EM: Inductive Sources

DISC

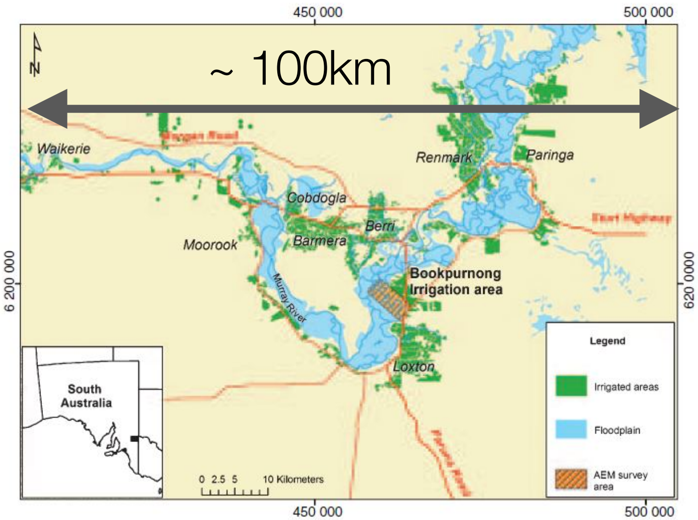
2017

Electromagnetics

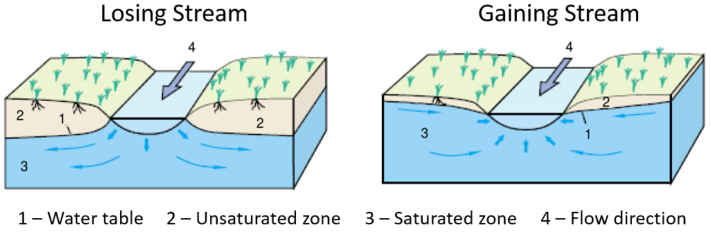
Fundamentals and Applications

Motivation

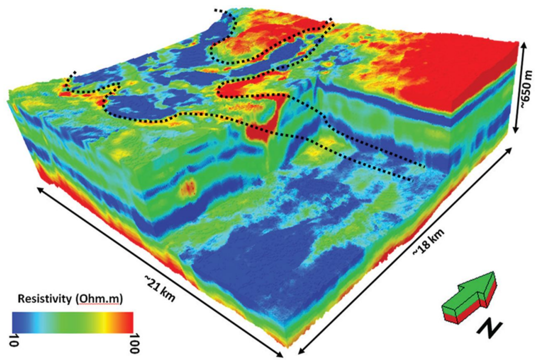
Large areas to be covered



Groundwater



High resolution near surface



Rugged terrain

Minerals

Outline

Setup

- Basic experiment
- Transmitters, Receivers

Frequency Domain EM

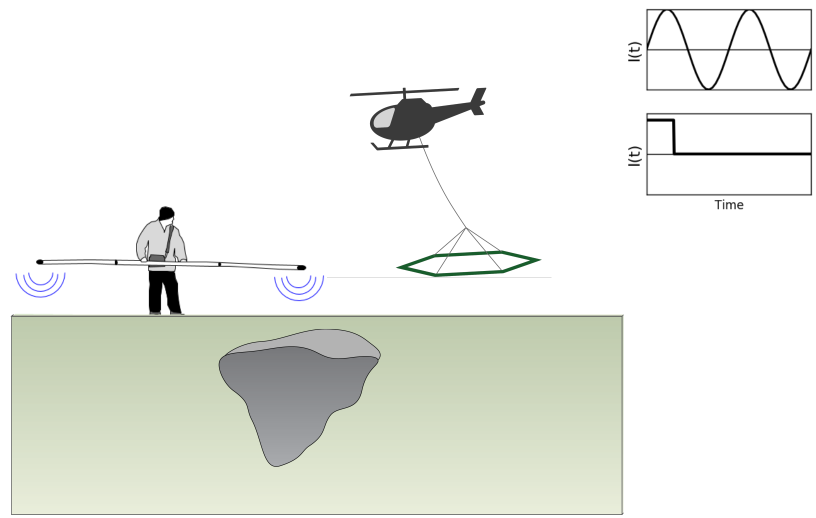
- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Groundwater

Time Domain EM

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

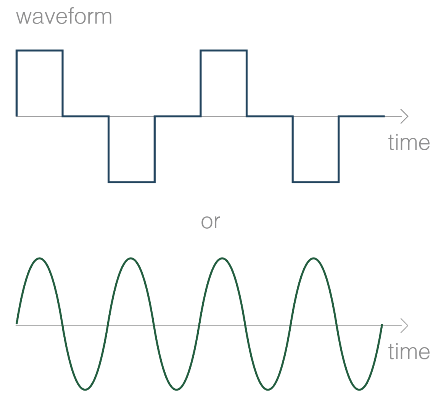
Important questions

- 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?

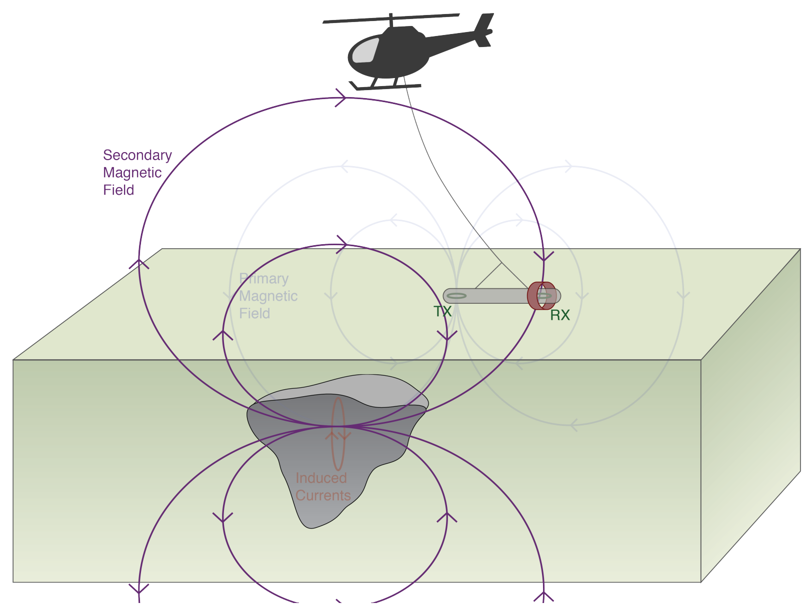


- Where to collect data? How many? How accurate?
- What is depth of investigation?
- What is the “footprint” of the transmitter”
  - These are questions of SURVEY DESIGN

Basic Experiment

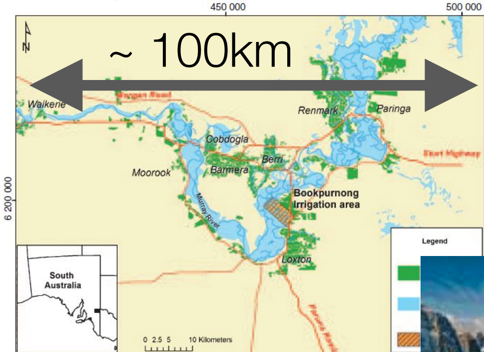


- **Transmitter:**
  - Produces a primary magnetic field
- **Exciting the target:**
  - Time varying magnetic fields generate electric fields everywhere
  - Producing currents in conductors
- **Receiver:**
  - Induced currents produce secondary magnetic fields



Transmitter

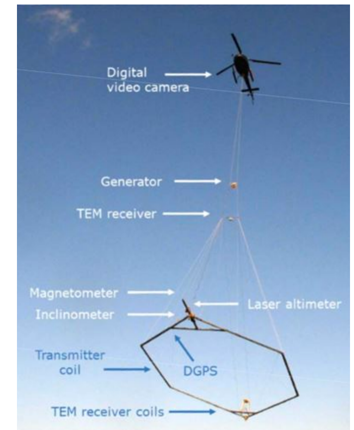
Large areas



Rugged terrain

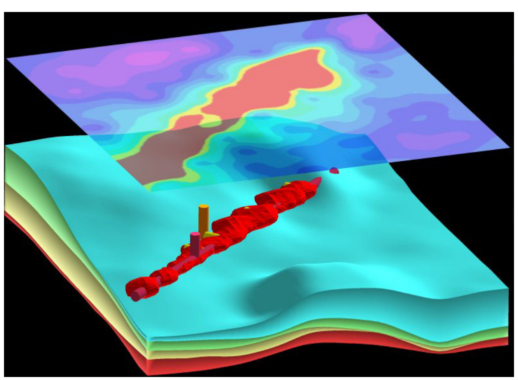
Airborne Survey

Resolve

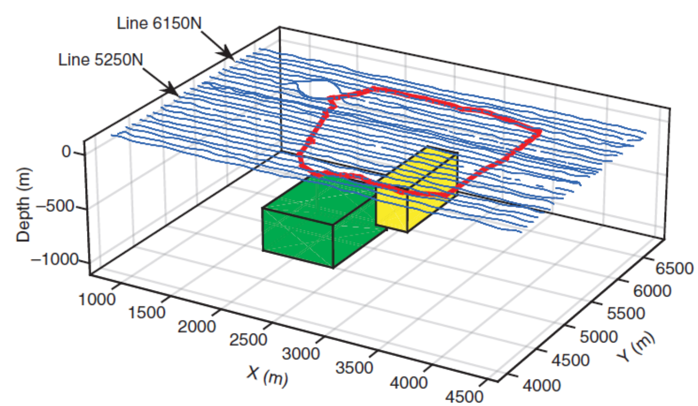


SkyTEM

Deep Targets

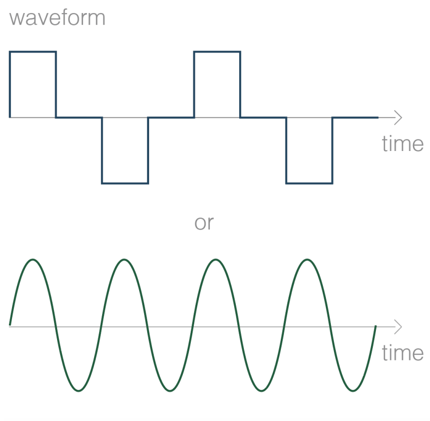


Large Loop



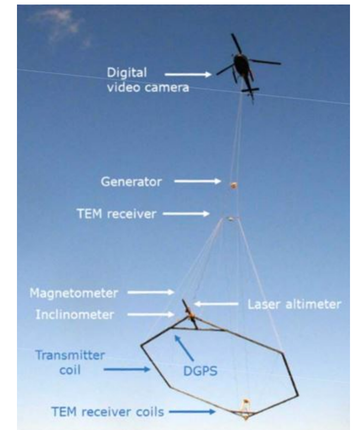
Transmitter

- Frequency or Time?



Airborne Survey

Resolve

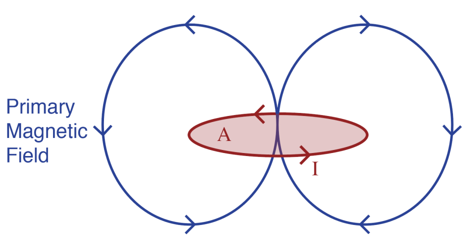


SkyTEM

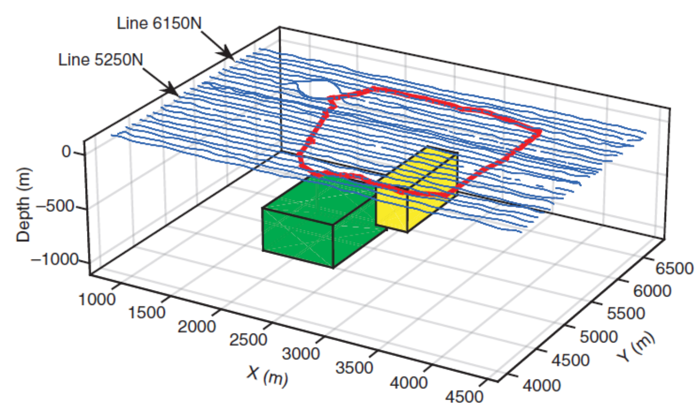
- Key factor is moment

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

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



Large Loop

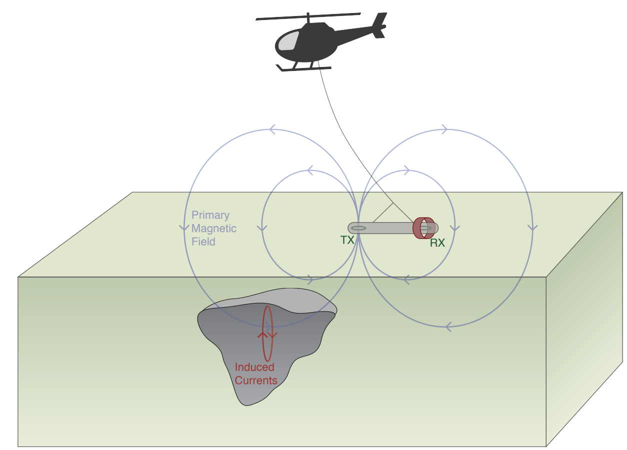


Exciting the target

- 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

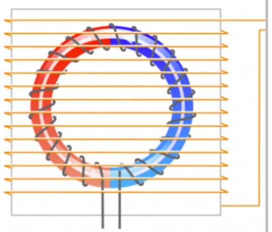


Receiver and Data

Magnetometer

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

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

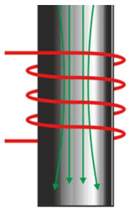


Fluxgate

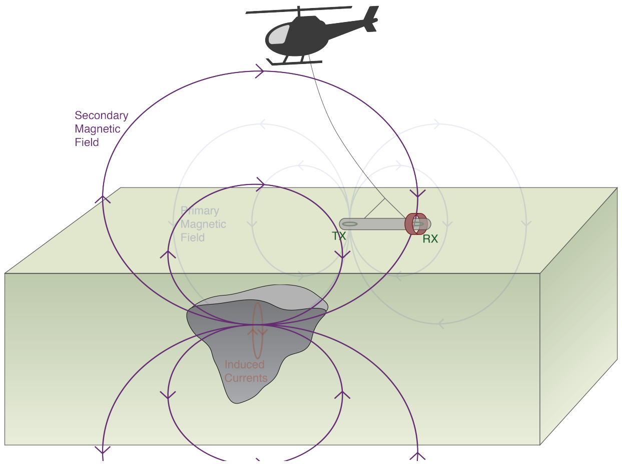
Coil

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

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

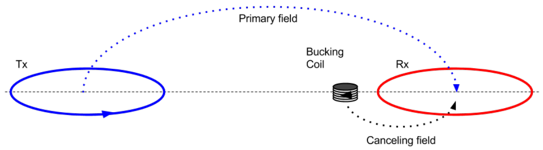


Coil

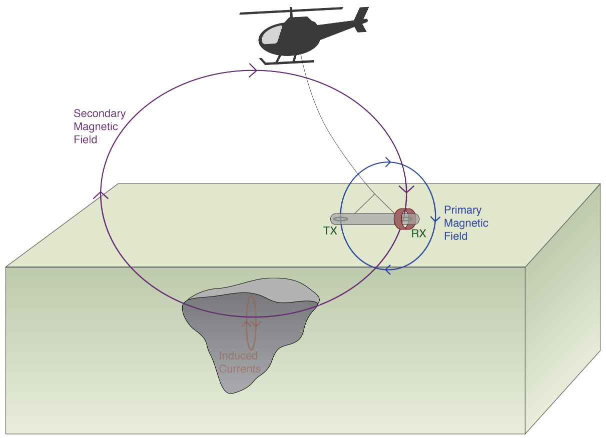


Receiver: Frequency Domain

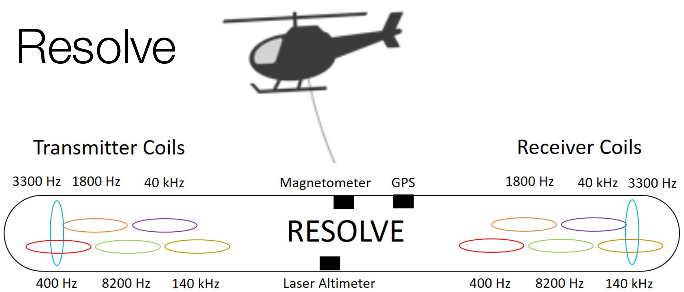
- Primary field
  - always "on"
  - large compared to secondary fields
- Primary removal
  - Compute and subtract
  - Bucking coil



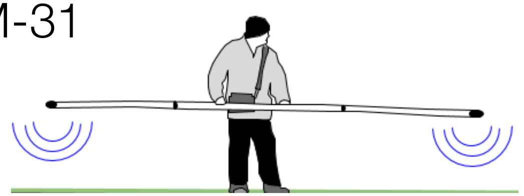
- Main requirement:
  - Know positions of Tx and Rx
  - Keep them in one unit



Resolve



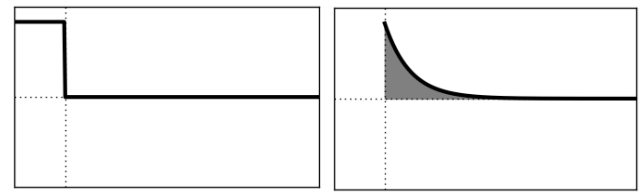
EM-31



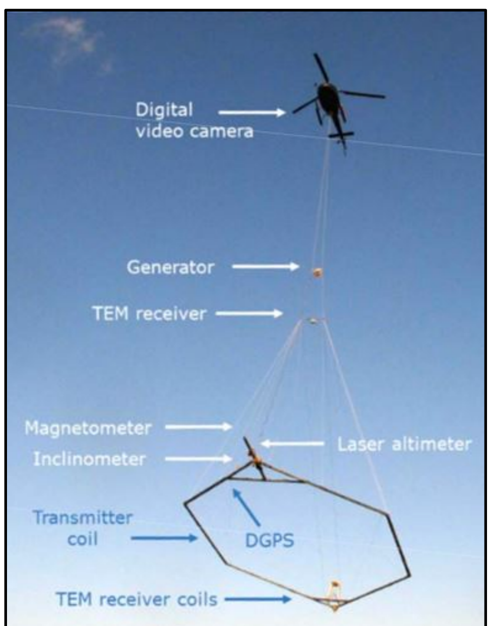
Receiver: Time Domain

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

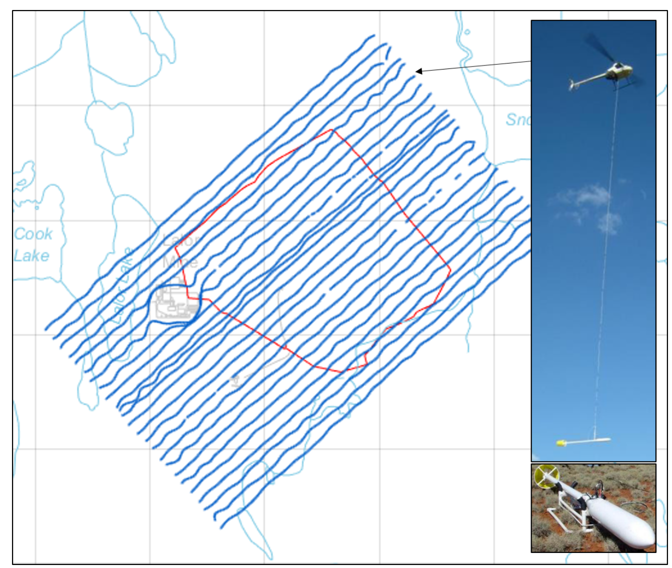
Current Response



SkyTEM

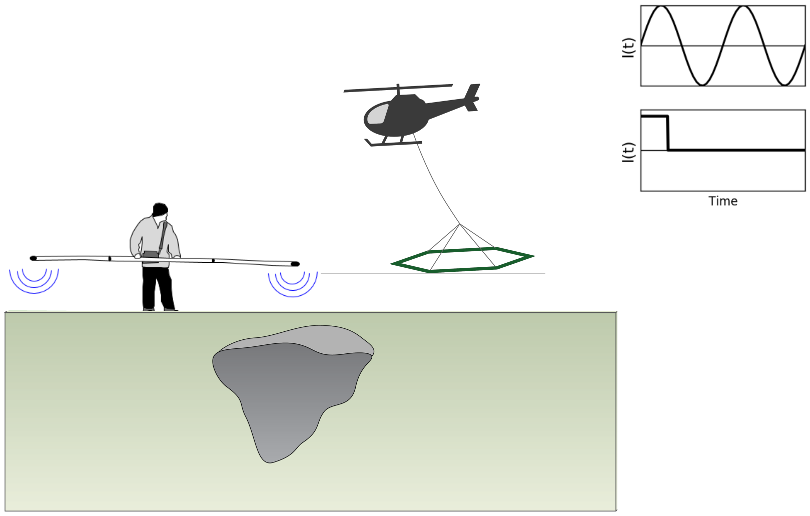


HeliSAM



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

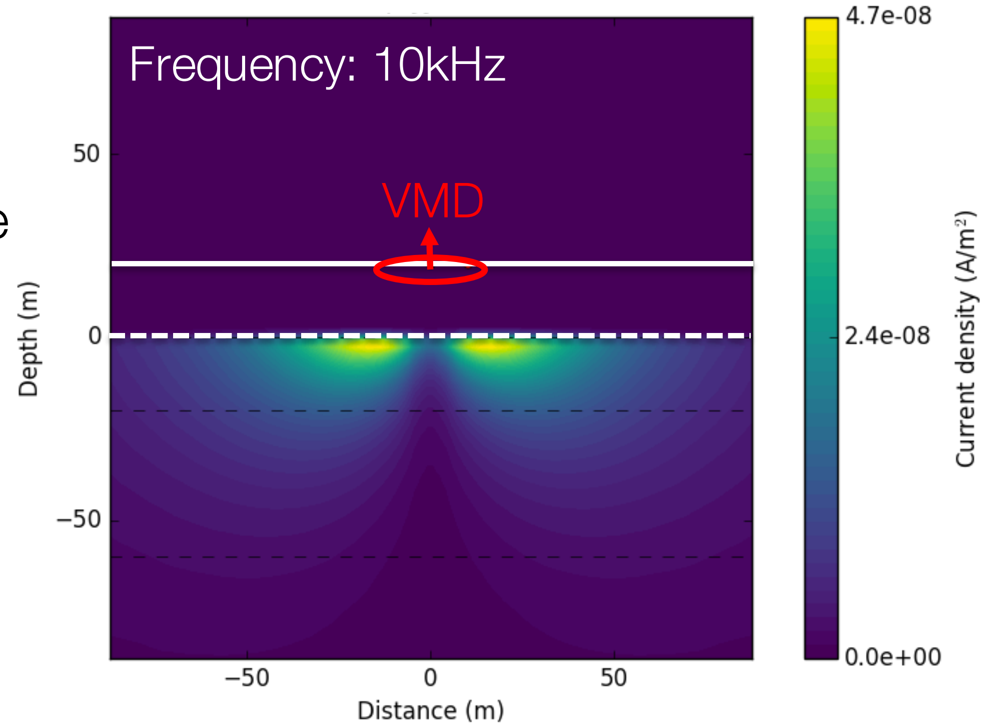
Footprint of Airborne EM system

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

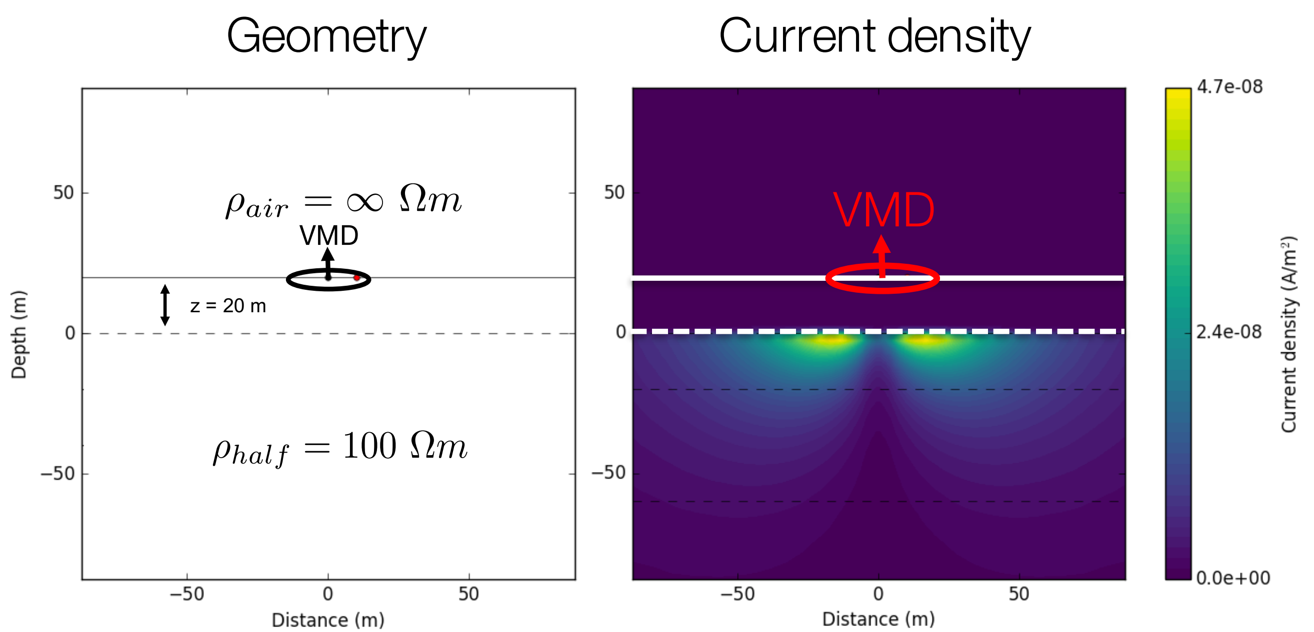
- Currents depend on
  - Transmitter
  - Waveform: frequency or time
  - Background conductivity

- Simple case: loop source over homogeneous earth

Current density

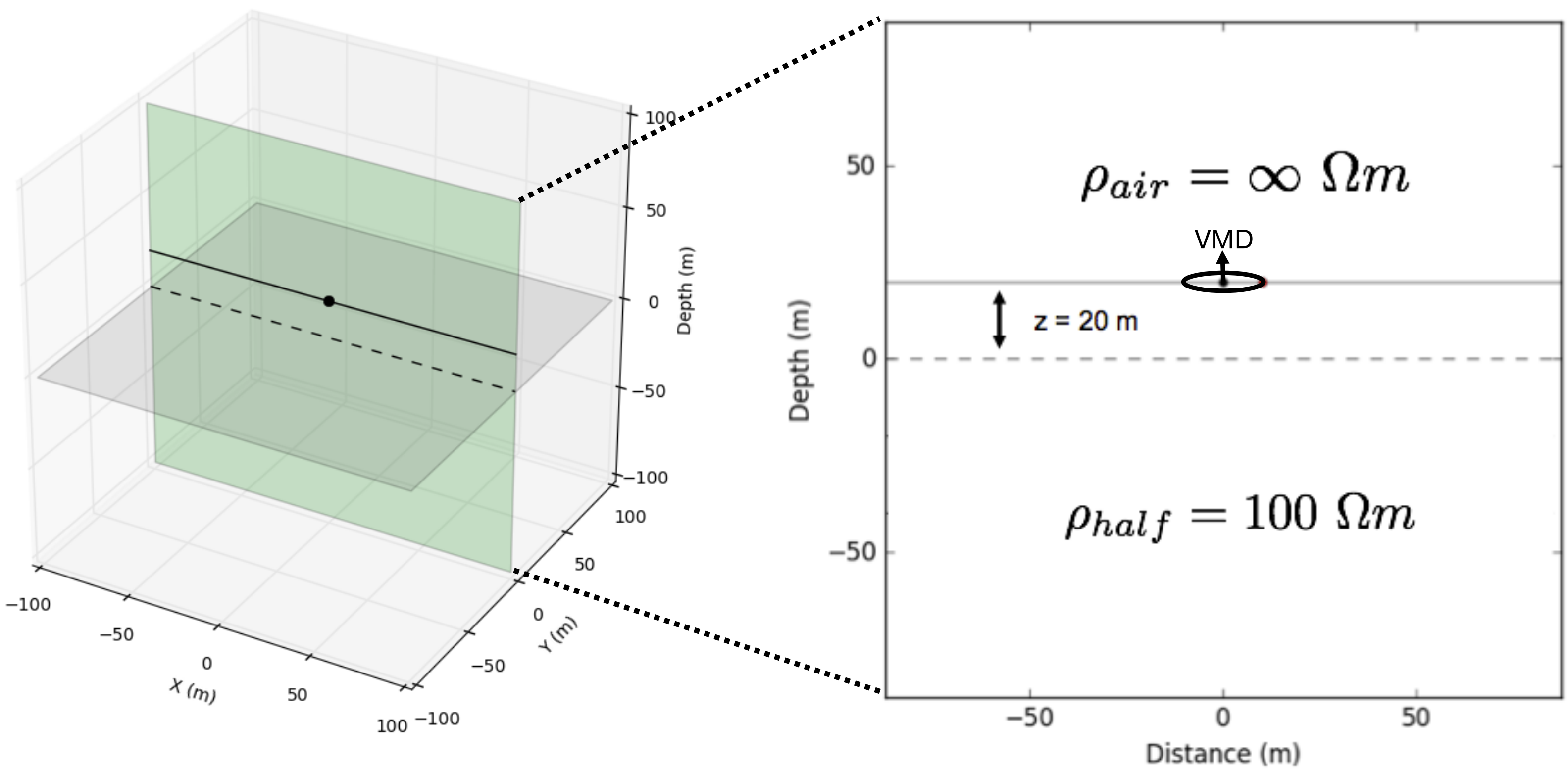


Vertical Magnetic Dipole (VMD)



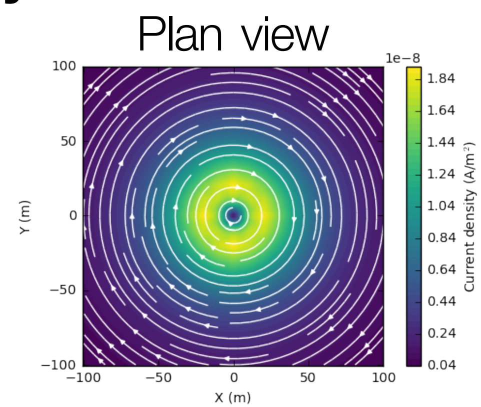
- Some questions
  - Where, and how strong, are the currents?
  - How do they change with transmitter frequency?
  - How do they depend upon the conductivity?
  - What do the resulting magnetic fields look like?

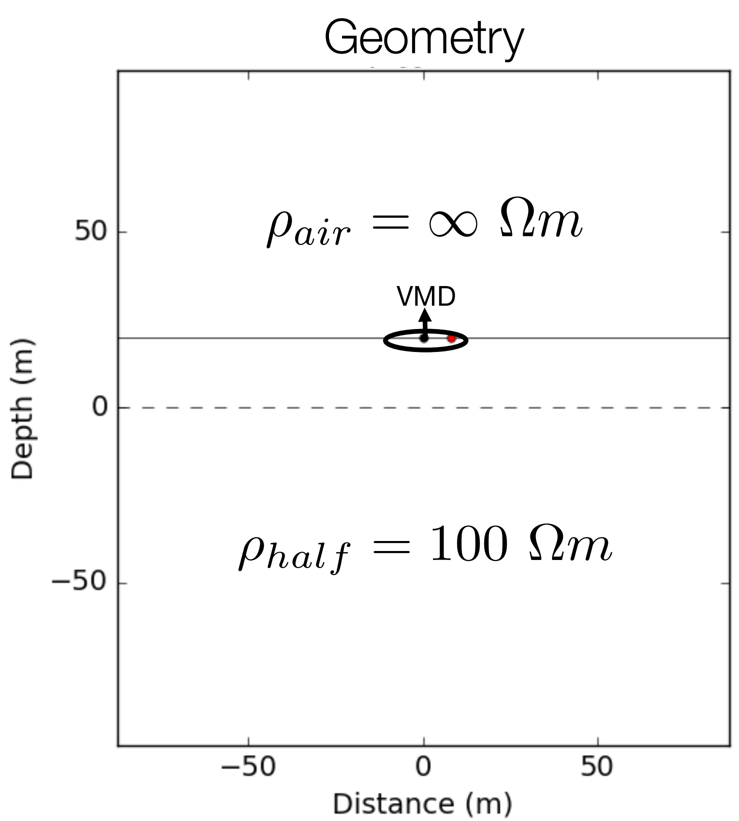
Vertical Magnetic Dipole over a halfspace (FDEM)

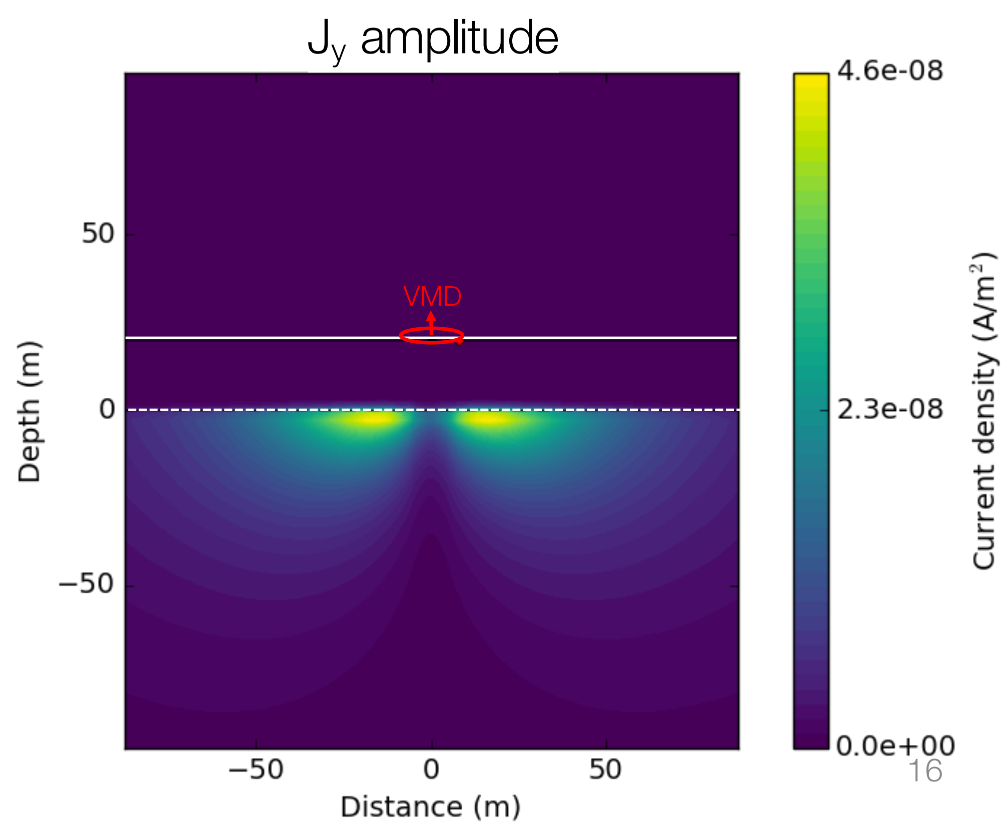


Current Density

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

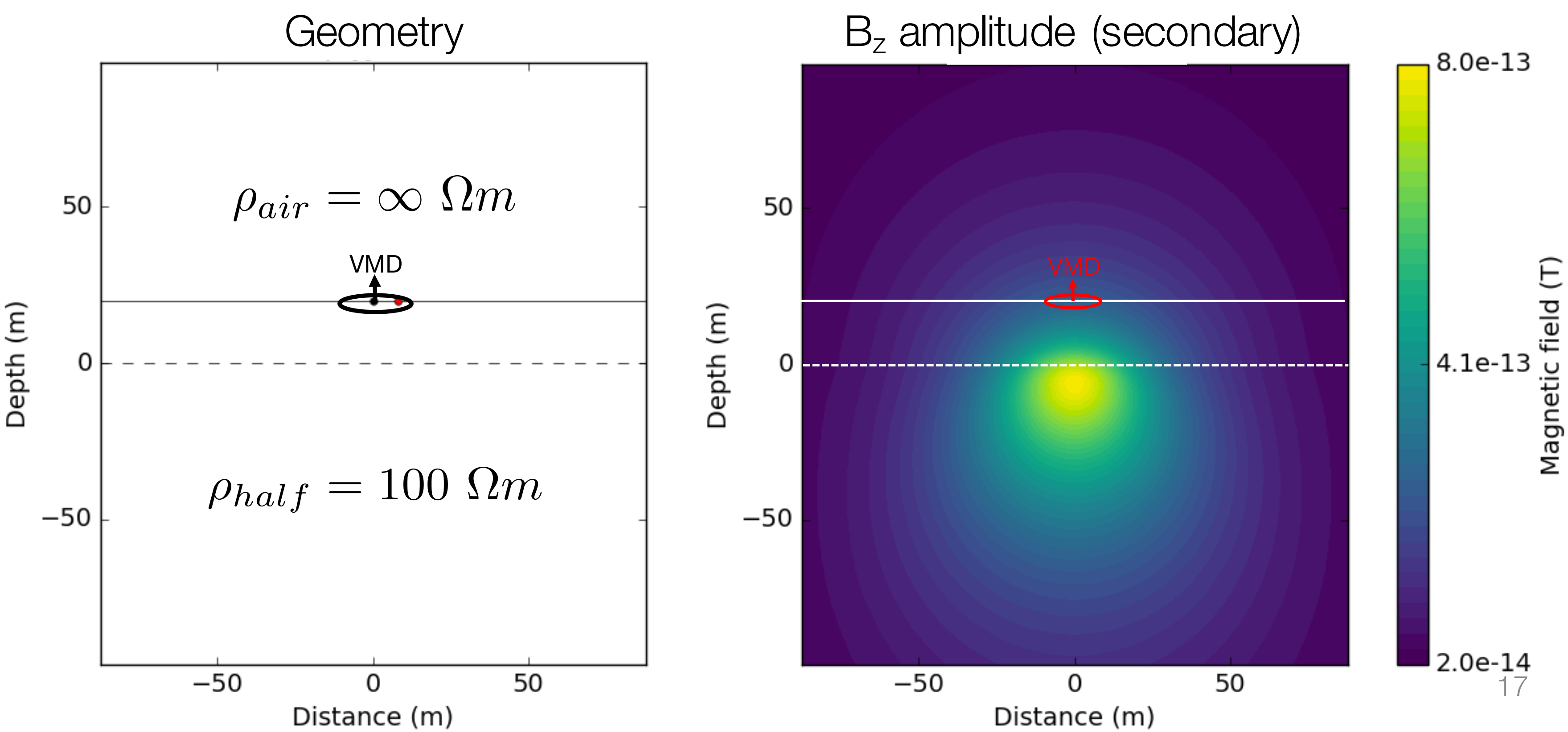






Secondary Magnetic Flux Density

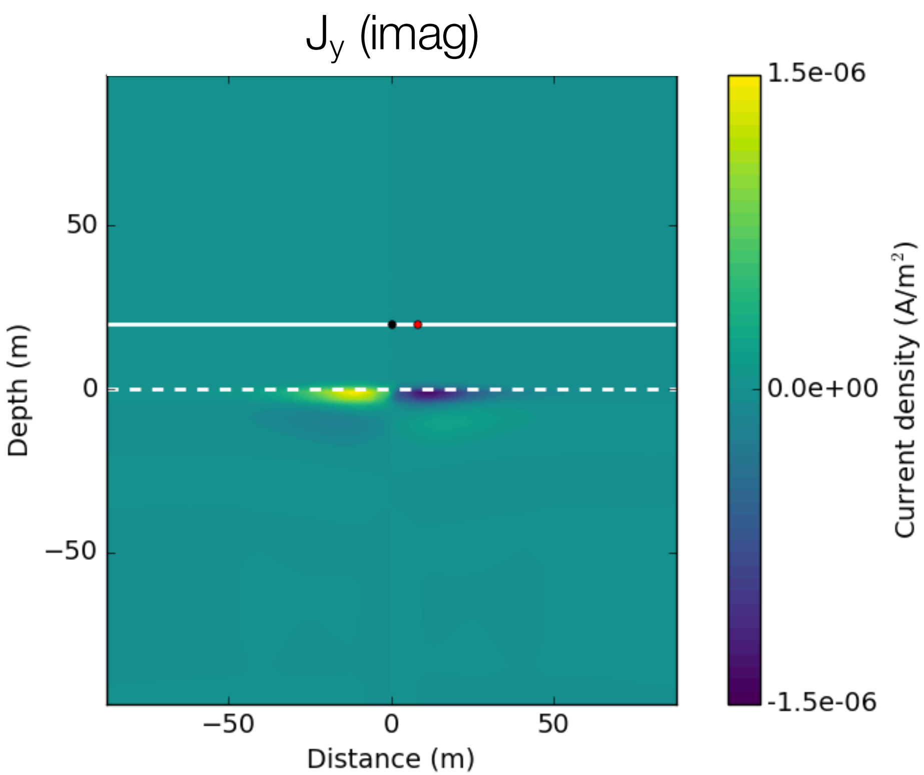
- Frequency = 10 kHz

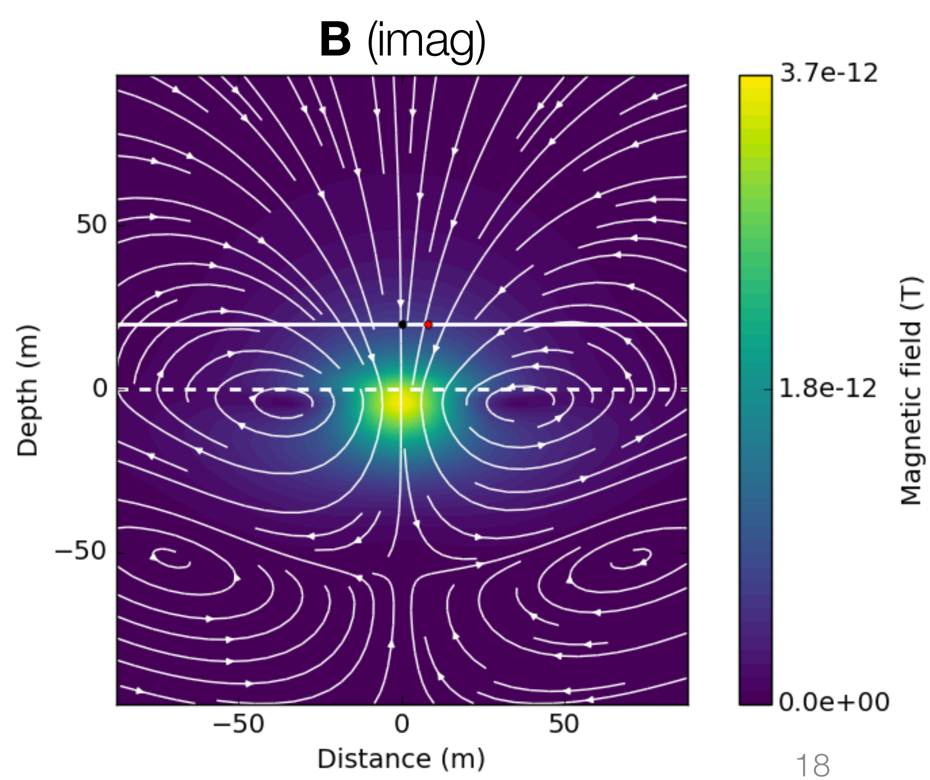


Effects of Frequency

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

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

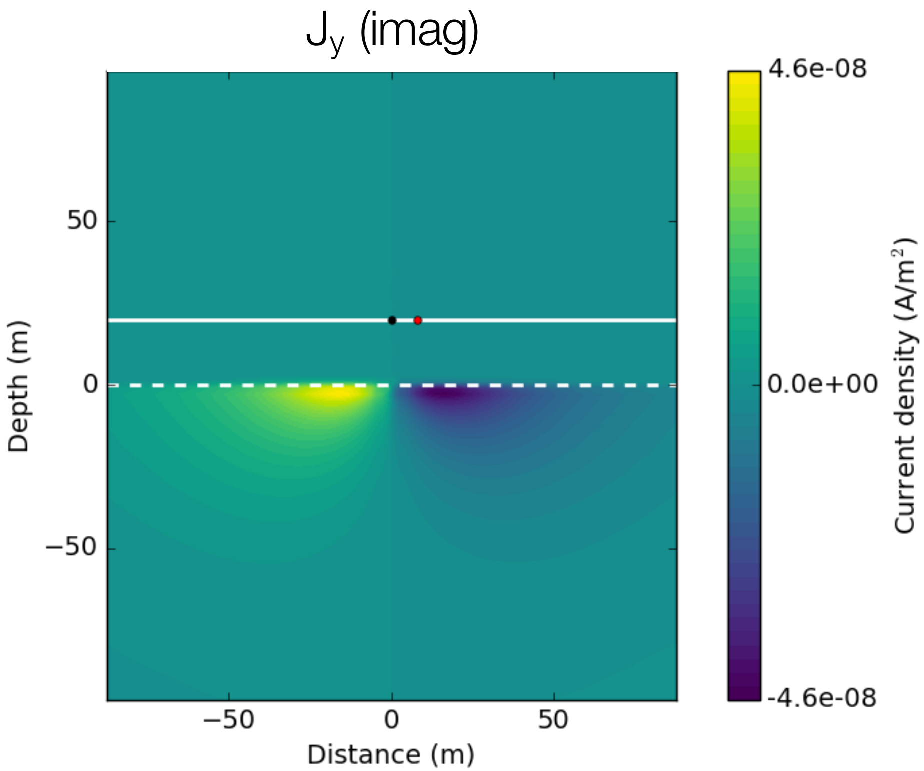


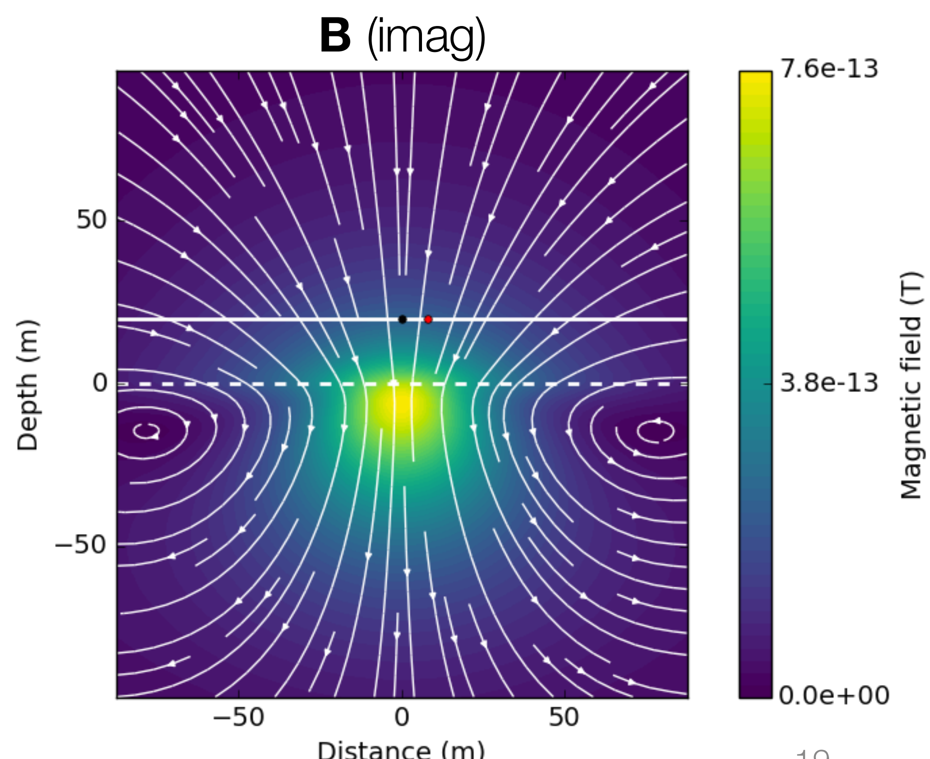


Effects of Frequency

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

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



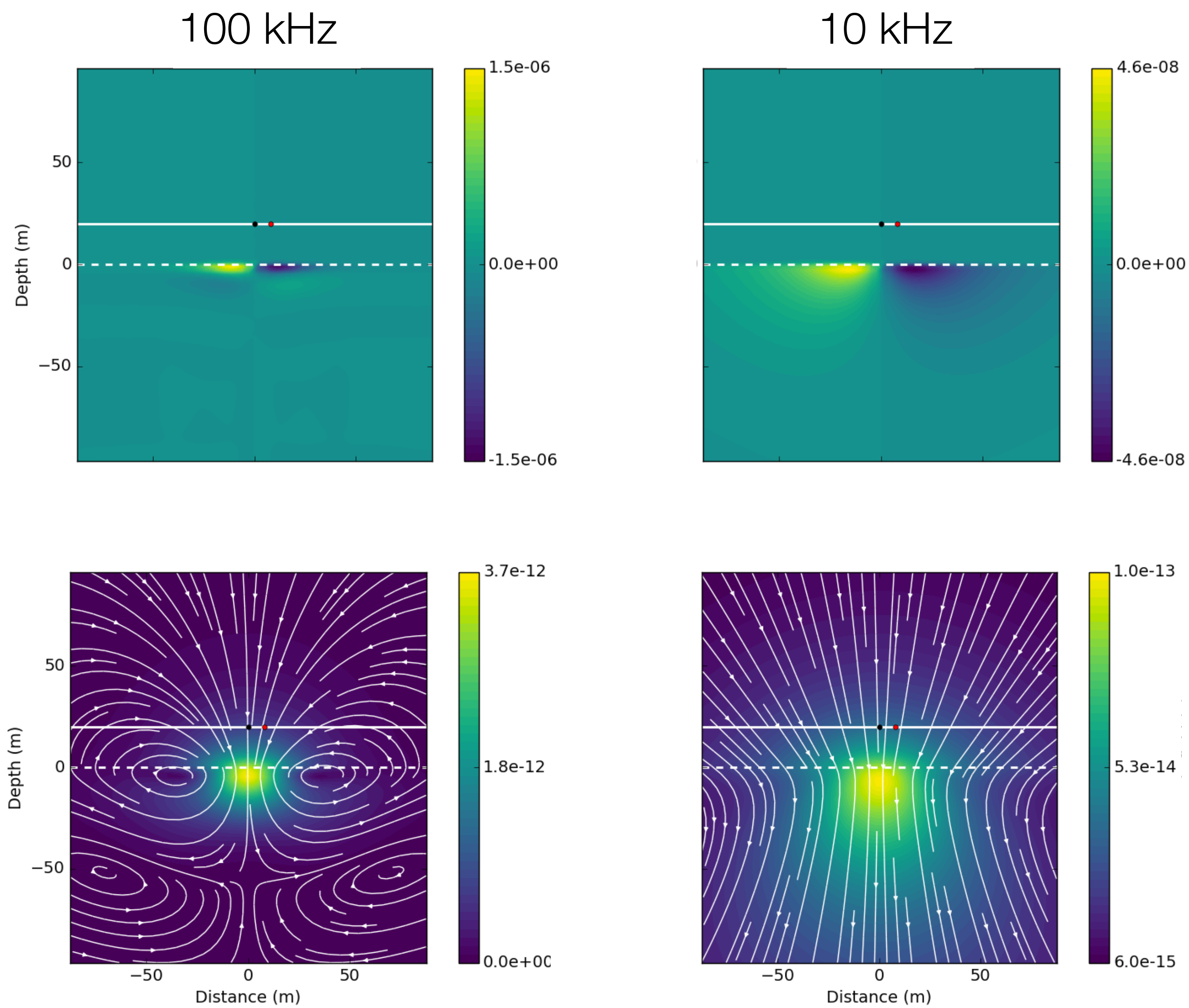


$$\delta = 503\sqrt{\frac{\rho}{f}}$$

Summary: Effects of Frequency

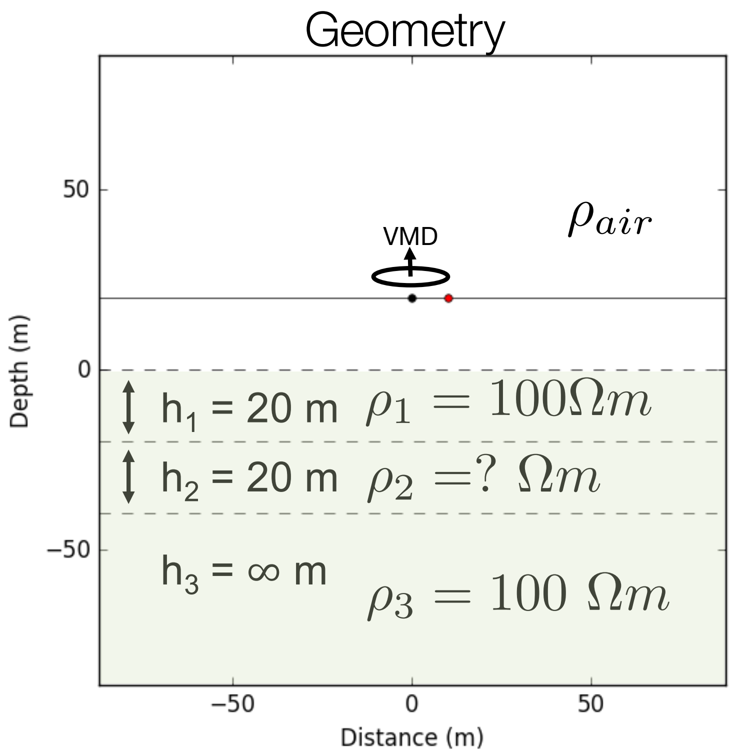
J_y imag.

B imag.



Layered earth

- 3 layers + air,
- ρ_2 varies



- Four different cases:
  - Halfspace

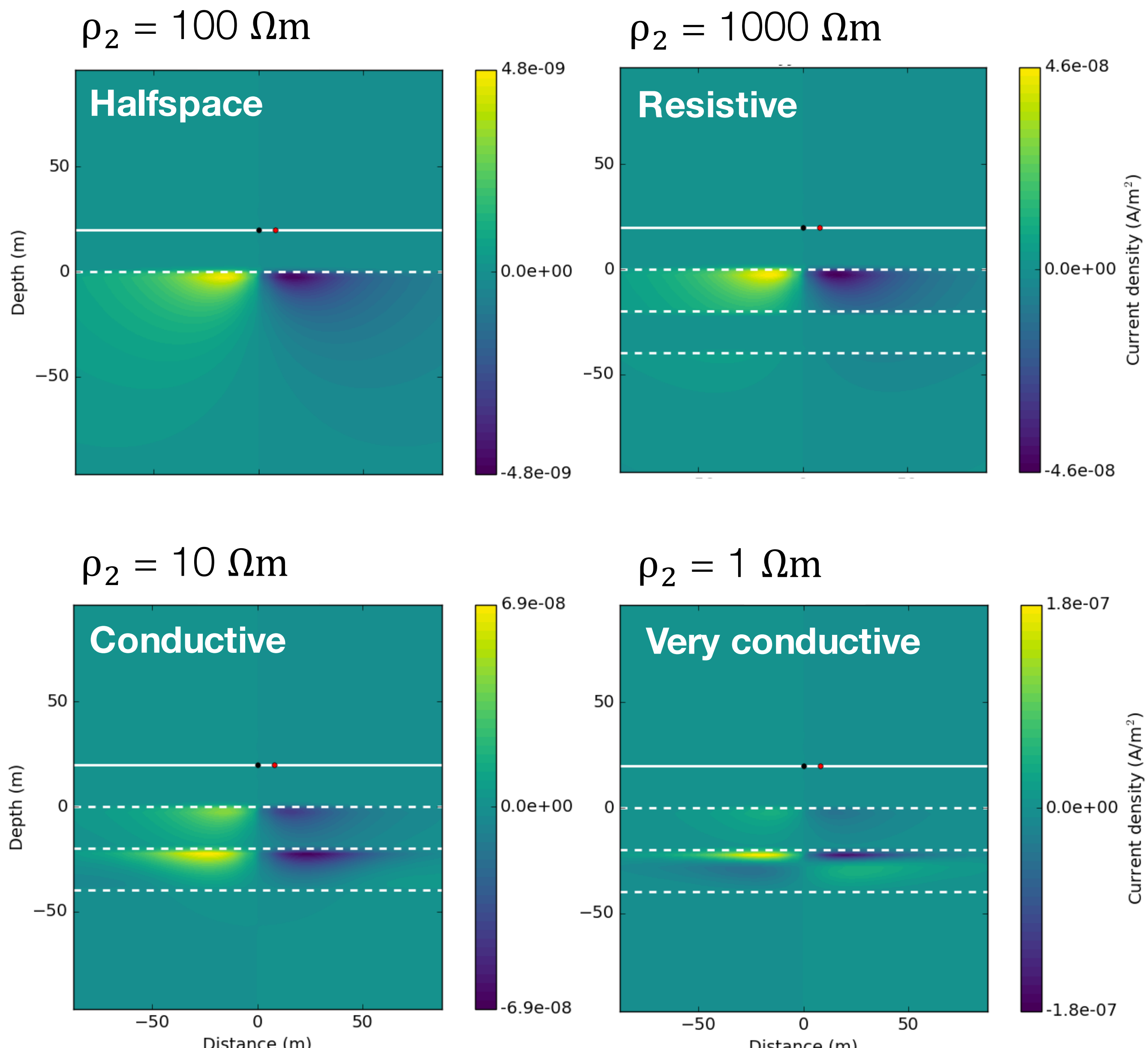
    $\rho_2 = 100\ \Omega\mathrm{m}$
  - Resistive

    $\rho_2 = 1000\ \Omega\mathrm{m}$
  - Conductive

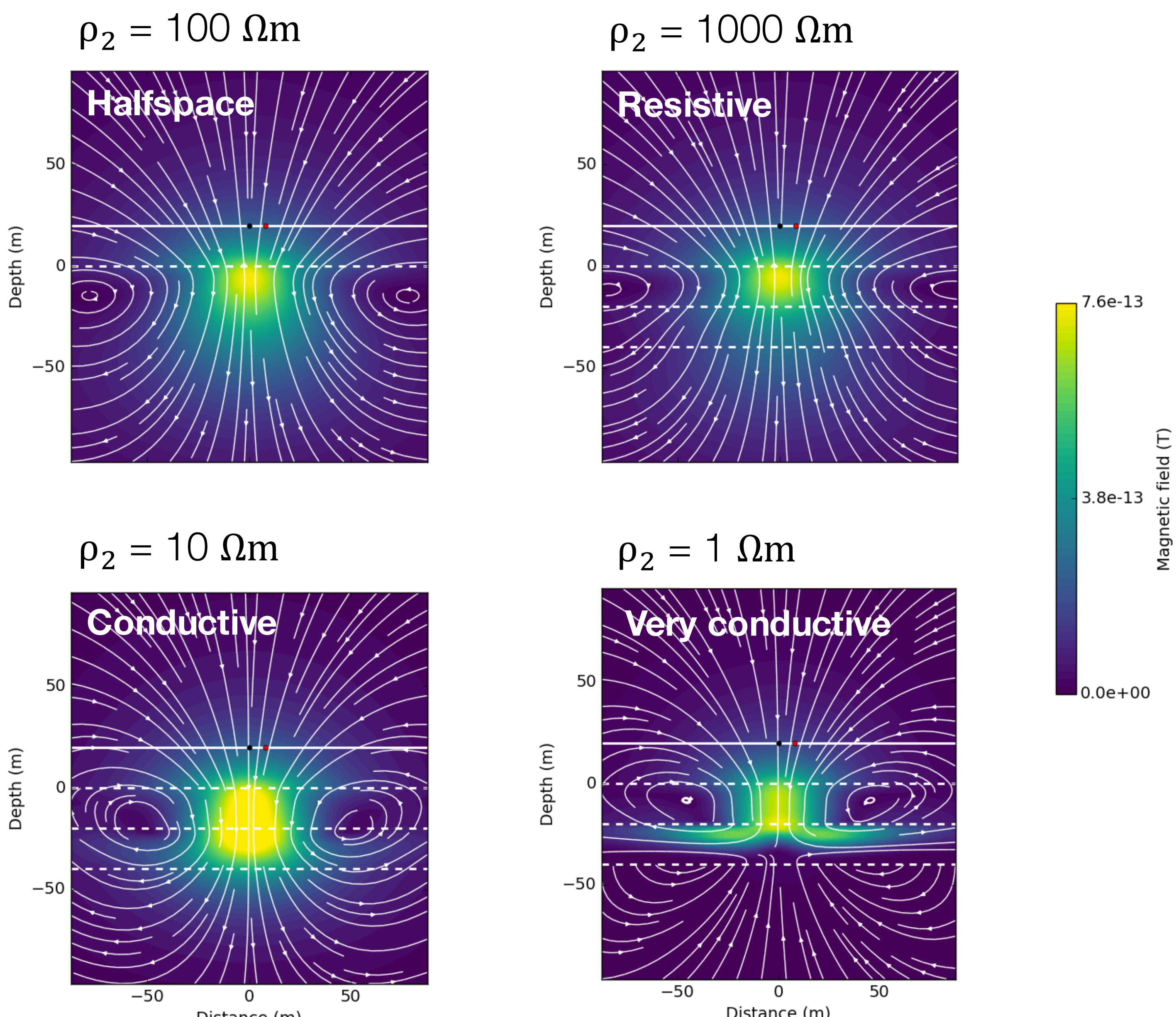
    $\rho_2 = 10\ \Omega\mathrm{m}$
  - Very conductive

    $\rho_2 = 1\ \Omega\mathrm{m}$
- Fields
  - J_y imag
  - Secondary **B** imag

Current density (J_y imag)

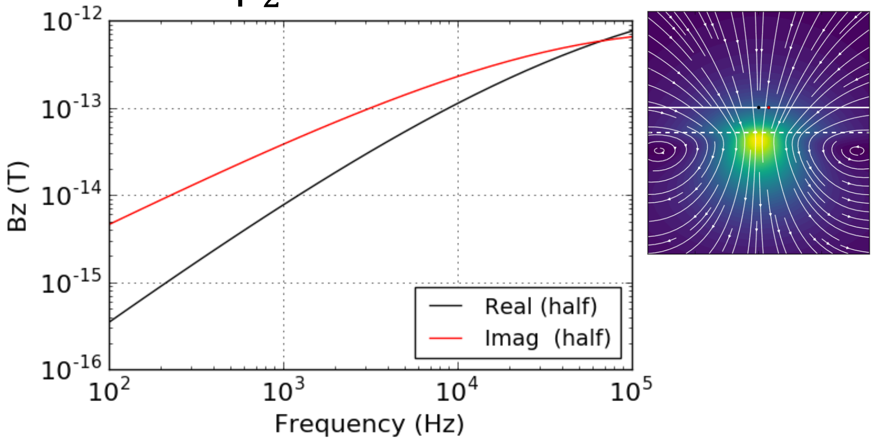


Magnetic flux density (**B** imag)

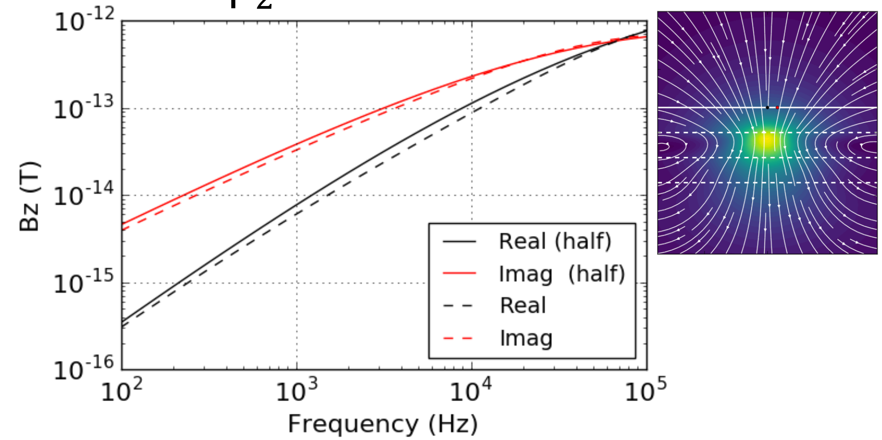


B_z sounding curves

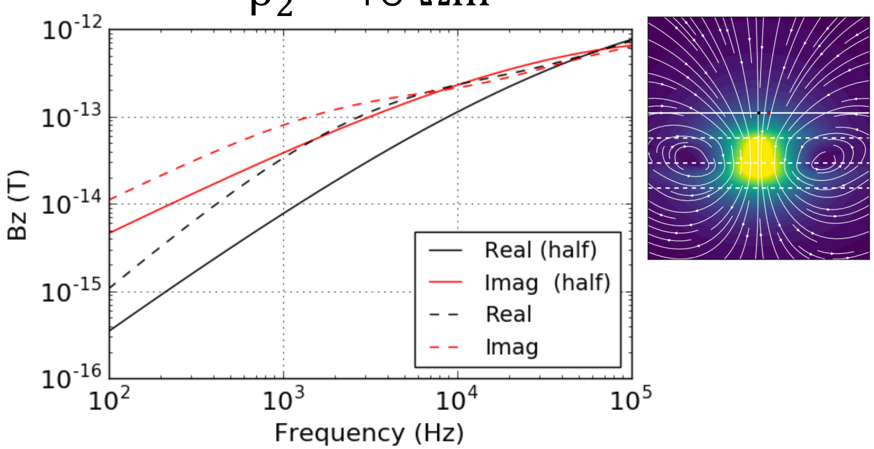
ρ_2 = 100 Ωm



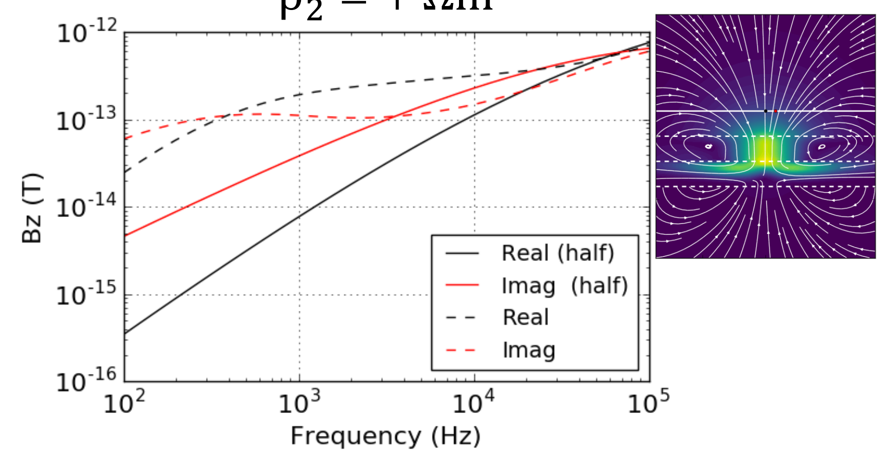
ρ_2 = 1000 Ωm



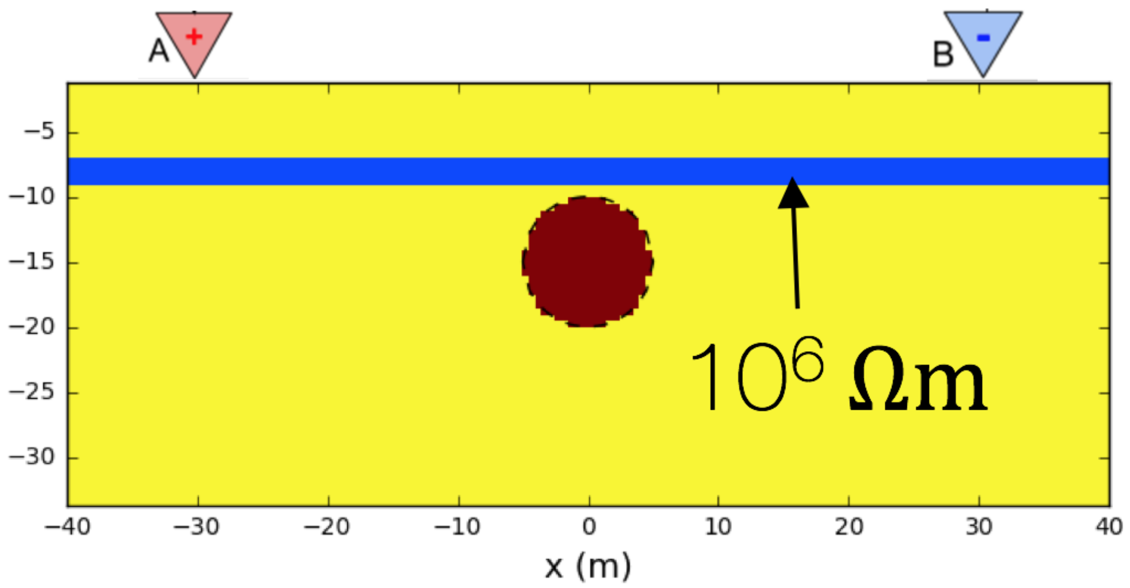
ρ_2 = 10 Ωm



ρ_2 = 1 Ωm

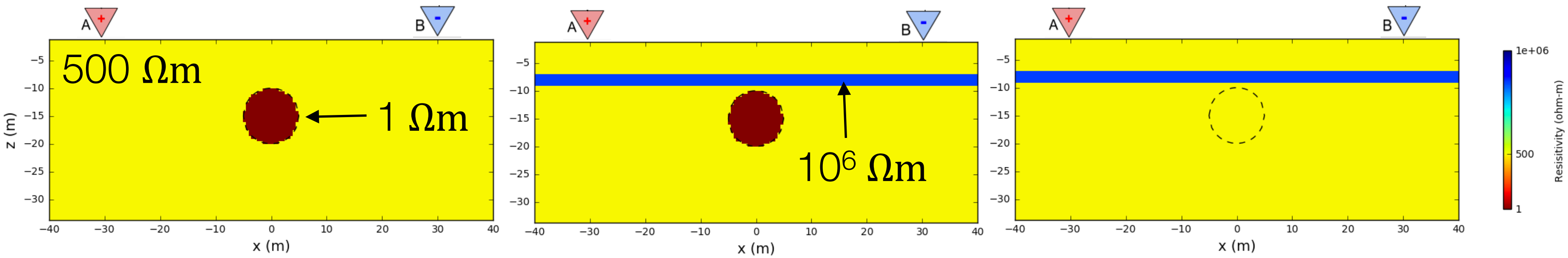


Back to the "shielding" problem



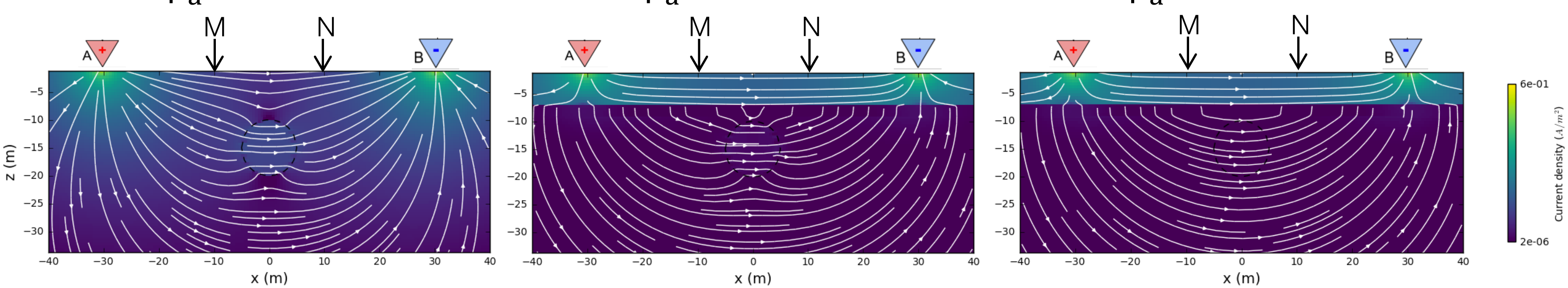
Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



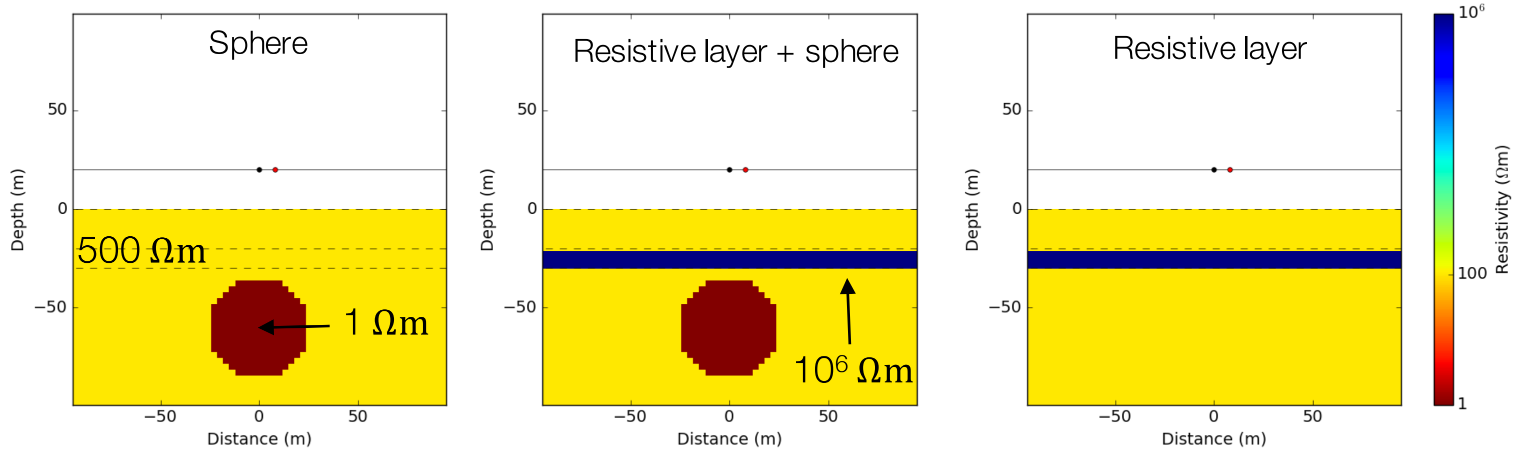
Currents and measured data at MN

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

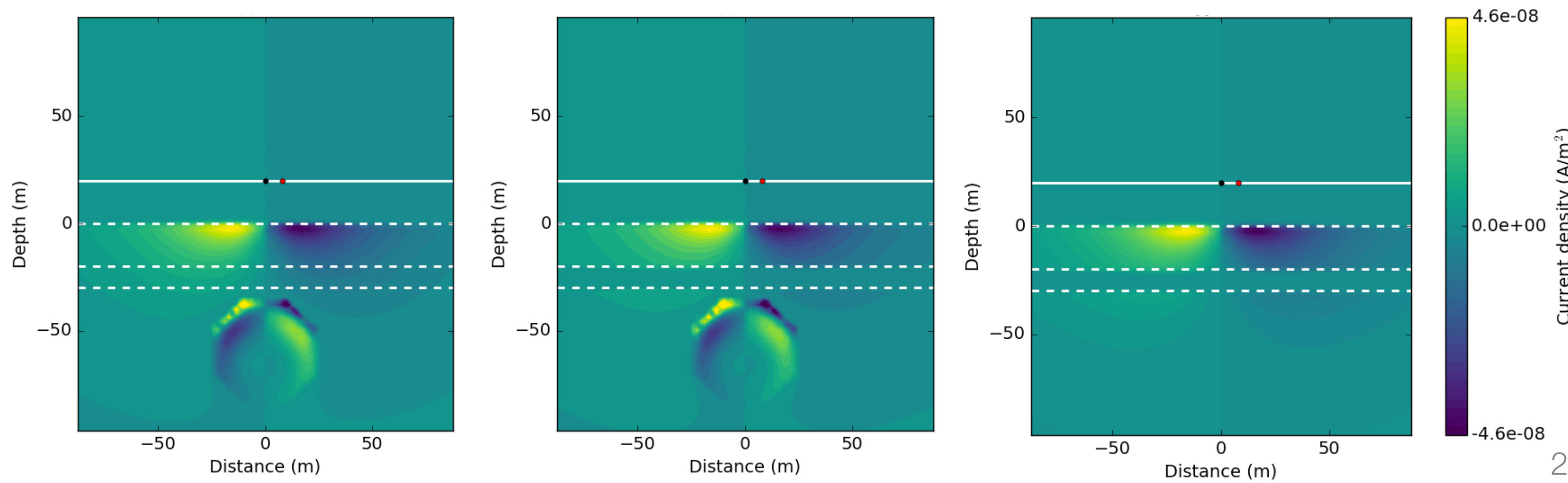


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

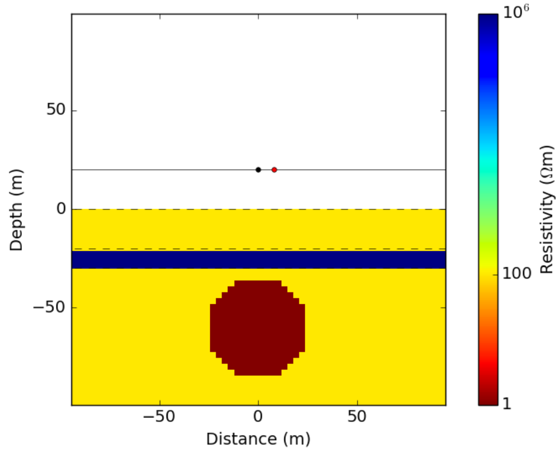


Currents (J_y imag)

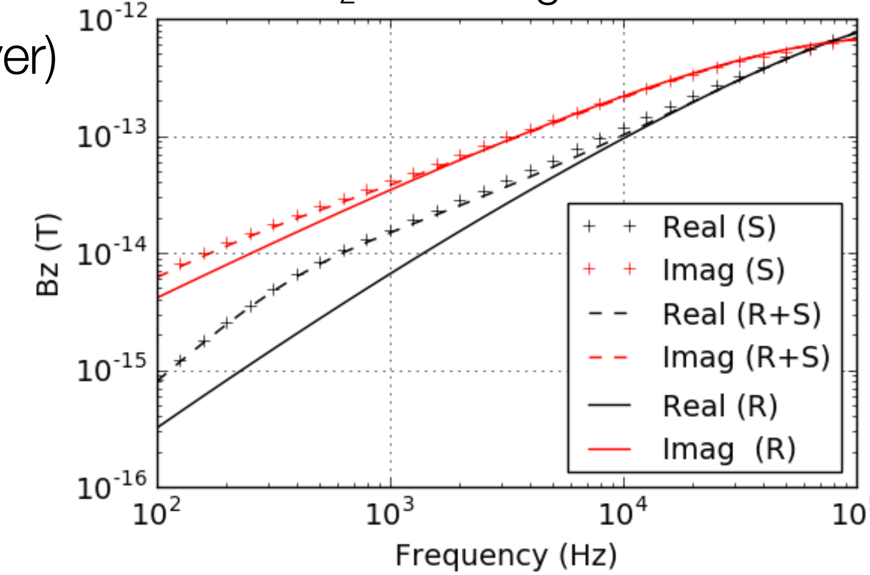


Shielding: EM with resistive layer

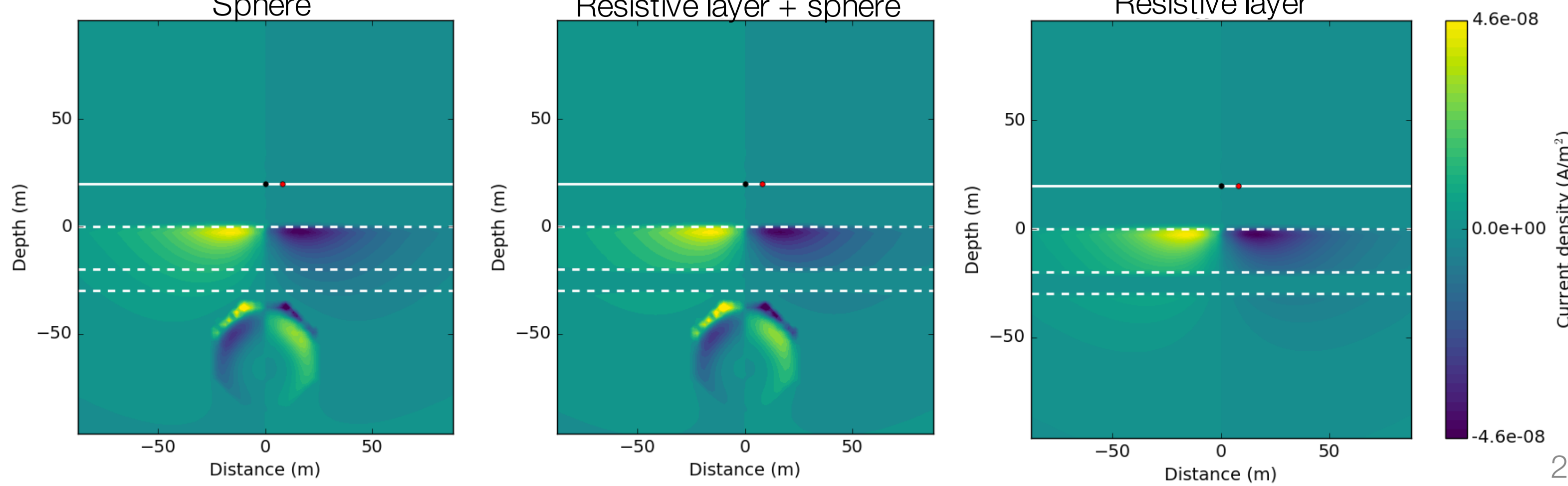
Resistivity models (thin **resistive** layer)



B_z sounding curves

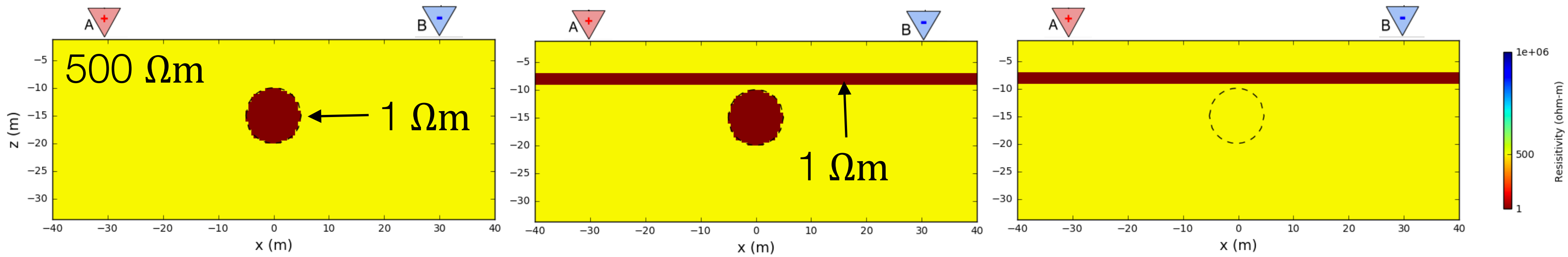


Currents (J_y imag)



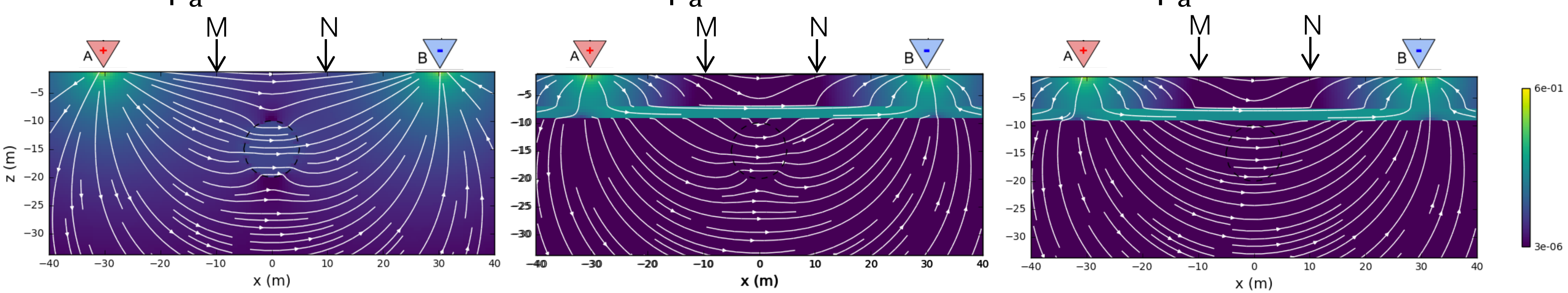
Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)



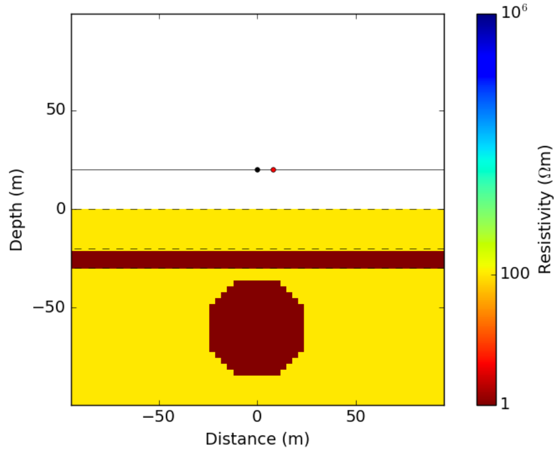
Currents and measured data at MN

$\rho_a = 430\ \Omega\mathrm{m}$ $\rho_a = 47\ \Omega\mathrm{m}$ $\rho_a = 47\ \Omega\mathrm{m}$

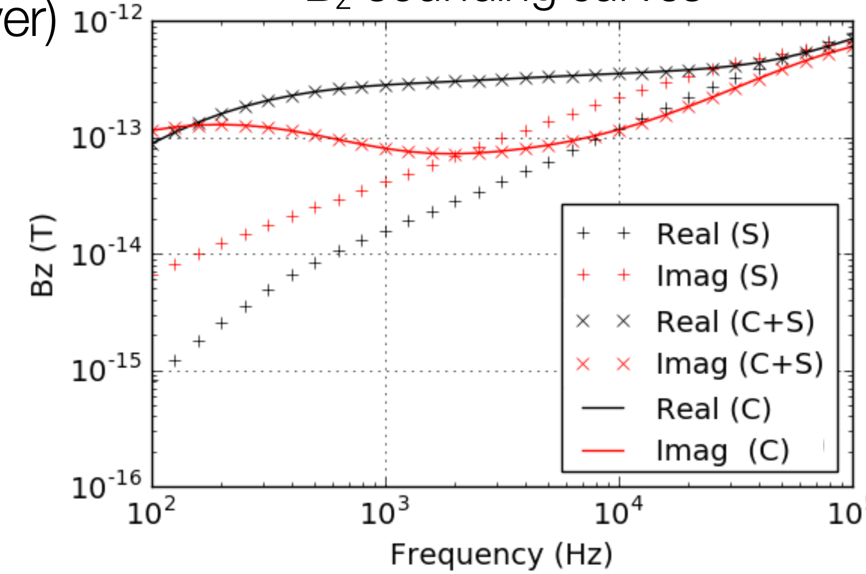


Shielding: EM with conductive layer

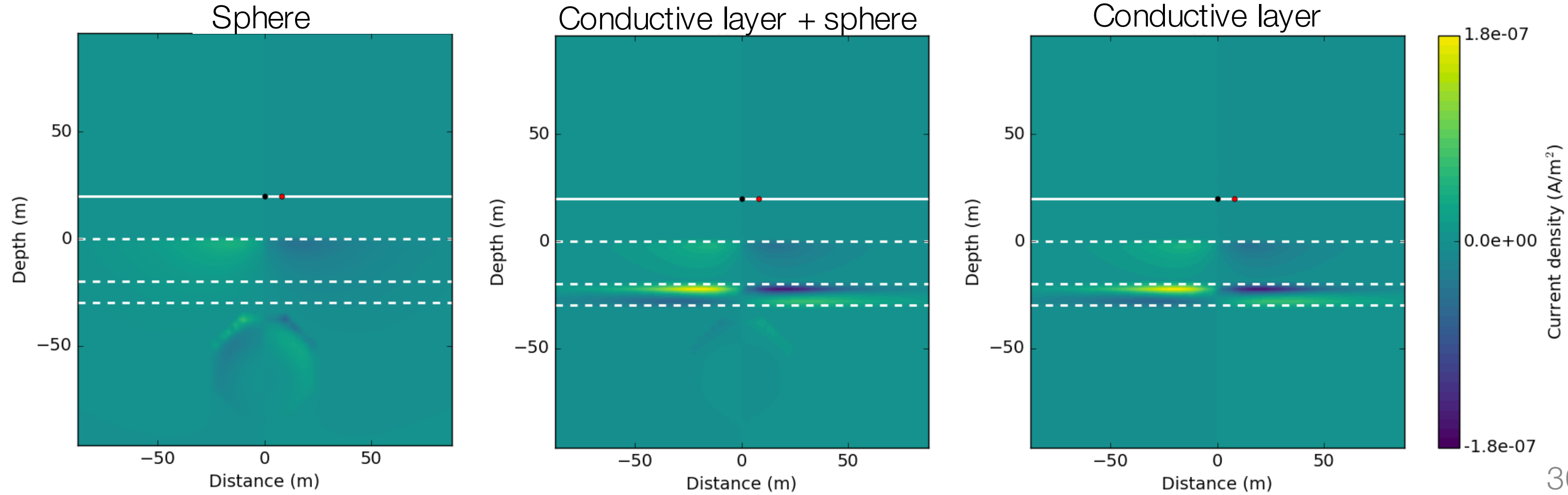
Conductivity models (thin **resistive** layer)



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

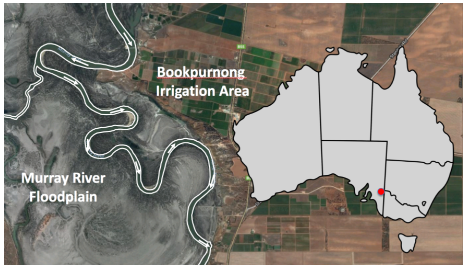
Time Domain EM

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

Case History: Bookpurnong

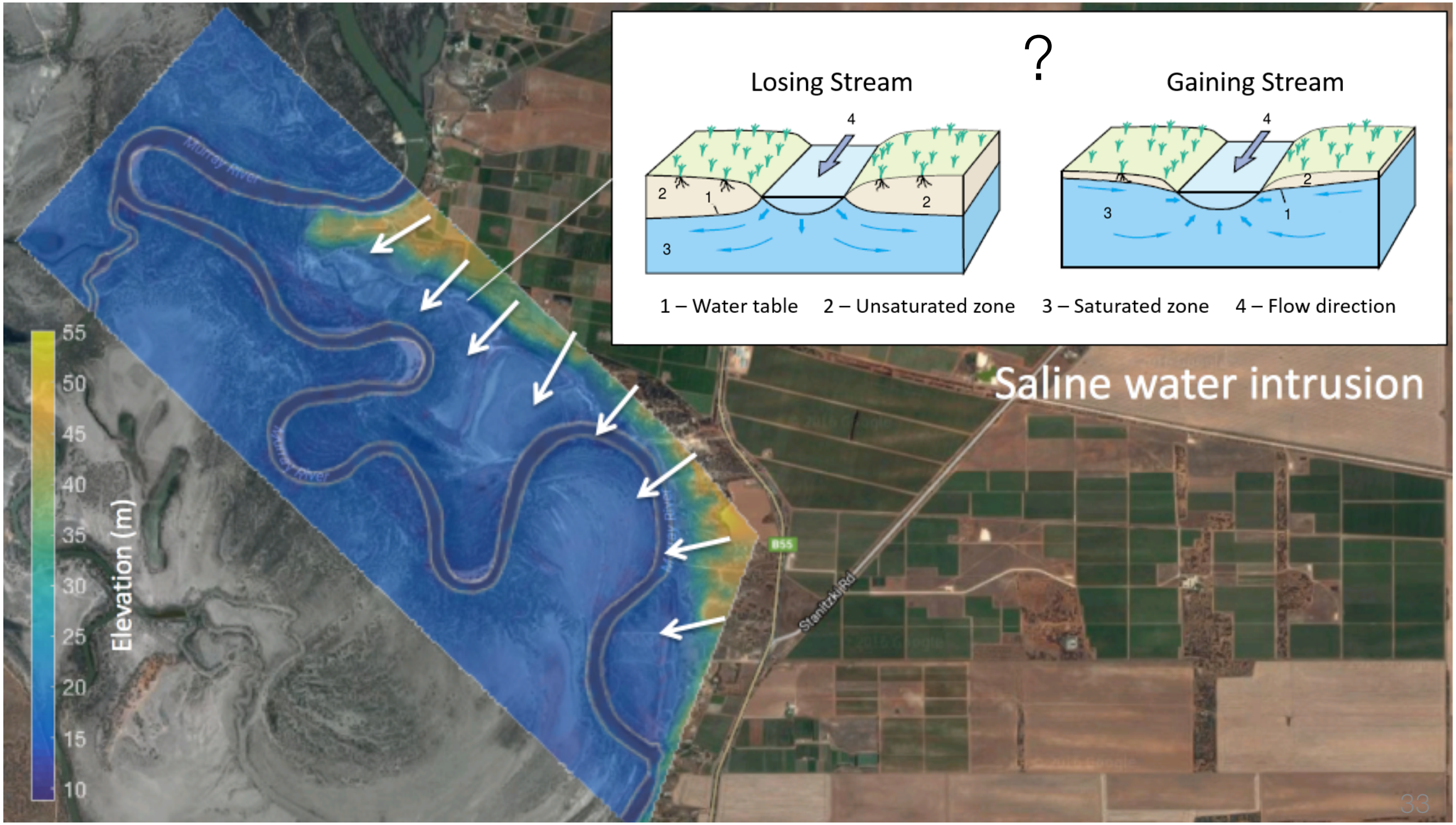
Viezzoli et al., 2009

Setup



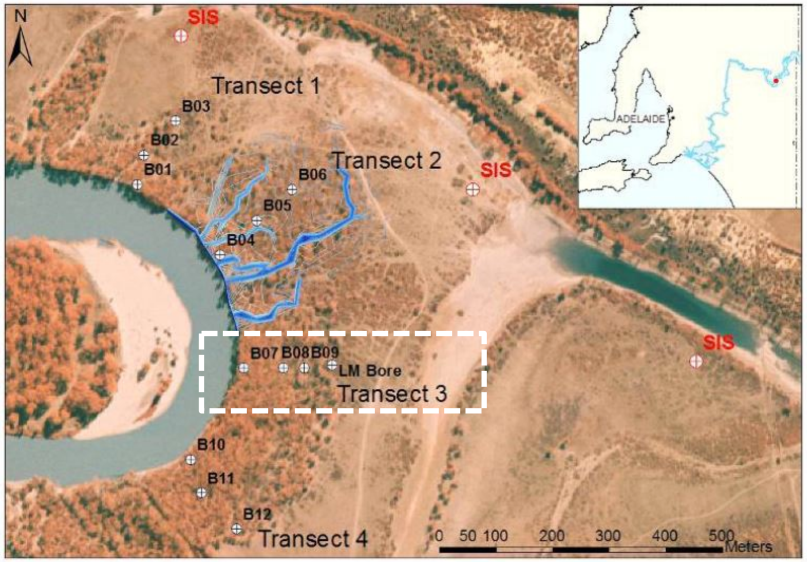
Geoscience Australia project

- Characterizing river salination



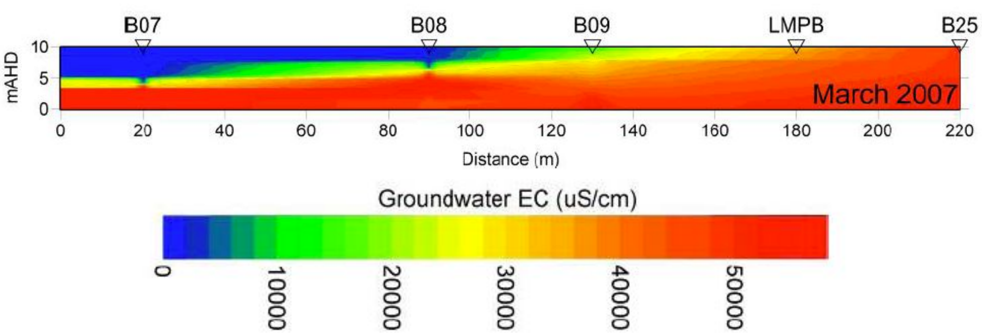
Properties

Location map for salinity measurements



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

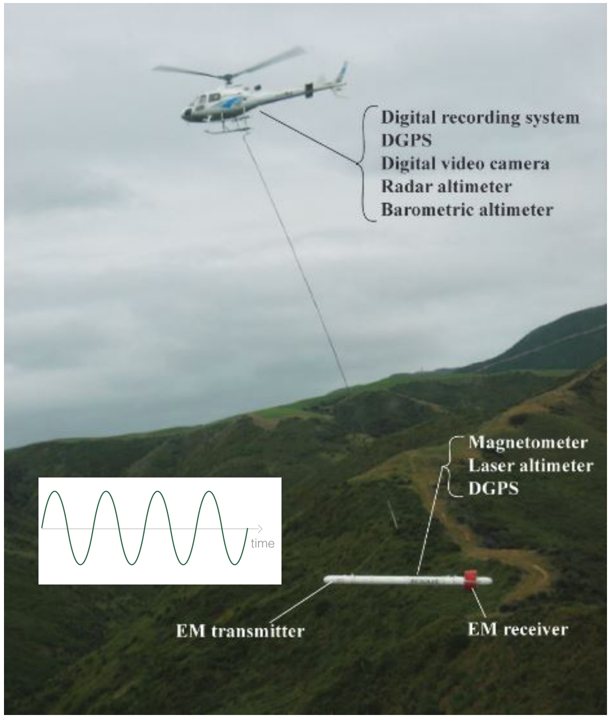
Conductivity from salinity measurements



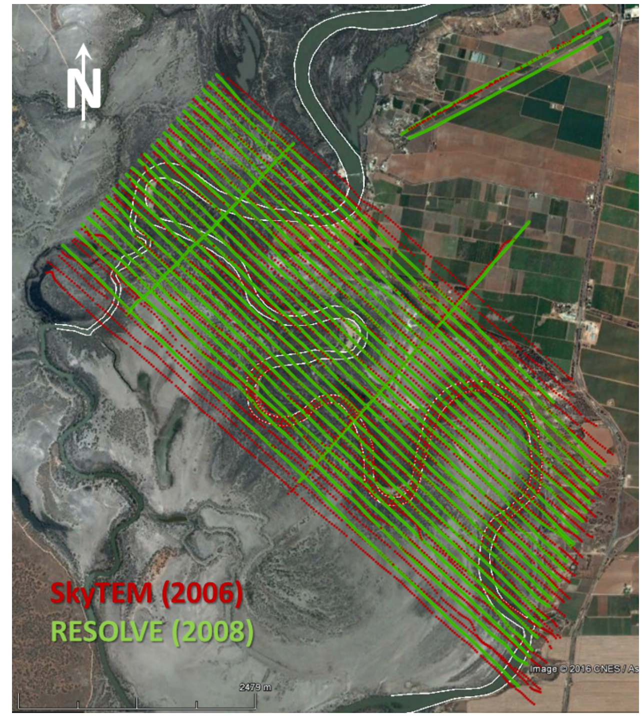
Holland et. al., 2008.

Survey

Resolve system (2008)



Flight lines

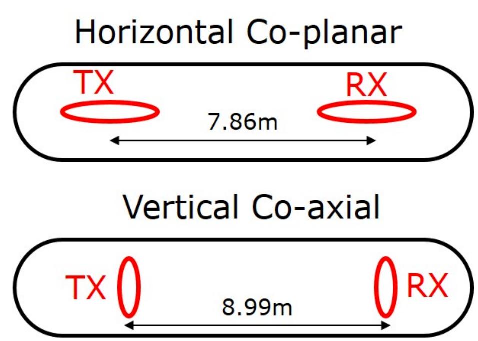


Horizontal Co-planar (HCP) frequencies:

- 382, 1822, 7970, 35920 and 130100 Hz

Vertical Co-axial (VCA) frequencies:

- 3258 Hz

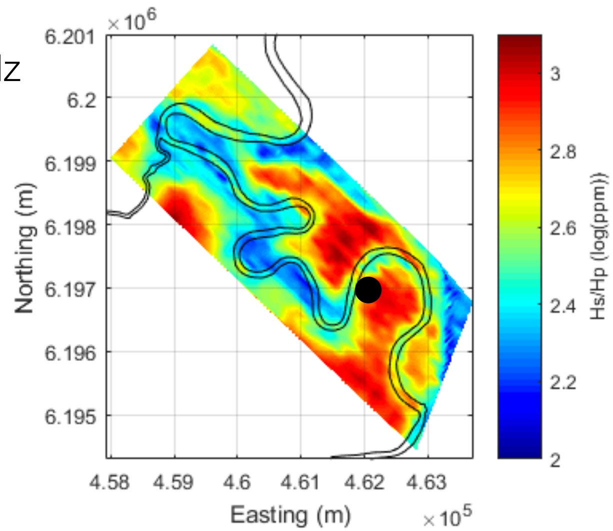


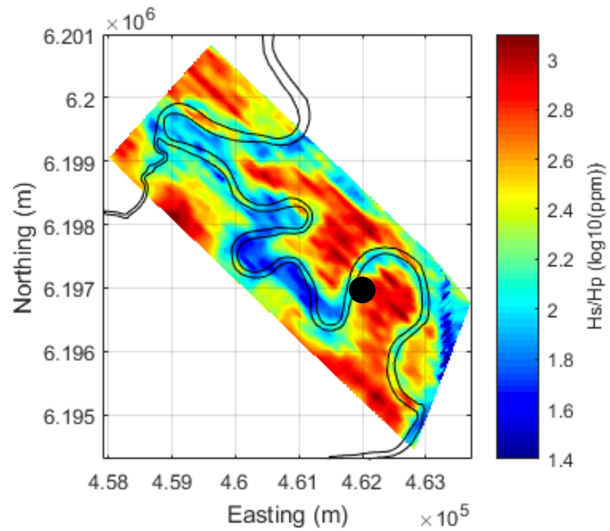
Horizontal Co-planar (HCP) data

In-Phase (Real)

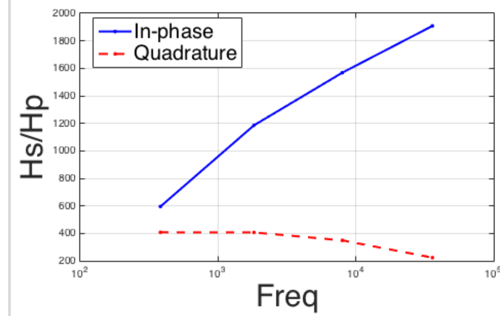
Quadrature (Imaginary)

382 Hz

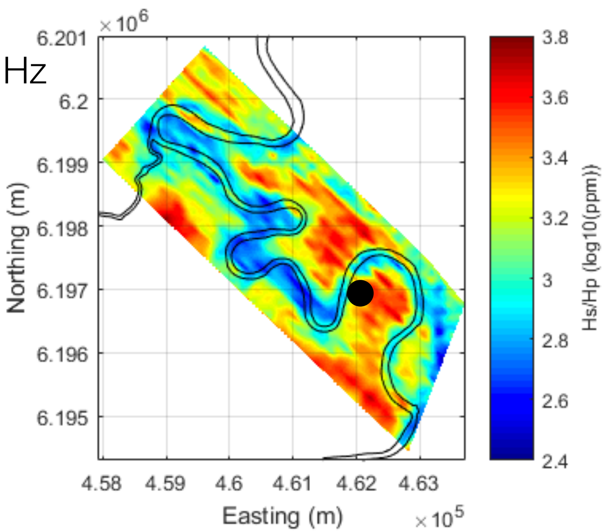


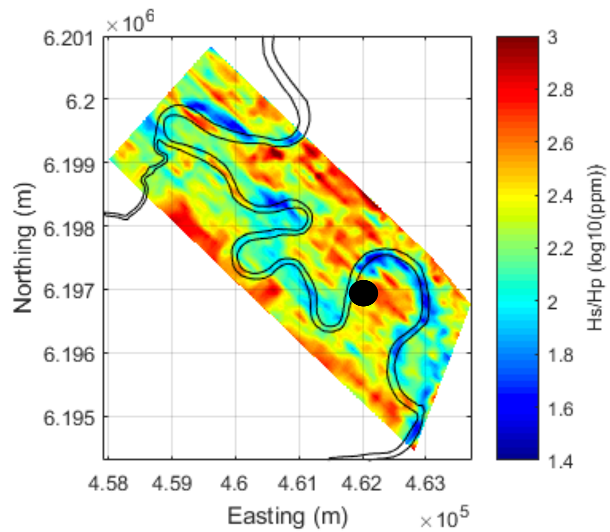


Sounding curve

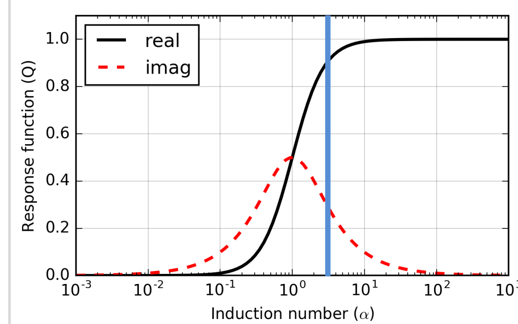


35920 Hz



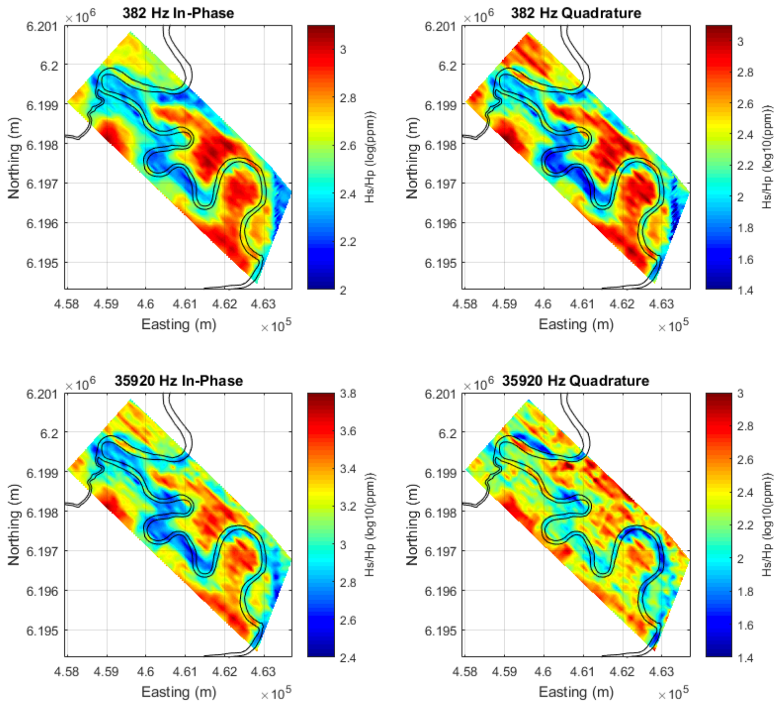


Response curve

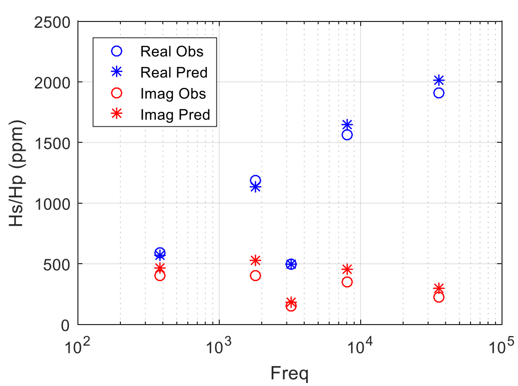


Processing: 1D inversion

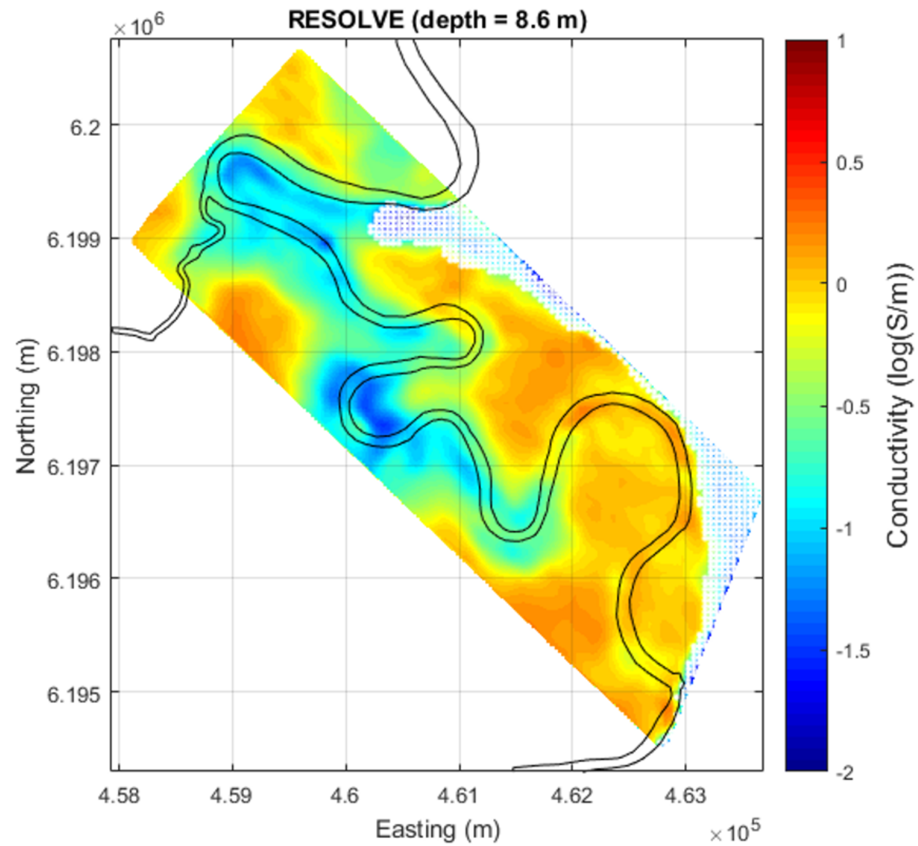
Data



Data fit

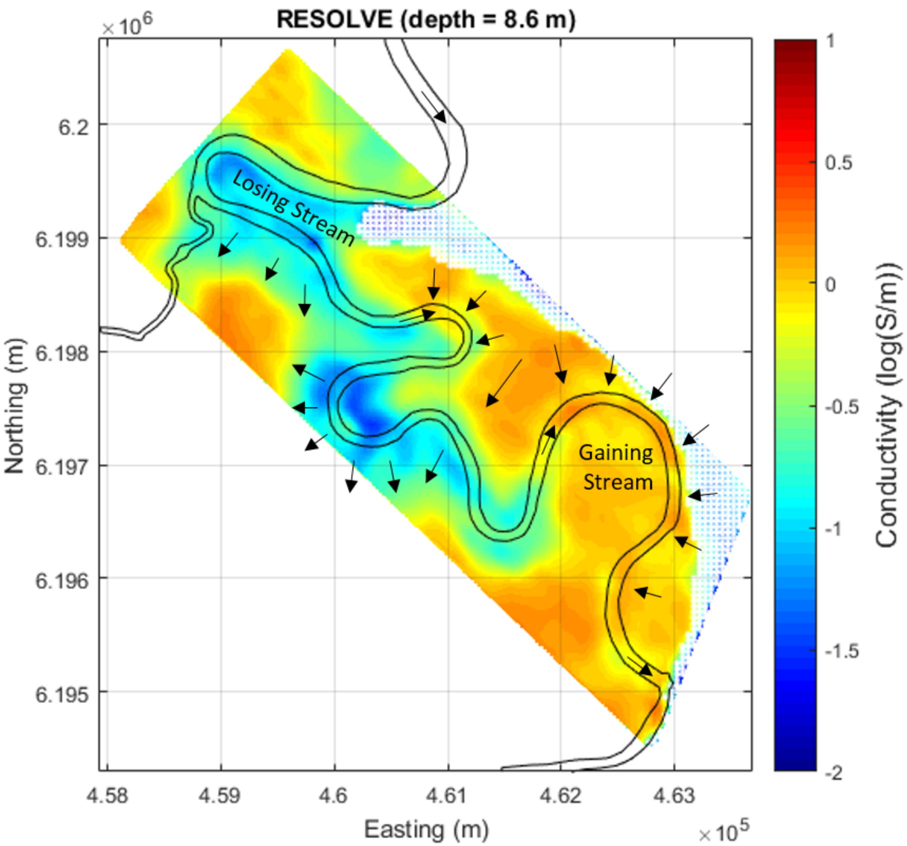


Conductivity model (stitched)

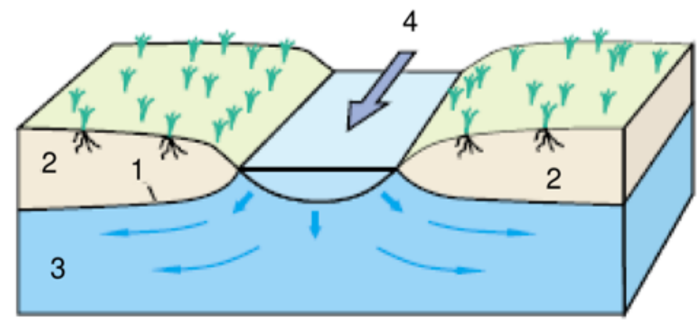


Interpretation

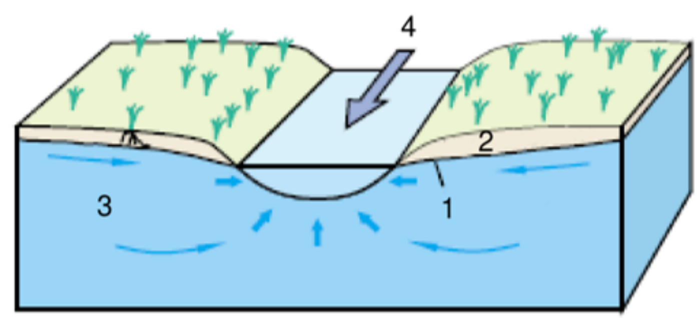
Conductivity model (stitched)



Losing Stream



Gaining Stream

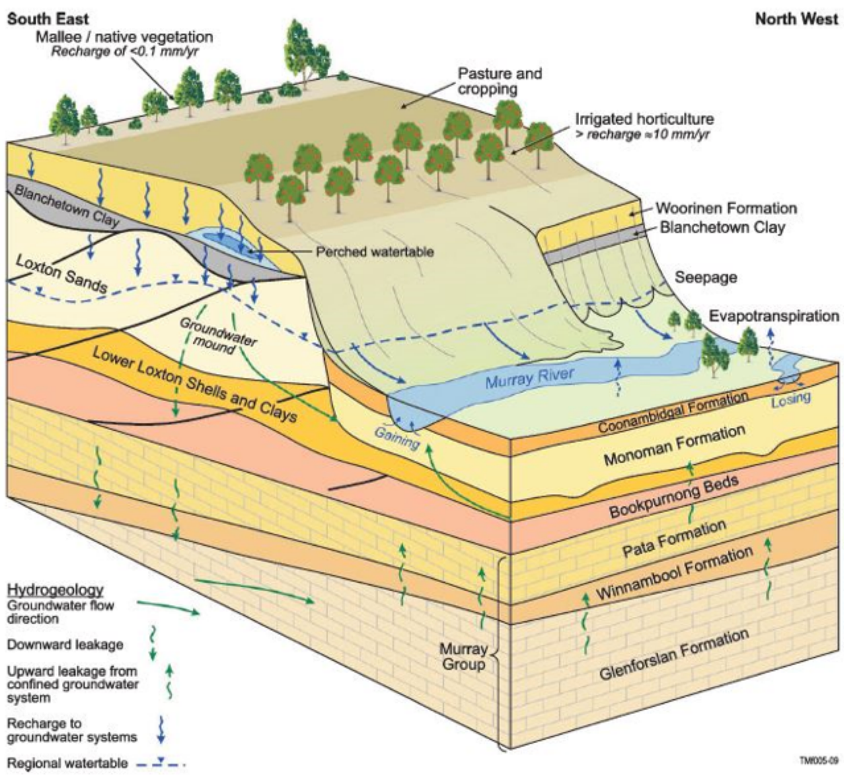


1 – Water table 2 – Unsaturated zone

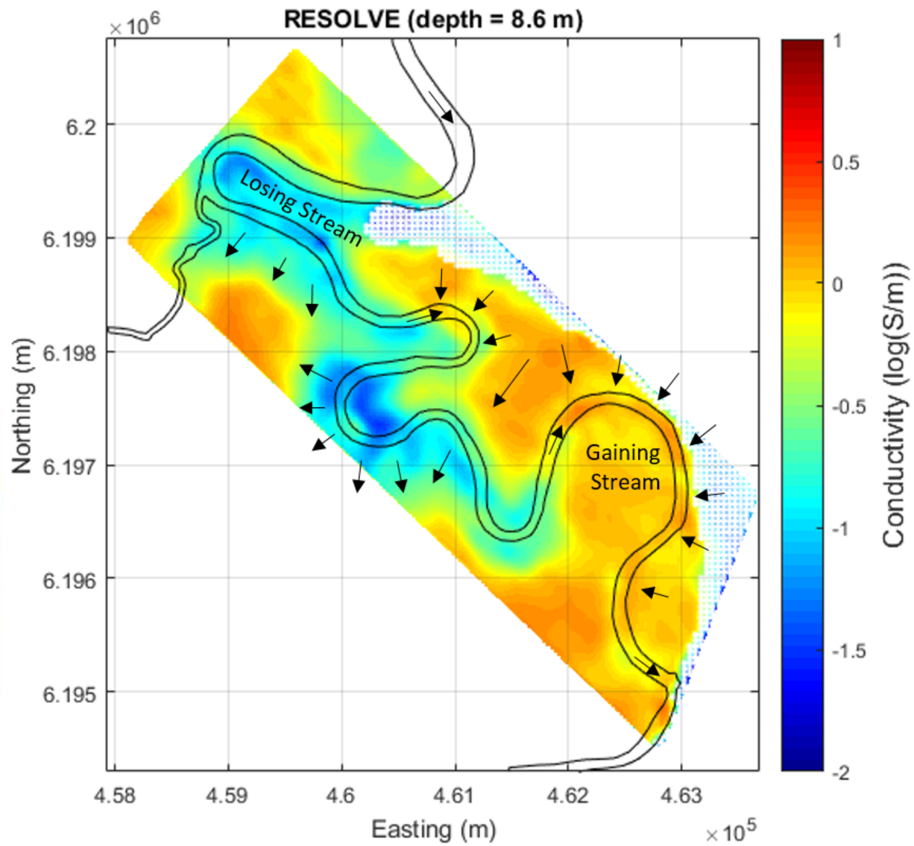
3 – Saturated zone 4 – Flow direction

Synthesis

Hydrological model



Conductivity model (stitched)



Outline

Setup

- Basic experiment
- Transmitters, Receivers

Frequency Domain EM

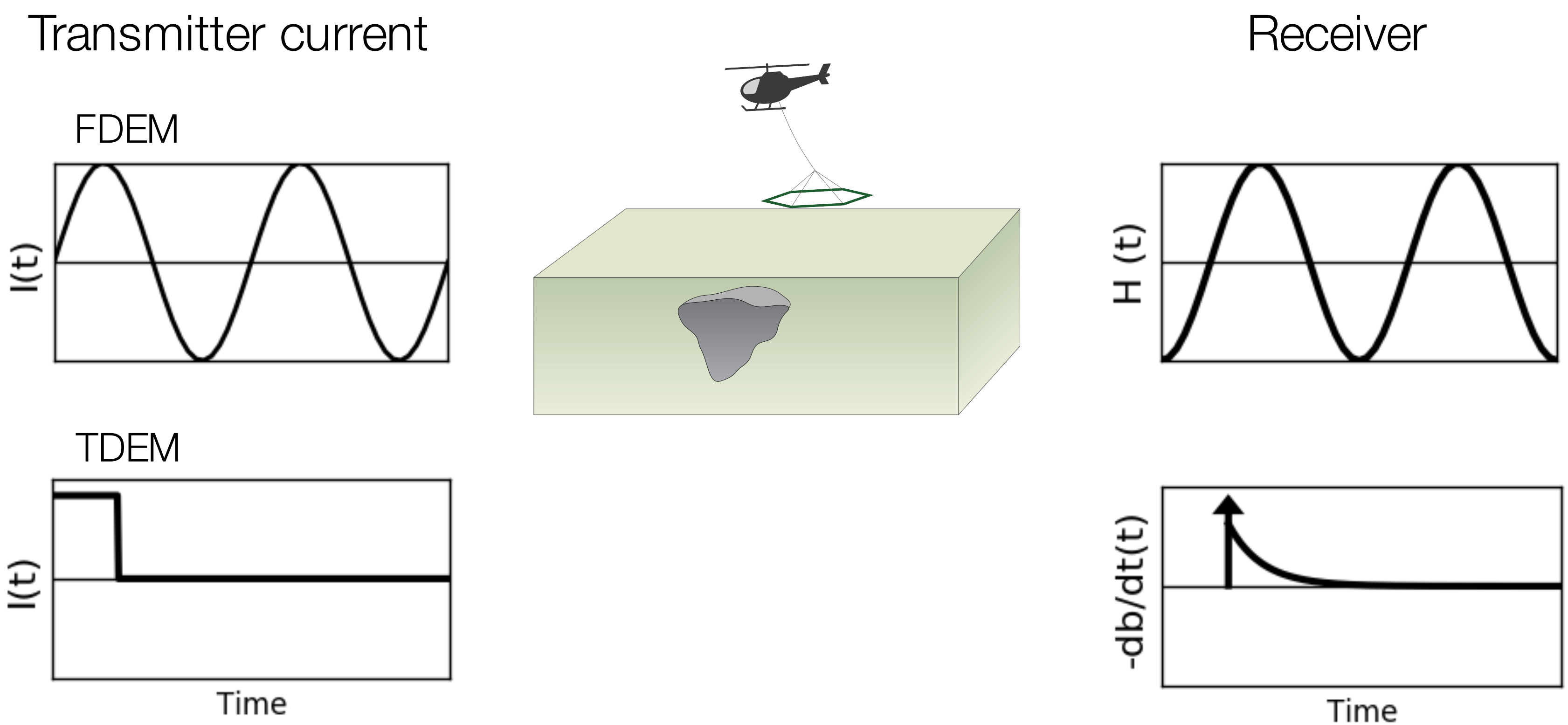
- Vertical Magnetic Dipole
- Effects of Frequency
- Case History – Ground water

Time Domain EM

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

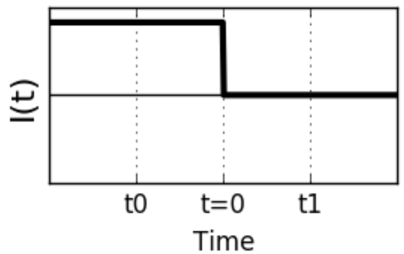
EM with Inductive Sources

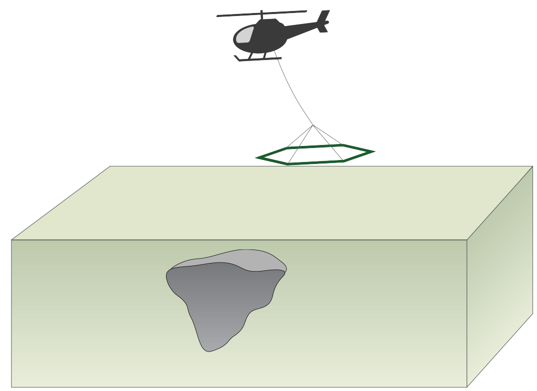
- Induction principles are the same for
  - FDEM: Frequency domain EM
  - TDEM: Time domain EM



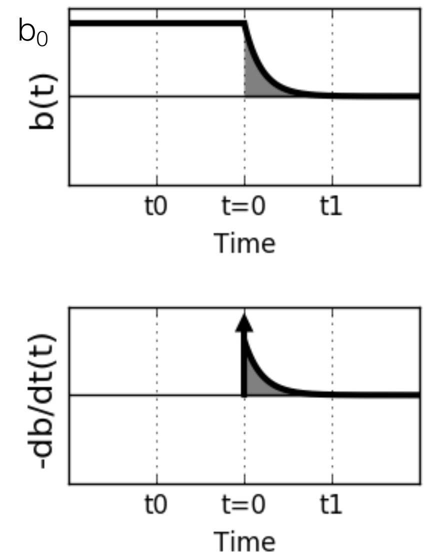
EM with Inductive Sources: Time Domain

Transmitter current





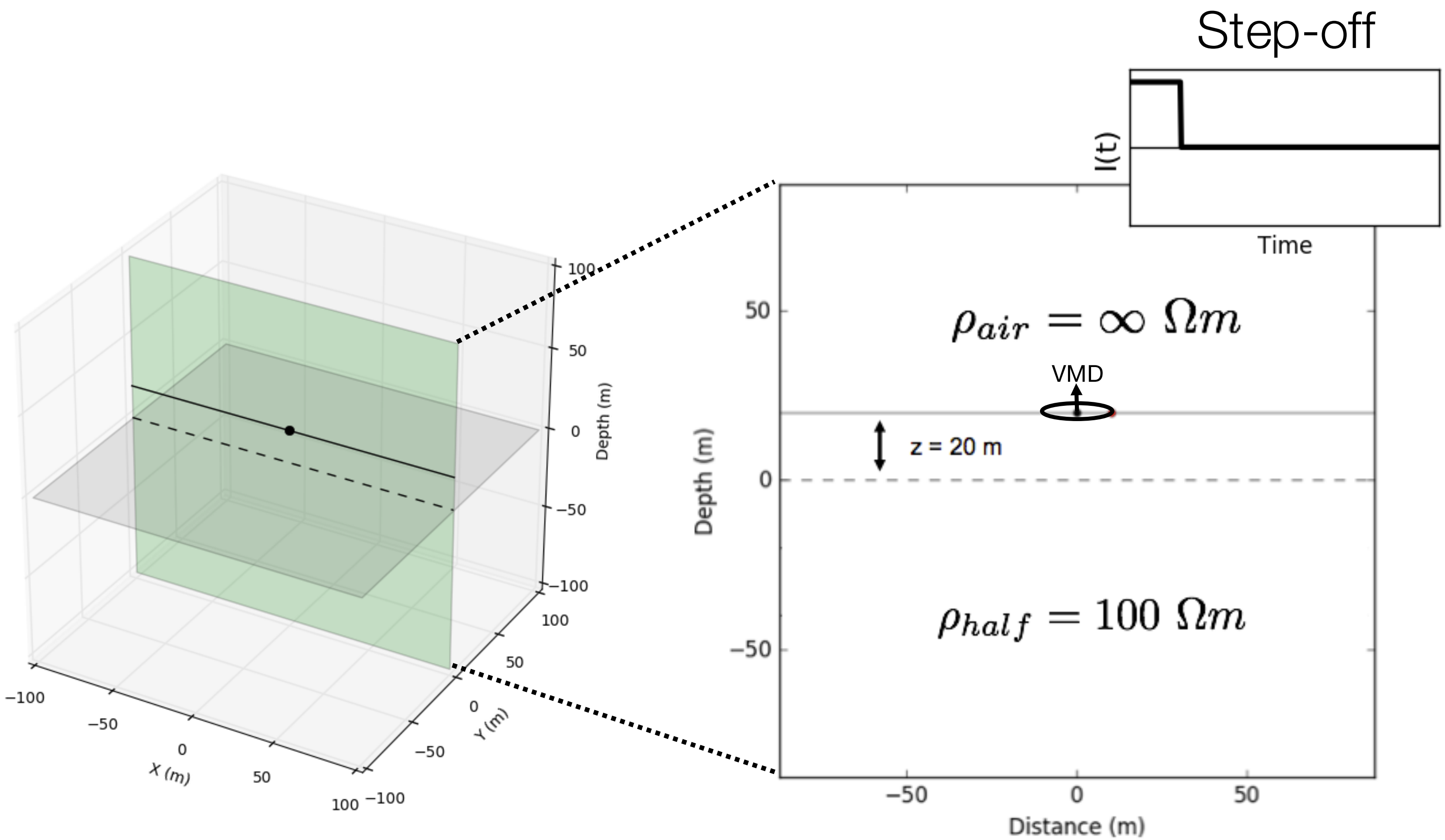
Receiver



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

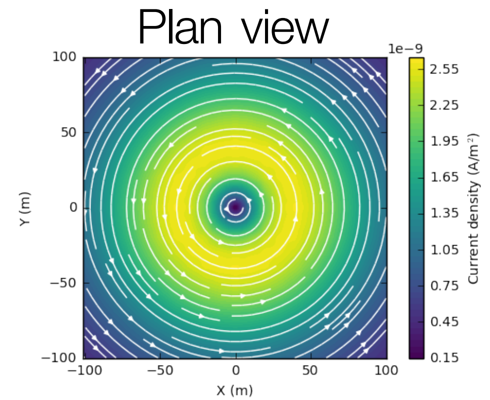
$\delta(t)$: Dirac-delta function

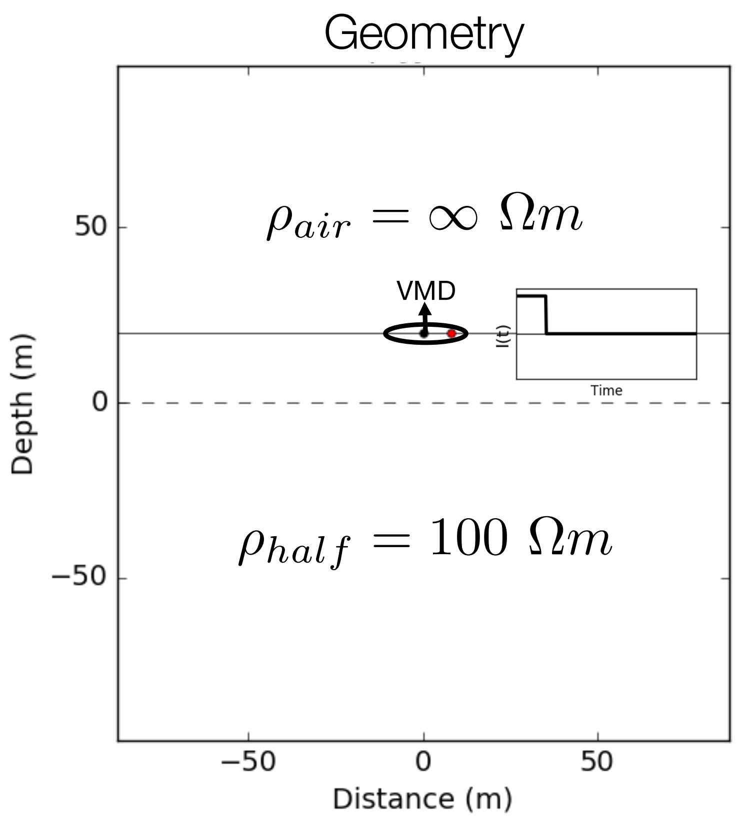
Vertical Magnetic Dipole over a halfspace (TDEM)

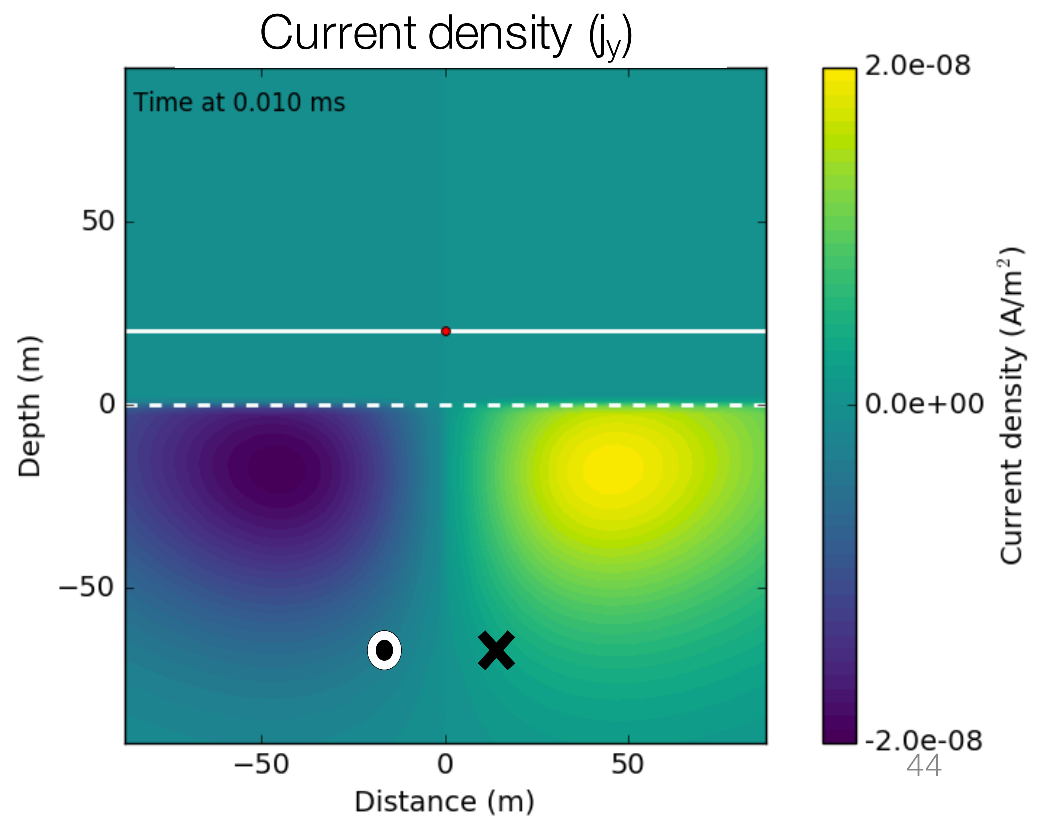


Current Density

- Time: 0.01ms

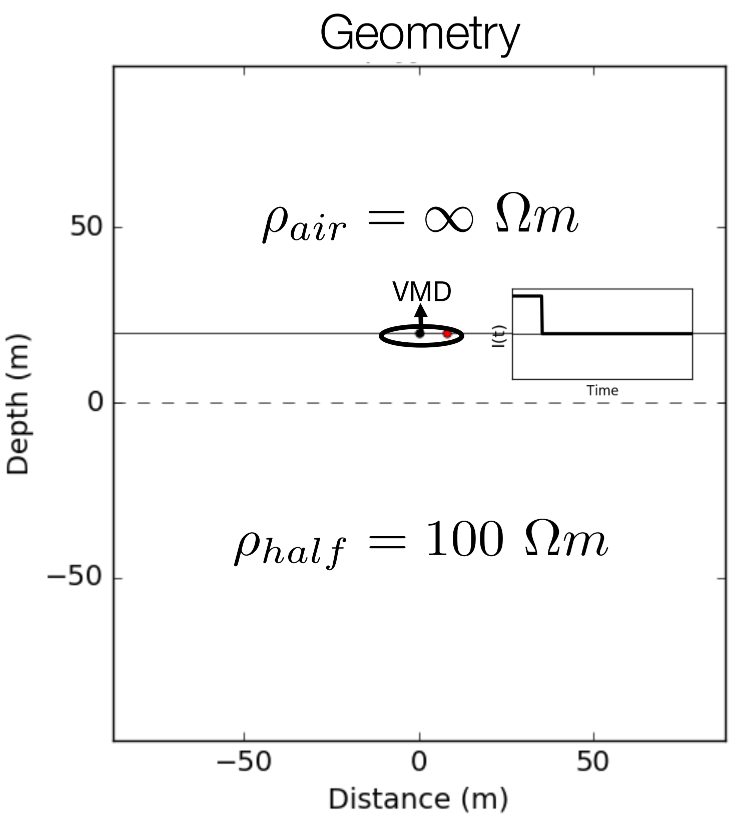


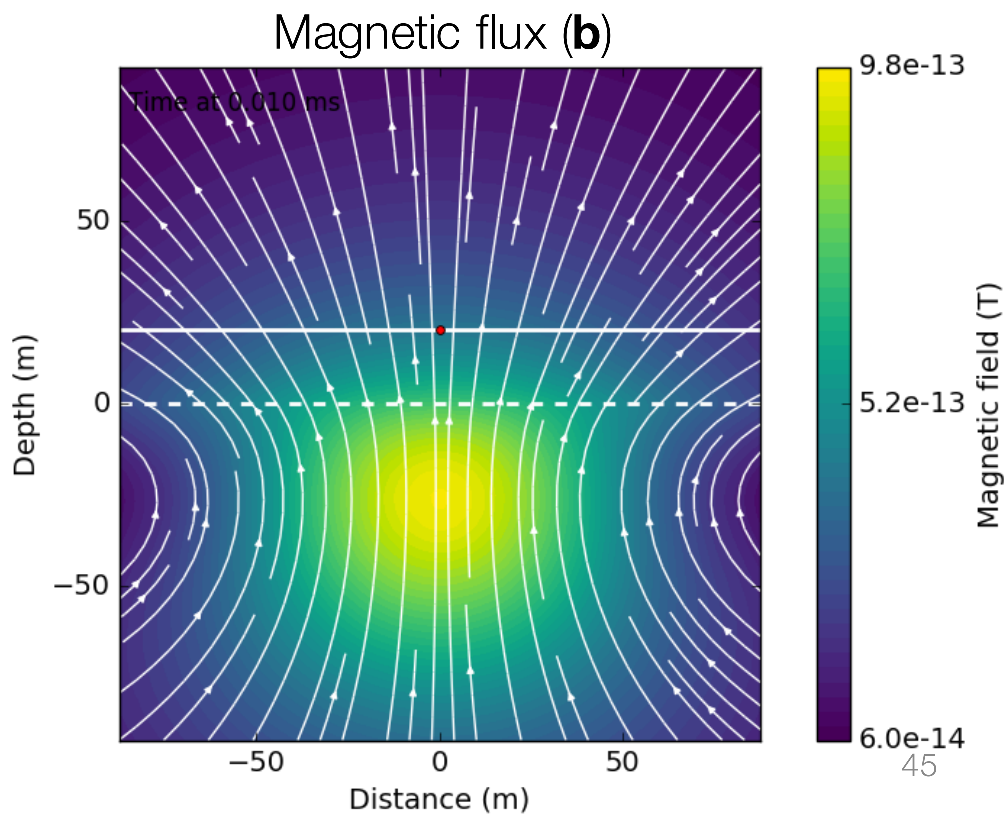




Magnetic flux density

- Time: 0.01ms

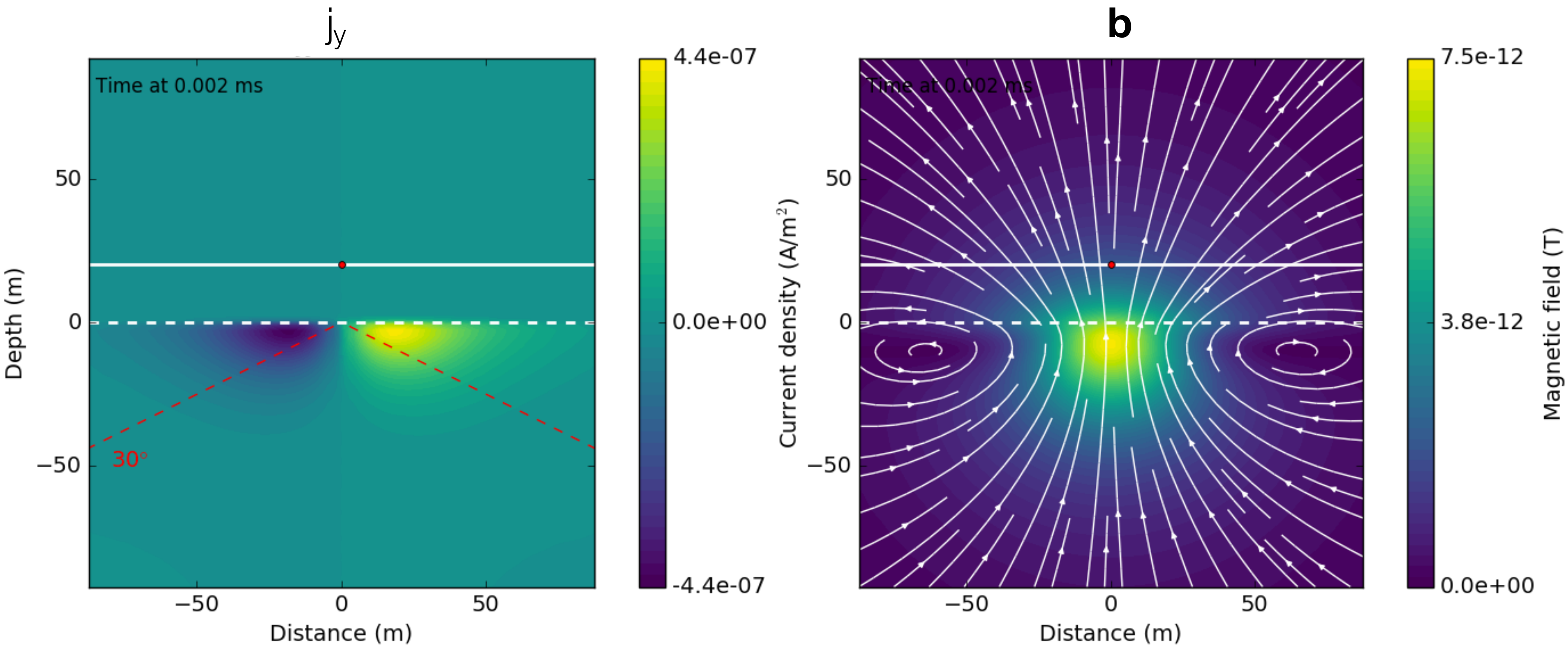




Propagation through time

- Time: 0.002ms
- diffusion distance = 18 m

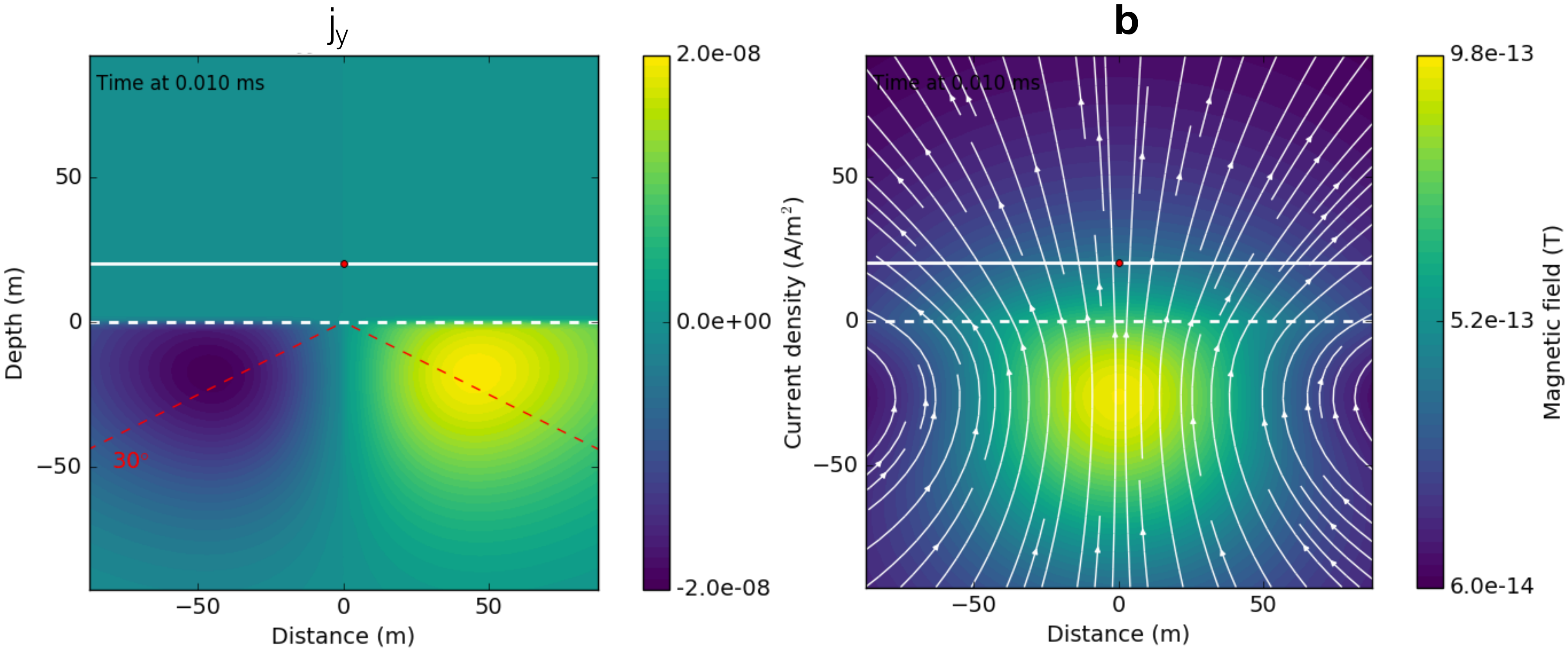
$$d = 1260\sqrt{t\rho}$$



Propagation through time

- Time: 0.01ms
- diffusion distance = 38 m

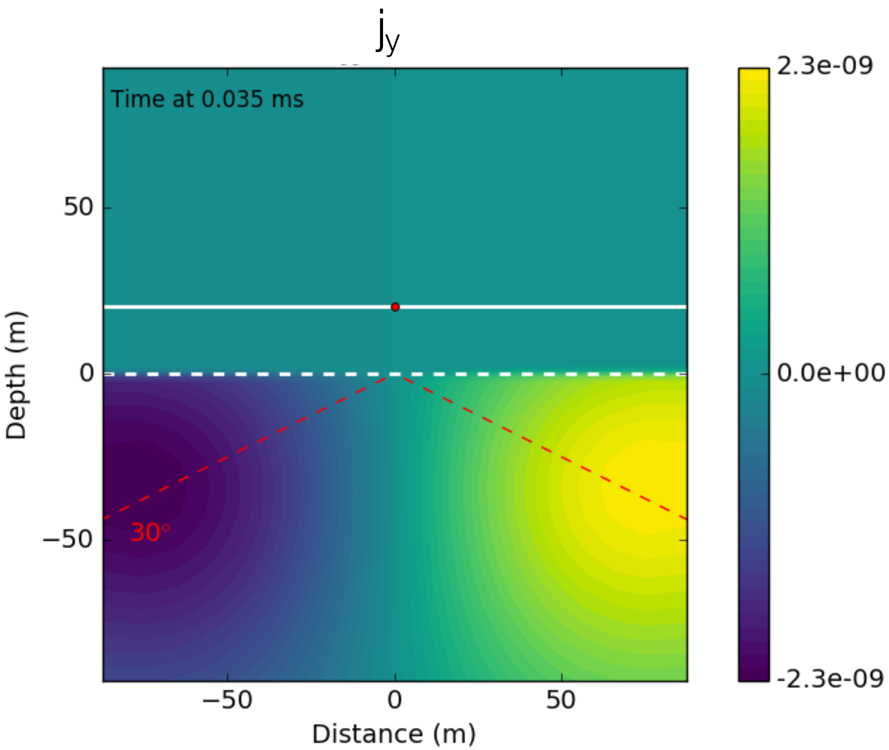
$$d = 1260\sqrt{t\rho}$$

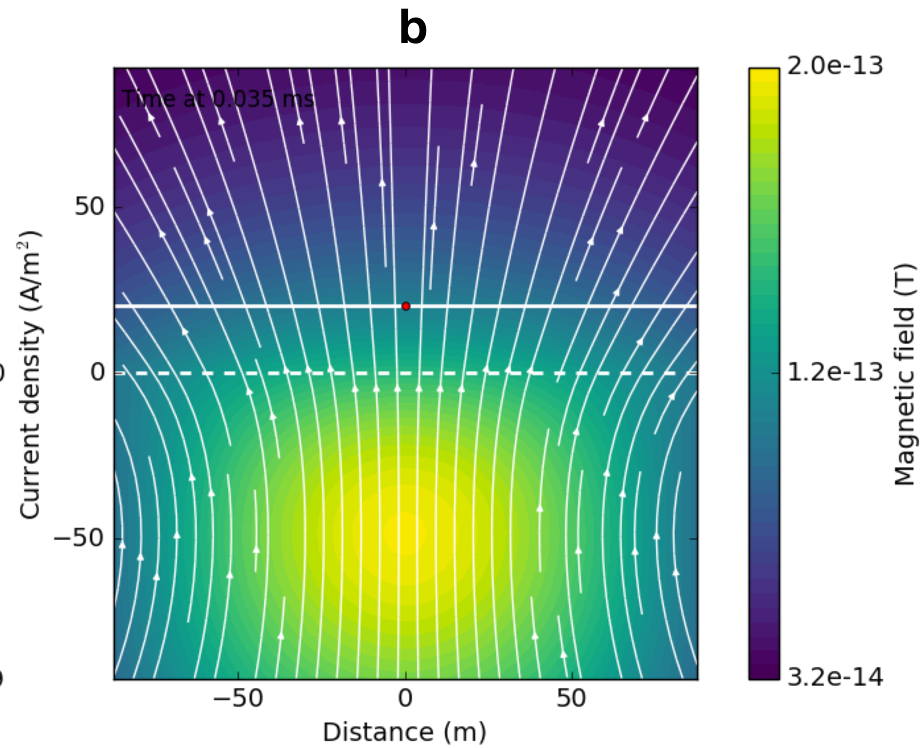


Propagation through time

- Time: 0.035ms
- diffusion distance = 75 m

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

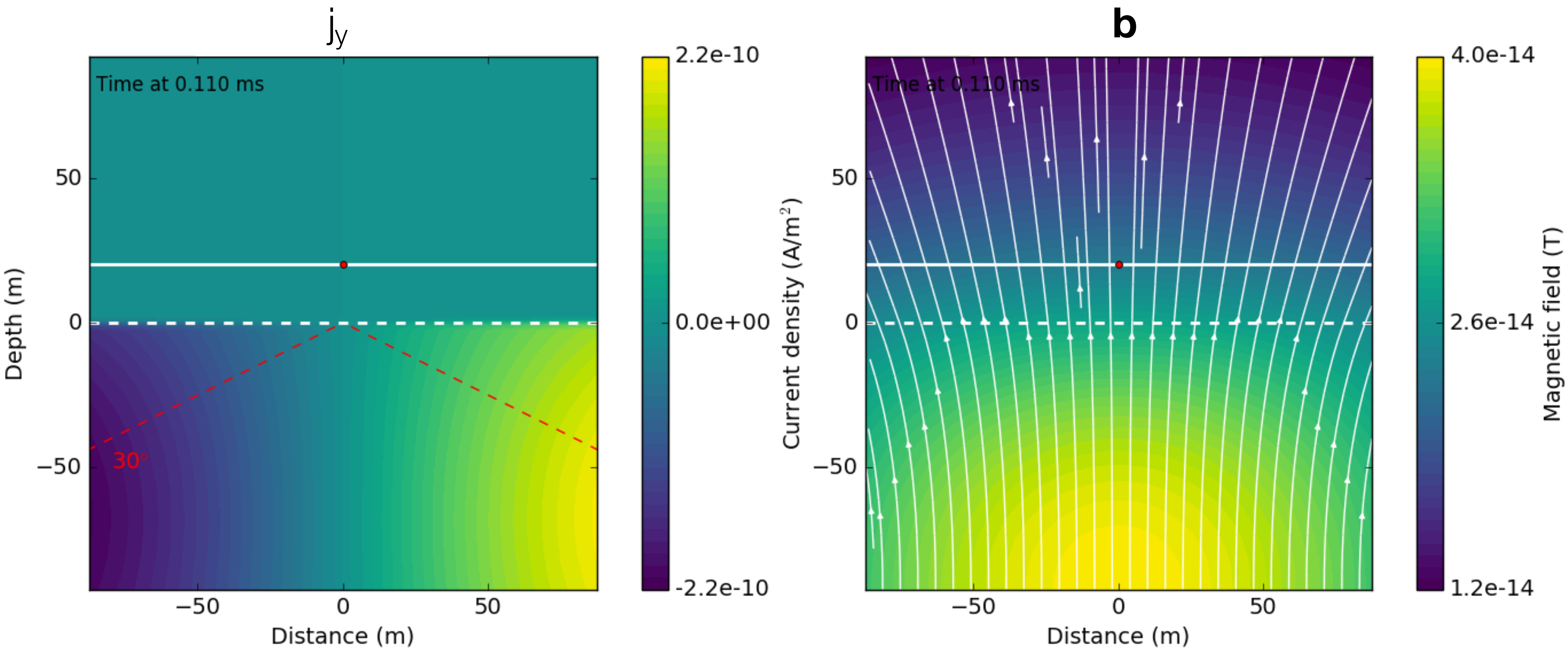




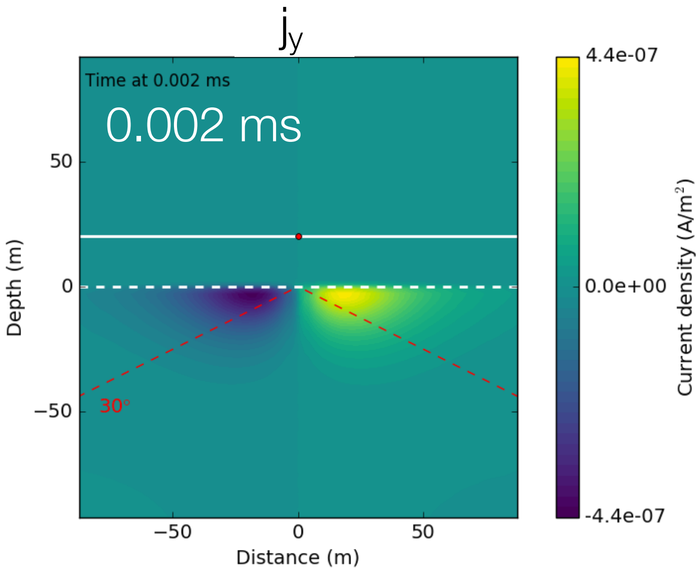
Propagation through time

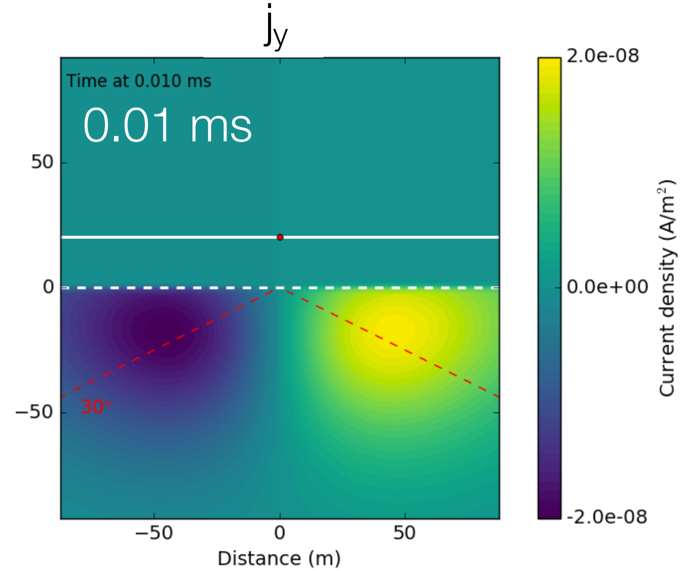
- Time: 0.110ms
- diffusion distance = 132 m

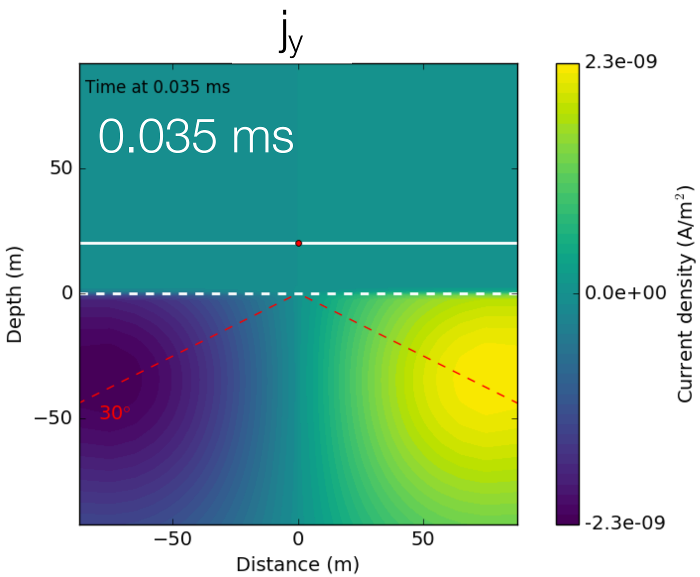
$$d = 1260\sqrt{t\rho}$$



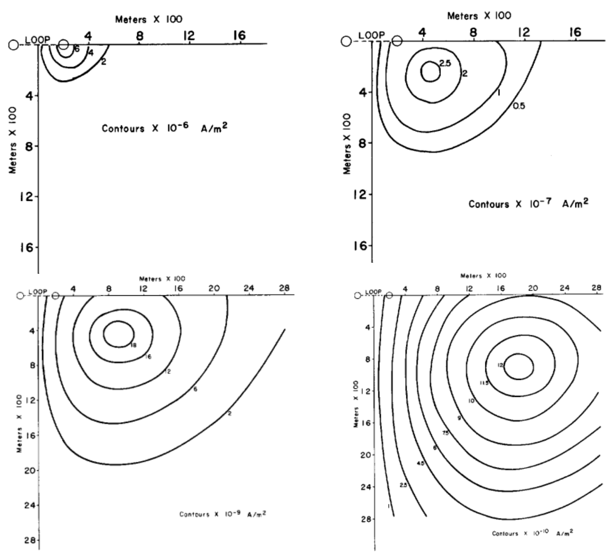
Summary: propagation through time







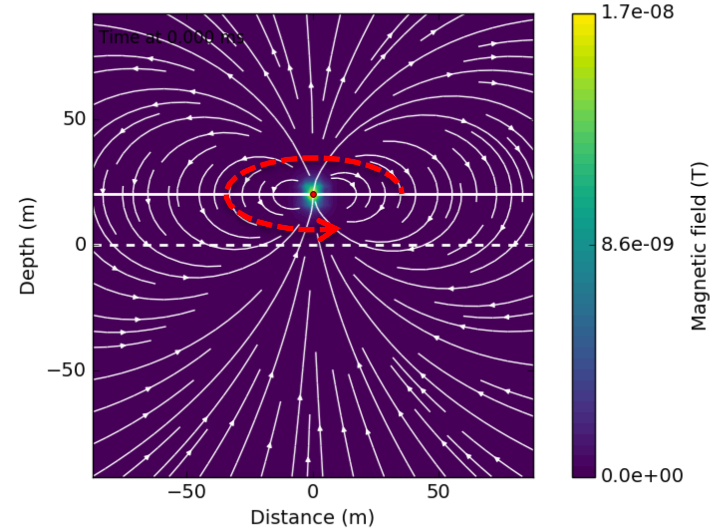
Nabighian (1979)



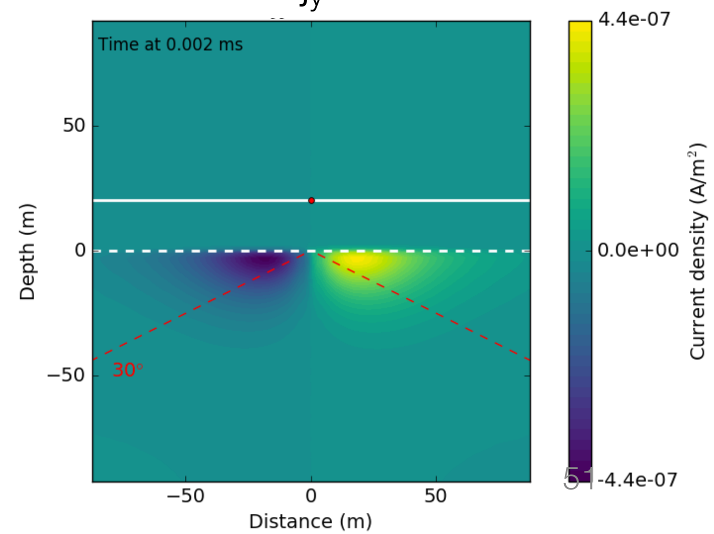
Important points

- 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)



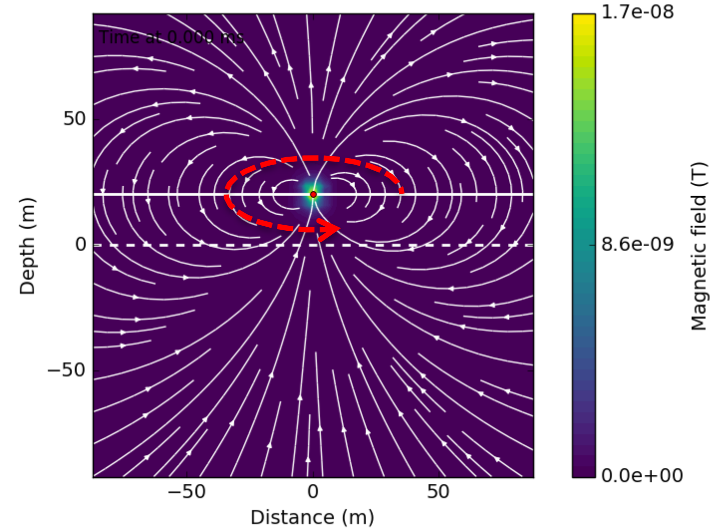
j_y



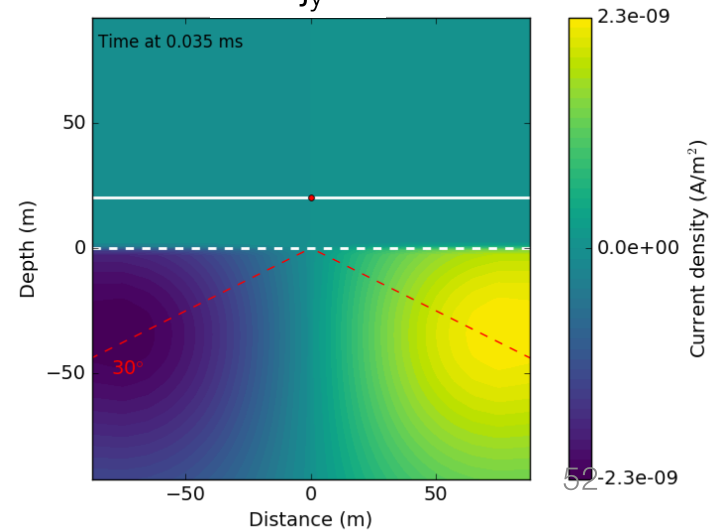
Important points

- 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)

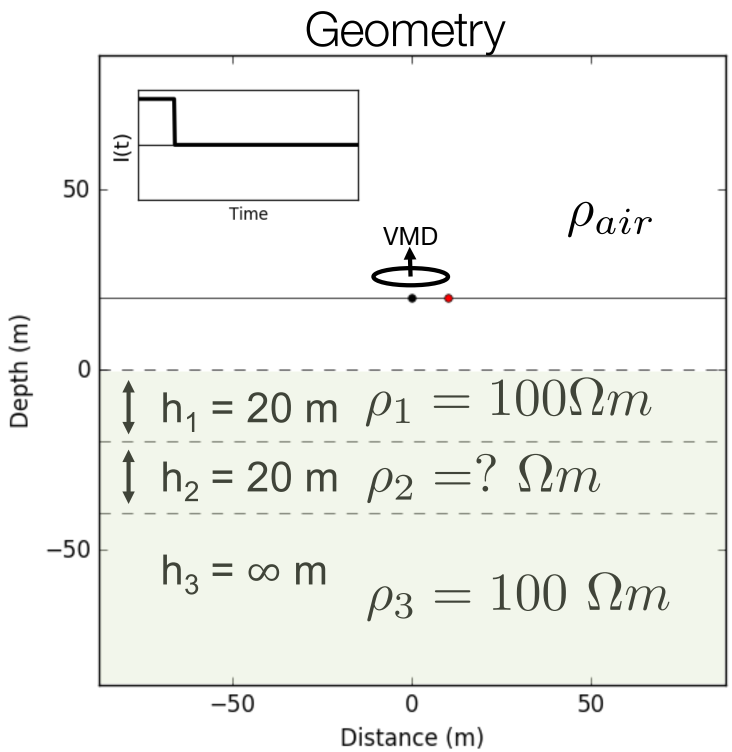


j_y



Layered earth

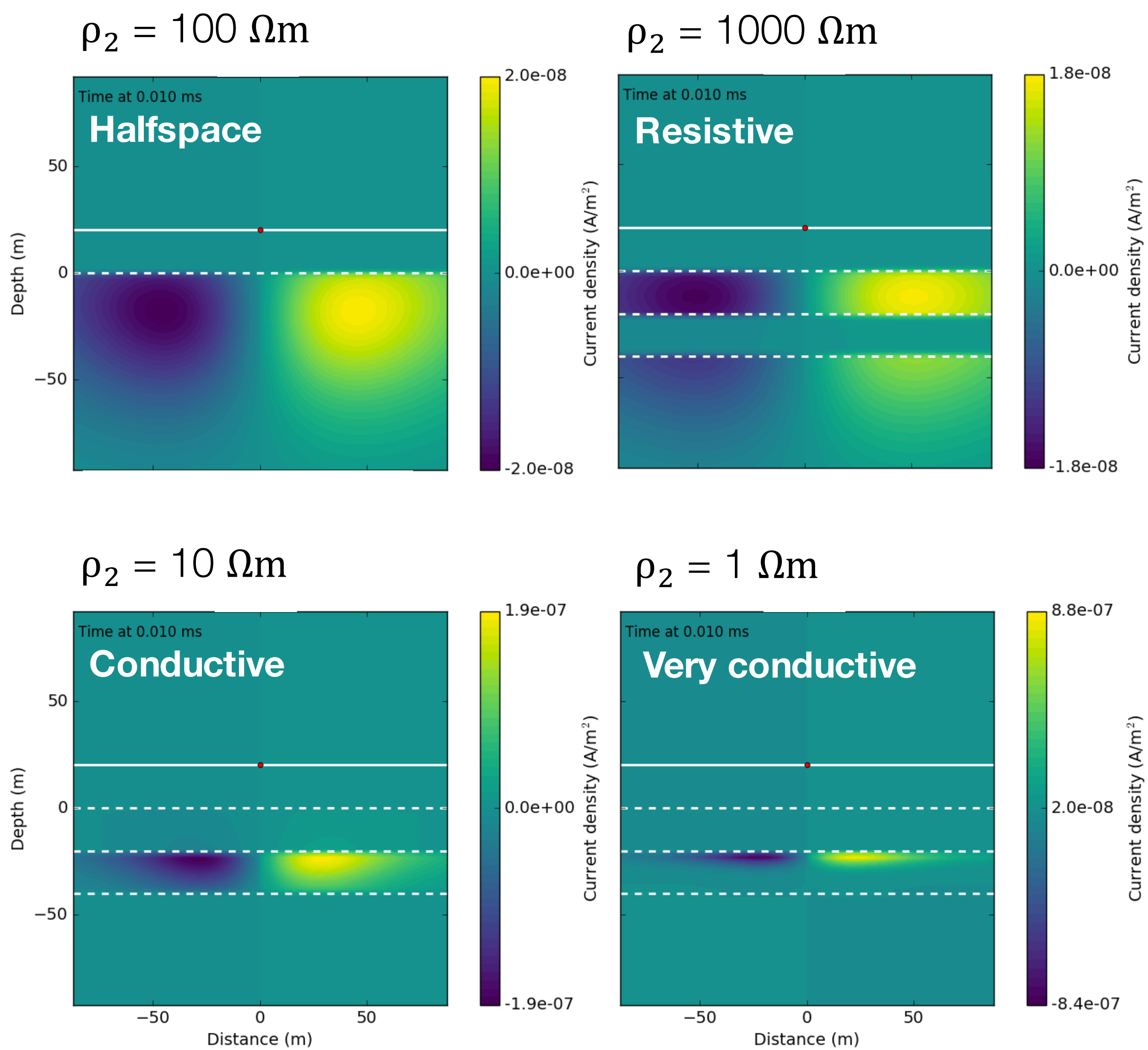
- 3 layers + air,
- ρ_2 varies



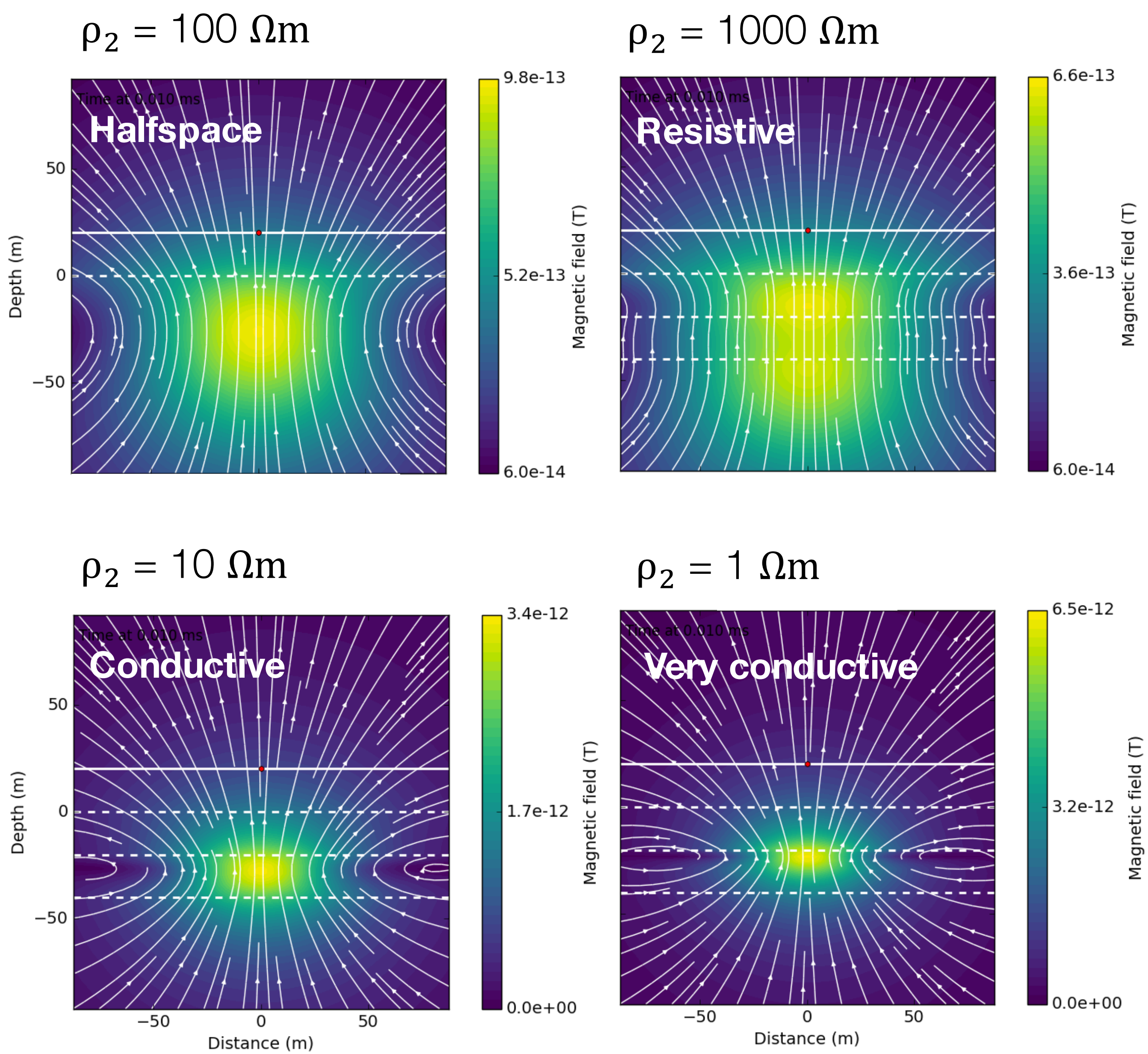
- Four different cases:
  - Halfspace
    ρ_2 = 100 Ωm
  - Resistive
    ρ_2 = 1000 Ωm
  - Conductive
    ρ_2 = 10 Ωm
  - Very conductive
    ρ_2 = 1 Ωm

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

Layered earth currents (j_y)

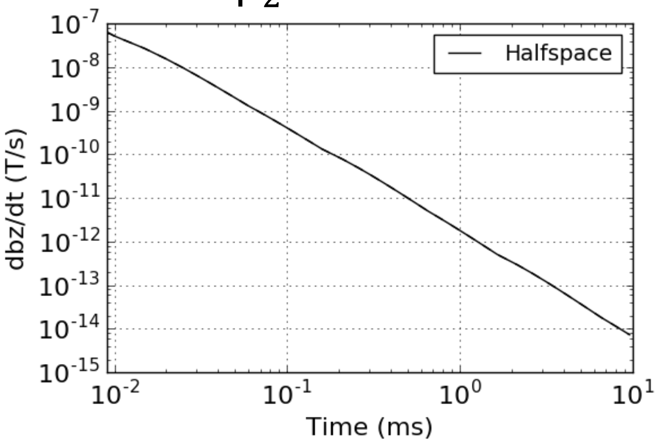


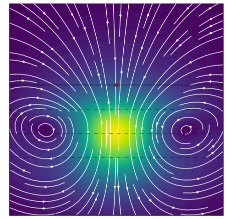
Layered earth mag. fields (**b**)



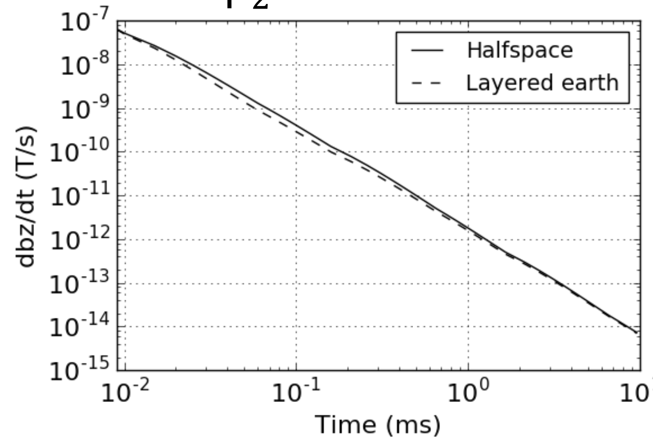
db_z/dt sounding curves

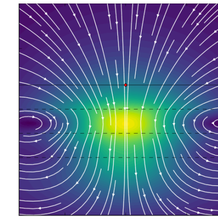
ρ_2 = 100 Ωm



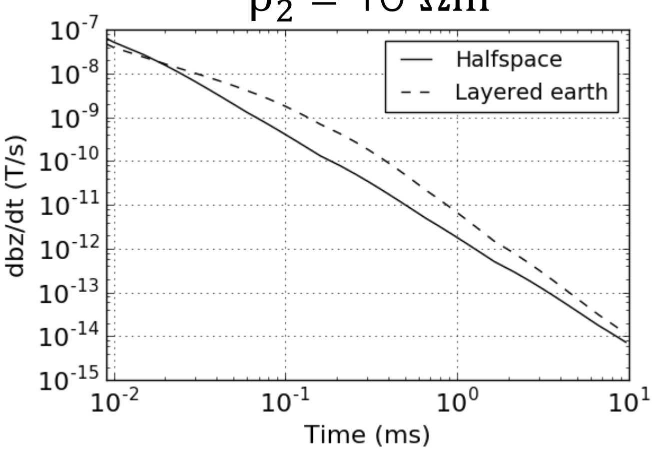


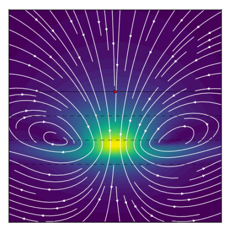
ρ_2 = 1000 Ωm



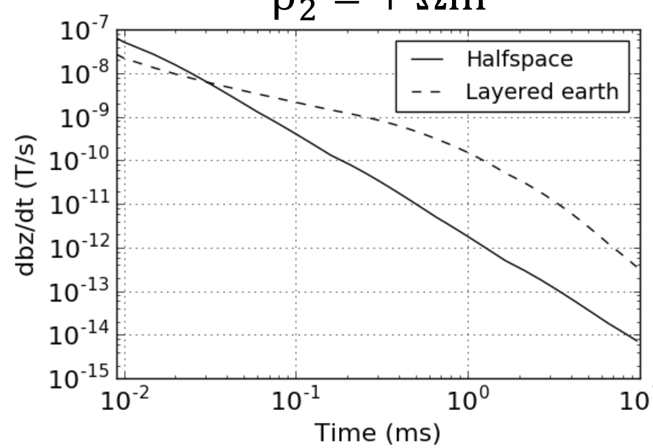


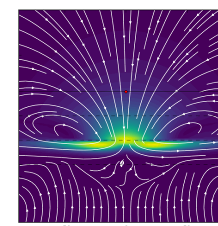
ρ_2 = 10 Ωm





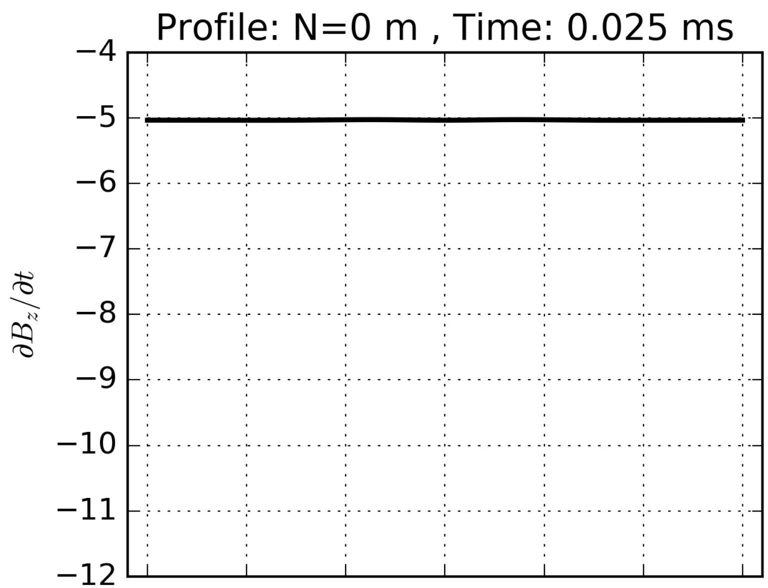
ρ_2 = 1 Ωm



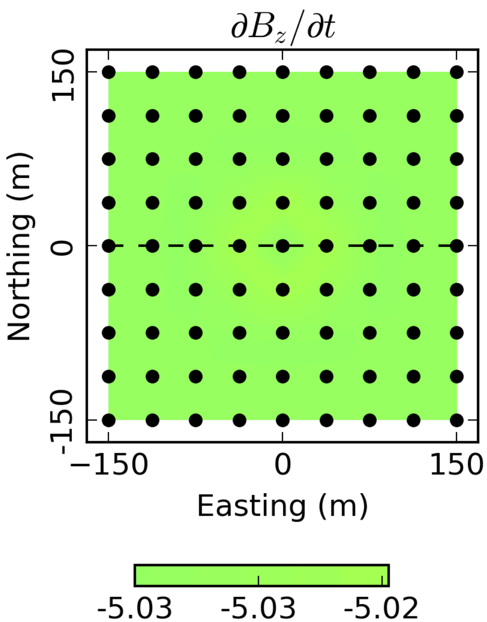


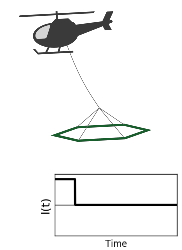
Airborne example: conductive sphere

Data profile

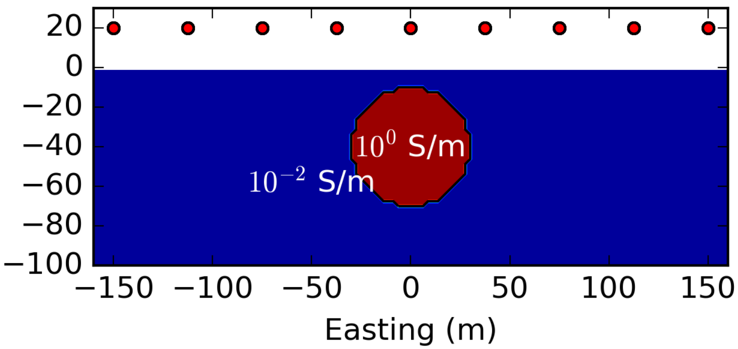


Data map



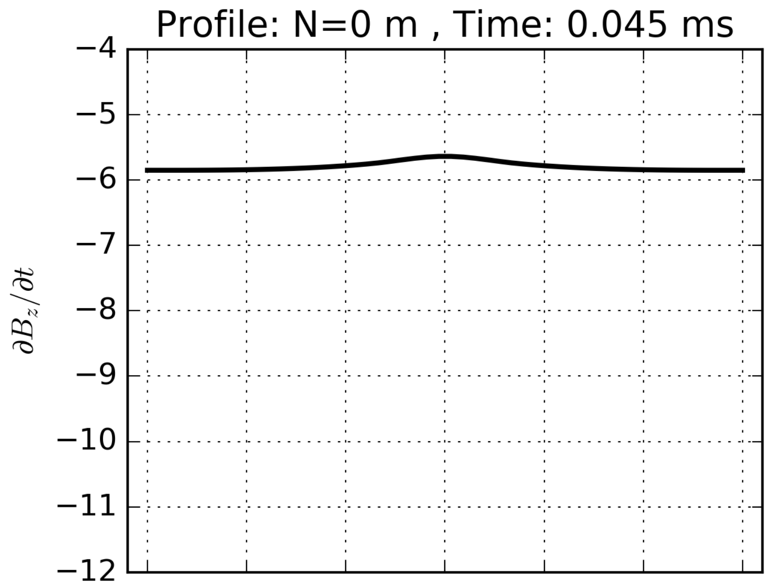


Conductivity

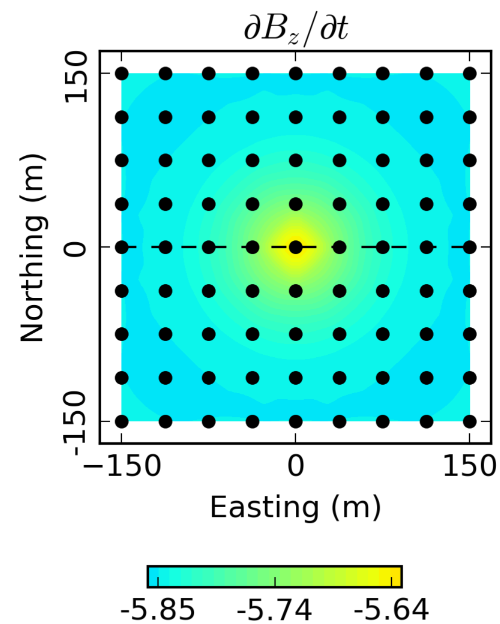


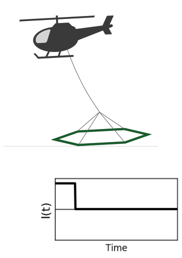
Airborne example: conductive sphere

Data profile

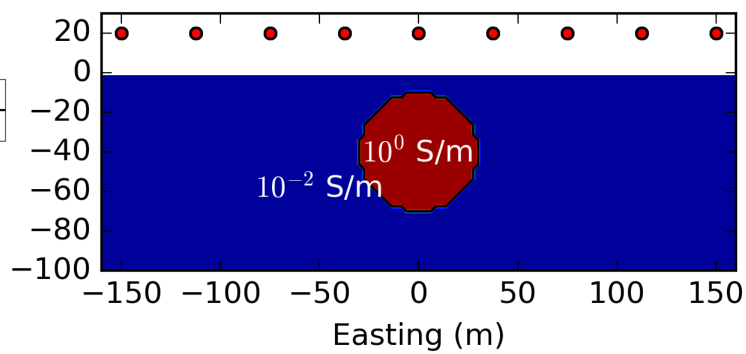


Data map



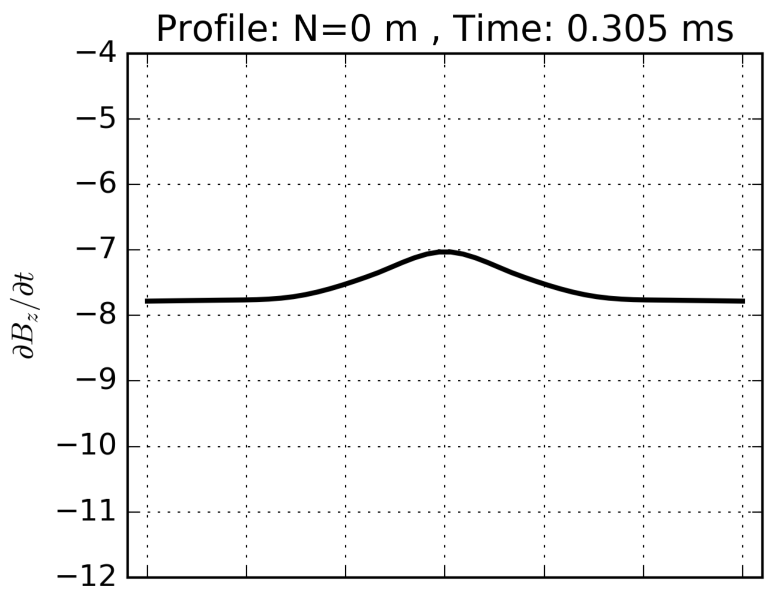


Conductivity

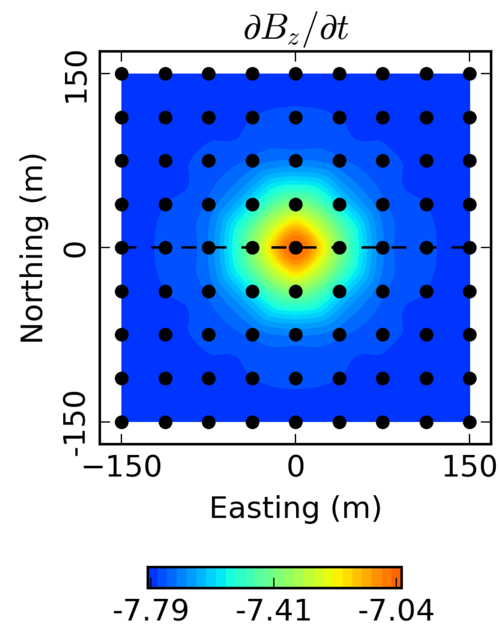


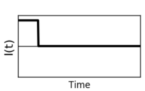
Airborne example: conductive sphere

Data profile

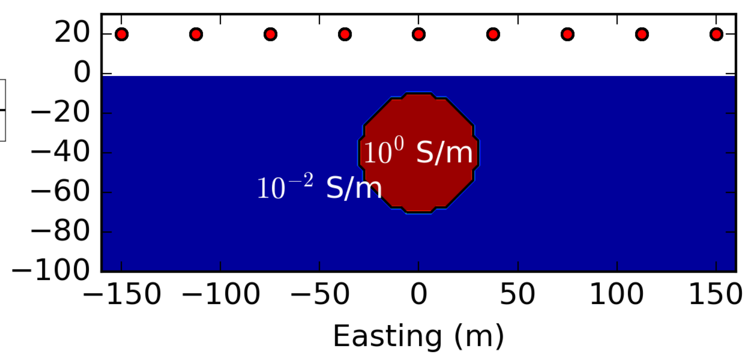


Data map



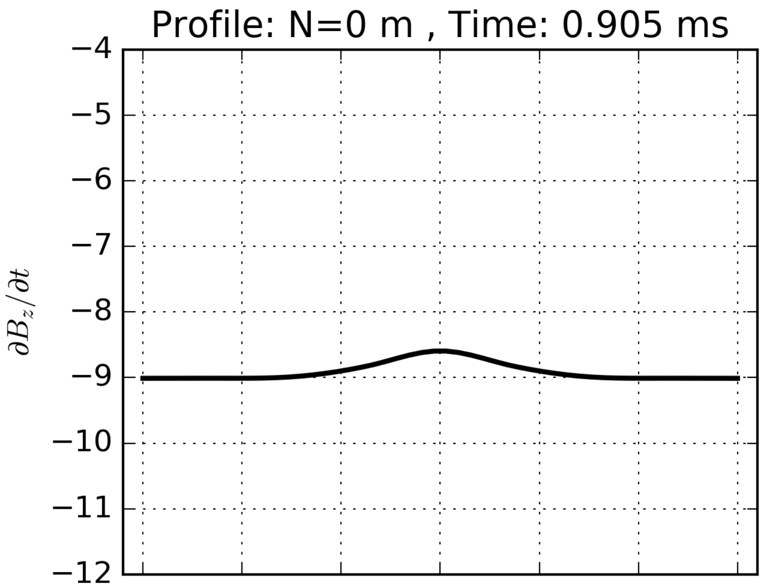


Conductivity

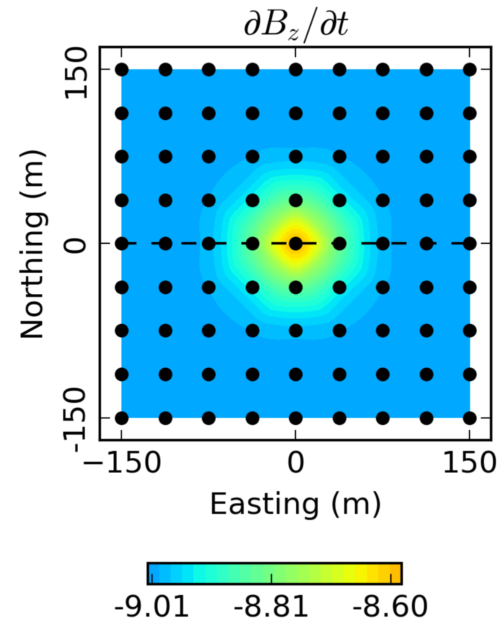


Airborne example: conductive sphere

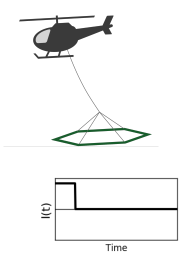
Data profile

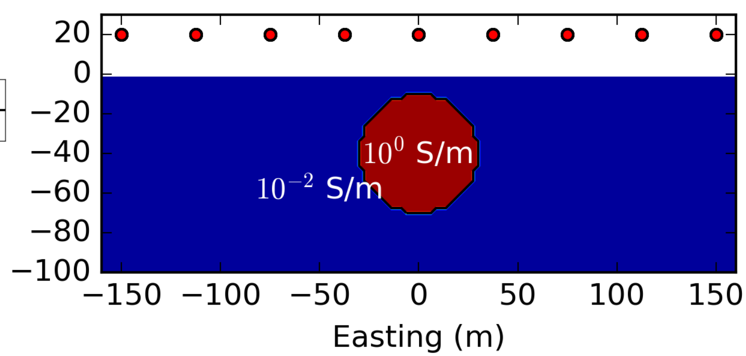


Data map



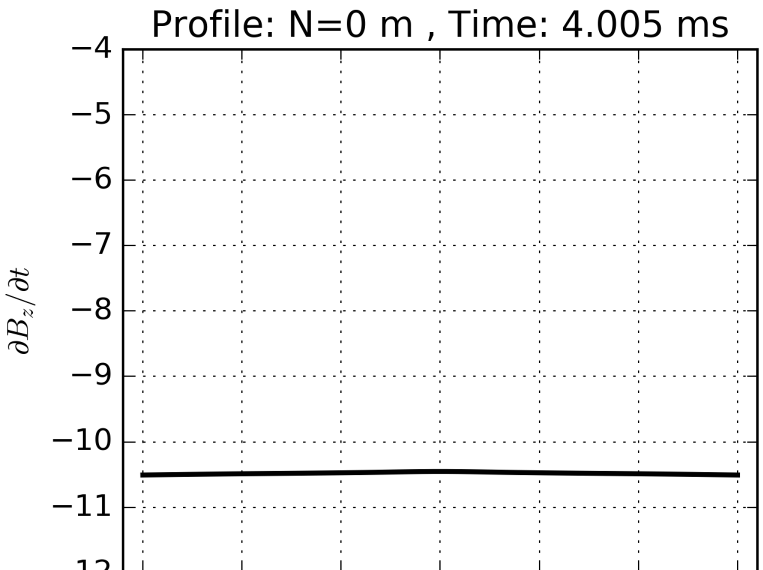
Conductivity



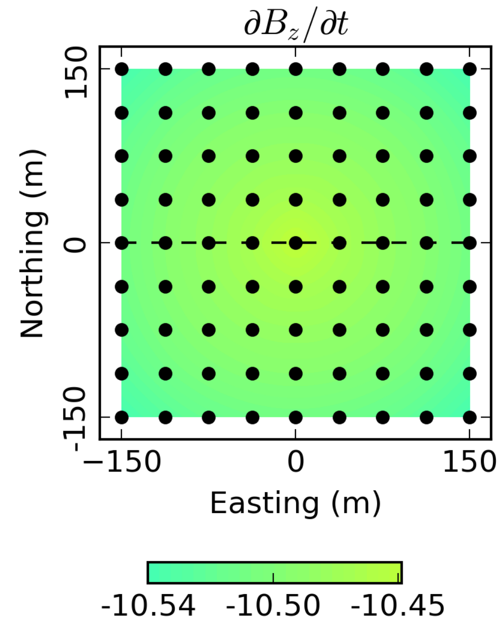


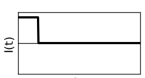
Airborne example: conductive sphere

Data profile

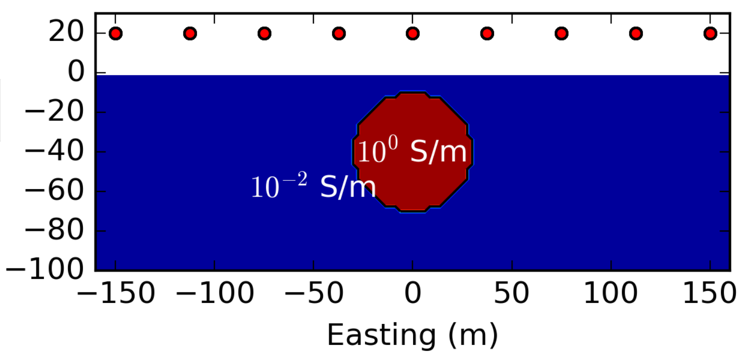


Data map



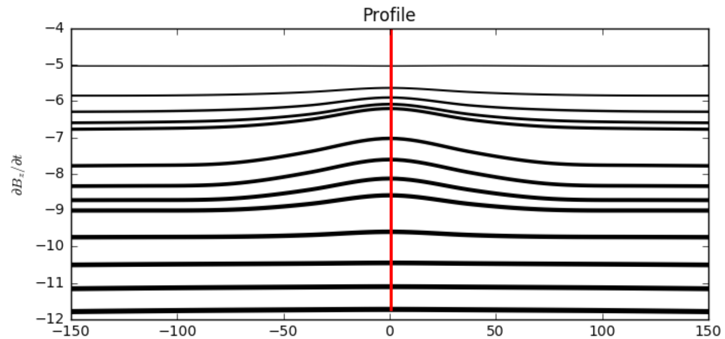


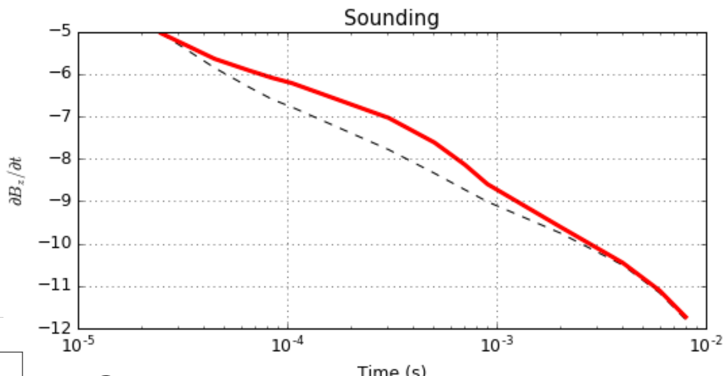
Conductivity

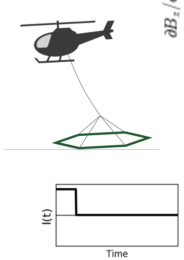


Summary: airborne example

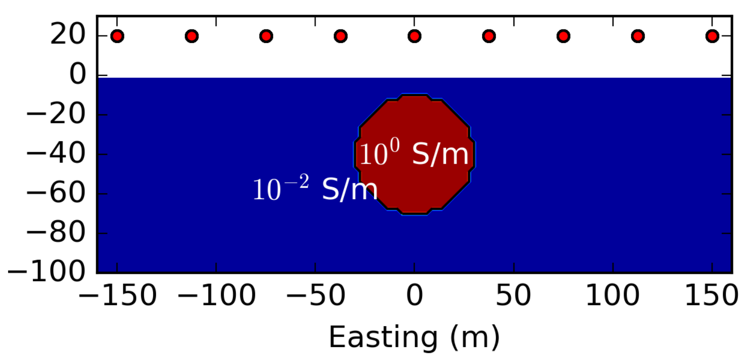
Data profile



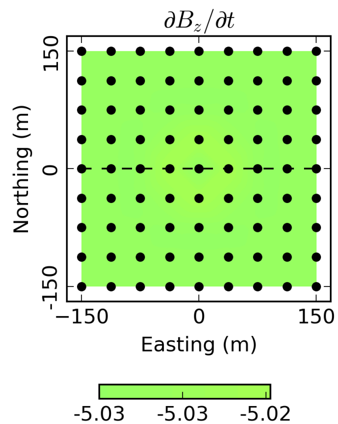




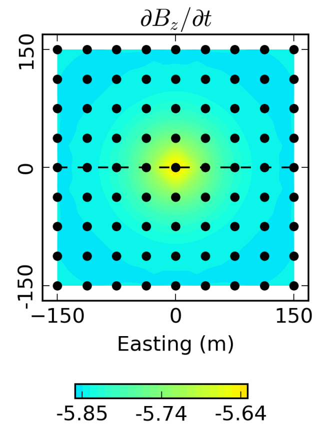
Conductivity



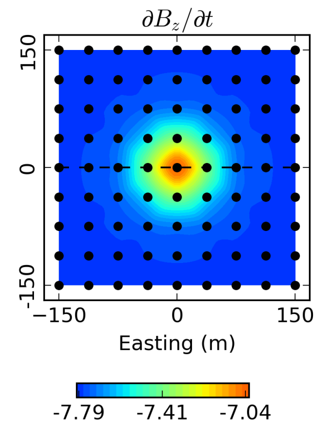
0.025 ms



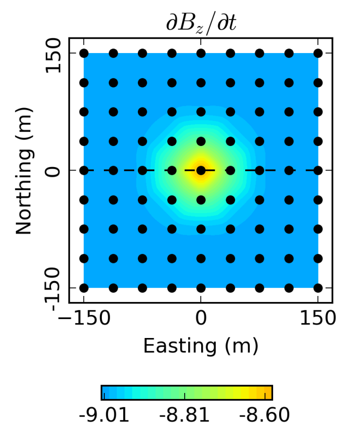
0.045 ms



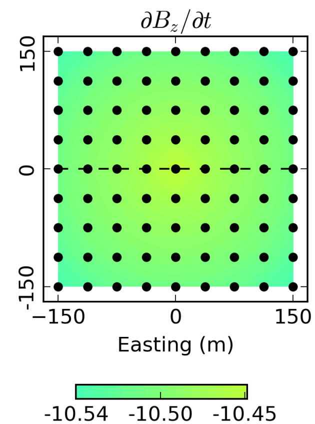
0.305 ms



0.905 ms



4.005 ms

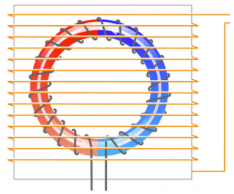


TDEM Receiver

Magnetometer

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

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



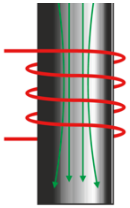
Fluxgate

Squid

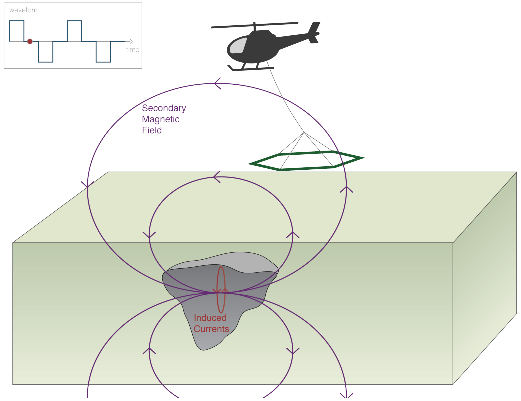
Coil

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

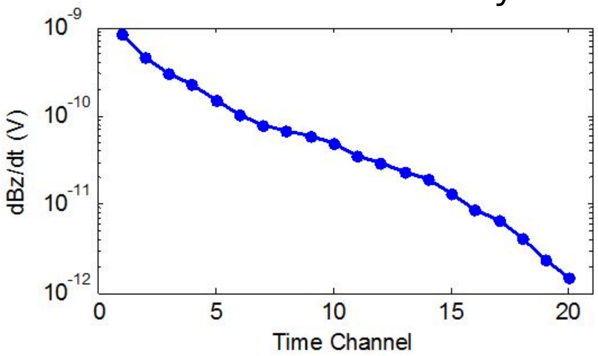
- Measures:
  - Voltage
  - Single component that depends on coil orientation
    - Coupling matters
- Airborne TDEM: measure db/dt



Coil

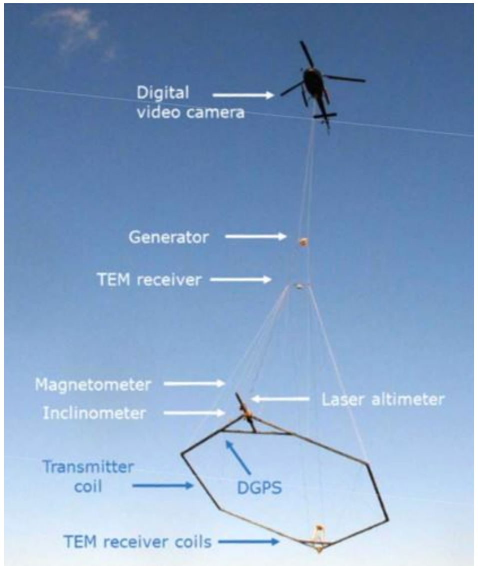


Measured decay



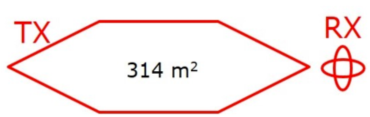
Some Airborne TDEM Systems

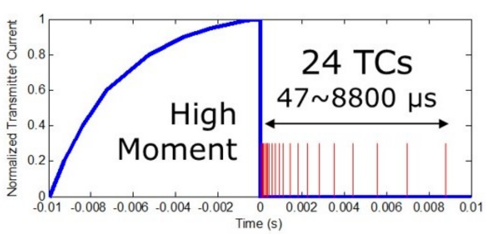
SkyTEM (2006)



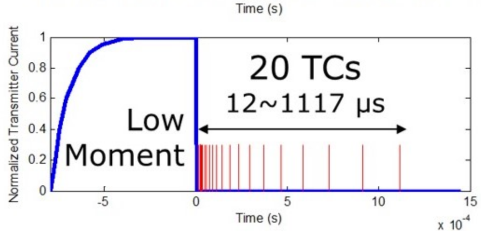
Area = 314 m^2

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



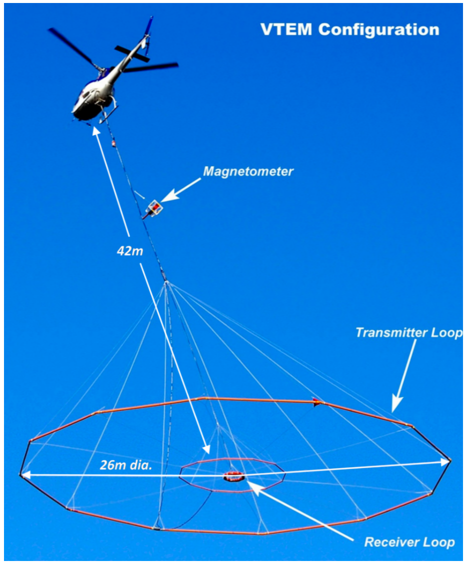


Peak current: 90 A
Turns: 4
On-time: 10 ms
Off-time: 10 ms



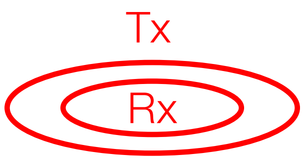
Peak current: 40 A
Turns: 1
On-time: 0.8 ms
Off-time: 1.45 ms

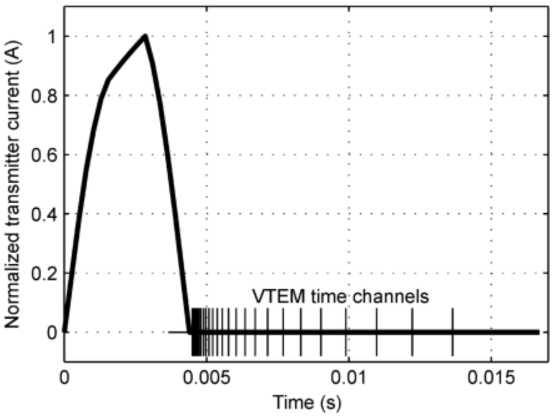
VTEM (2007)



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

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

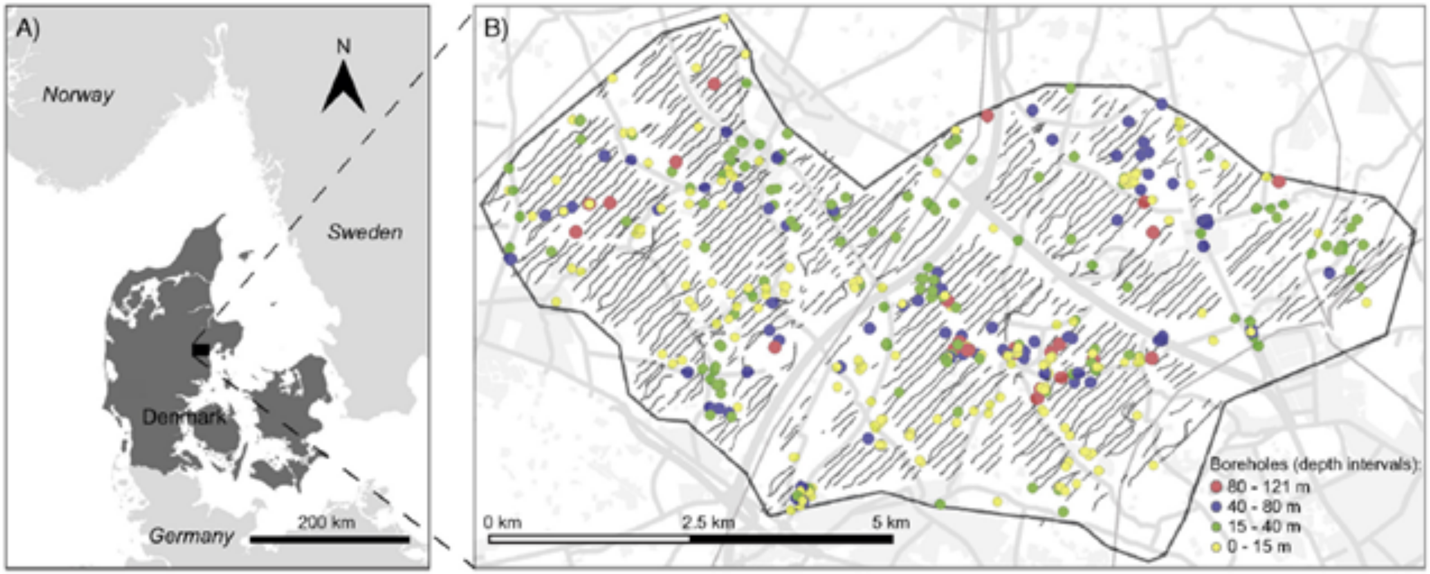
Case History: Kasted

Vilhelmsen et al. (2016)

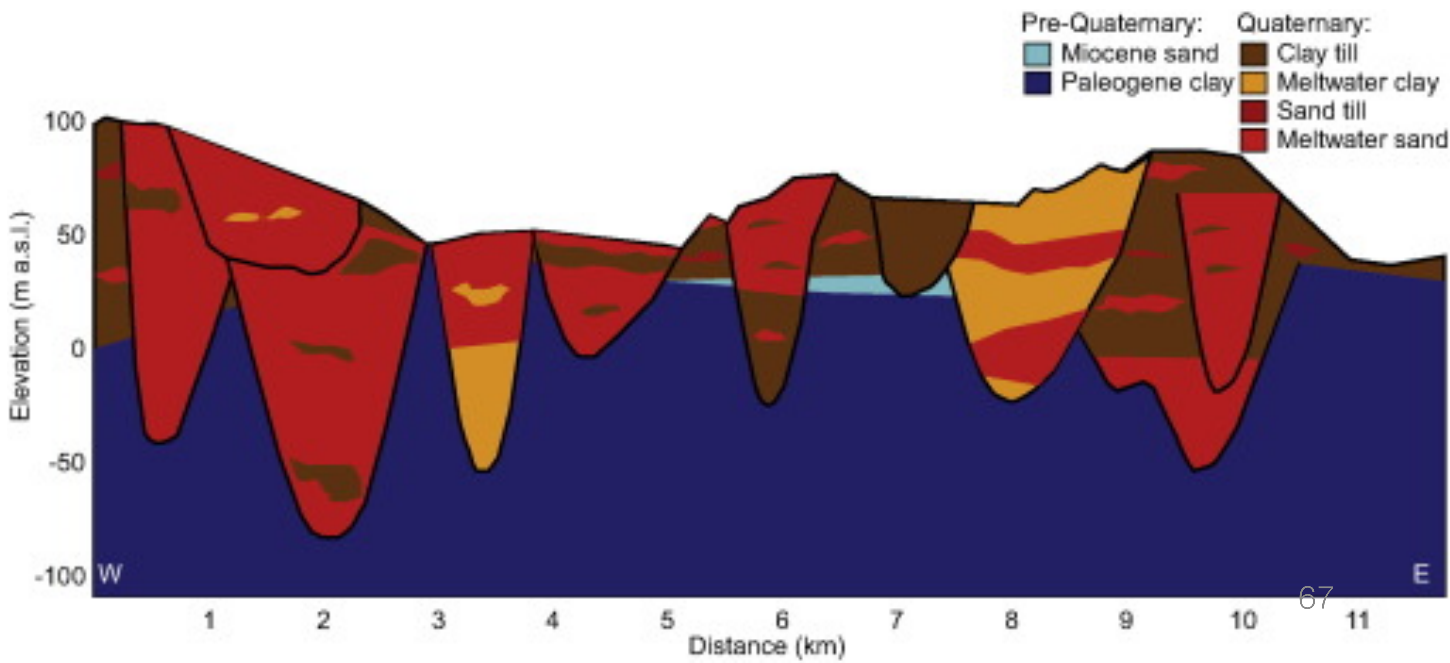
Setup

A) Survey Area: Kasted, Demark

B) Borehole locations

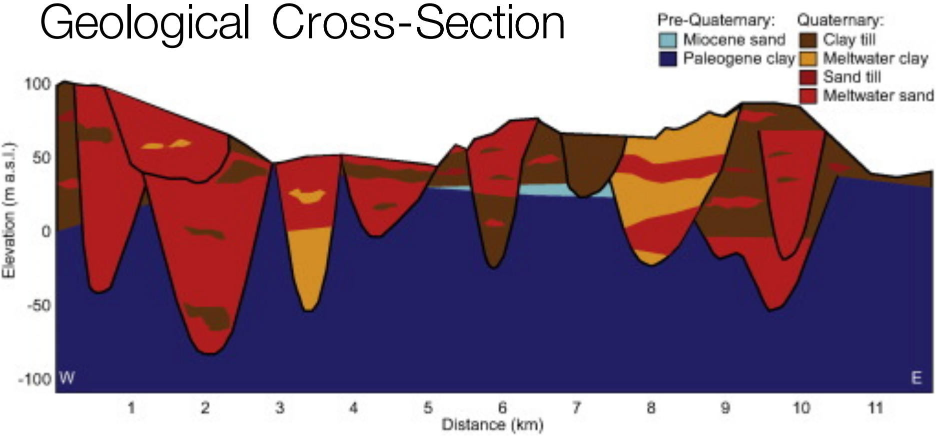


Local Geology: W-E cross-section



Properties

Geological Cross-Section

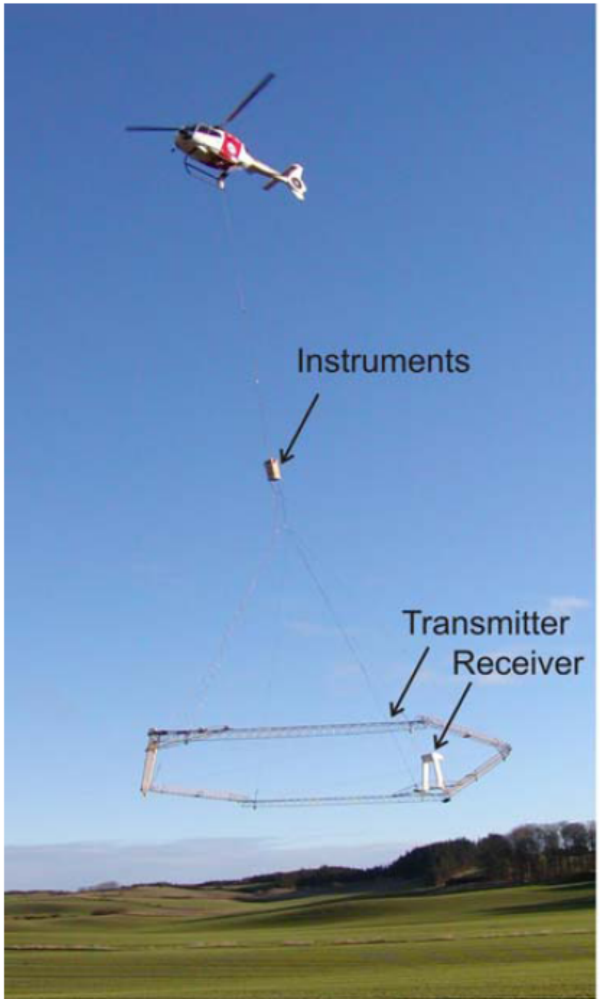


Geological Units	Resistivity (Ωm)
Palaeogene Clay	1-10
Clay Till	25-60
Sand Till	>50
Meltwater Sand and Gravel	>60
Glaciolacustrine Clay	10-40
Miocene Silt and Sand	>40
Miocene Clay	10-40
Sand	>40
Clay	1-60

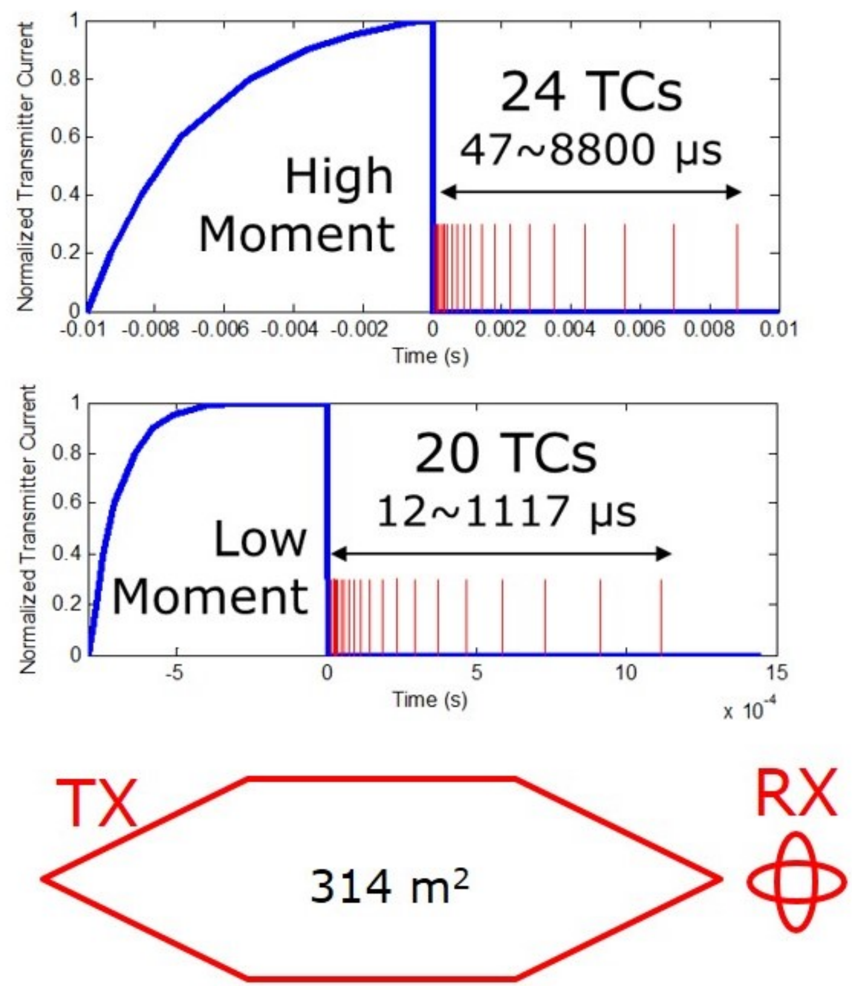
- Buried valleys with clays beneath
- Infill (water-bearing): coarse sand and gravel
- Clays are conductive (1-40 Ωm)
- Water-bearing sands and gravels are more resistive (>40 Ωm)

Survey

SkyTEM System



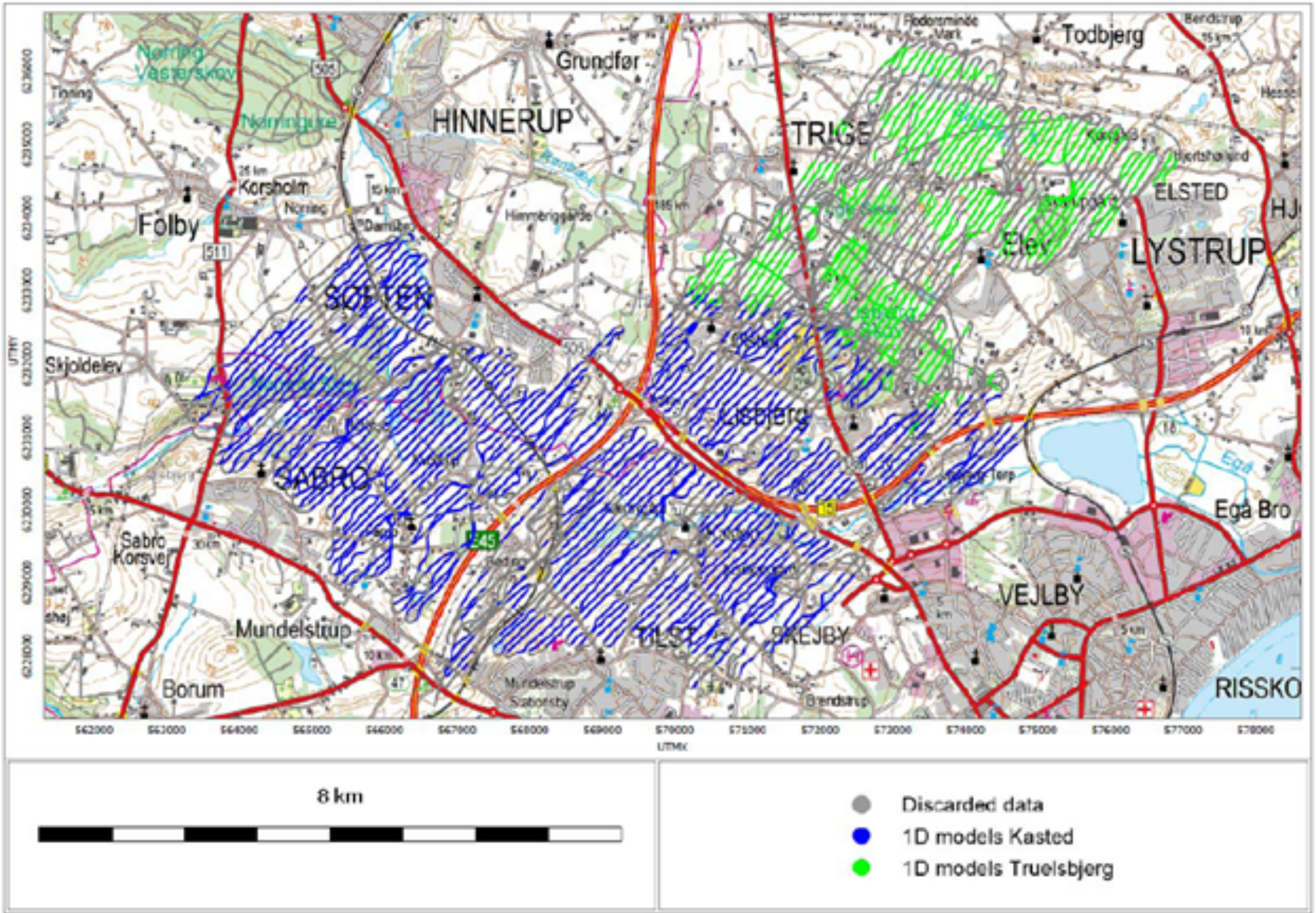
System Configuration



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

Data

Blue: data used for Kasted study

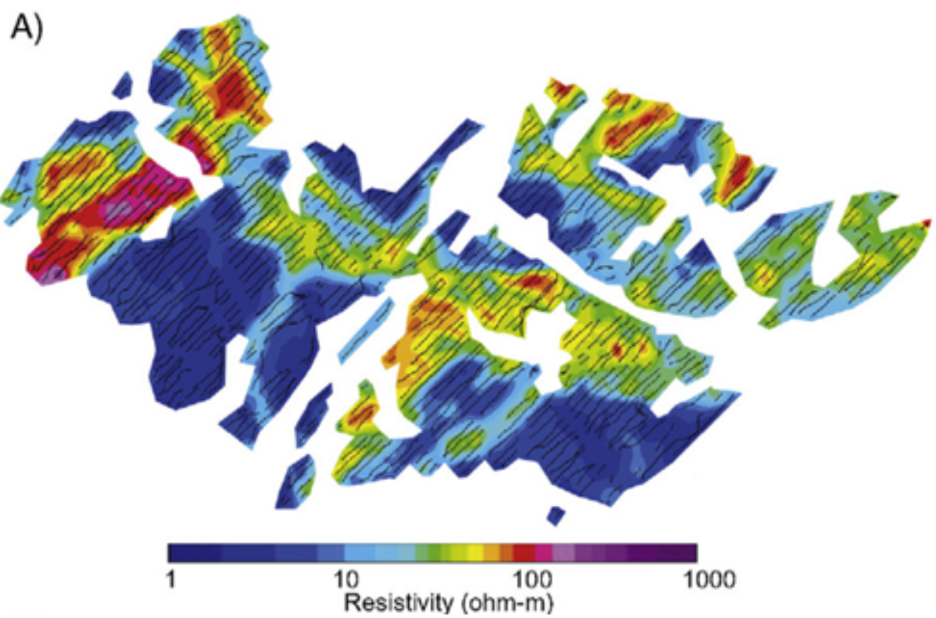


- 333 line km of data, 100 m line-spacing
- Data points with strong coupling to cultural noise were removed (~30%)

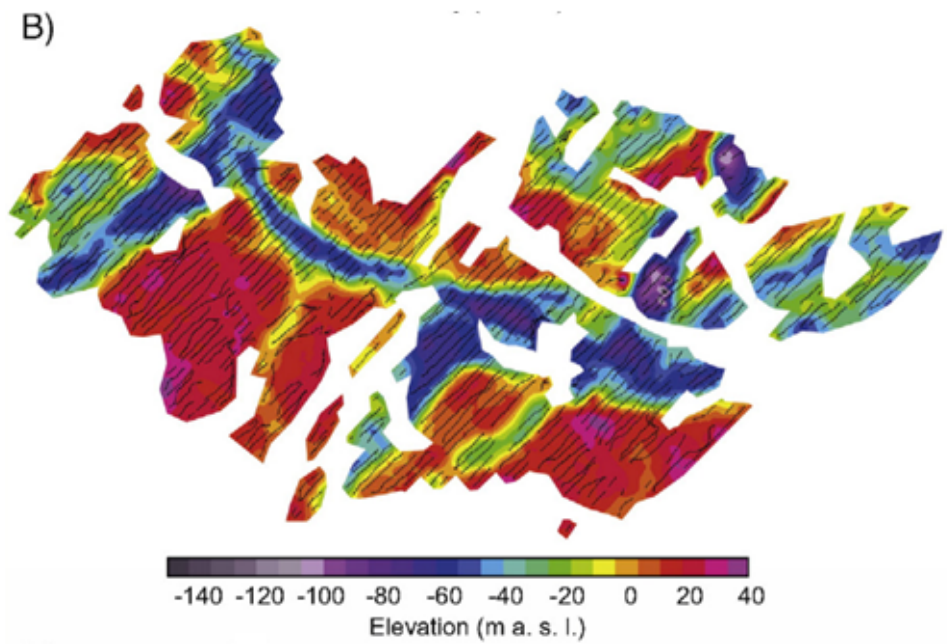
Processing (inversion)

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

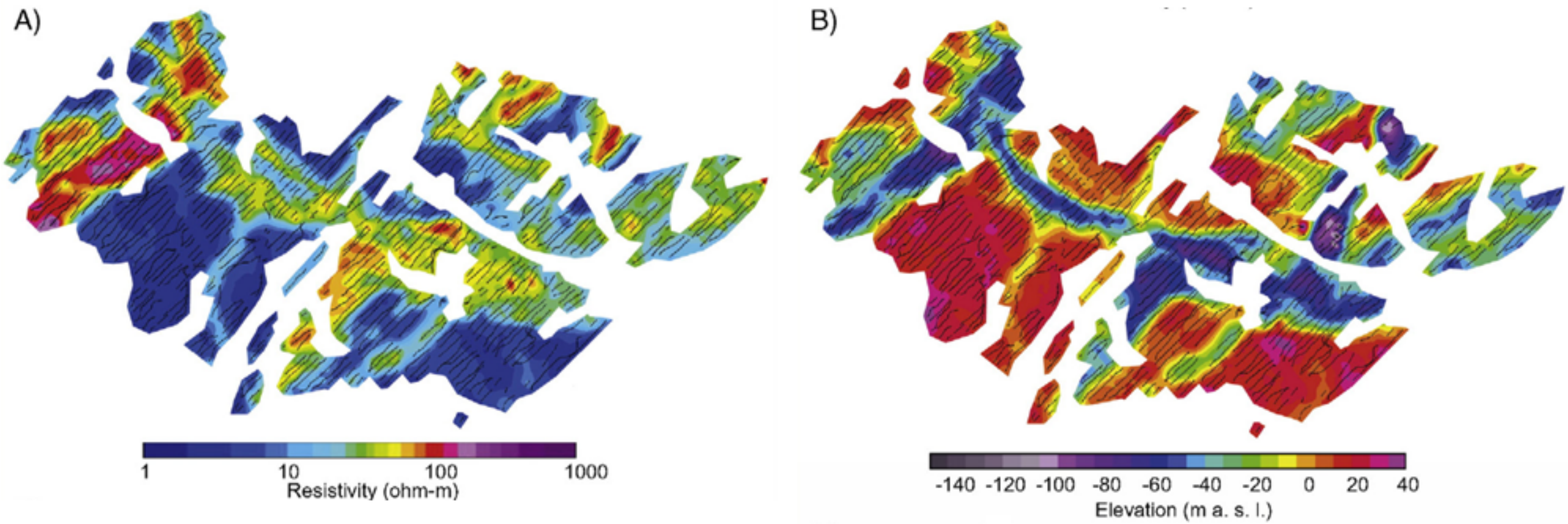
Depth slice 5 m above sea-level



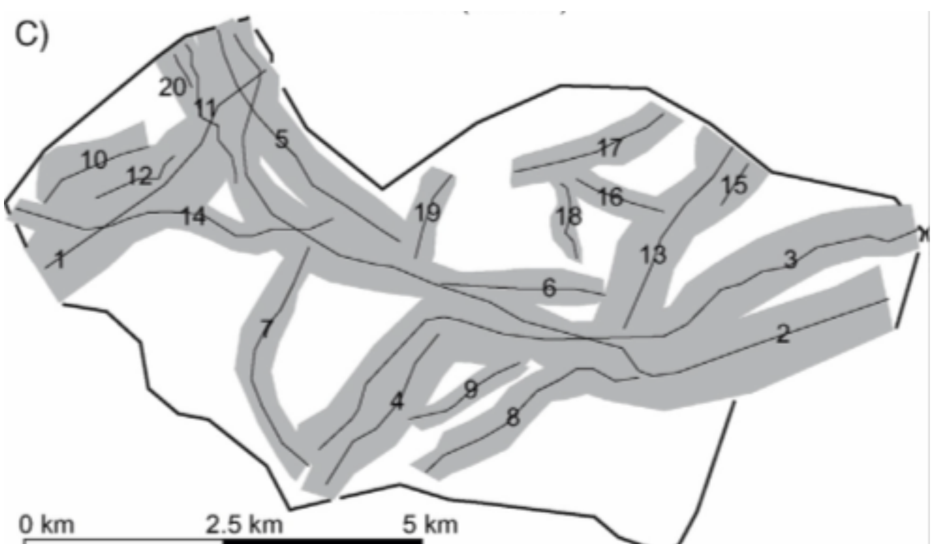
Approximate depth to the top of Paleogene clay layer



Interpretation

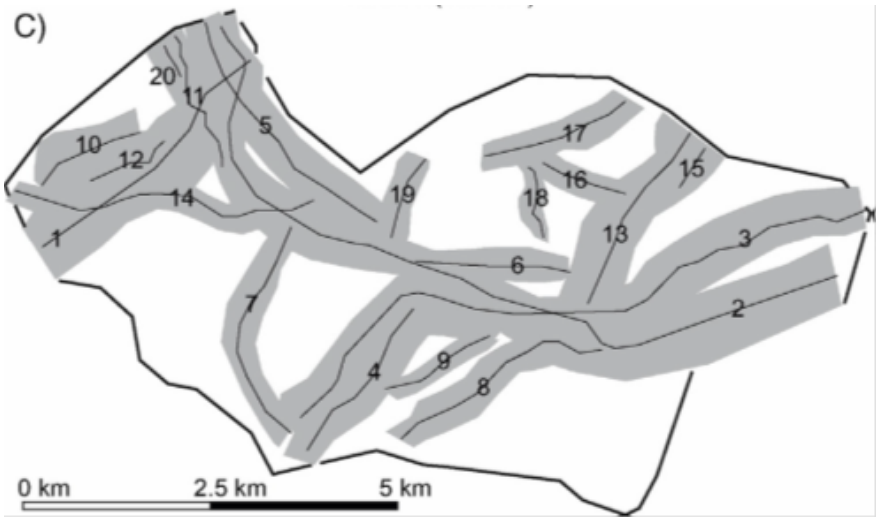


Delineation of valley structures

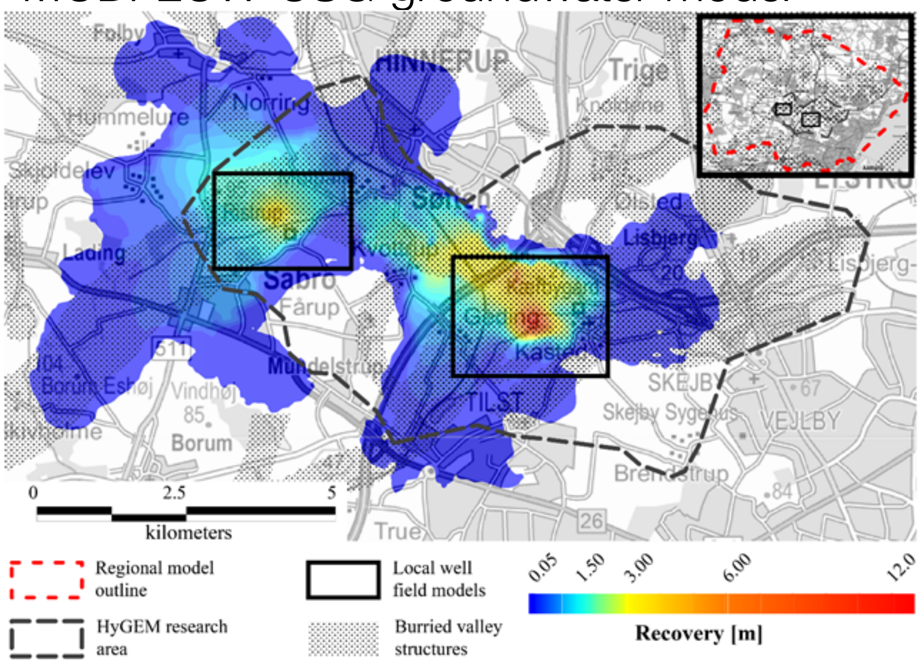


- Inversion results used to construct geological model.
- Delineated 20 buried and cross-cutting valley structures.

Synthesis

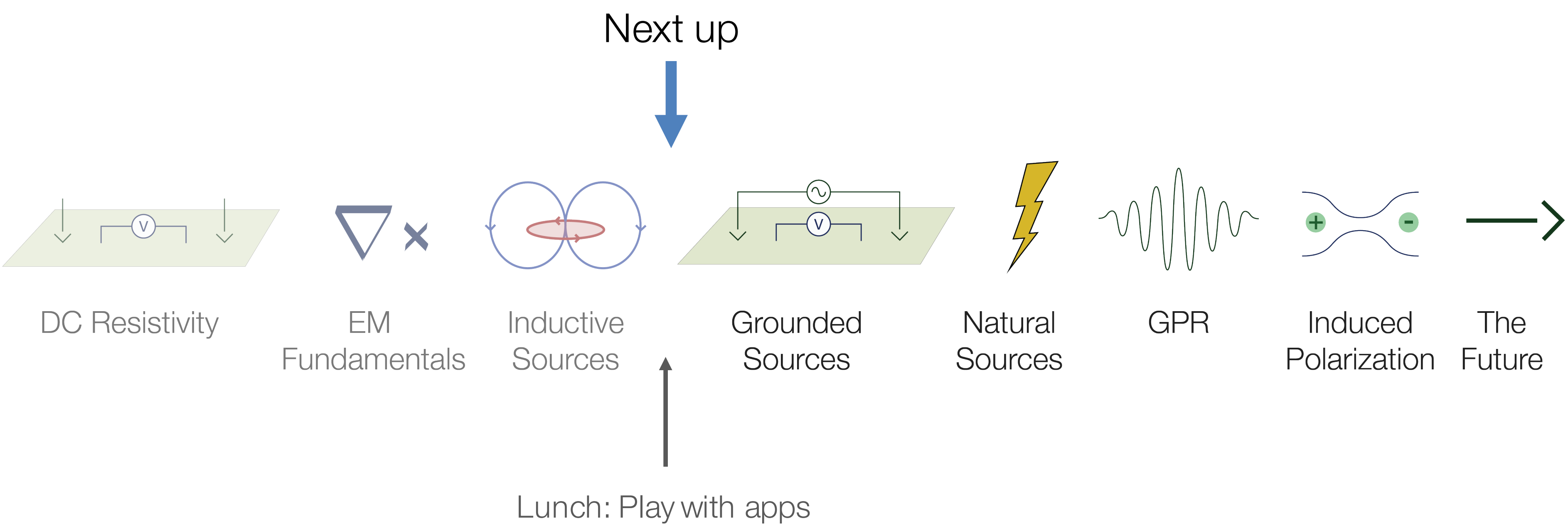


MODFLOW-USG groundwater model



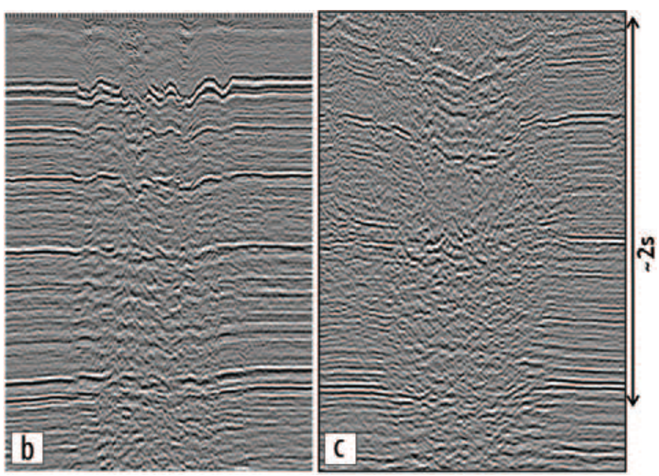
- 3D geologic model incorporated into MODFLOW-USG groundwater modeling tool
- Extracted water from 2 wells.
- Downdraw between the two wells correlated with the resistive valley structures

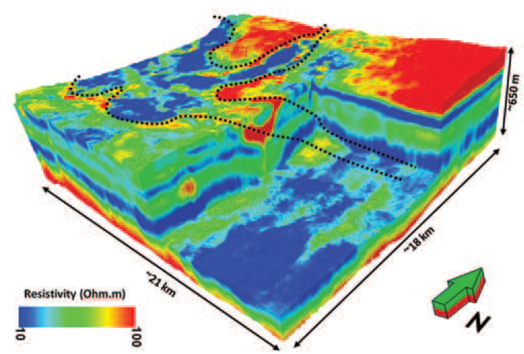
End of Inductive Sources



Case History: Wadi Sahba

Colombo et al. 2016

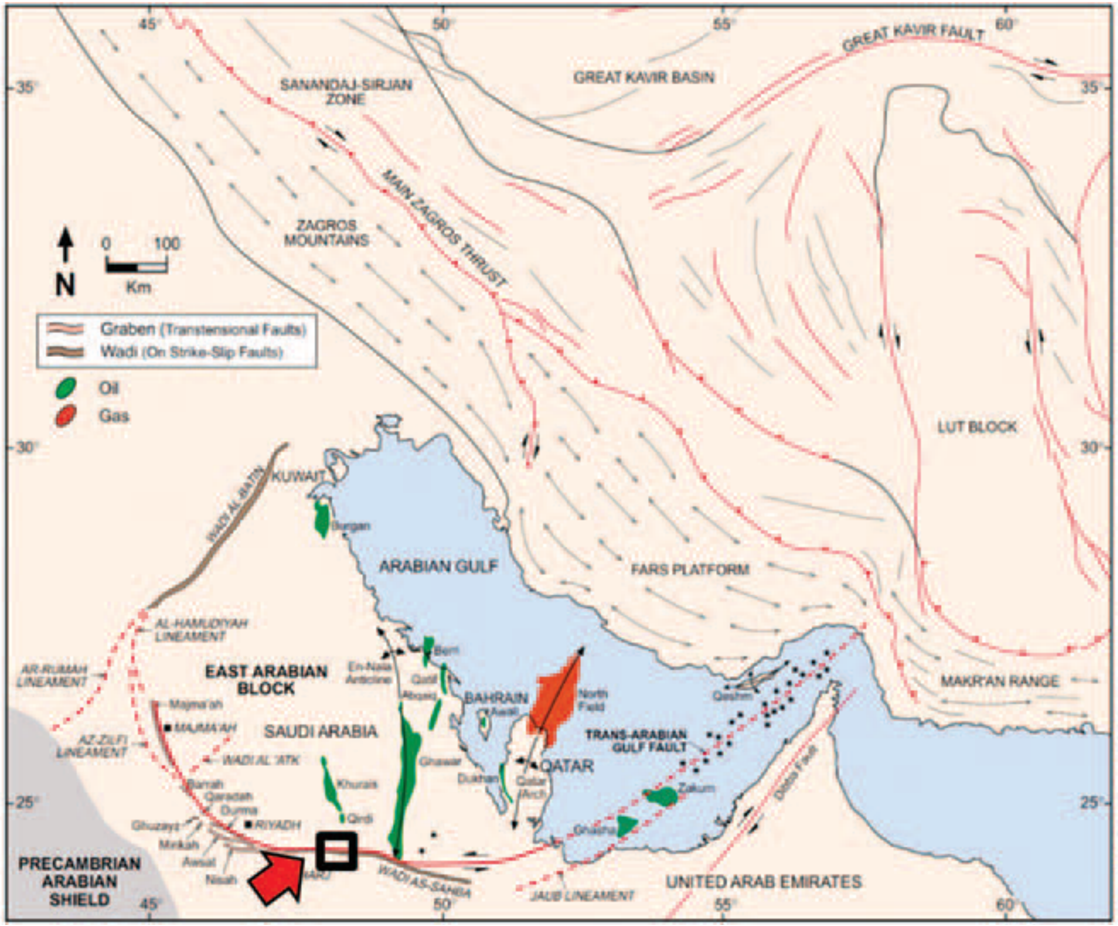




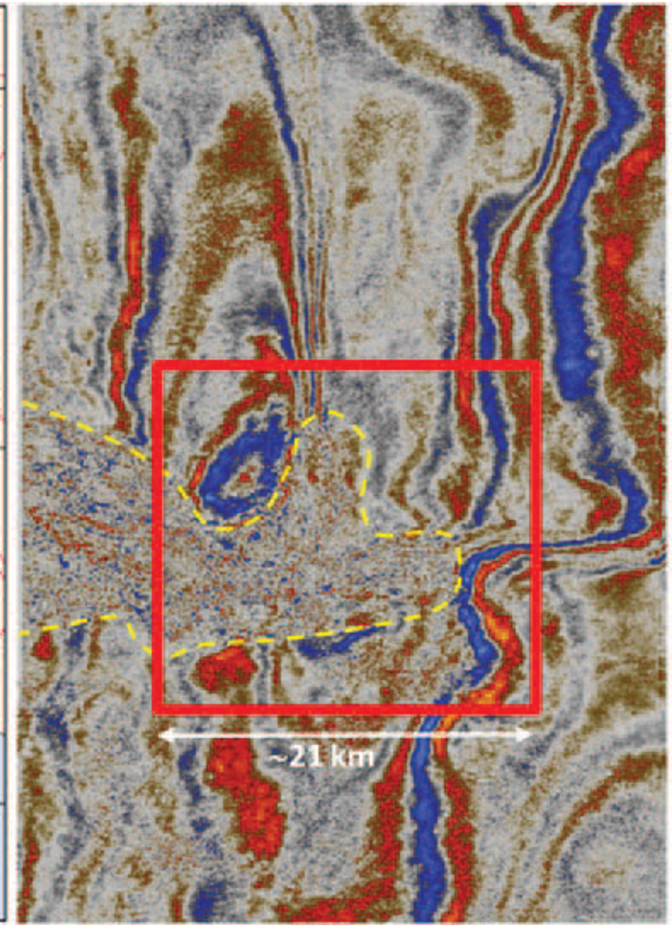
?

Setup

Location of Wadi area, Saudi Arabia



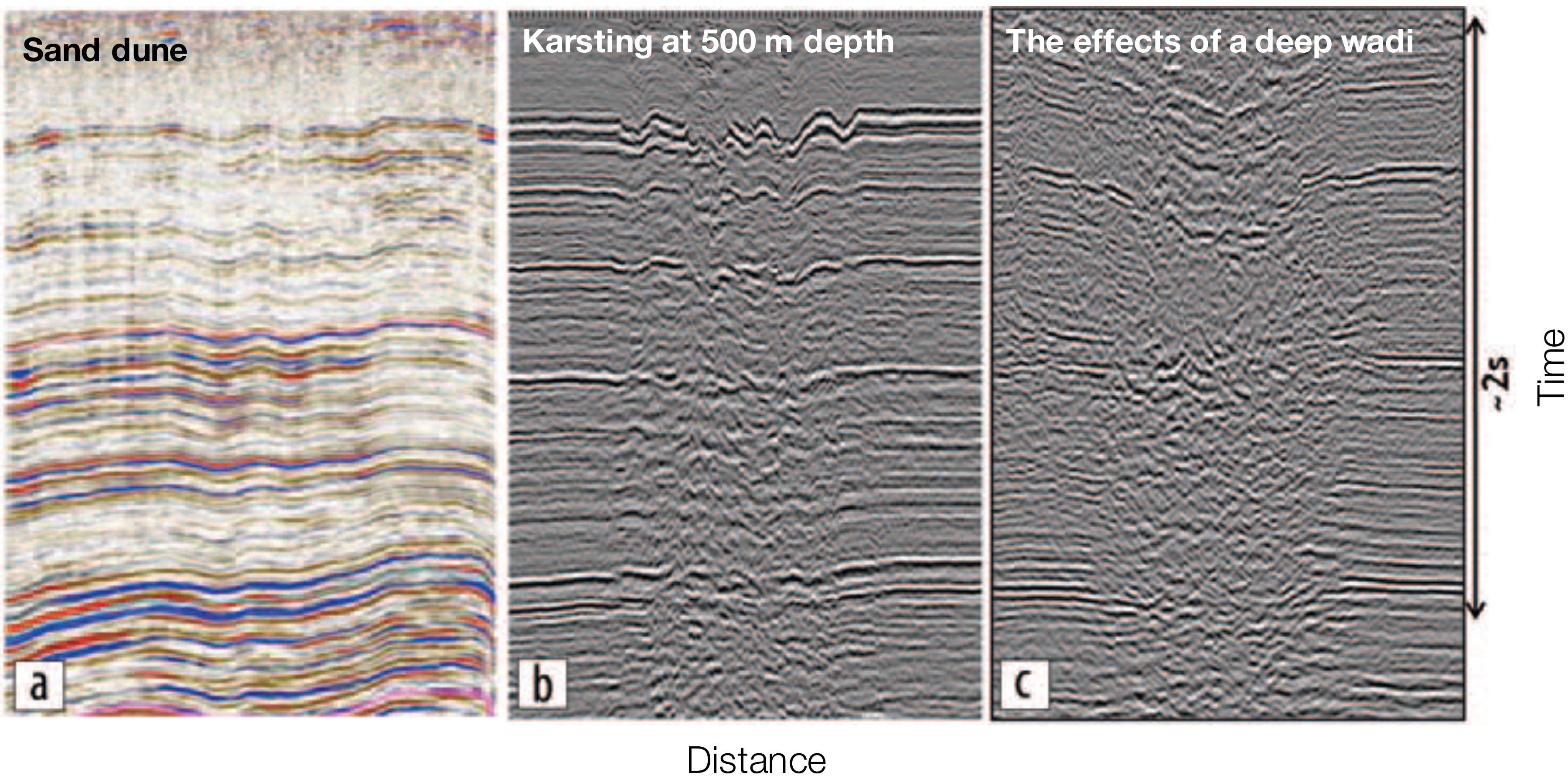
Seismic slice



- 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:

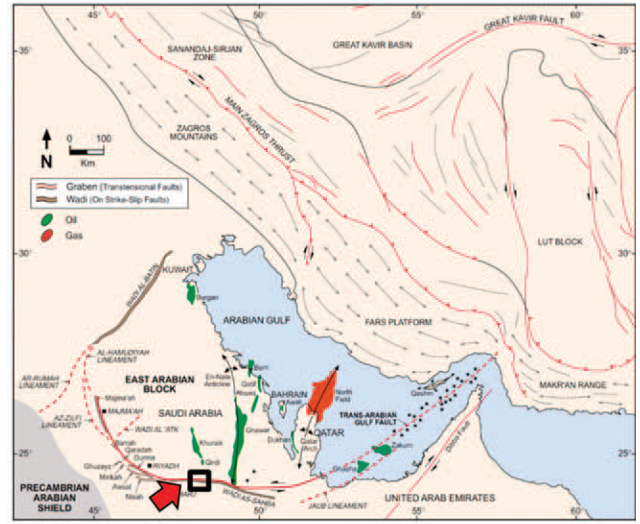
$$v_p = g(\phi)$$
$$\sigma = f(\phi)$$

v_p: P-velocity
ϕ: porosity

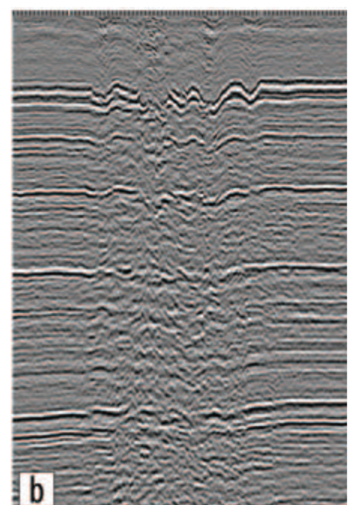
- Poor seismic data:
  - strong scattering effects probably caused by flower faults
  - velocity inversions (high to low v_p)

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

Geologic map



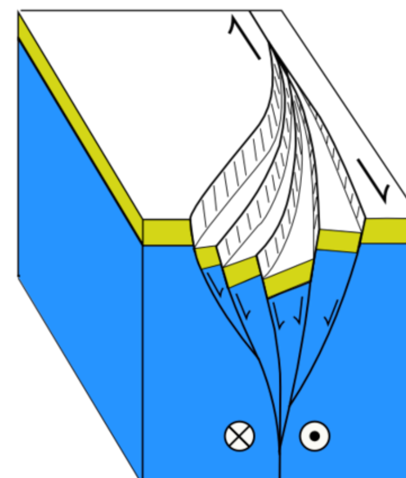
Seismic section



Time

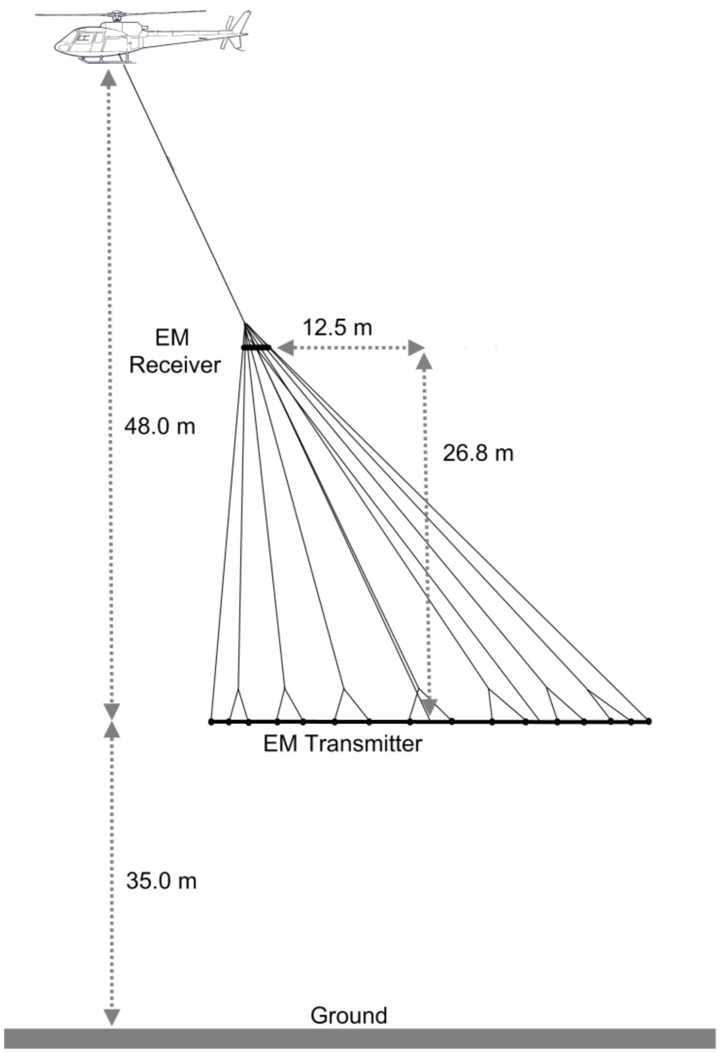
Distance

Flower faults

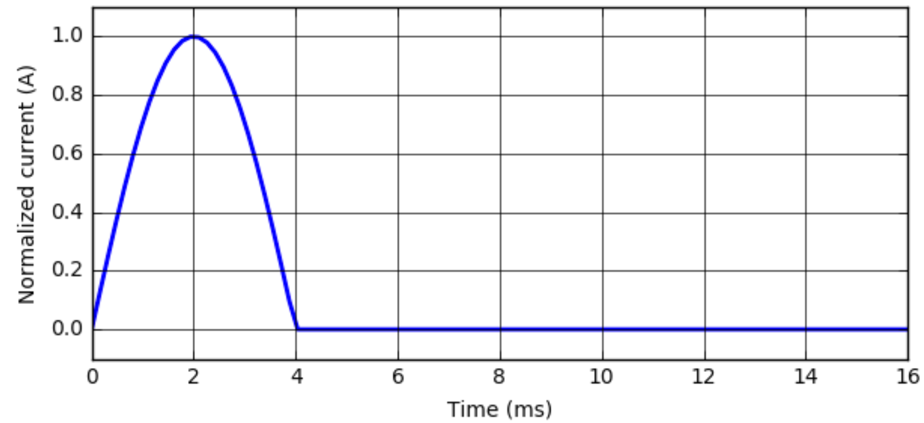


Survey

HELITEM

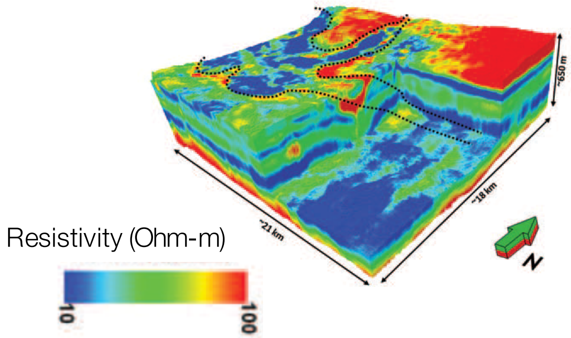


System Configuration

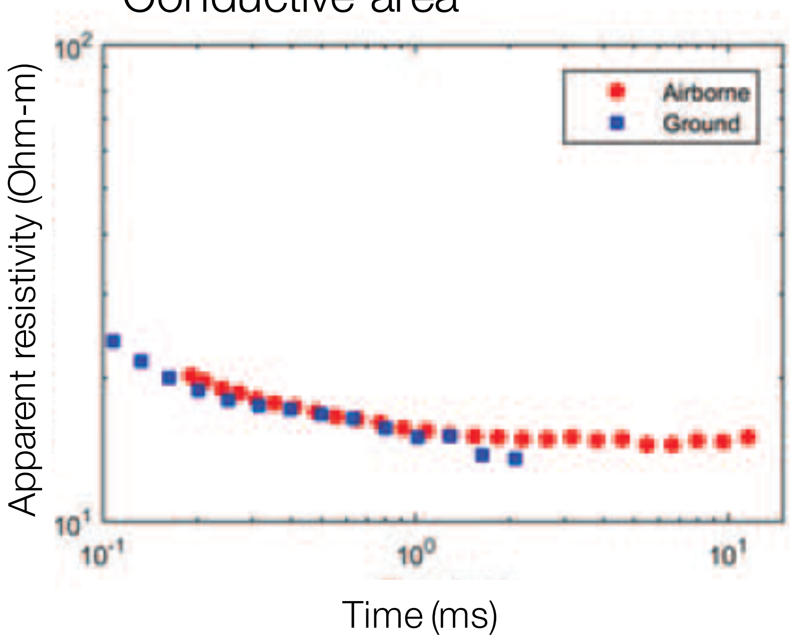


- Peak Tx current: 1200 A
- Dipole moment: 1.7×10^6 A-m^2
- Stacked TEM curve spacing: ~2.7 m
- Total soundings: ~1.6 million

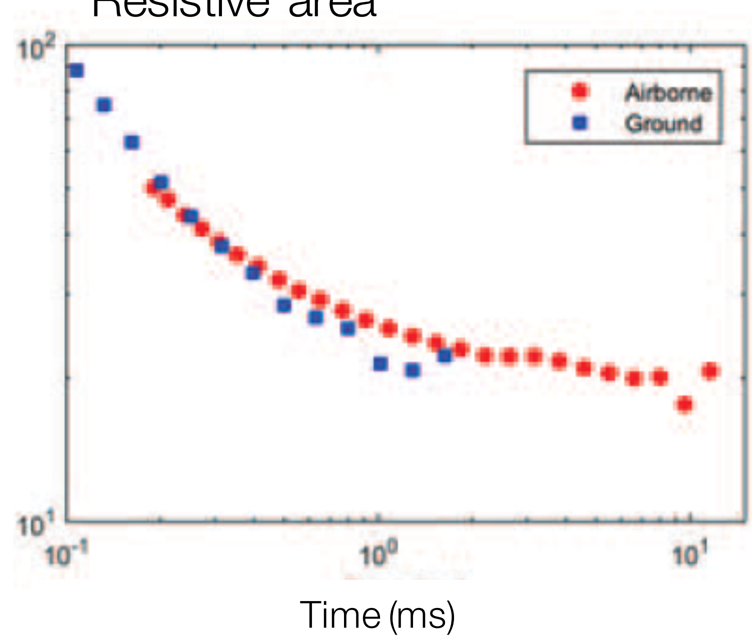
Comparisons: airborne and ground EM



Conductive area

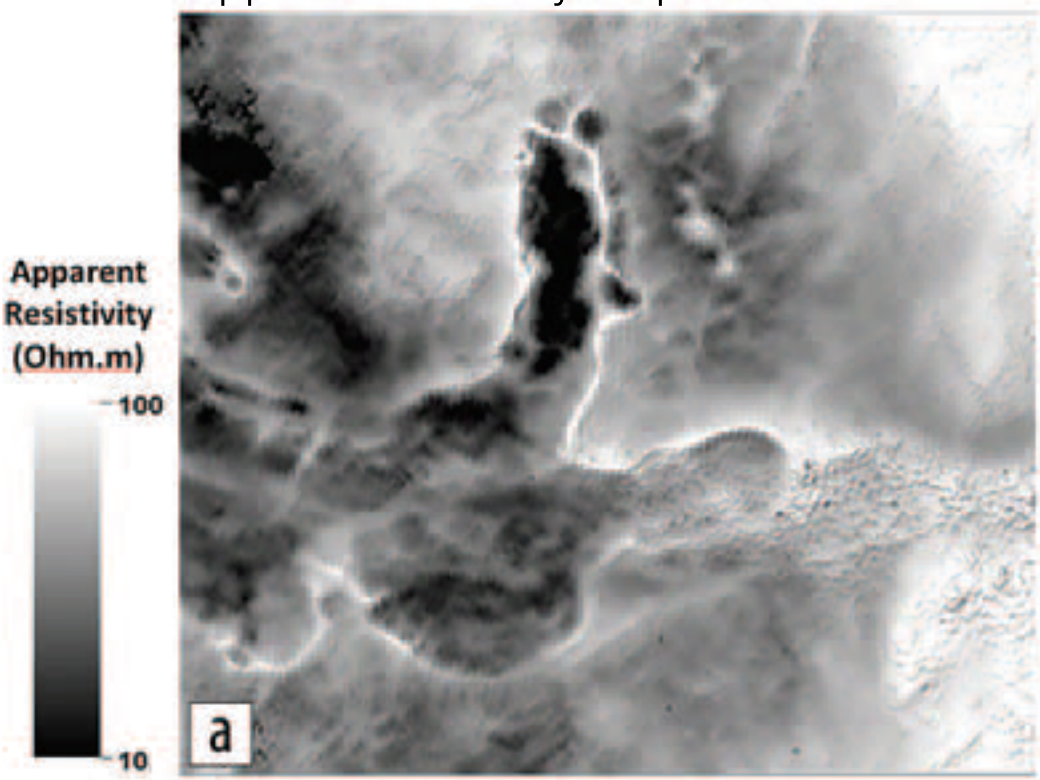


Resistive area

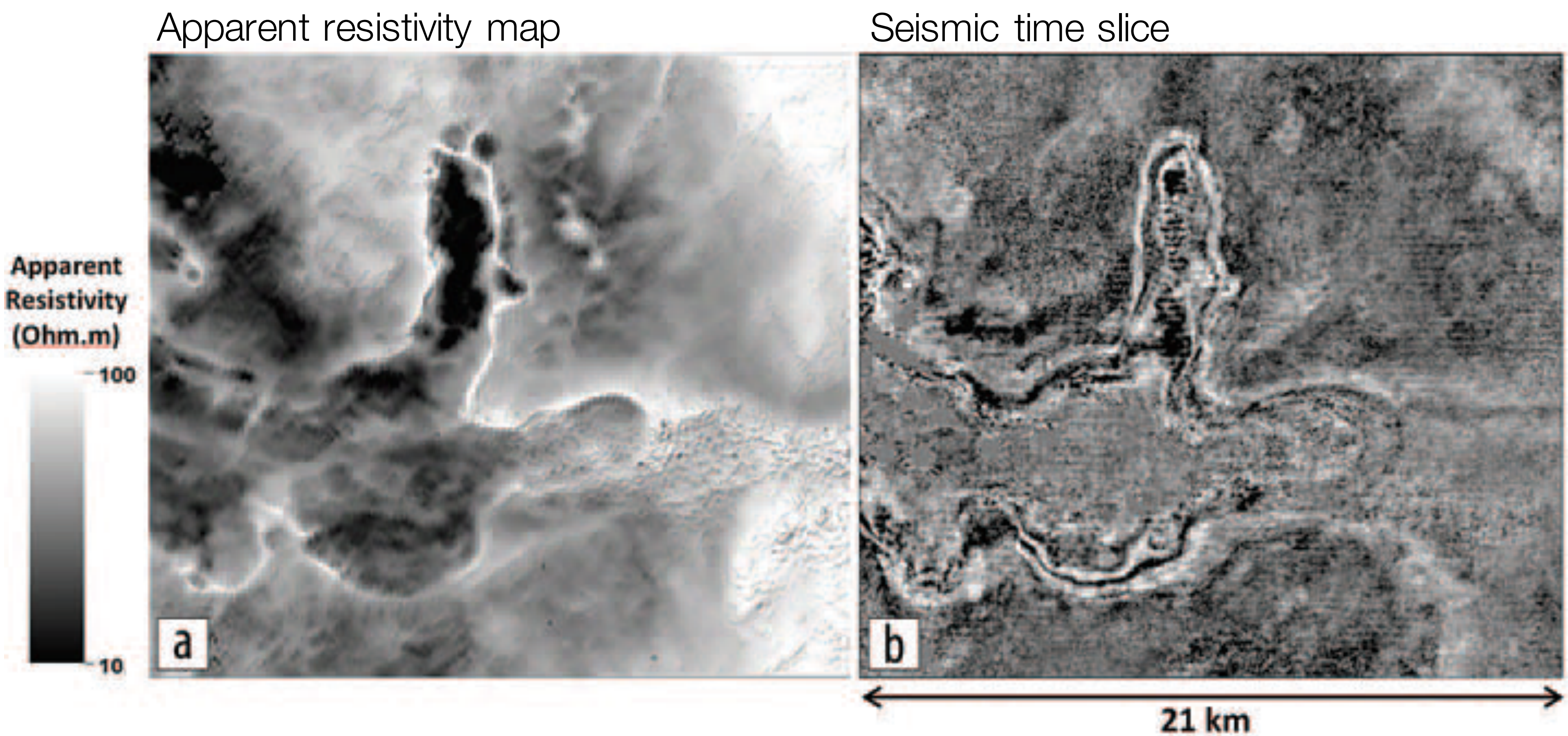


EM data

Apparent resistivity map

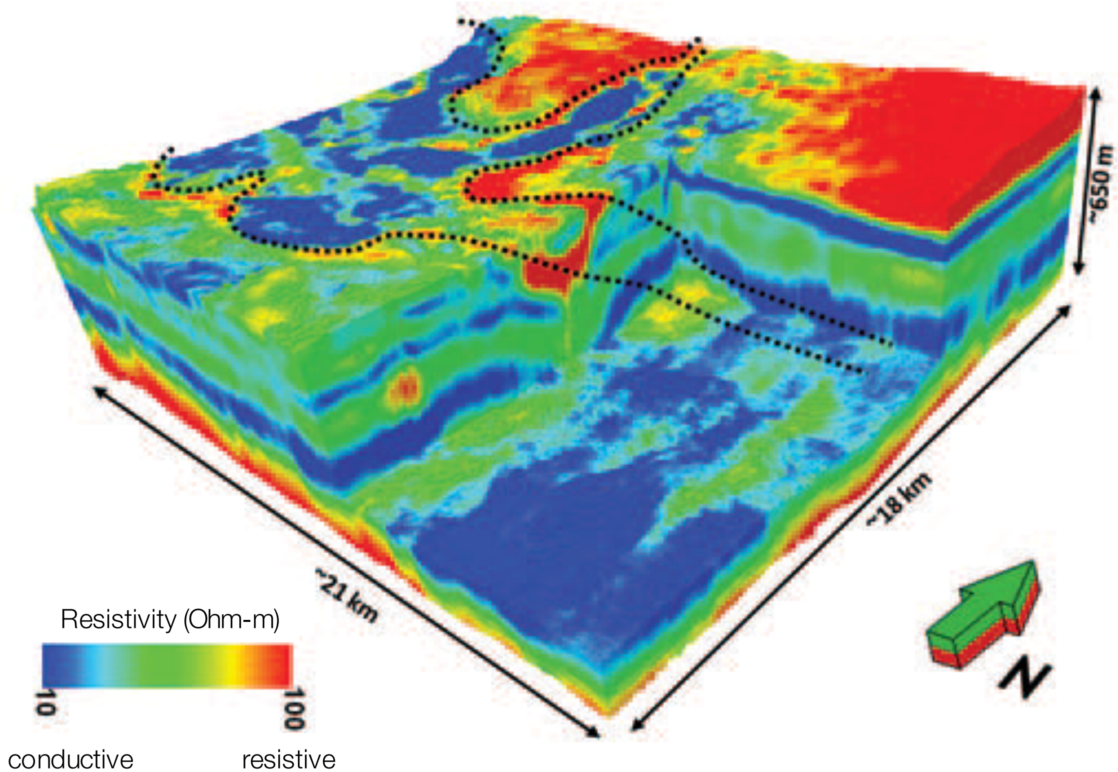


Comparison: EM and Seismic data



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

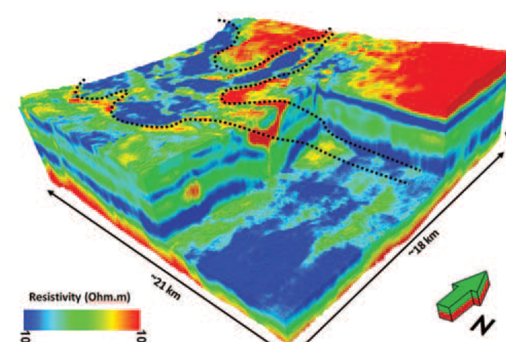
$\mathbf{m}_s$: Slowness

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

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

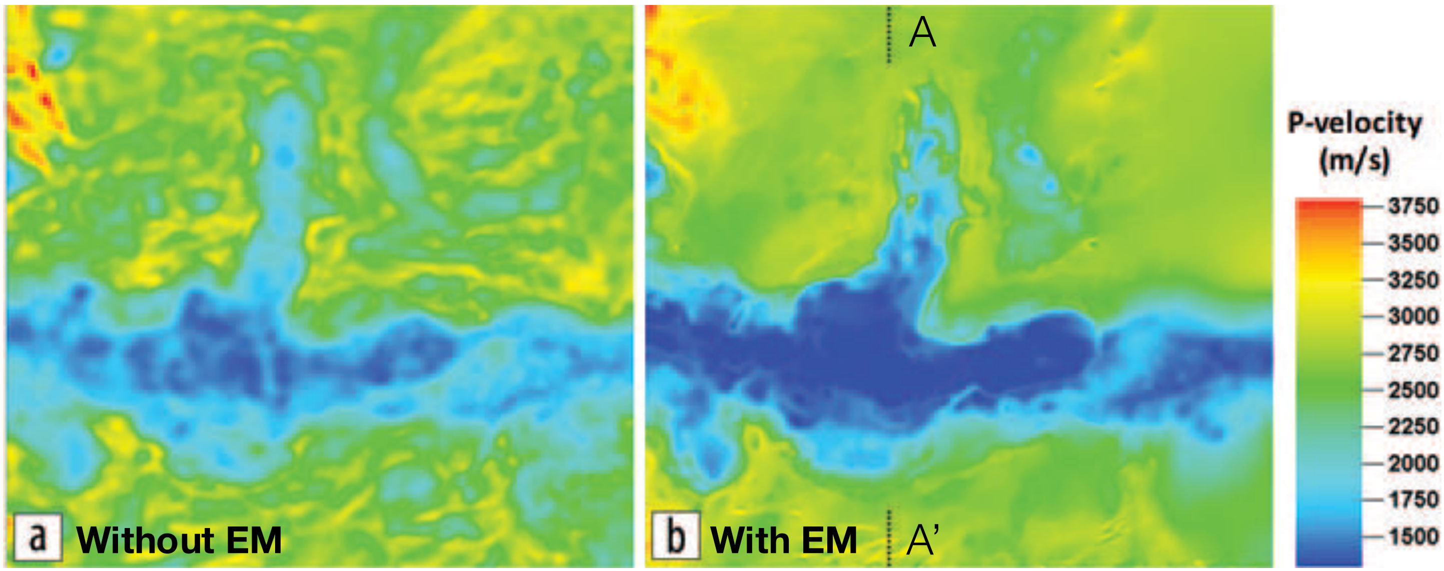
$$\|\nabla \mathbf{m_s} \times \nabla \mathbf{m}_\sigma\|_2^2$$

Gallardo and Meju, 2004



Cooperative inversion: Seismic + EM

V_p depth slices at 340 m below sea level

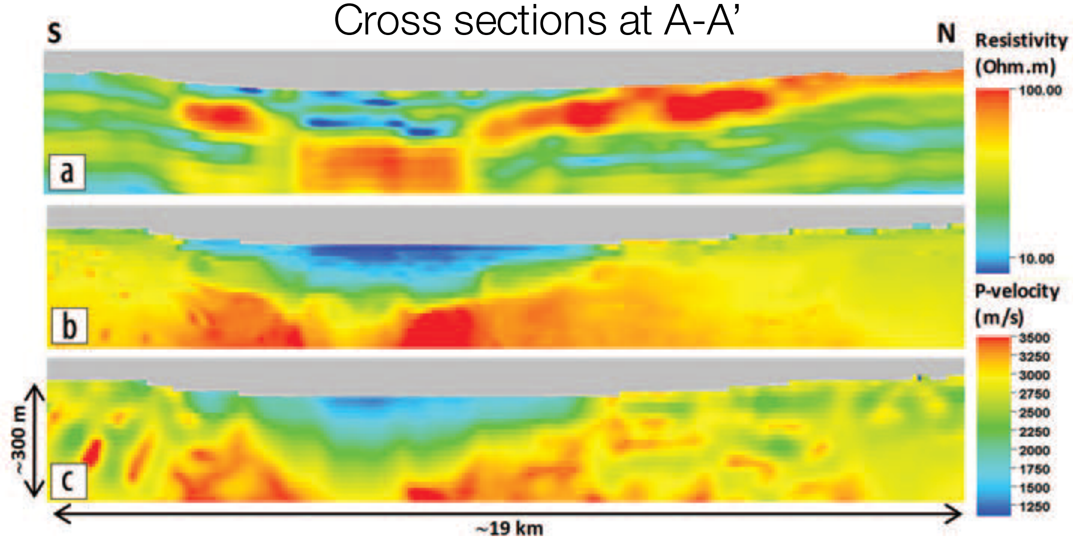


Cross sections at A-A'

Conductivity

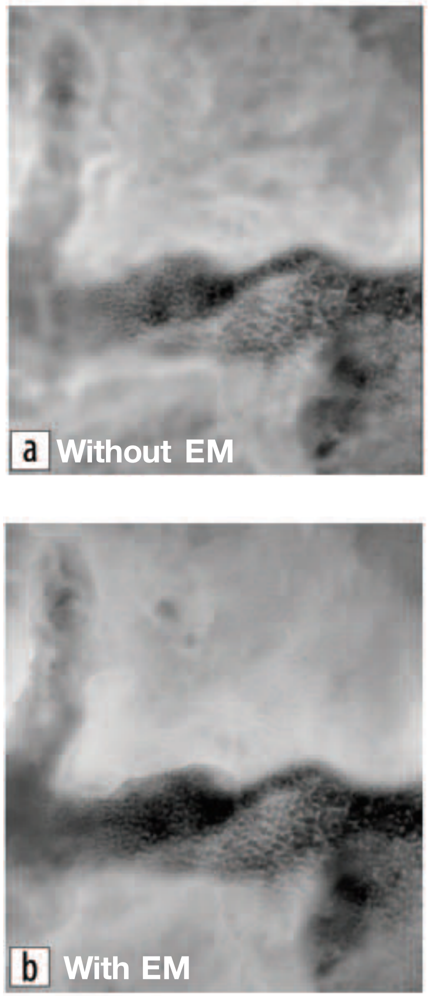
v_p **with EM**

v_p **without EM**

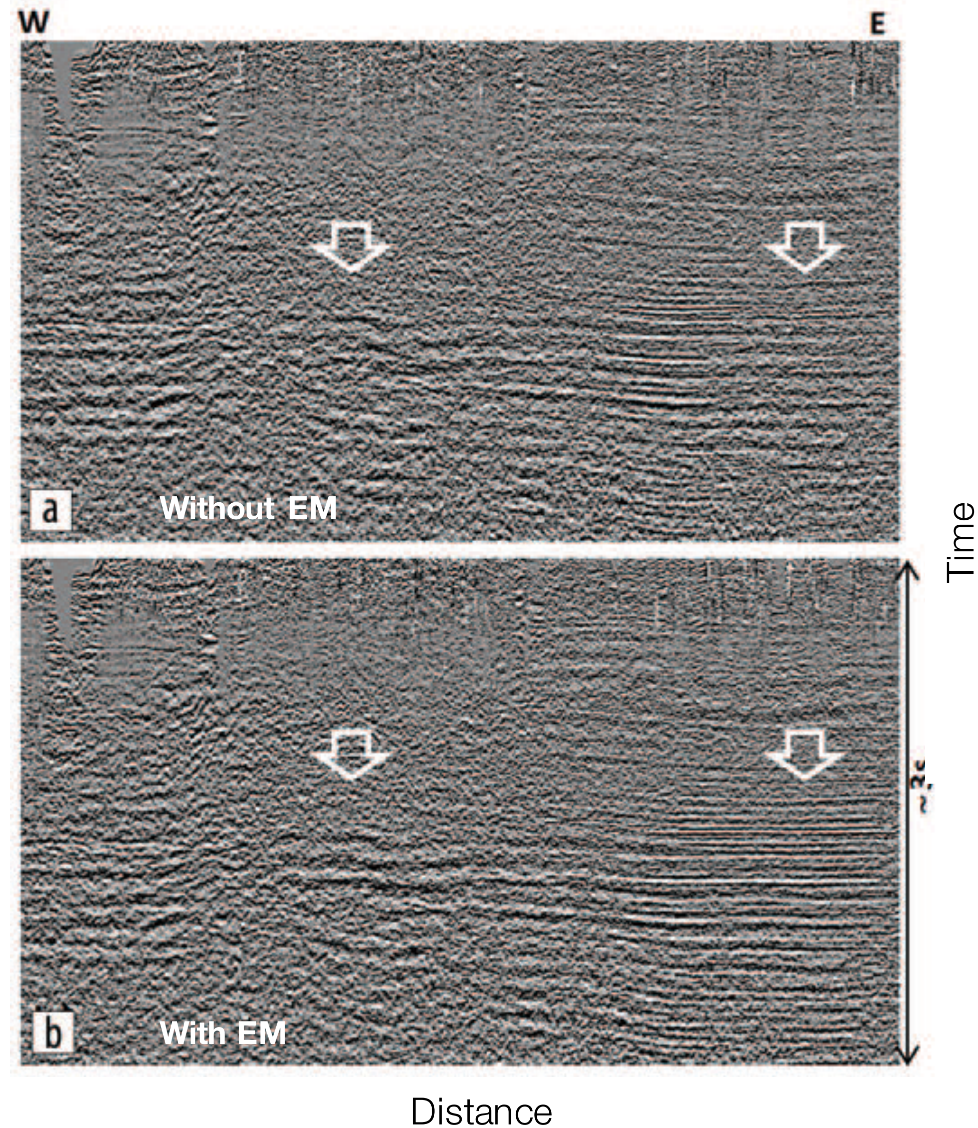


Static correction

Estimated statics on plan map



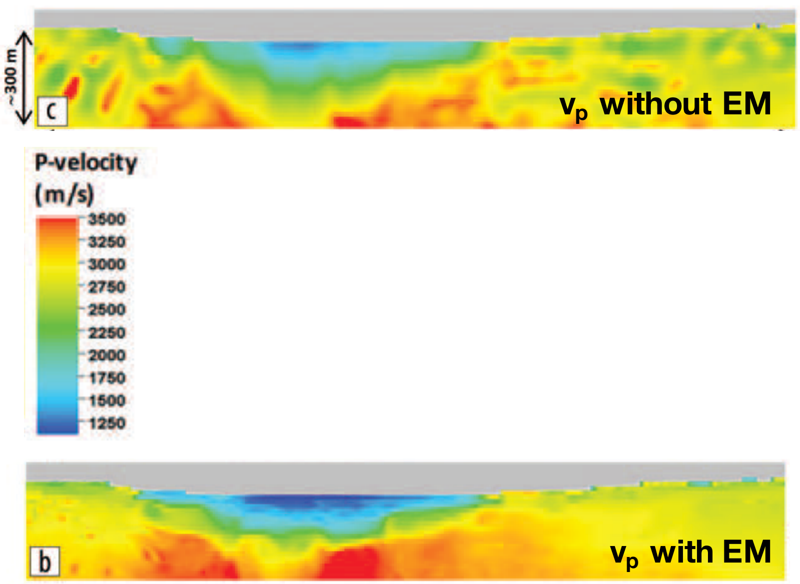
Static corrected sections



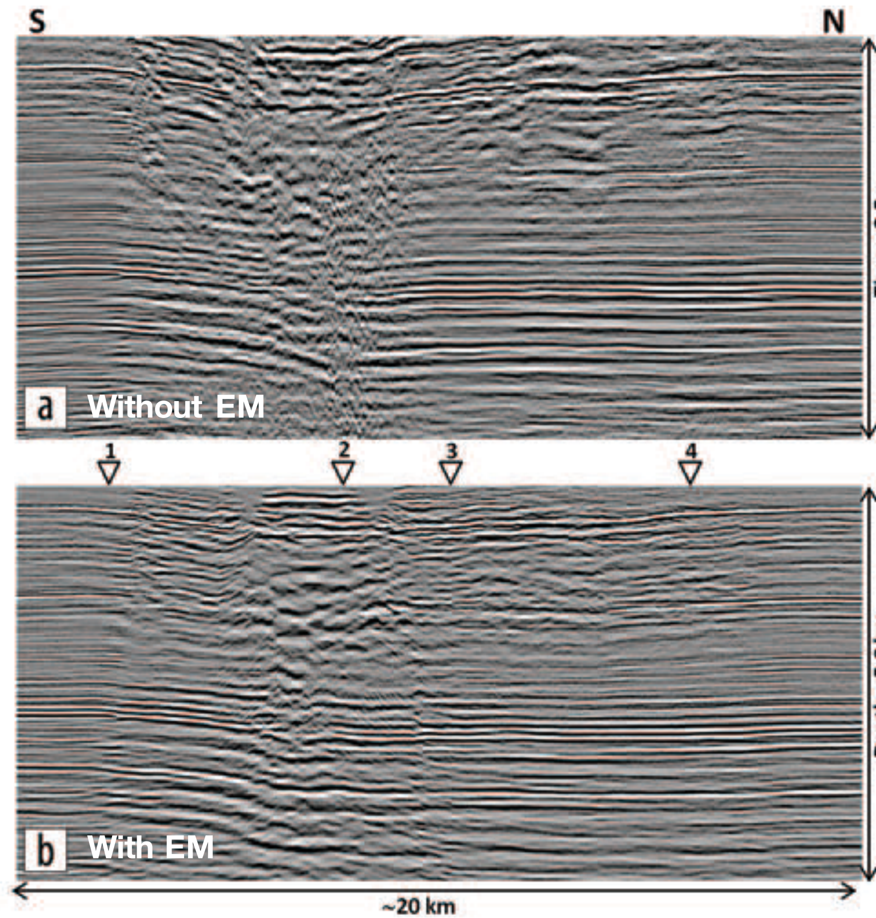
Pre-stack depth migration

- 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’



Time

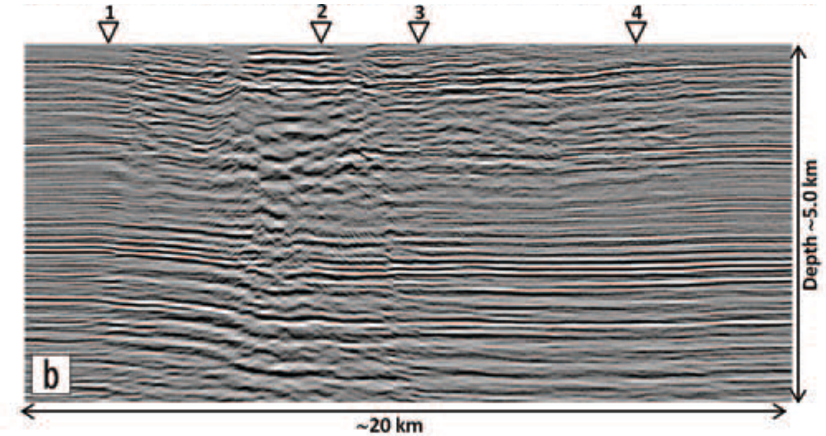
Depth

Distance

Interpretation and Synthesis

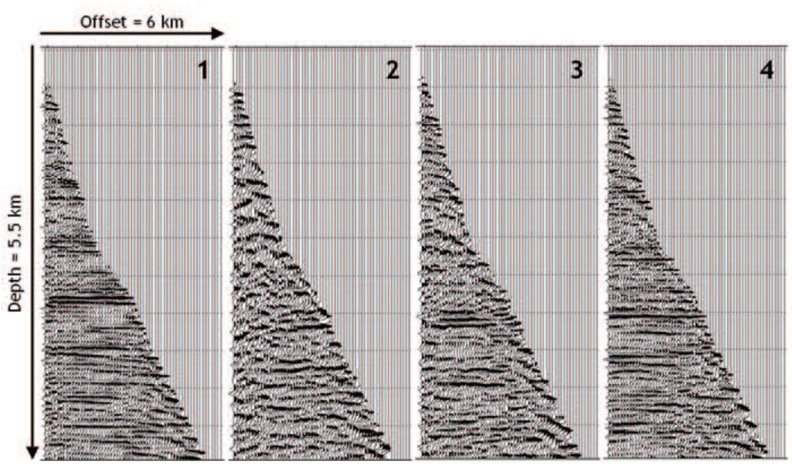
Depth section at A-A’

Depth



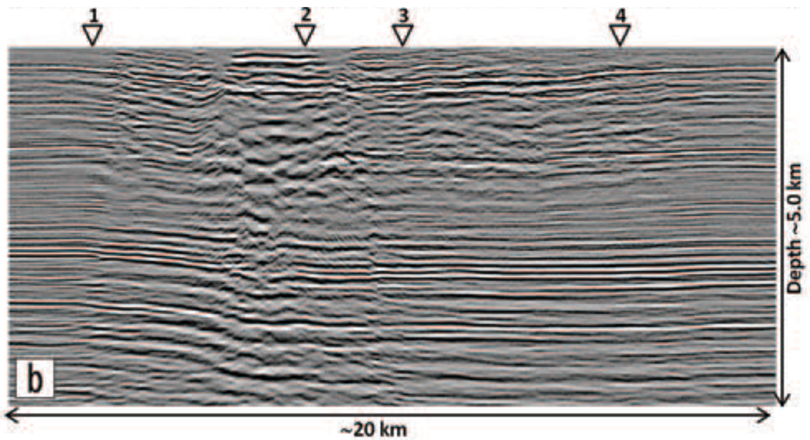
Distance

Common image gathers



Interpretation and Synthesis

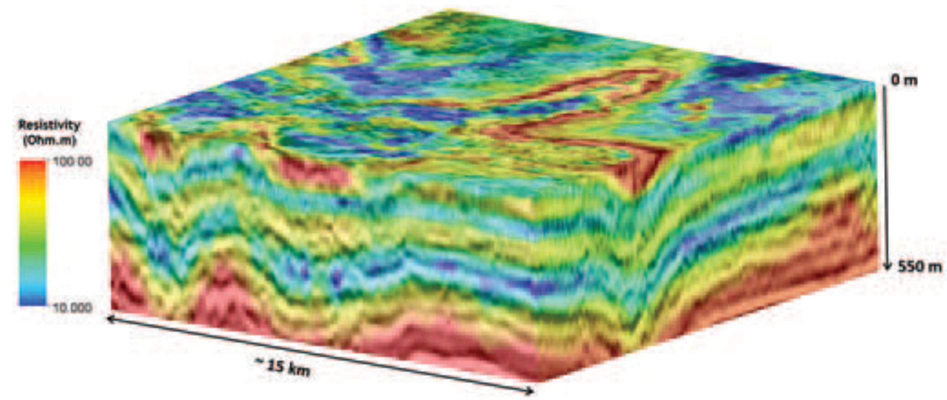
Depth section at A-A'



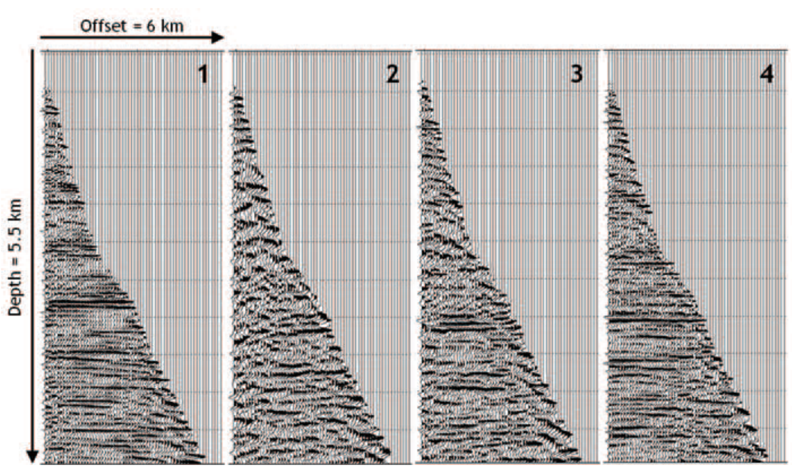
Depth

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