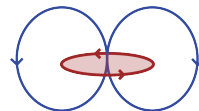
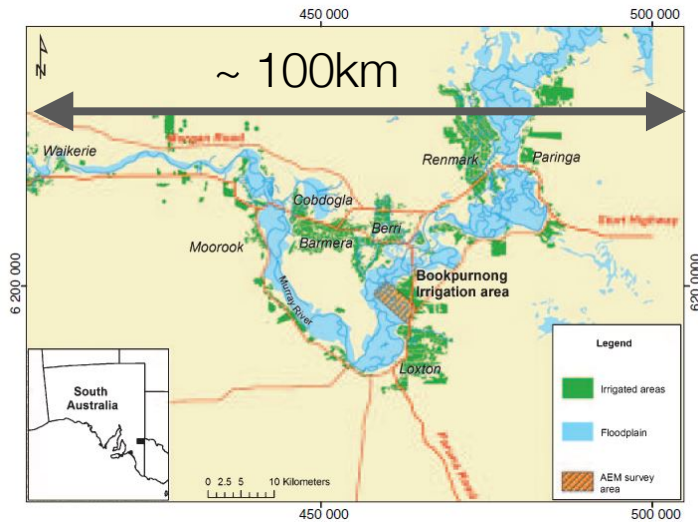


# EM: Inductive Sources

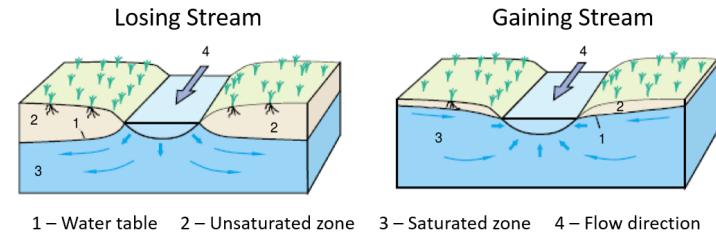


# Motivation

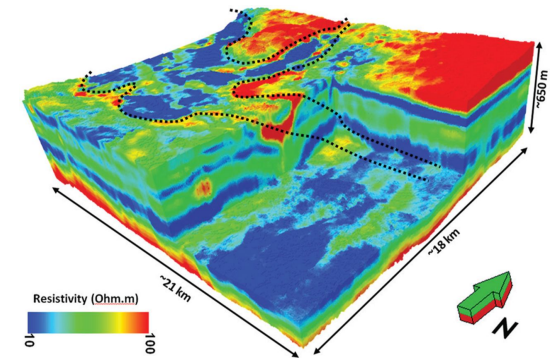
Large areas to be covered



Groundwater



High resolution near surface



Rugged terrain



Minerals





# Outline

## Setup

- Basic experiment
- Transmitters, Receivers

## Frequency Domain EM

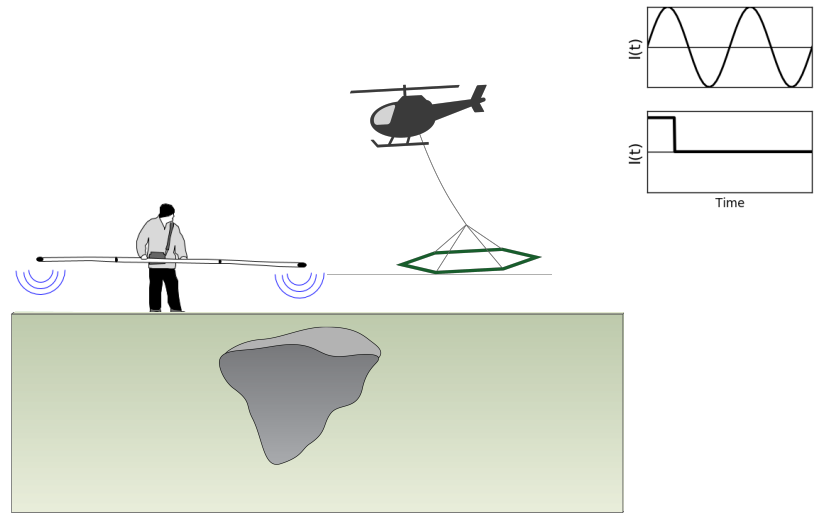
- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Groundwater

## Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Case History – Oil and gas

# 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:**

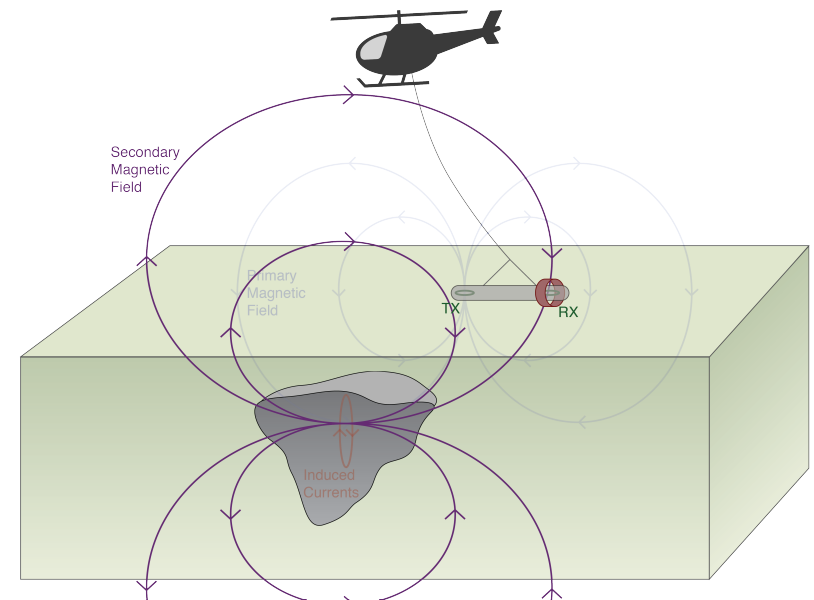
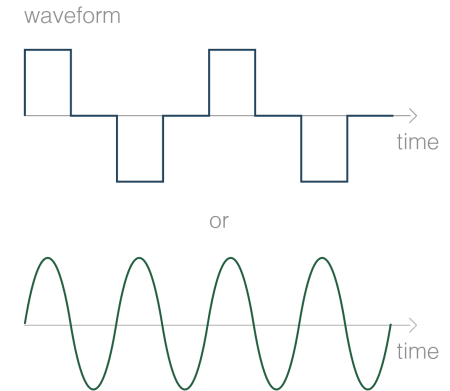
- Produces a primary magnetic field

- **Exciting the target:**

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

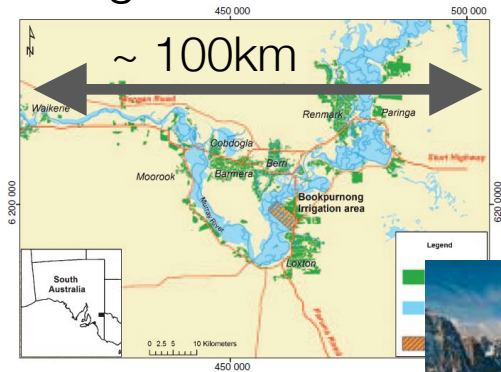
- **Receiver:**

- Induced currents produce secondary magnetic fields



# Transmitter

Large areas



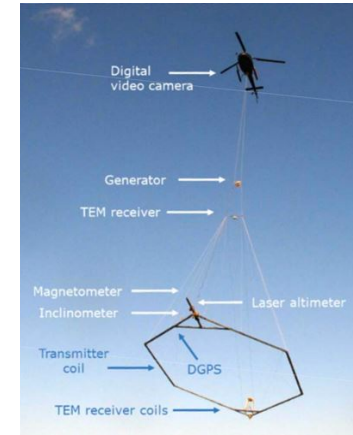
Rugged terrain



Airborne Survey

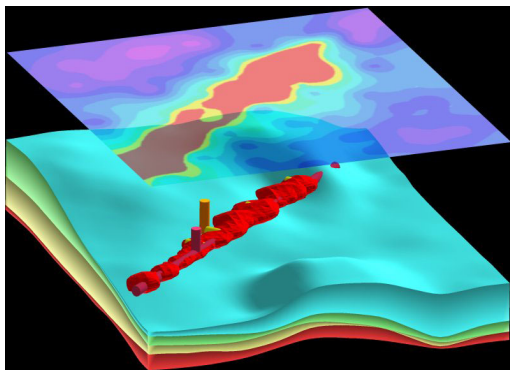


Resolve

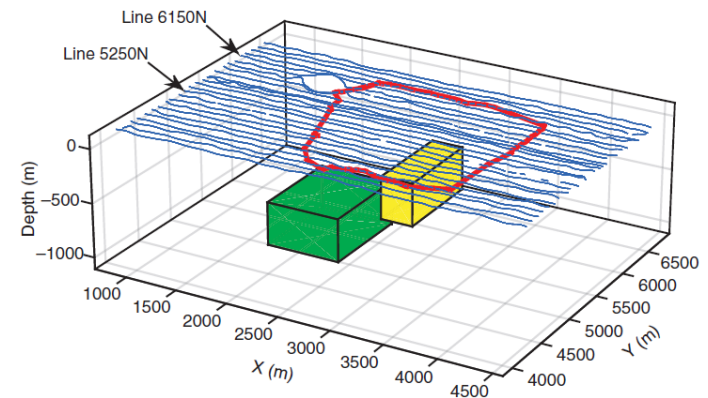


SkyTEM

Deep Targets

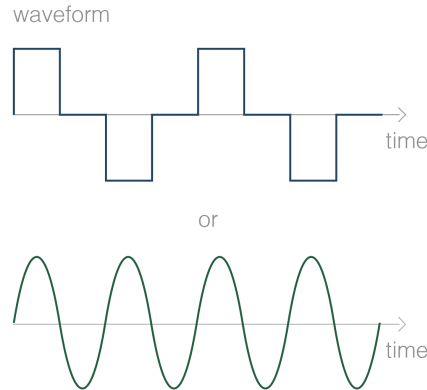


Large Loop



# Transmitter

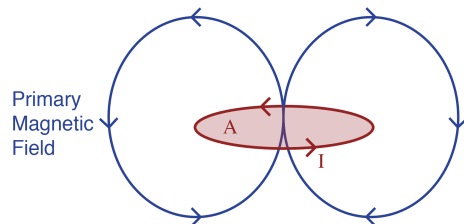
- Frequency or Time?



- Key factor is moment

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

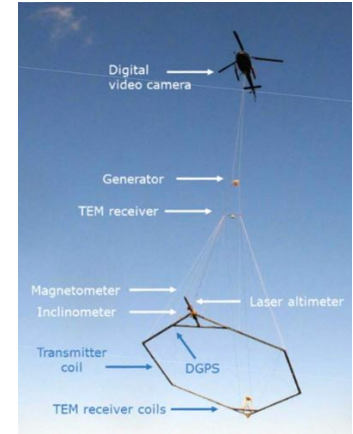
$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi} \left( \frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3} \right)$$



## Airborne Survey

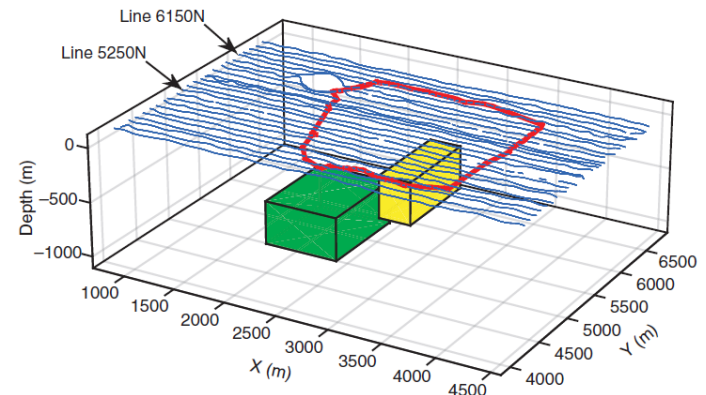


Resolve



SkyTEM

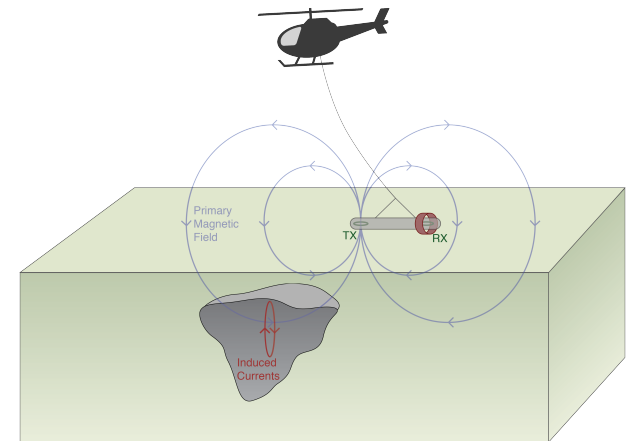
## Large Loop



# 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

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



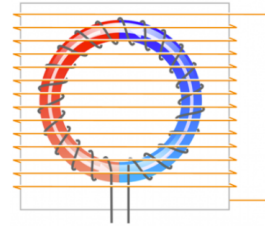


# Receiver and Data

## Magnetometer

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

$\mathbf{b}(t)$

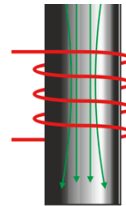


Fluxgate

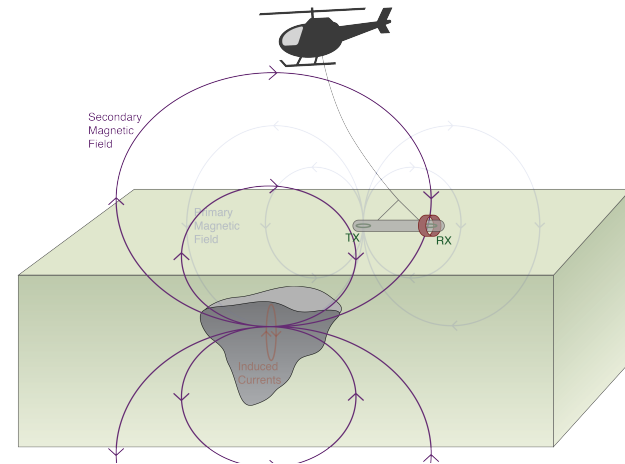
## Coil

- 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  $V_s/V_p$

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

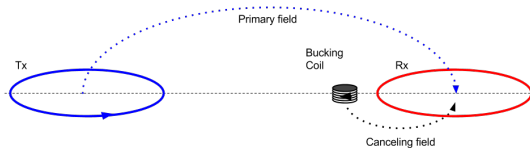


Coil

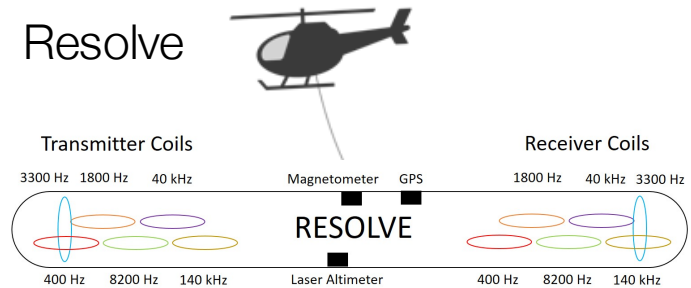
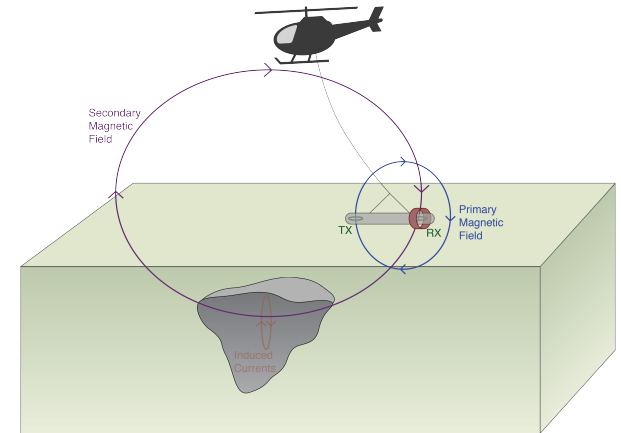


# Receiver: Frequency Domain

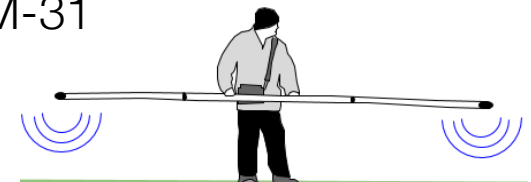
- Primary field
  - always “on”
  - large compared to secondary fields
- Primary removal
  - Compute and subtract
  - Bucking coil



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

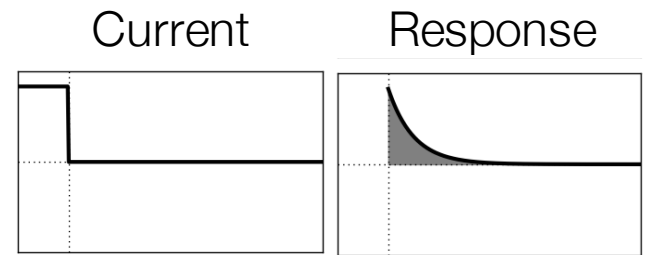


EM-31

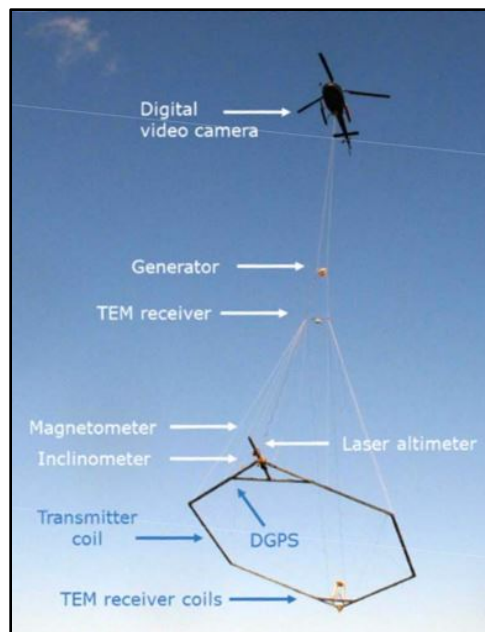


# Receiver: Time Domain

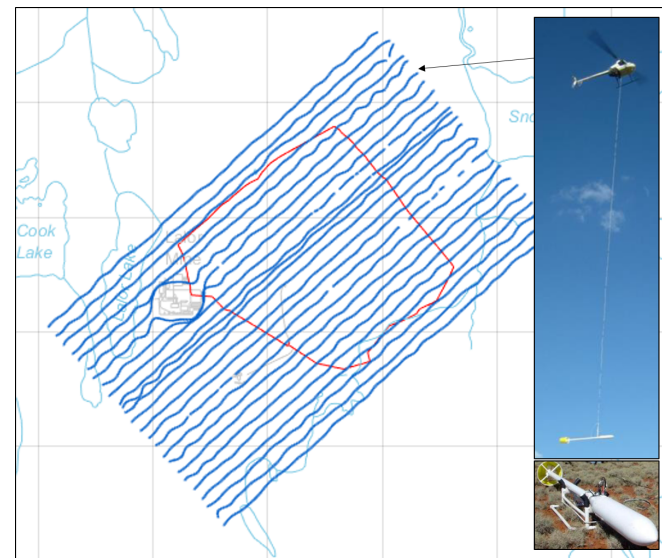
- Primary field has off-time
- Measure secondary fields
- Receivers can be mounted on transmitter loop or above it



SkyTEM

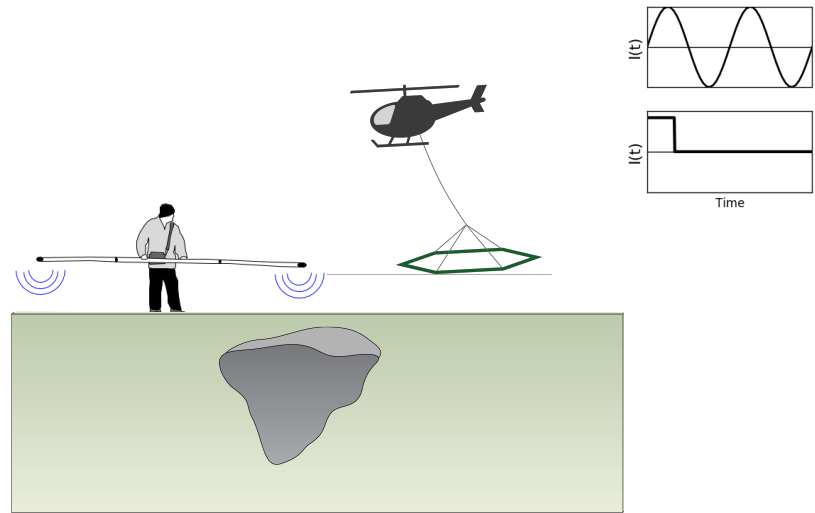


HeliSAM



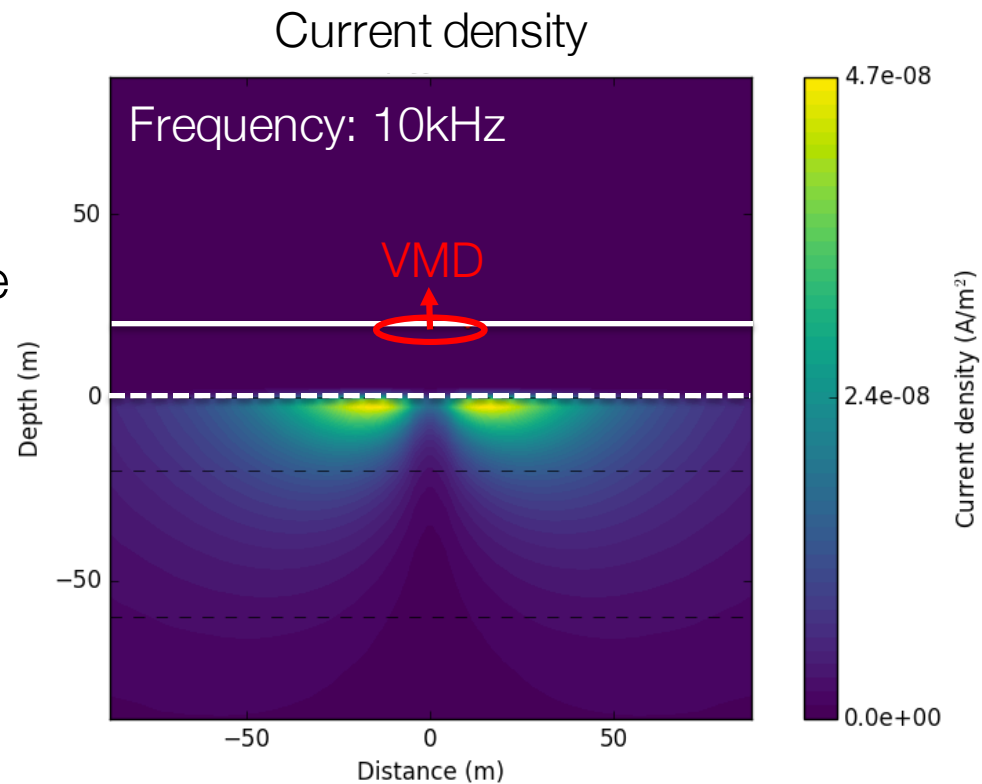
# Important questions

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

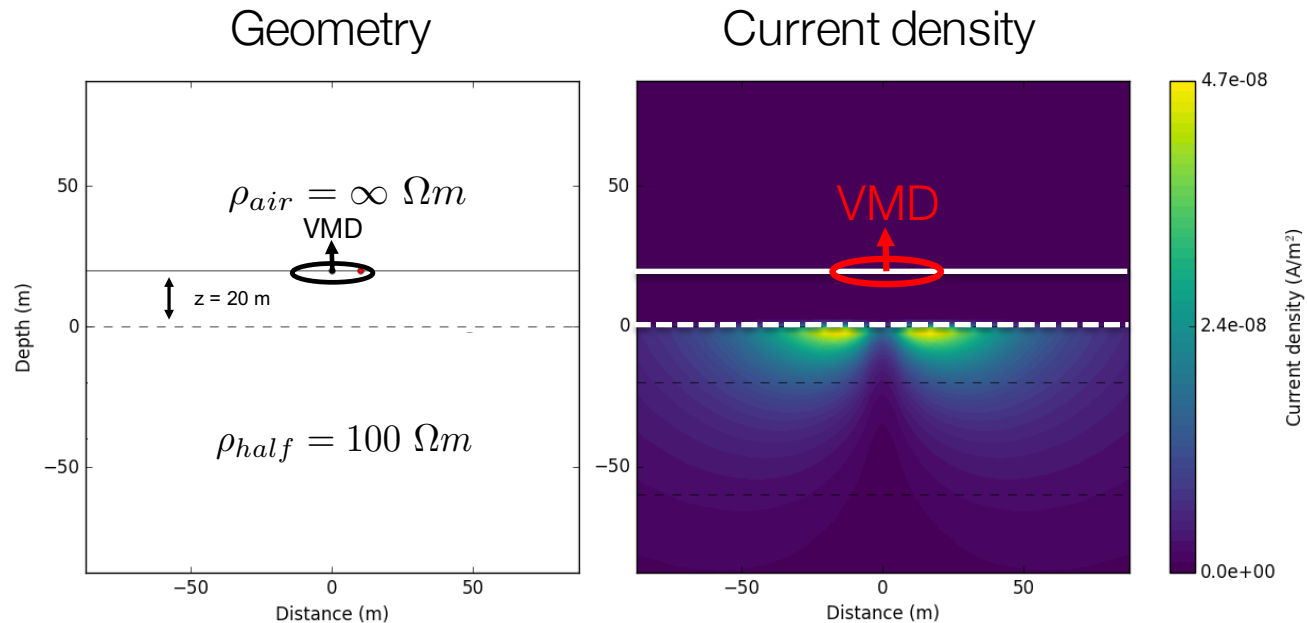


# Footprint of Airborne EM system

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

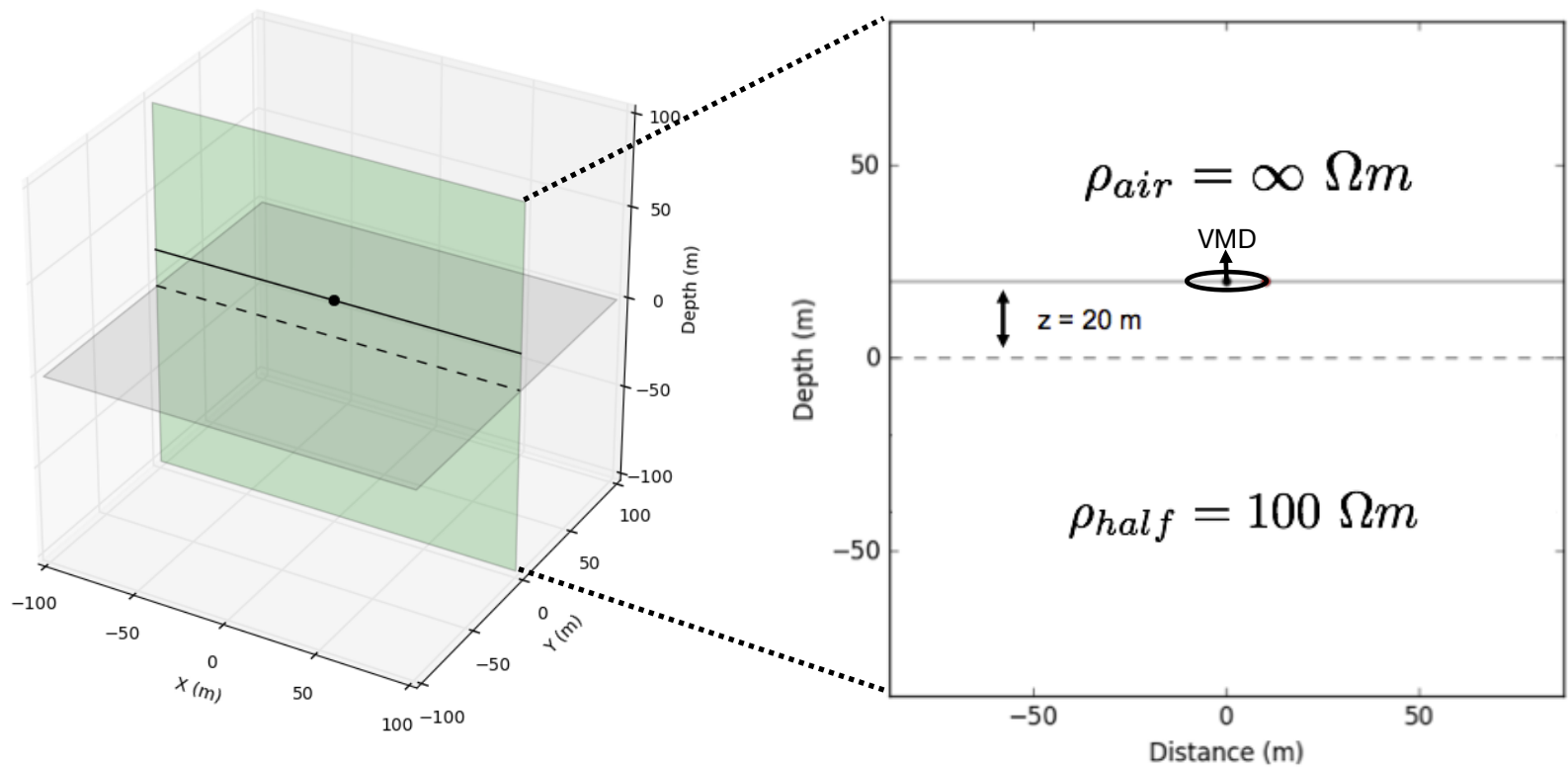


# Vertical Magnetic Dipole (VMD)



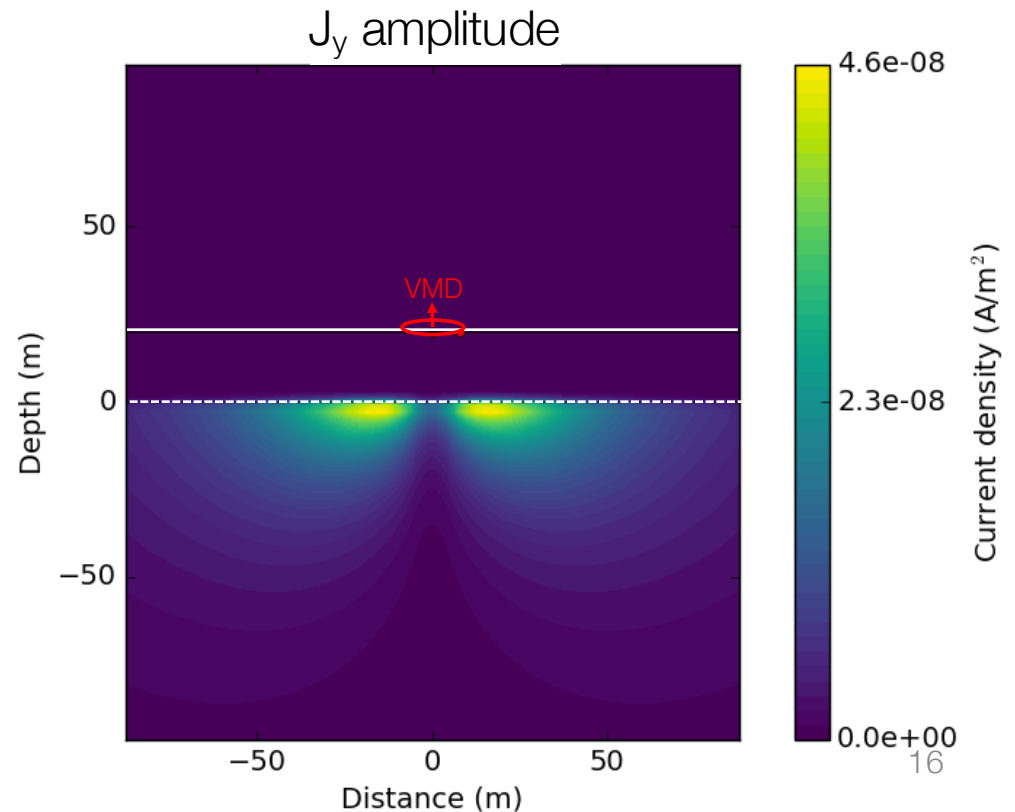
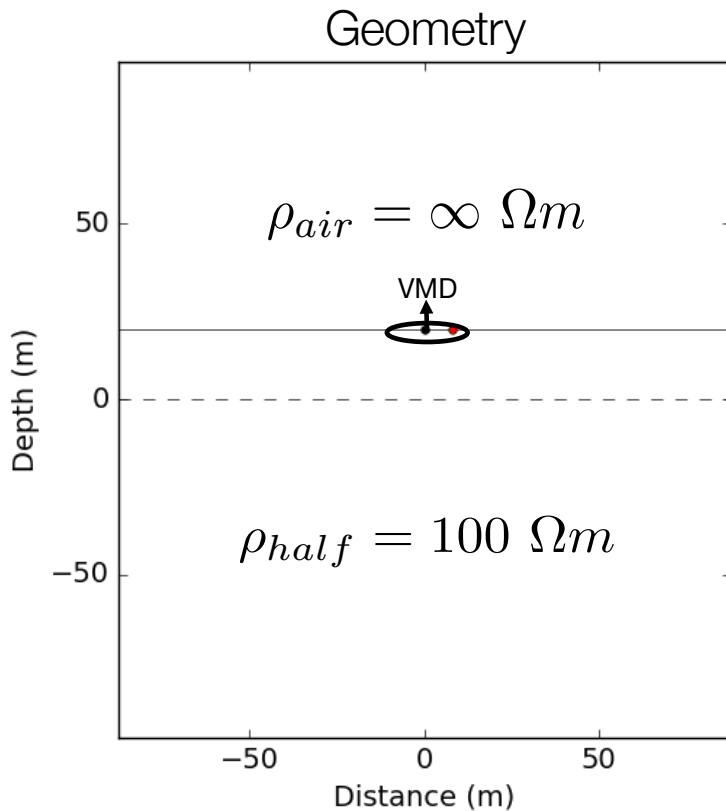
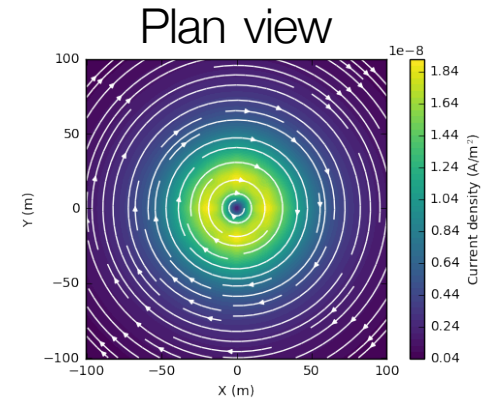
- Some questions
  - Where, and how strong, are the currents?
  - How do they change with transmitter frequency?
  - How do they depend upon the conductivity?
  - What do the resulting magnetic fields look like?

# Vertical Magnetic Dipole over a halfspace (FDEM)



# Current Density

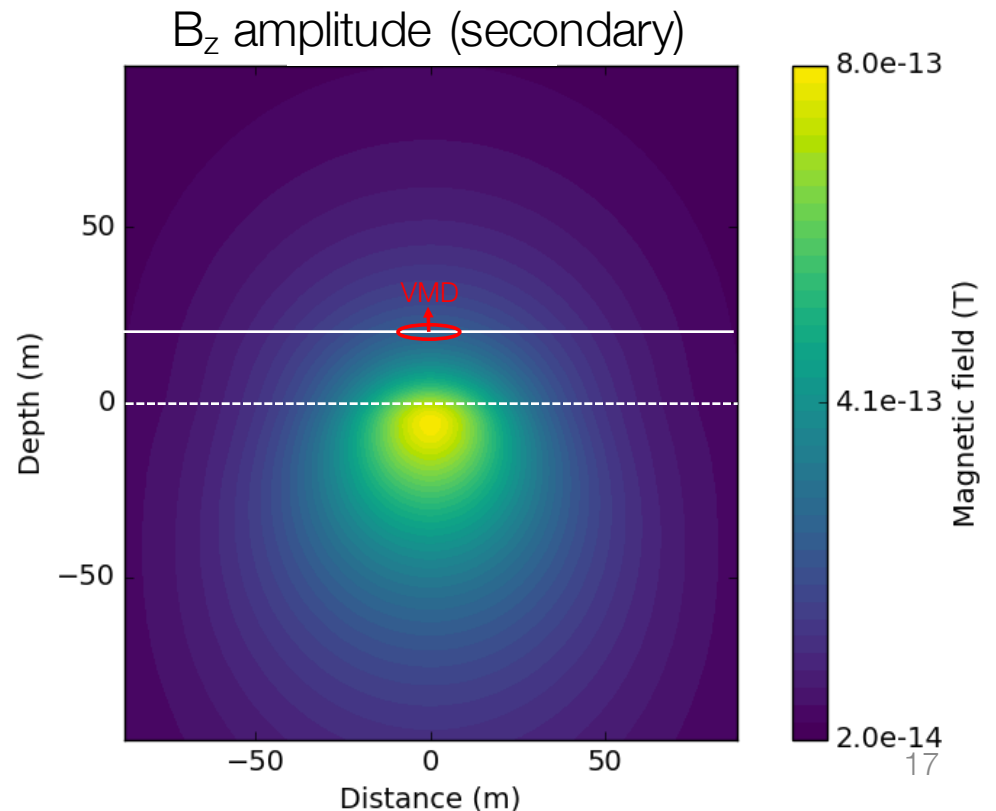
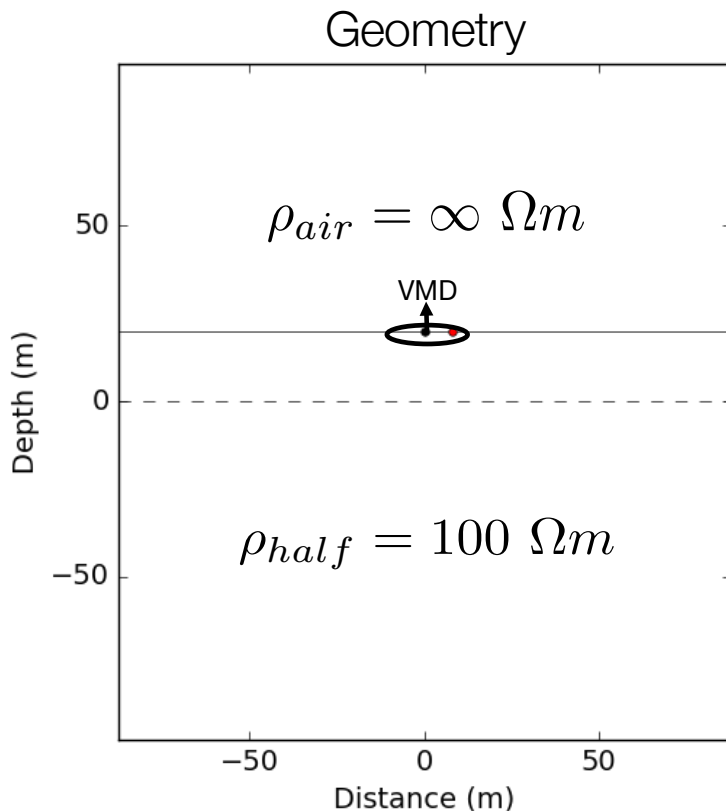
- Frequency = 10 kHz
- Currents in the earth flow in planes parallel to the Tx





# Secondary Magnetic Flux Density

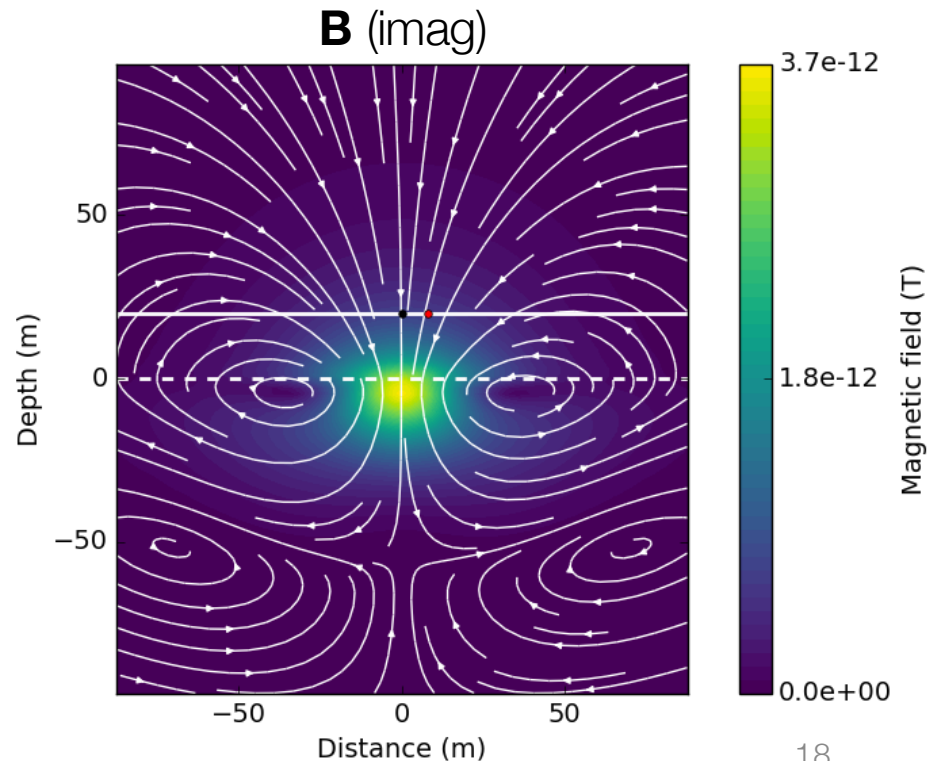
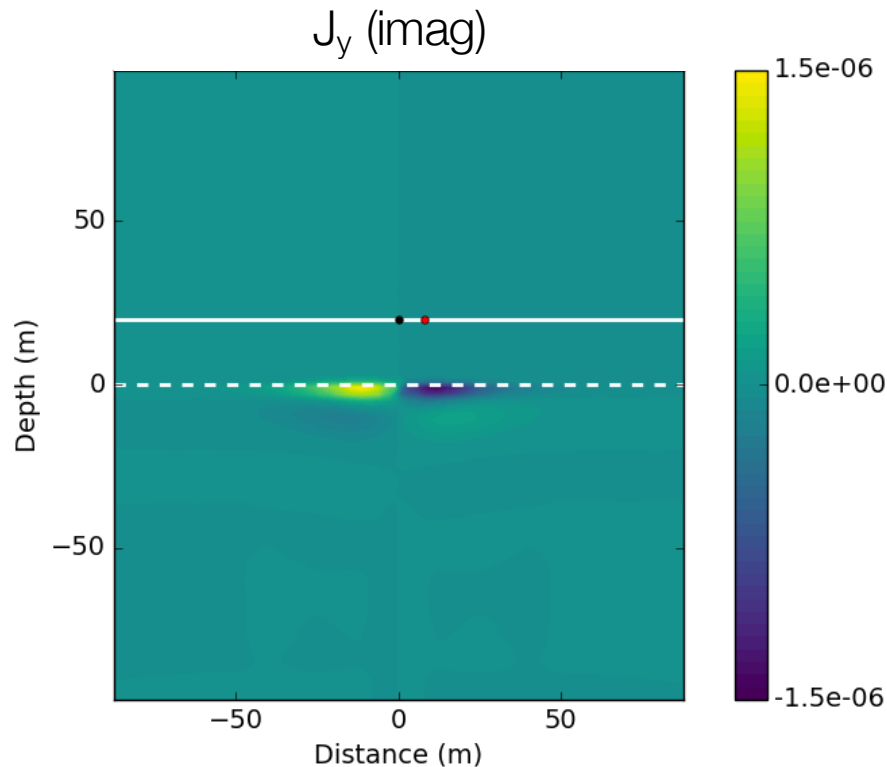
- Frequency = 10 kHz



# Effects of Frequency

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

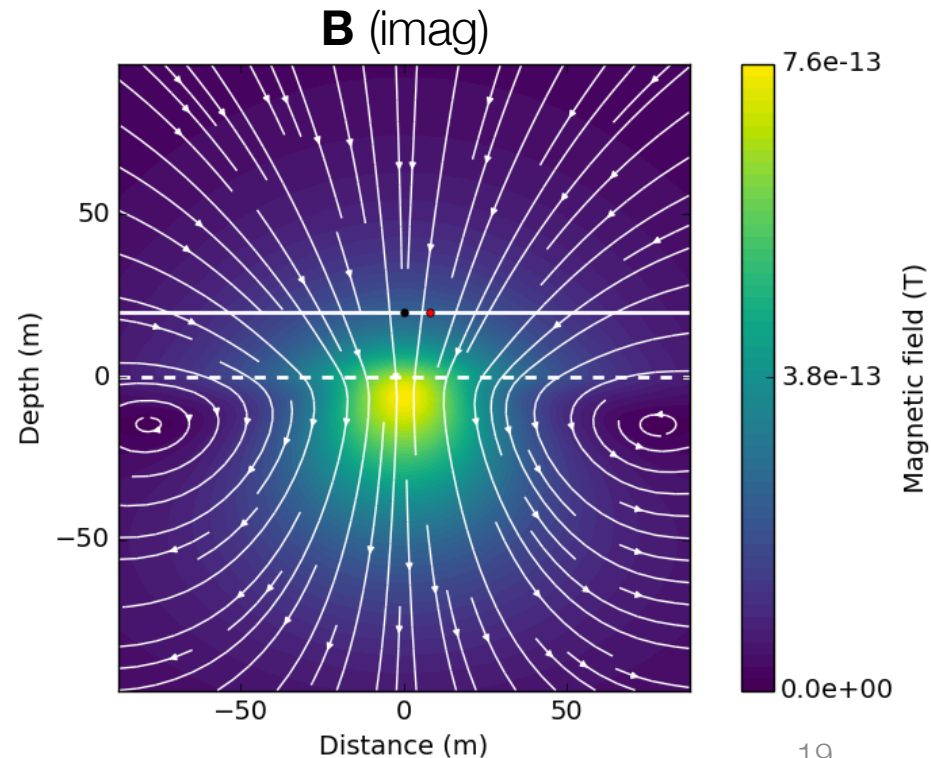
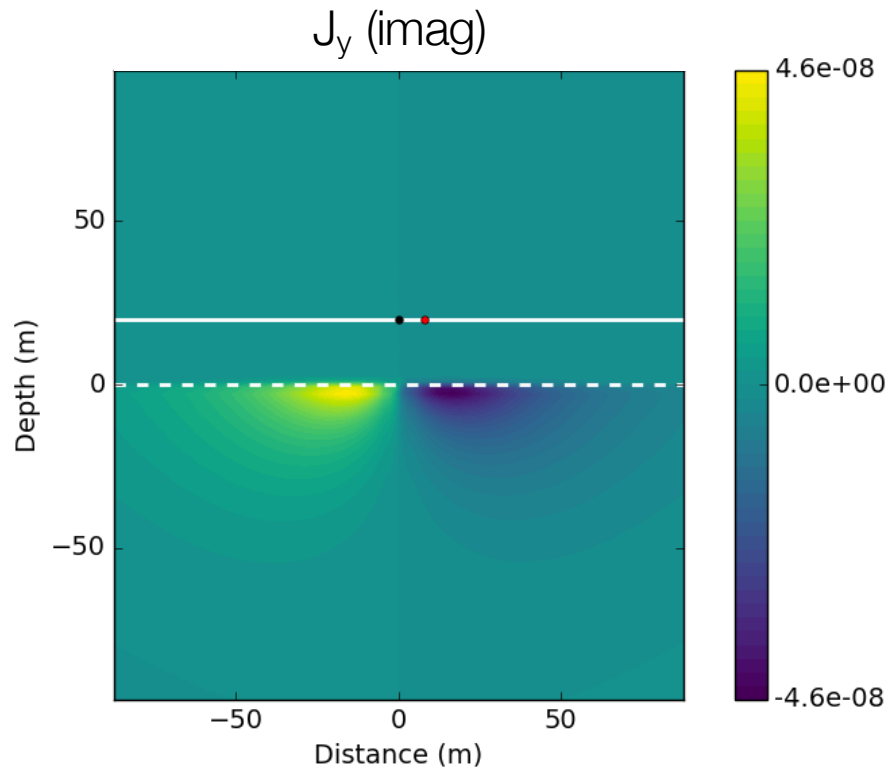
$$\delta = 503 \sqrt{\frac{\rho}{f}}$$



# Effects of Frequency

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

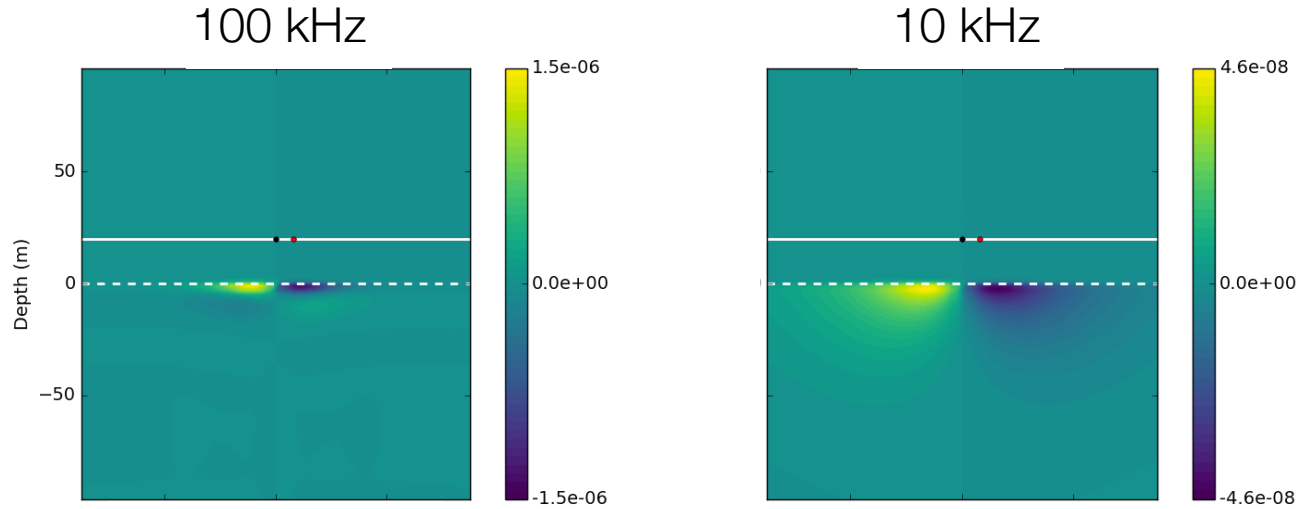
$$\delta = 503 \sqrt{\frac{\rho}{f}}$$



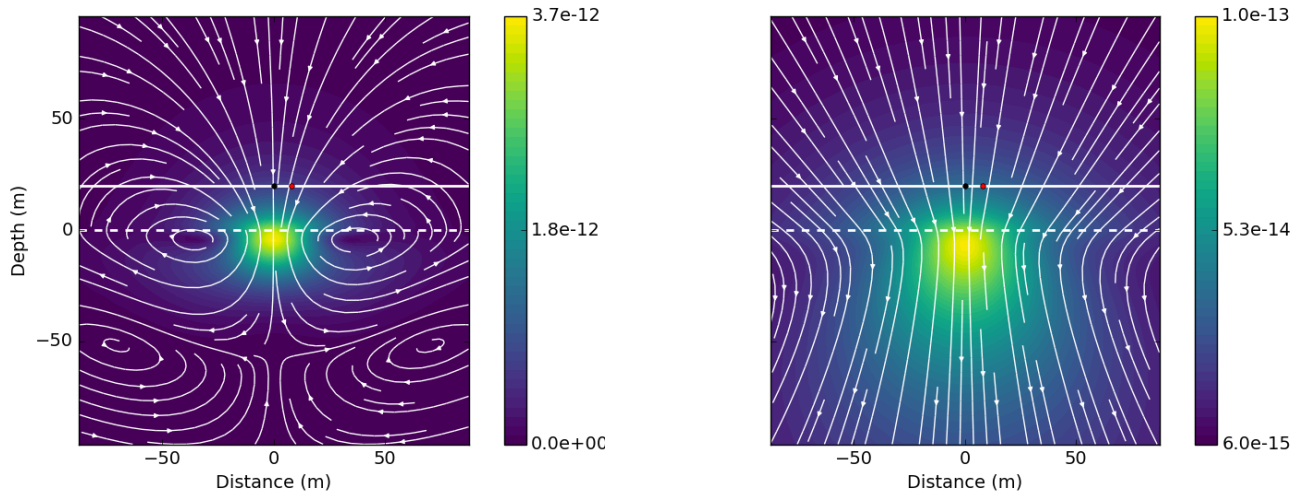
# Summary: Effects of Frequency

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

$J_y$  imag.

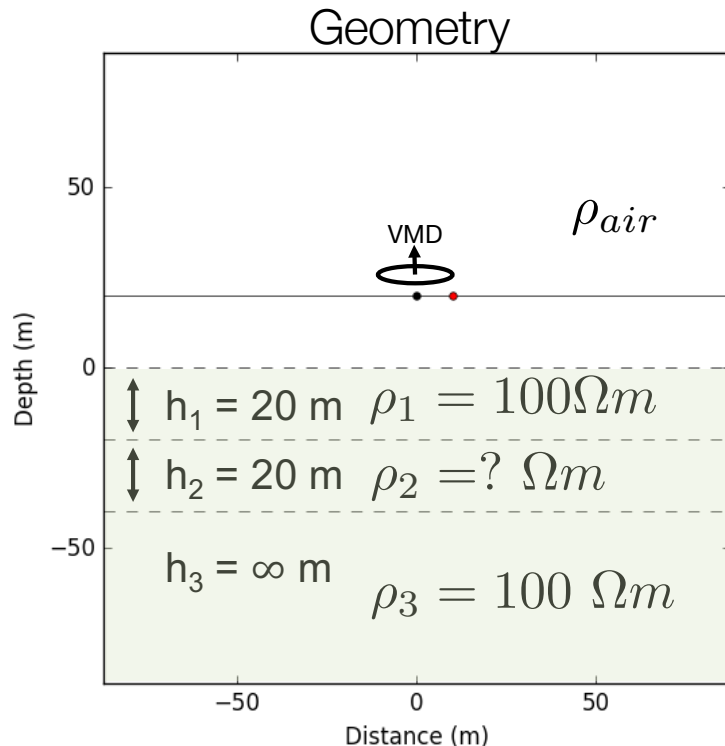


**B** imag.



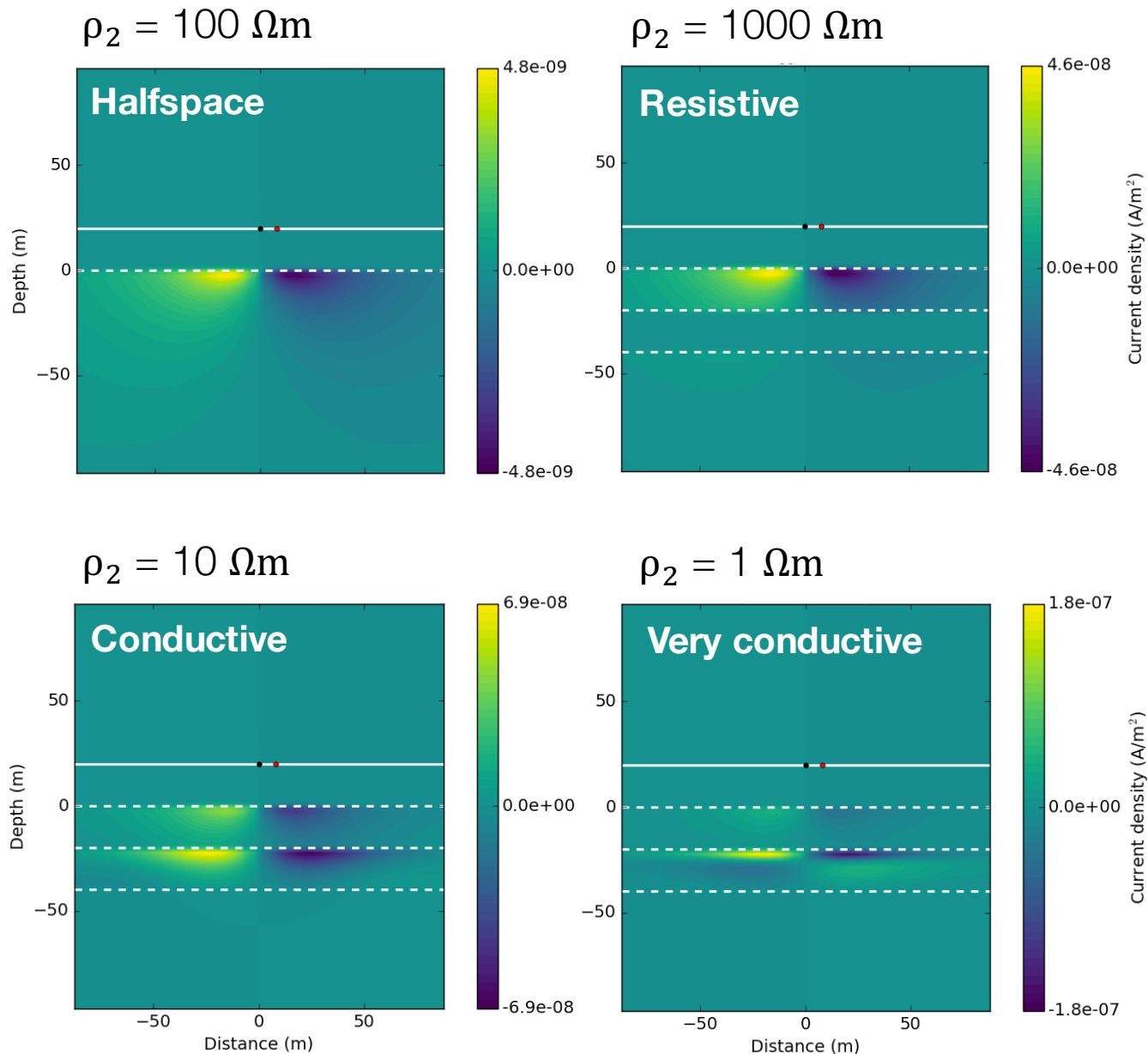
# Layered earth

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

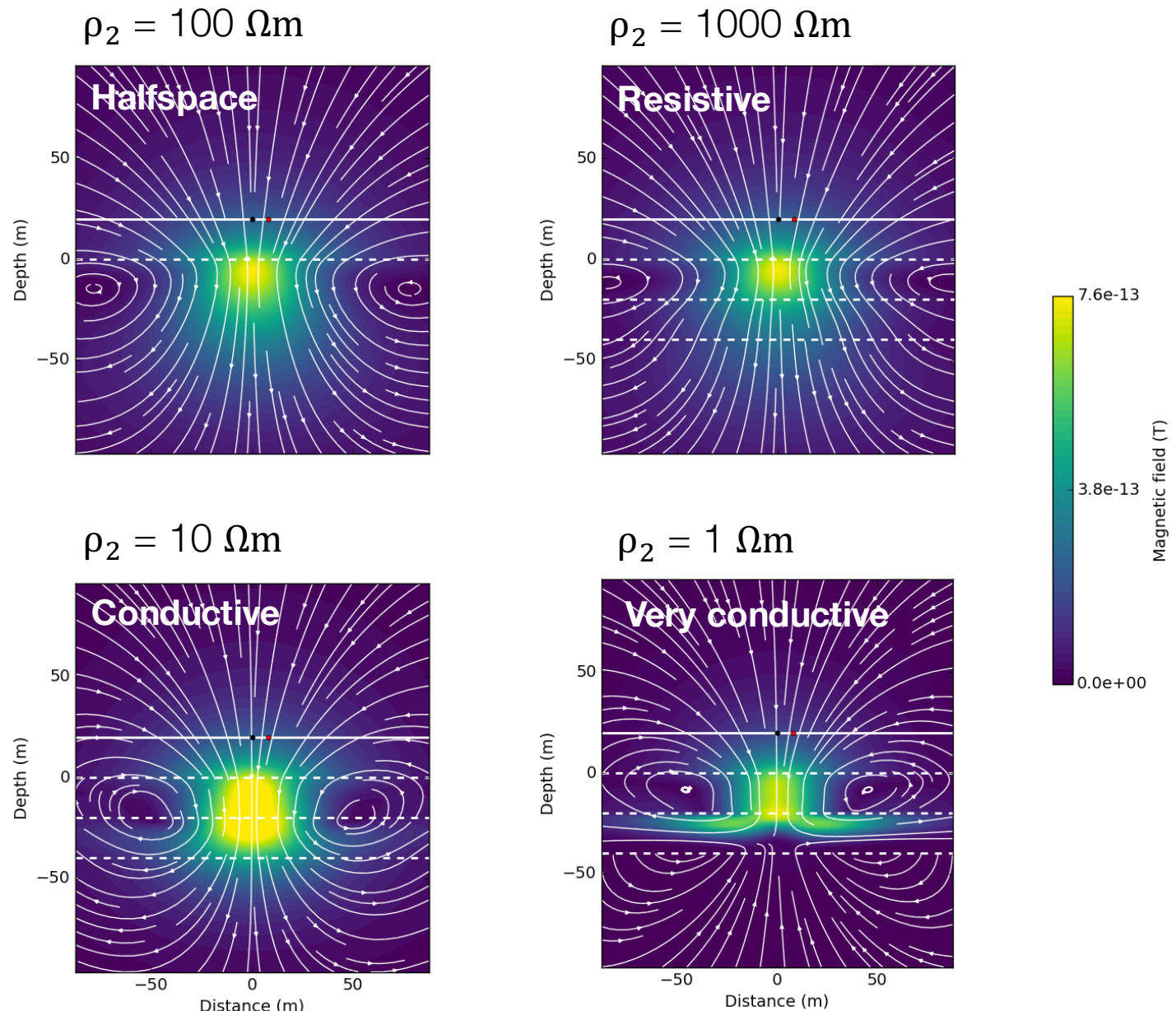


- Four different cases:
  - Halfspace  
 $\rho_2 = 100 \Omega m$
  - Resistive  
 $\rho_2 = 1000 \Omega m$
  - Conductive  
 $\rho_2 = 10 \Omega m$
  - Very conductive  
 $\rho_2 = 1 \Omega m$
- Fields
  - $J_y$  imag
  - Secondary **B** imag

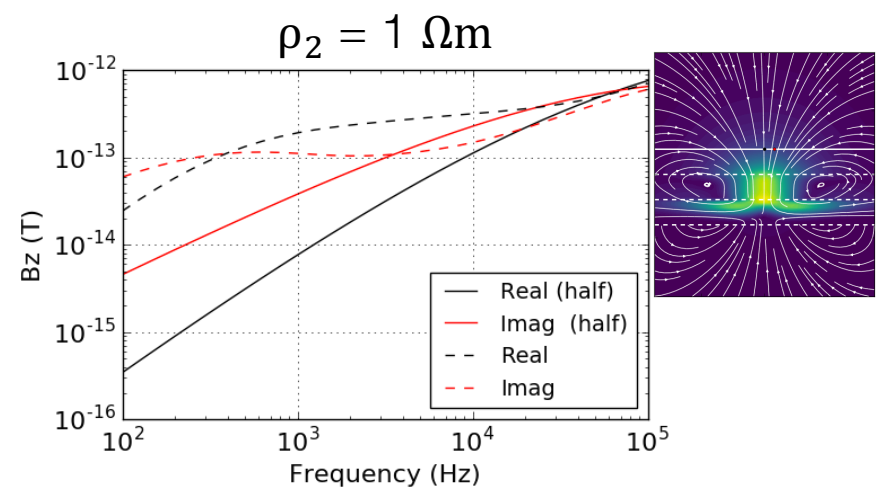
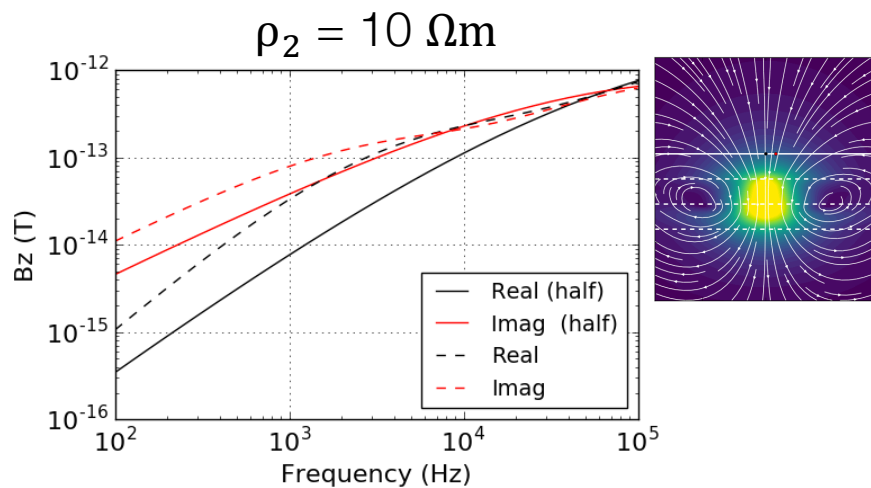
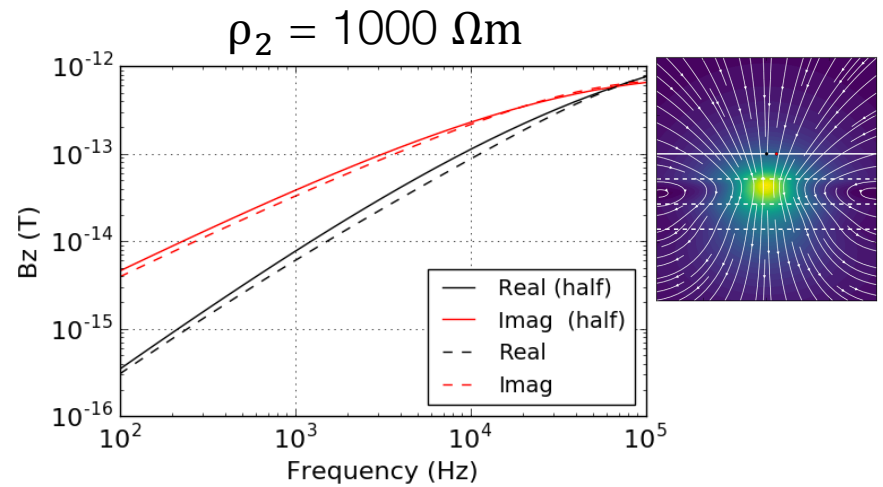
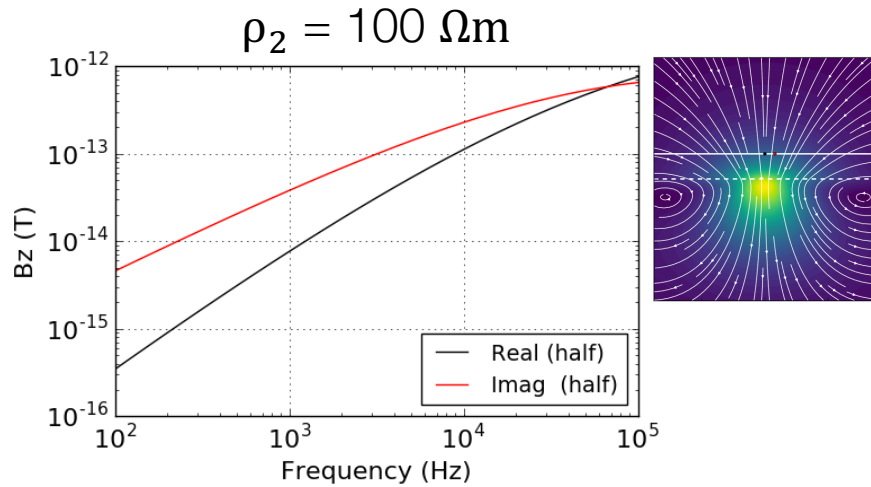
# Current density ( $J_y$ imag)



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

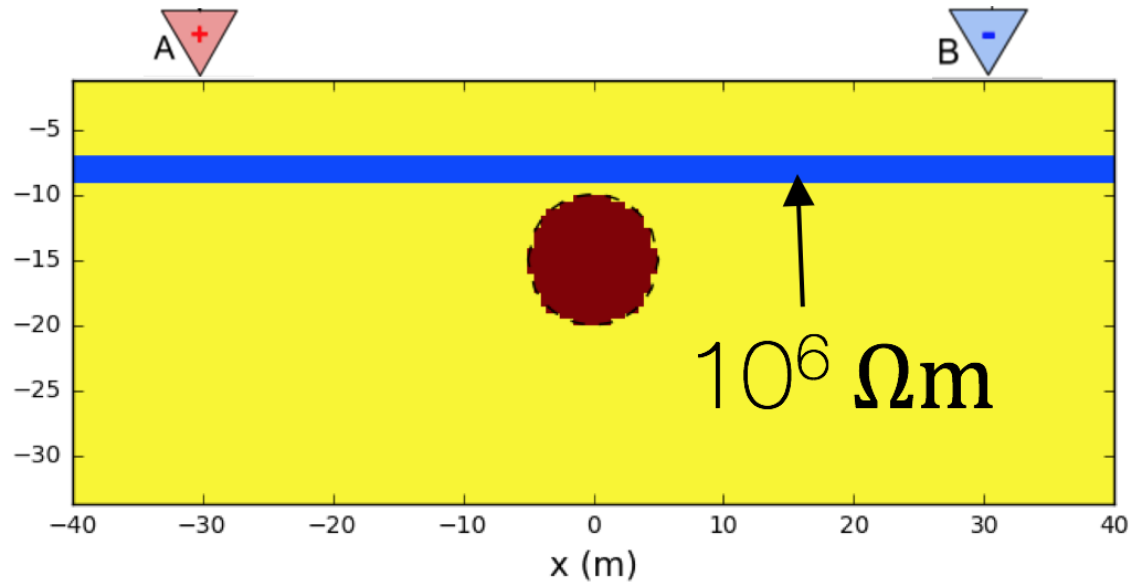


# $B_z$ sounding curves



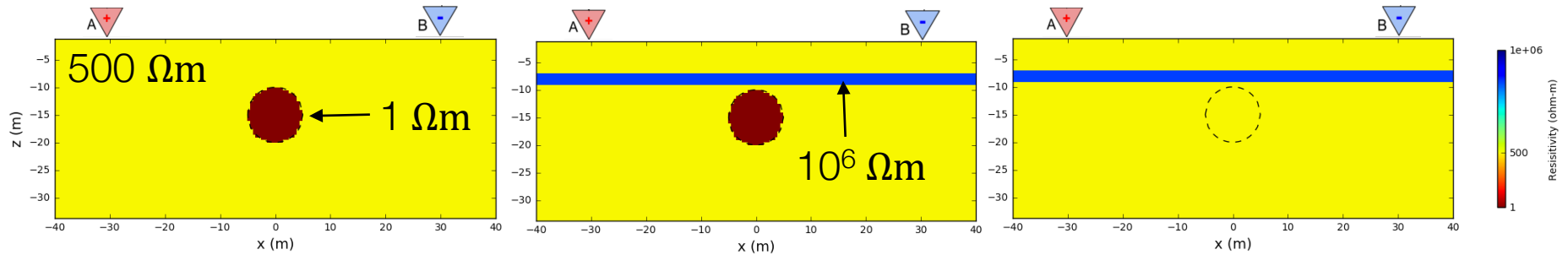


# Back to the “shielding” problem

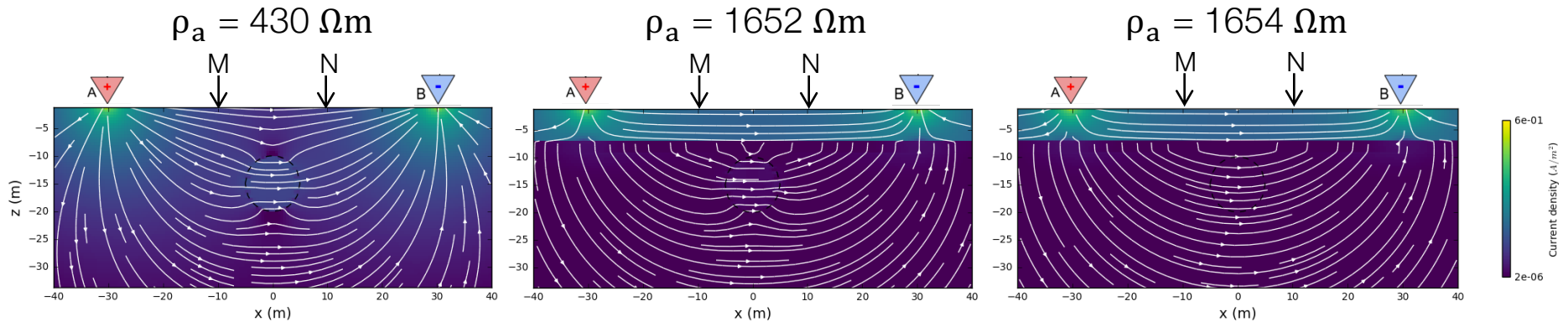


# Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)

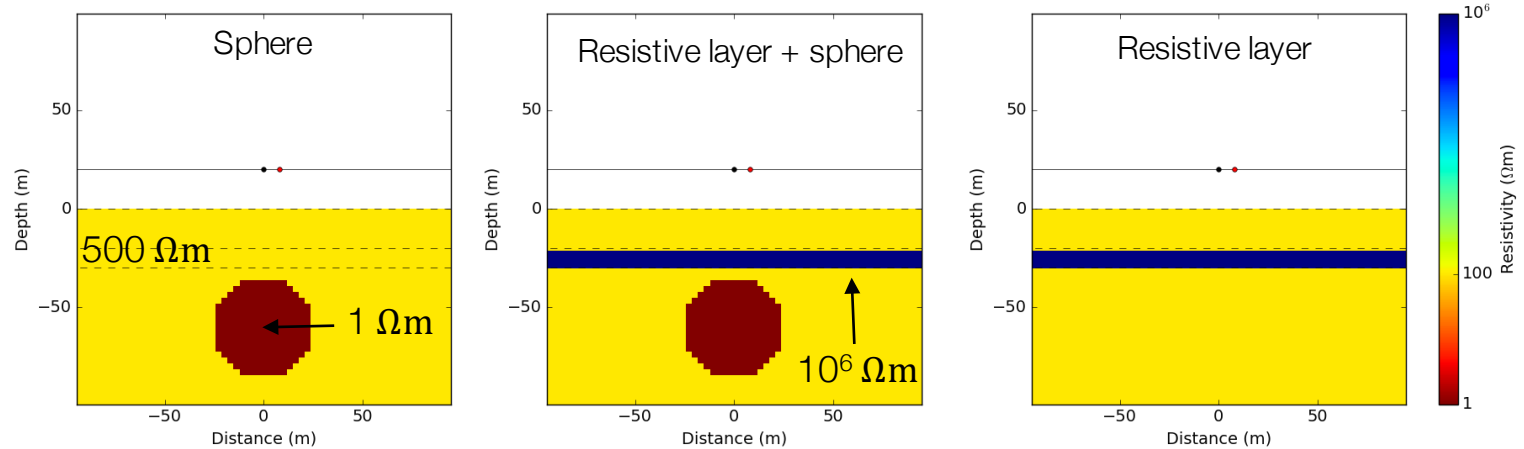


Currents and measured data at MN

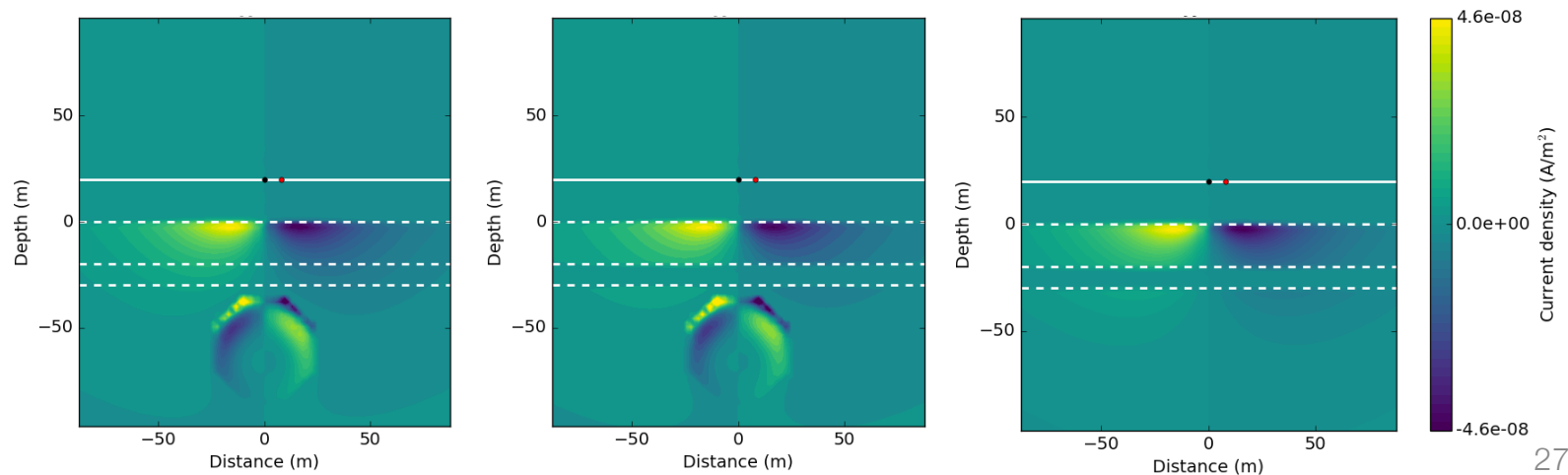


# Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

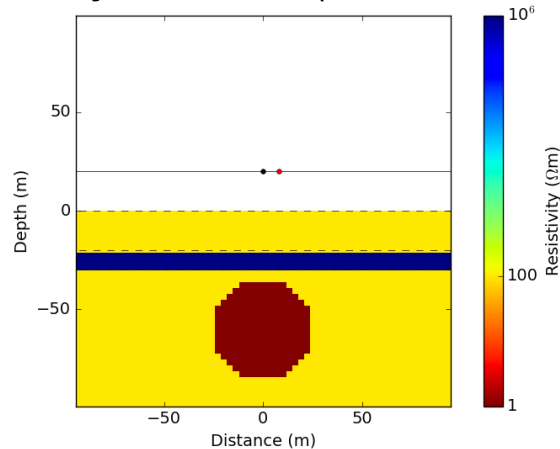


Currents ( $J_y$  imag)

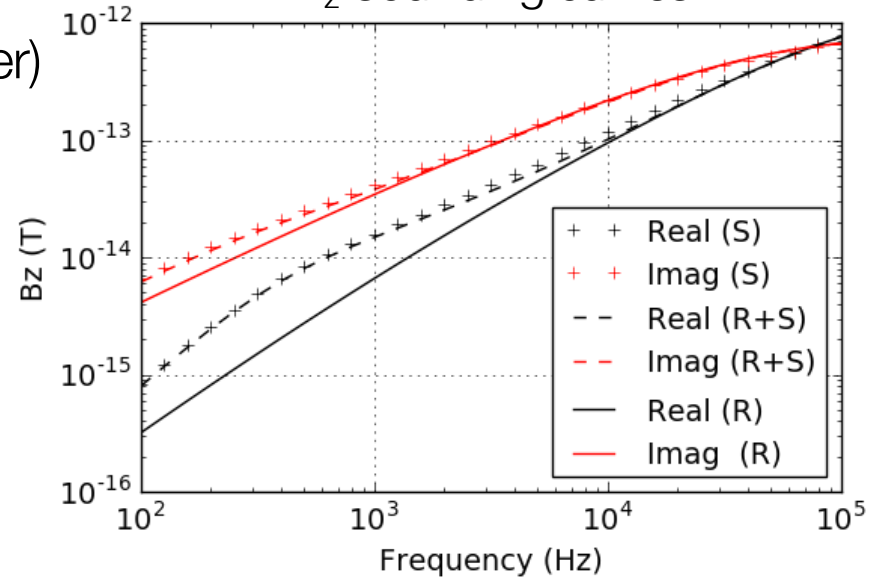


# Shielding: EM with resistive layer

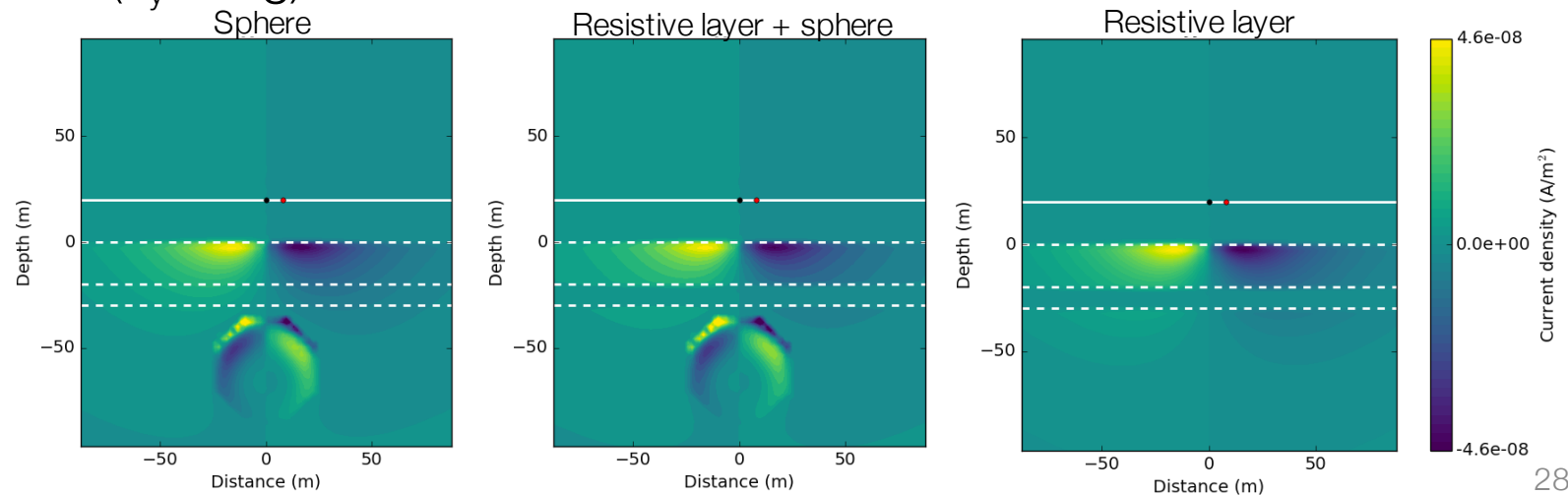
Resistivity models (thin **resistive** layer)



$B_z$  sounding curves

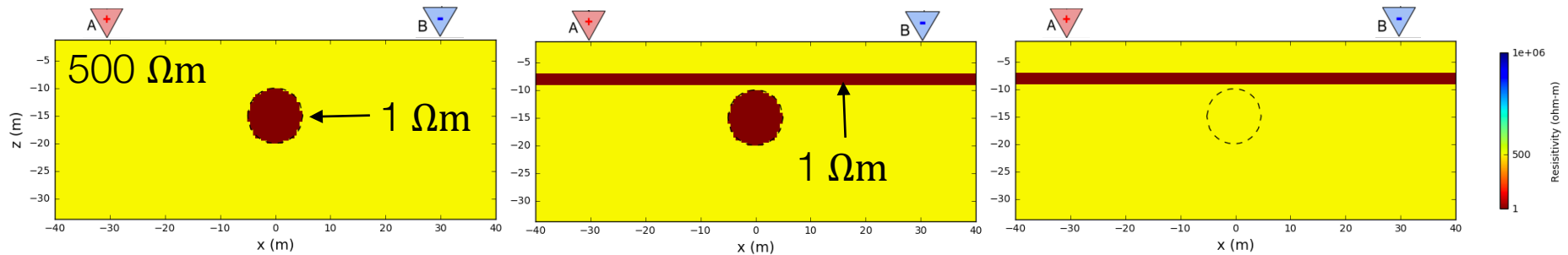


Currents ( $J_y$  imag)

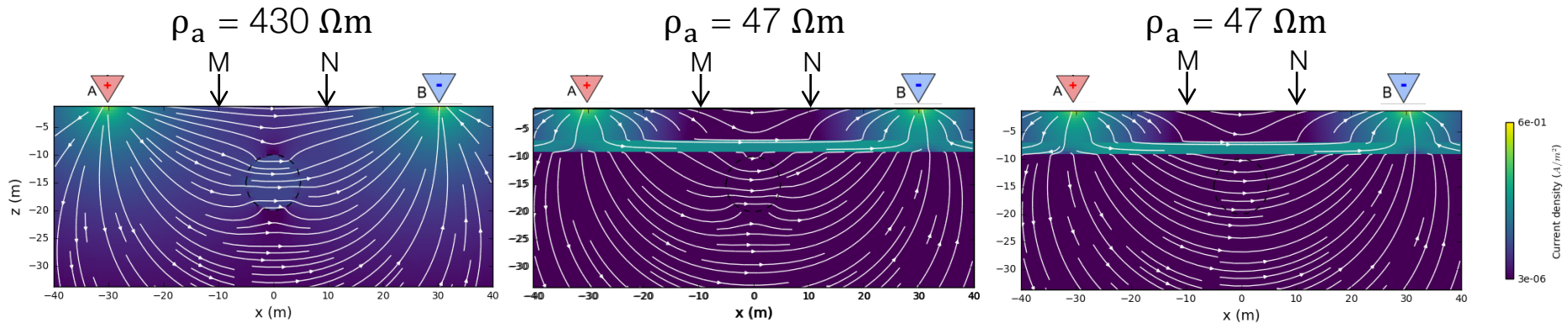


# Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)

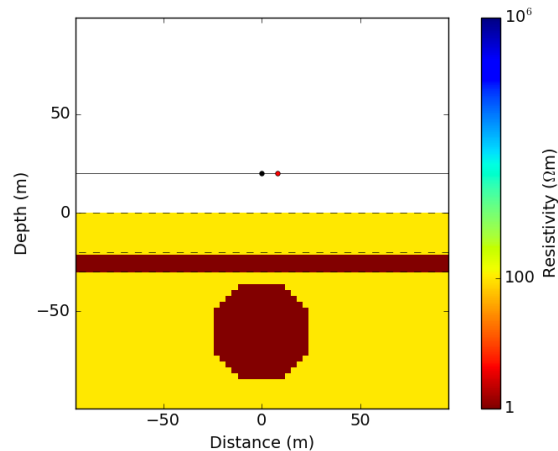


Currents and measured data at MN

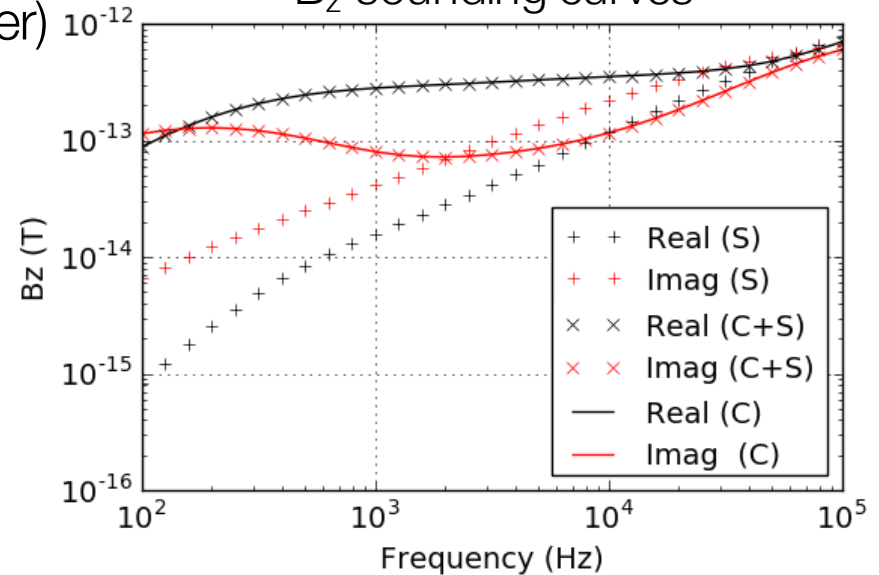


# Shielding: EM with conductive layer

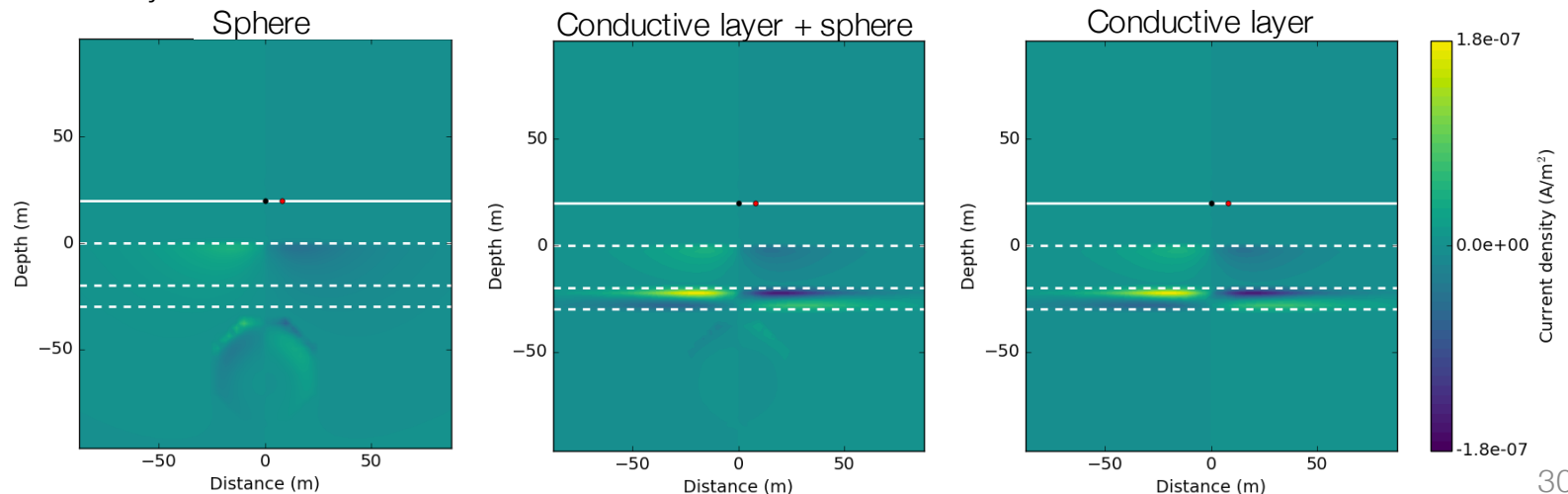
Conductivity models (thin **resistive** layer)



$B_z$  sounding curves



Currents ( $J_y$  imag)



# Outline

## Setup

- Basic experiment
- Transmitters, Receivers

## Frequency Domain EM

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

## Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Case History – Oil and gas

# Case History: Bookpurnong

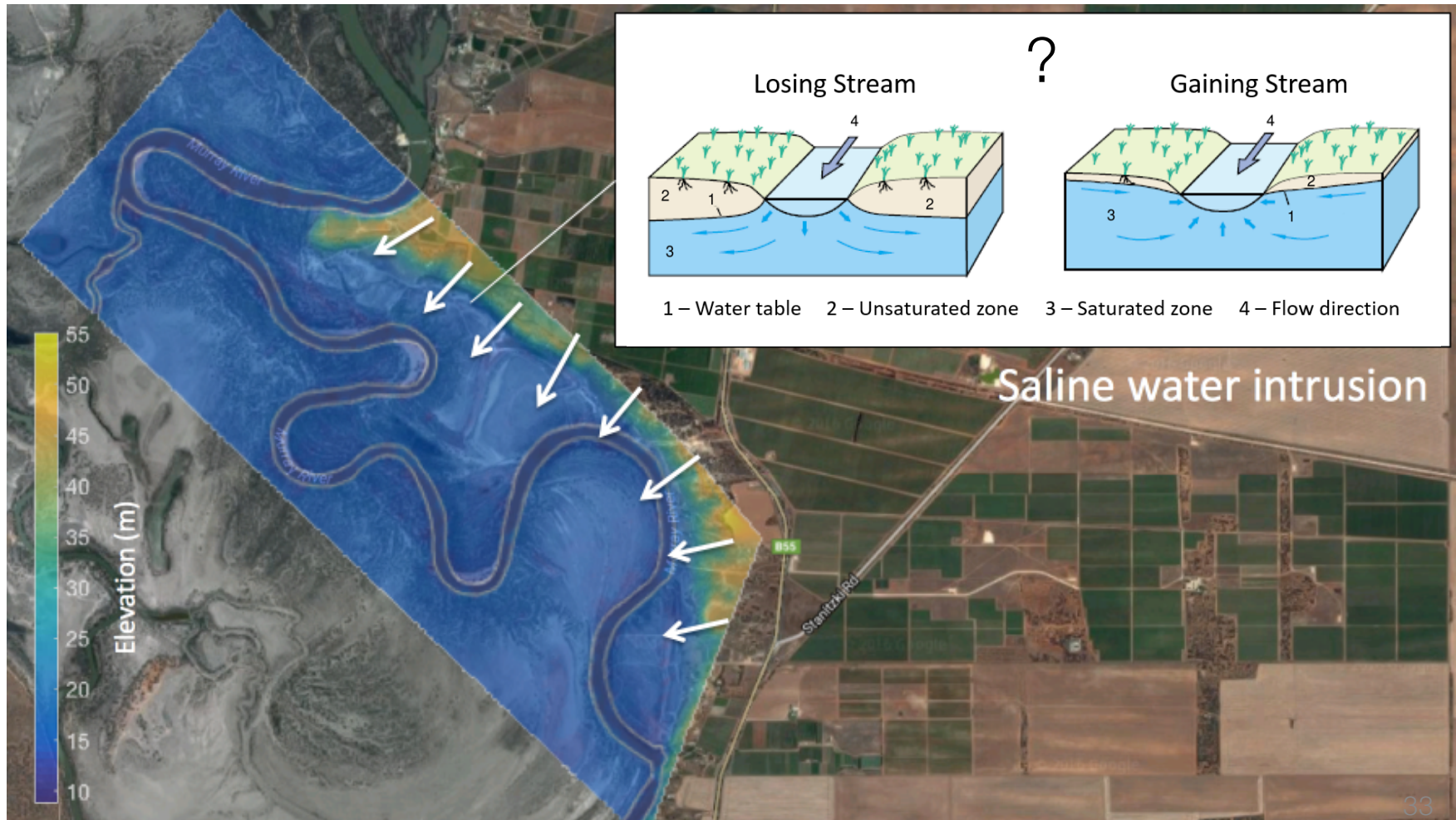
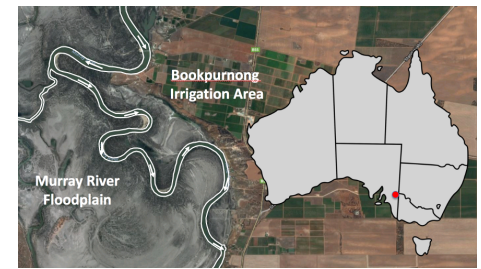
Viezzoli et al., 2009



# Setup

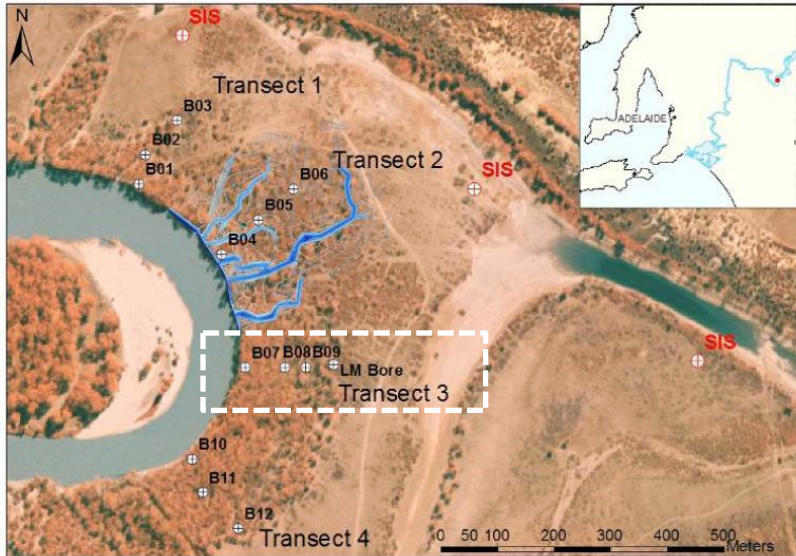
Geoscience Australia project

- Characterizing river salination



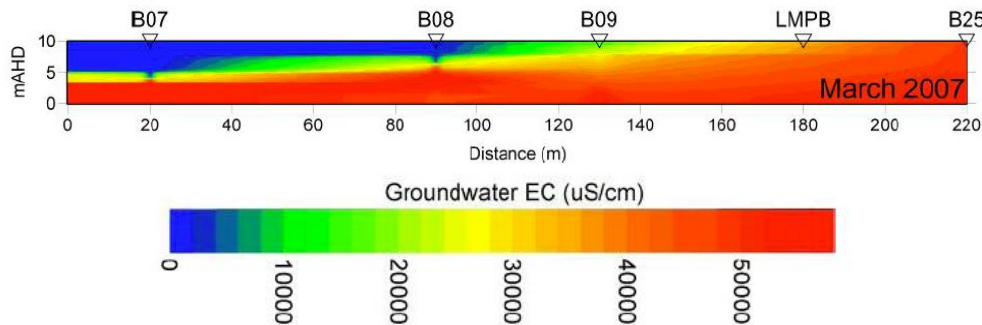
# Properties

Location map for salinity measurements



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

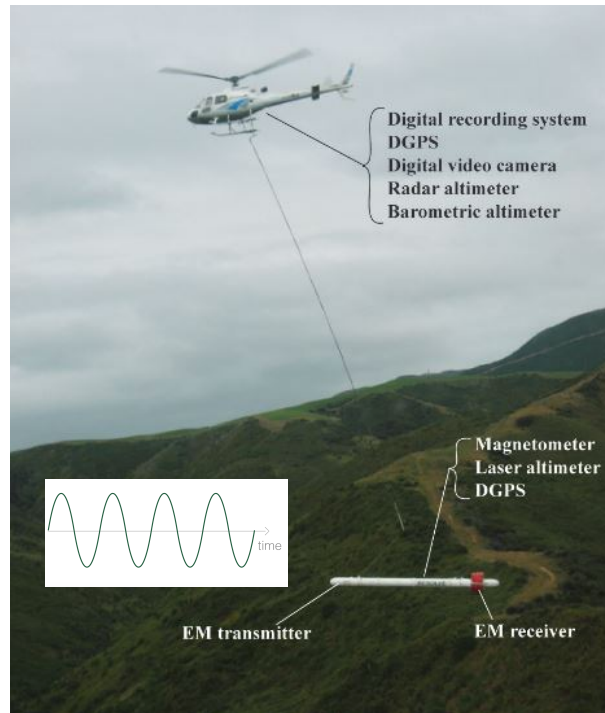
Conductivity from salinity measurements



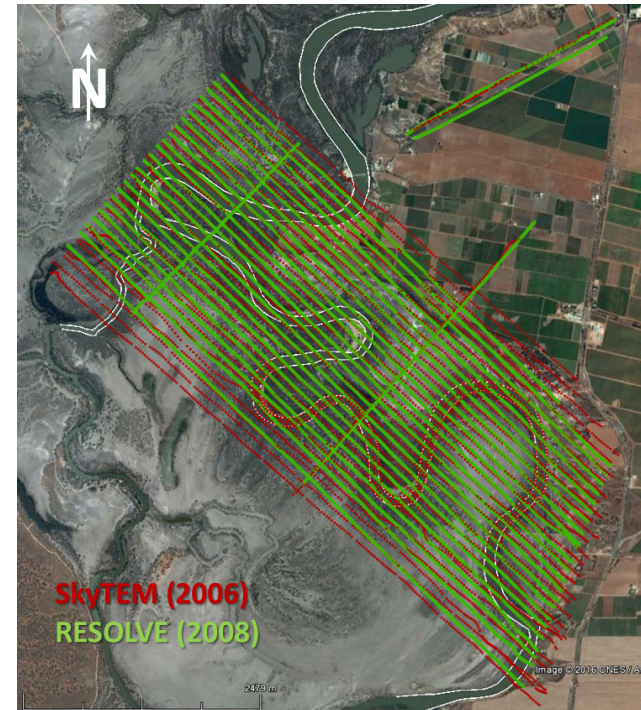


# Survey

## Resolve system (2008)



## Flight lines



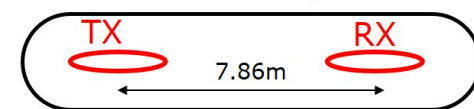
## Horizontal Co-planar (HCP) frequencies:

- 382, 1822, 7970, 35920 and 130100 Hz

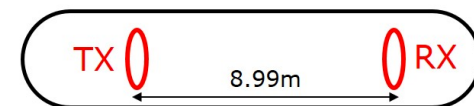
## Vertical Co-axial (VCA) frequencies:

- 3258 Hz

## Horizontal Co-planar



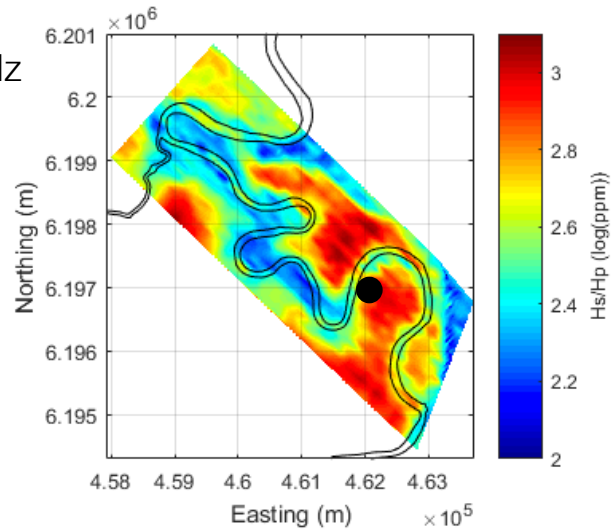
## Vertical Co-axial



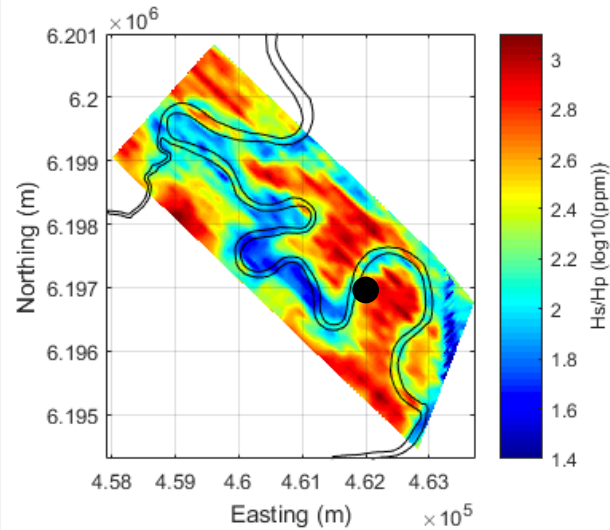
# Horizontal Co-planar (HCP) data

In-Phase (Real)

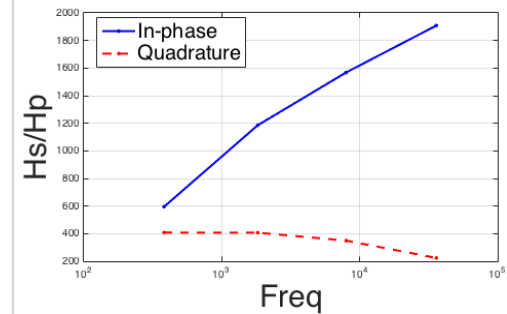
382 Hz



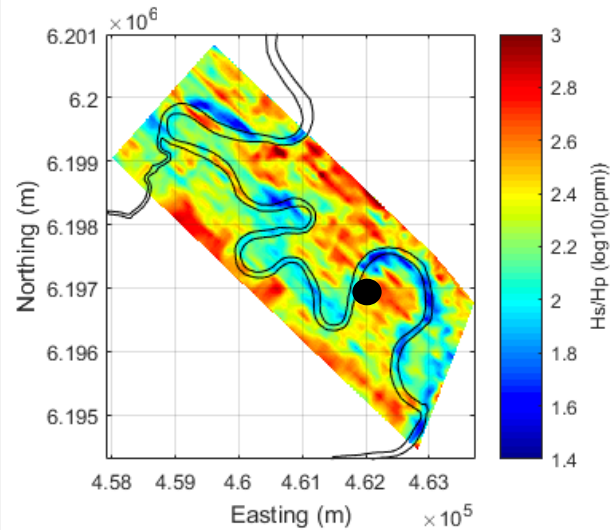
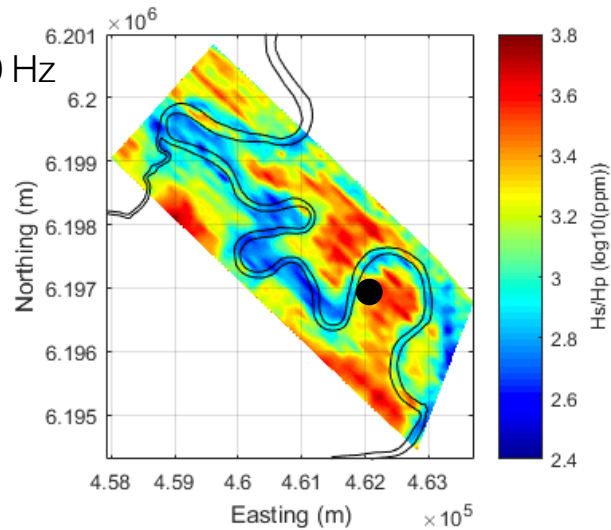
Quadrature (Imaginary)



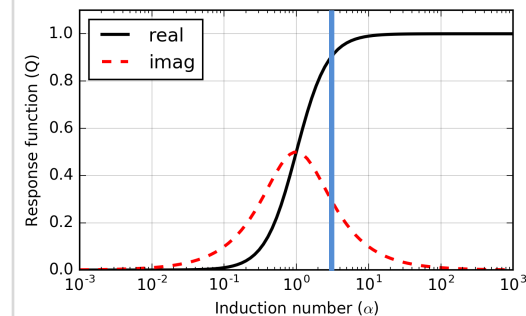
Sounding curve



35920 Hz

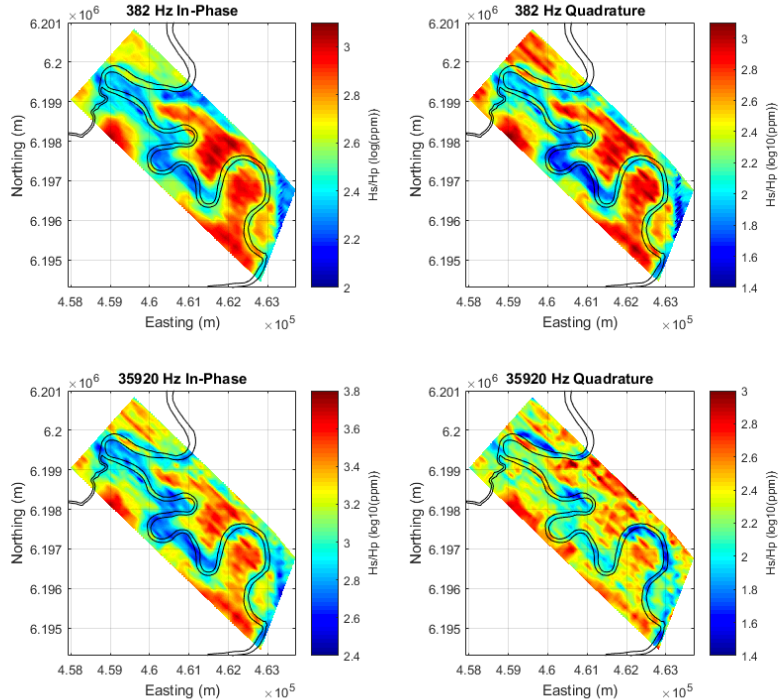


Response curve

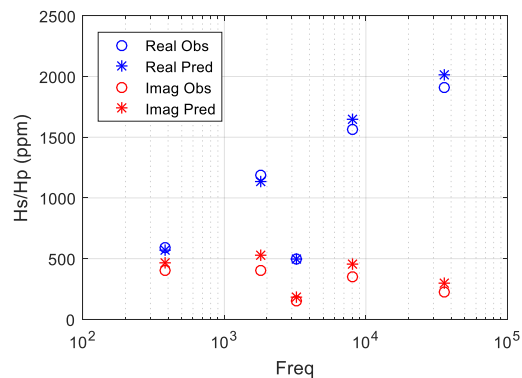


# Processing: 1D inversion

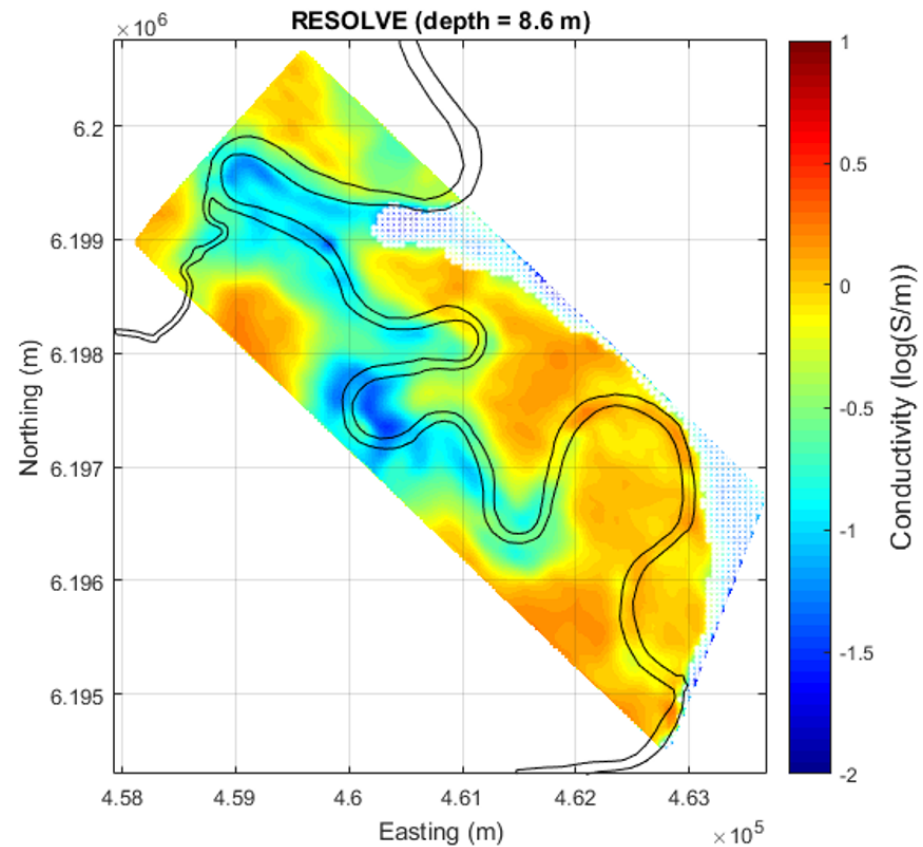
## Data



## Data fit

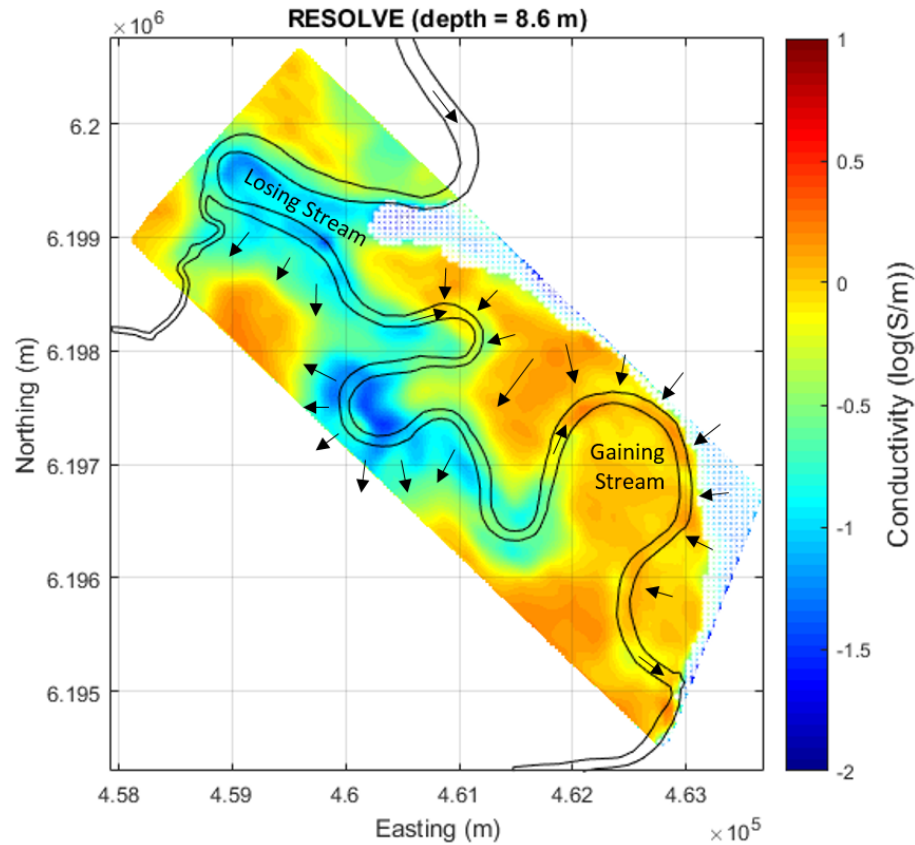


## Conductivity model (stitched)

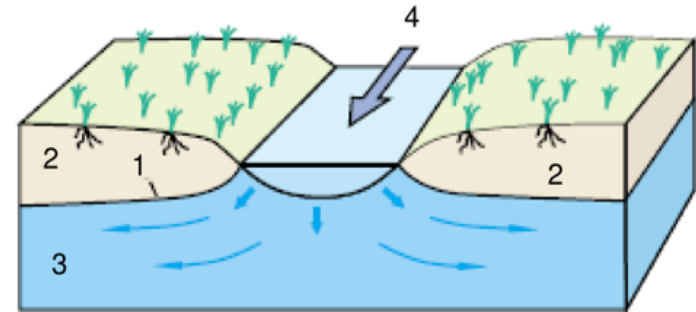


# Interpretation

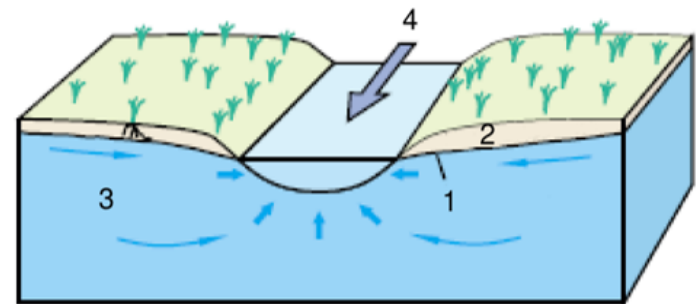
Conductivity model (stitched)



Losing Stream



Gaining Stream

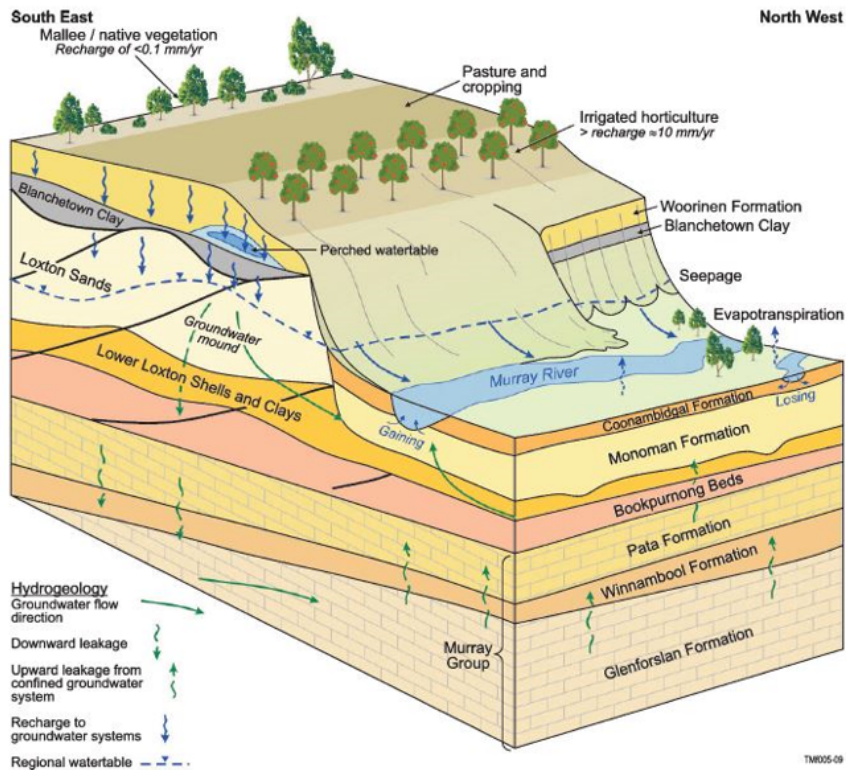


- 1 – Water table    2 – Unsaturated zone  
3 – Saturated zone    4 – Flow direction

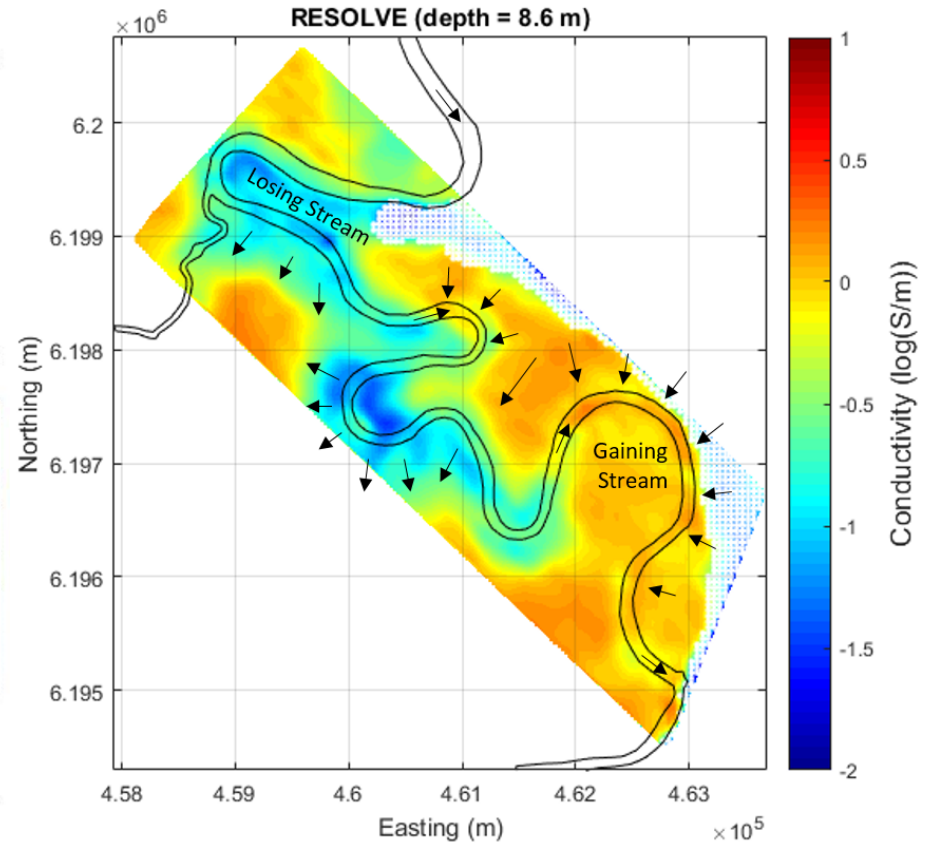


# Synthesis

## Hydrological model



## Conductivity model (stitched)



# Outline

## Setup

- Basic experiment
- Transmitters, Receivers

## Frequency Domain EM

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

## Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Case History – Oil and gas

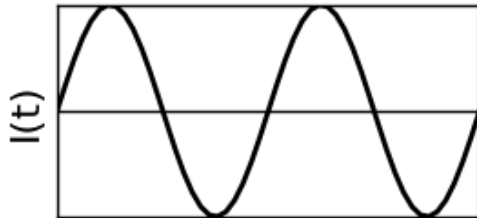


# EM with Inductive Sources

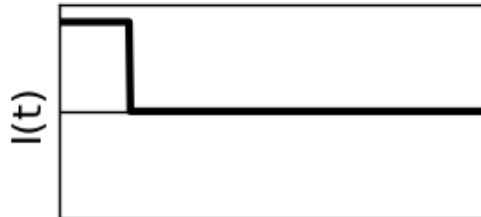
- Induction principles are the same for
  - FDEM: Frequency domain EM
  - TDEM: Time domain EM

Transmitter current

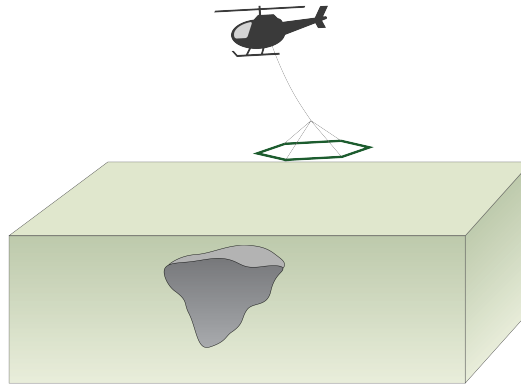
FDEM



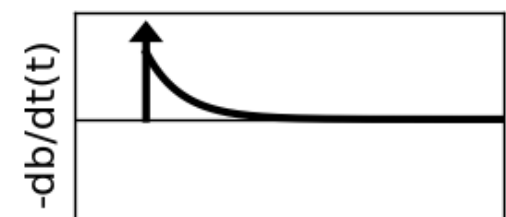
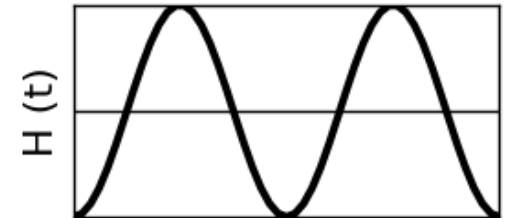
TDEM



Time



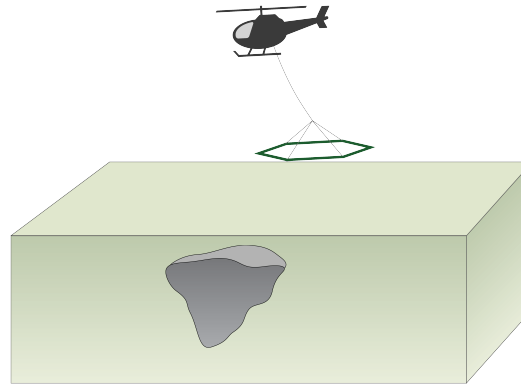
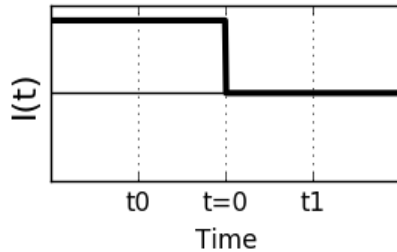
Receiver



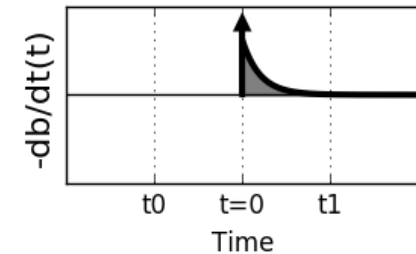
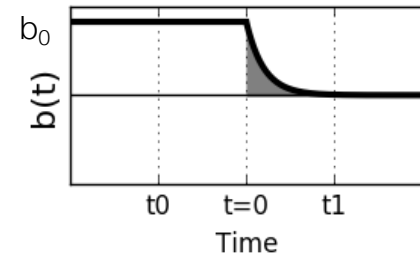
Time

# EM with Inductive Sources: Time Domain

Transmitter current



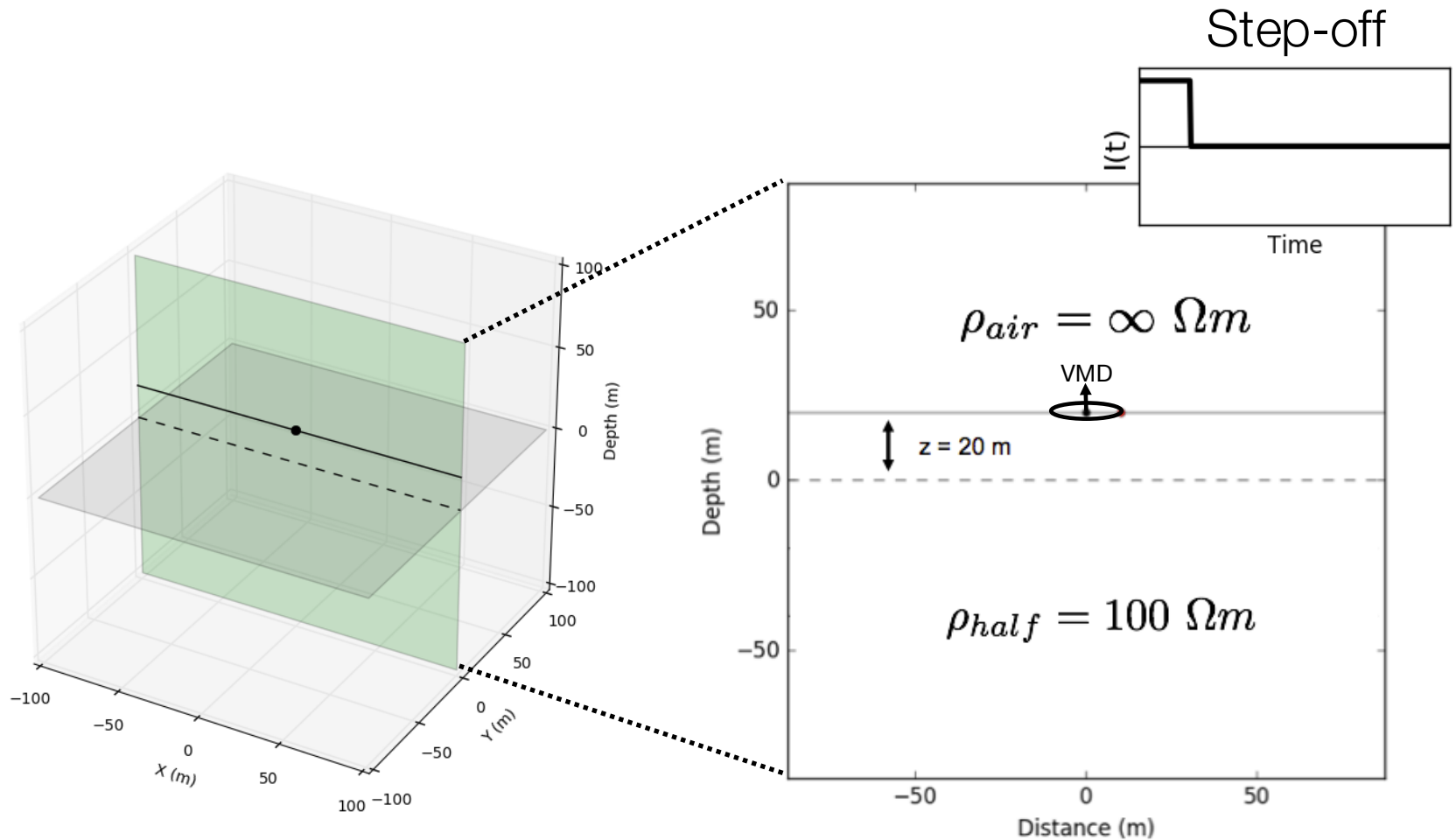
Receiver



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

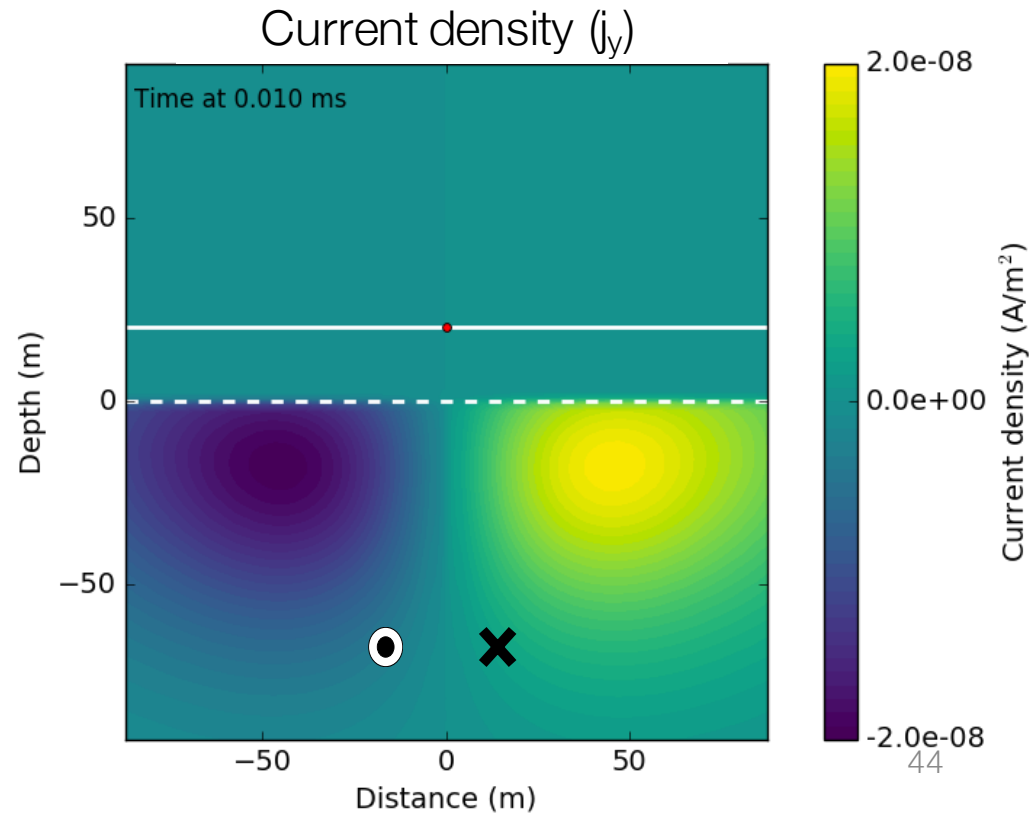
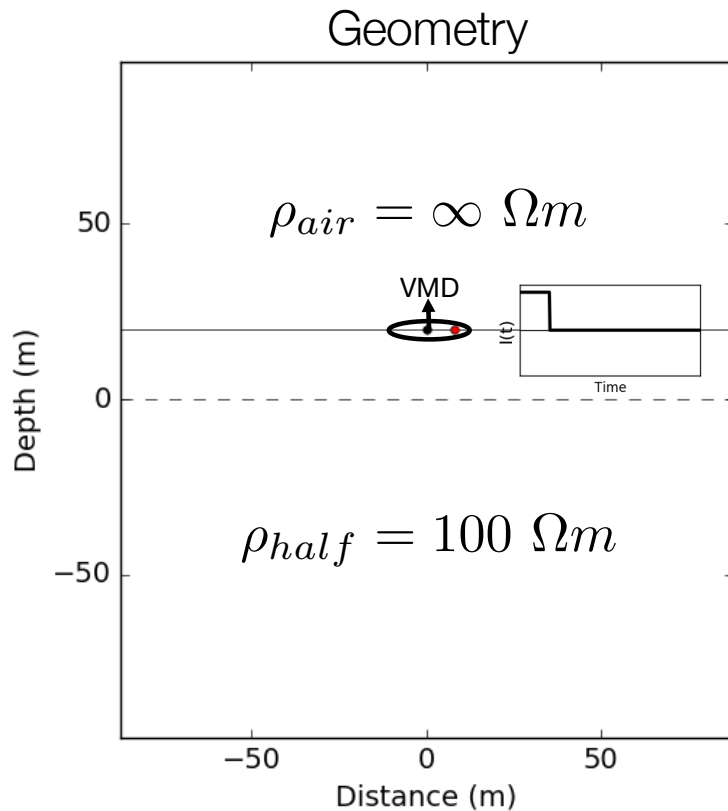
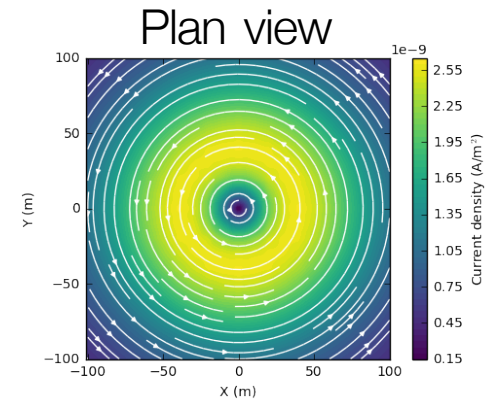
$\delta(t)$ : Dirac-delta function

# Vertical Magnetic Dipole over a halfspace (TDEM)



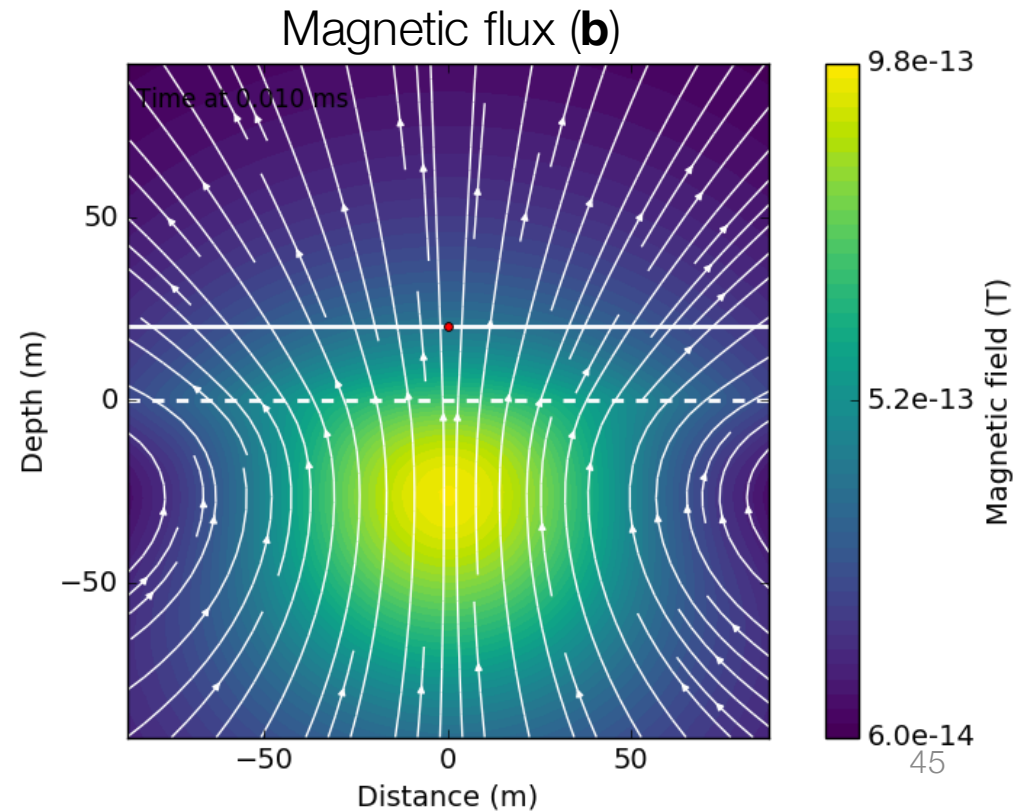
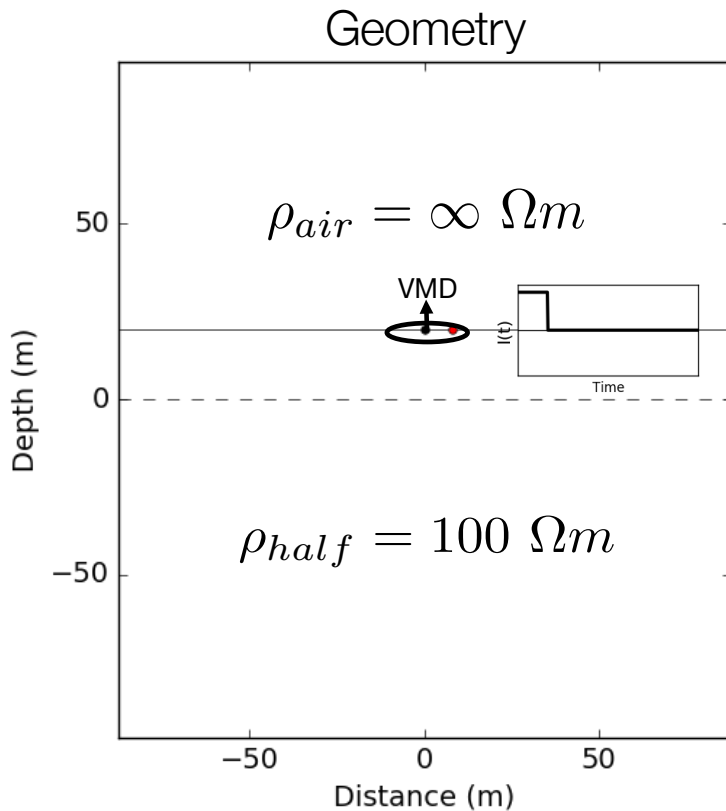
# Current Density

- Time: 0.01ms



# Magnetic flux density

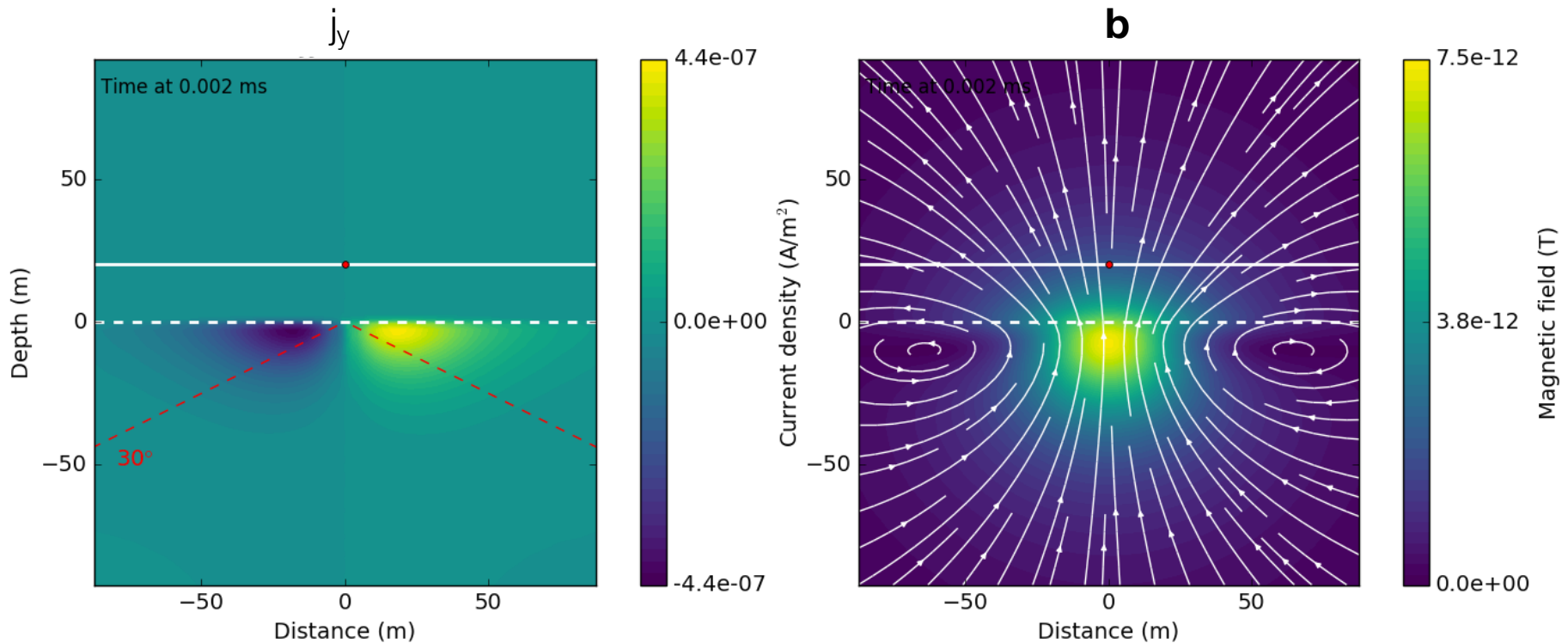
- Time: 0.01ms



# Propagation through time

- Time: 0.002ms
- diffusion distance = 18 m

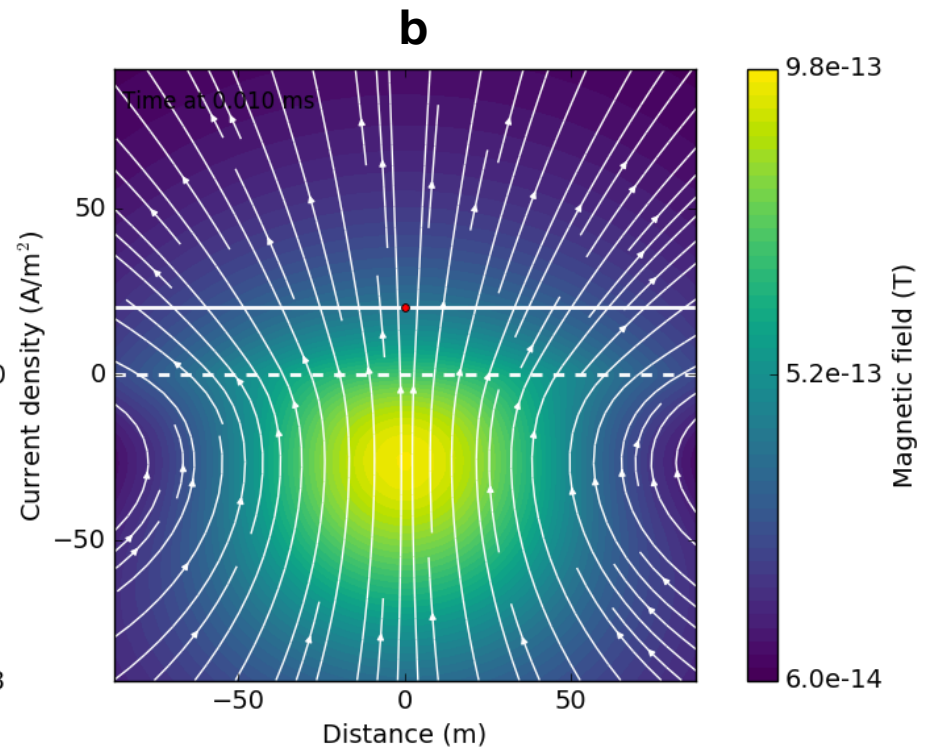
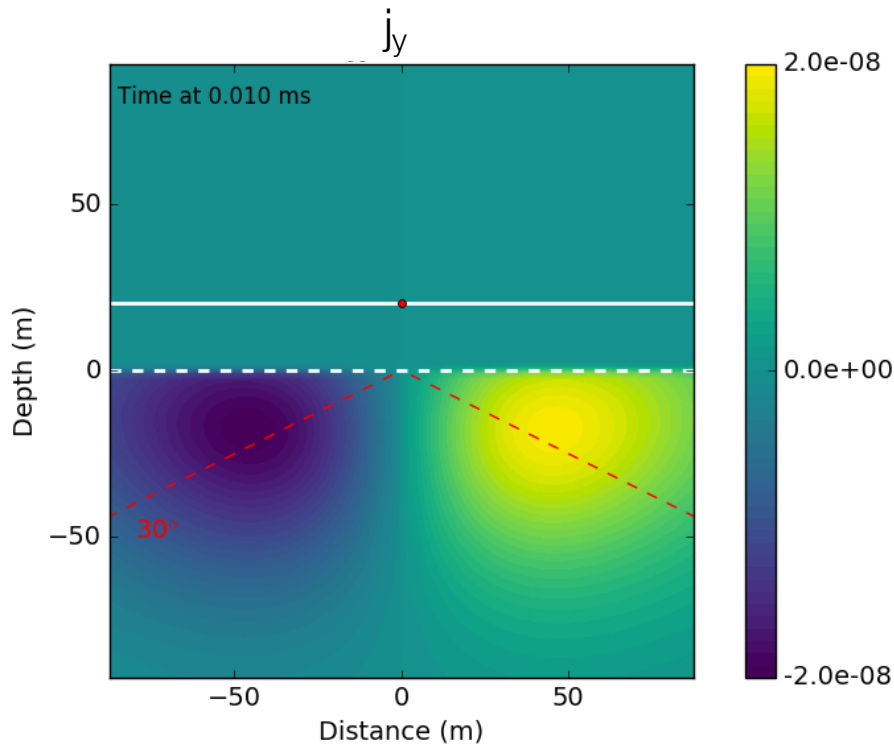
$$d = 1260\sqrt{t\rho}$$



# Propagation through time

- Time: 0.01ms
- diffusion distance = 38 m

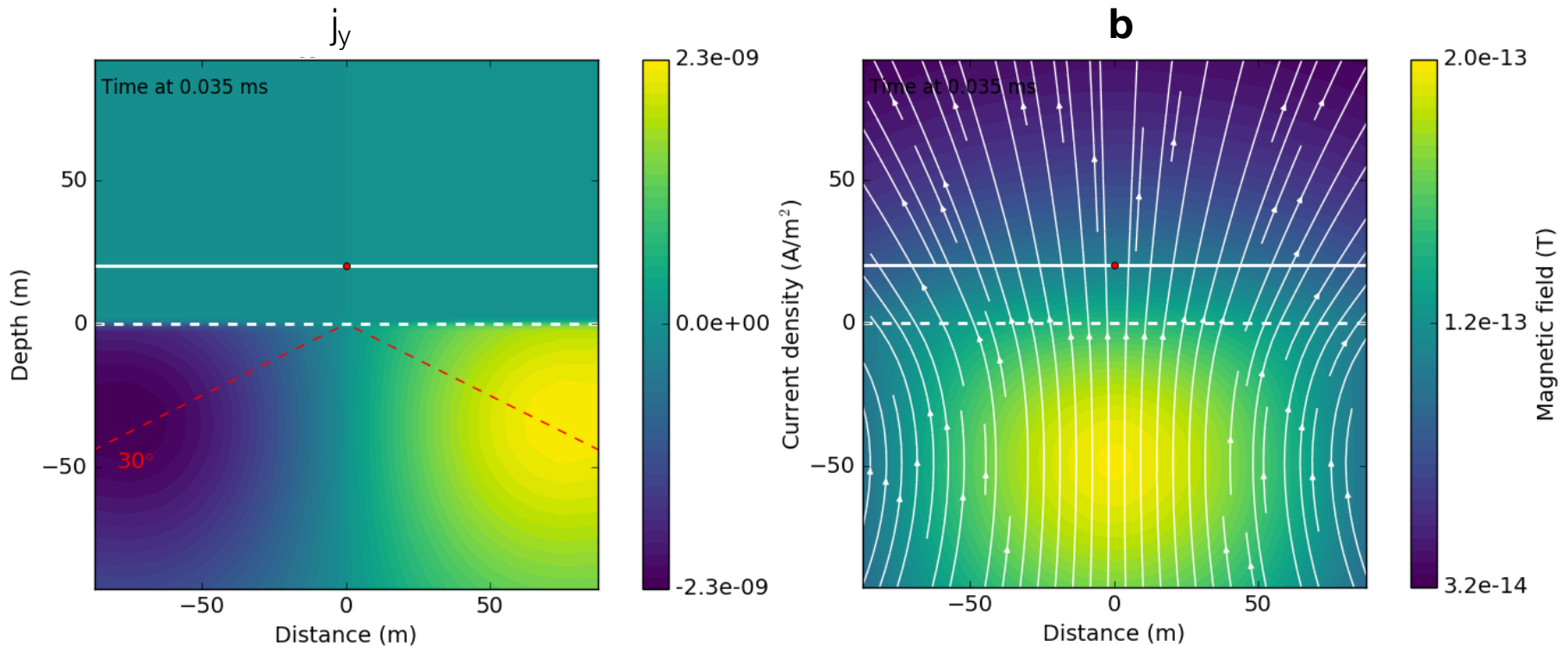
$$d = 1260\sqrt{t\rho}$$



# Propagation through time

- Time: 0.035ms
- diffusion distance = 75 m

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

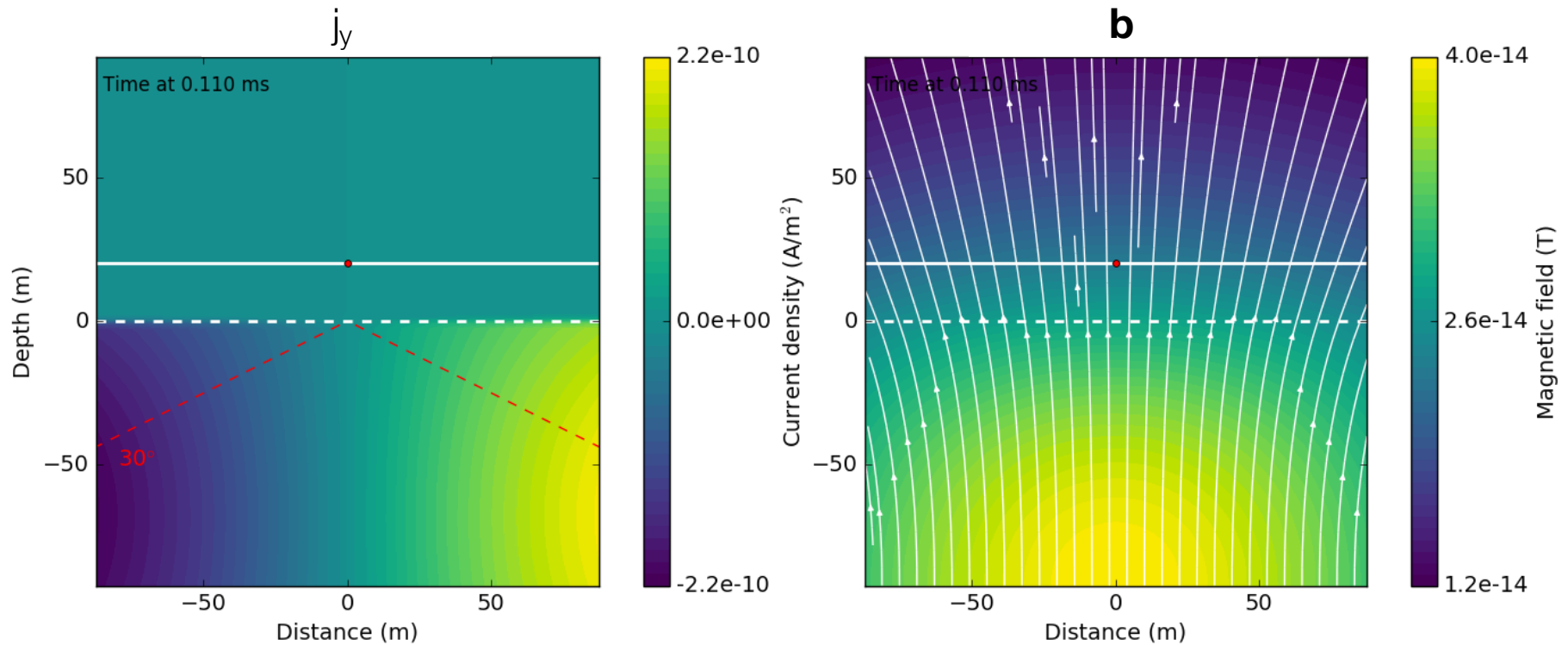




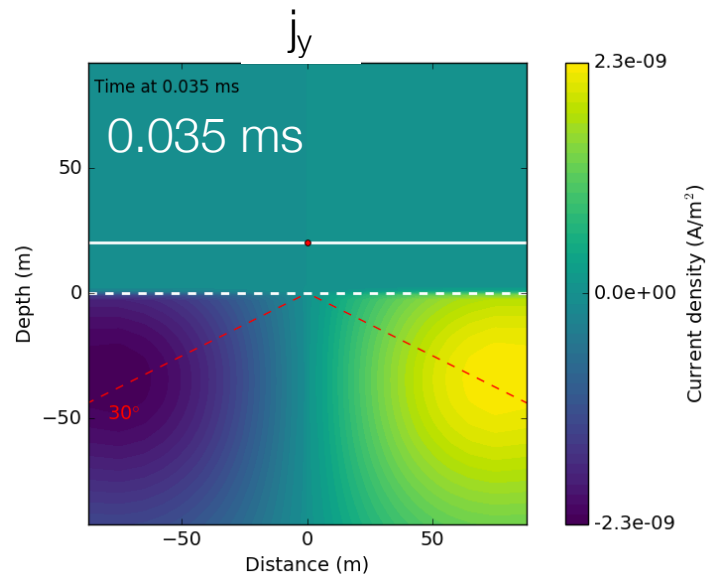
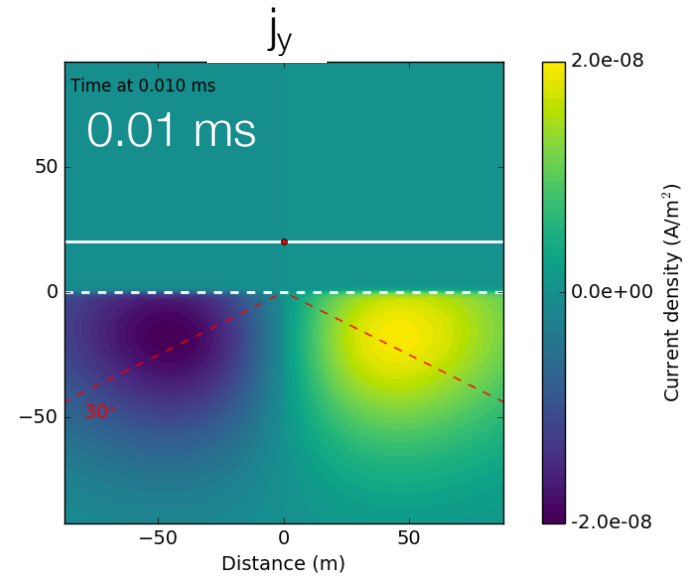
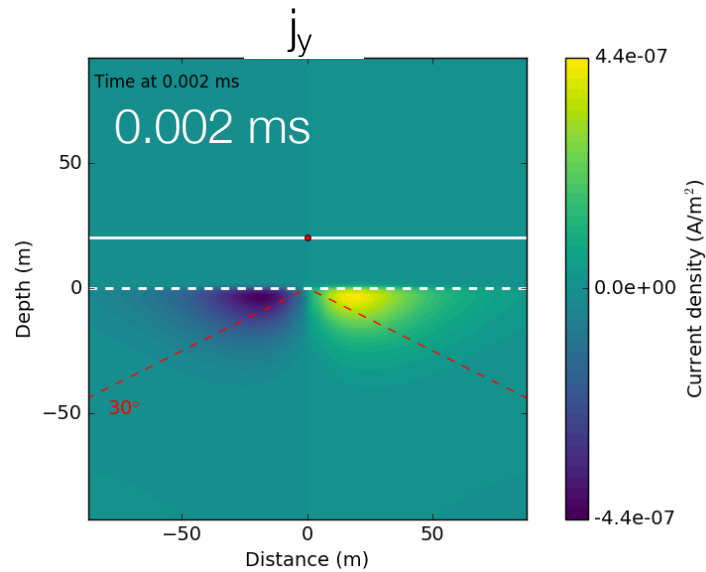
# Propagation through time

- Time: 0.110ms
- diffusion distance = 132 m

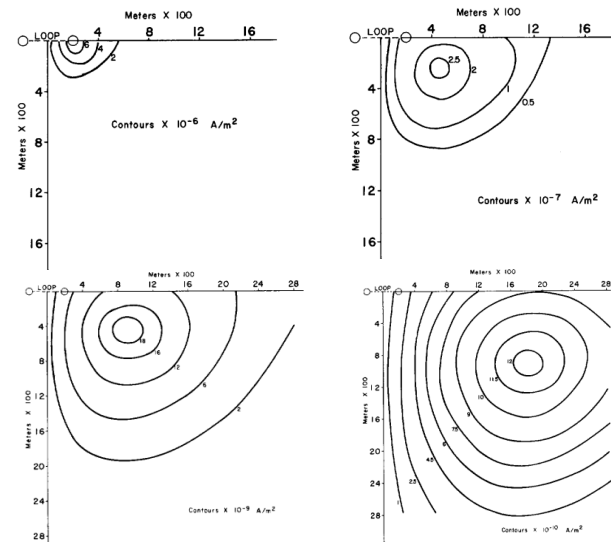
$$d = 1260\sqrt{t\rho}$$



# Summary: propagation through time



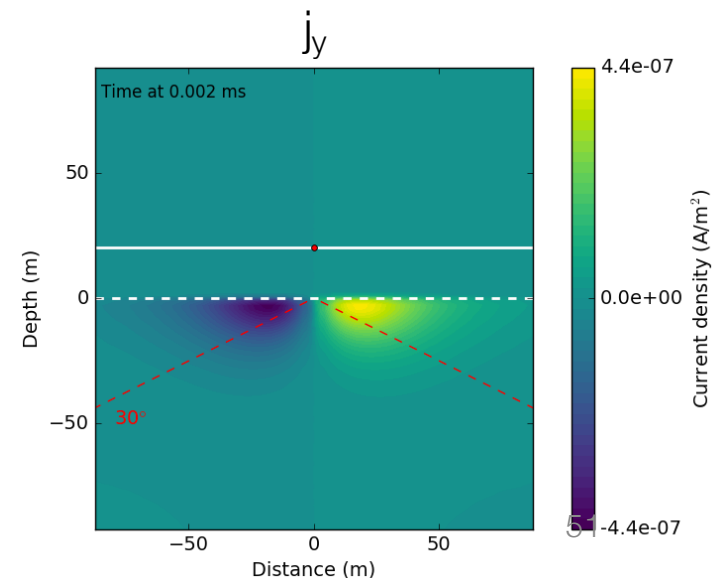
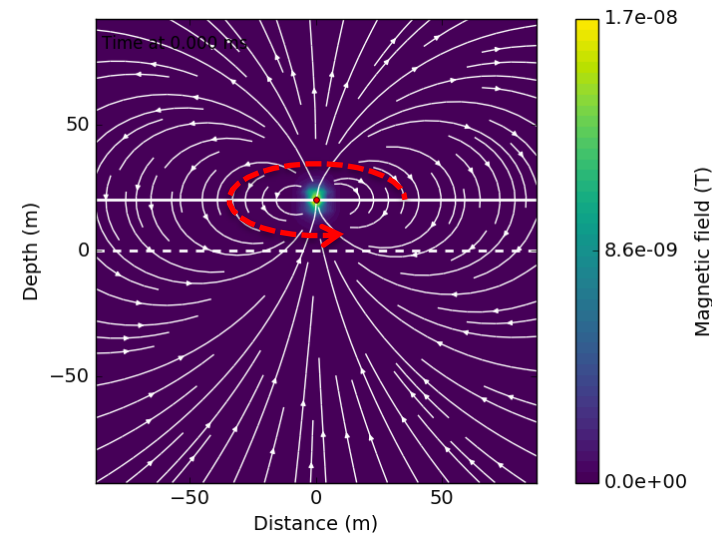
Nabighian (1979)



# 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

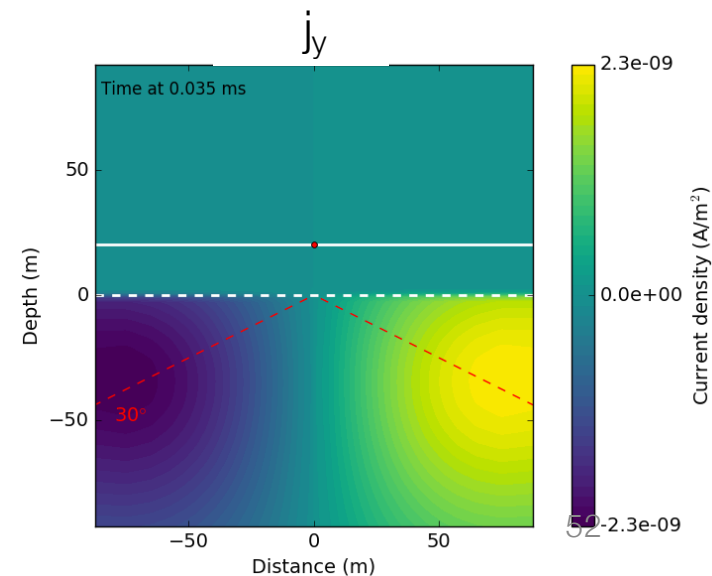
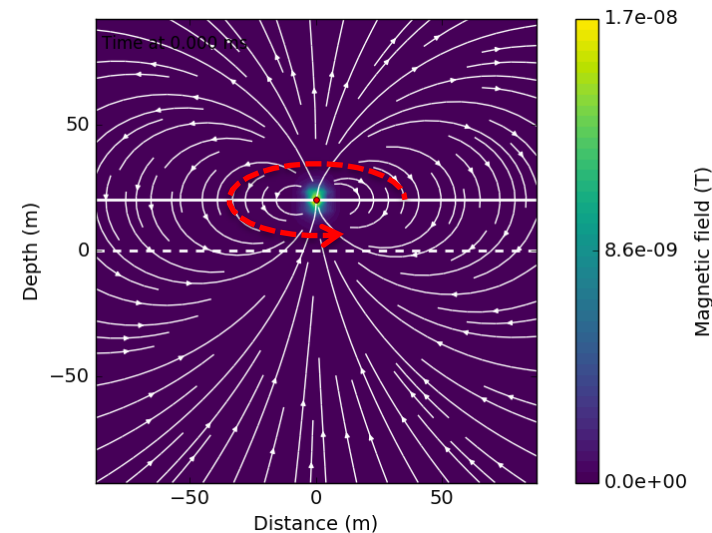
magnetic field (on-time)



# Important points

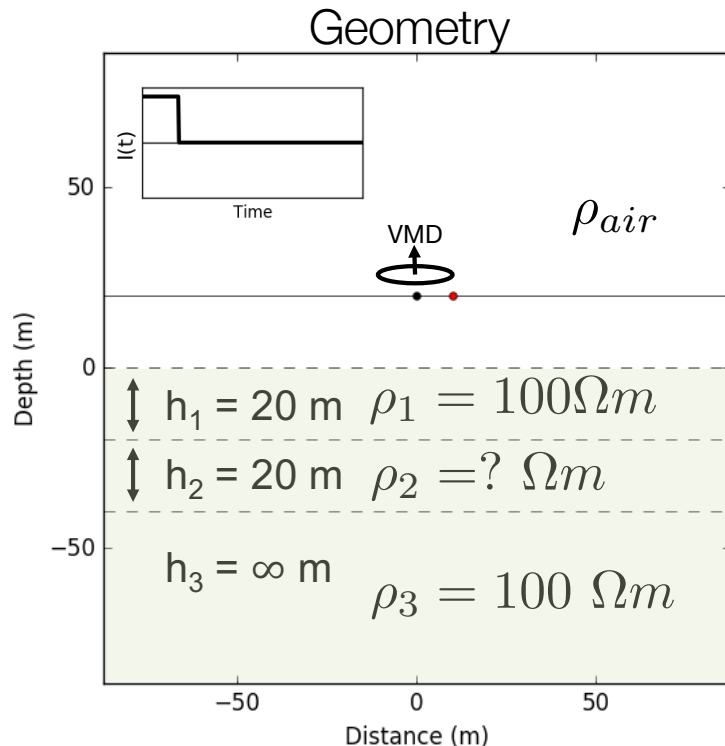
- Currents flow in same plane as transmitter currents
- Currents diffuse outward downward
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magnetic field (on-time)



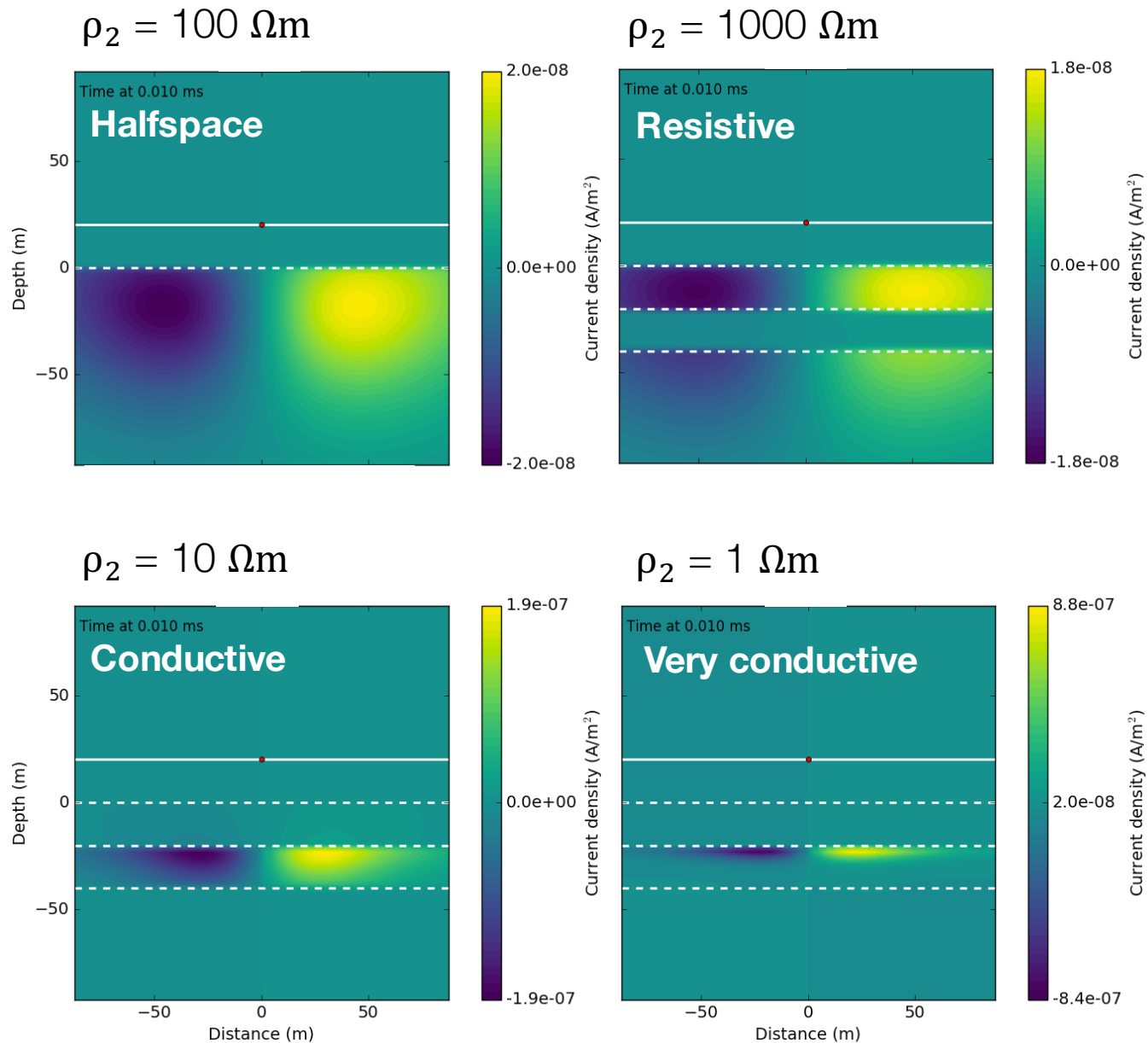
# Layered earth

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



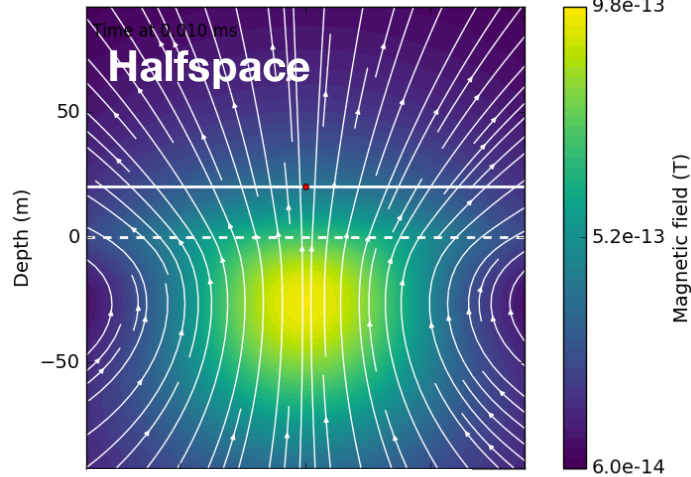
- Four different cases:
  - Halfspace
    - $\rho_2 = 100 \Omega m$
  - Resistive
    - $\rho_2 = 1000 \Omega m$
  - Conductive
    - $\rho_2 = 10 \Omega m$
  - Very conductive
    - $\rho_2 = 1 \Omega m$
- Fields
  - $j_y$  off-time
  - **b** off-time

# Layered earth currents ( $j_y$ )

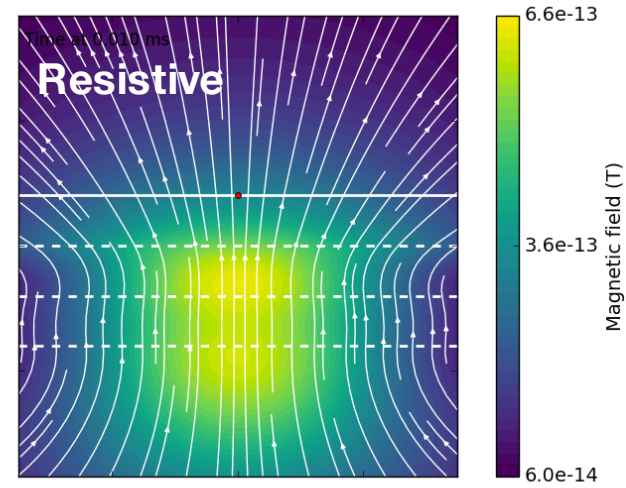


# Layered earth mag. fields (**b**)

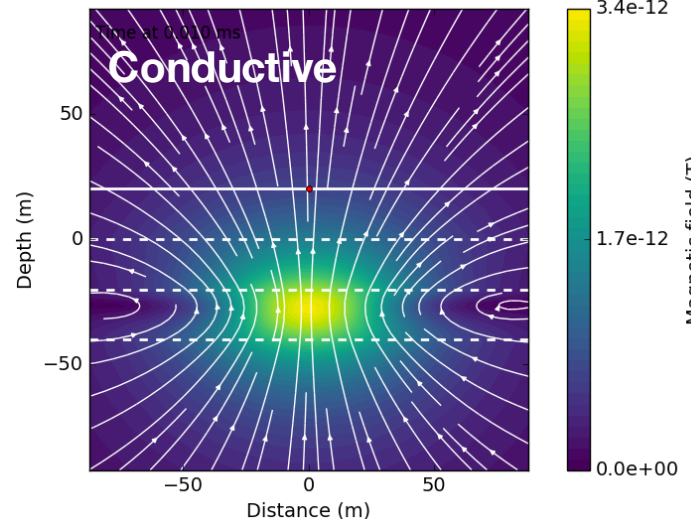
$\rho_2 = 100 \Omega\text{m}$



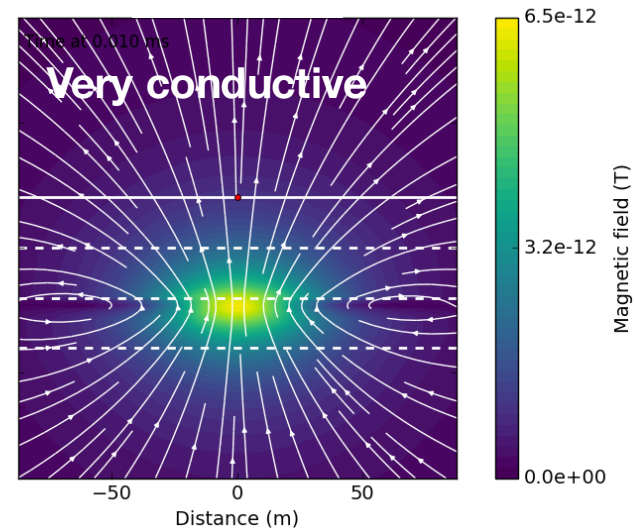
$\rho_2 = 1000 \Omega\text{m}$



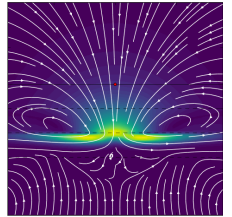
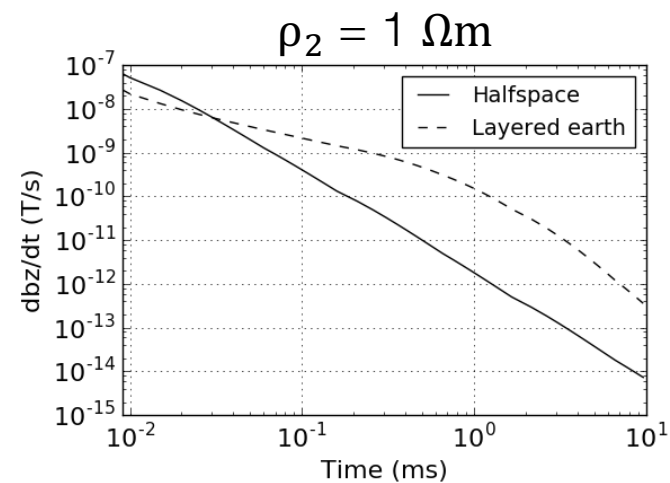
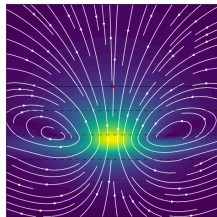
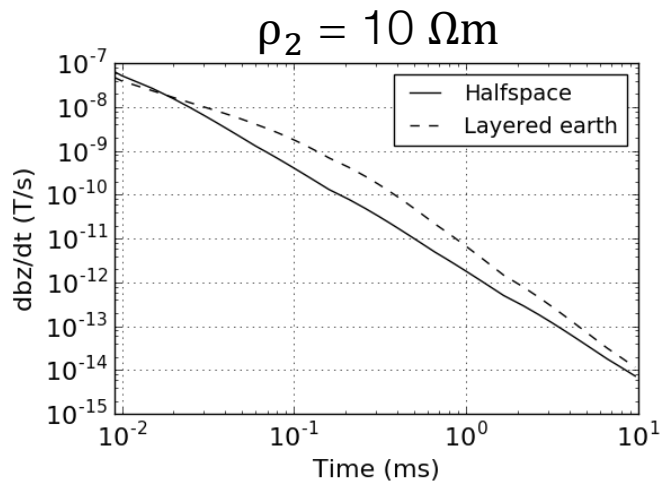
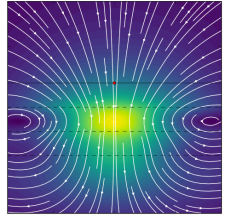
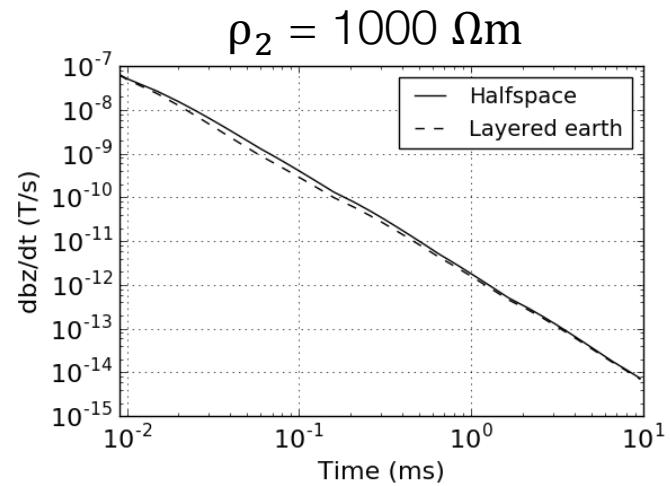
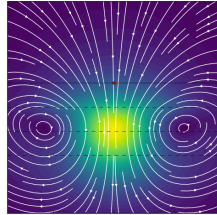
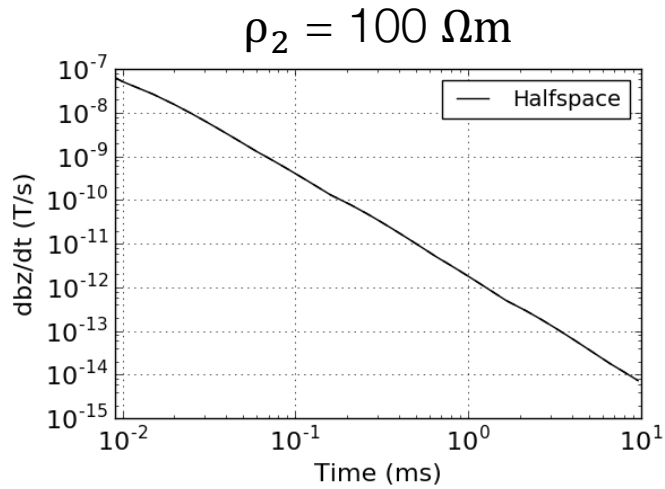
$\rho_2 = 10 \Omega\text{m}$



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



# $db_z/dt$ sounding curves

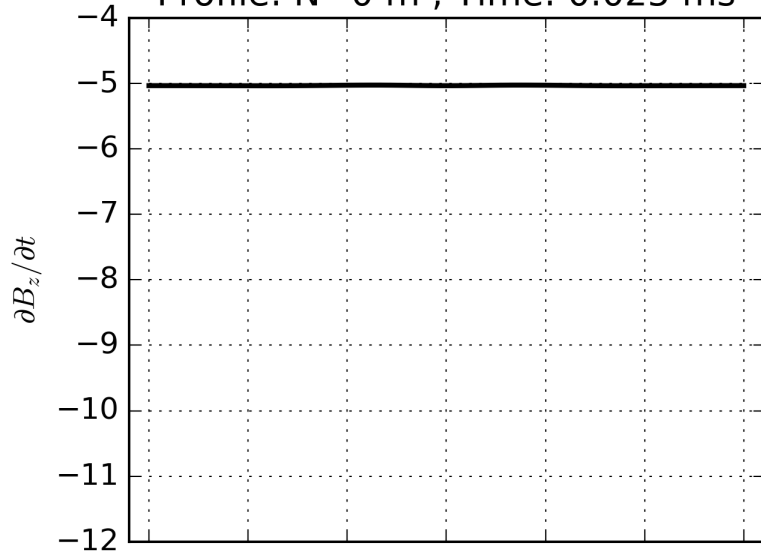




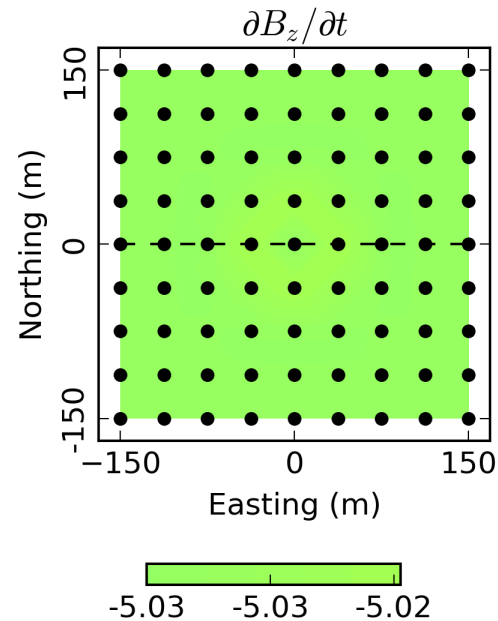
# Airborne example: conductive sphere

Data profile

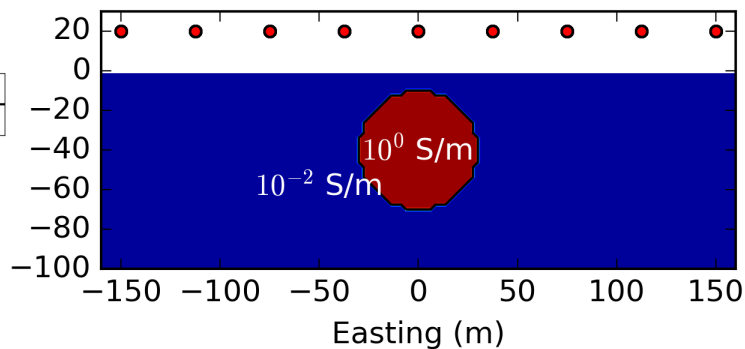
Profile: N=0 m , Time: 0.025 ms



Data map



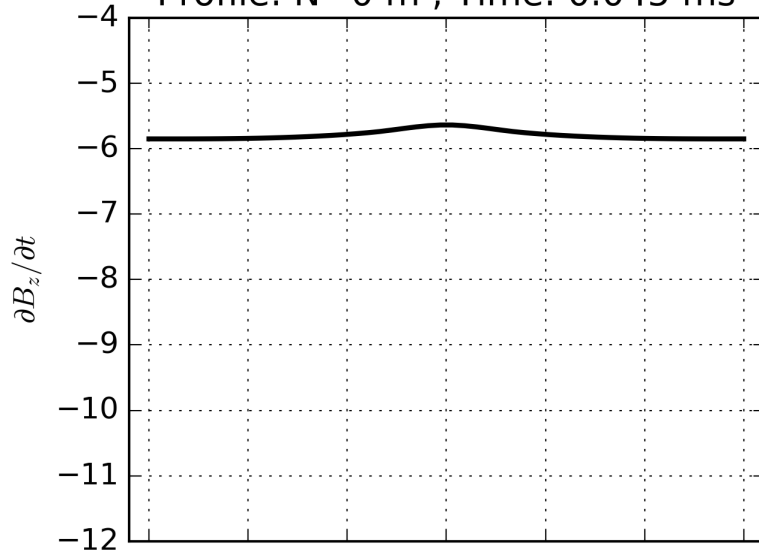
Conductivity



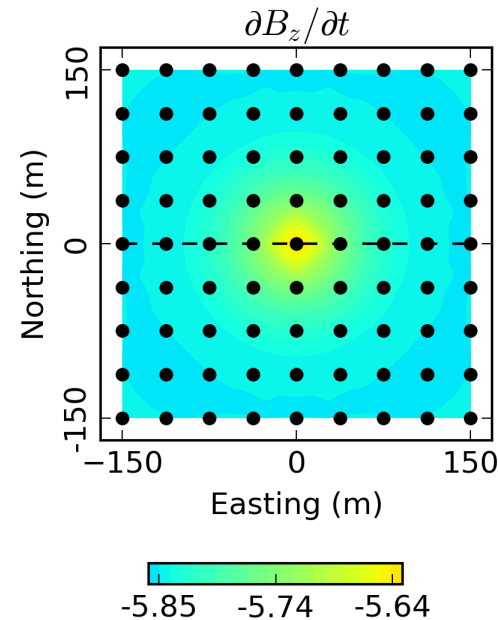
# Airborne example: conductive sphere

Data profile

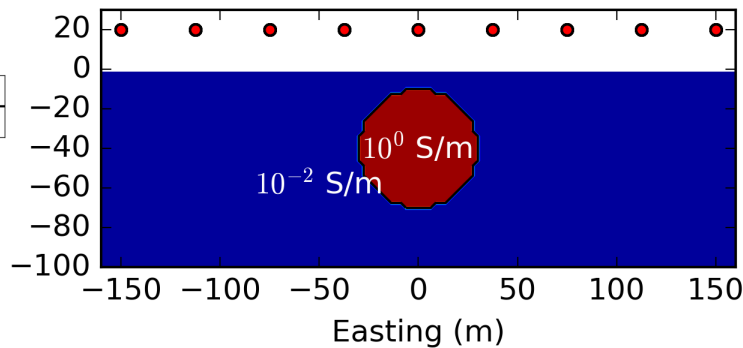
Profile: N=0 m , Time: 0.045 ms



Data map



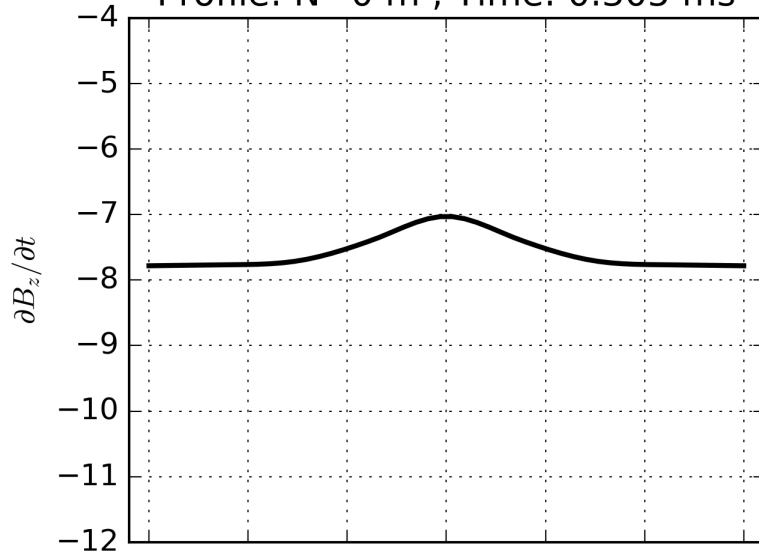
Conductivity



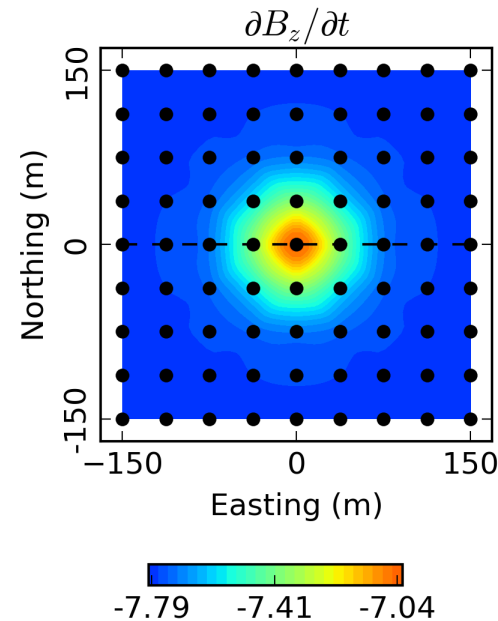
# Airborne example: conductive sphere

Data profile

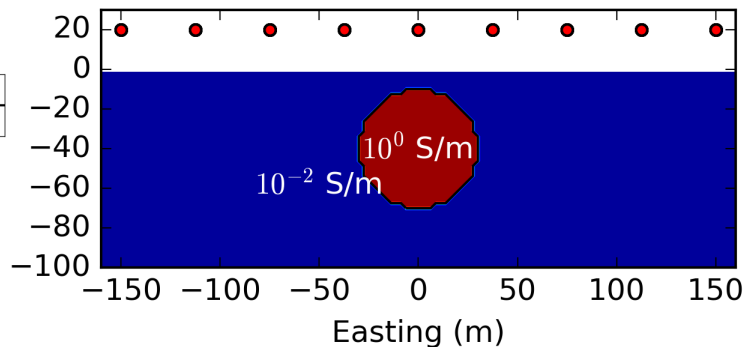
Profile: N=0 m , Time: 0.305 ms



Data map



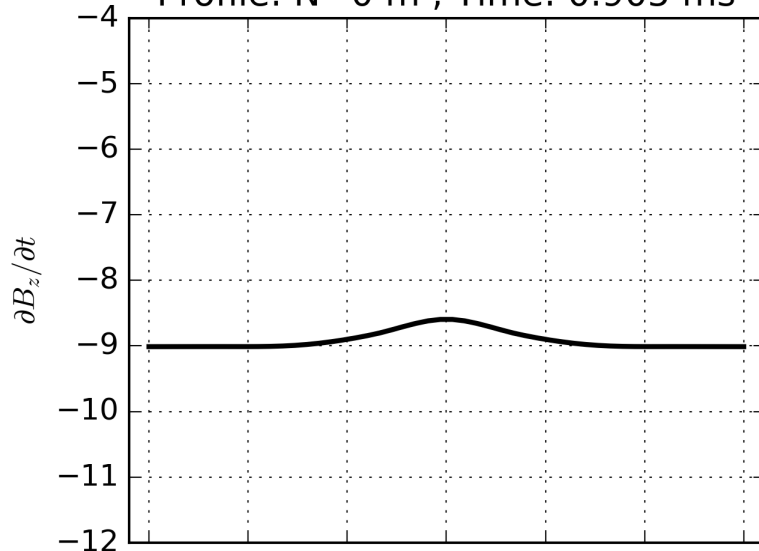
Conductivity



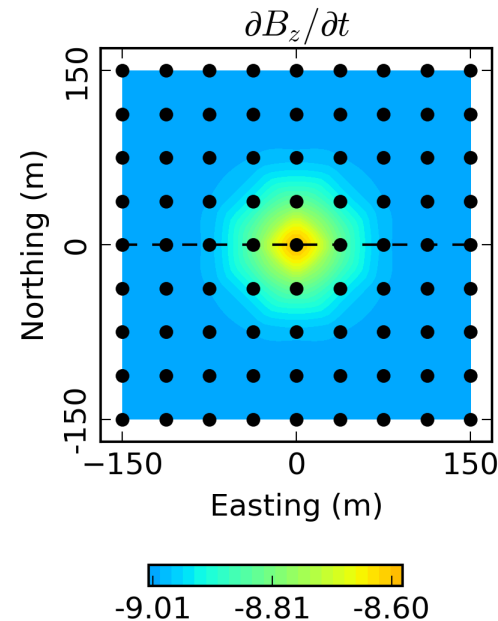
# Airborne example: conductive sphere

Data profile

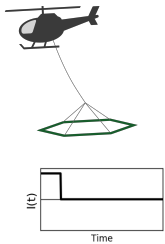
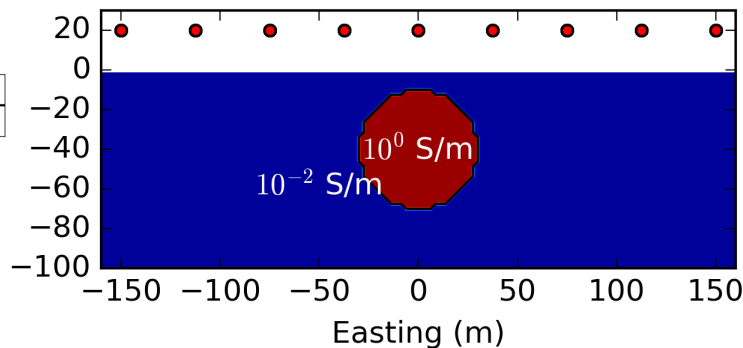
Profile: N=0 m , Time: 0.905 ms



Data map



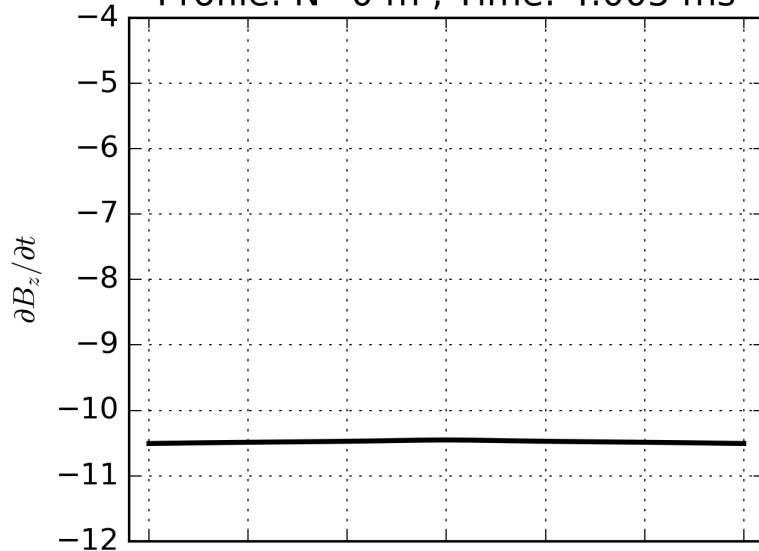
Conductivity



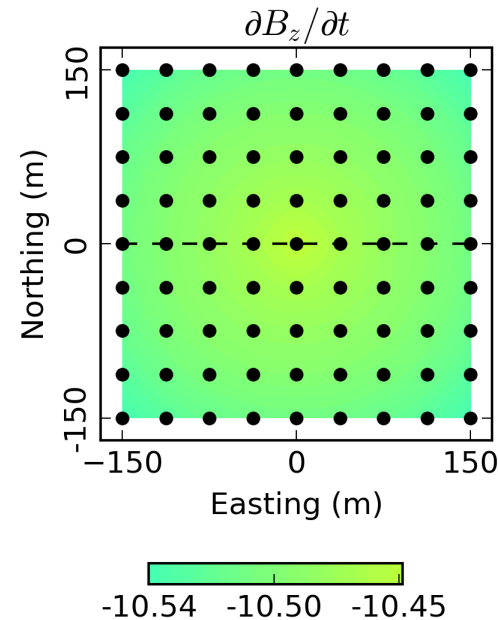
# Airborne example: conductive sphere

Data profile

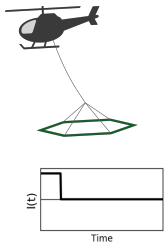
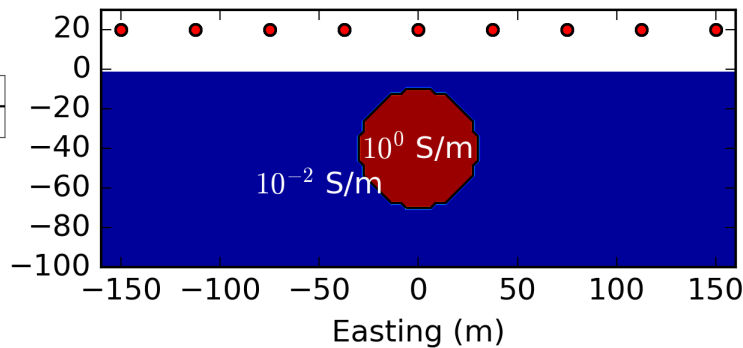
Profile: N=0 m , Time: 4.005 ms



Data map

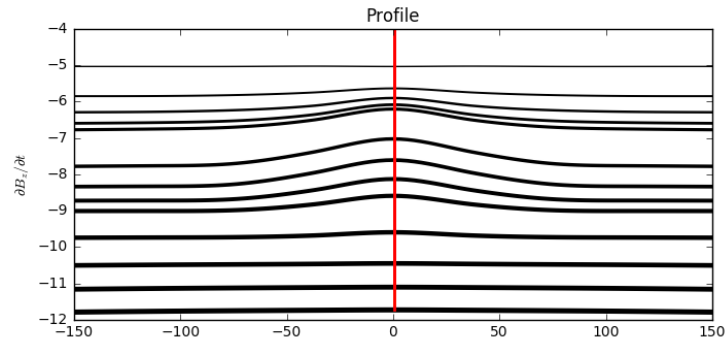


Conductivity

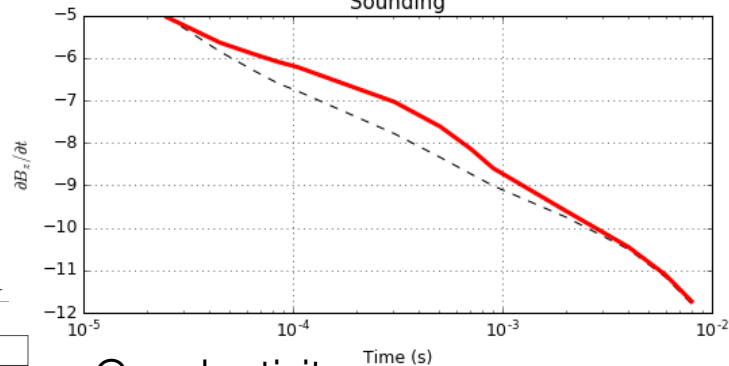


# Summary: airborne example

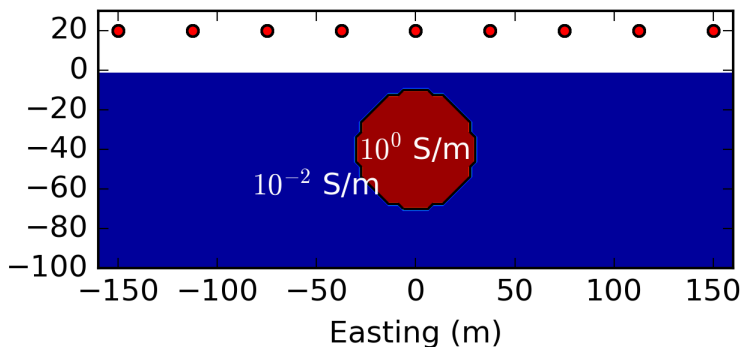
Data profile



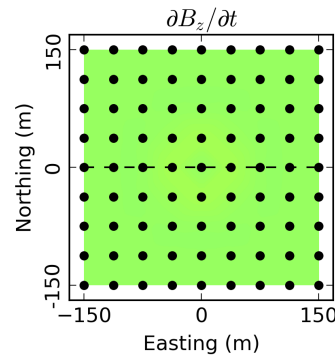
Sounding



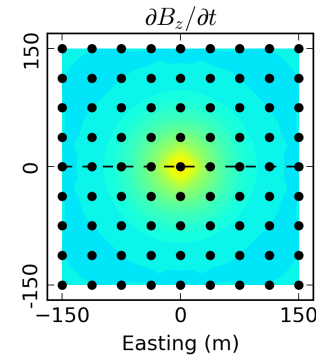
Conductivity



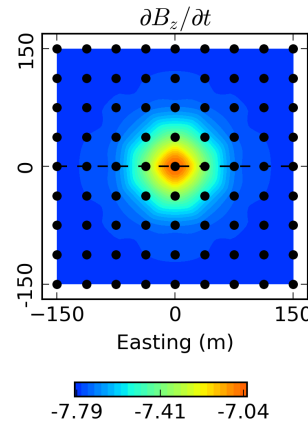
0.025 ms



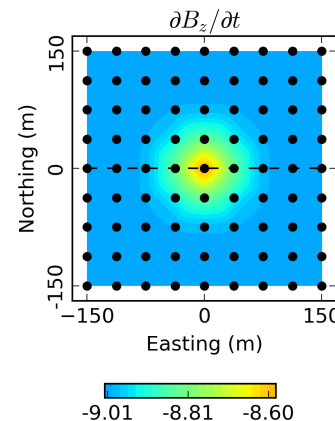
0.045 ms



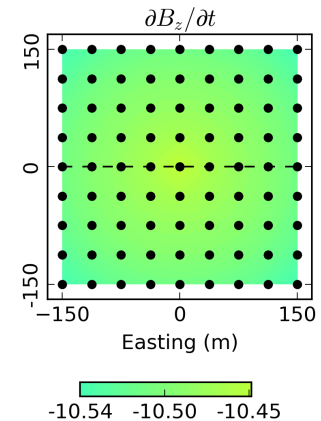
0.305 ms



0.905 ms



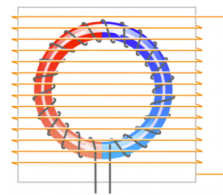
4.005 ms



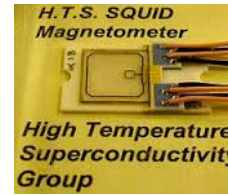
# TDEM Receiver

## Magnetometer

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



Fluxgate



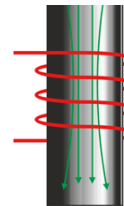
Squid

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

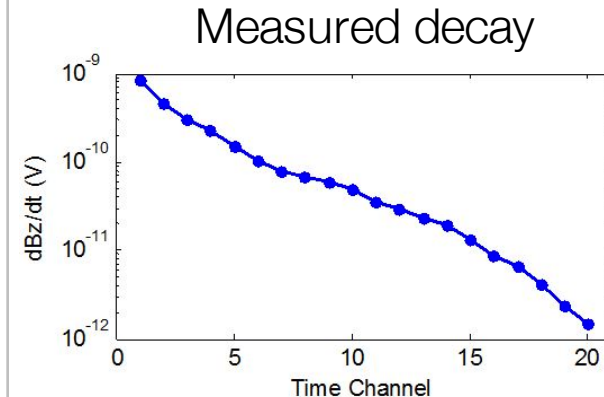
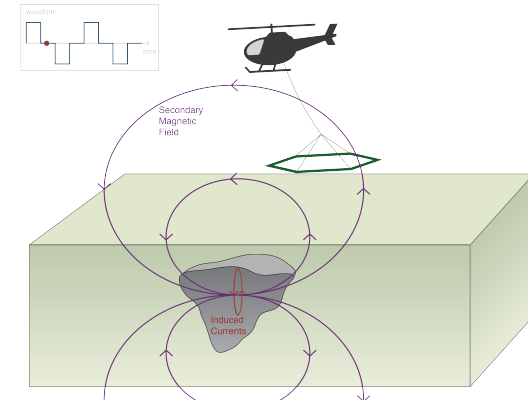
## Coil

- Measures:
  - Voltage
  - Single component that depends on coil orientation
    - Coupling matters
- Airborne TDEM: measure  $db/dt$

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

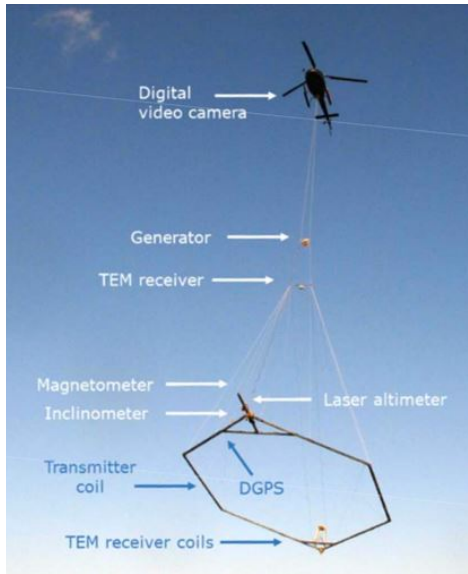


Coil



# Some Airborne TDEM Systems

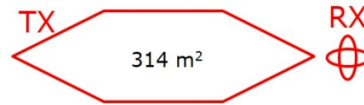
## SkyTEM (2006)



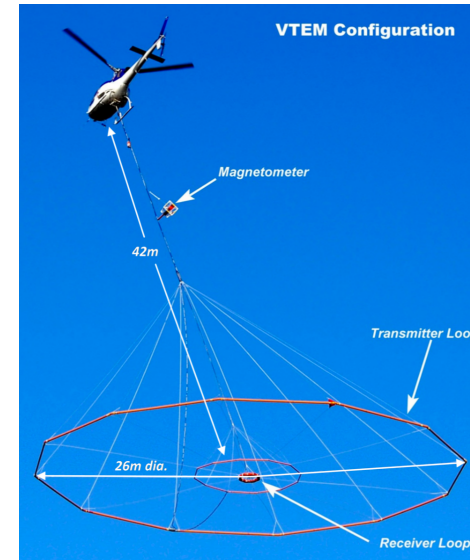
Area = 314 m<sup>2</sup>

Peak dipole moment:

- HM: 113040 NIA
- LM: 12560 NIA



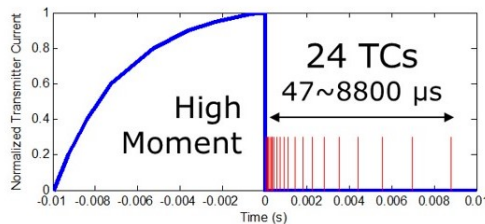
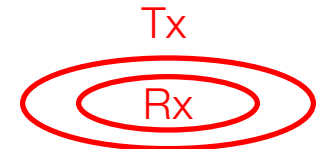
## VTEM (2007)



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

Peak dipole moment:

- 503,100 NIA

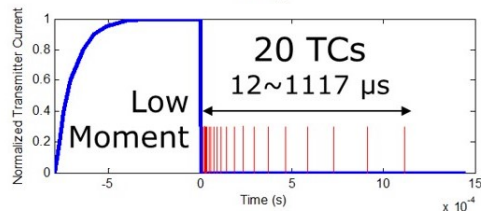


Peak current: 90 A

Turns: 4

On-time: 10 ms

Off-time: 10 ms

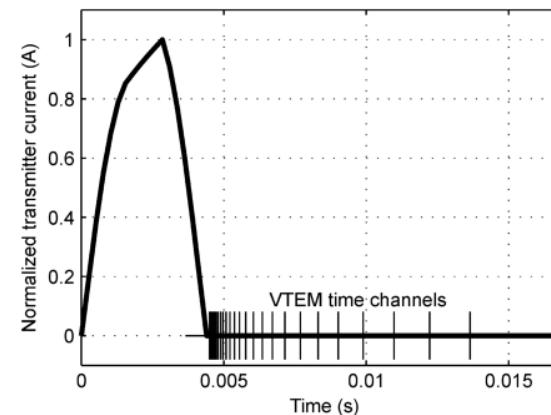


Peak current: 40 A

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

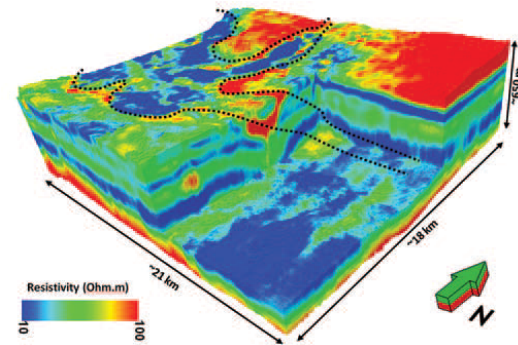
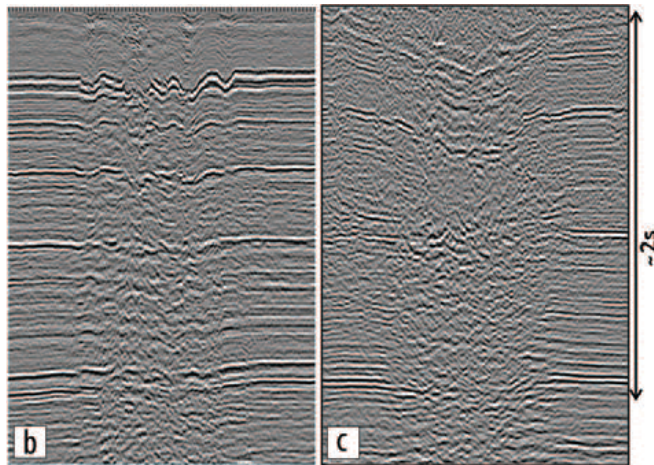
Frequency Domain EM

Time Domain EM

- Vertical Magnetic Dipole
- Propagation with Time
- Effects of Background Conductivity
- Transmitters and receivers
- Decay Curves
- Questions
- Case History – Oil and gas

# Case History: Wadi Sahba

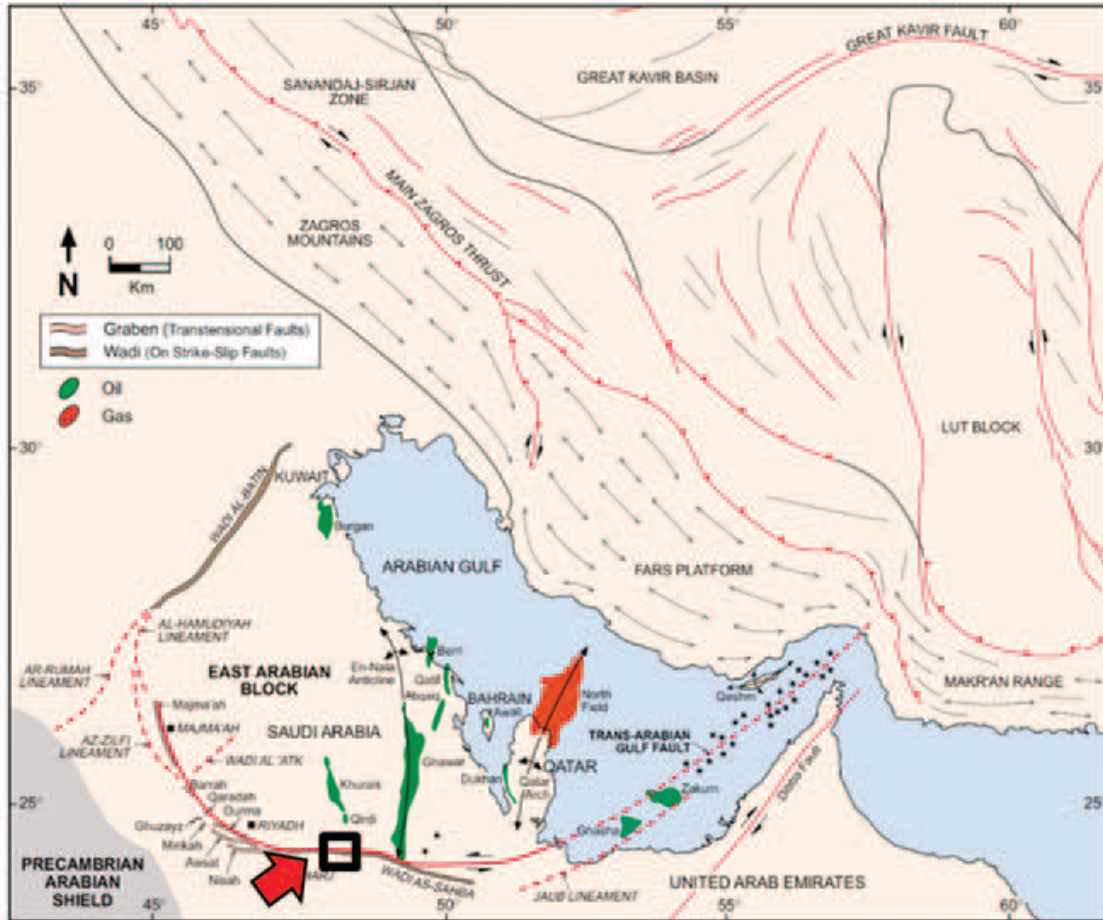
Colombo et al. 2016



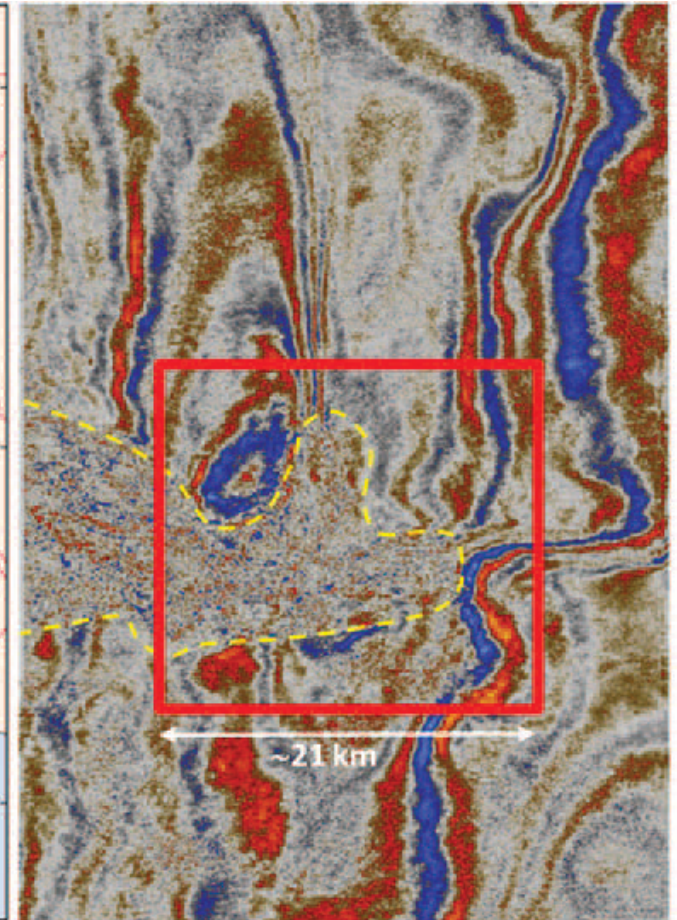
?

# Setup

Location of Wadi area, Saudi Arabia



Seismic slice

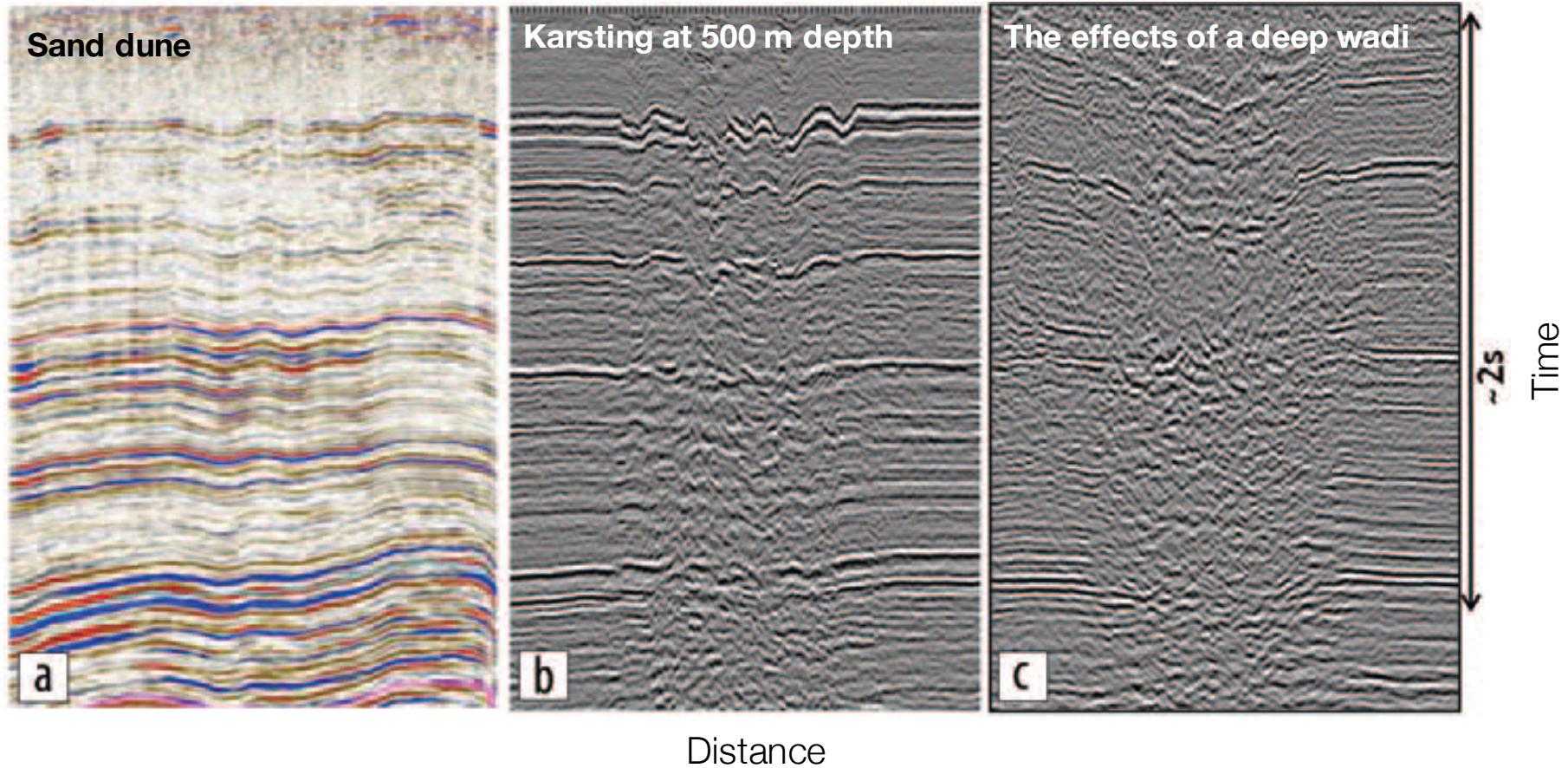


- Oil and gas exploration in the Middle East: Major structures to stratigraphic traps and low relief structures



# 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

$\phi$ : porosity

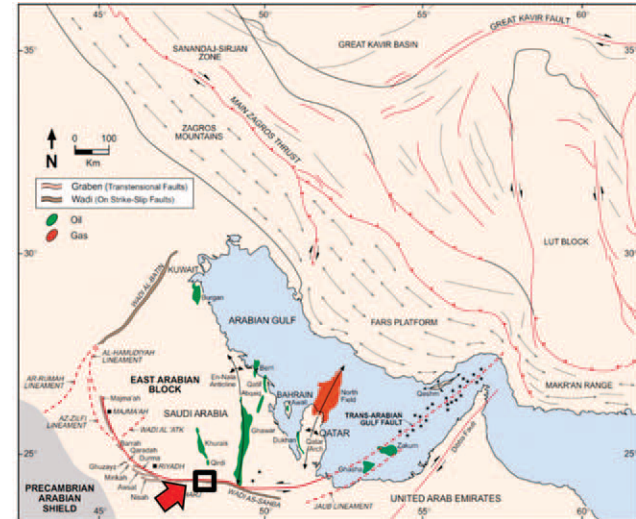
- Poor seismic data:

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

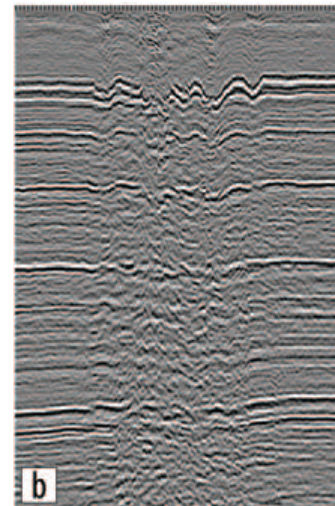
- From previous multi-physics analyses:

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

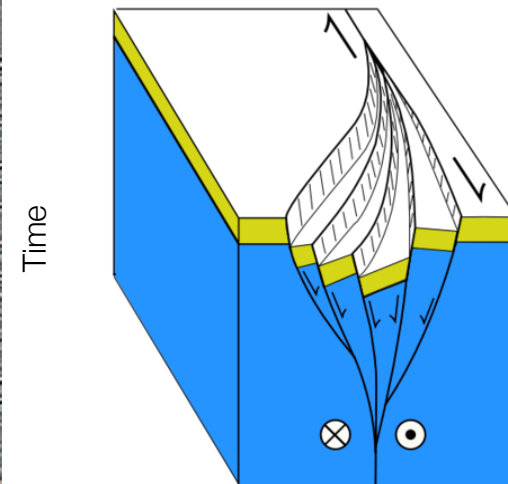
Geologic map



Seismic section



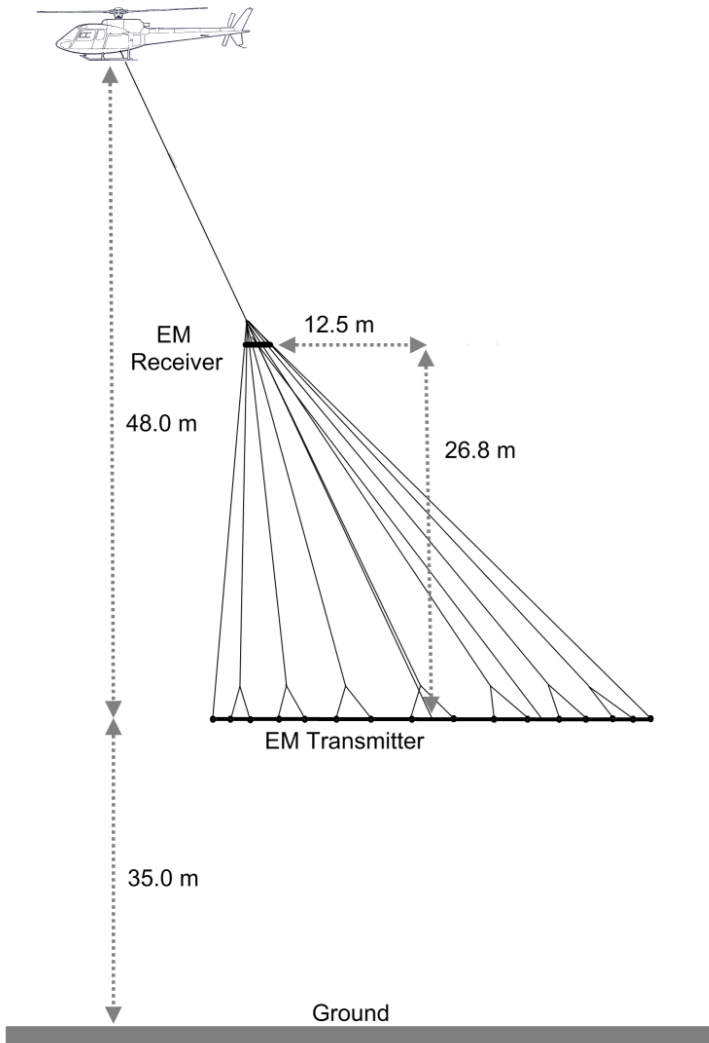
Flower faults



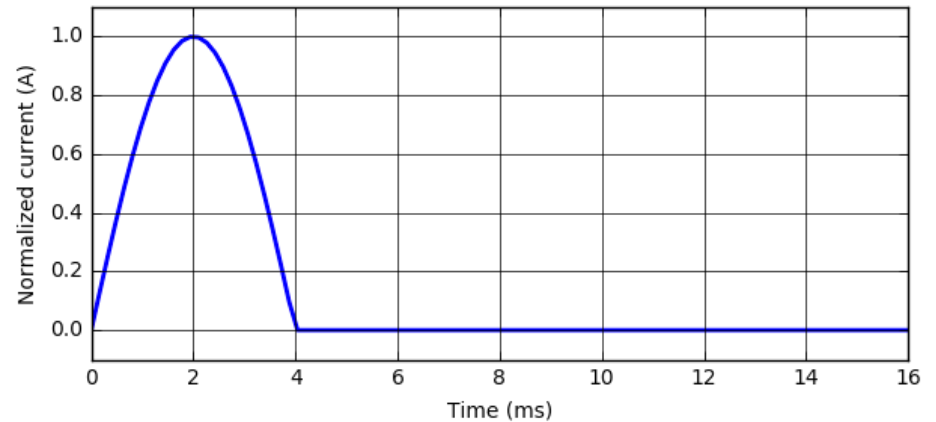
Distance

# Survey

## HELITEM

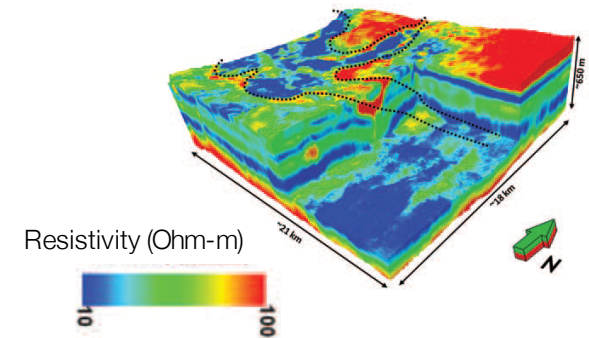


## System Configuration

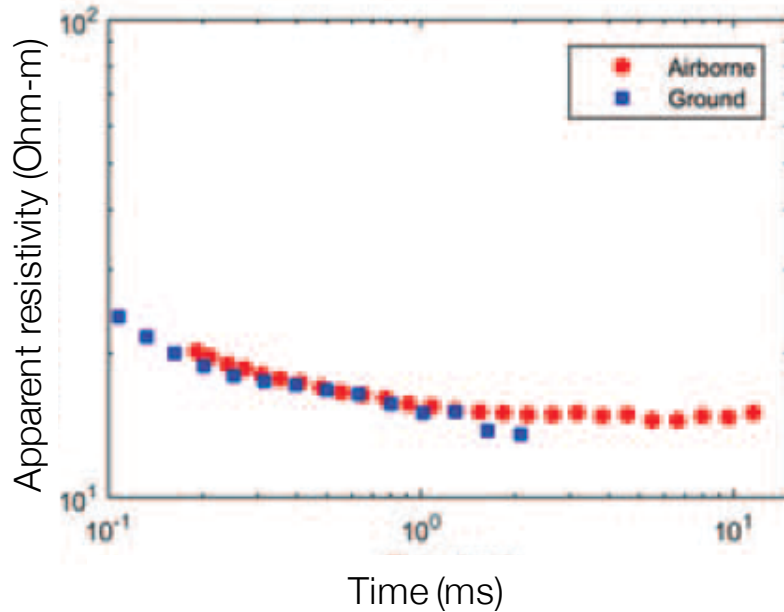


- Peak Tx current: 1200 A
- Dipole moment:  $1.7 \times 10^6 \text{ A-m}^2$
- Stacked TEM curve spacing:  $\sim 2.7 \text{ m}$
- Total soundings:  $\sim 1.6 \text{ million}$

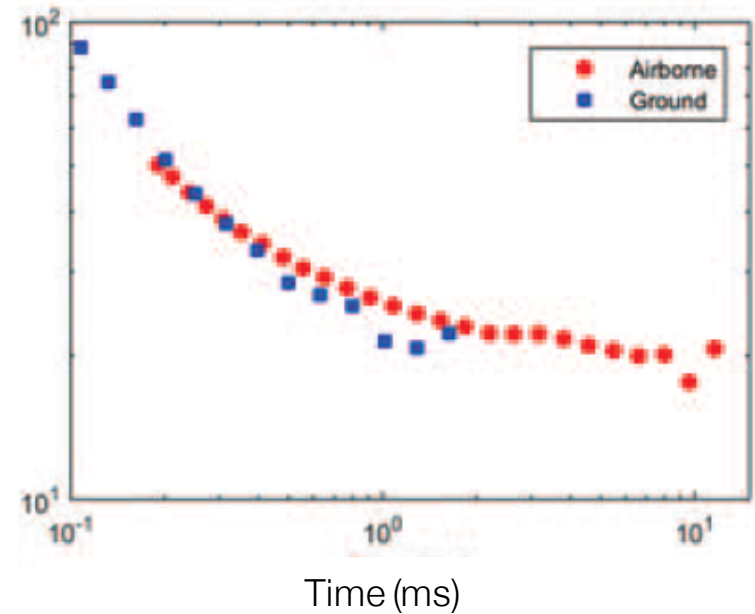
# Comparisons: airborne and ground EM



Conductive area



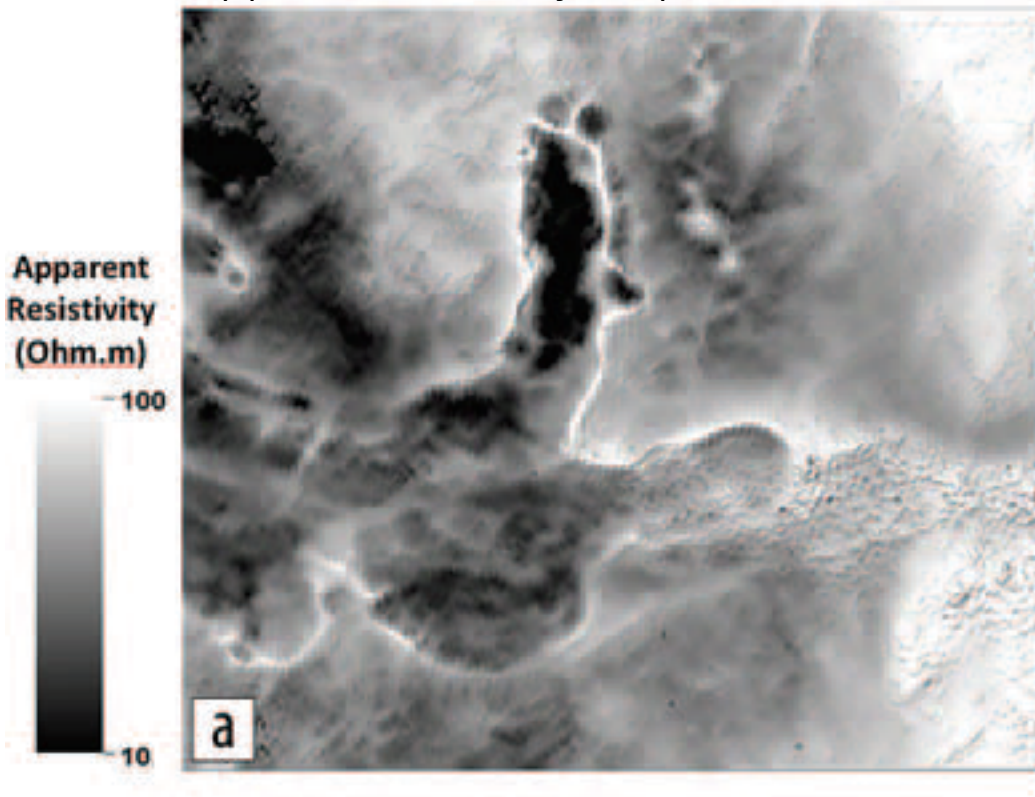
Resistive area





# EM data

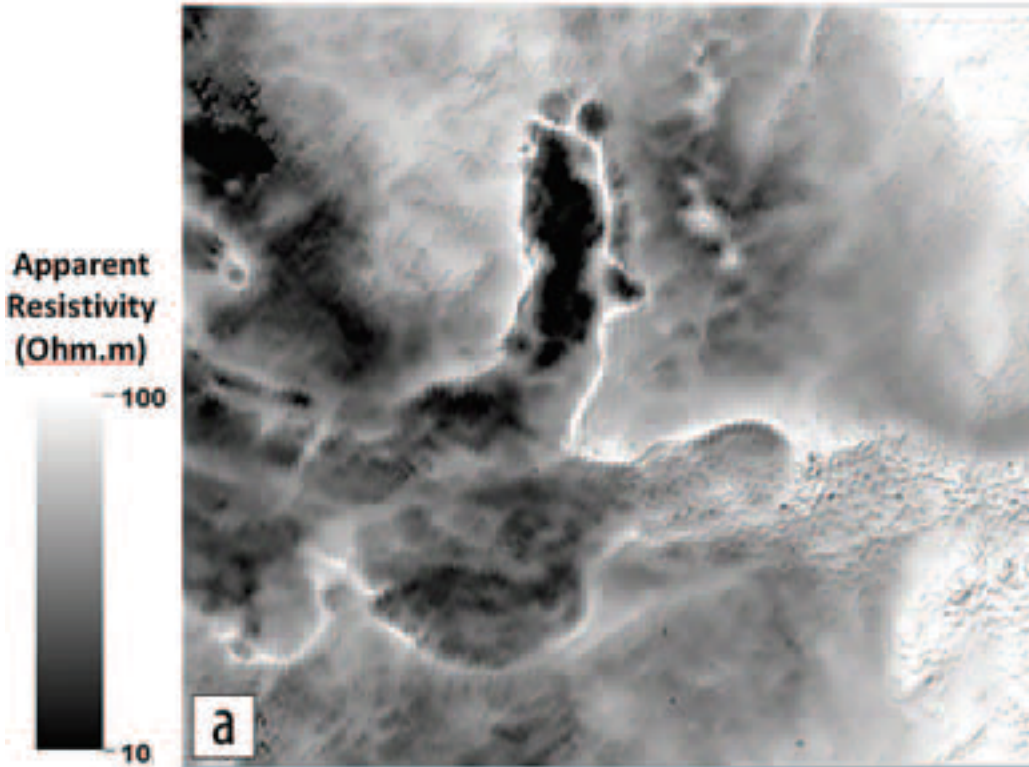
Apparent resistivity map



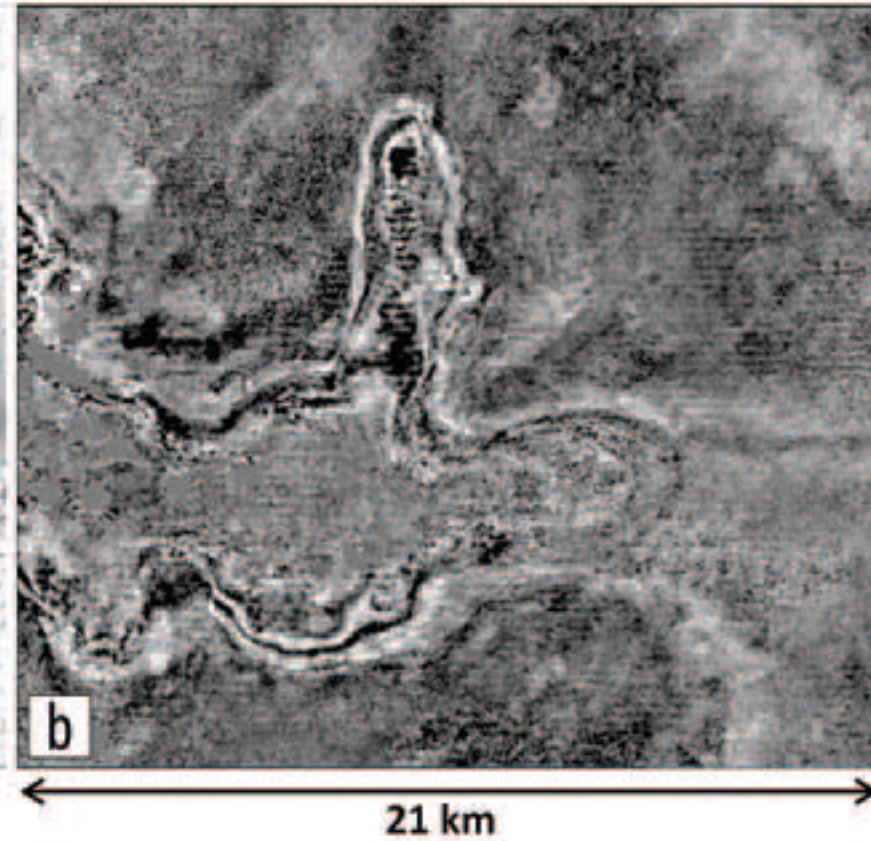


# Comparison: EM and Seismic data

Apparent resistivity map

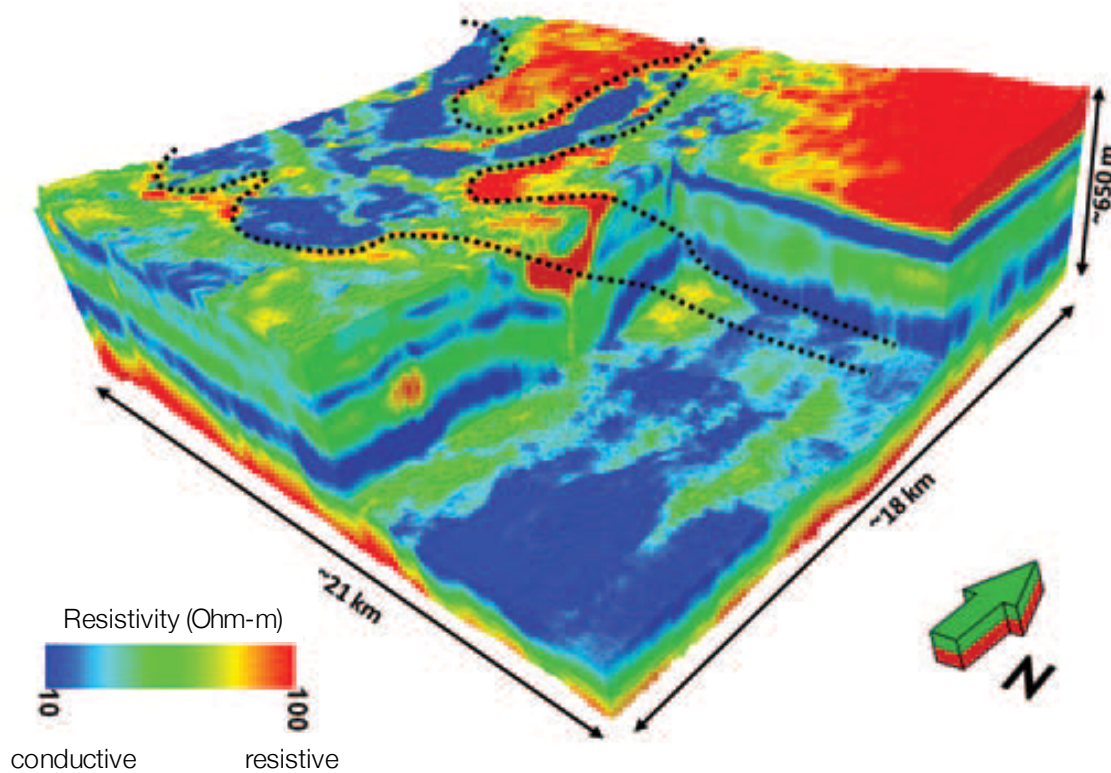


Seismic time slice



# Processing: EM inversion

## Conductivity model



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

# Cooperative inversion: Seismic + EM

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

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

Conductivity ( $\sigma$ ): high to low

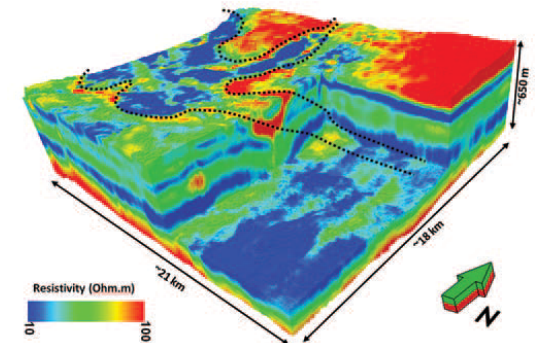
$$\begin{aligned} v_p &= g(\phi) \\ \sigma &= f(\phi) \end{aligned} \quad \phi: \text{porosity}$$

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

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

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

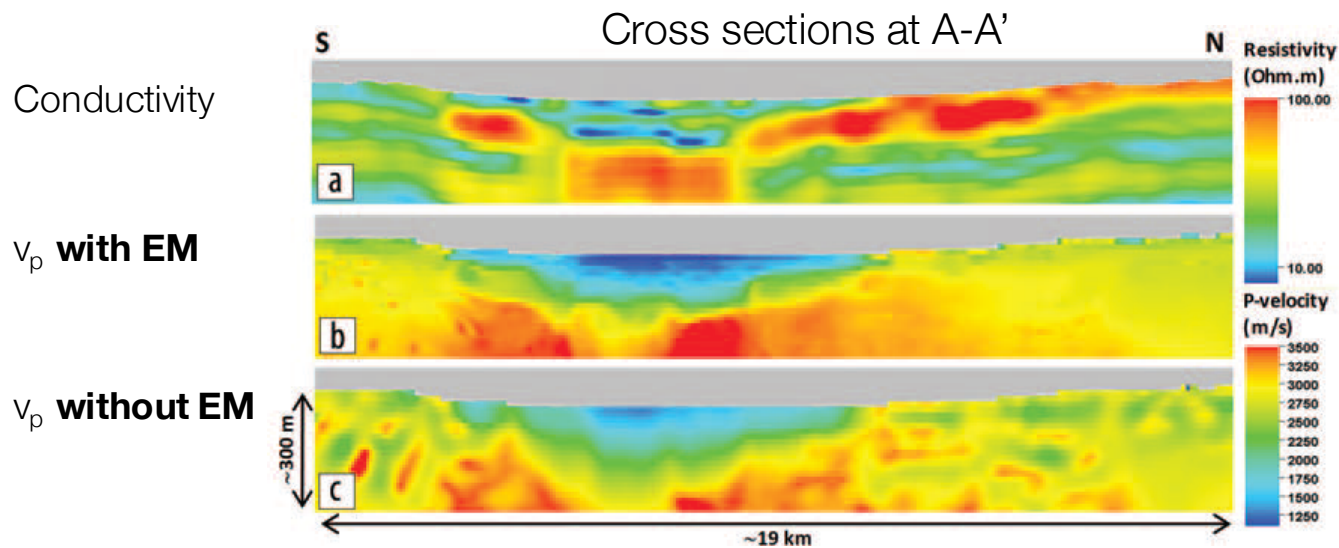
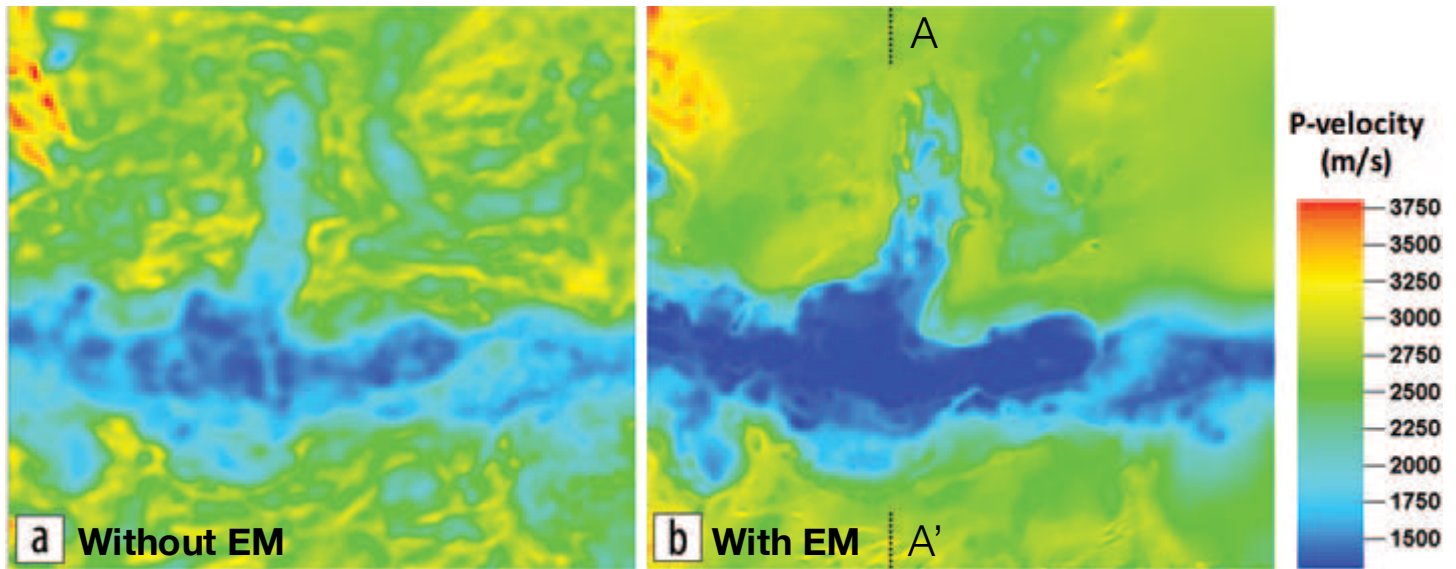
Gallardo and Meju, 2004





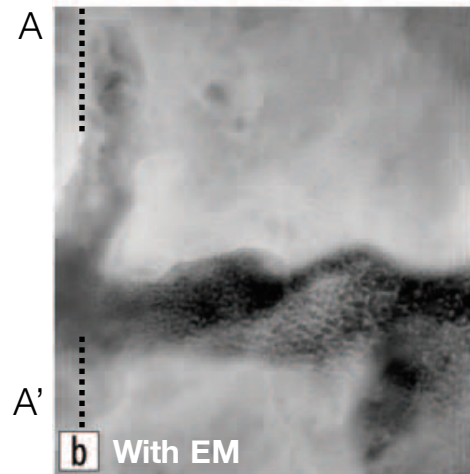
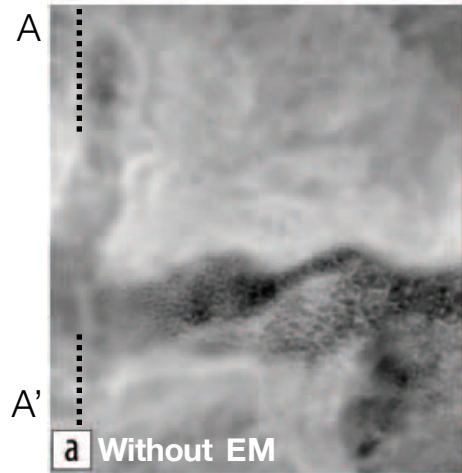
# Cooperative inversion: Seismic + EM

$V_p$  depth slices at 340 m below sea level

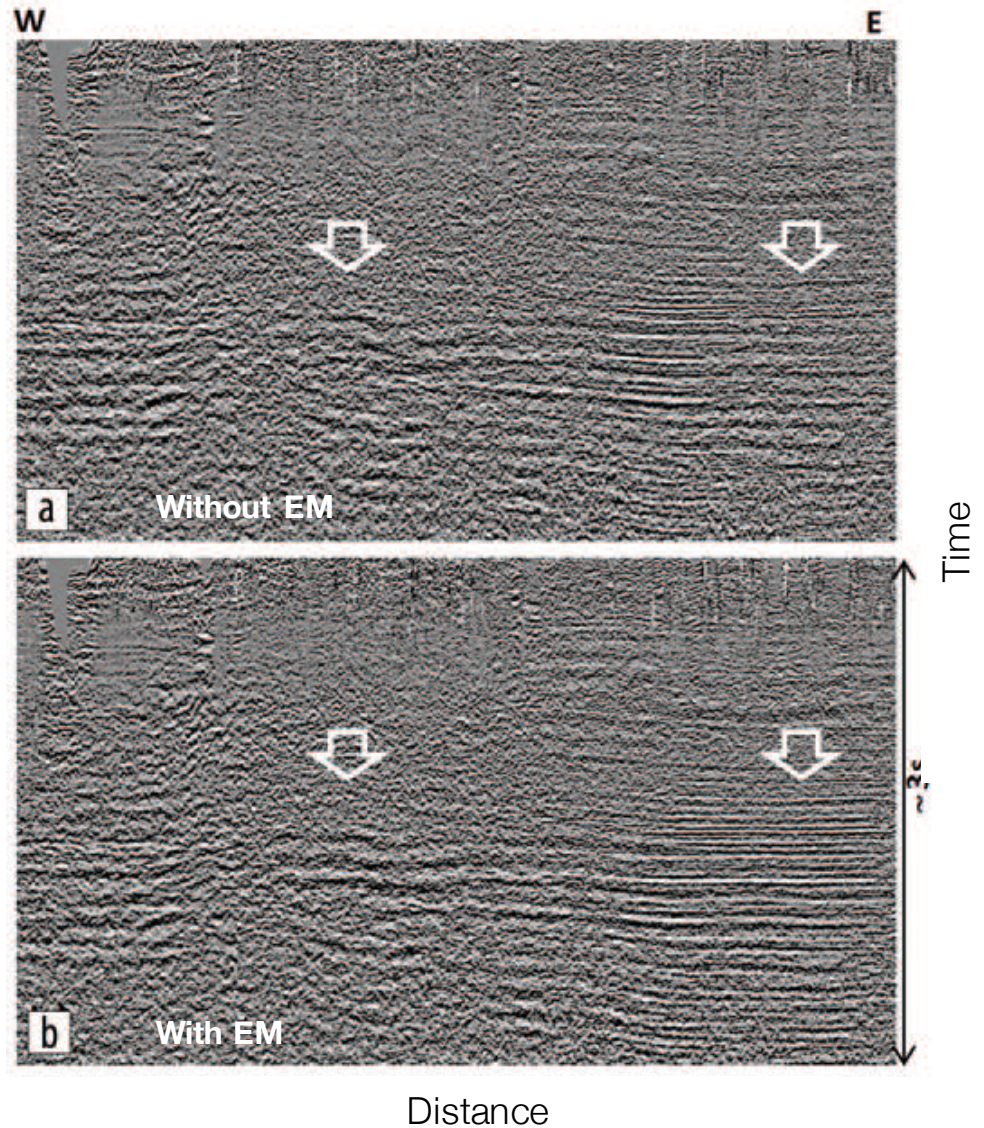


# Static correction

Estimated statics on plan map



Static corrected sections at A-A'

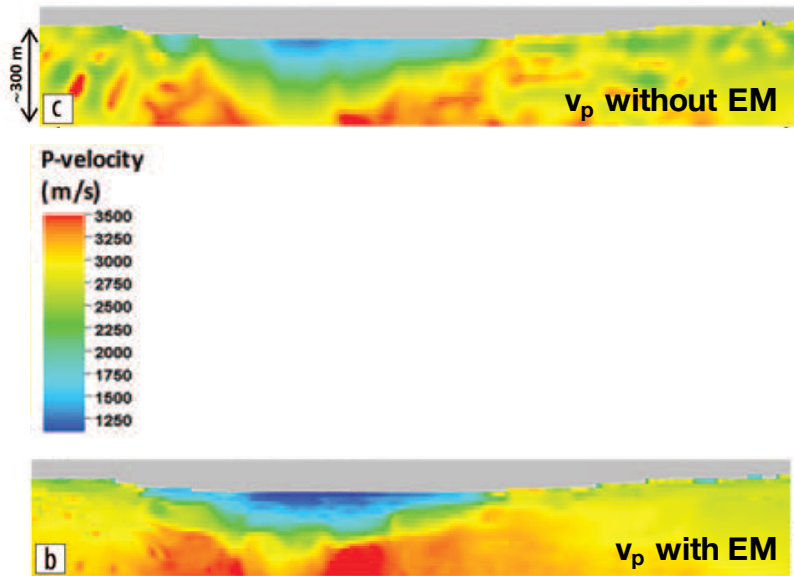




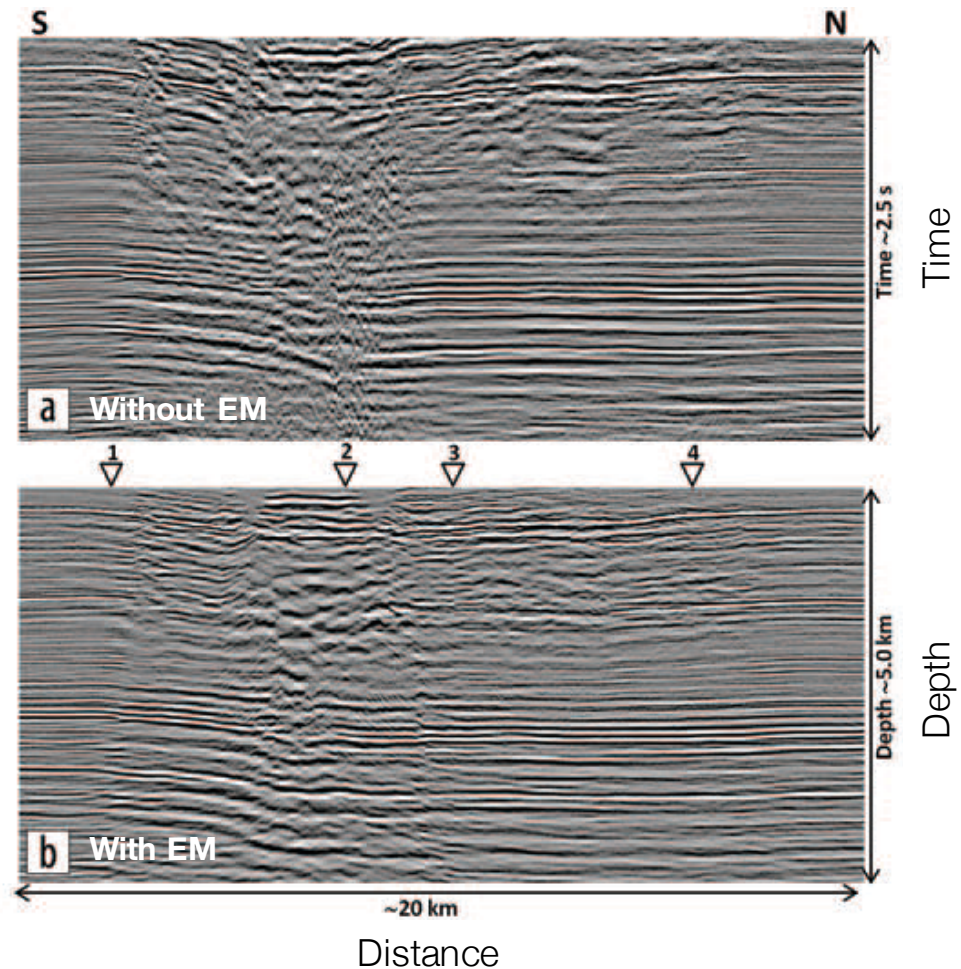
# Pre-stack depth migration

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

$v_p$  cross sections at A-A'

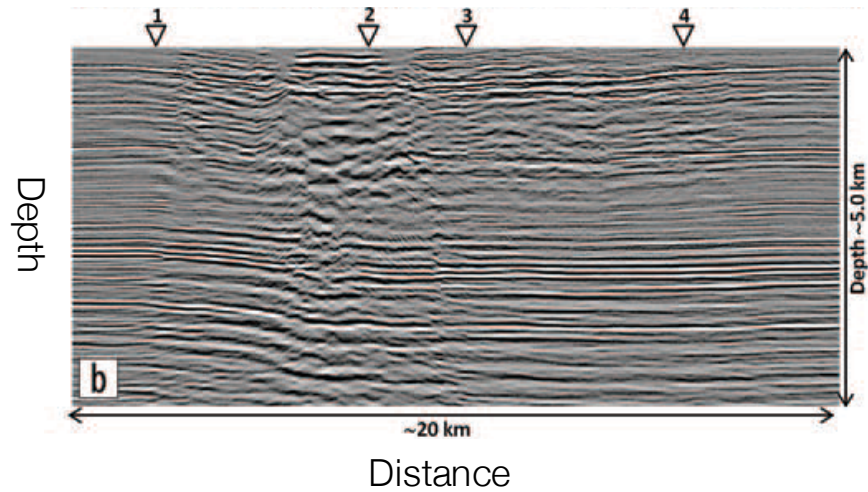


Cross sections at A-A'

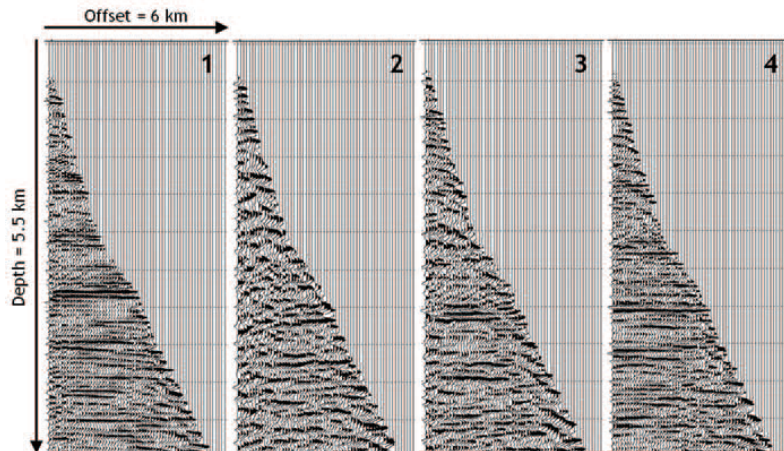


# Interpretation and Synthesis

Depth section at A-A'



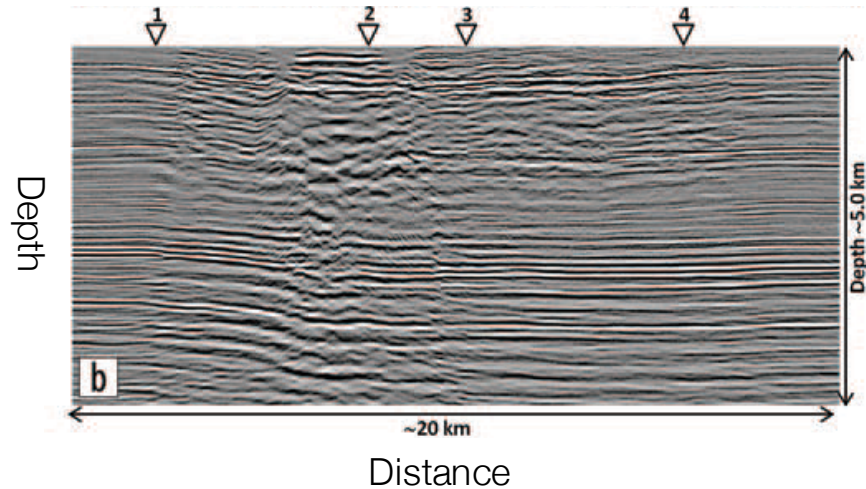
Common image gathers



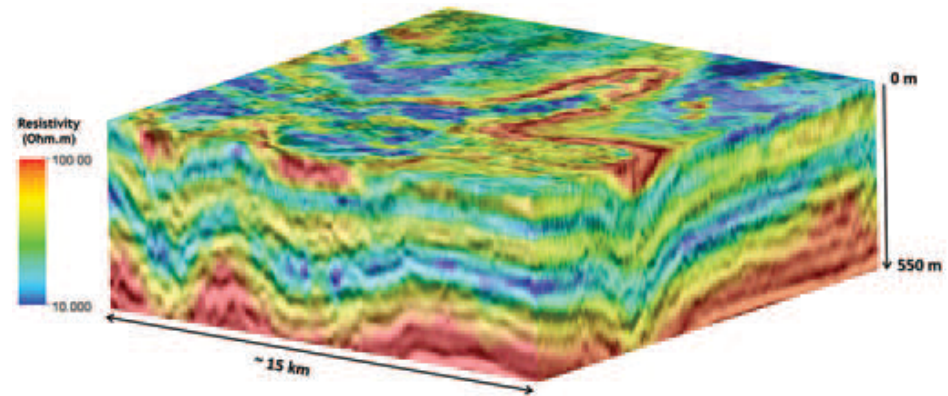


# Interpretation and Synthesis

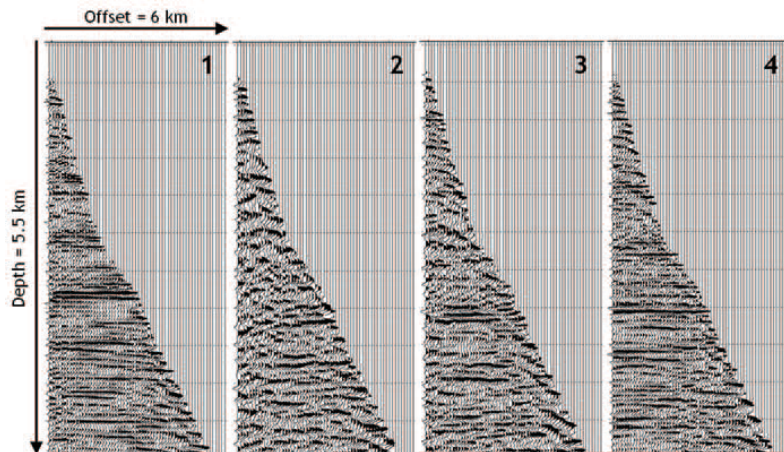
Depth section at A-A'



3D prestack depth migration co-rendered with EM



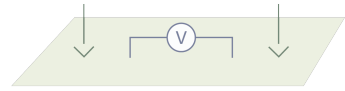
Common image gathers



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

# End of Inductive Sources

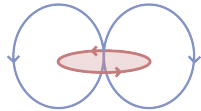
Next up



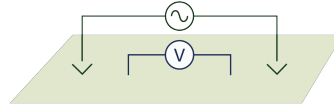
DC Resistivity



EM  
Fundamentals



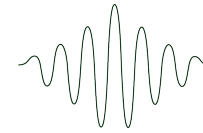
Inductive  
Sources



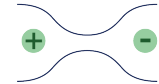
Grounded  
Sources



Natural  
Sources



GPR



Induced  
Polarization



The  
Future

Lunch: Play with apps

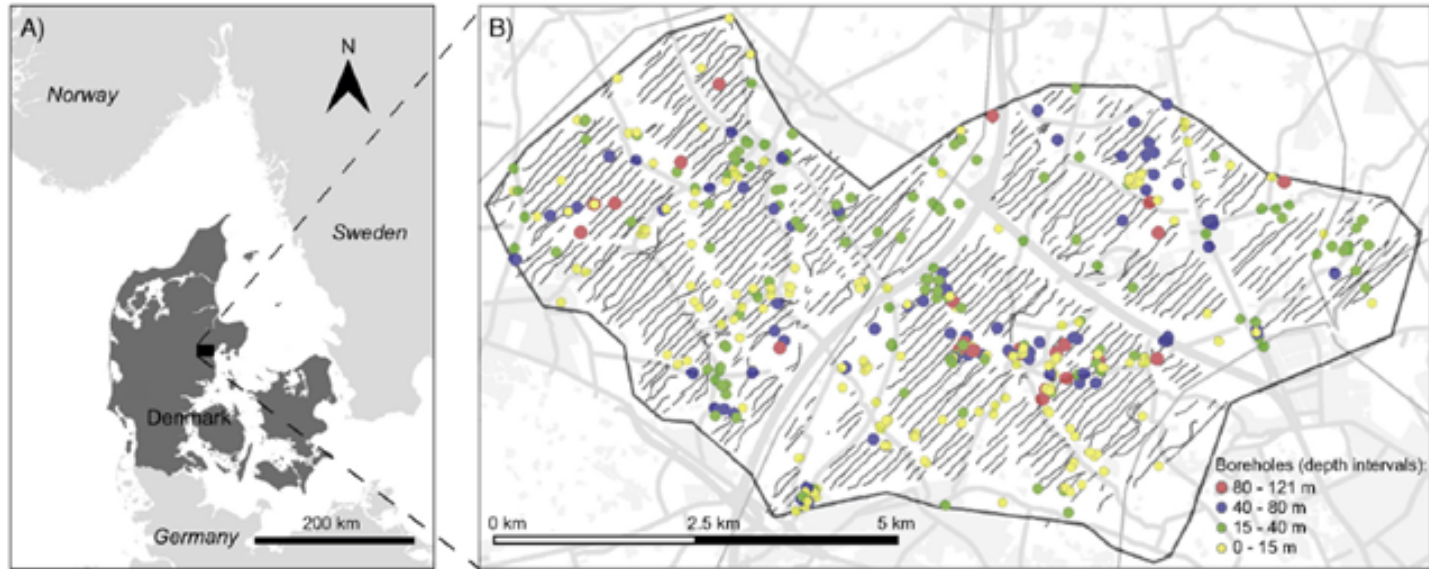
# Case History: Kasted

Vilhelmsen et al. (2016)

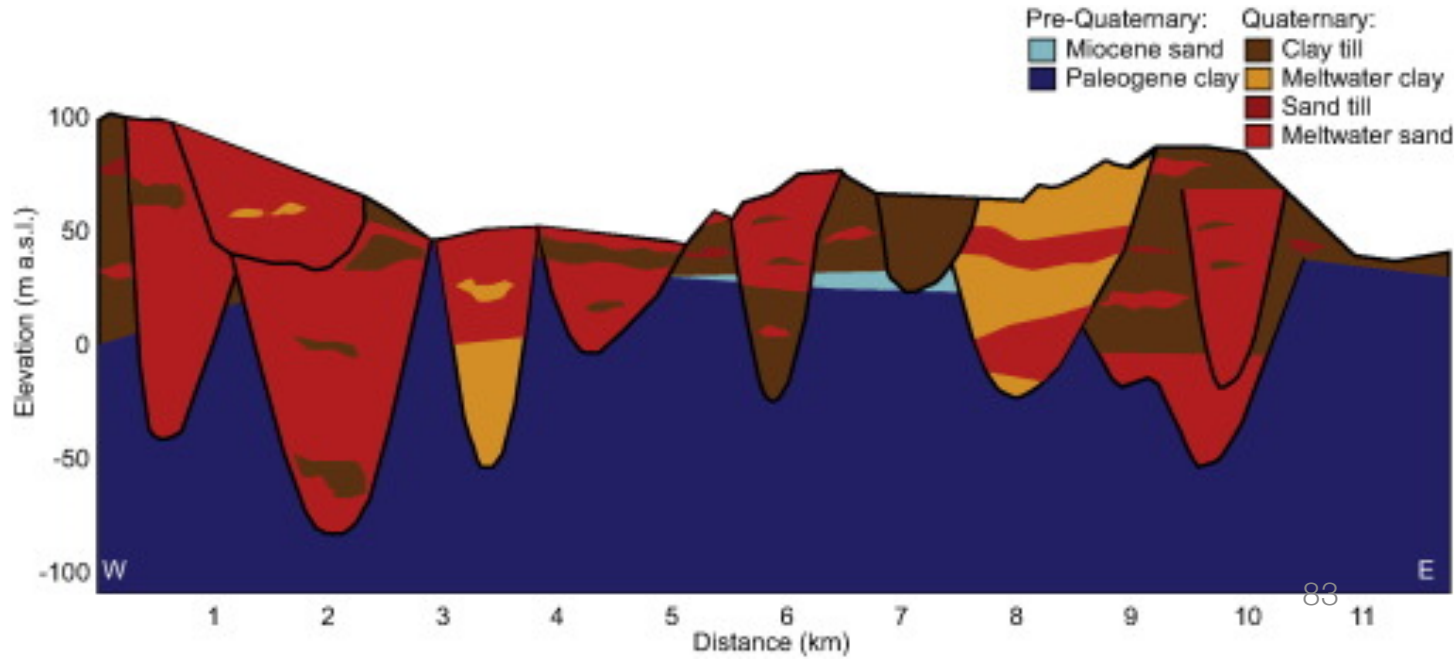
# Setup

A) Survey Area:  
Kasted,  
Demark

B) Borehole  
locations

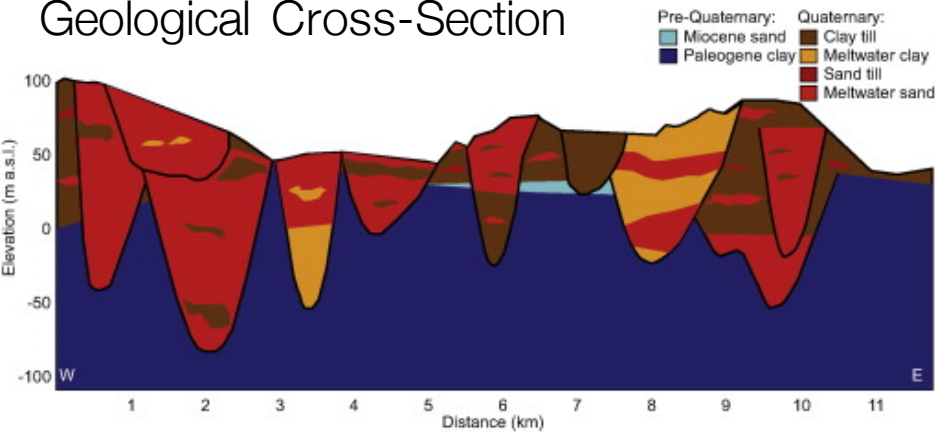


Local Geology:  
W-E cross-section



# Properties

## Geological Cross-Section

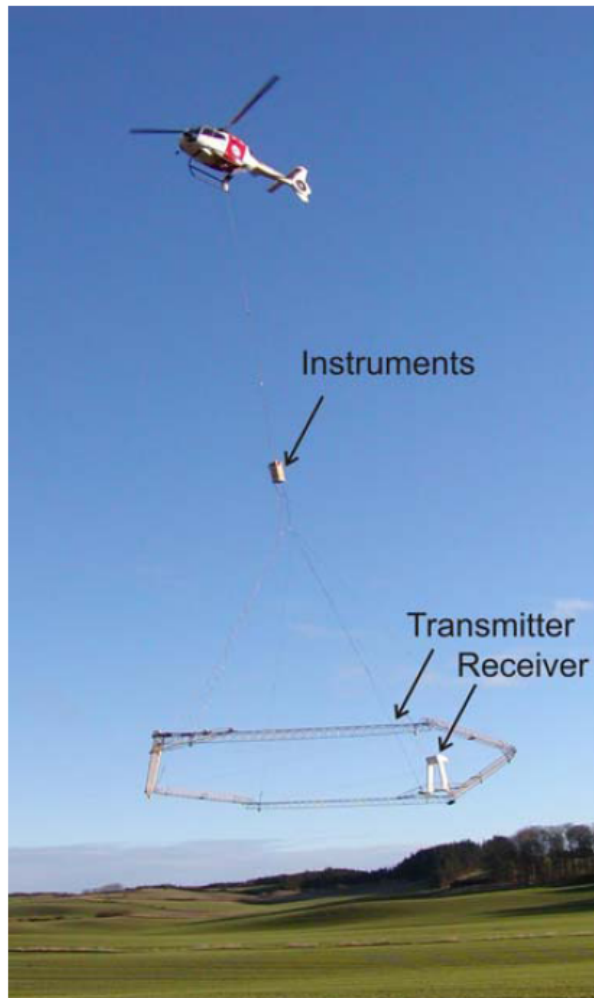


- Buried valleys with clays beneath
- Infill (water-bearing): coarse sand and gravel
- Clays are conductive (1-40  $\Omega m$ )
- Water-bearing sands and gravels are more resistive (>40  $\Omega m$ )

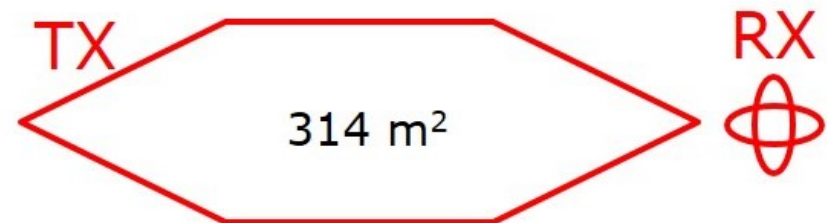
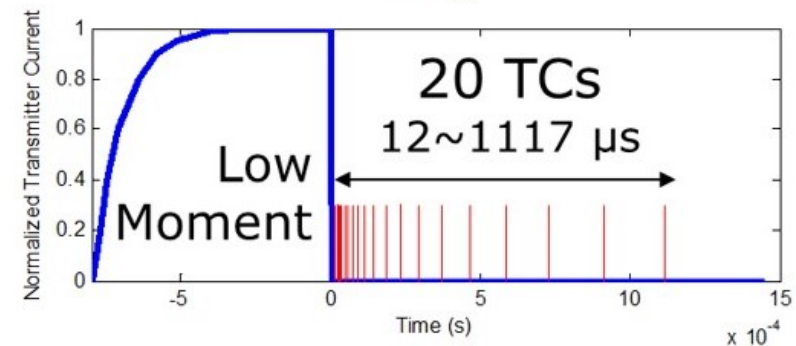
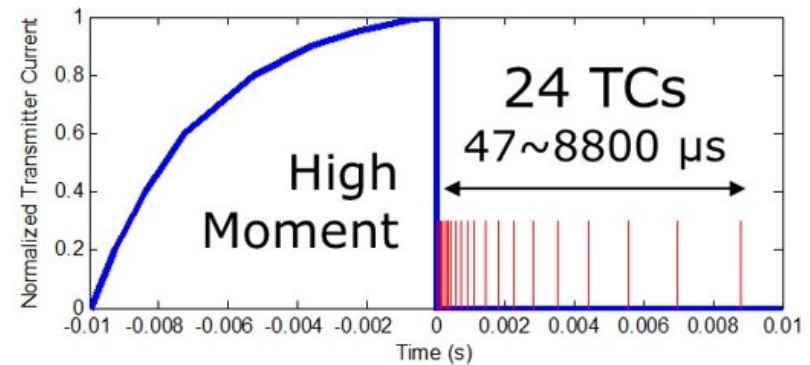
| Geological Units          | Resistivity ( $\Omega m$ ) |
|---------------------------|----------------------------|
| Palaeogene Clay           | 1-10                       |
| Clay Till                 | 25-60                      |
| Sand Till                 | >50                        |
| Meltwater 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

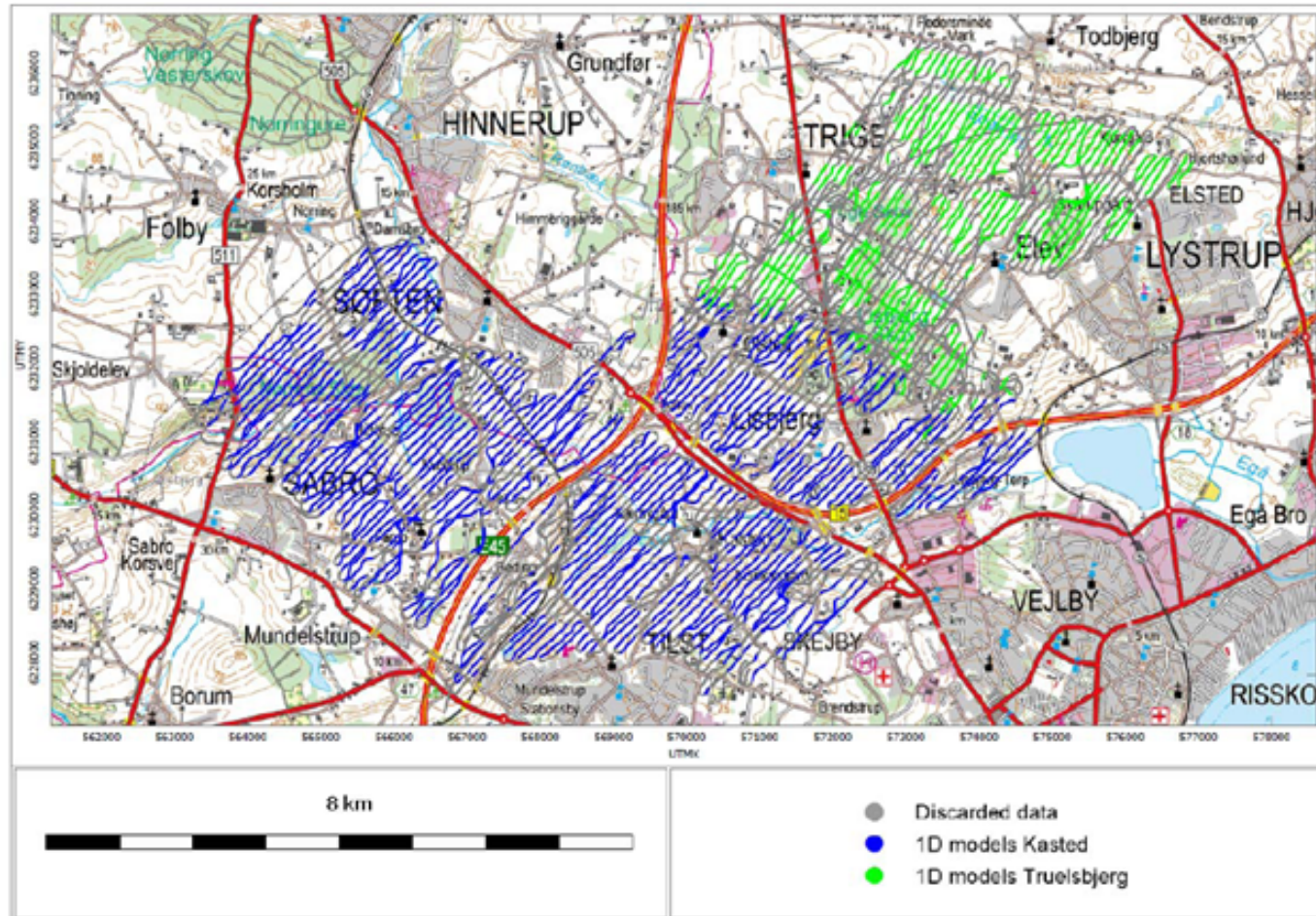


- Low moment (LM) used to image near surface structures
- High moment (HM) used to image deeper structures



# Data

Blue: data used for Kasted study



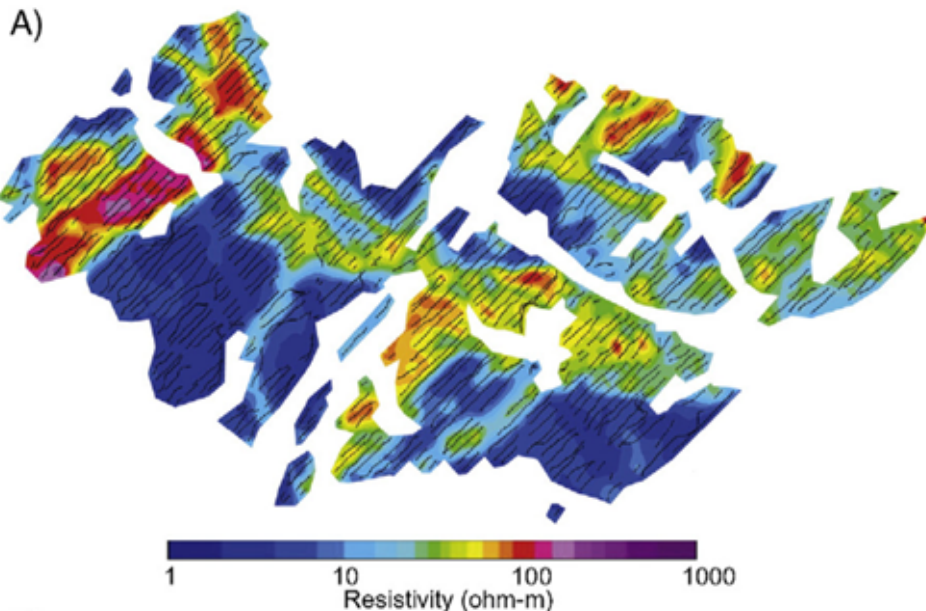
- 333 line km of data, 100 m line-spacing
- Data points with strong coupling to cultural noise were removed (~30%)



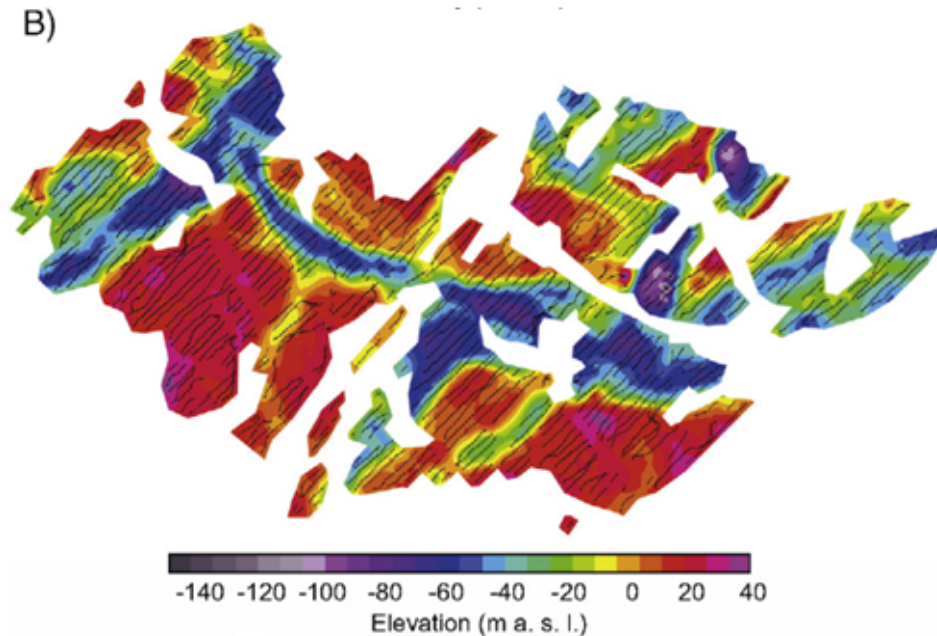
# Processing (inversion)

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

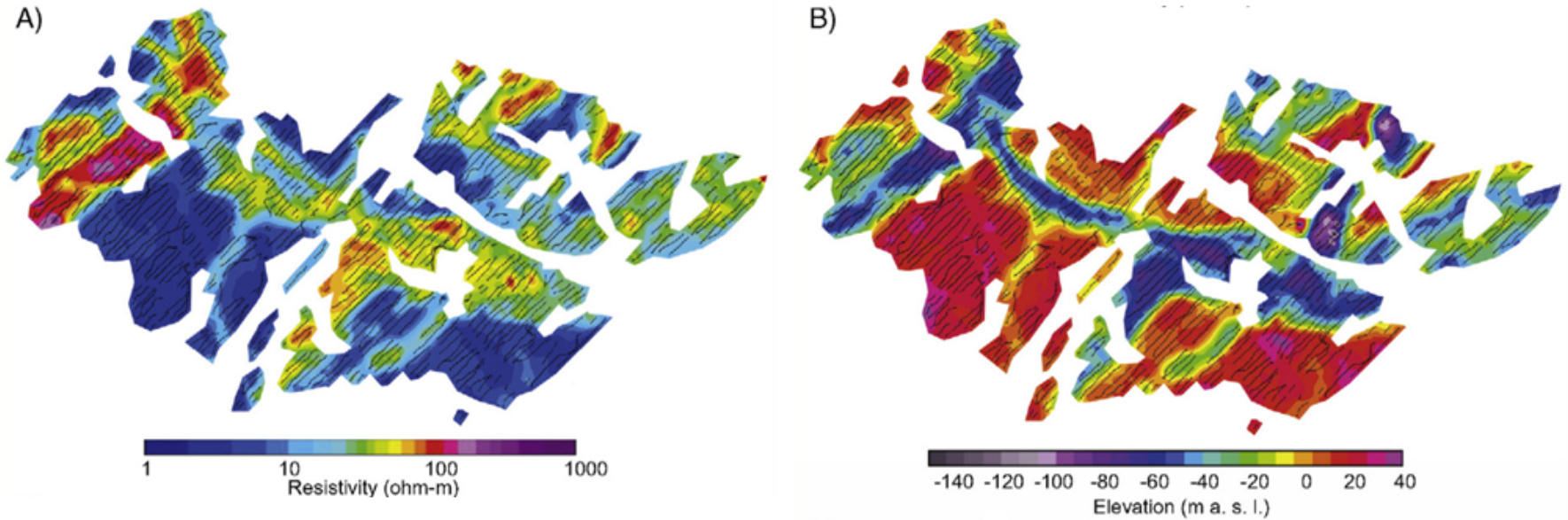
Depth slice 5 m above sea-level



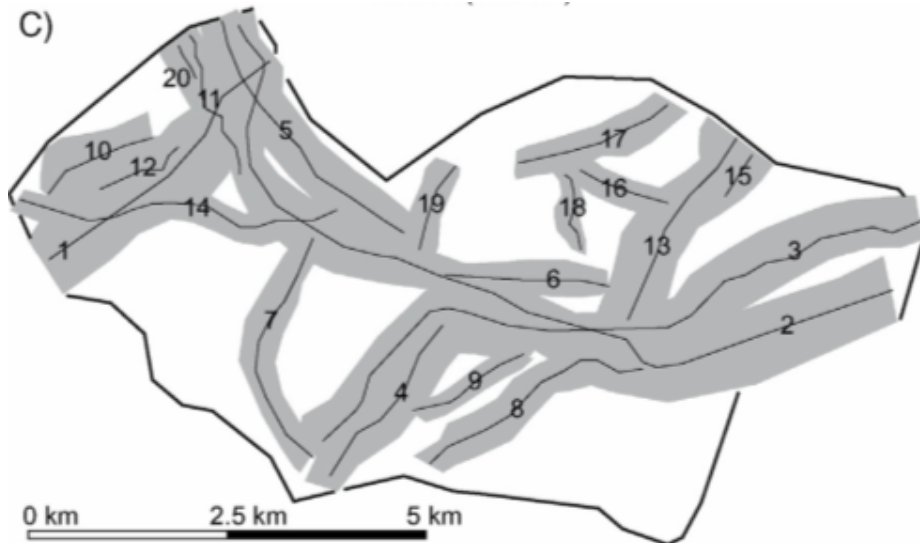
Approximate depth to the top of Paleogene clay layer



# Interpretation

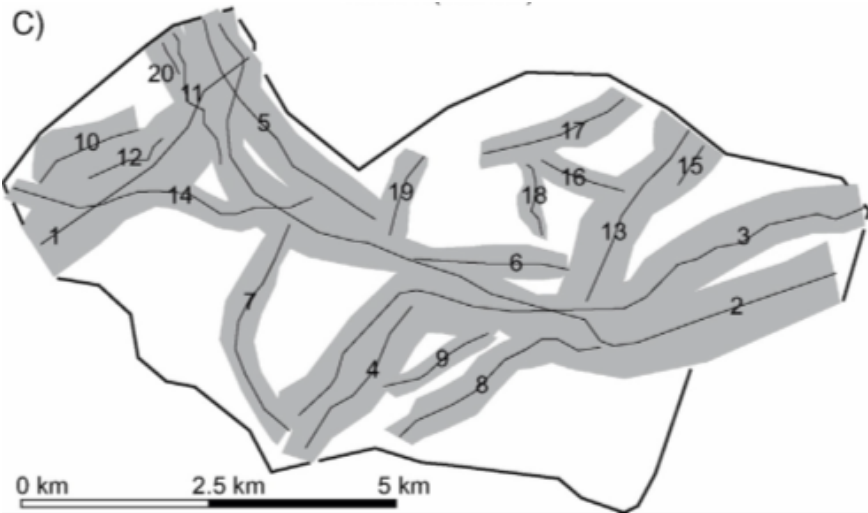


Delineation of valley structures

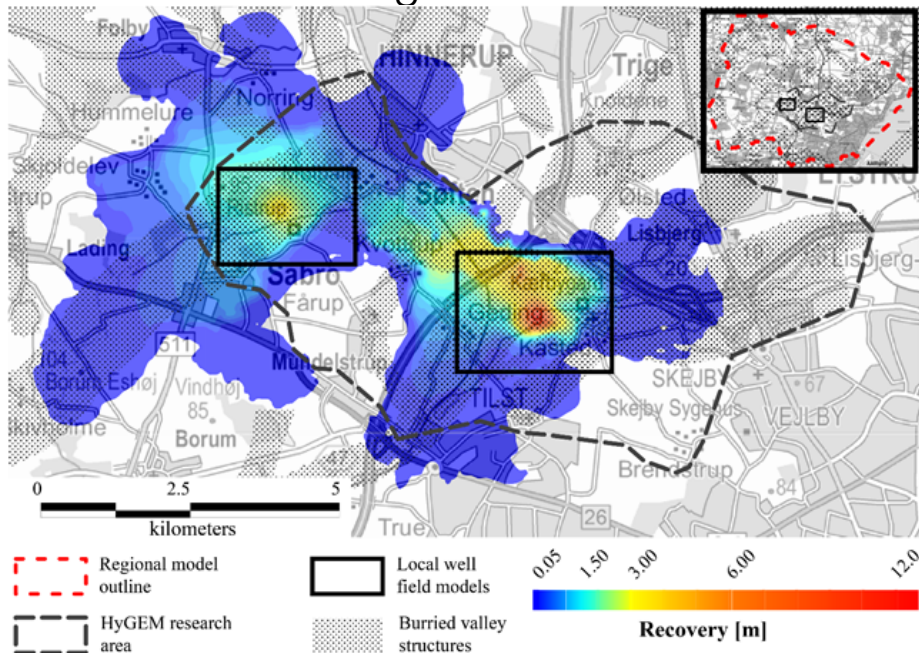


- Inversion results used to construct geological model.
- Delineated 20 buried and cross-cutting valley structures.

# Synthesis



MODFLOW-USG groundwater model



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