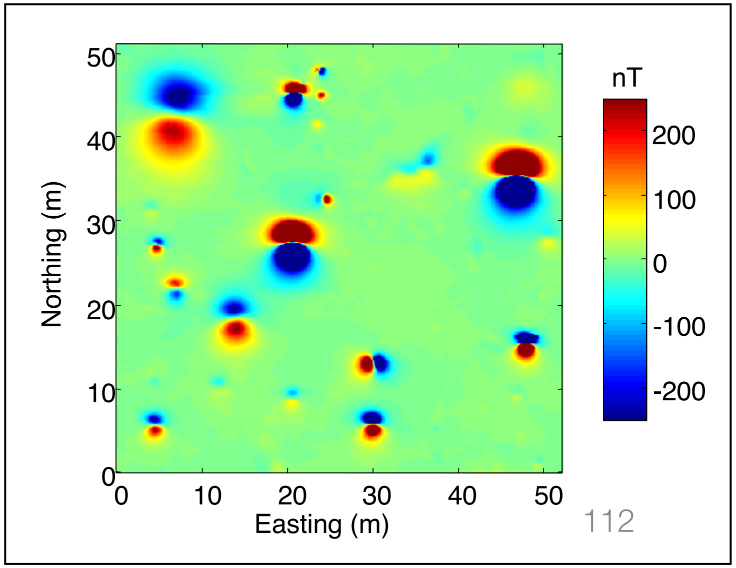
Magnetic Surveys: Locate Anomalies

- Analogue data
- Flag anomaly locations

Ferrex

- Digital data
- Look for magnetic dipoles

TM4



Magnetic Survey: Dig Anomalies

76Cpacgar

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

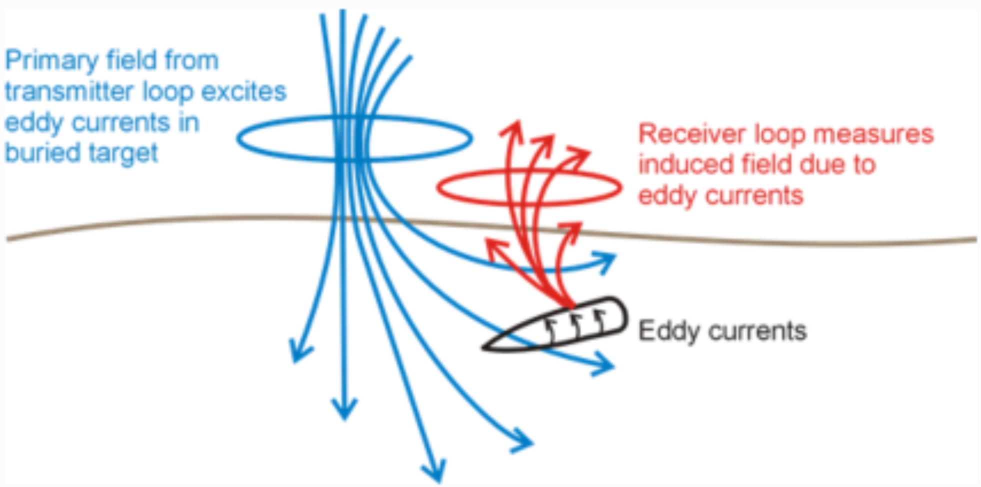
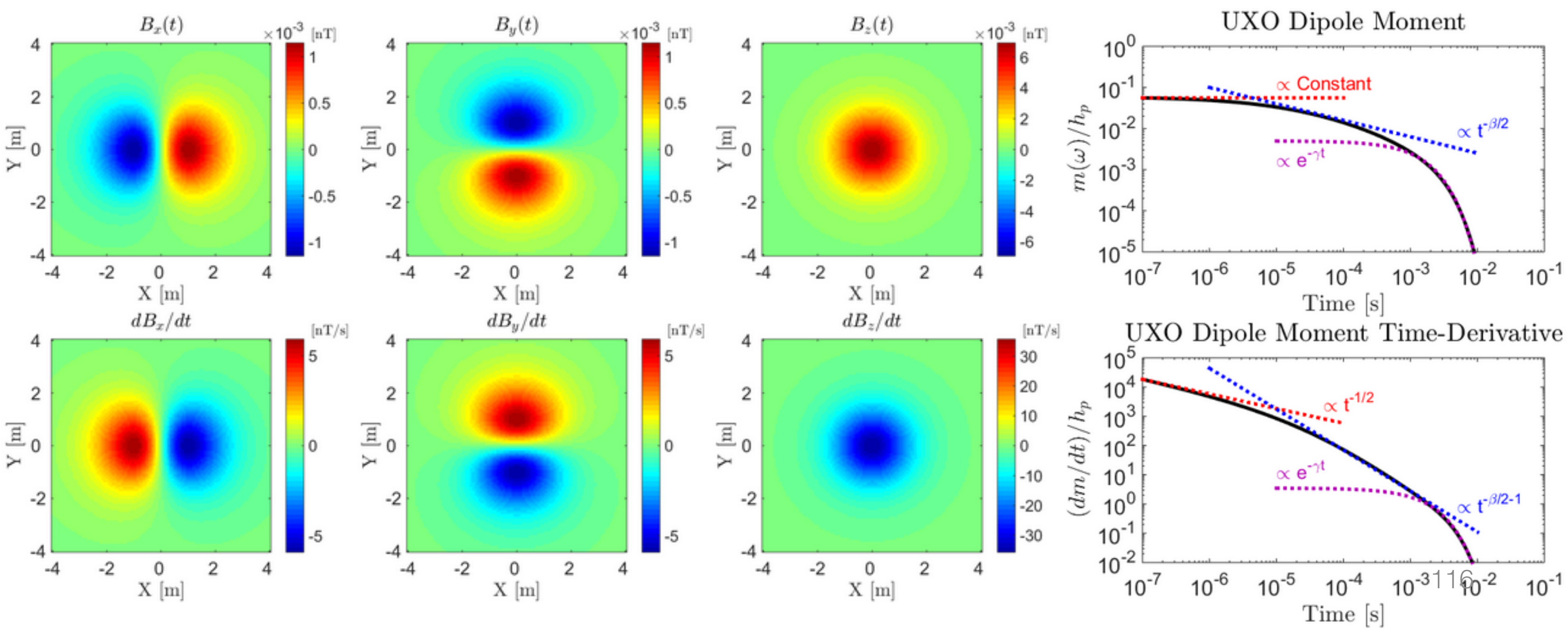


Fig. 260 Electromagnetic induction (EMI) survey for UXO location.

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:

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

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

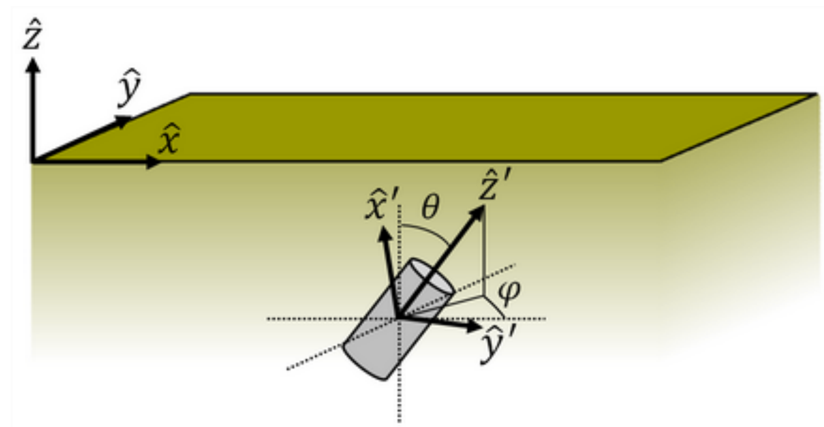
- m(t) depends on:
  1. Orientation of the inducing field
  2. The polarization tensor

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

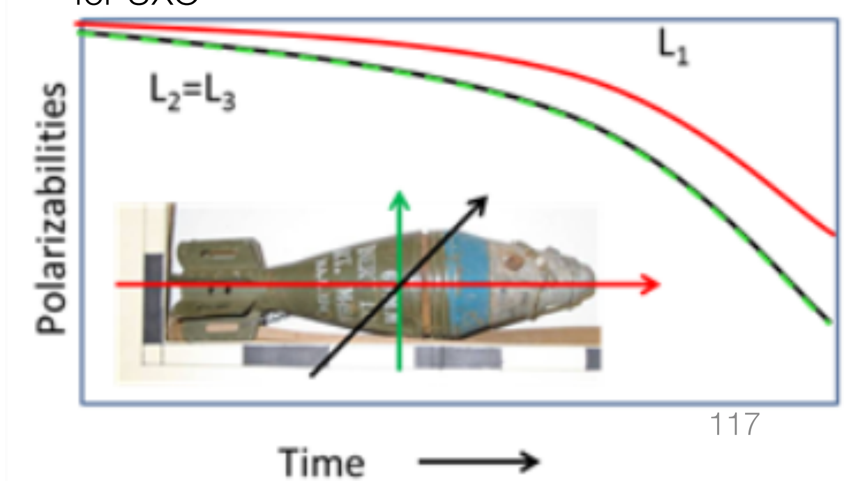
- The polarization tensor L:

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

Field and UXO coordinate systems

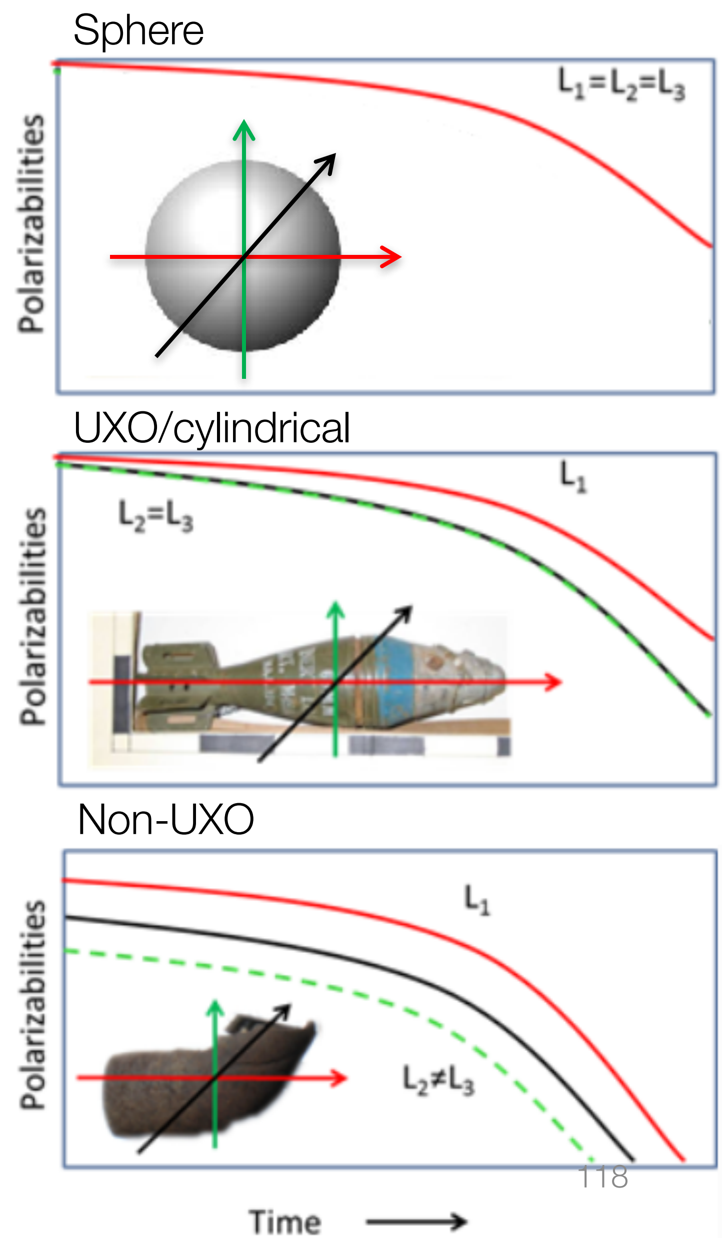


Primary (L1) and secondary (L2,L3) polarizations for UXO



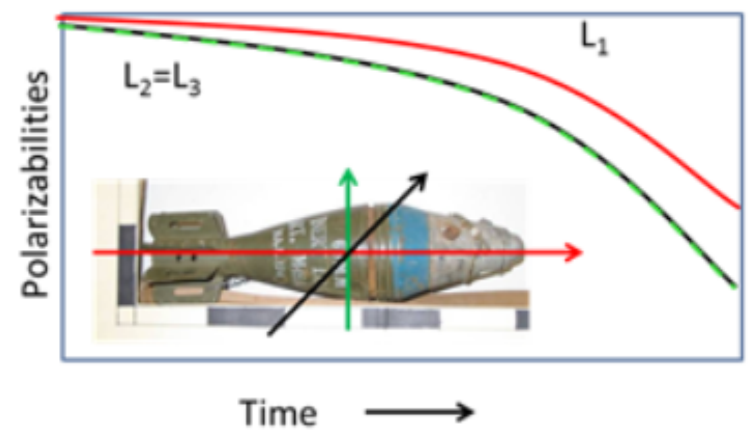
Objects and Polarization Tensors

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



UXO Classification in Practice

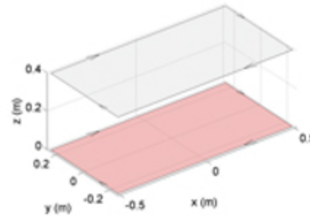
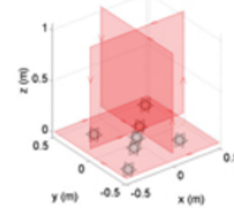
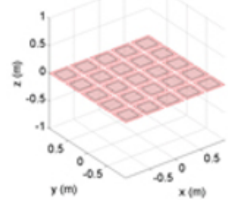
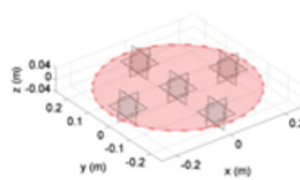
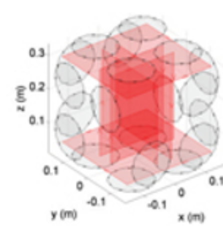
- Survey area and pick targets
- Collect high-resolution data over a target
- Recover the elements of the polarization tensor
- Use the polarization tensor to infer information about the object's shape
- Match the recovered polarization tensor to those of object stored in a library to classify



To carry out inversion for polarization tensor need data:

- multiple transmitters (orientations)
- multiple components of data

Common Systems

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

Survey Design

Line and Station Spacing:

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

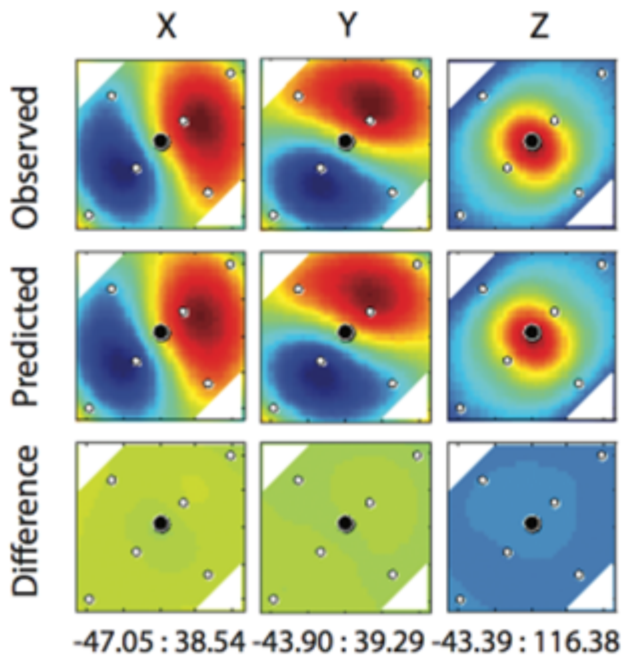
Excitation Orientation

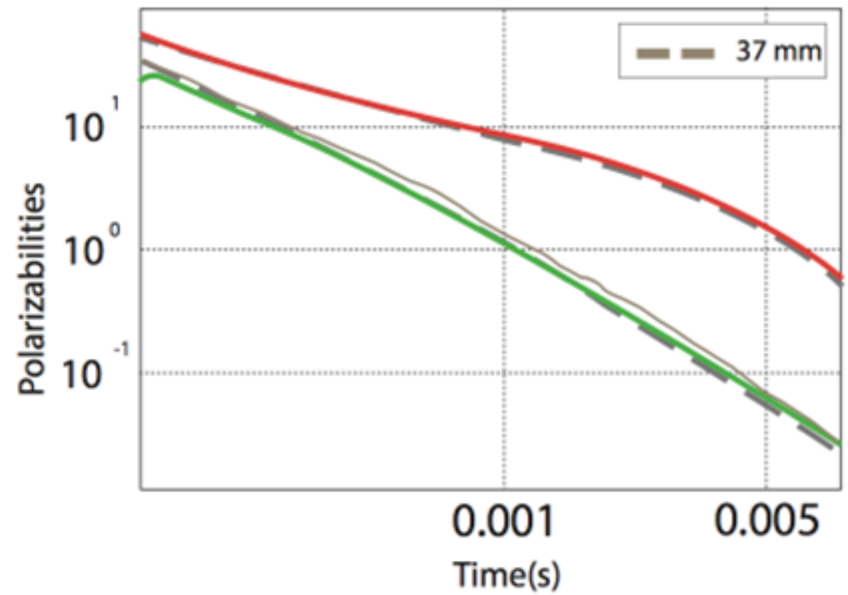
- To recover polarization tensor, target must be polarized from as many angles as possible.
- May require multiple passes with single transmitter or use of multi-transmitter system.

Time Channels

- Sufficient time-channels required to characterize decay behaviour.

Example: Metal Mapper Data

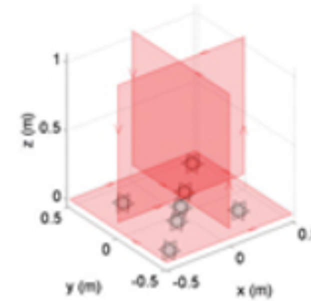


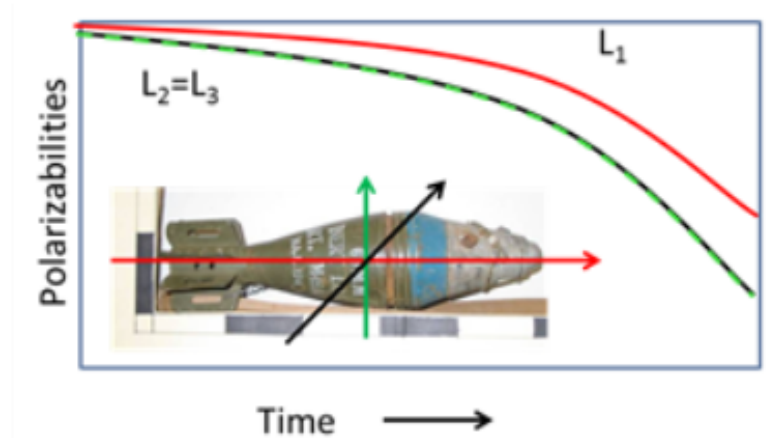


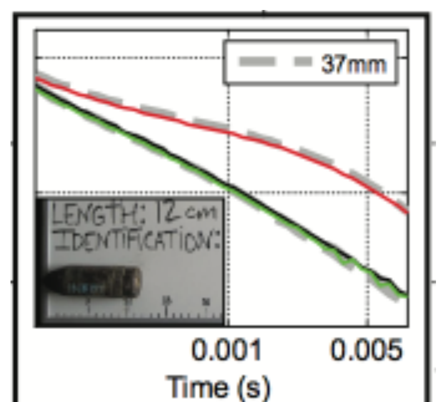
- Polarizations indicate a cylindrical object
- Predicted data using recovered polarization tensor fits the observed data
- Recovered polarizations match those of a 37 mm projectile

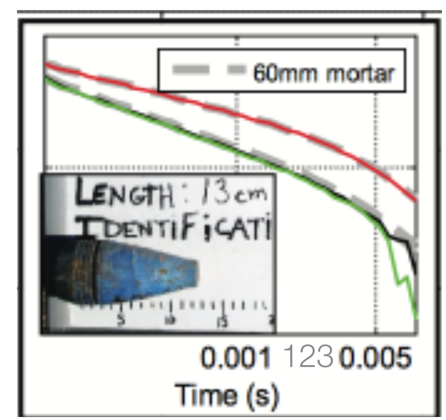
Summary

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









Field Example: Pole Mountain

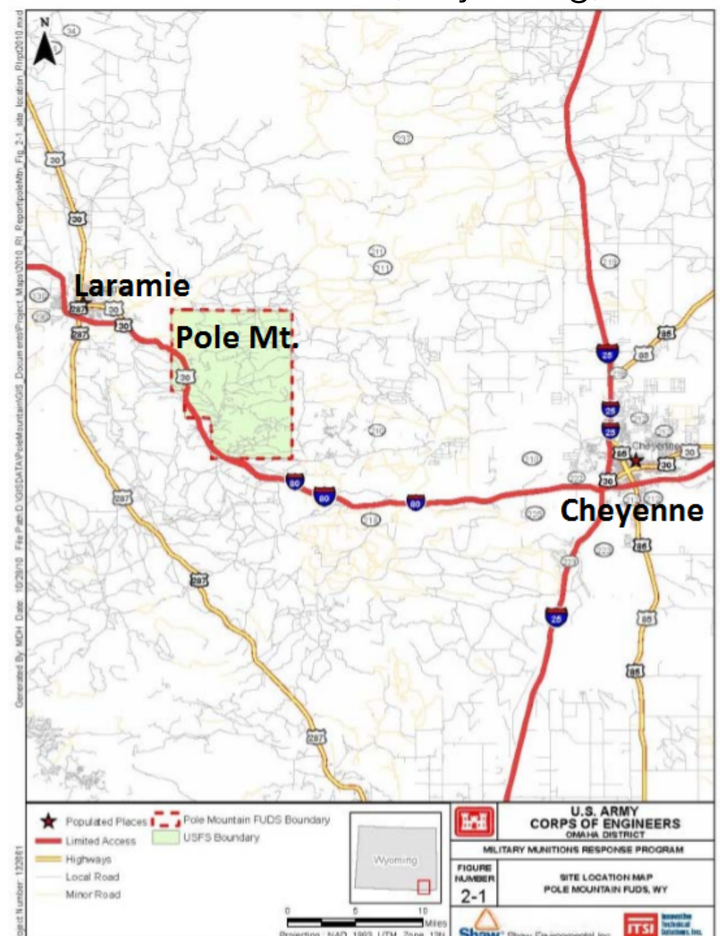
History

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

Goals:

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

Location of Pole Mt., Wyoming, US



Field Example: Pole Mountain

EM61-MK2:

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

Metal Mapper:

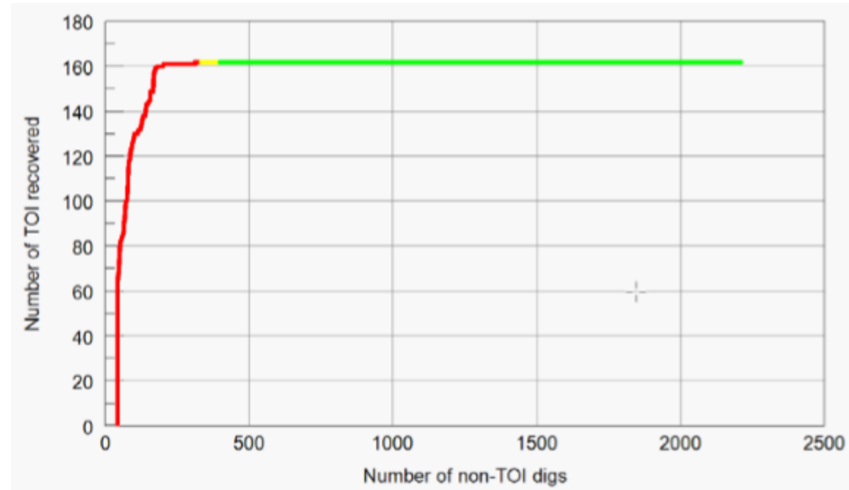
- Multiple Tx and Rx loops
- Cued interrogation data over anomalies
- Data used for classification and prioritize dig list

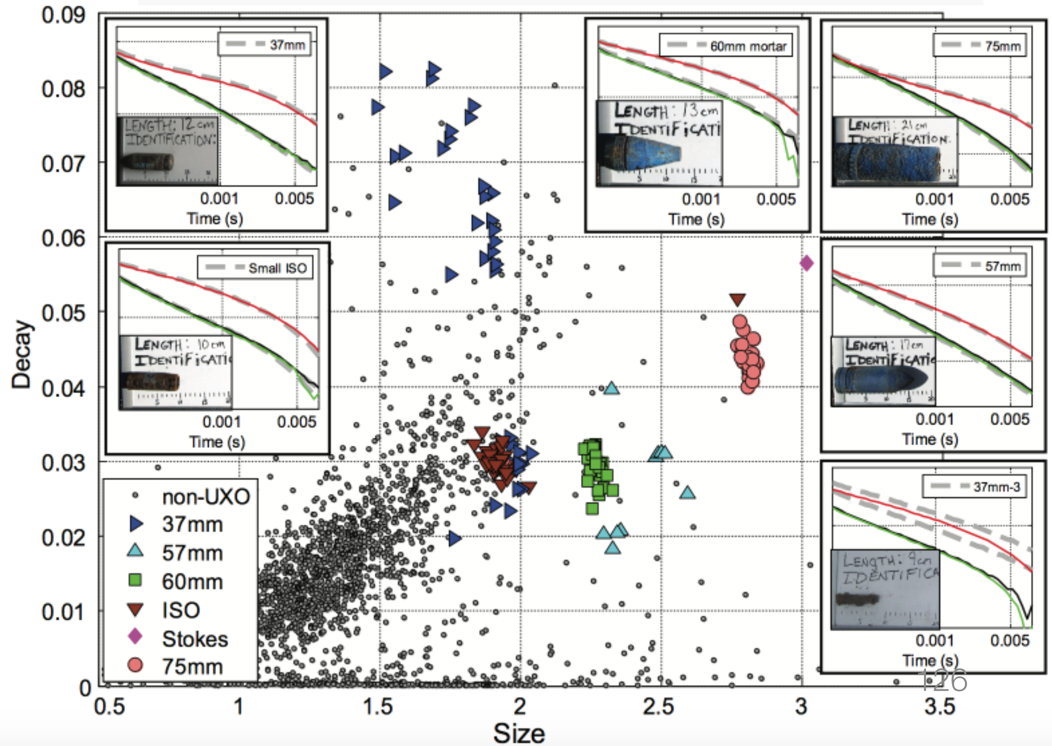
EM61-MK2 (locate anomalies)

Metal Mapper (cued interrogation)

Field example: Pole Mountain

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





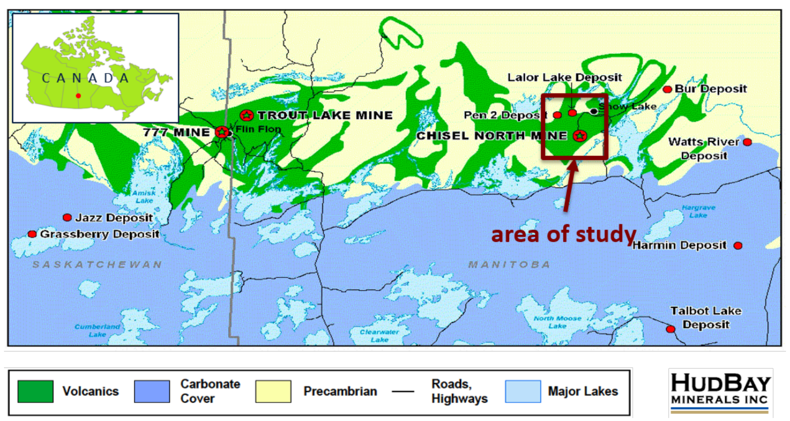
Case History: HeliSAM at Lalore

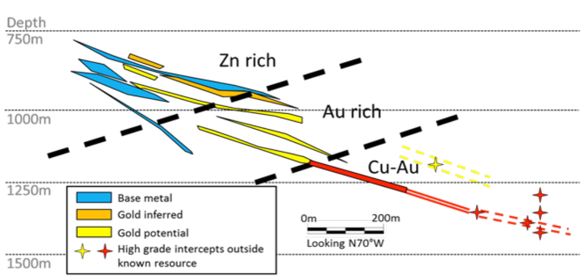
Yang & Oldenburg, 2016

Setup

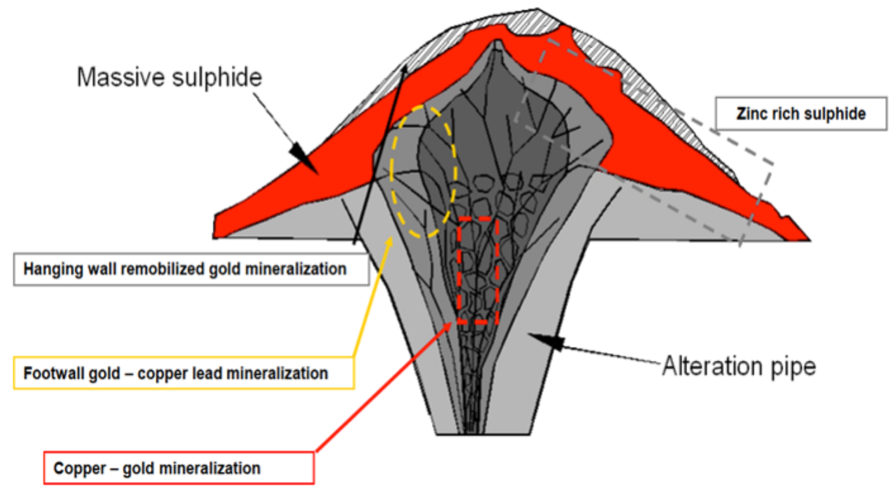
Geological framework

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





Typical cross-section

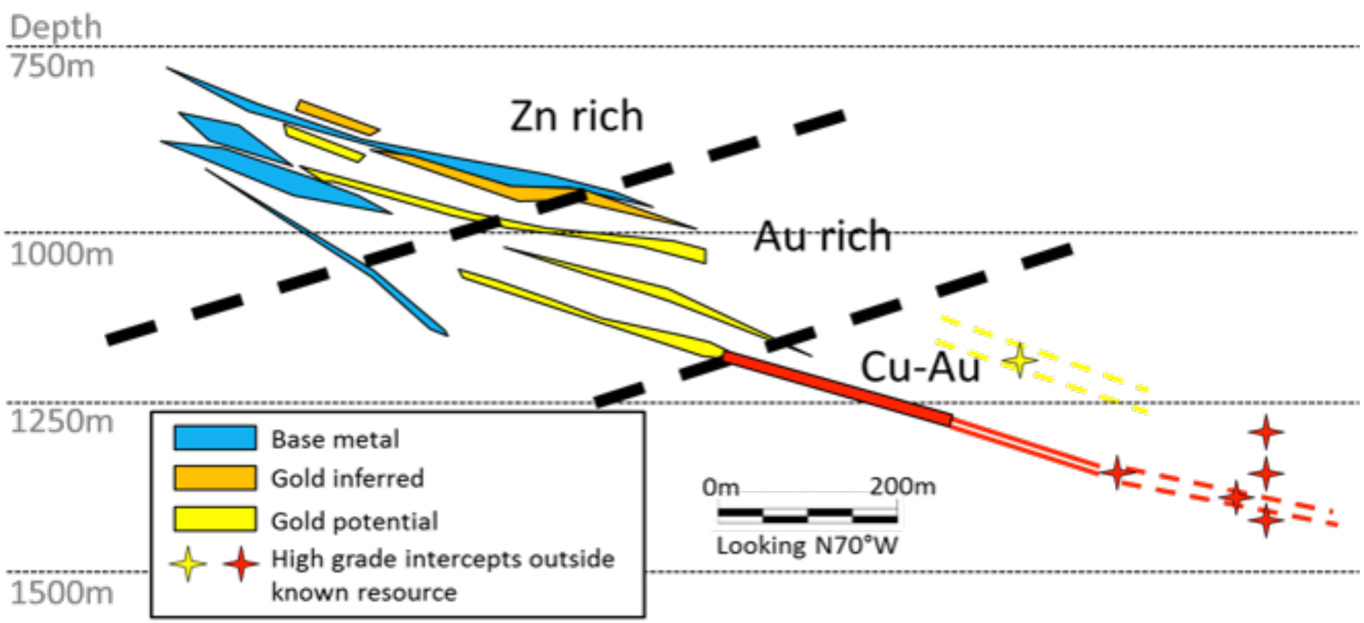


Goal:

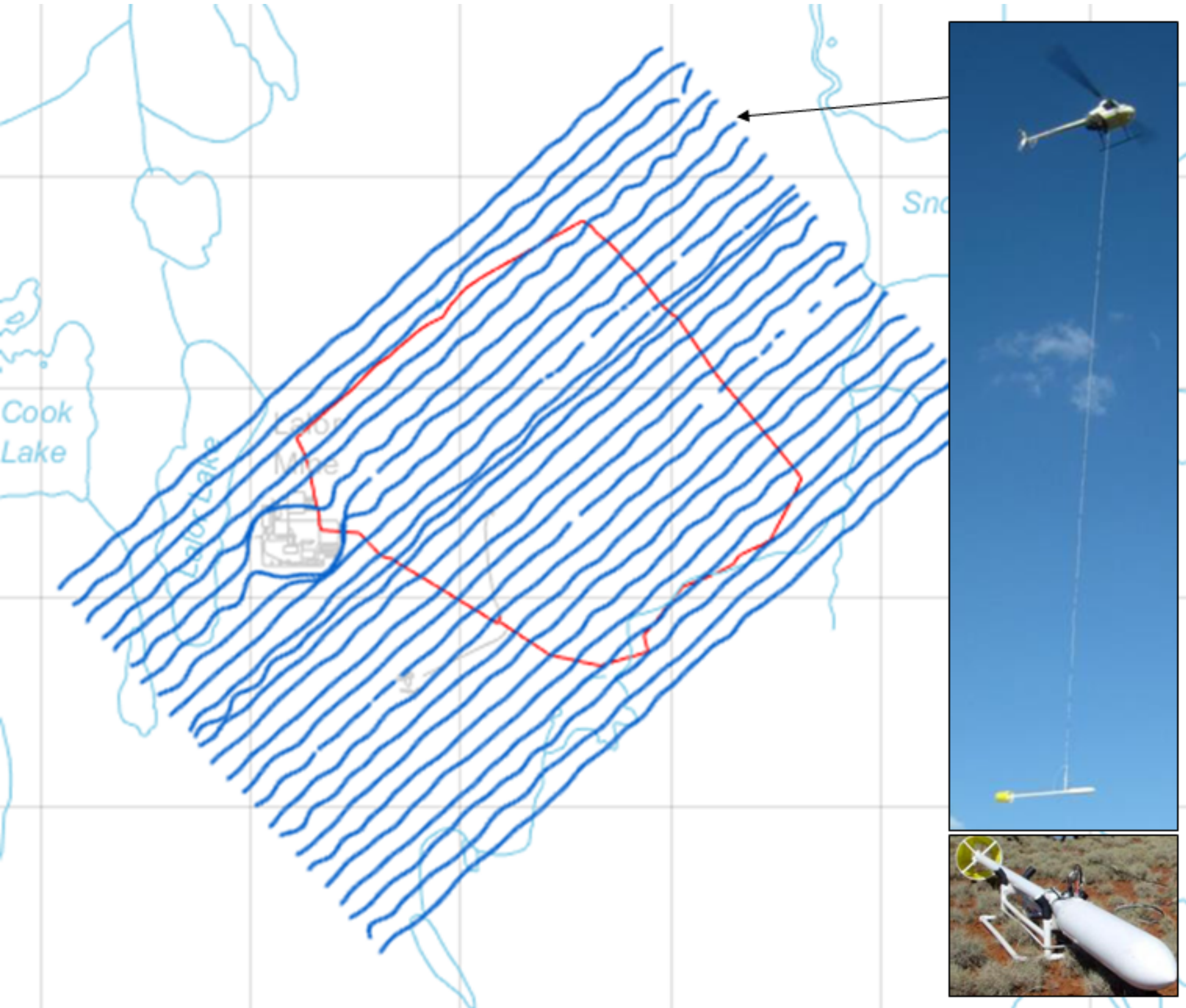
- Find deposits
- TDEM to find deeper off-hole targets

Properties

Rocks/minerals	Resistivity
volcanics	~1000 Ωm
sulfides	~ 1 Ωm



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

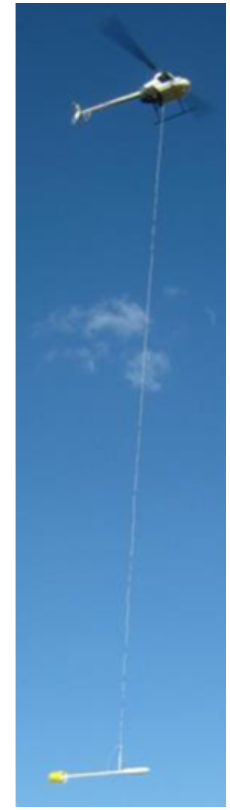
induced EM field

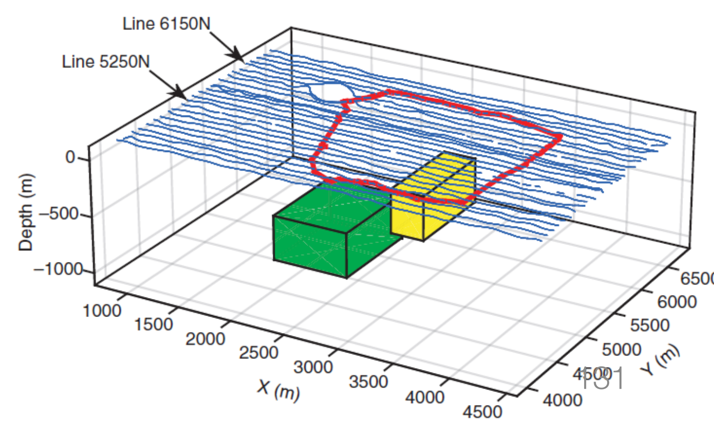
- Project secondary fields onto $\hat{\mathbf{B}}_0$

$$\Delta|\mathbf{B}| = |\mathbf{B_0} + \mathbf{B_a} + \mathbf{B_{em}}| - |\mathbf{B_0}|$$
$$\approx (\mathbf{B_a} + \mathbf{B_{em}}) \cdot \hat{\mathbf{B}}_0$$

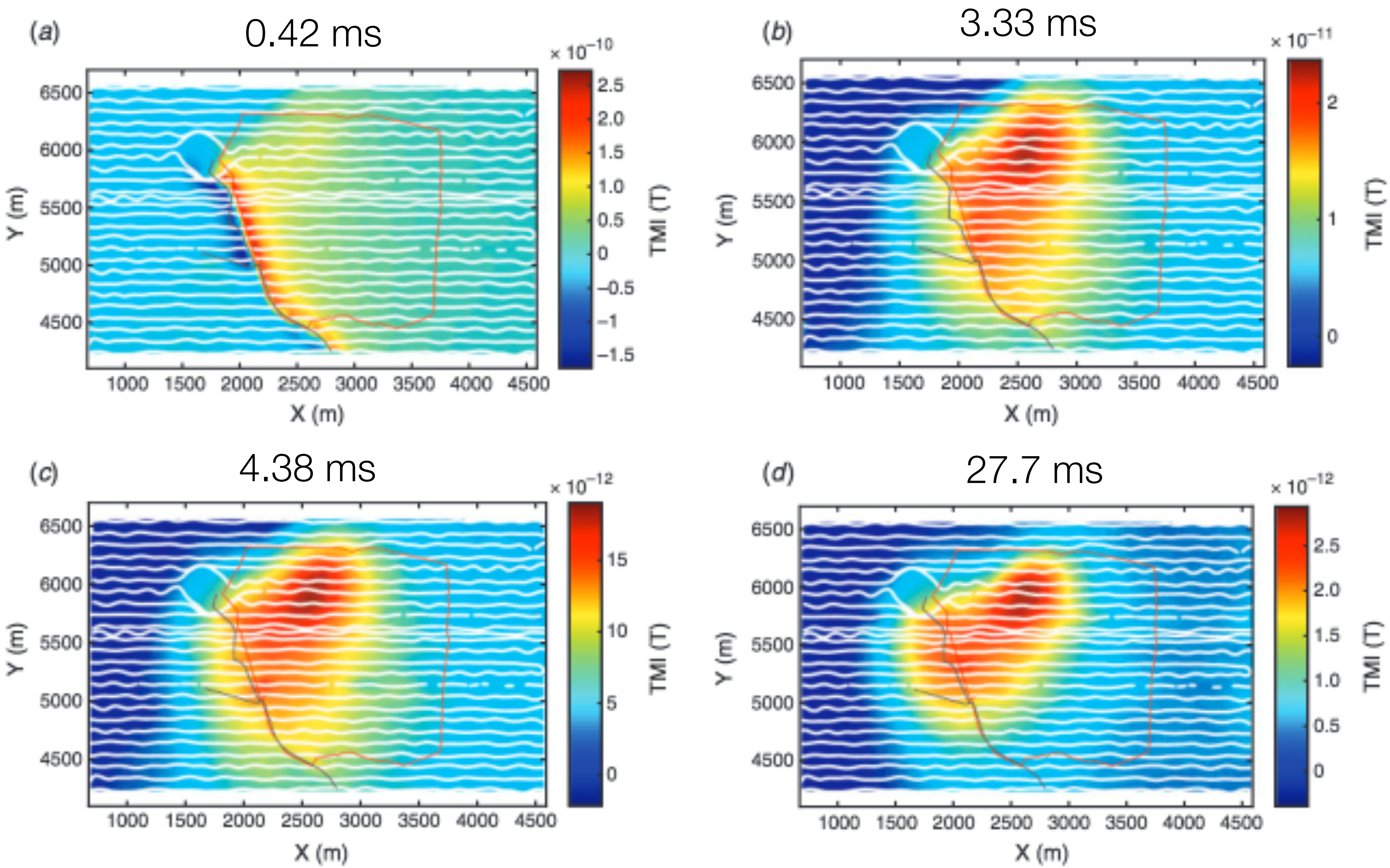
- Change polarity on TX
- Subtract to obtain HeliSAM data

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





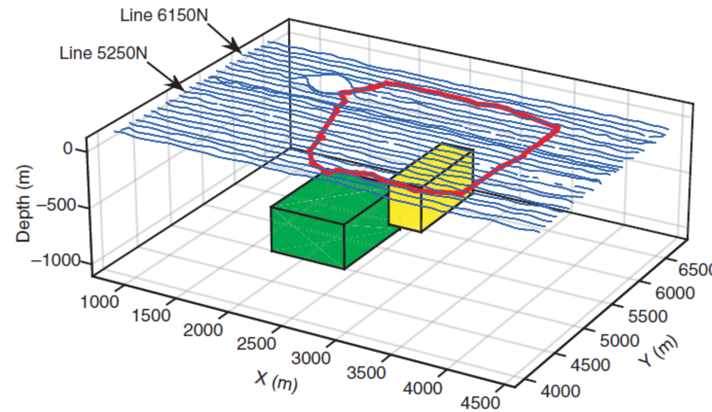
Data

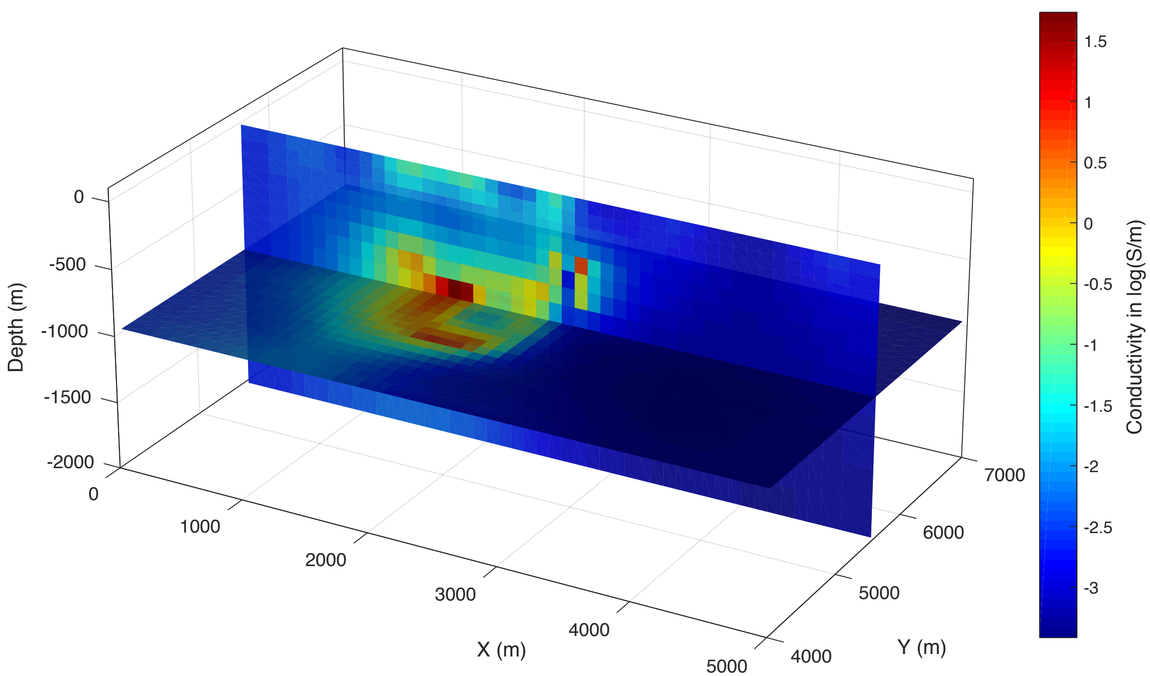


(a)
0.42 ms
× 10−10
2.5
2.0
1.5
1.0
0.5
0
−0.5
−1
−1.5
TMI (T)
(b)
3.33 ms
× 10−11
2
1
0
TMI (T)
(c)
4.38 ms
× 10−12
15
10
5
0
TMI (T)
(d)
27.7 ms
× 10−12
2.5
2.0
1.5
1.0
0.5
0
TMI (T)
Y (m)
6500
6000
5500
5000
4500
X (m)
1000
1500
2000
2500
3000
3500
4000
4500

Processing: Inversion of Late Time Data

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

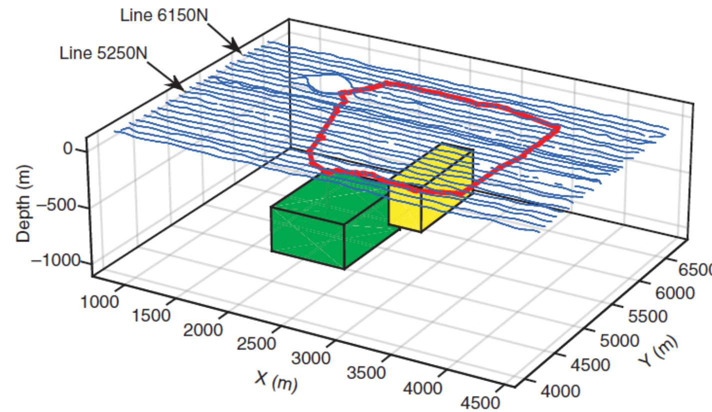


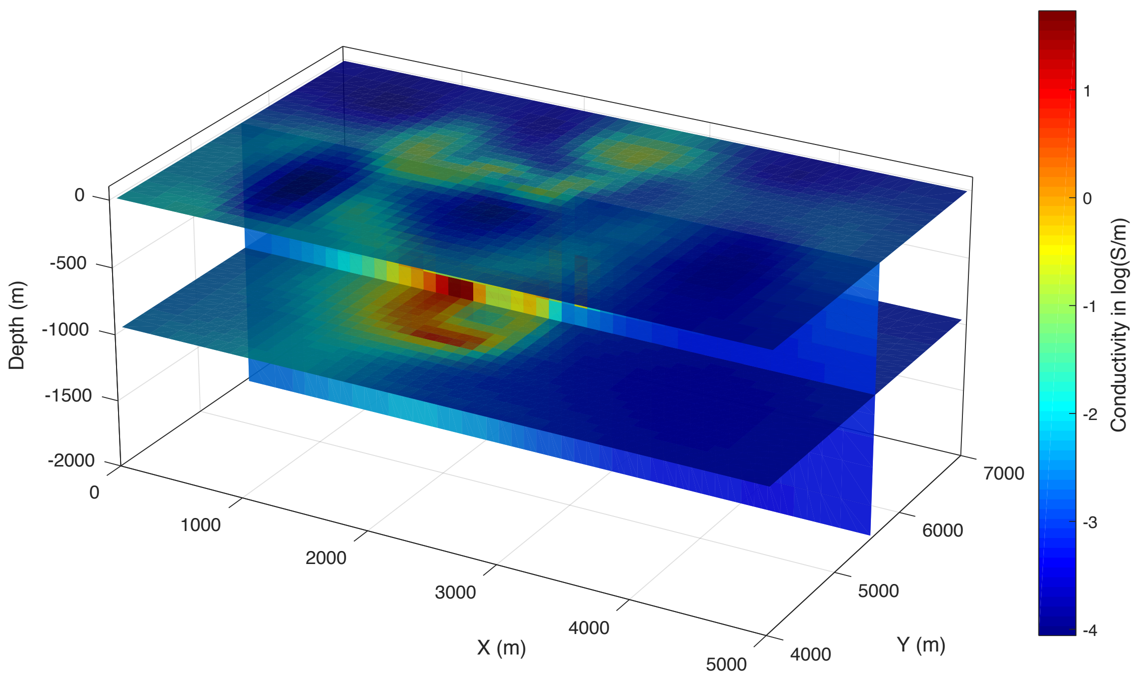


- Image deep structure

Processing: Inversion of Late Time Data

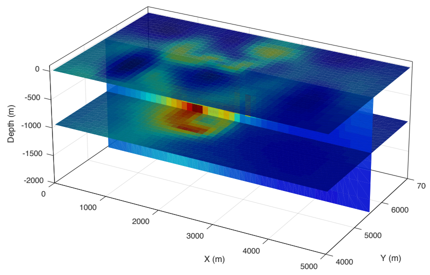
- Discard early time data
  - Contaminated by infrastructure
- Invert Time Ch 8-16 (4.44-28 ms)
- Inversion needs a "warm start"
  - Maxwell used to generate 2 prisms





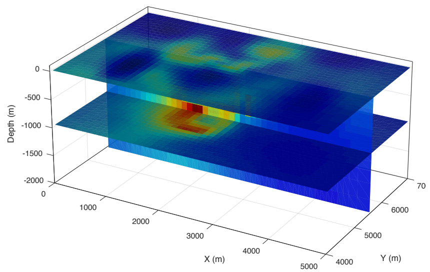
- Image deep structure
- See near surface conductive features

Processing: Inversion of Early Time Data



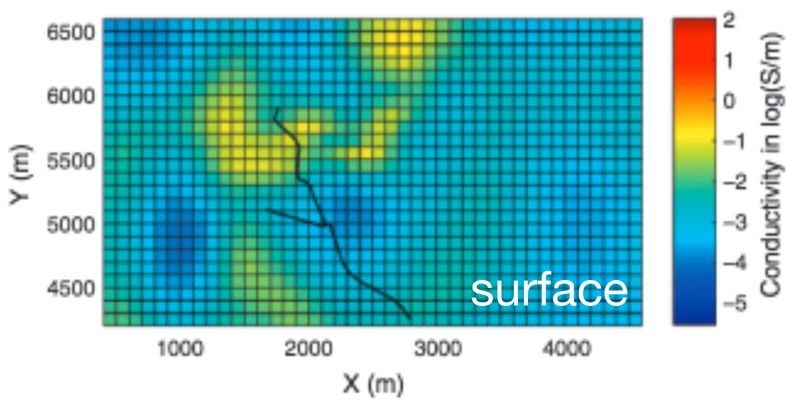
- Late-time inversion sees deep structure
- Some conductive features near surface
- **What is the effect of throwing away the early time data?**

Processing: Inversion of Early Time Data



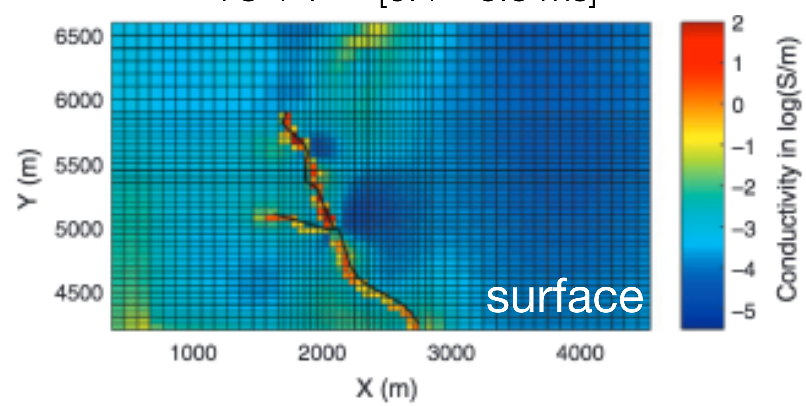
- Late-time inversion sees deep structure
- Some conductive features near surface
- **What is the effect of throwing away the early time data?**

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



- erroneous near surface structure

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

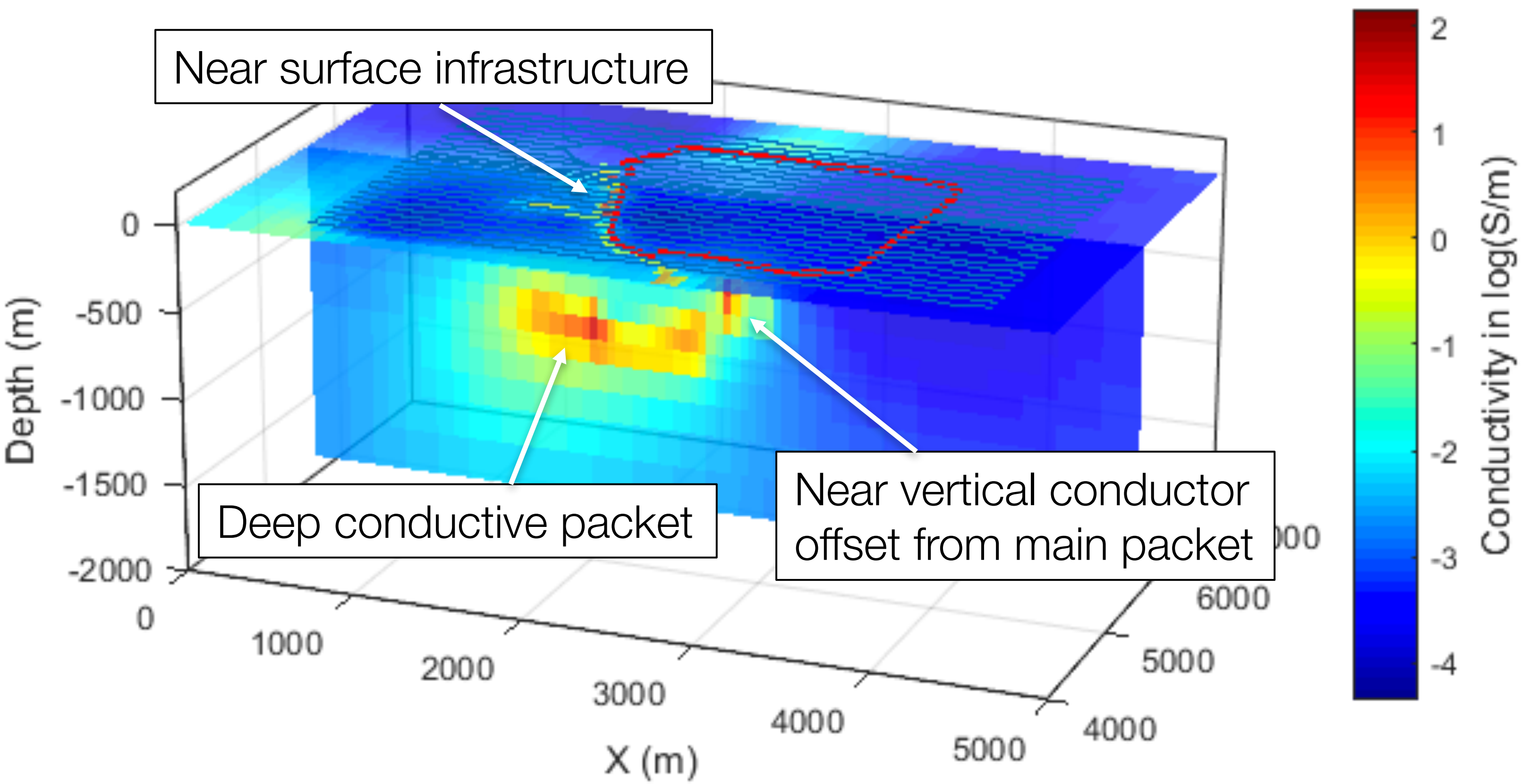


- information about infrastructure and near-surface conductivity

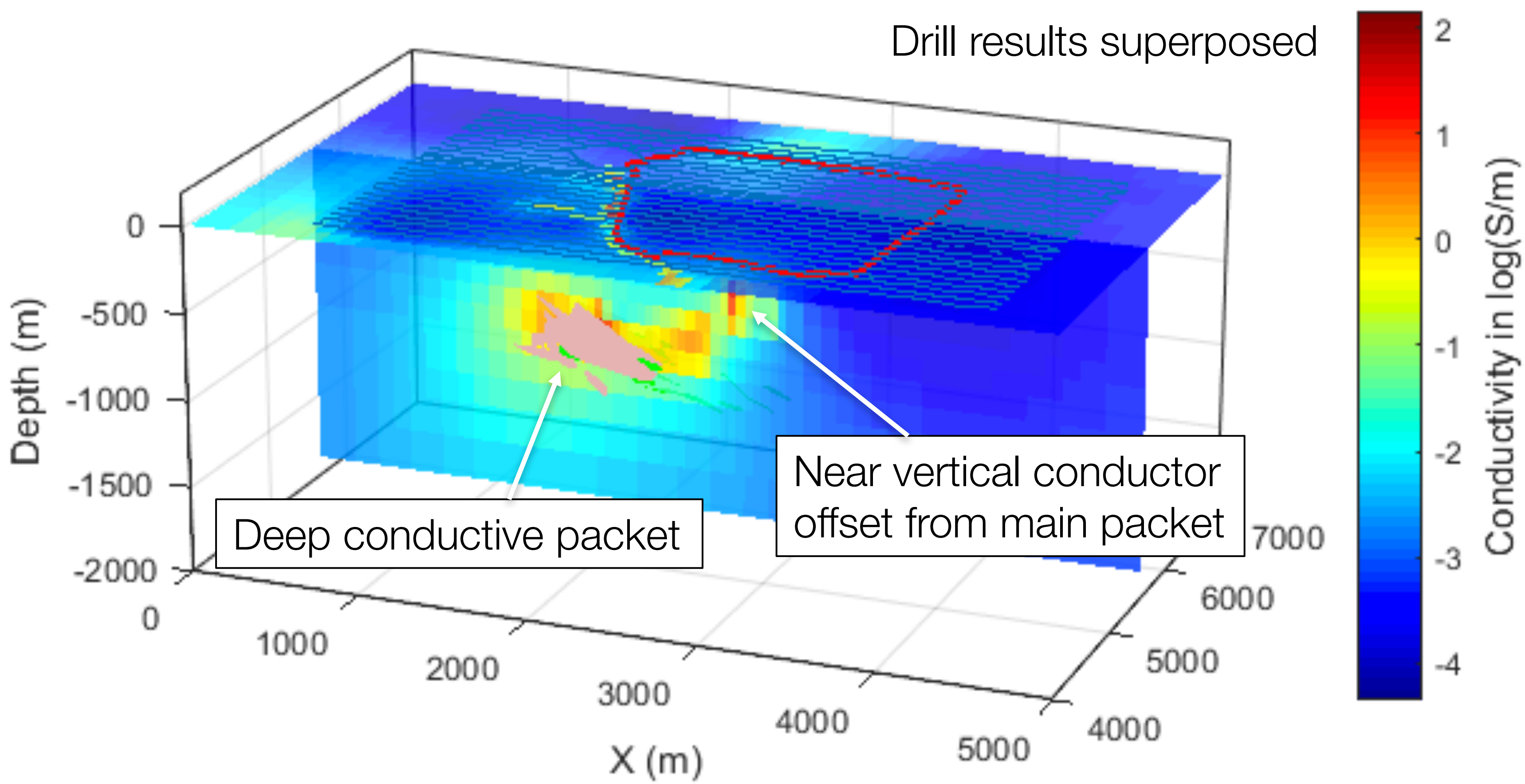
Processing: Inversion of all time channels

Starting and reference model:

- High conductivity from early time inversion
- Two conductive blocks

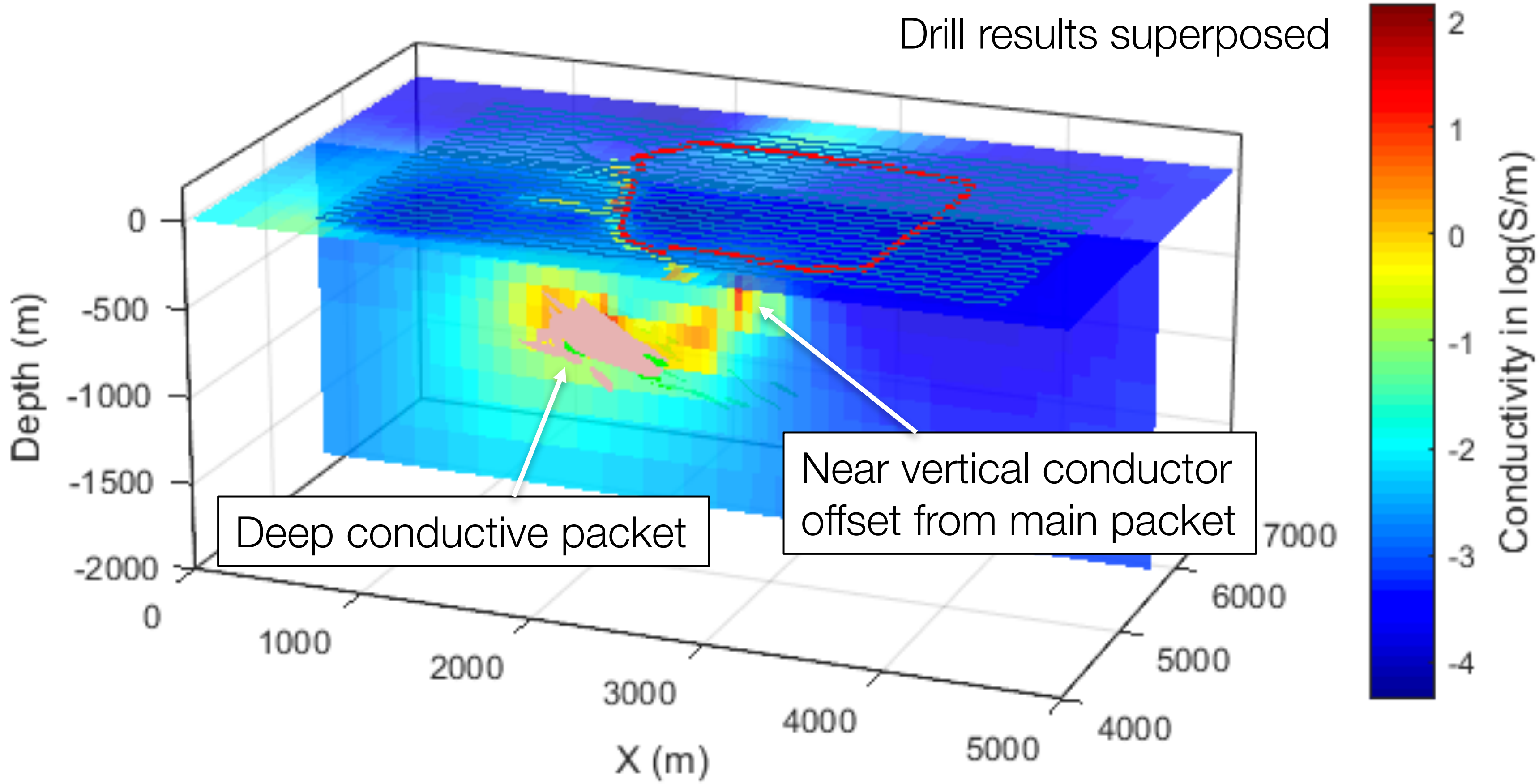


Synthesis



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

Takeaways



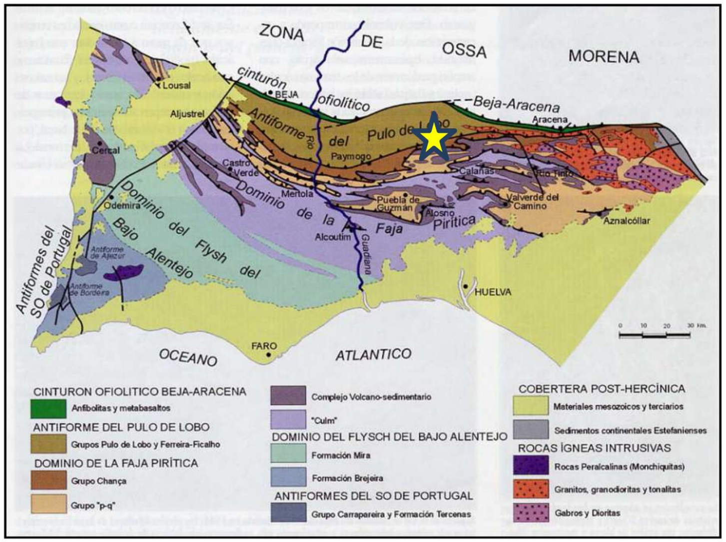
- Early time data:
  - constrain near surface structure infrastructure
  - Improved inversion for late time
- Warm start of inversion was necessary for deep conductors

Case History: La Magdalena

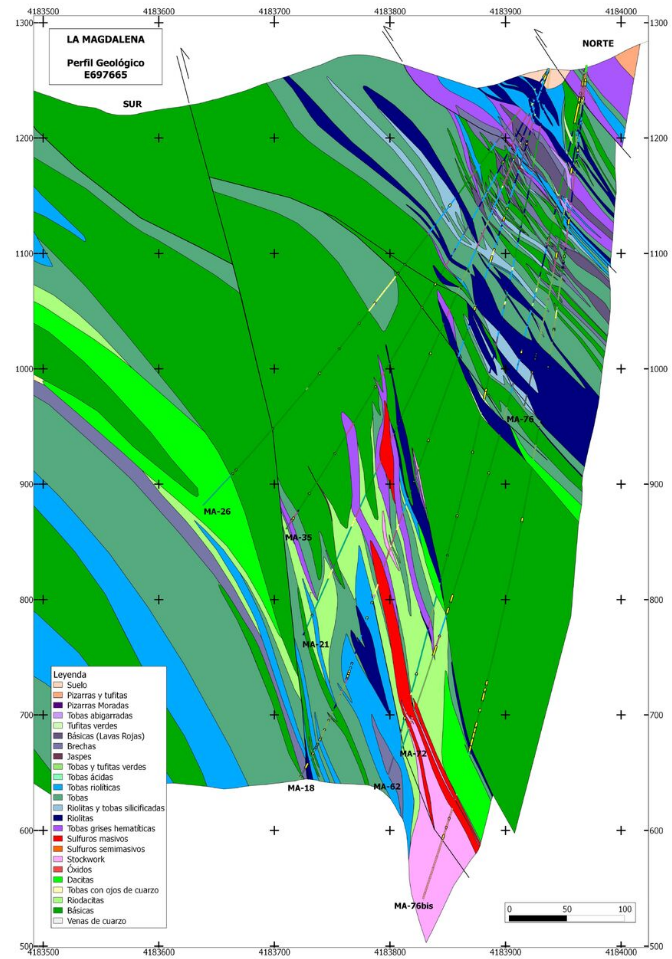
Granda et al., 2016

Setup

Geological setting



Typical cross section



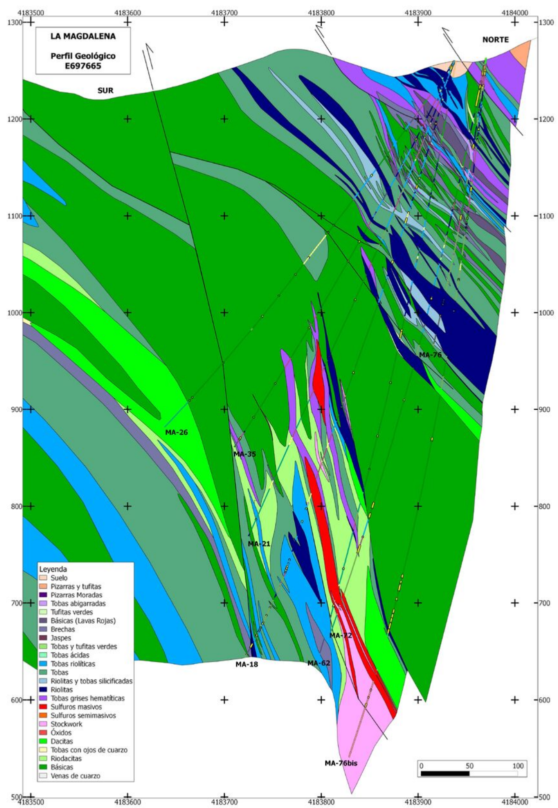
- Volcano-Sedimentary (VS) mineralization
- Thin, steeply dipping veins

Goal: Find deposits

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

Properties

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

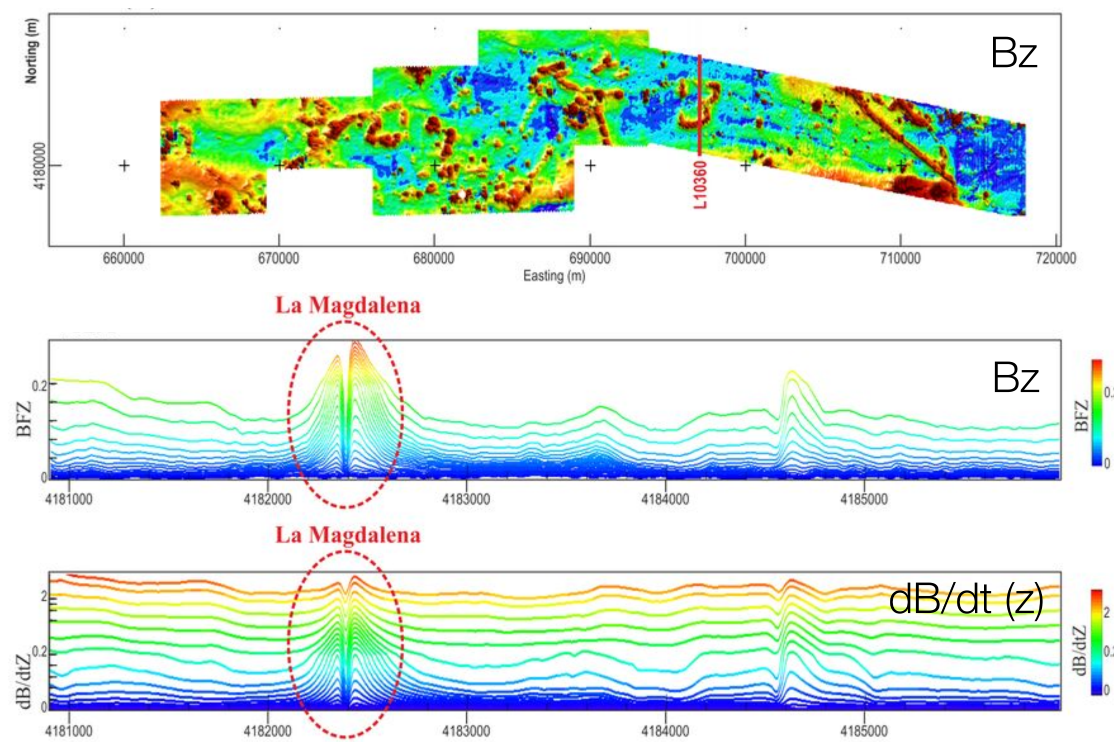


Surveys: Strategic Campaigns

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

Initial Discovery: VTEM

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

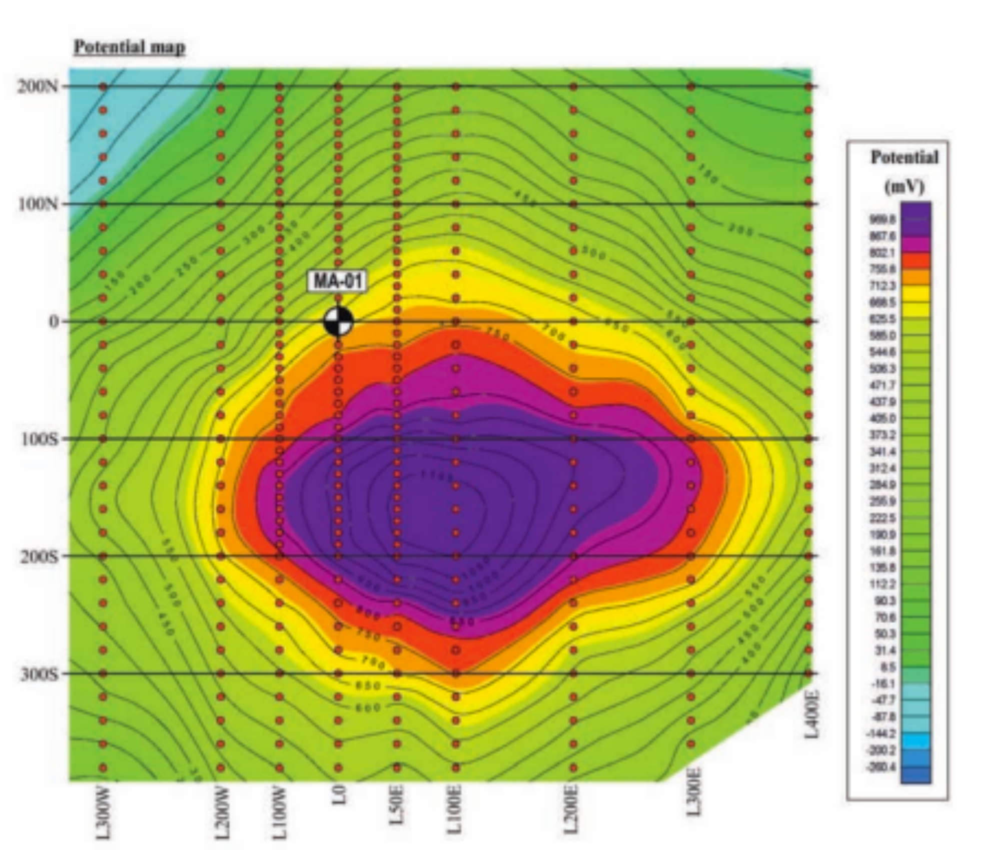


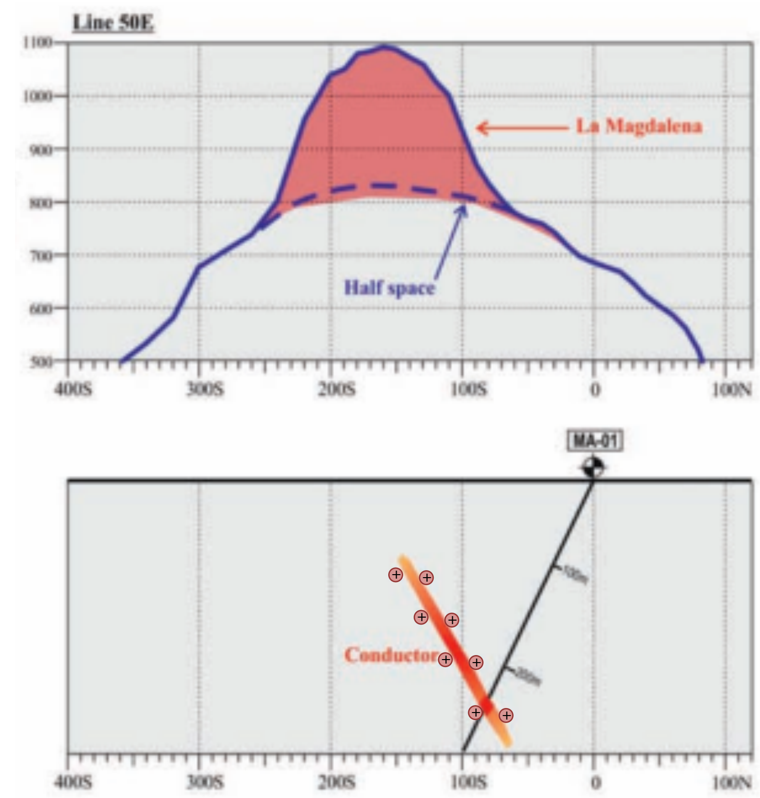
Survey Parameters

Sensor height	50 m
TX radius	17.5 m
Current Peak in TX	234 A
Magnetic Moment in TX	900.437 nIA
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

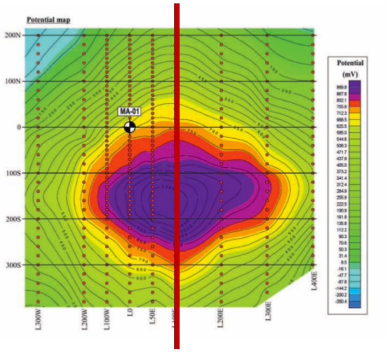
- Electrode coupled to massive sulphides at 230m
- Measure potentials (gradient mode) on surface

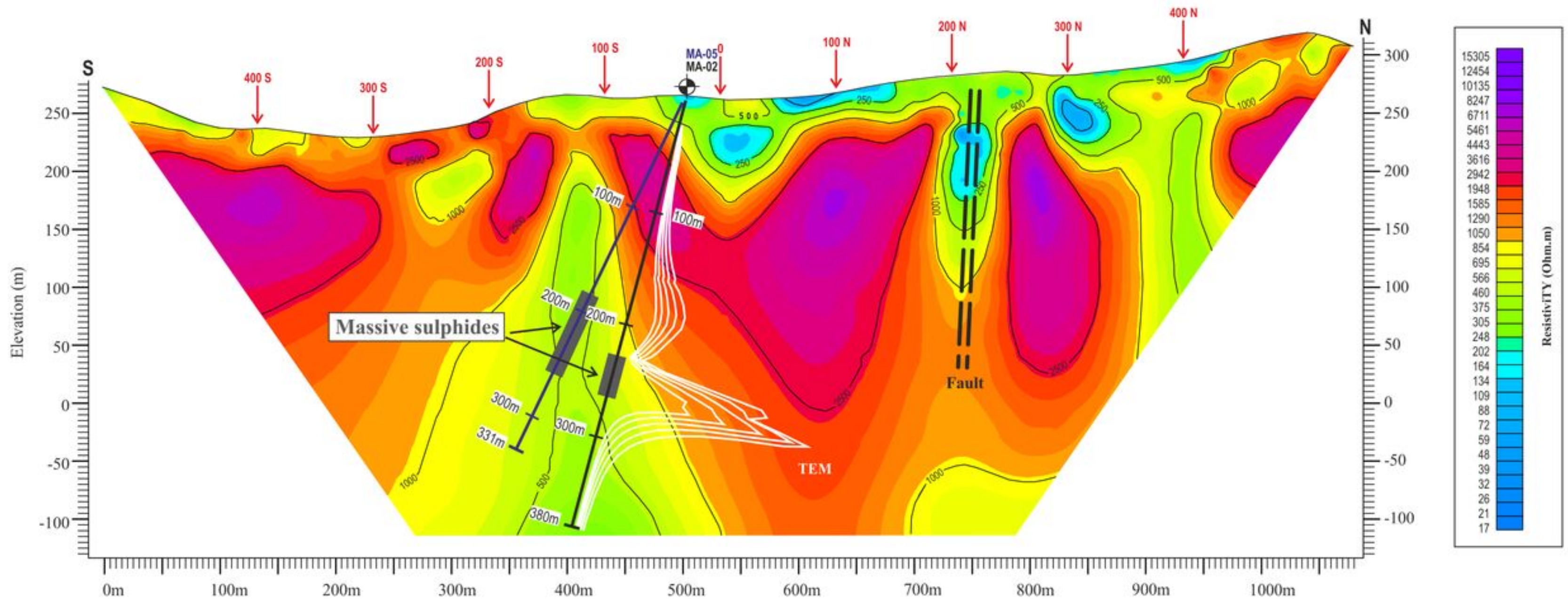




Methodological Test: ERT

- Pole-dipole
  - a = 20m and n = 40

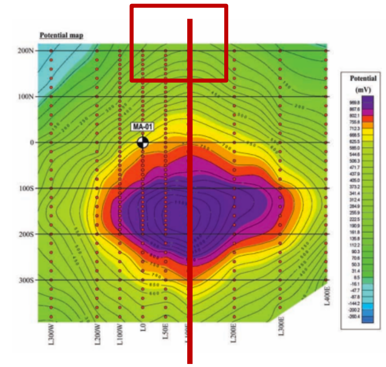


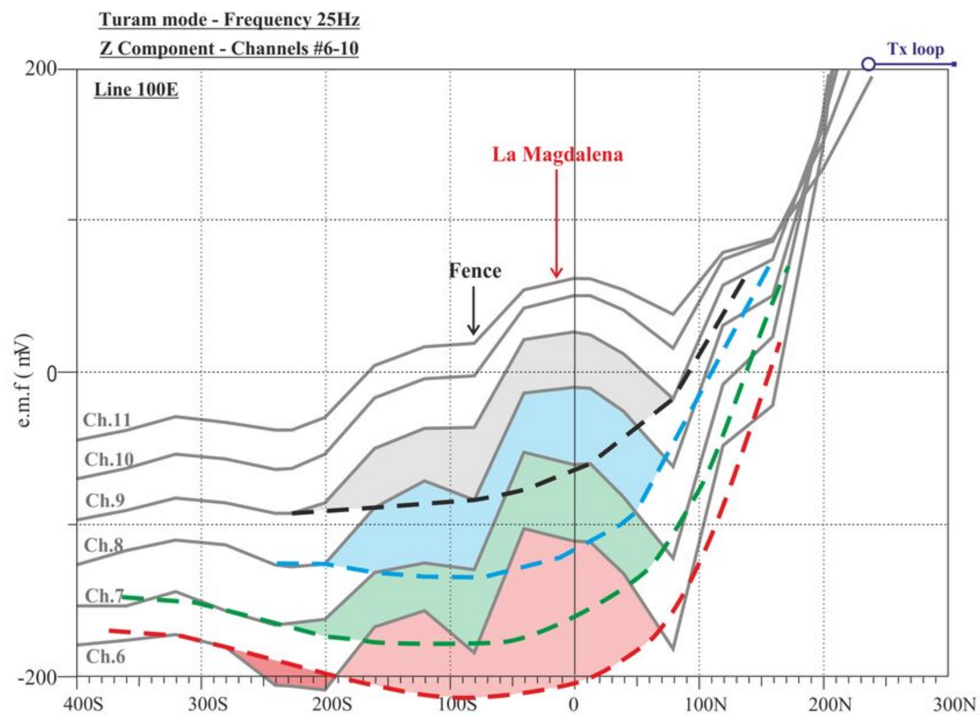


Results: found a moderately low resistivity region, not as low as anticipated

Methodological Test: Turam

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



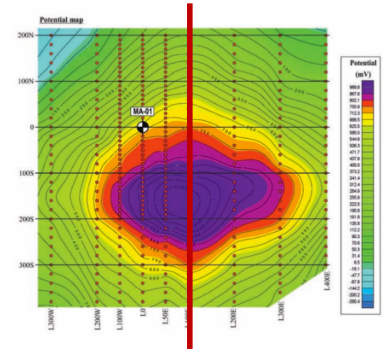


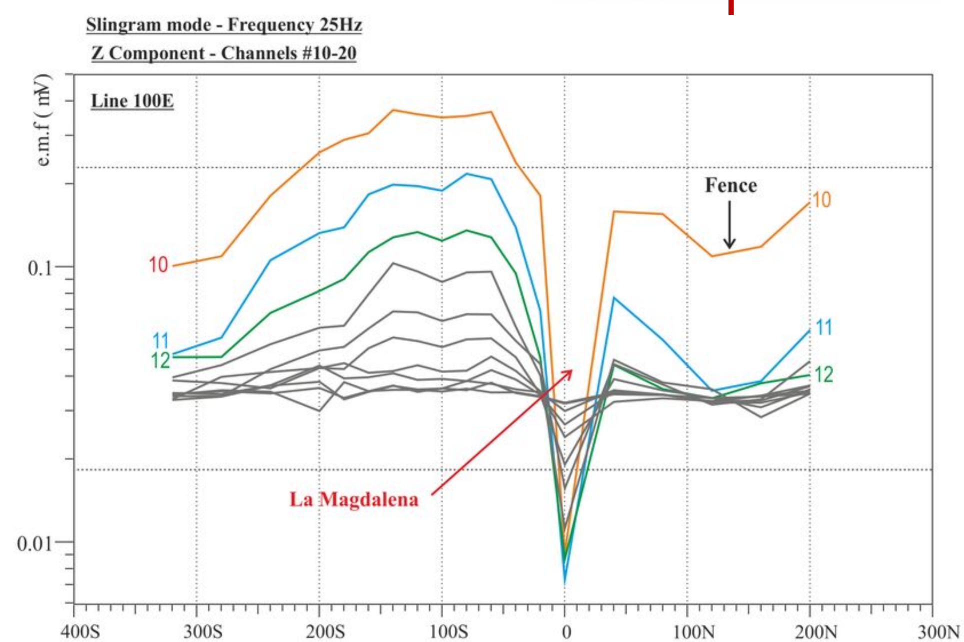
Specification	Turam
TX Loop size	700 m x 400 m
TX-RX synchronization	Crystal
Current pulses	15.5 A
T/O time	295 µs
Measured parameters	dBdt (z, x)
Base frequency	Hi: 25 Hz MD: 6.25 Hz
Measurement mode	Off time

Results: Strong detectability.

Methodological Test: Slingram

- Ground based, moving loop: Slingram
- PROTEM induction coil
  - RX Equivalent area: 100 m^2





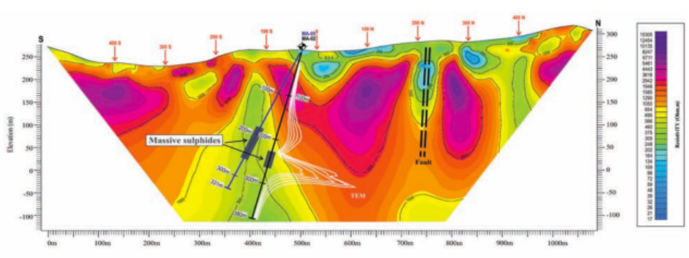
Specification	Turam	Slingram
TX Loop size	700 m x 400 m	100 m x 100 m
TX-RX synchronization	Crystal	Ref. Cable
Current pulses	15.5 A	22 A
T/O time	295 µs	75 µs
Measured parameters	dBdt (z, x)	dBdt (z, x)
Base frequency	Hi: 25 Hz MD: 6.25 Hz	Hi: 25 Hz MD: 6.25 Hz
Measurement mode	Off time	Off time

Characteristic plate-like conductor.
Dipping north

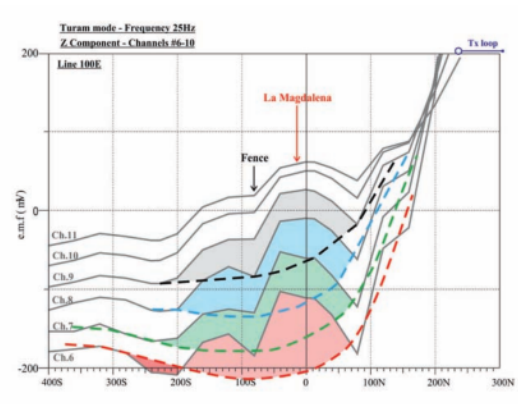
Results: Strong detectability.

Methodological Test: Final choice Turam

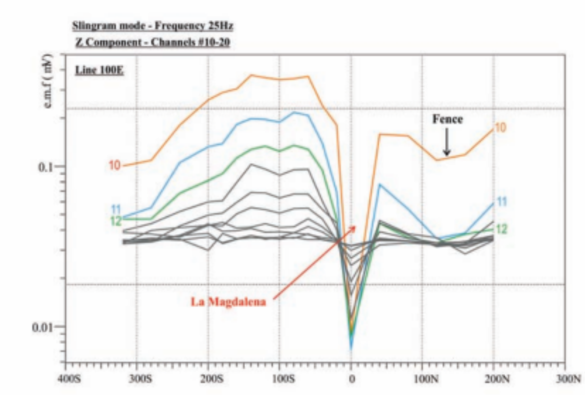
ERT: Inconclusive



Turam: Strong signal

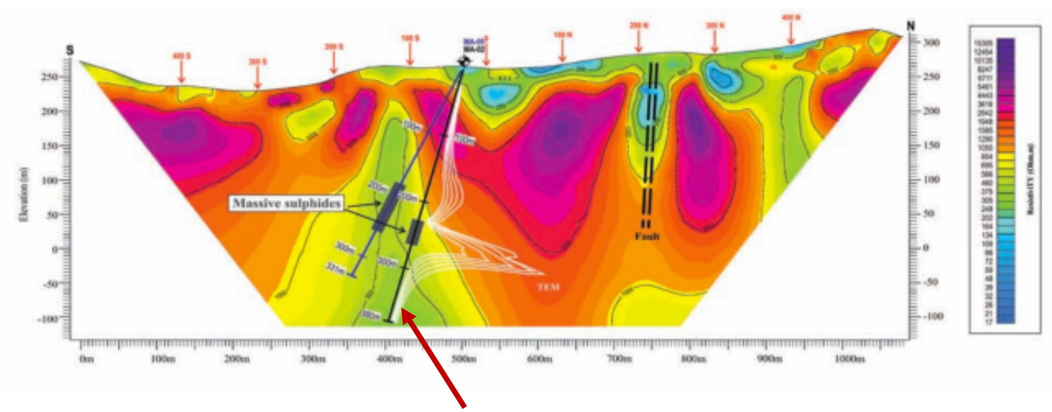


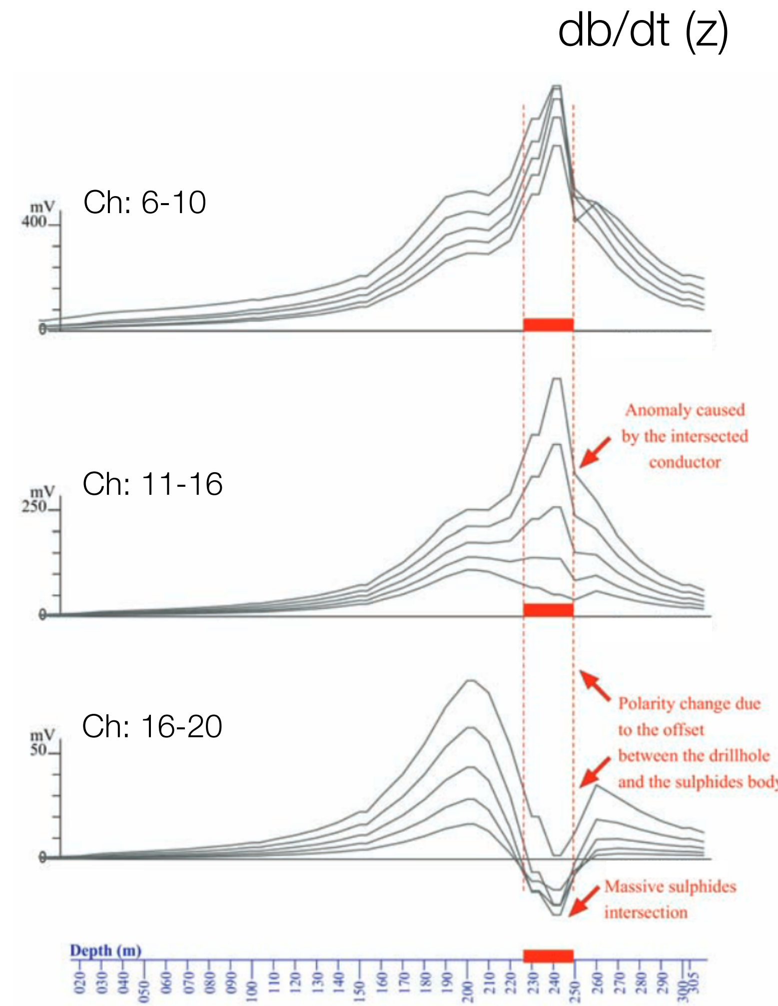
Slingram: Strong signal



Borehole TDEM

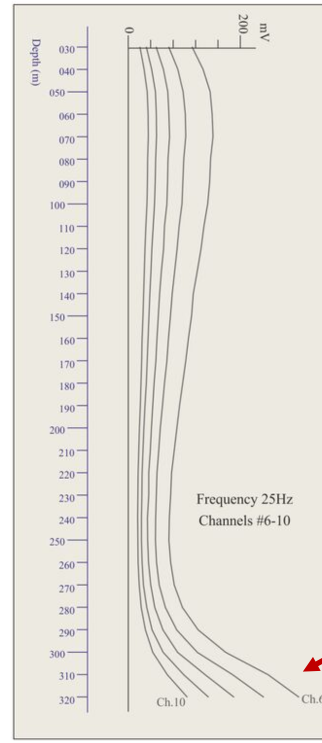
- PROTEM system
  - TEM-67 transmitter
  - BH-43-3D probe (3-components)
  - Base Frequencies: Hi (25 Hz), MD (6.25 Hz)





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

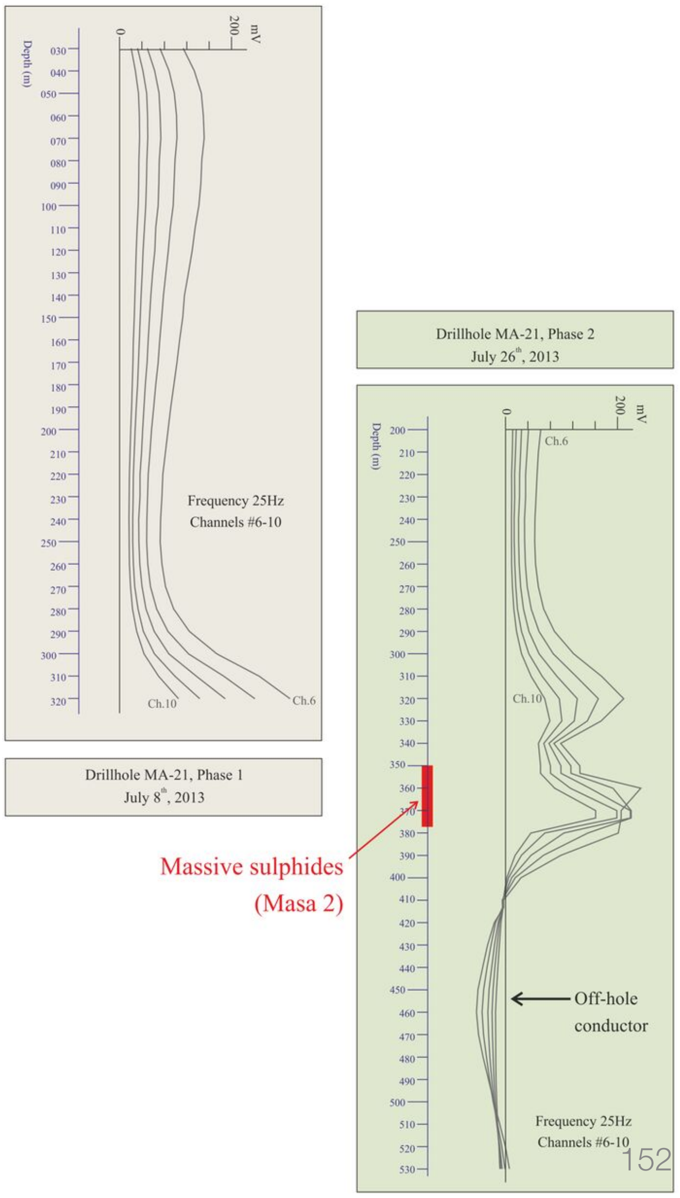


Drillhole MA-21, Phase 1
July 8th, 2013

Possible off-hole conductor

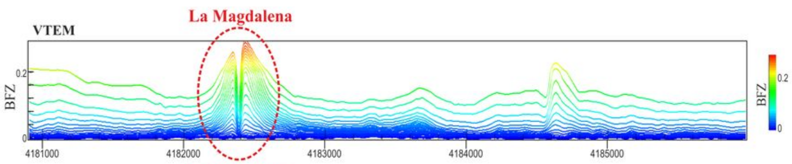
Borehole TDEM: Discovery of Masa 2

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

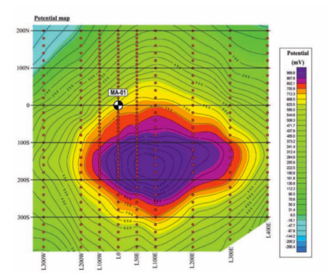


Synthesis

- VTEM: initial discovery

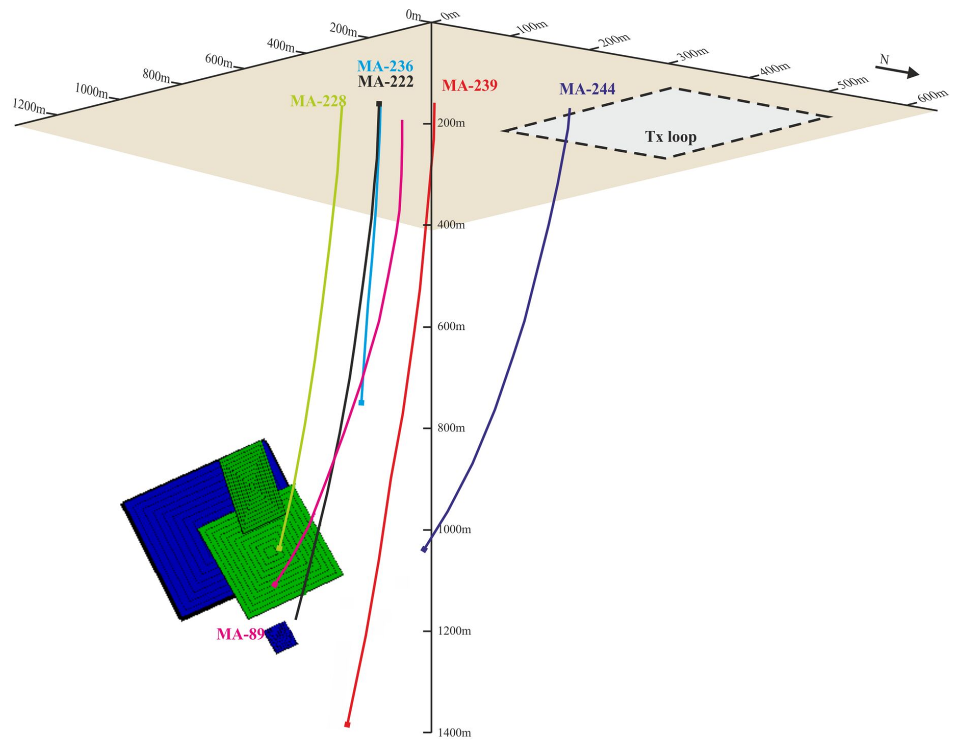


- Mise a la Masse: evaluation



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

- Borehole TDEM: find off-hole conductors



End of Inductive Sources