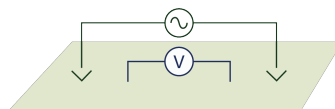


# EM: Grounded Sources

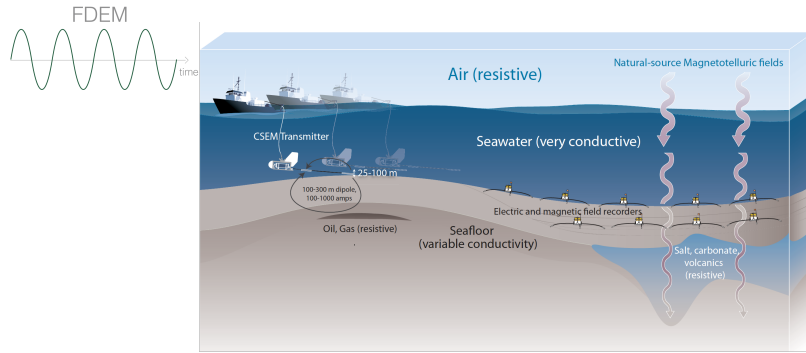


# Outline

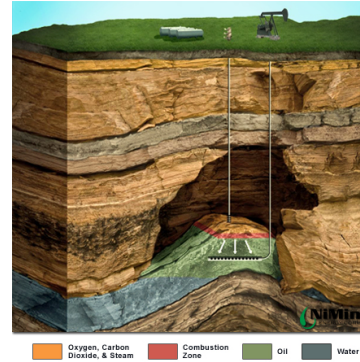
- Basic experiment
- TDEM: Electric dipole in a whole space
- FDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets
- Resistive Targets
- Case History: Deccan Traps
- Case History: Offshore Hydrocarbon De-risking
- Marine CSEM: Overview
- Case History: Methane hydrates

# Motivational examples

## Marine EM for hydrocarbon



## Oil and Gas (EOR)

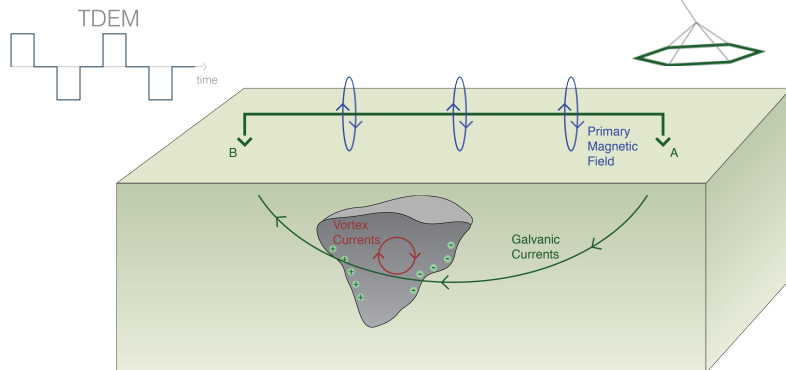


## Methane hydrates



## Galvanic source TEM

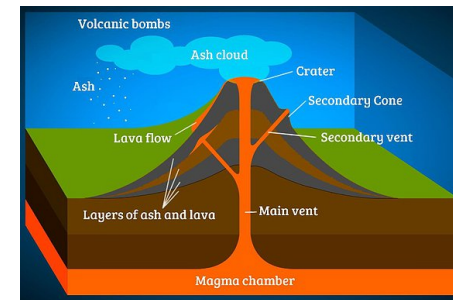
- LoTEM (ground)
- HeliSAM (Rx in the air)
- GREATEM (Rx in the air)



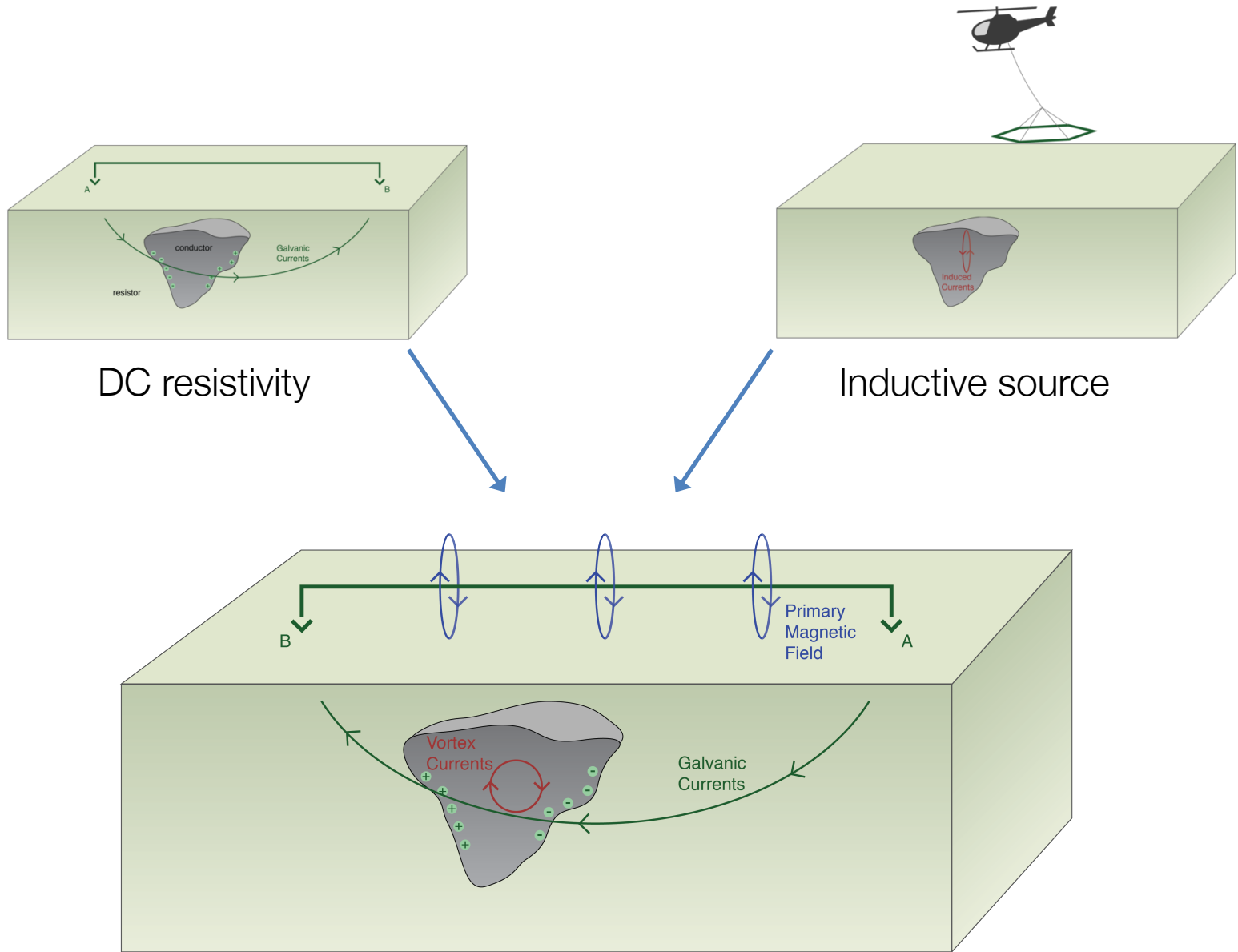
## Minerals



## Volcanoes

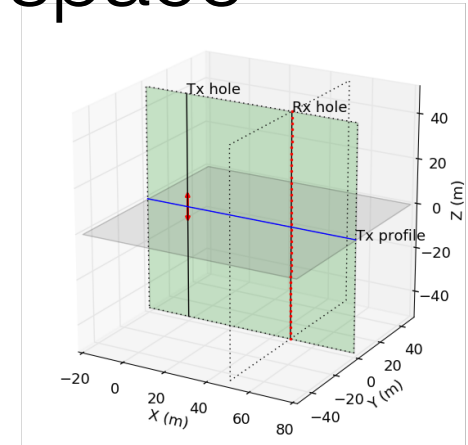


# Basic experiment

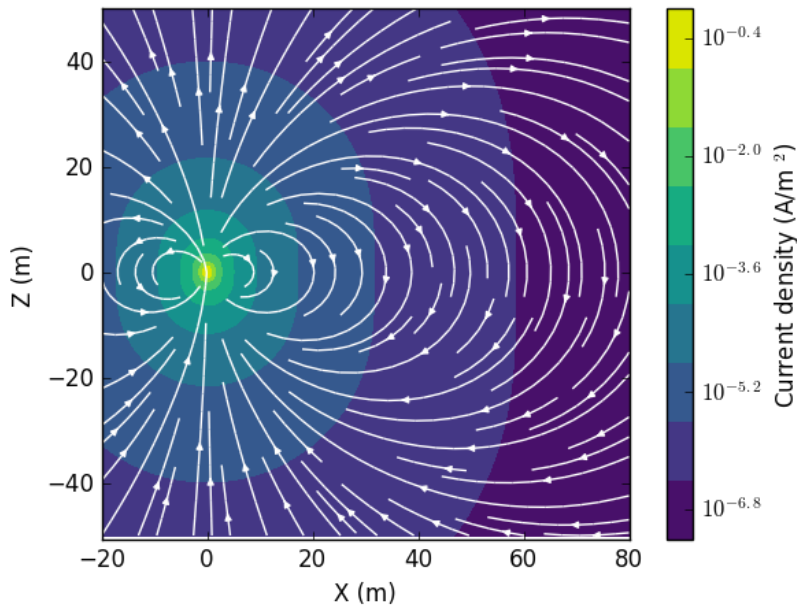


# Electric Dipole in a whole space

- Electric dipole in a whole space
  - DC, 0.01 S/m



DC current density

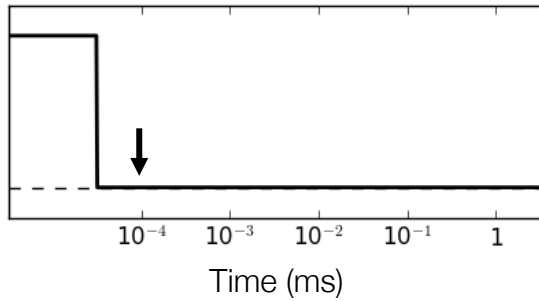


$$\mathbf{E}_{DC}(\mathbf{r}) = \frac{1}{4\pi\sigma|\mathbf{r}|^3} \left( \frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m} \right)$$

$$\mathbf{J}_{DC}(\mathbf{r}) = \frac{1}{4\pi|\mathbf{r}|^3} \left( \frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m} \right)$$

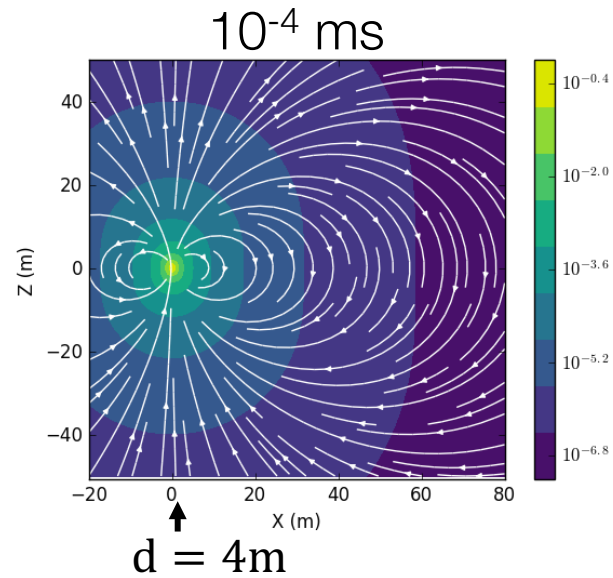
- Geometric decay:  $1/r^3$
- Current path is geometric for homogeneous earth
- Electric field is dependent upon  $\sigma$

# Electric Dipole in a whole space: TDEM

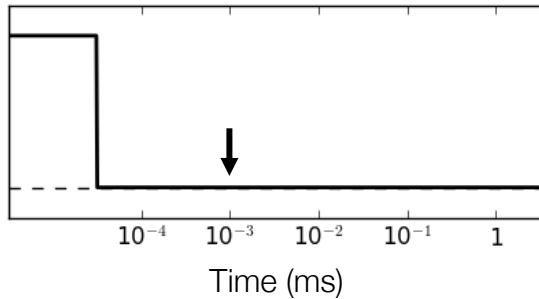


Diffusion  
distance

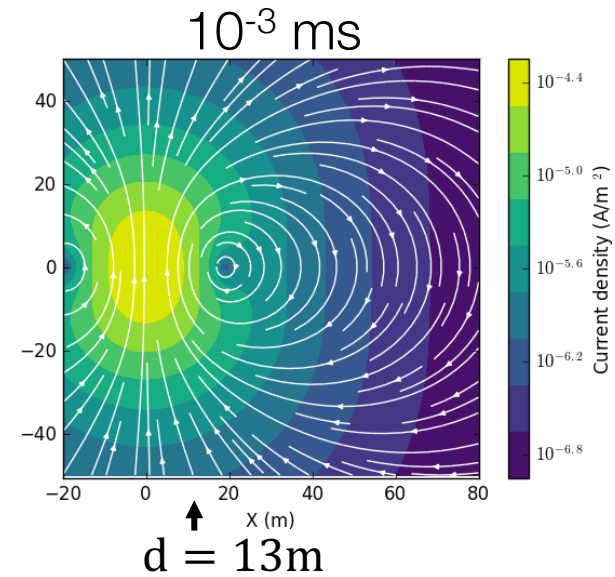
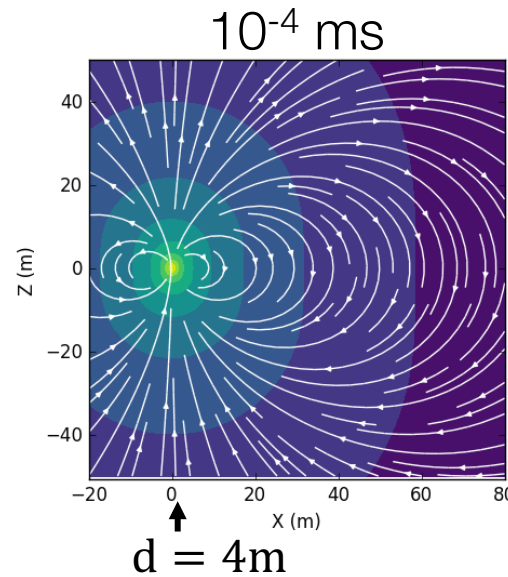
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$



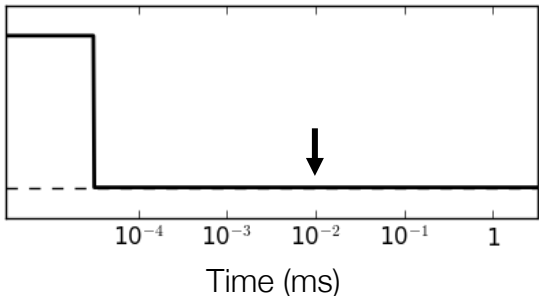
# Electric Dipole in a whole space: TDEM



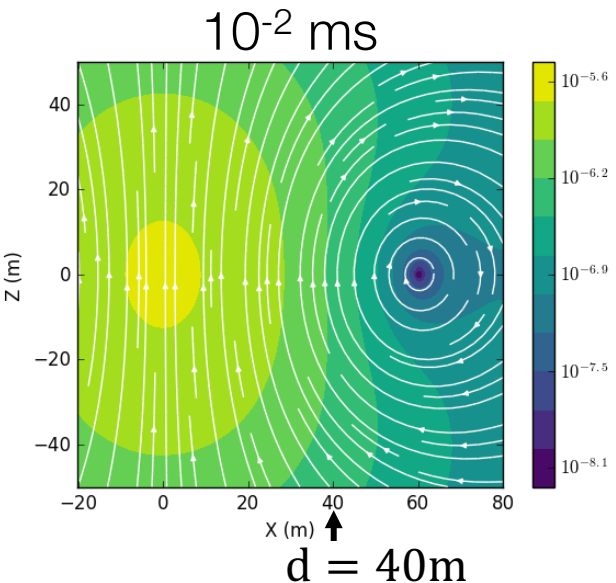
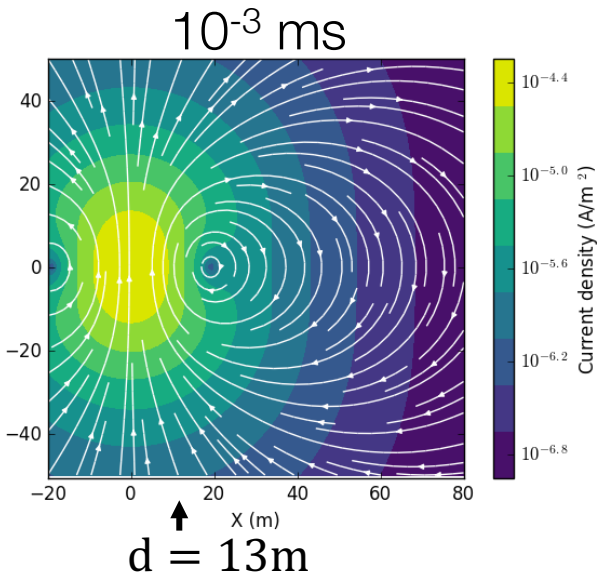
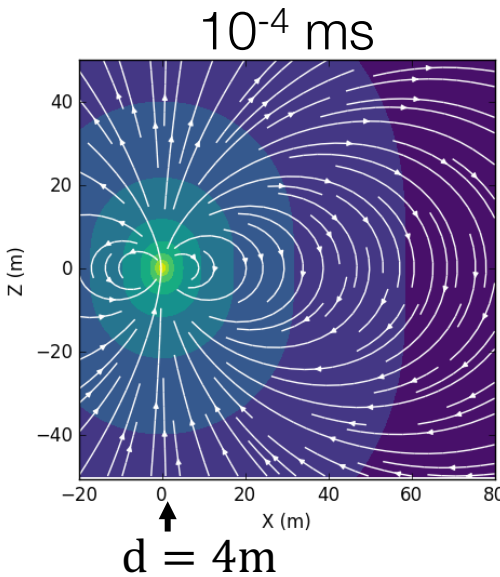
Diffusion distance  $d = \sqrt{\frac{2t}{\mu\sigma}}$



# Electric Dipole in a whole space: TDEM

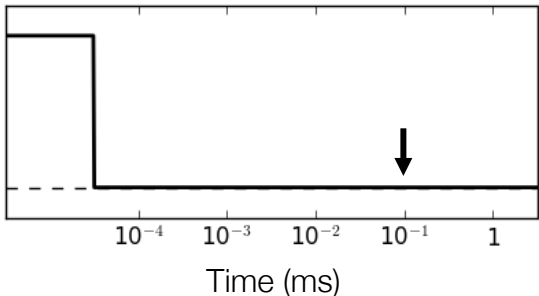


Diffusion distance  $d = \sqrt{\frac{2t}{\mu\sigma}}$





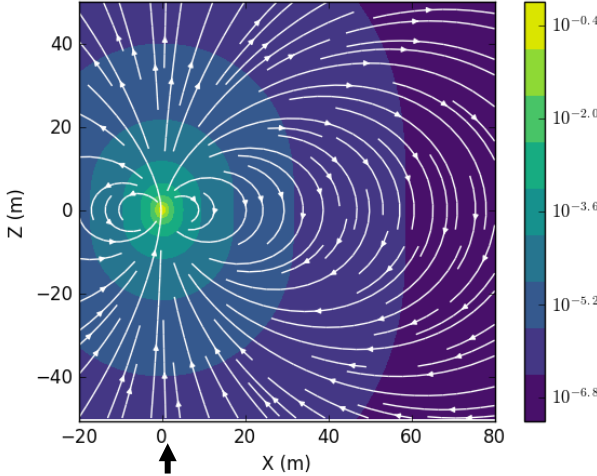
# Electric Dipole in a whole space: TDEM



Diffusion distance

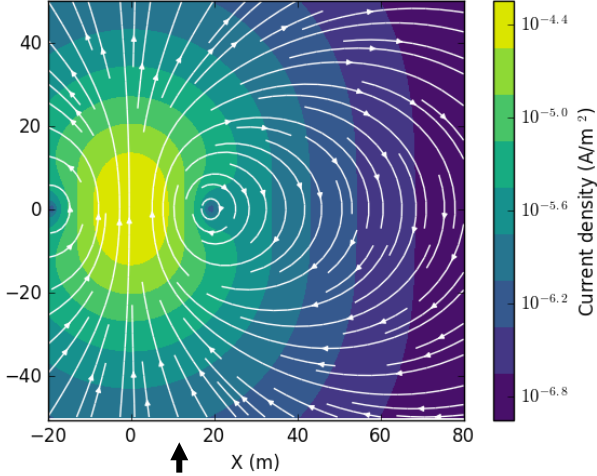
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

10<sup>-4</sup> ms



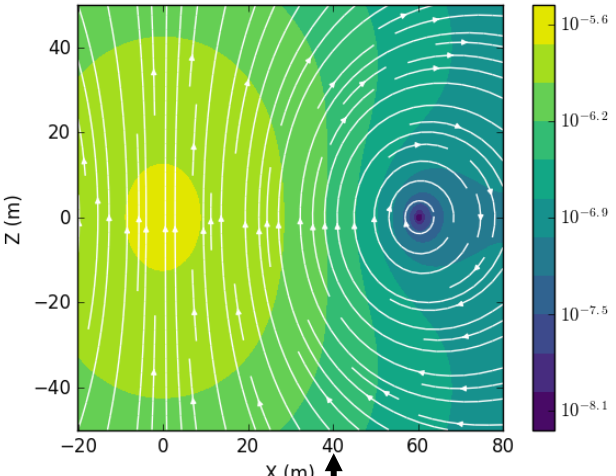
d = 4m

10<sup>-3</sup> ms



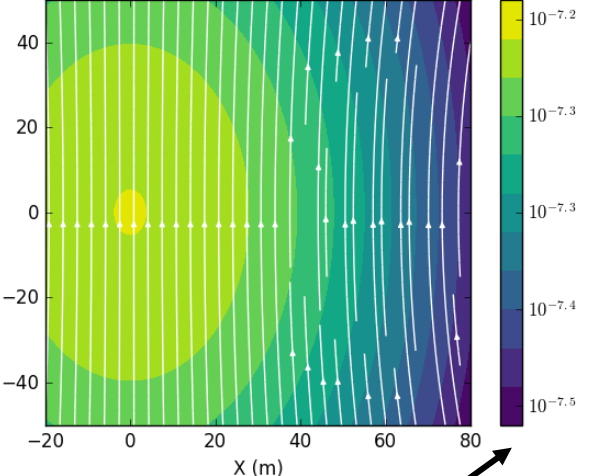
d = 13m

10<sup>-2</sup> ms



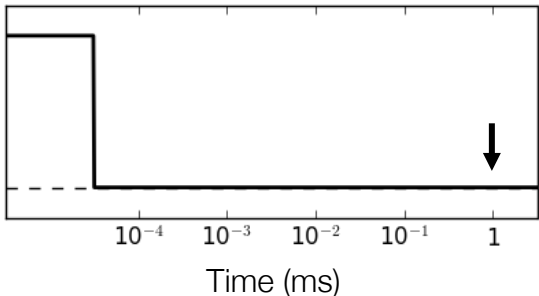
d = 40m

10<sup>-1</sup> ms



d = 126m

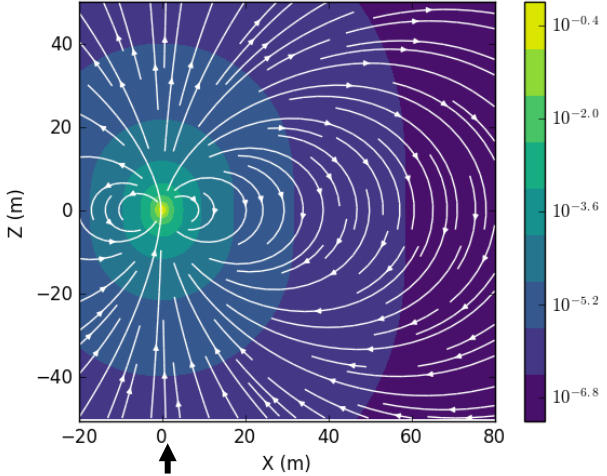
# Electric Dipole in a whole space: TDEM



Diffusion distance

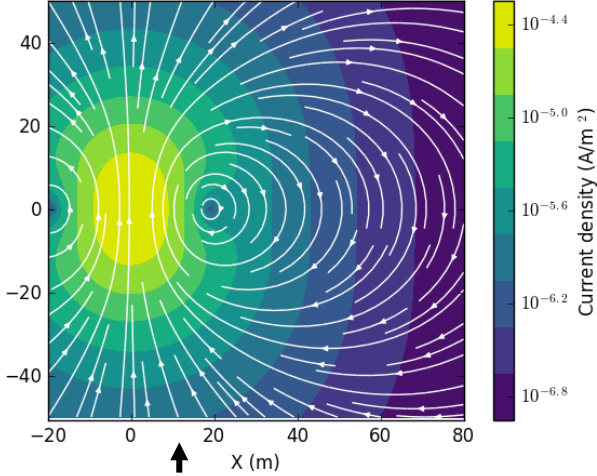
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

$10^{-4}$  ms



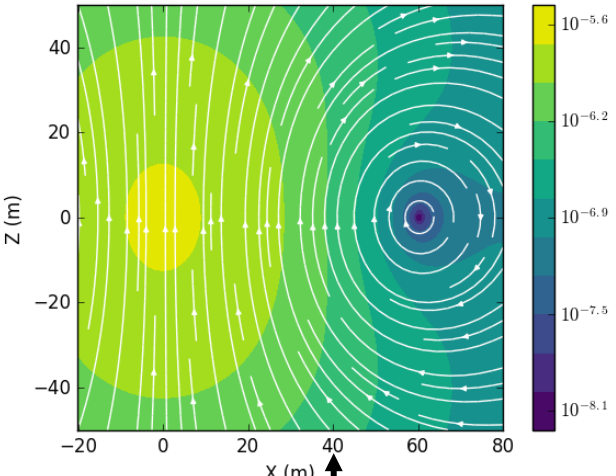
$d = 4\text{m}$

$10^{-3}$  ms



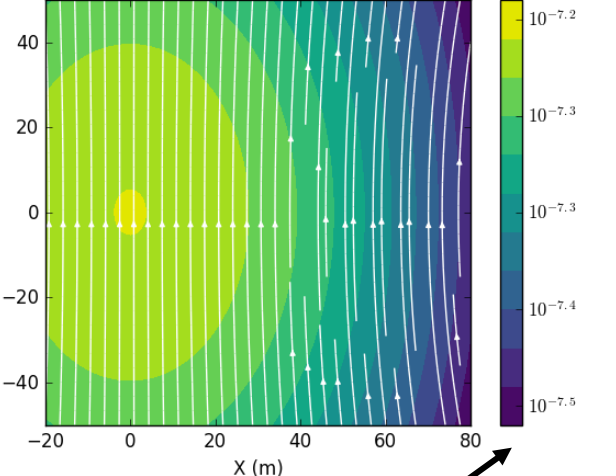
$d = 13\text{m}$

$10^{-2}$  ms



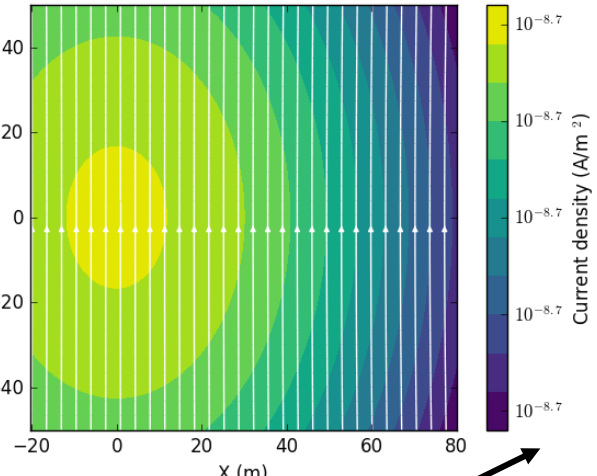
$d = 40\text{m}$

$10^{-1}$  ms



$d = 126\text{m}$

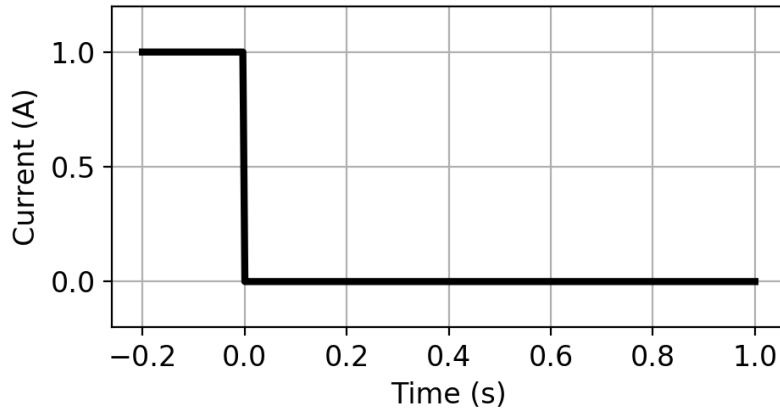
1 ms



$d = 400\text{m}$

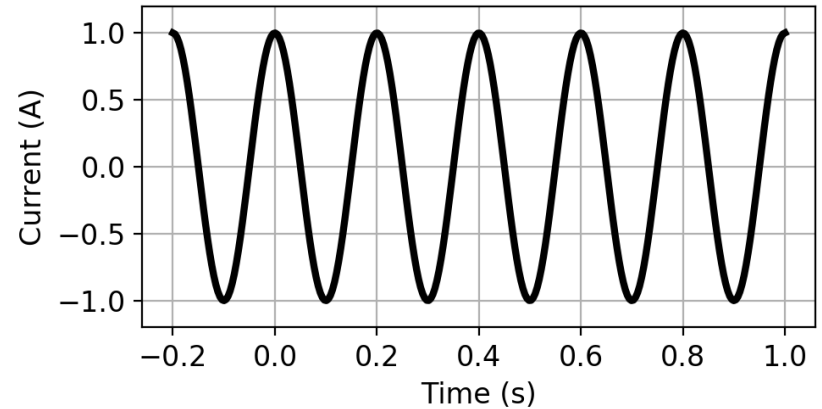
# TDEM vs. FDEM

## Step-off



- Waveform: Shut off
- No primary
- Measure in “Off-time”

## Harmonic



- Waveform: harmonic
- Primary always on
- Data partitioned into
  - Real (In-phase)
  - Imag (Quadrature)

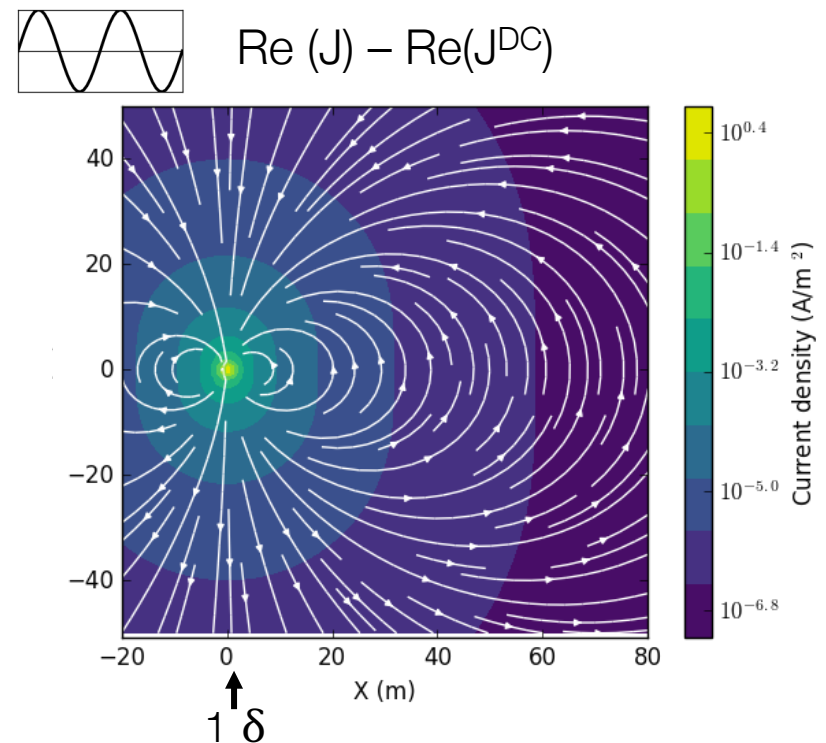
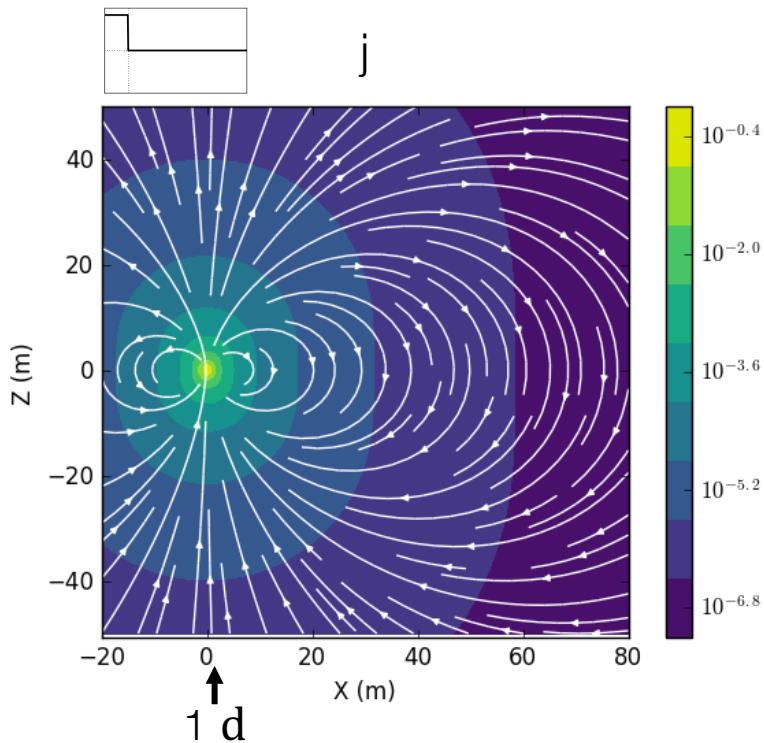
# Electric Dipole in a whole space: FDEM

$t=10^{-4}$  ms,  $d = 4$  m

$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

$f=10^4$  kHz,  $\delta = 2$  m

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



# Electric Dipole in a whole space: FDEM

$t=10^{-3}$  ms,  $d = 13$  m

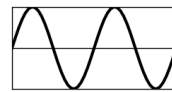
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

$f=10^3$  kHz,  $\delta = 5$  m

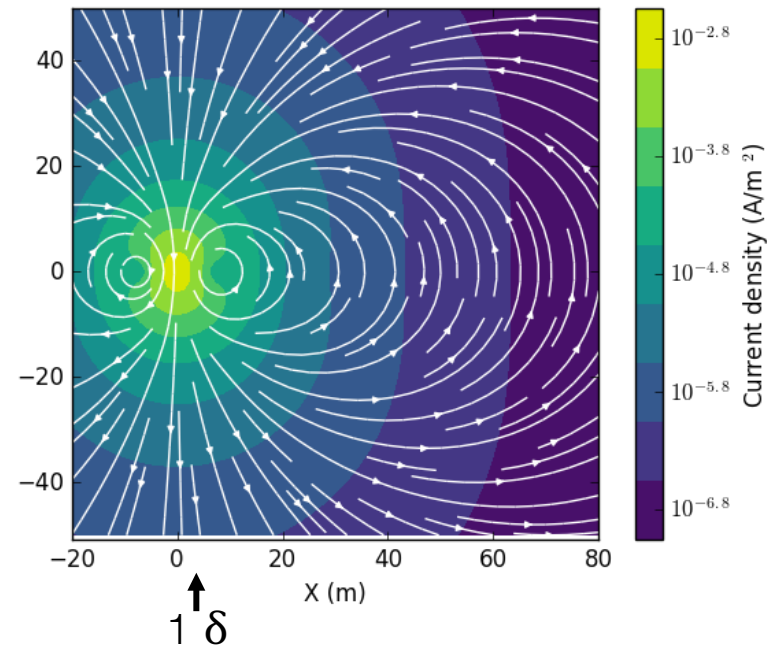
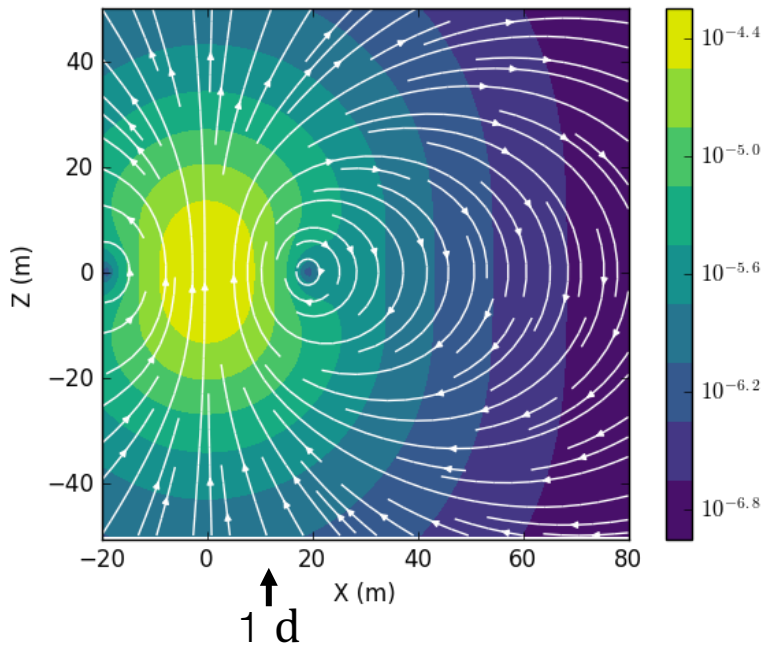
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



$j$



$\text{Re}(J) - \text{Re}(J^{\text{DC}})$



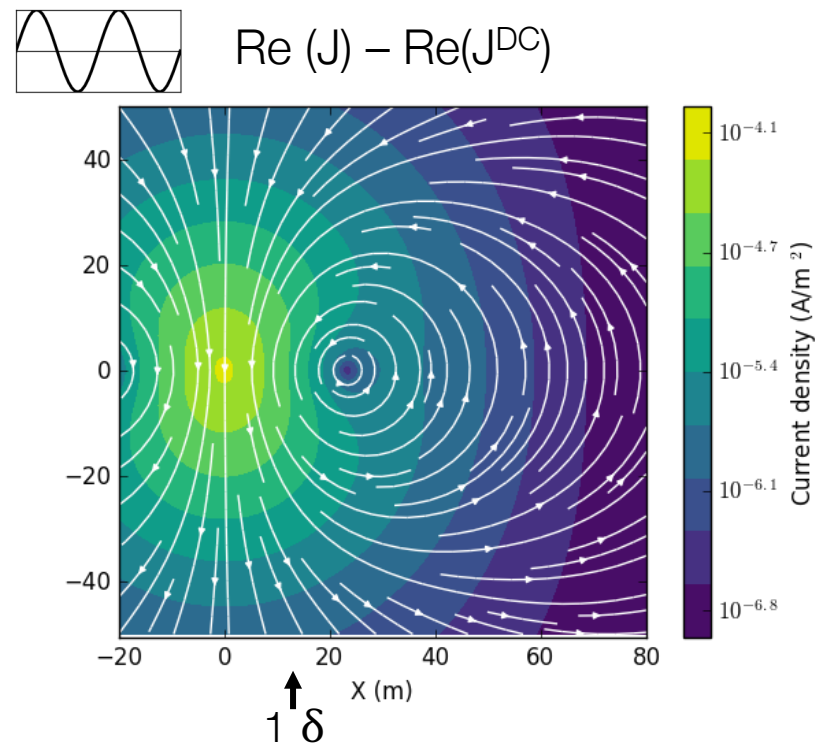
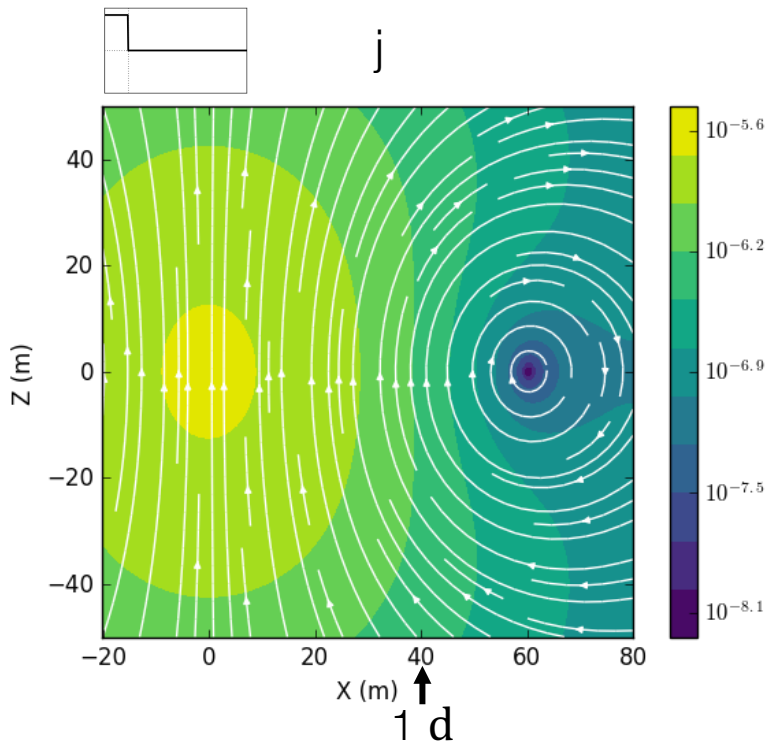
# Electric Dipole in a whole space: FDEM

$t=10^{-2}$  ms,  $d = 40$ m

$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

$f=10^2$  kHz,  $\delta = 16$  m

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



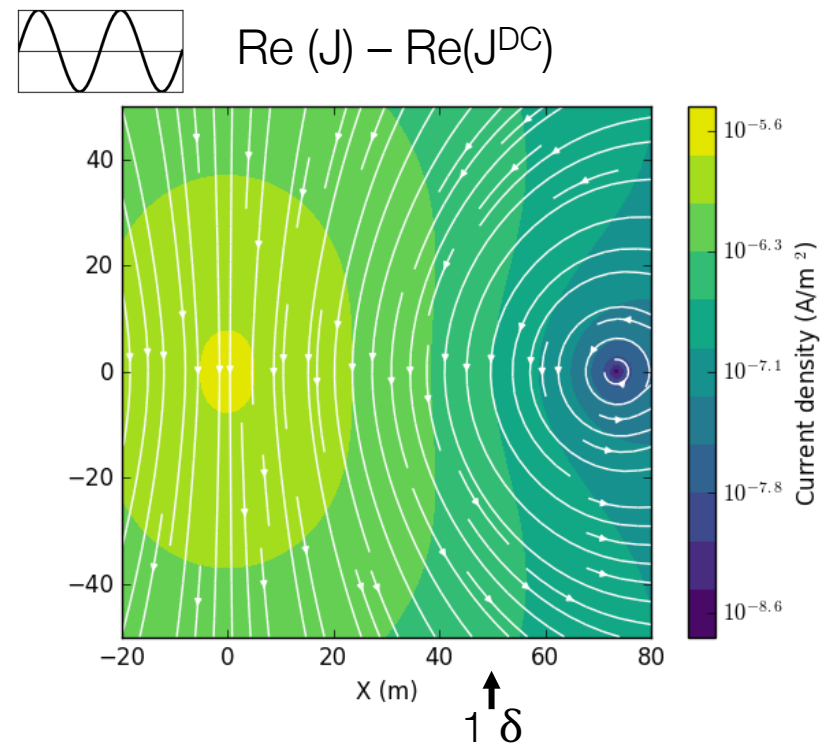
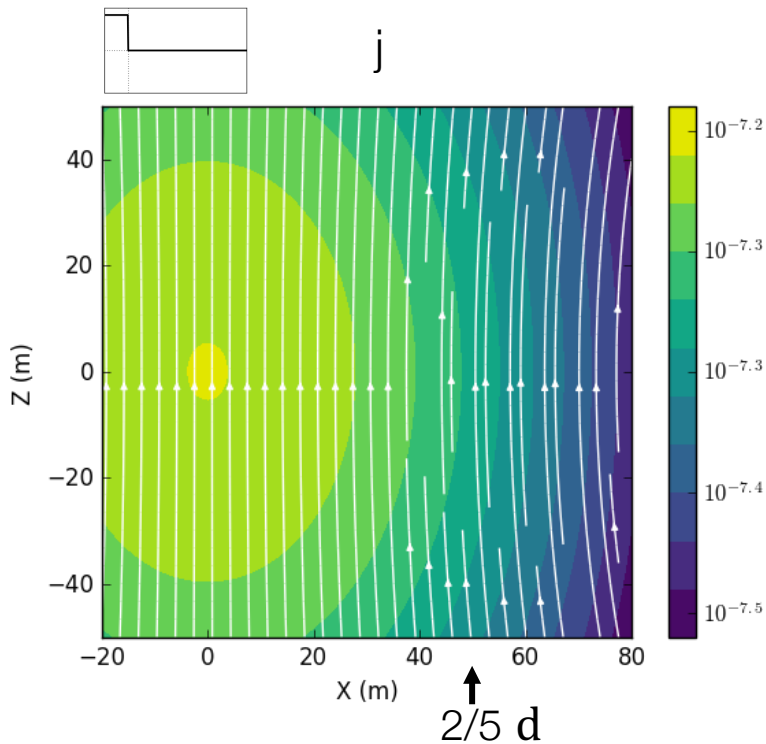
# Electric Dipole in a whole space: FDEM

$t=10^{-1}$  ms,  $d = 126$ m

$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

$f=10^1$  kHz,  $\delta = 50$  m

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



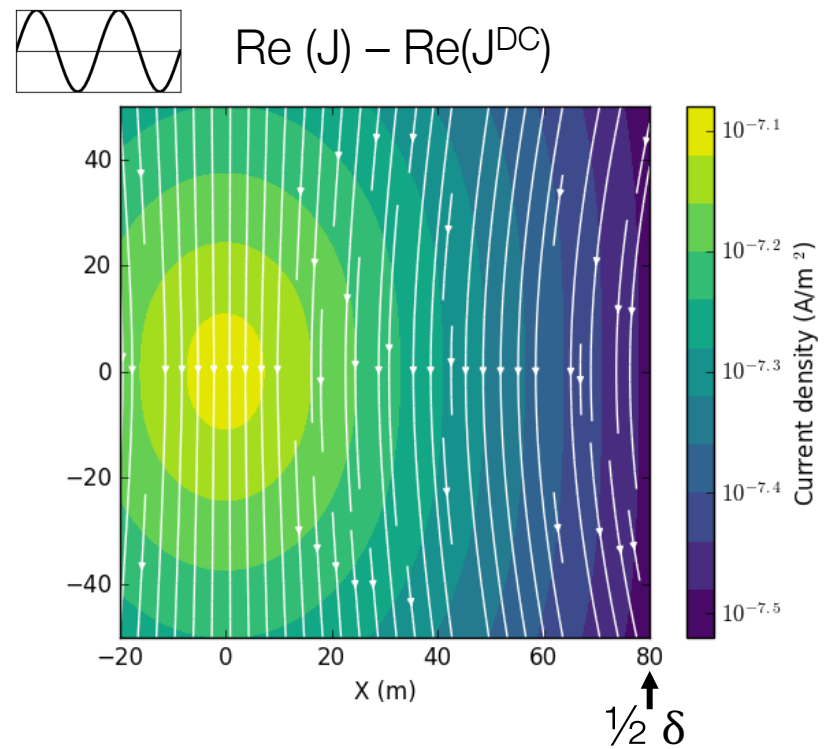
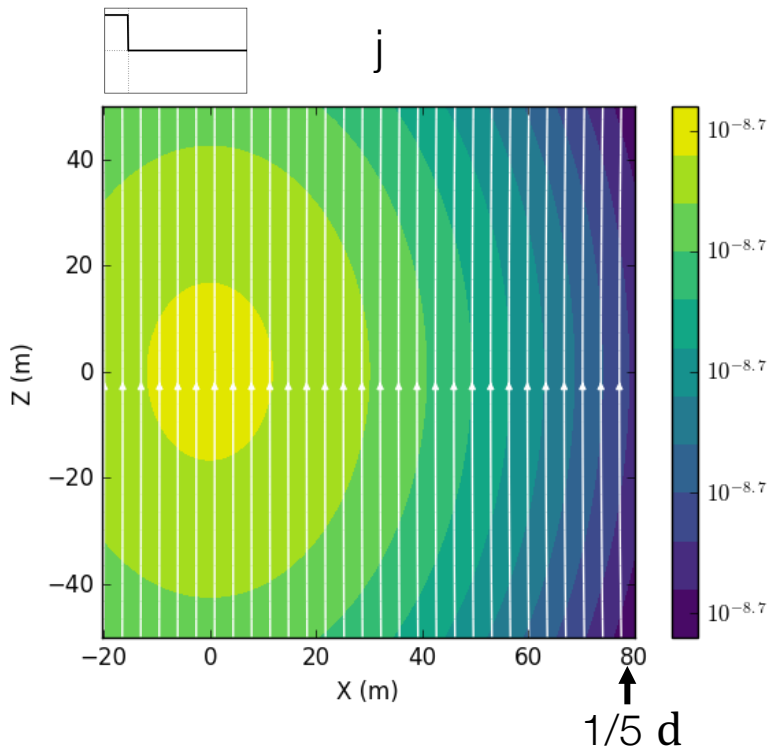
# Electric Dipole in a whole space: FDEM

$t=1 \text{ ms}$ ,  $d = 400 \text{ m}$

$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

$f=1 \text{ kHz}$ ,  $\delta = 160 \text{ m}$

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

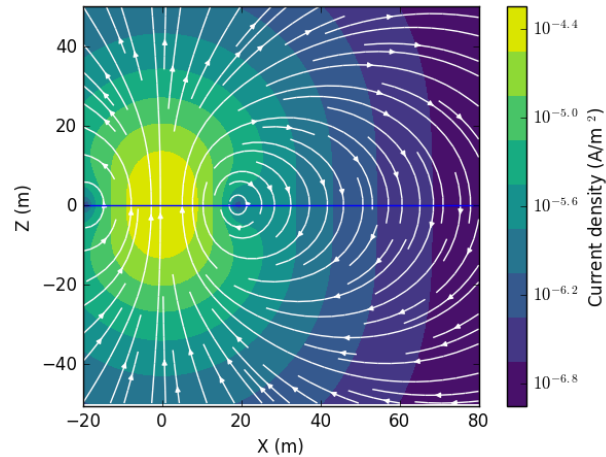




# Summary: Dipole in a whole space

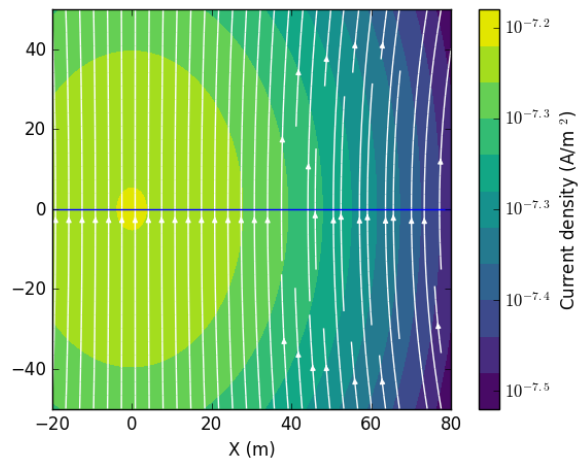
Currents diffuse into the earth

Early time  
High frequency



$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

Late time  
Low frequency



$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

# Bipole Sources

- Extended line sources
  - Grounded term (**galvanic**) + wire path (**inductive**)
  - Straight line

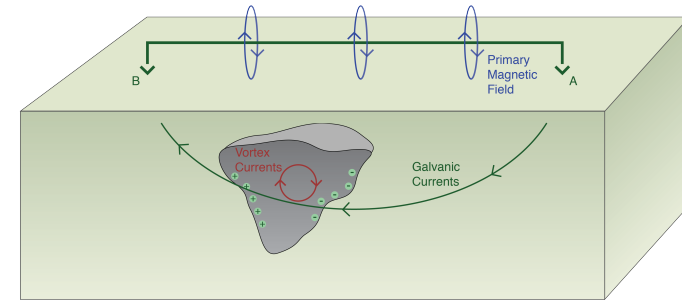


- Crooked line (horse shoe)



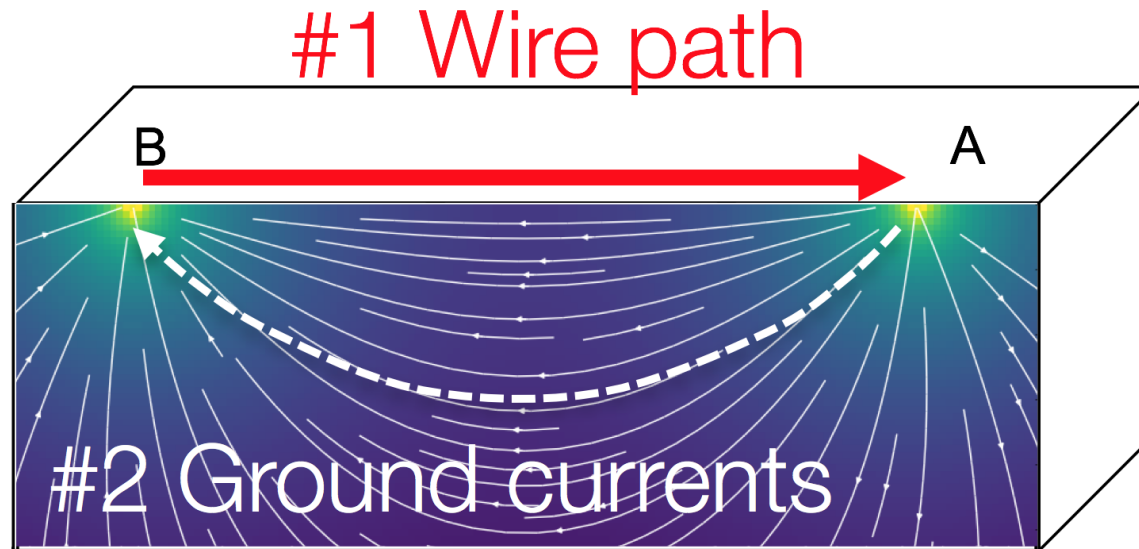
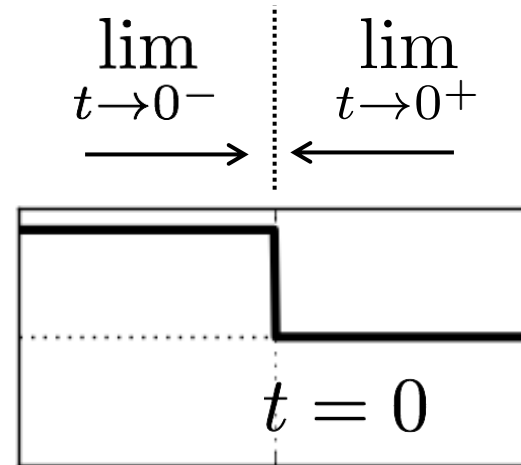
# Grounded Sources: On the surface

- Ability to detect target depends on
  - Geometry, conductivity of target & host
  - Geometry of TX
  - Frequency or time
  - Fields and components measured
    - $e$ ,  $b$ ,  $db/dt$
  - Location of Tx and Rx with respect to the target
- Lots of variables...
  - Use an example to highlight important concepts



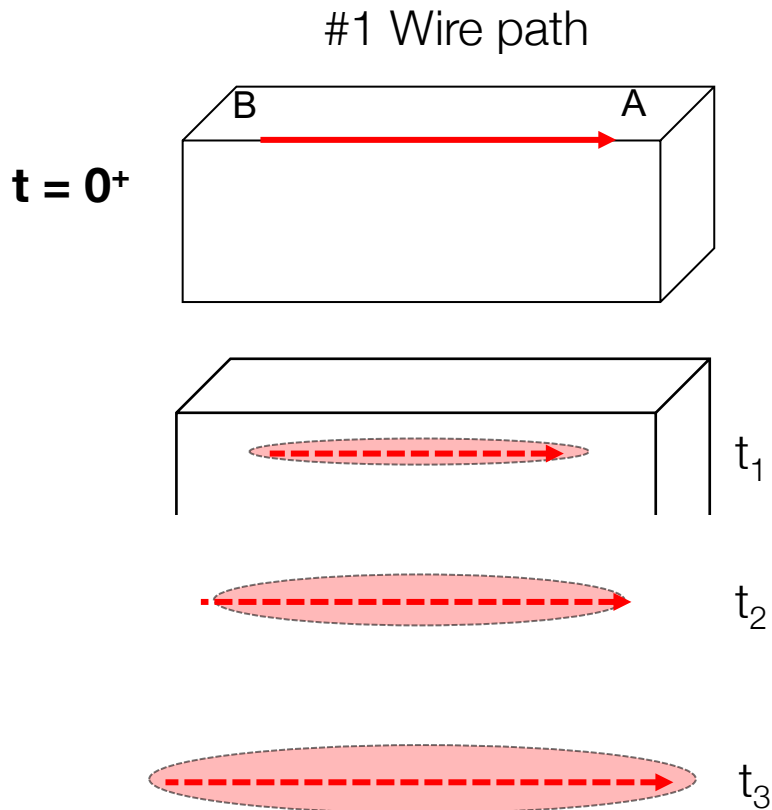
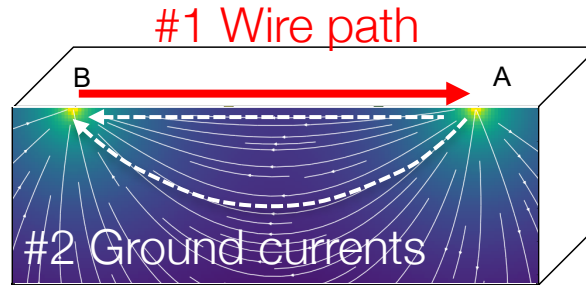
# Currents: Grounded System

- •  $t = 0^-$  Steady state
- $t = 0$  Shut off current
- $t = 0^+$  Off-time



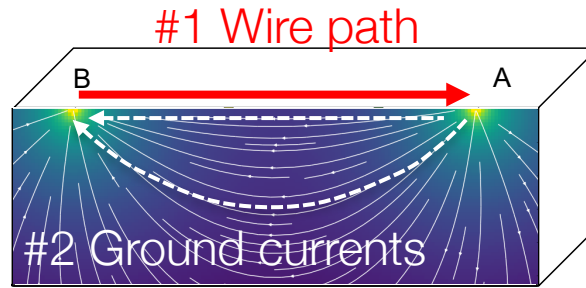
What happens when we shut the system off?

# Currents: Grounded System

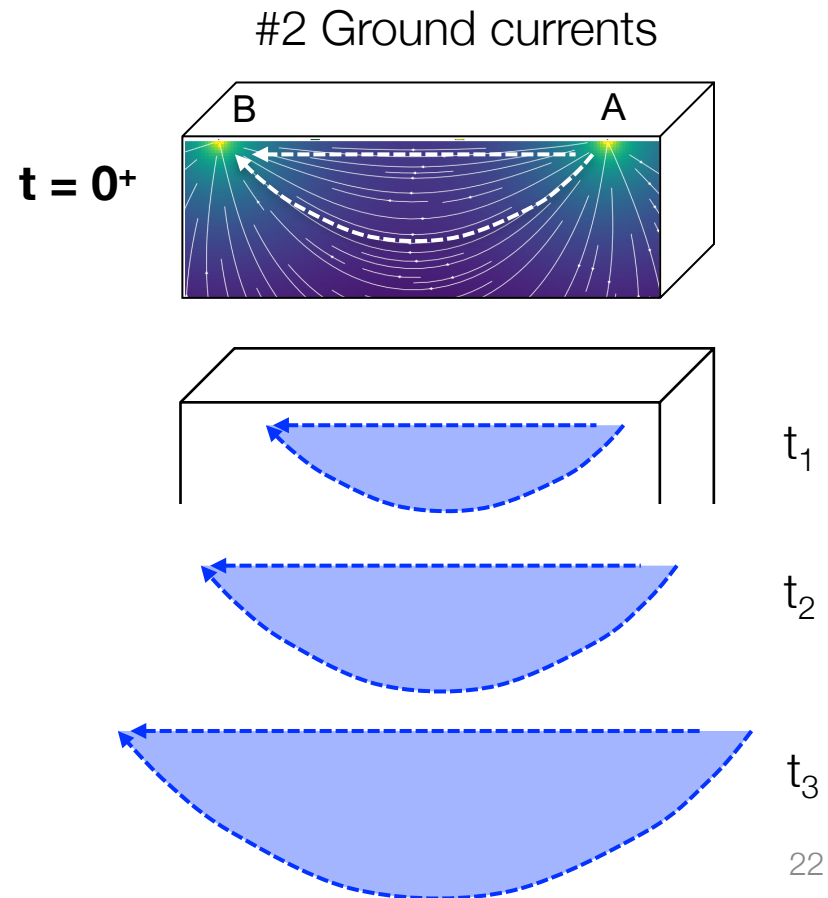


- Immediately after shut off: image current at the surface
- Successive time: currents diffuse downwards and outwards

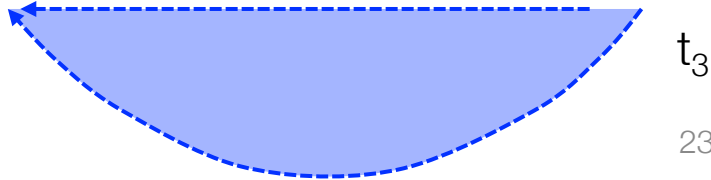
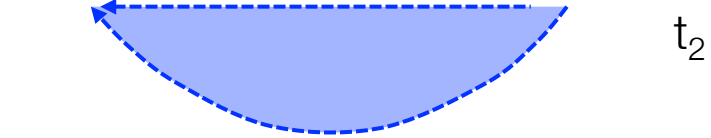
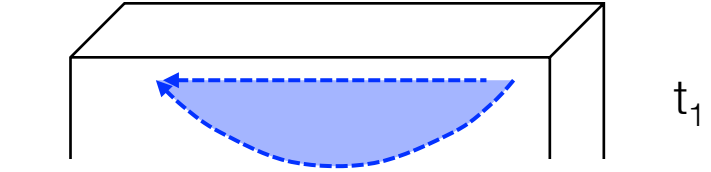
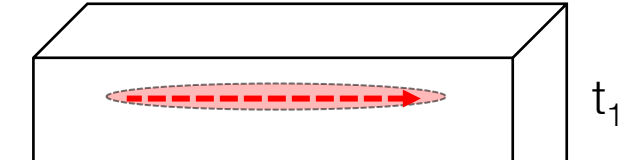
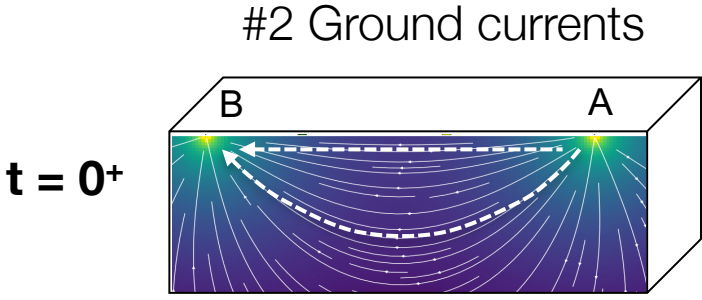
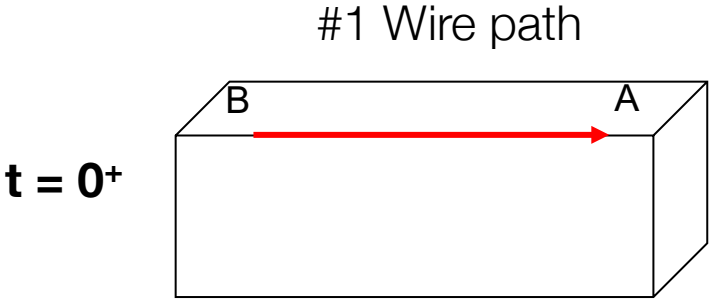
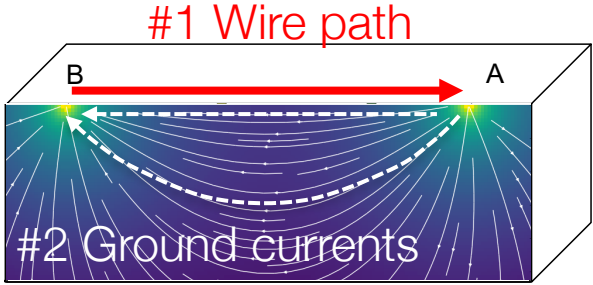
# Currents: Grounded System



- Immediately after shut off: ground currents are still there
- Successive time: currents diffuse downwards and outwards

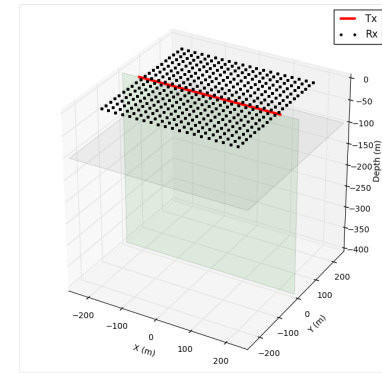


# Currents: Grounded System

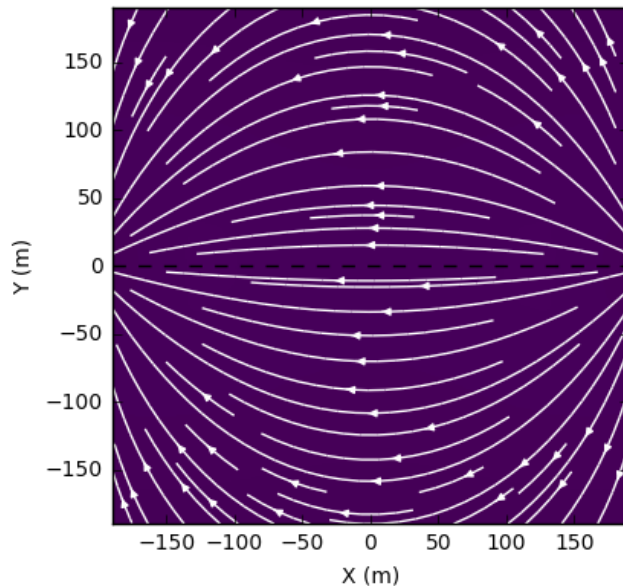


# Grounded Source: Halfspace Currents

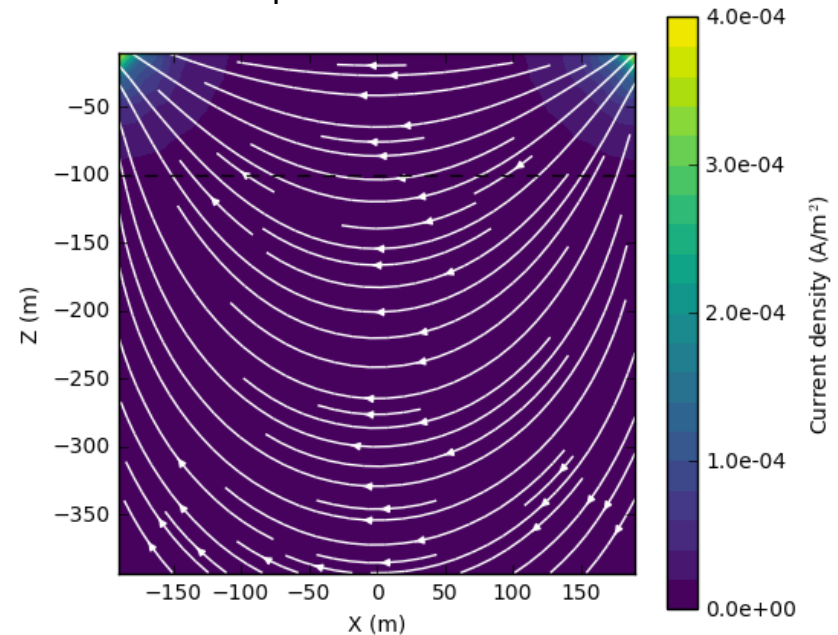
- Parameters:
  - halfspace (0.01 S/m)
  - $t=0^-$ , steady state



XY plane at Z=-100 m



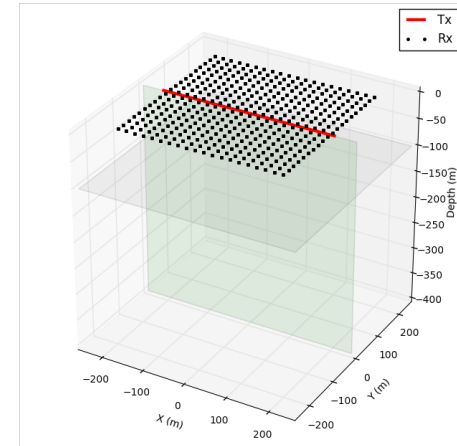
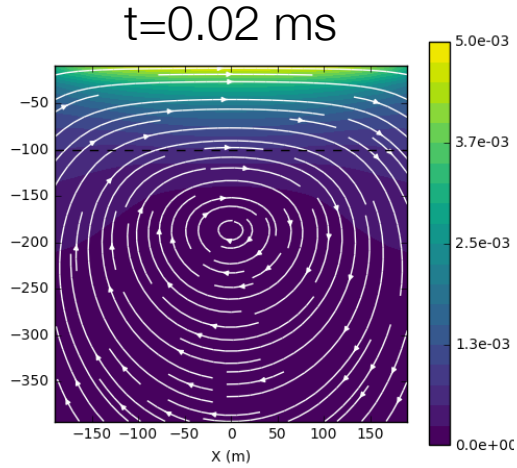
XZ plane at Y=0 m





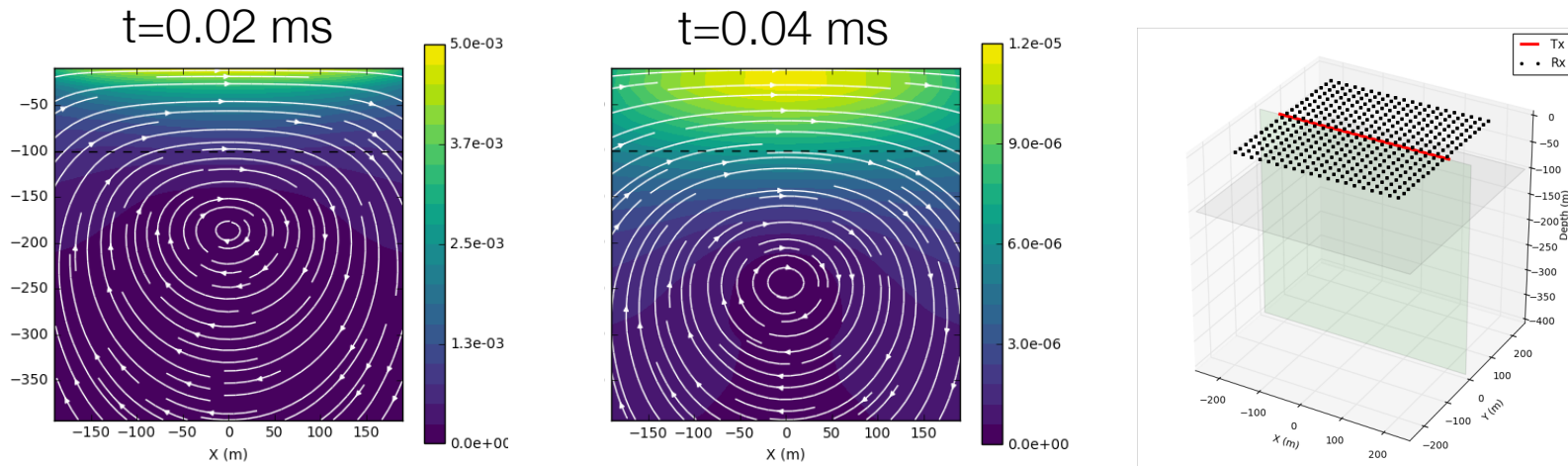
# Grounded Source: Halfspace currents

- Cross section of currents,  $t = 0.04$  to  $10$  ms



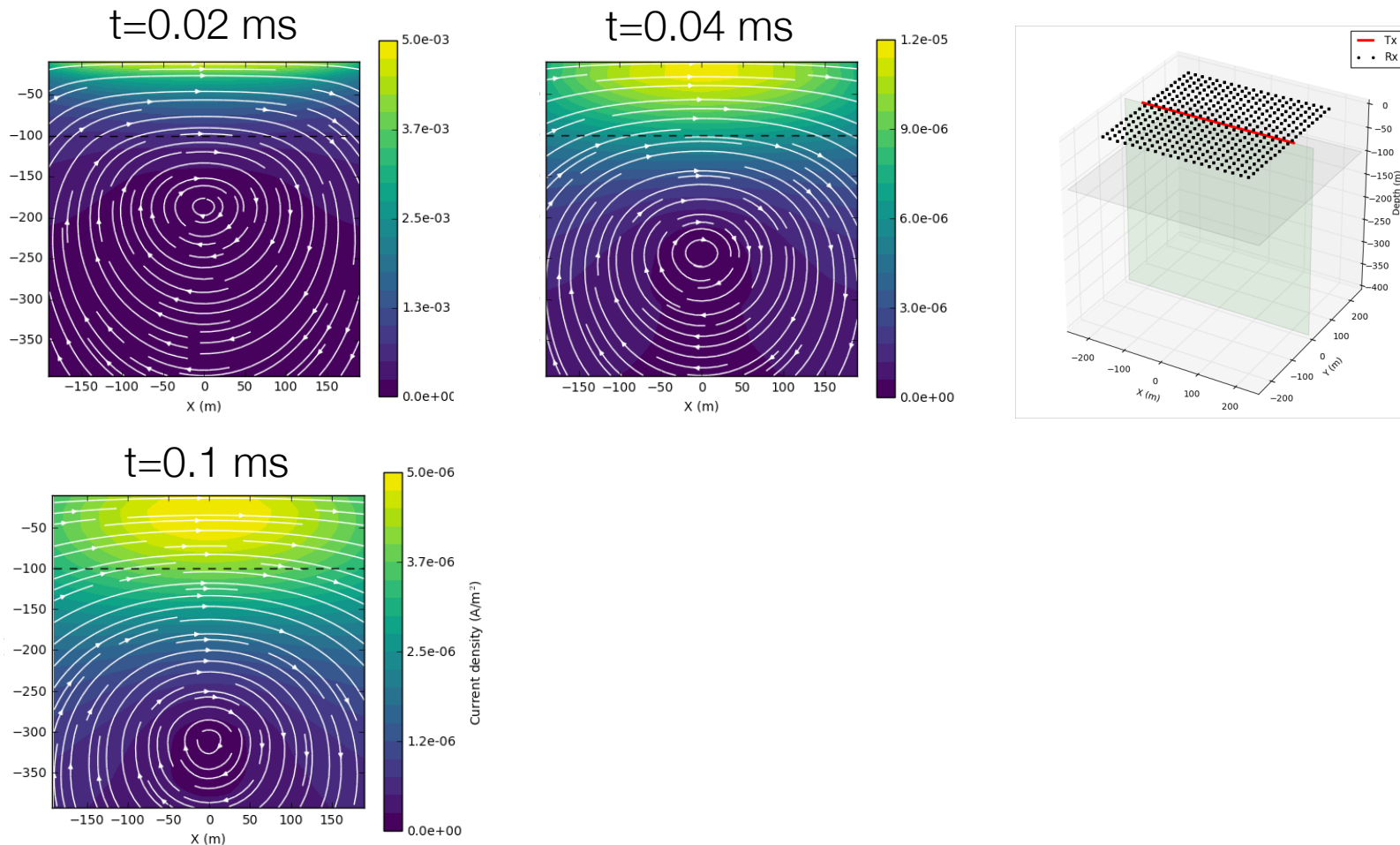
# Grounded Source: Halfspace currents

- Cross section of currents,  $t = 0.04$  to  $10$  ms



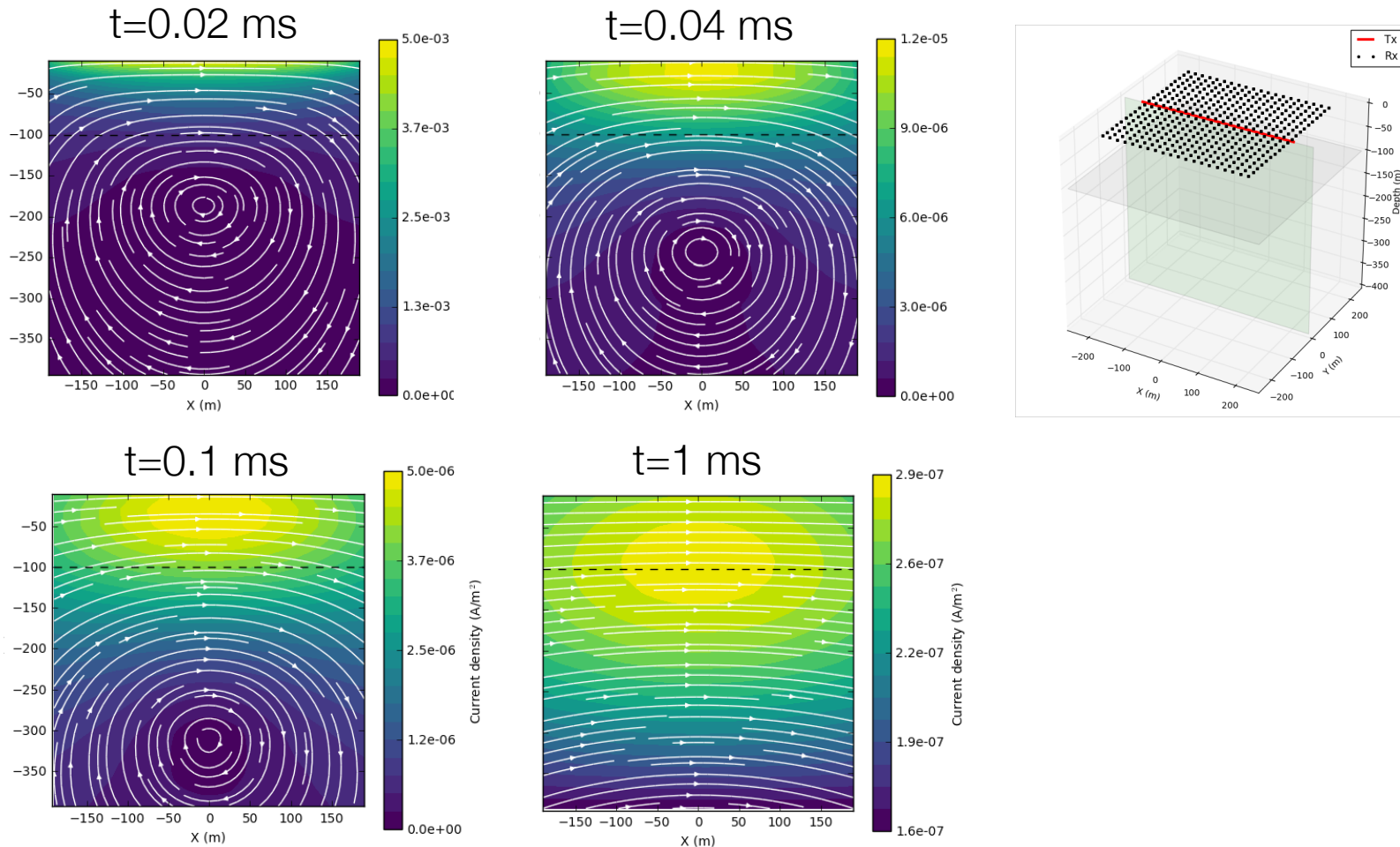
# Grounded Source: Halfspace currents

- Cross section of currents,  $t = 0.04$  to  $10$  ms



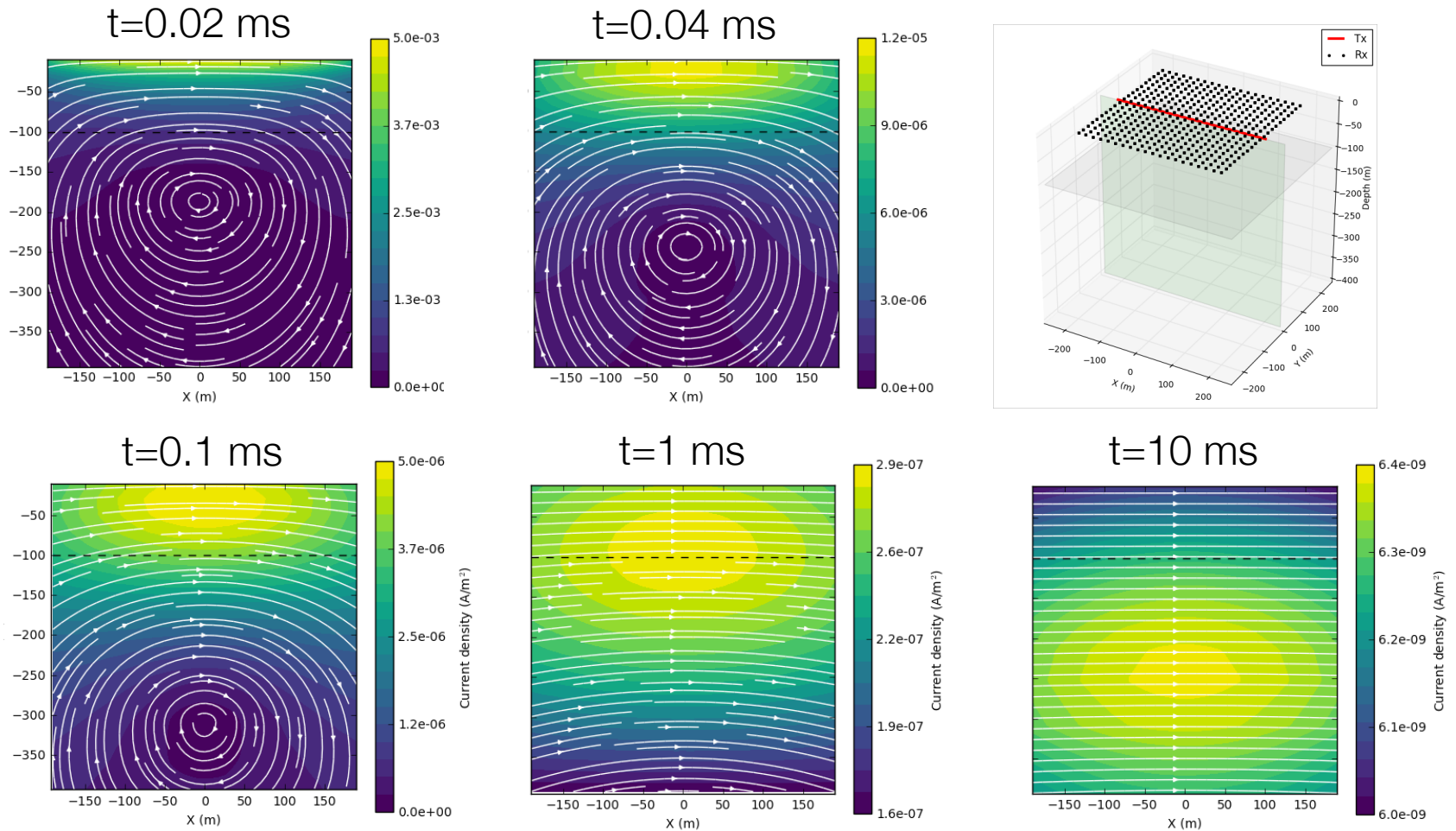
# Grounded Source: Halfspace currents

- Cross section of currents,  $t = 0.04$  to  $10$  ms



# Grounded Source: Halfspace currents

- Cross section of currents,  $t = 0.04$  to  $10$  ms

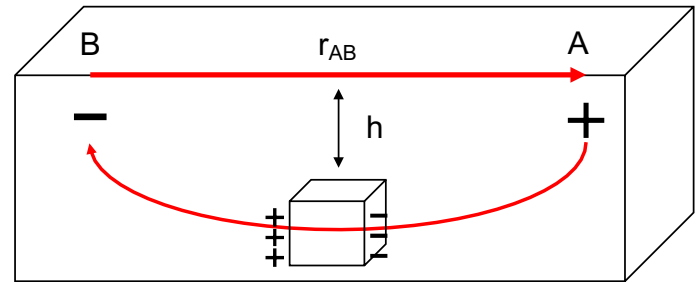


# Grounded sources: with a target

- Block in a halfspace

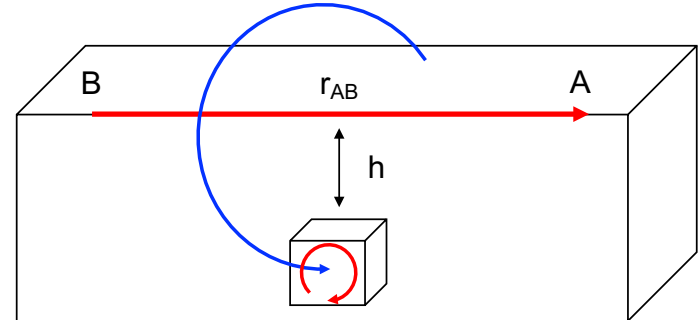
- DC

- Good coupling if  $h < r_{AB}$



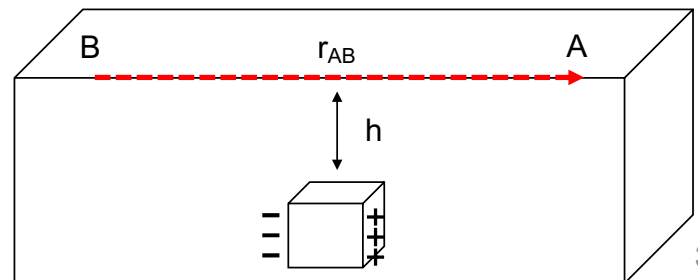
- Vortex currents

- Good coupling (magnetic fields)
    - Good signal for conductor
    - Resistor more difficult



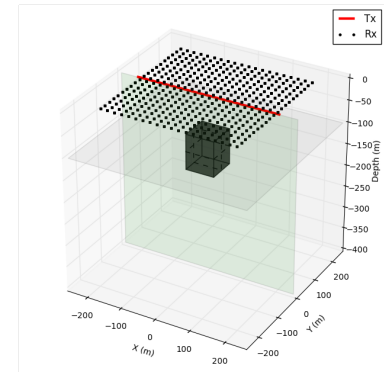
- Galvanic currents

- Good coupling (electric fields)
    - Good signal for conductor and resistor

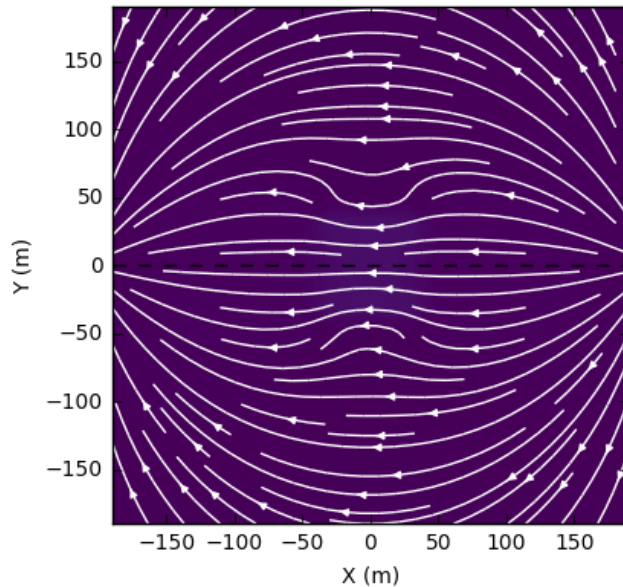


# Conductor: currents

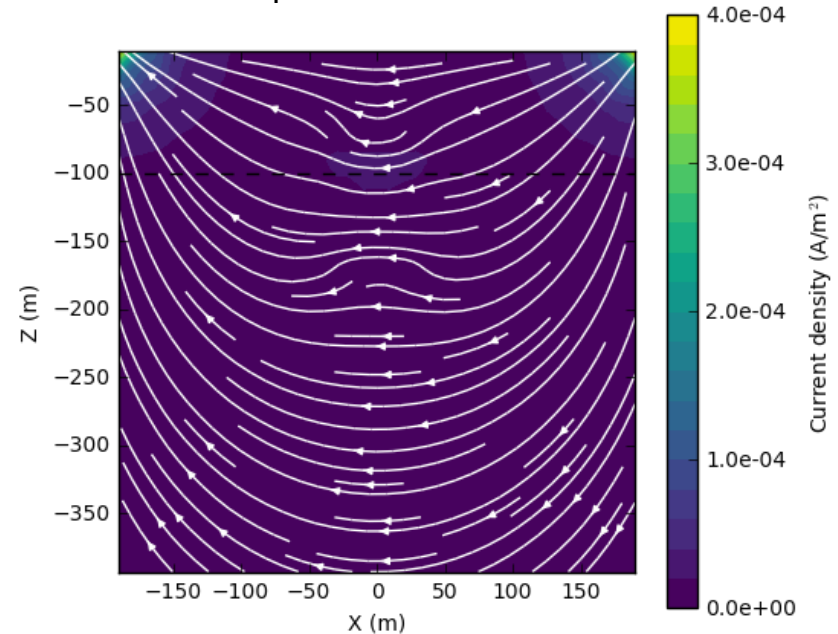
- Grounded wire
  - A conductor (1 S/m) in a halfspace (0.01 S/m)
  - $t=0^-$ , steady state



XY plane at Z=-100 m

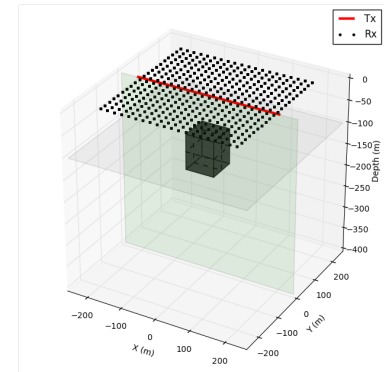


XZ plane at Y=0 m

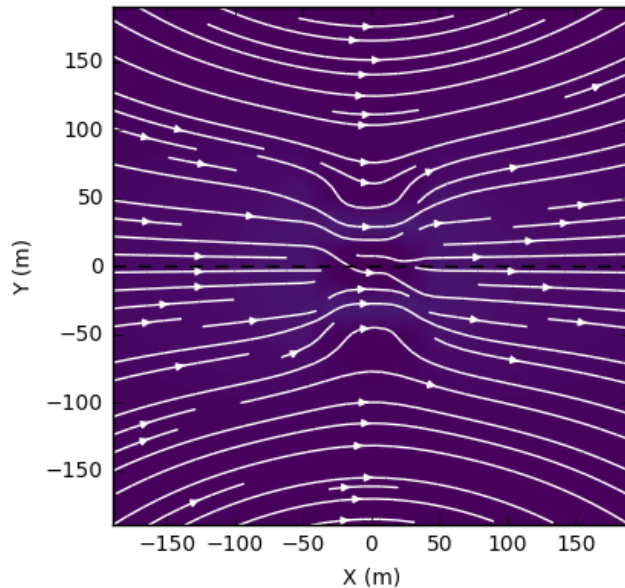


# Conductor: currents

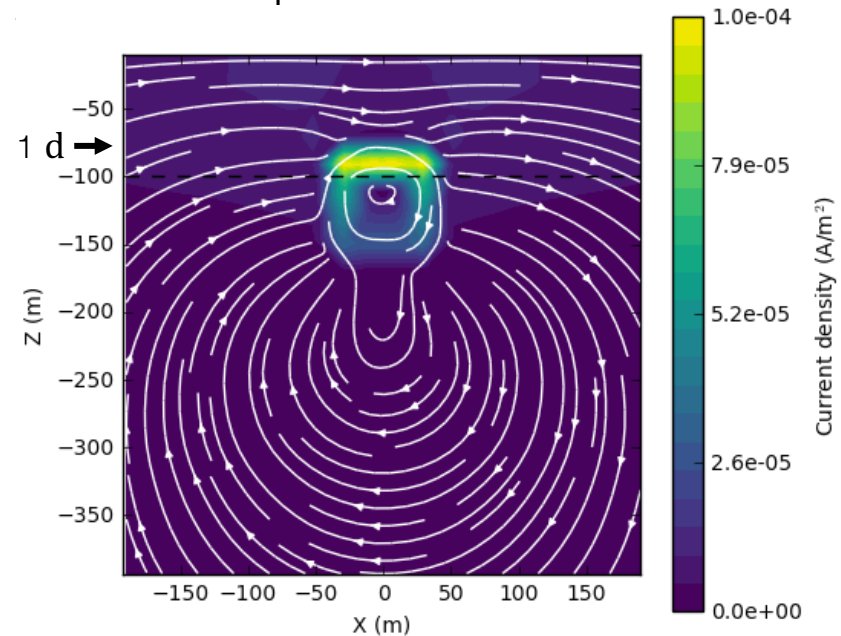
- Grounded wire
  - A conductor (1 S/m) in a halfspace (0.01 S/m)
  - **0.04** ms,  $d = 80$  m



XY plane at  $Z = -100$  m



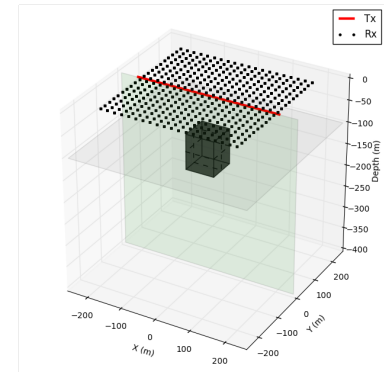
XZ plane at  $Y = 0$  m



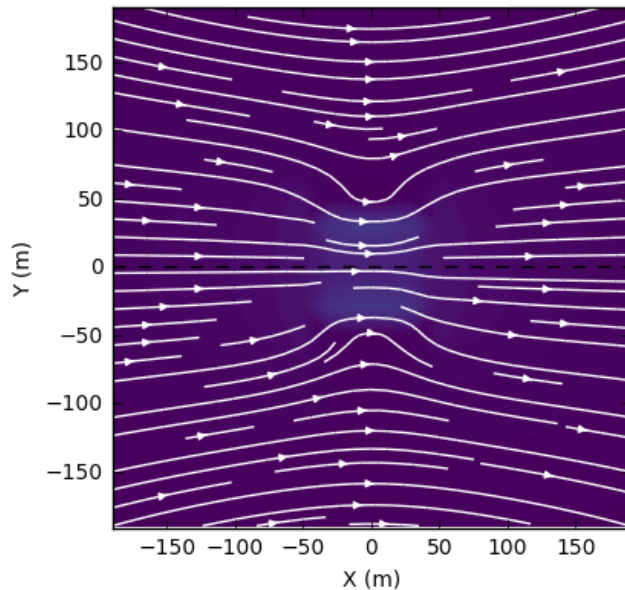


# Conductor: currents

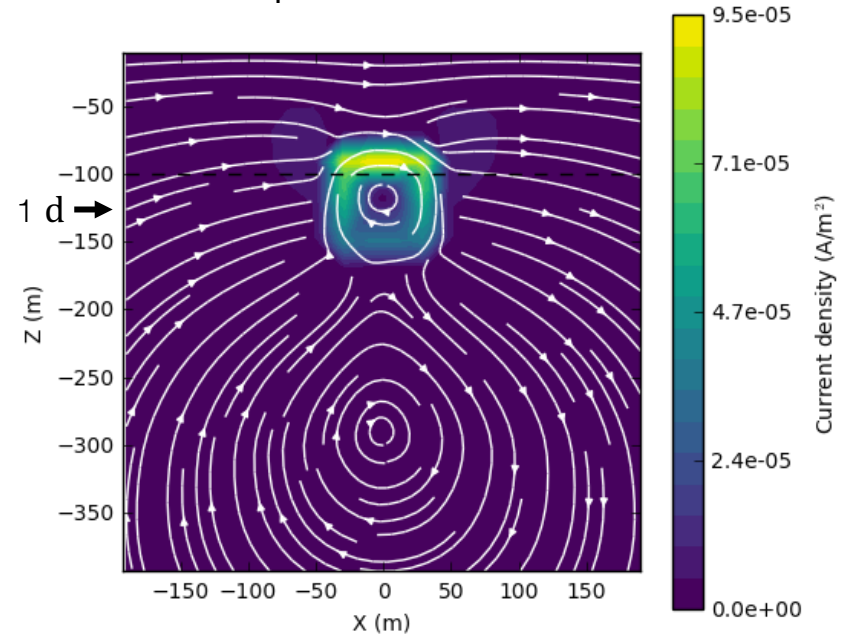
- Grounded wire
  - A conductor (1 S/m) in a halfspace (0.01 S/m)
  - **0.1** ms,  $d = 126$  m



XY plane at  $Z=-100$  m

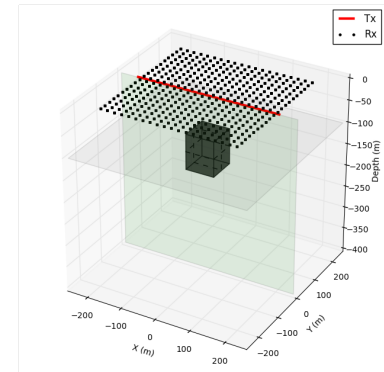


XZ plane at  $Y=0$  m

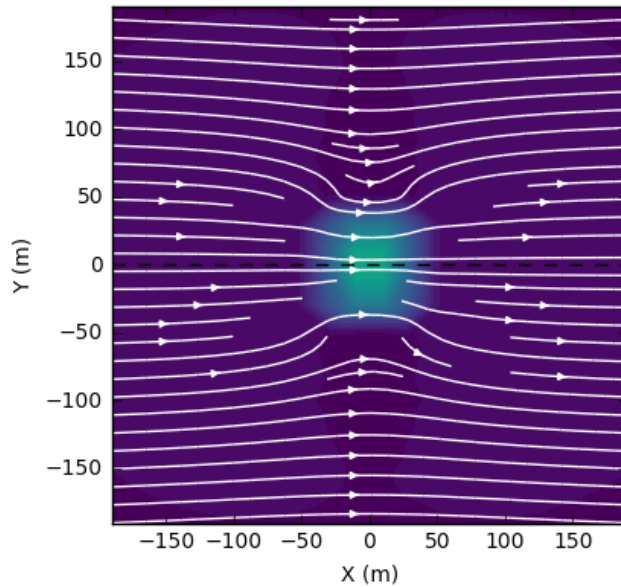


# Conductor: currents

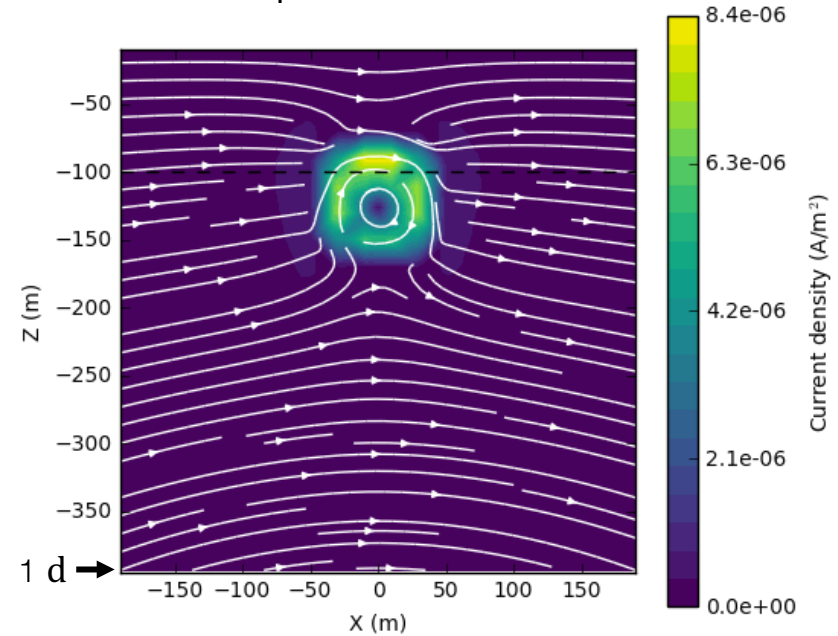
- Grounded wire
  - A conductor (1 S/m) in a halfspace (0.01 S/m)
  - 1 ms,  $d = 400$  m



XY plane at  $Z = -100$  m

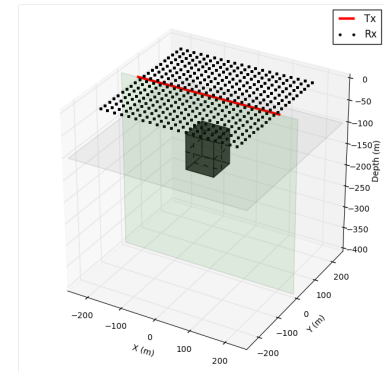


XZ plane at  $Y = 0$  m

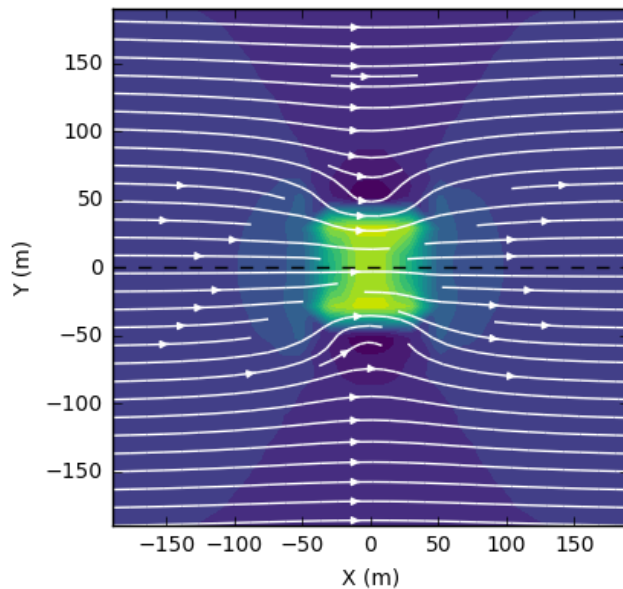


# Conductor: currents

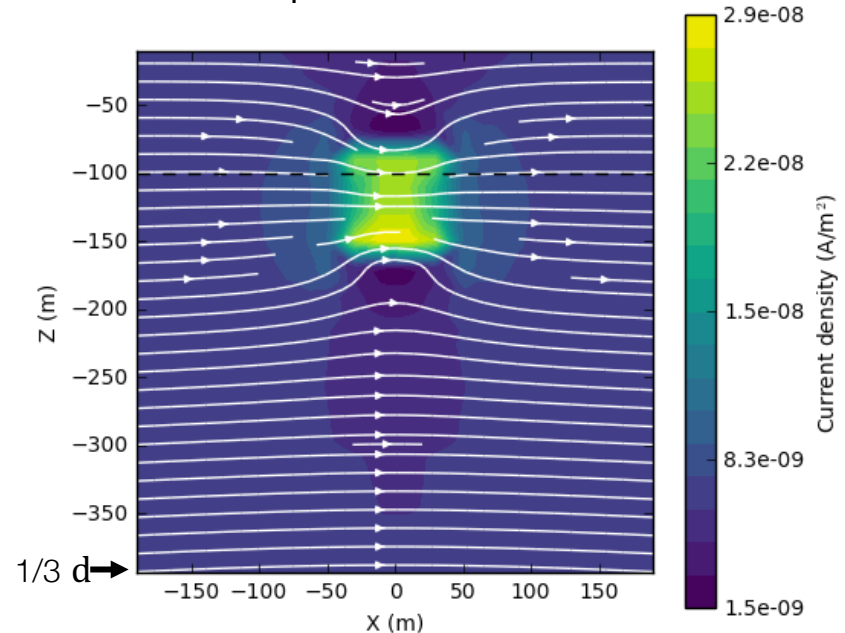
- Grounded wire
  - A conductor (1 S/m) in a halfspace (0.01 S/m)
  - **10** ms,  $d = 1270$  m



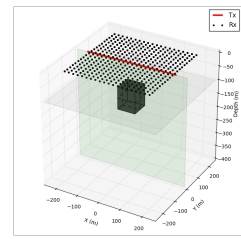
XY plane at  $Z = -100$  m



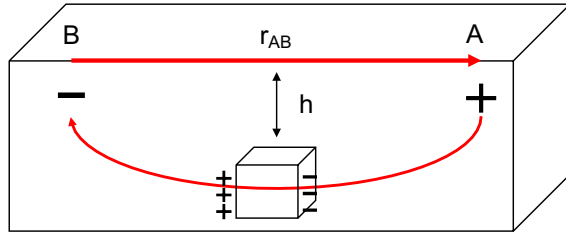
XZ plane at  $Y = 0$  m



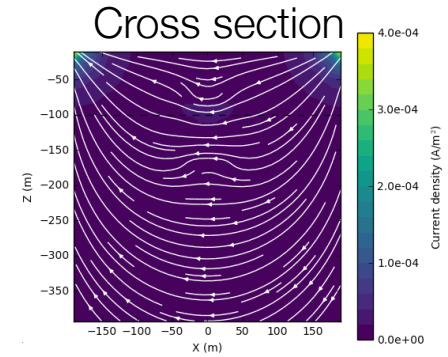
# Conductor: currents



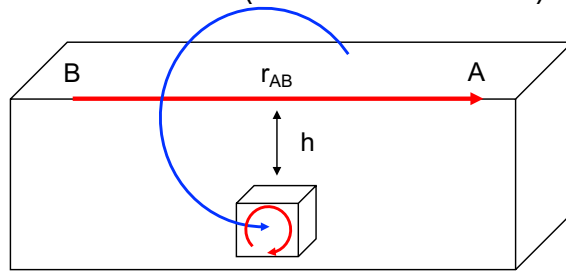
Steady State (galvanic current)



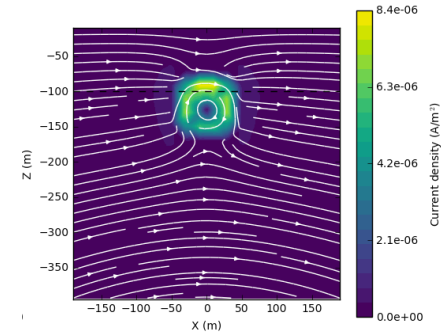
Galvanic current  
 $t = 0^-$



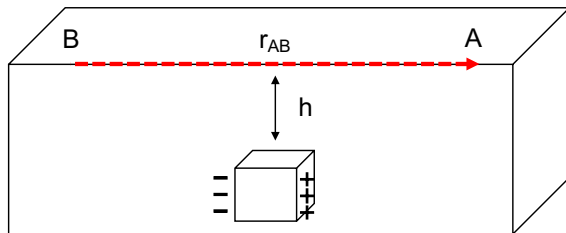
EM induction (vortex current)



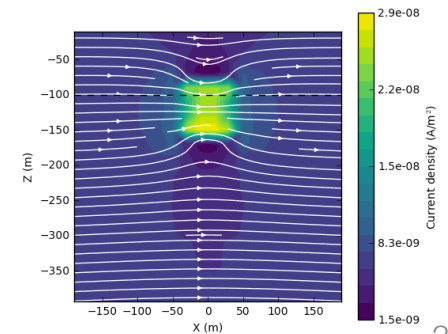
Vortex current  
 $t = 1 \text{ ms}$



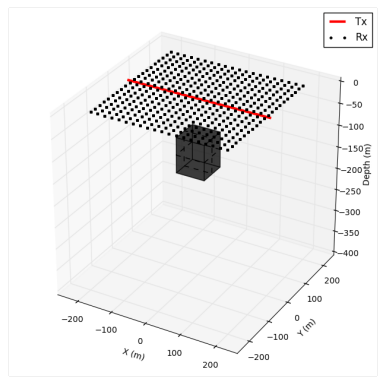
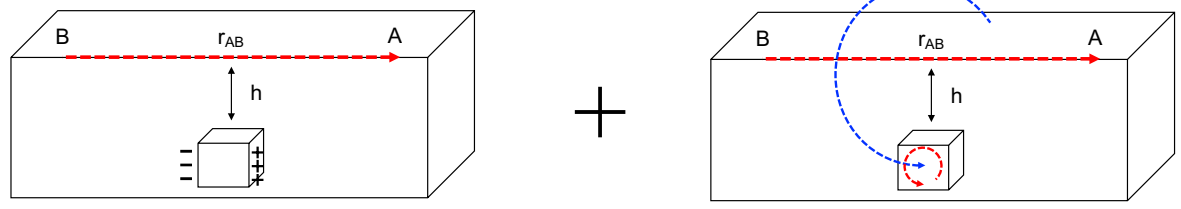
EM induction (galvanic current)



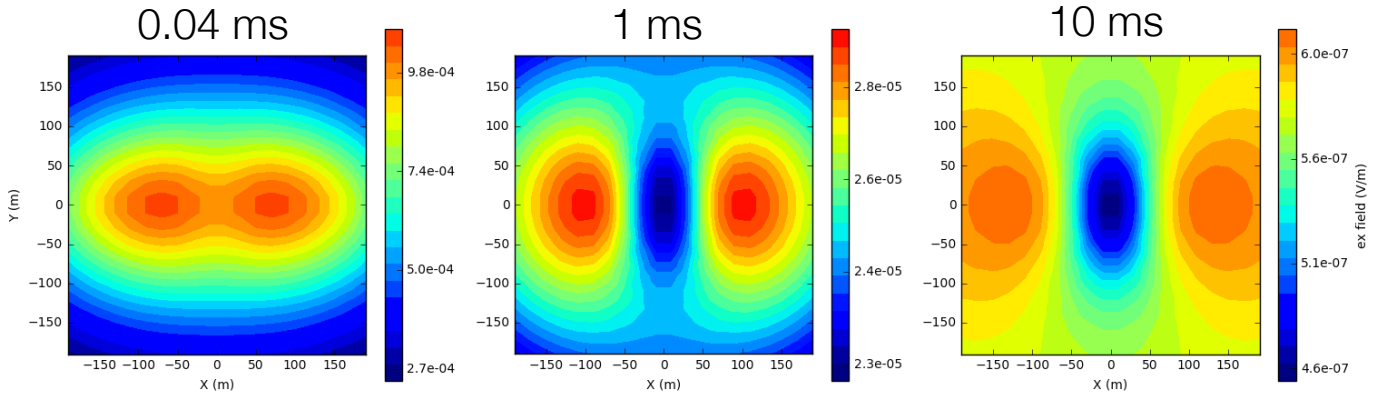
Galvanic current  
 $t = 10 \text{ ms}$



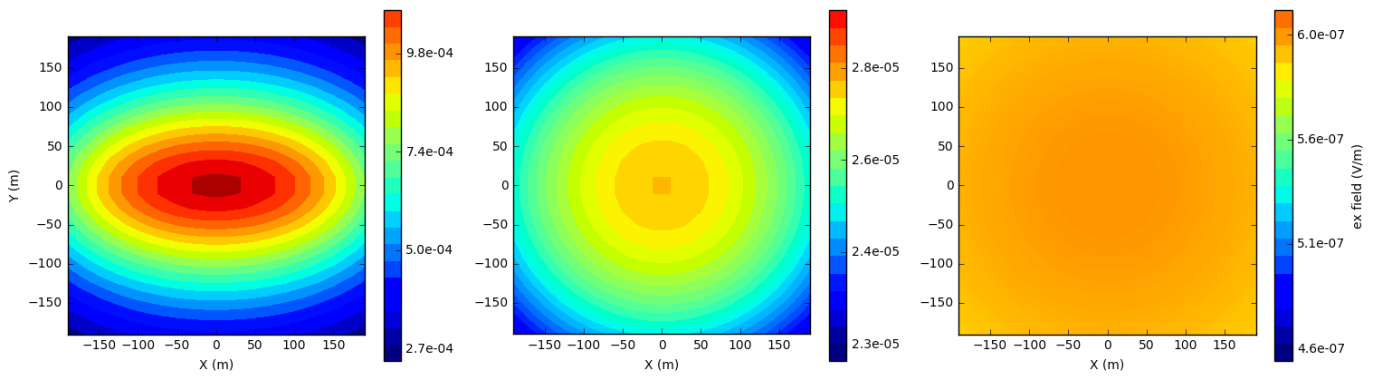
# Data: $e_x$ field



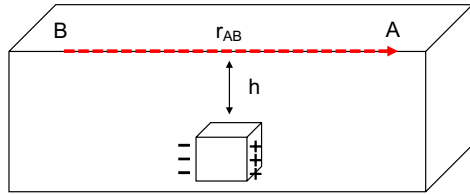
Conductor



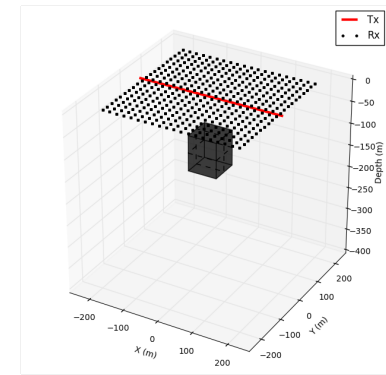
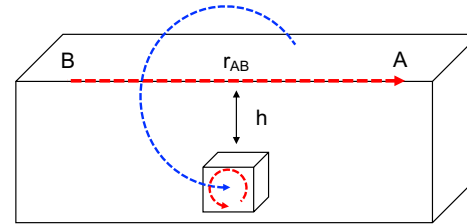
Halfspace



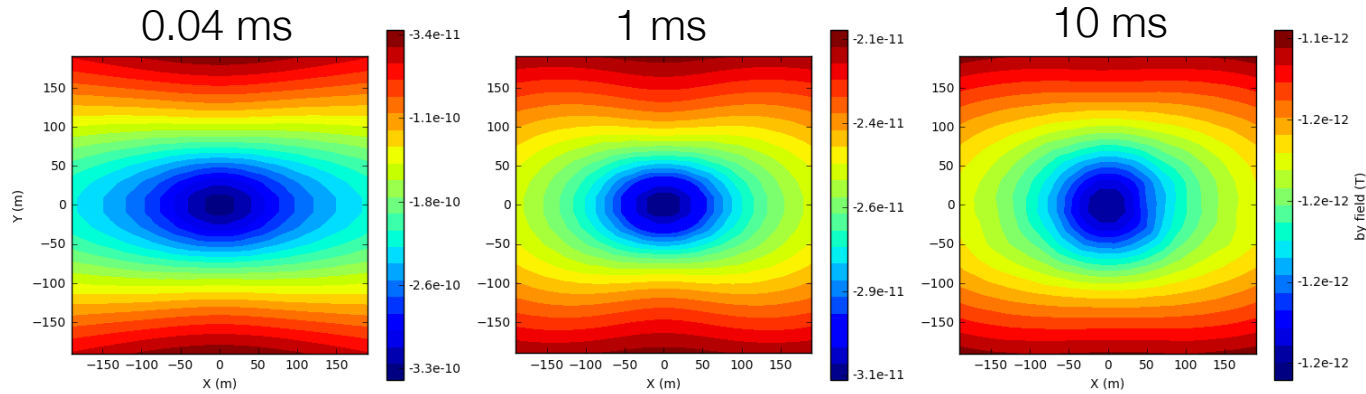
# Data: $b_y$ field



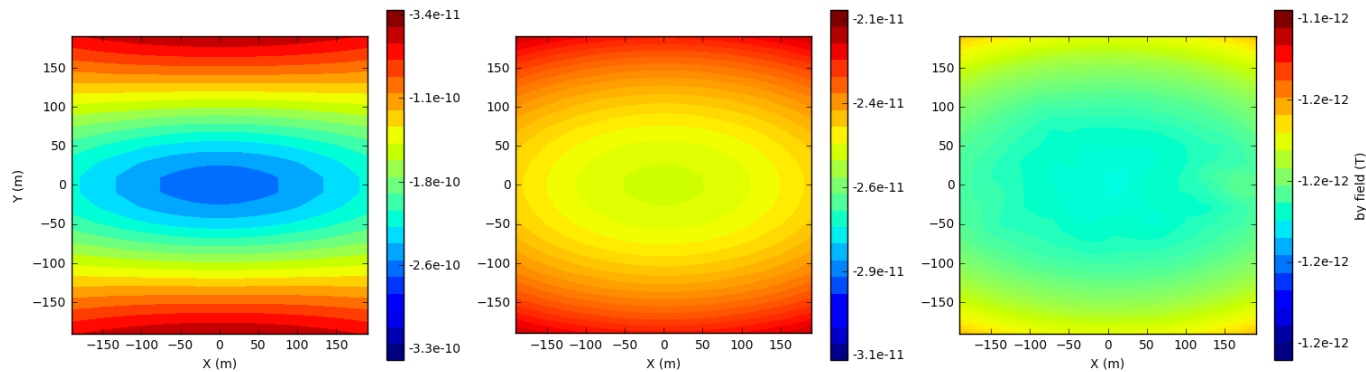
+



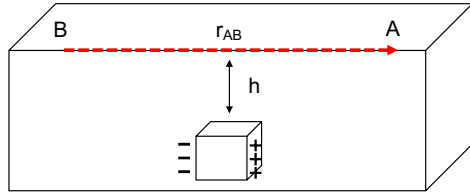
Conductor



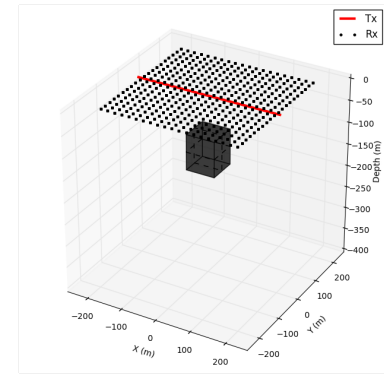
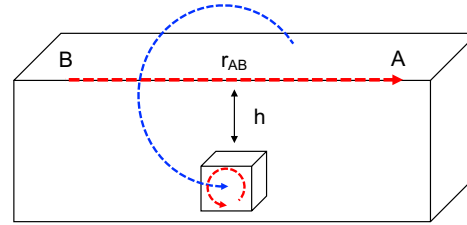
Halfspace



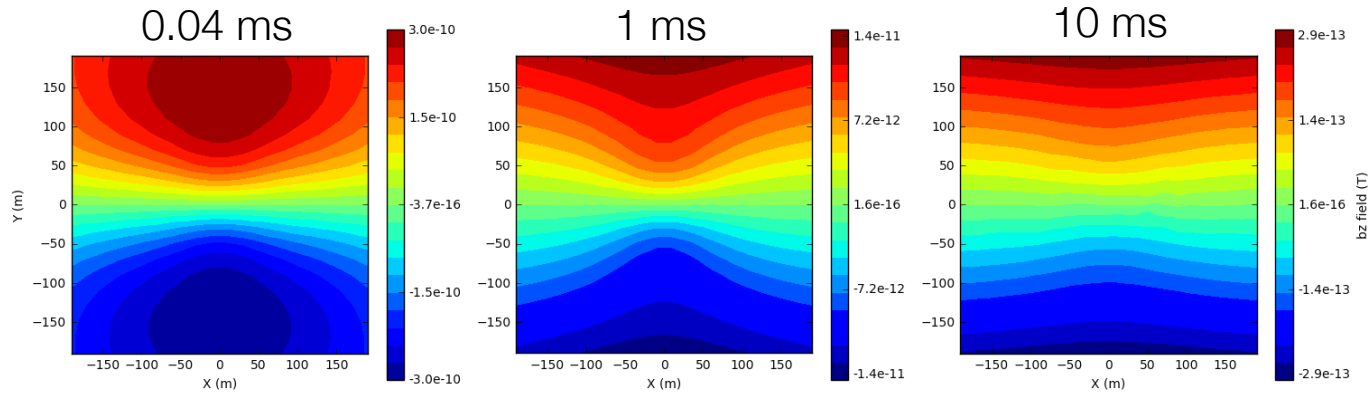
# Data: $b_z$ field



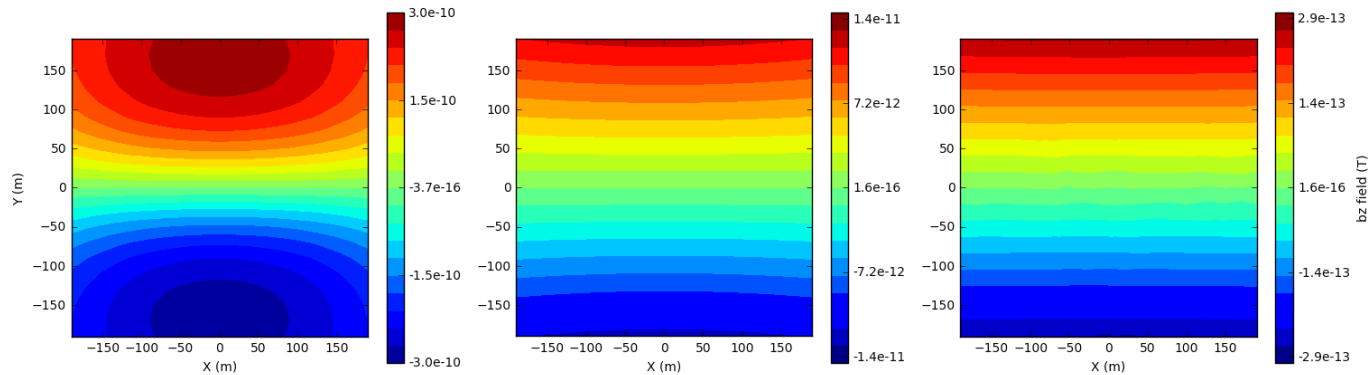
+



Conductor

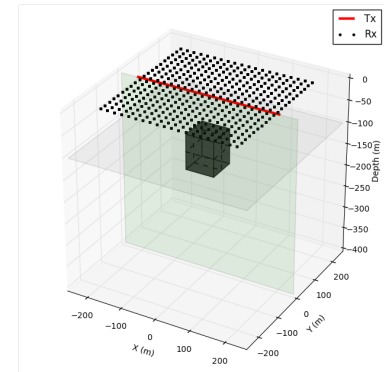


Halfspace

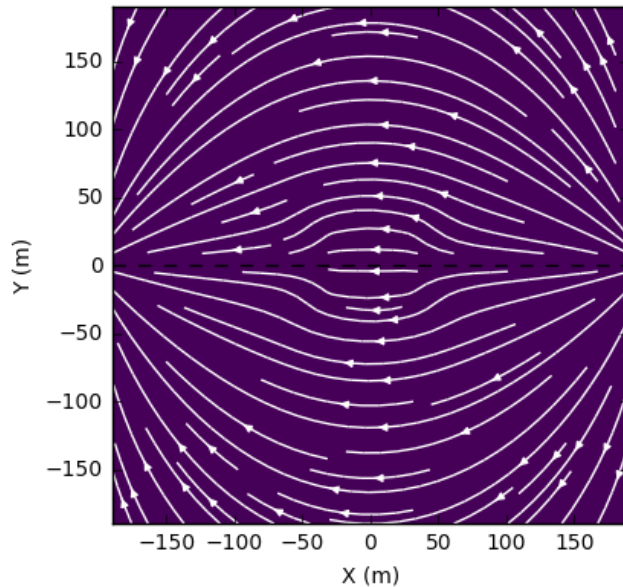


# Resistor: currents

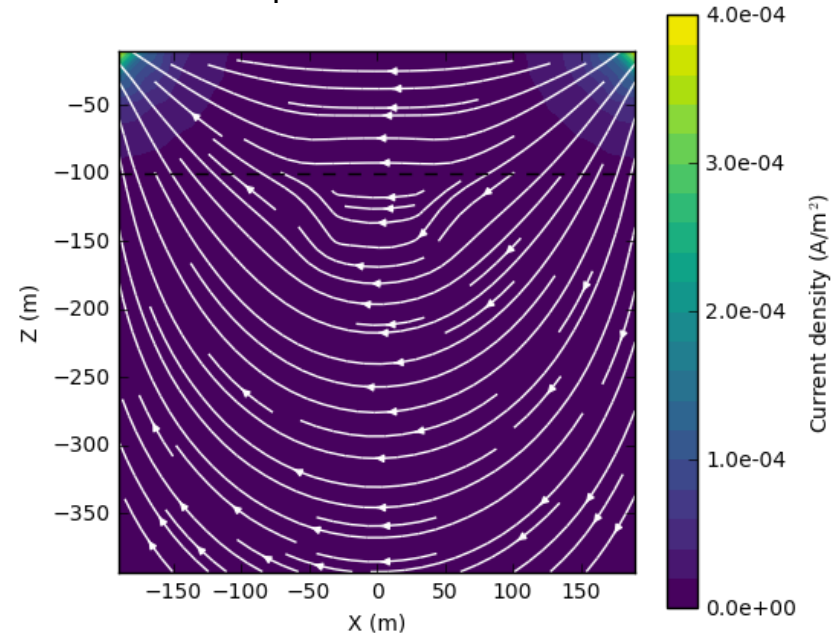
- Grounded wire
  - A resistor ( $10^{-4}$  S/m) in a halfspace ( $0.01$  S/m)
  - $t=0^-$ , steady state



XY plane at  $Z=-100$  m



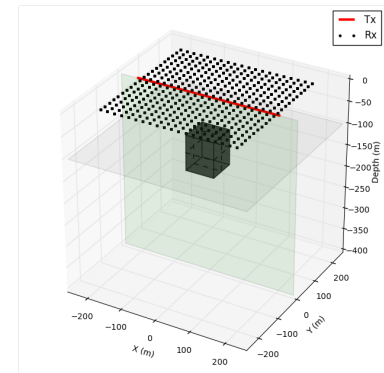
XZ plane at  $Y=0$  m



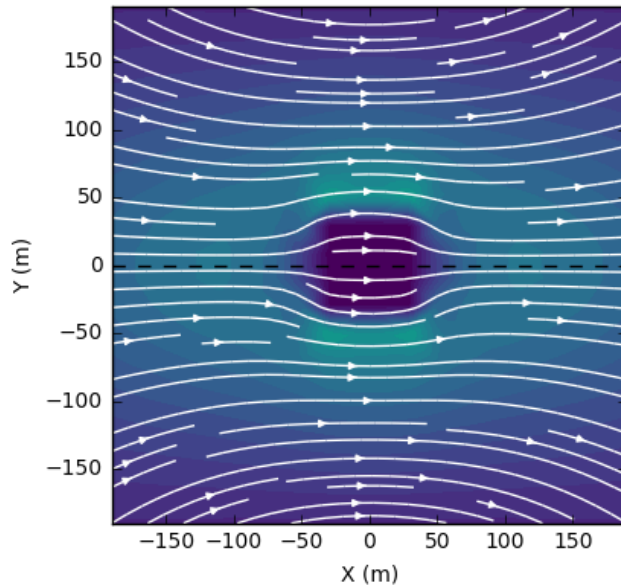


# Resistor: currents

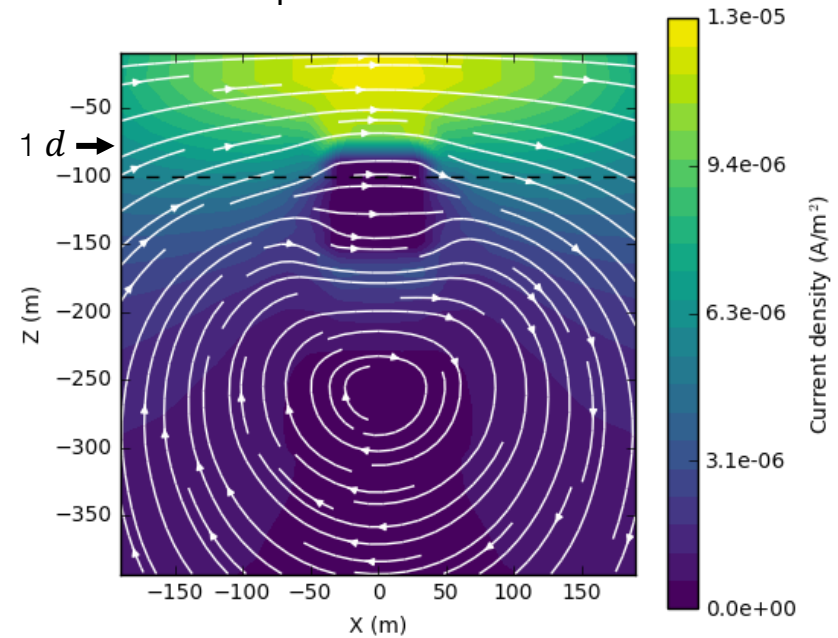
- Grounded wire
  - A resistor ( $10^{-4}$  S/m) in a halfspace (0.01 S/m)
  - **0.04** ms,  $d = 80$  m



XY plane at  $Z = -100$  m

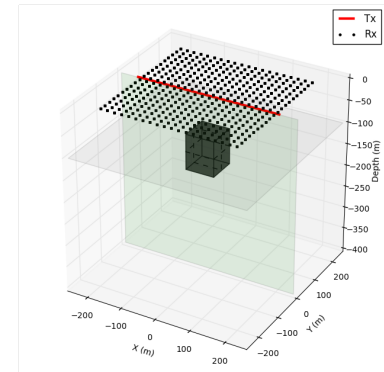


XZ plane at  $Y = 0$  m

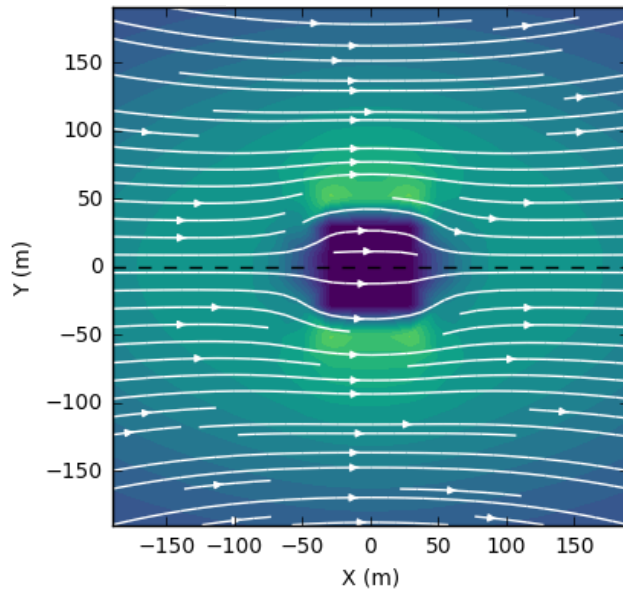


# Resistor: currents

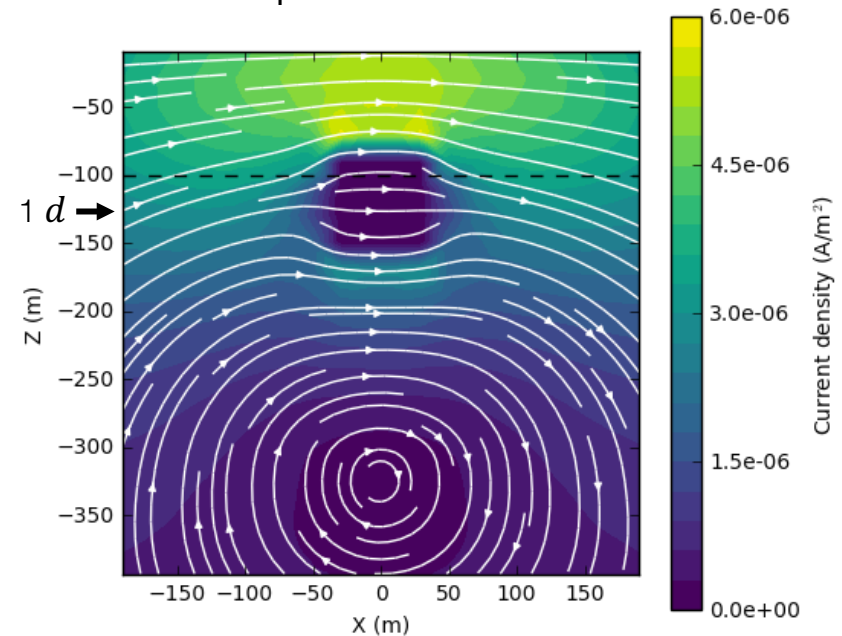
- Grounded wire
  - A resistor ( $10^{-4}$  S/m) in a halfspace ( $0.01$  S/m)
  - **0.1** ms,  $d = 126$  m



XY plane at  $Z=-100$  m

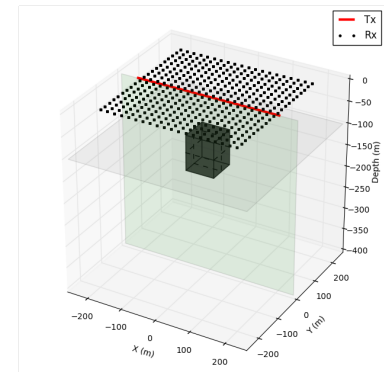


XZ plane at  $Y=0$  m

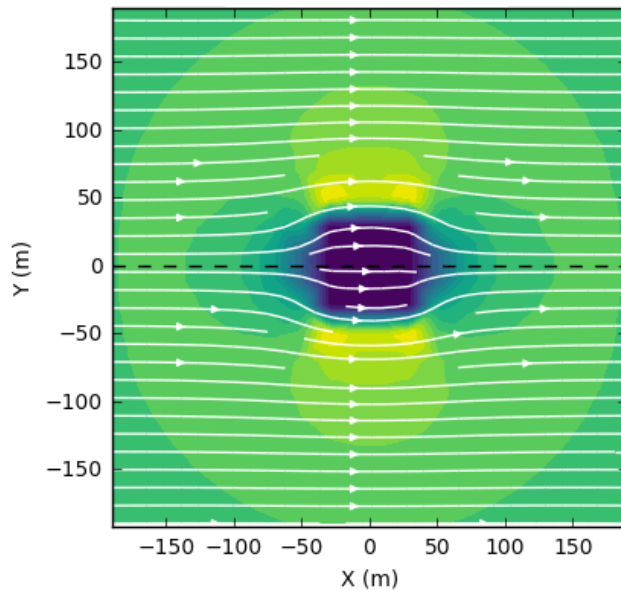


# Resistor: currents

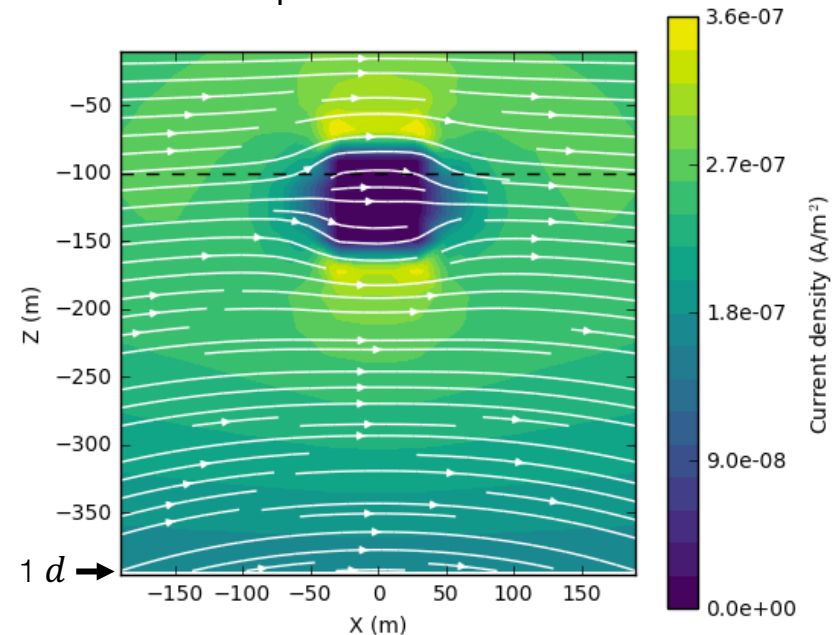
- Grounded wire
  - A resistor ( $10^{-4}$  S/m) in a halfspace ( $0.01$  S/m)
  - **1** ms,  $d = 400$  m



XY plane at  $Z = -100$  m

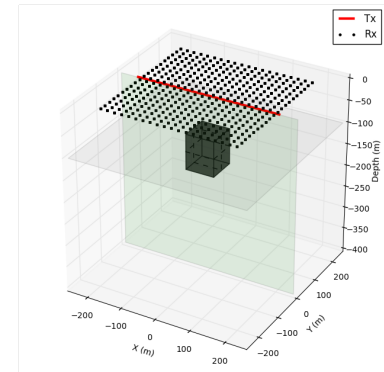


XZ plane at  $Y = 0$  m

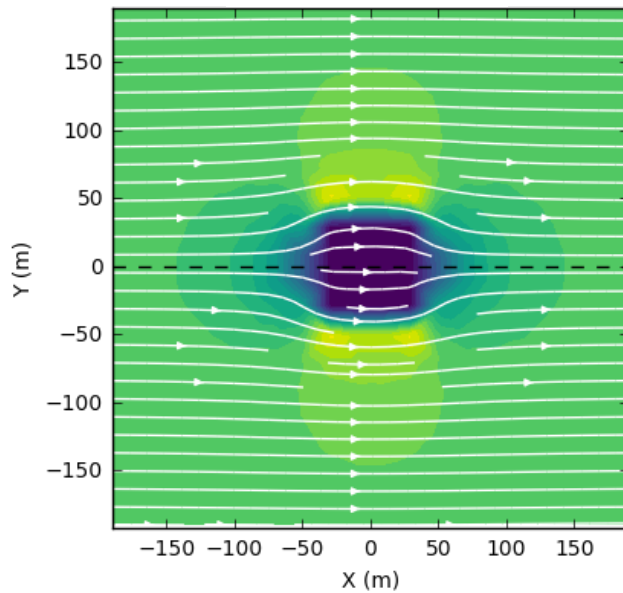


# Resistor: currents

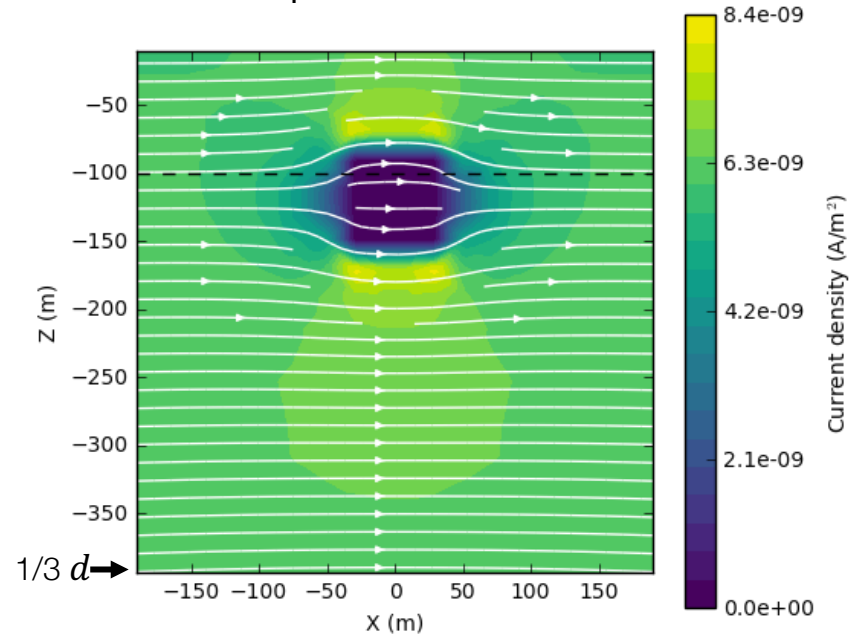
- Grounded wire
  - A resistor ( $10^{-4}$  S/m) in a halfspace (0.01 S/m)
  - **10** ms,  $d = 1270$  m



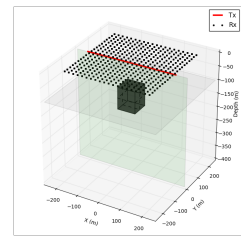
XY plane at  $Z = -100$  m



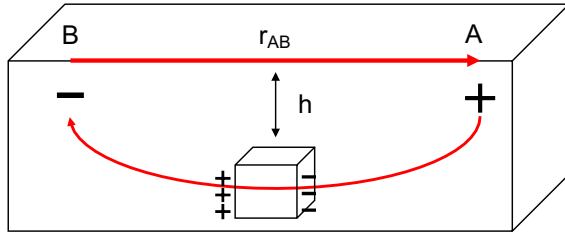
XZ plane at  $Y = 0$  m



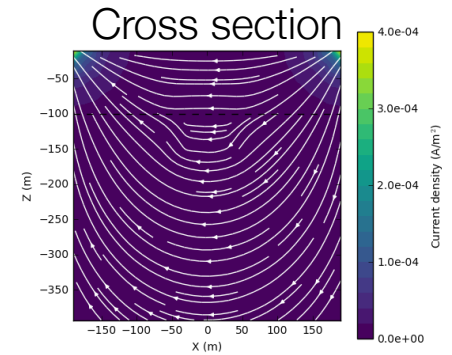
# Resistor: currents



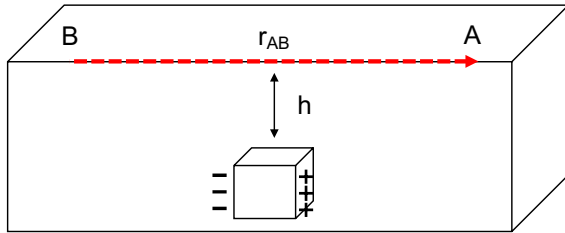
DC (galvanic current)



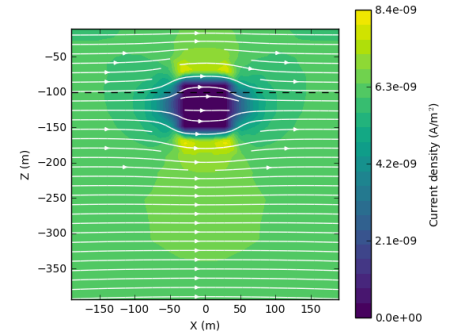
Galvanic current  
 $t = 0^-$



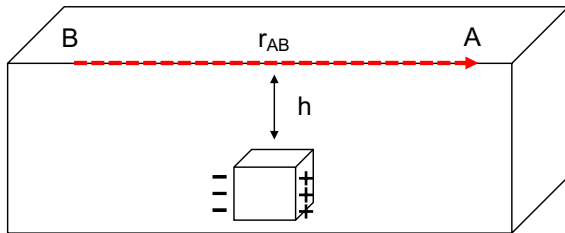
EM induction (galvanic current)



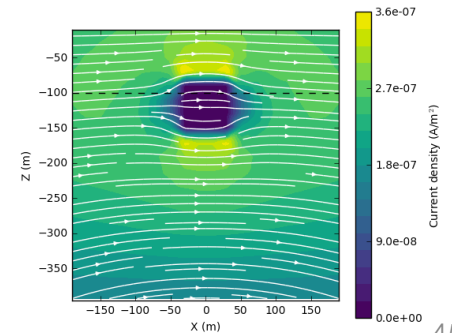
Galvanic current  
 $t = 1 \text{ ms}$



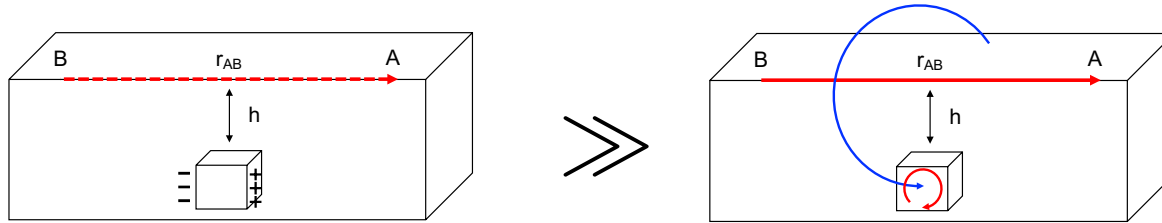
EM induction (galvanic current)



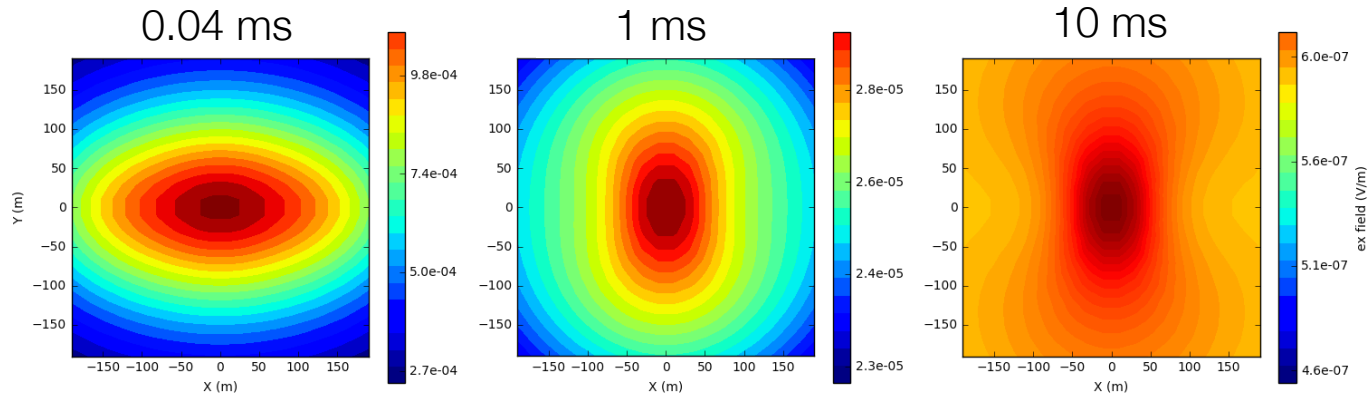
Galvanic current  
 $t = 10 \text{ ms}$



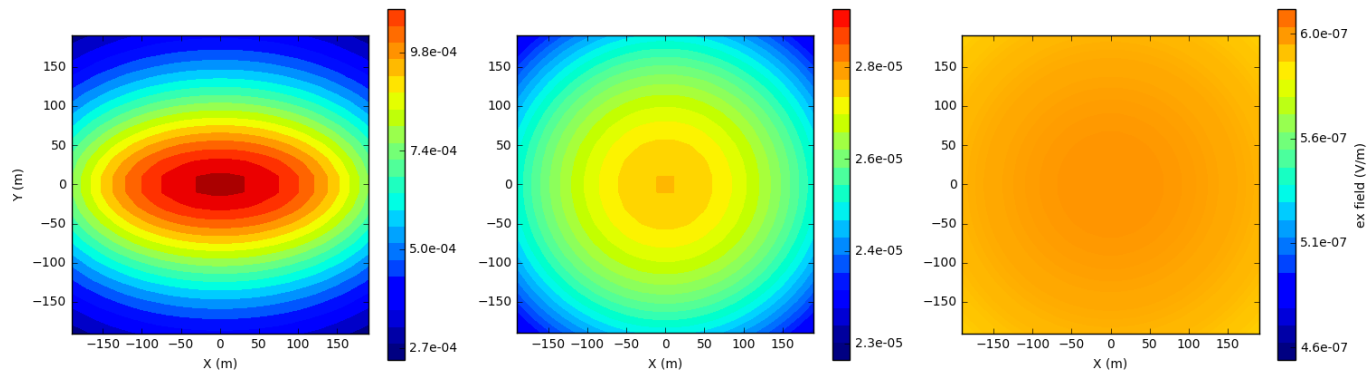
# Data: $e_x$ field



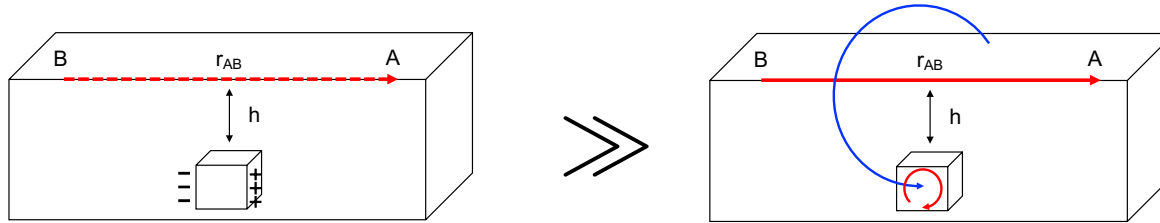
Resistor



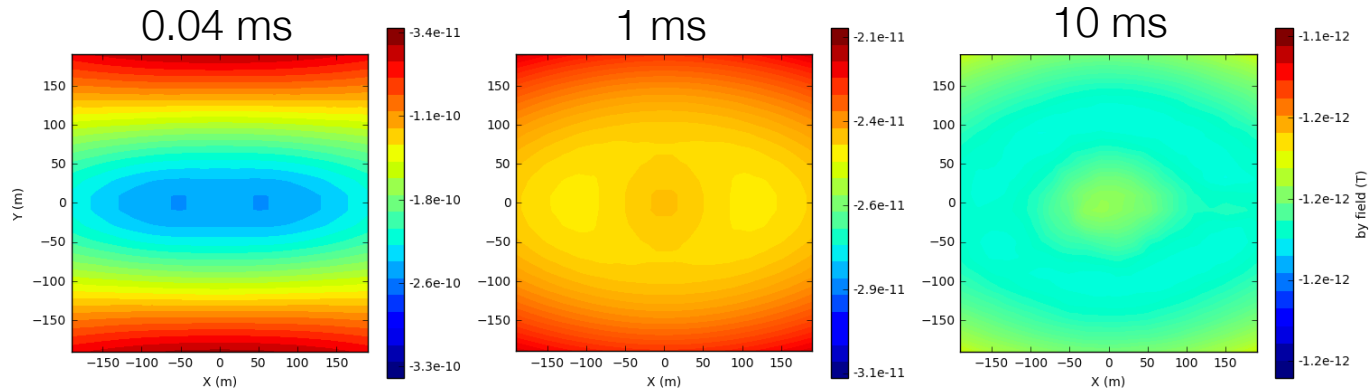
Halfspace



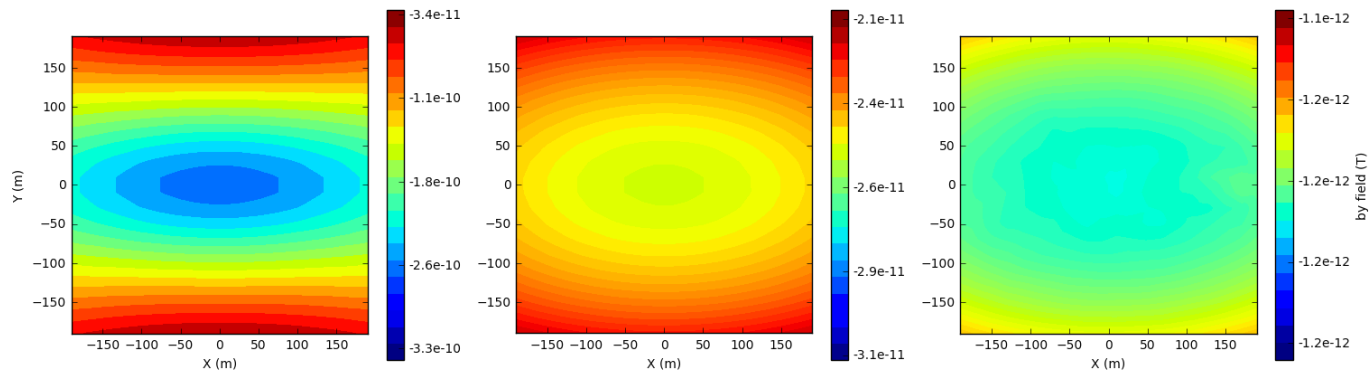
# Data: $b_y$ field



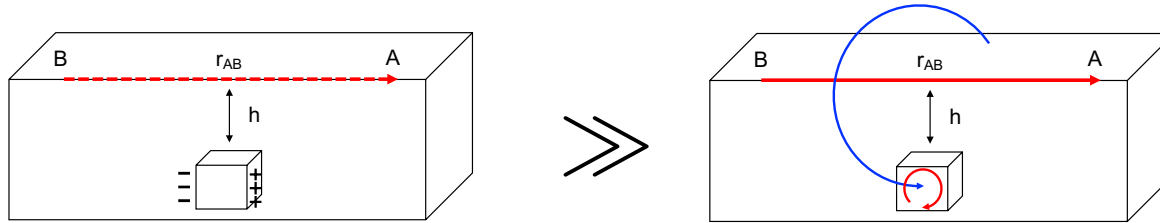
Resistor



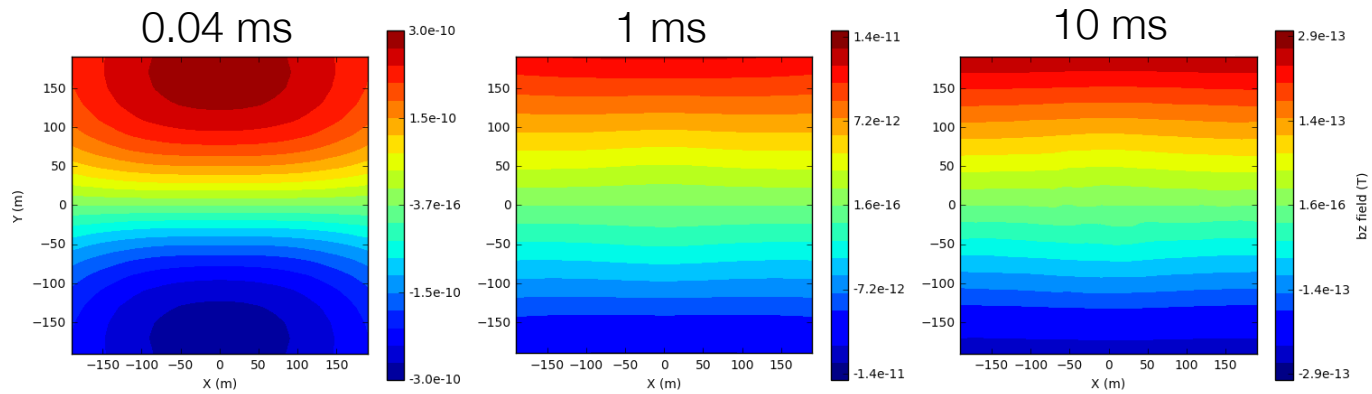
Halfspace



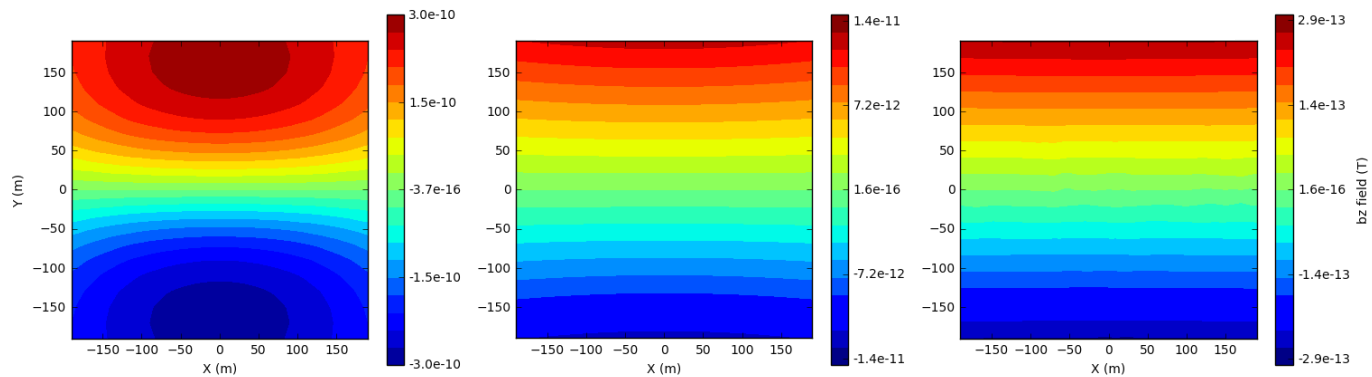
# Data: $b_z$ field



Resistor



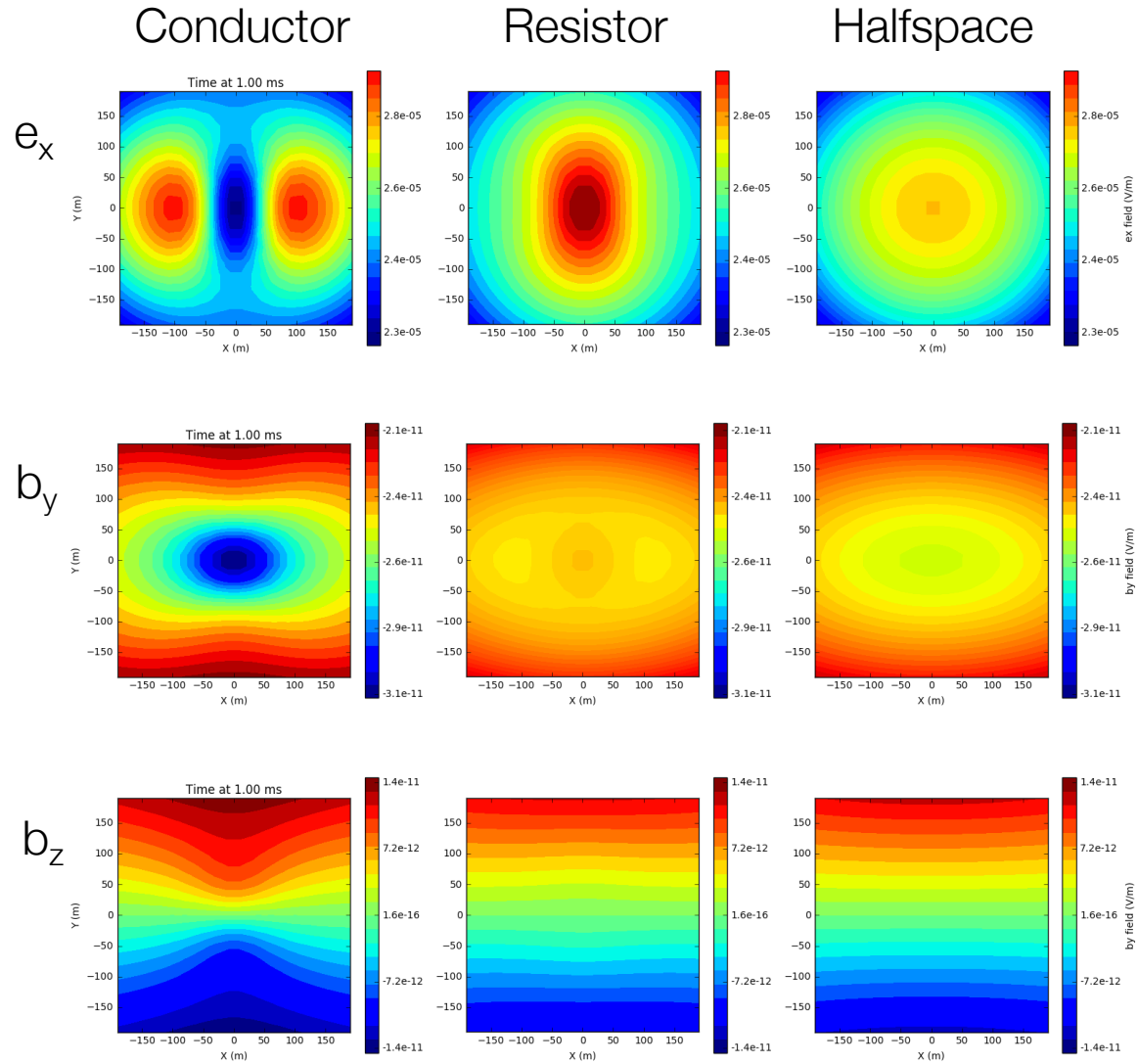
Halfspace





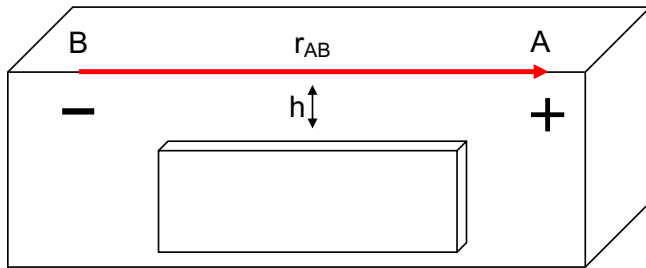
$t = 1\text{ms}$

# Data summary

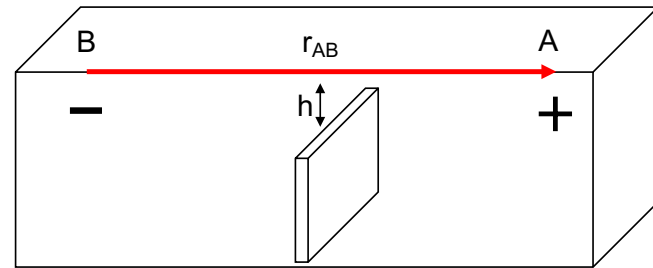


# Geometric Complexities

- Coupling: Back to finding thin plates...



- DCR: good coupling
- EM: good coupling



- DCR: poor coupling
- EM: poor coupling

- Arbitrary target requires multiple excitation directions
- Forward simulations necessary

# Grounded Sources: Summary

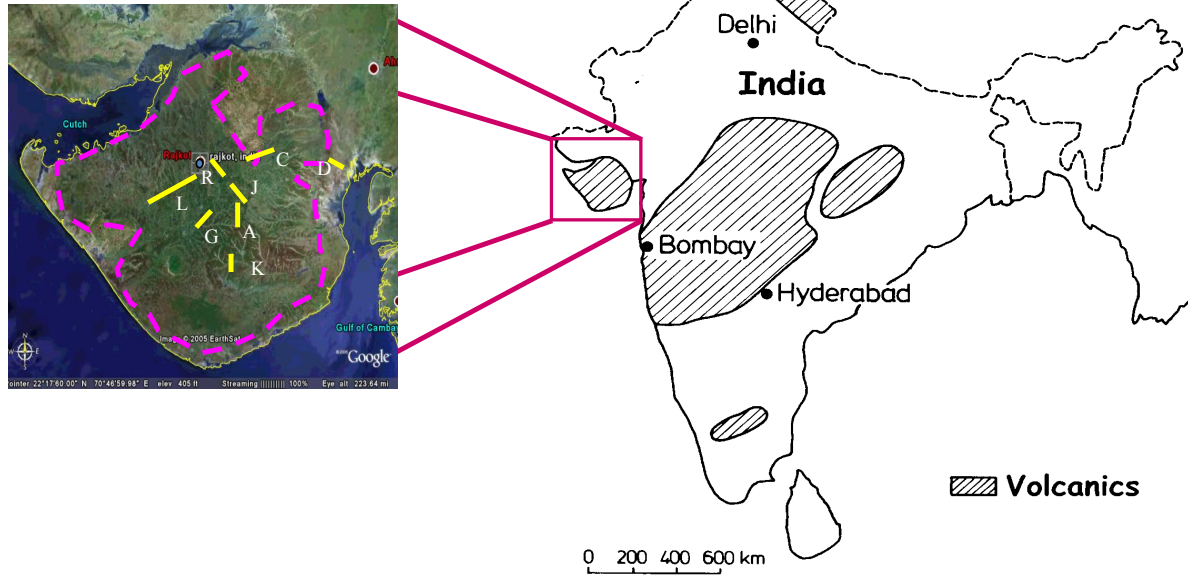
- Basic experiment
- TDEM: Electric dipole in a whole space
- FDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets
- Resistive Targets
  
- Case History: Deccan Traps
- Case History: Offshore Hydrocarbon De-risking
- Marine CSEM: Overview
- Case History: Methane hydrates
- DC/EM Inversion

# Case History: Mesozoic sediments beneath Deccan traps, India

Strack and Pandey, 2007

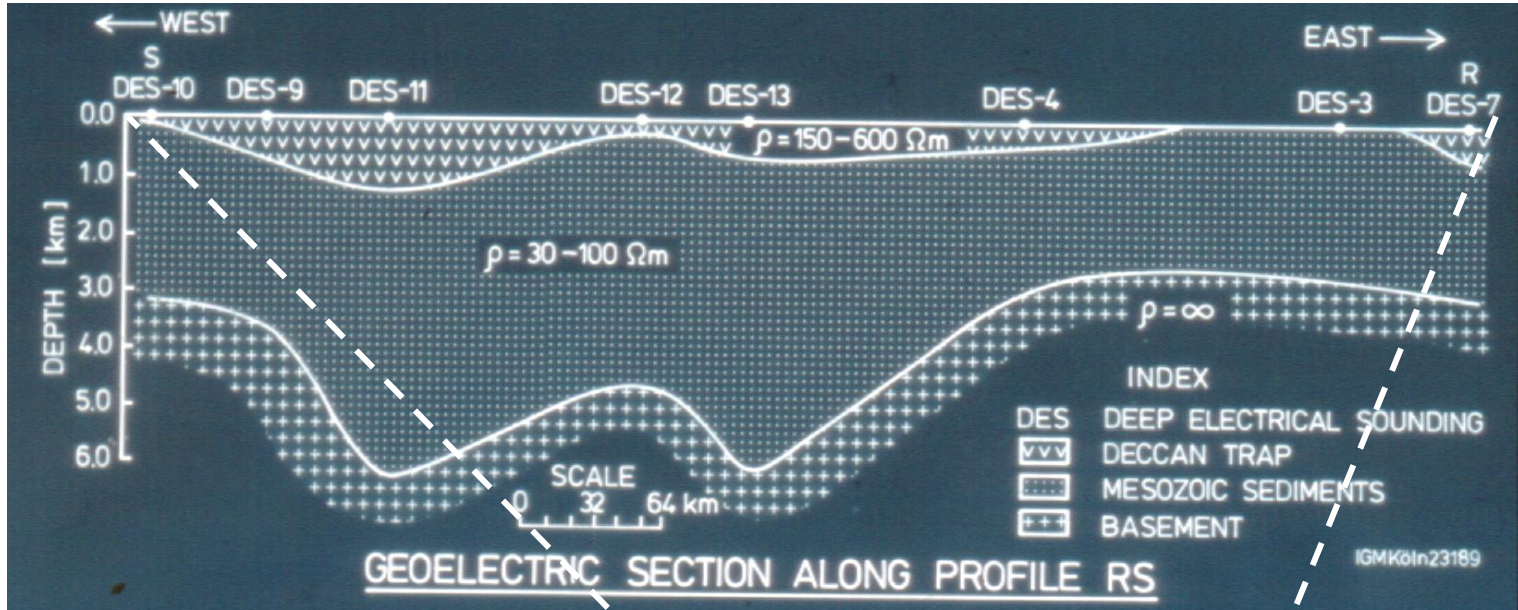
# Setup

Location map



# Previous DCR survey (ONGC)

## Resistivity section



- Sediments exist but unclear where and how thick. Interpretation weak

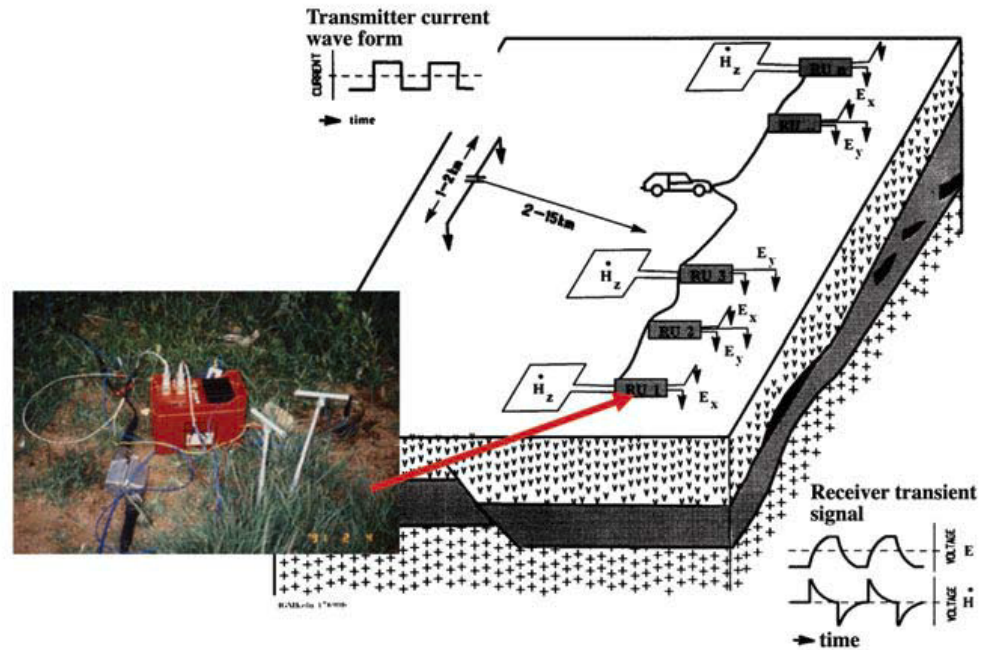


# Survey

Map

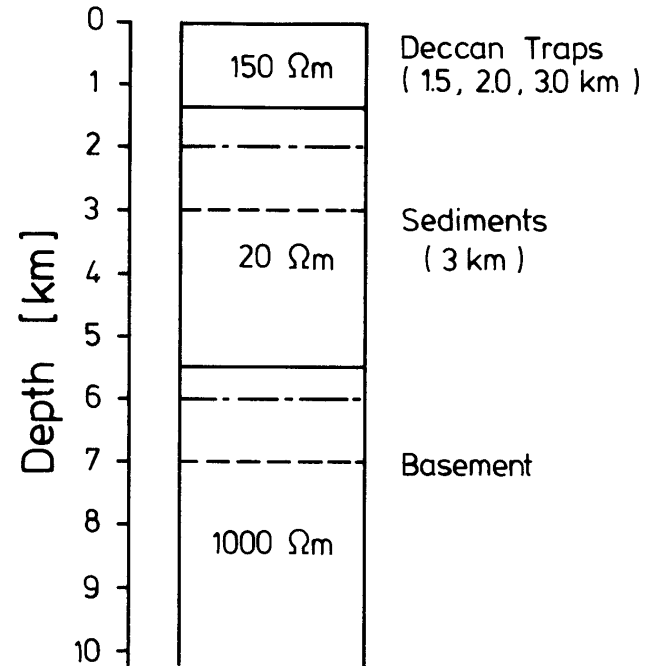
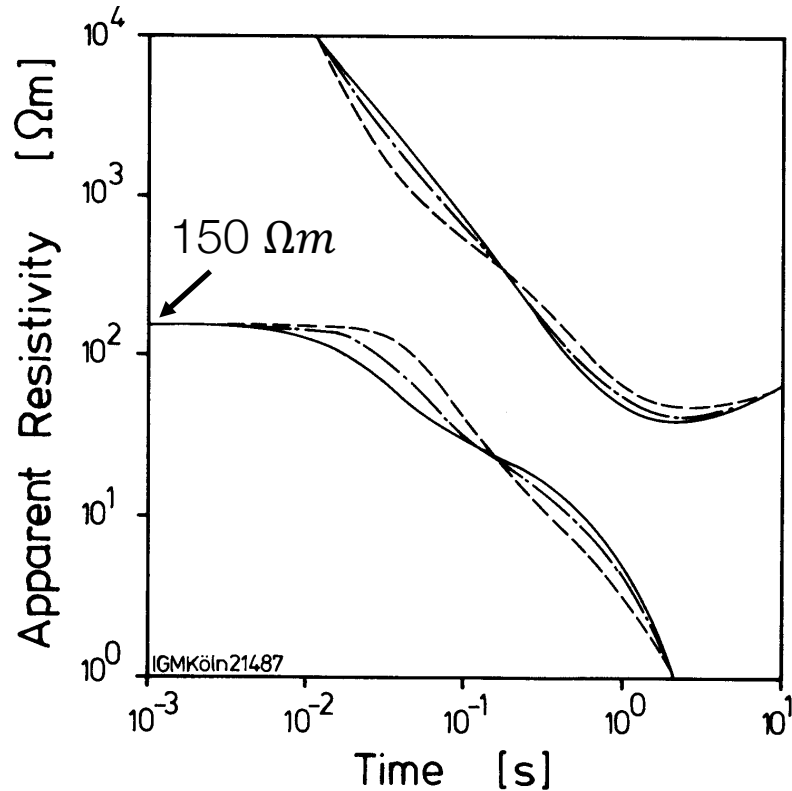


Long offset time domain EM (LOTEM)



- Rx component:  $E_x$ ,  $E_y$ , and  $H_z$
- # of Tx: 10
- Tx current: 400 A (full-duty cycle)

# Survey design: basalt thickness

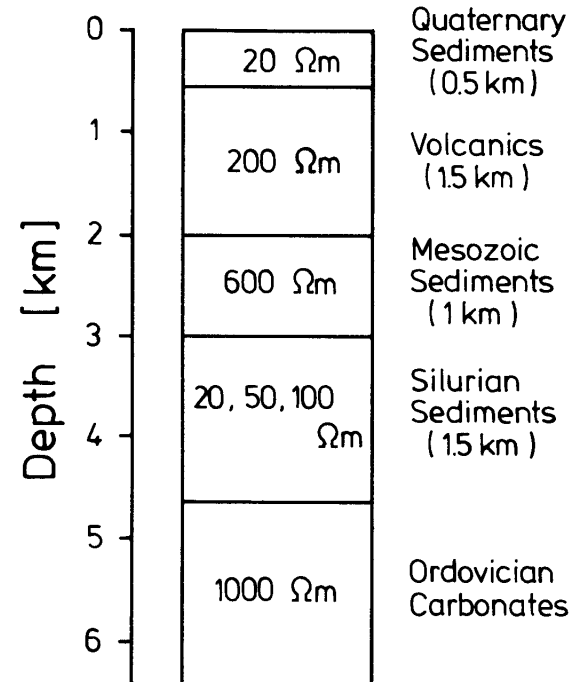
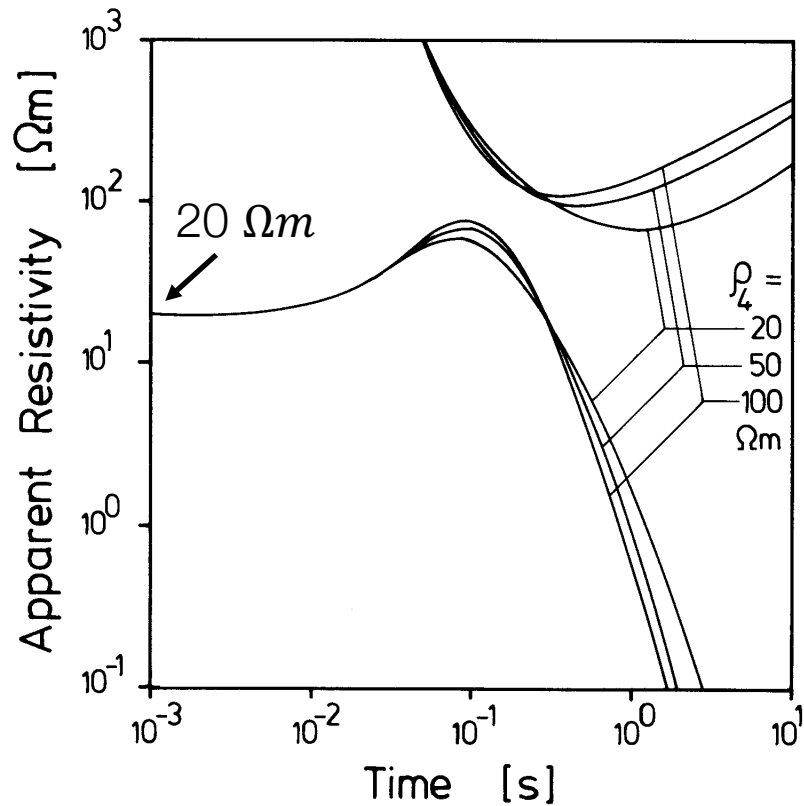


Varied : 1st layer thickness  
Offset : 10 km

- Apparent resistivity changes with varying thickness of Deccan Traps: 1.5, 2 and 3 km



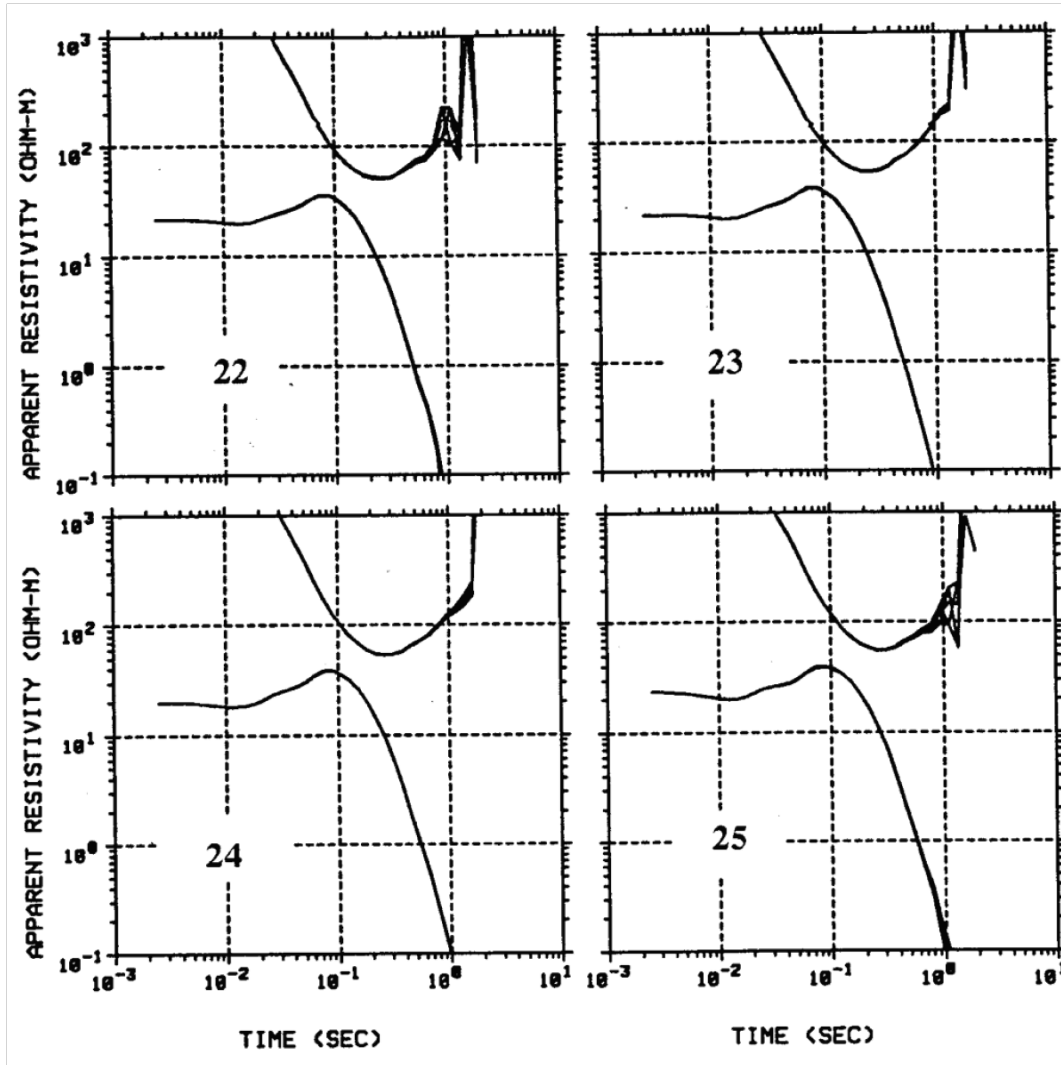
# Survey design: sediment resistivity



Varied : 4 th layer resistivity  
Offset : 9 km

- Apparent resistivity changes with varying resistivity of Silurian Sediments

# Data



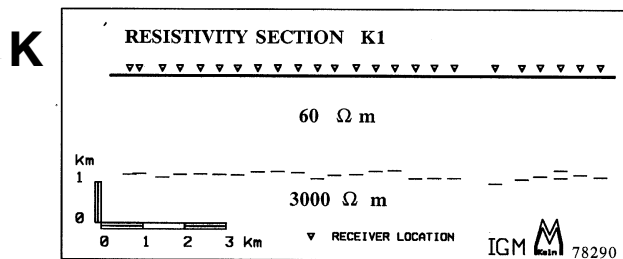
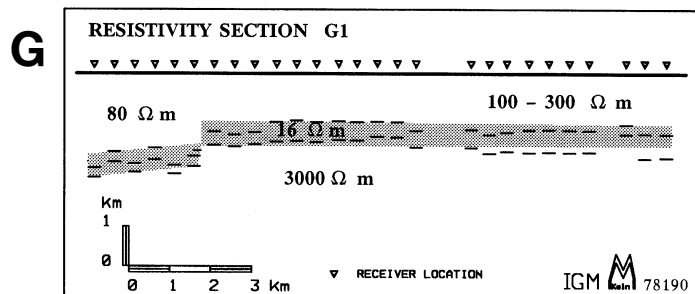
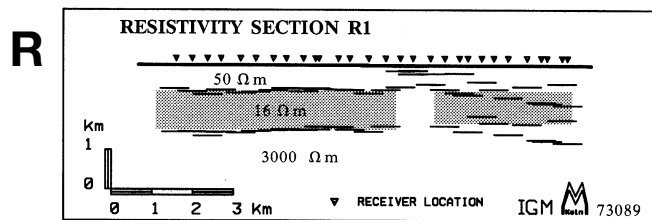
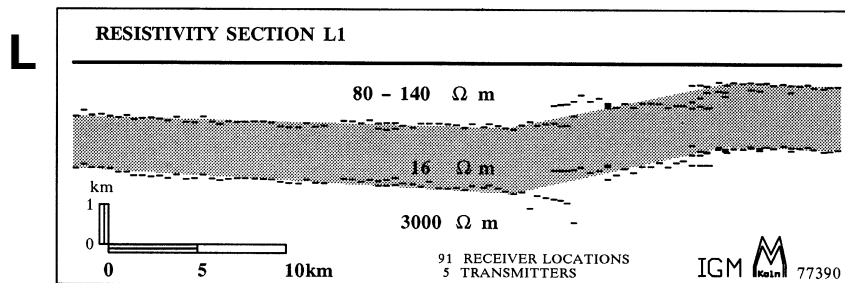
- Stacked data
- Time range: 1ms-10s
- High S/N ratio until 1s
- Similar to synthetic data

# Processing

1D inversions (stitched)

Location map

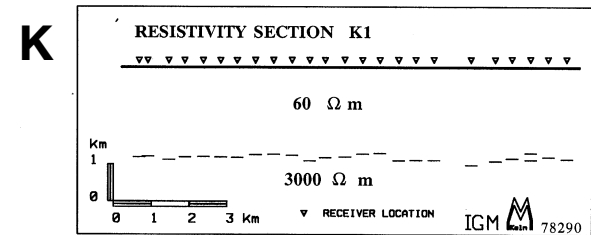
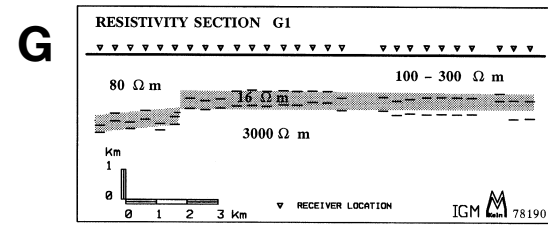
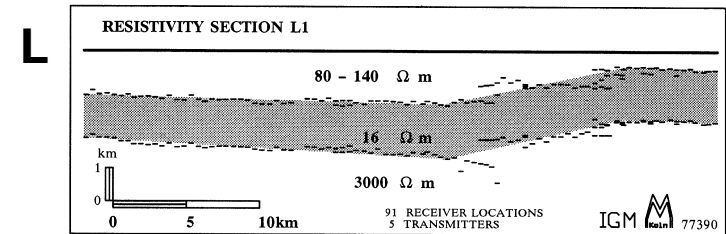
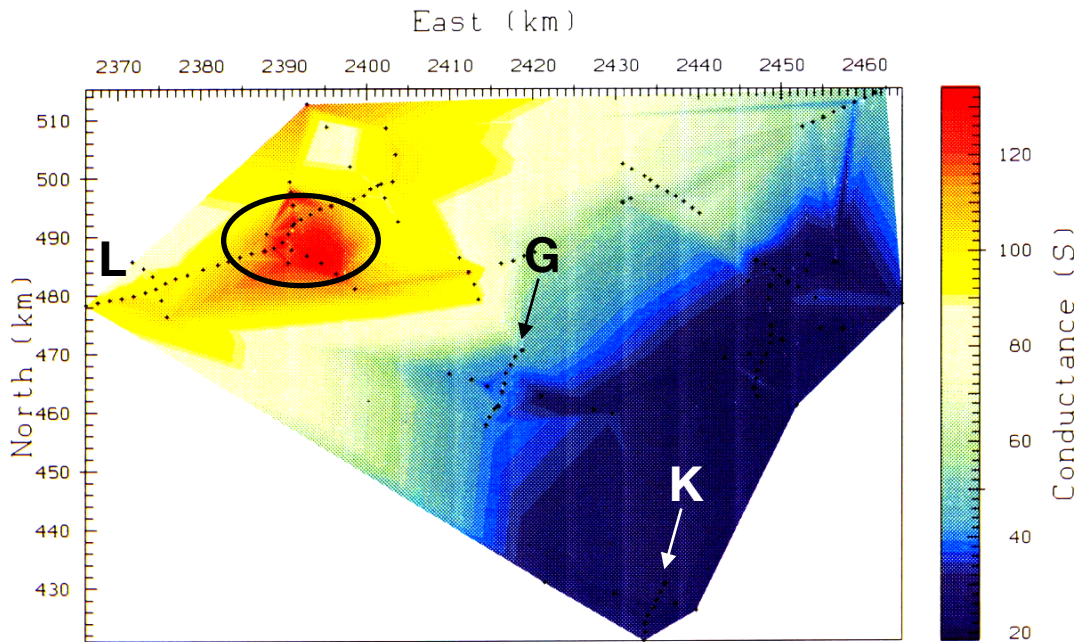
Thickness decreases



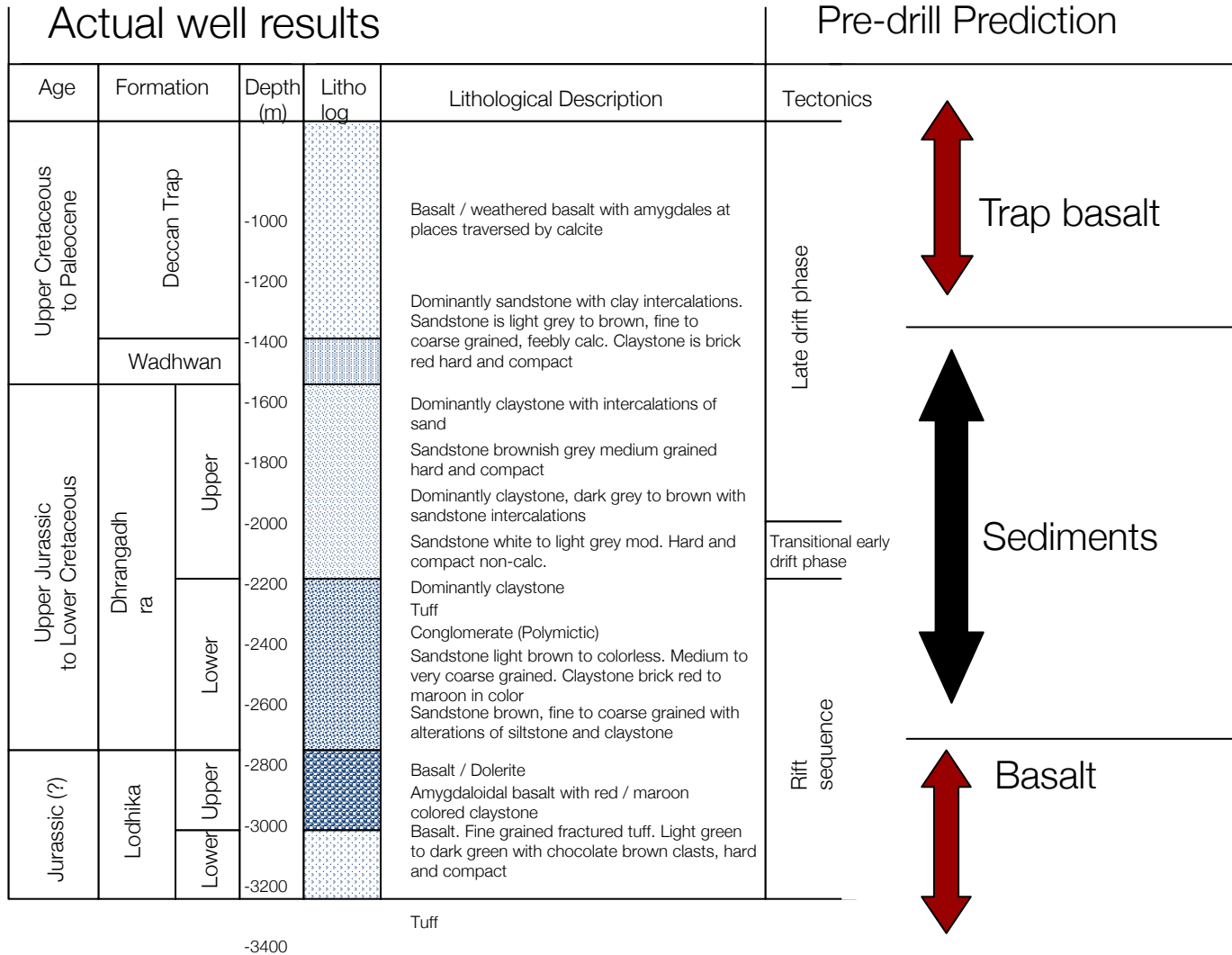
The sediment thickness:

- Largest at **L**
- Smallest at **K**

# Interpretation: sediment conductance and drill target



# Synthesis

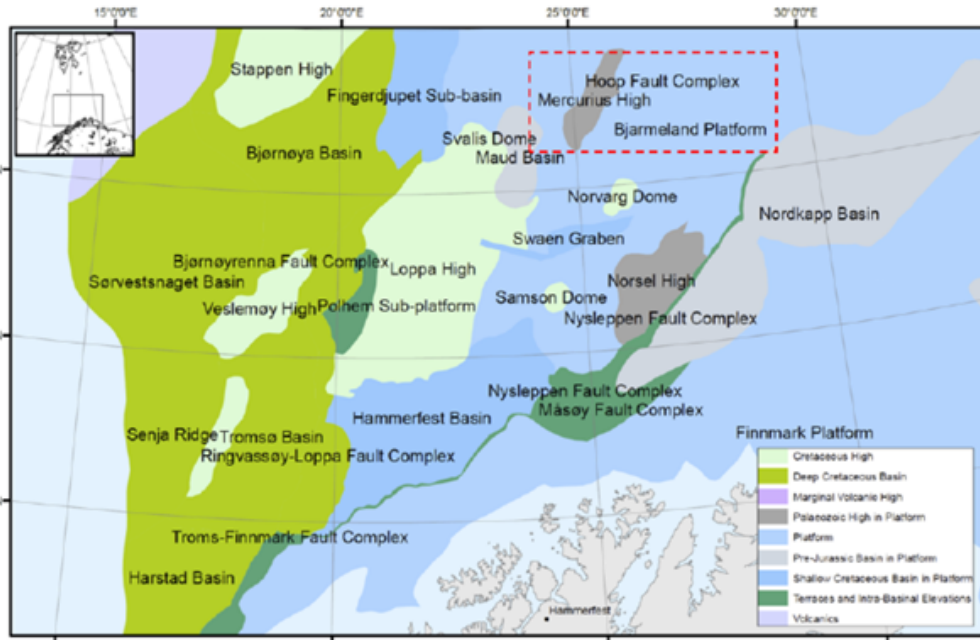


# Case History: Barents Sea

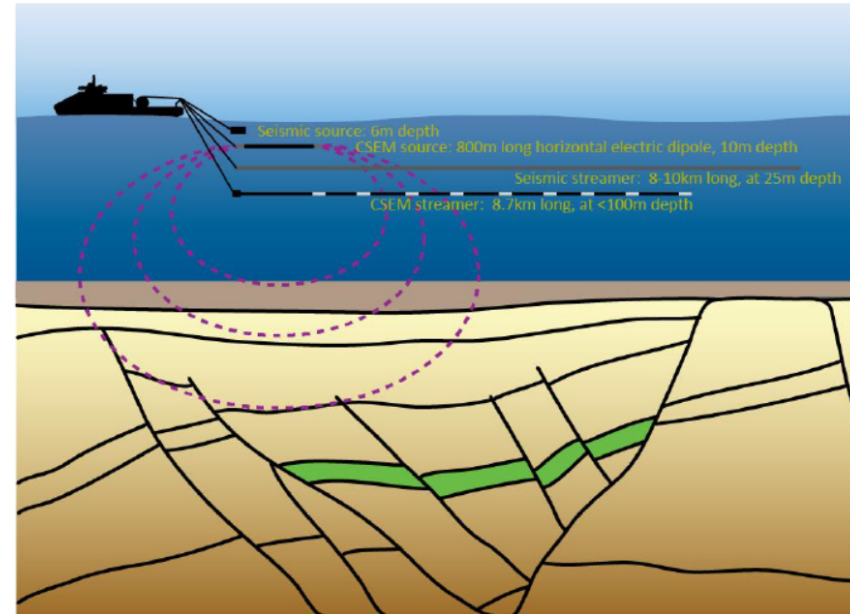
Alvarez et al., 2016. Rock Solid Images

# Setup

## Hoop Fault Complex, Barents Sea



## Marine CSEM

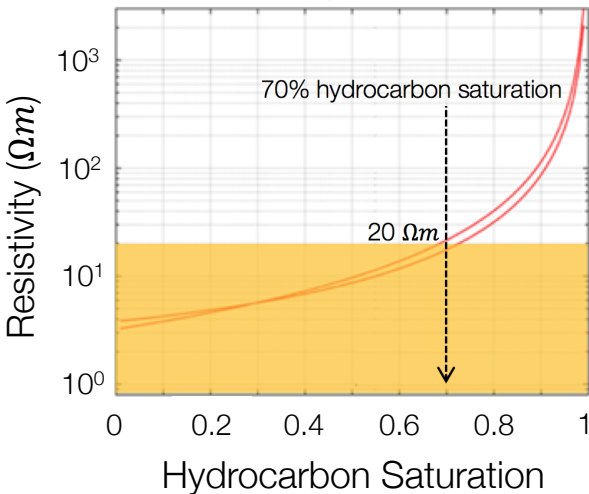
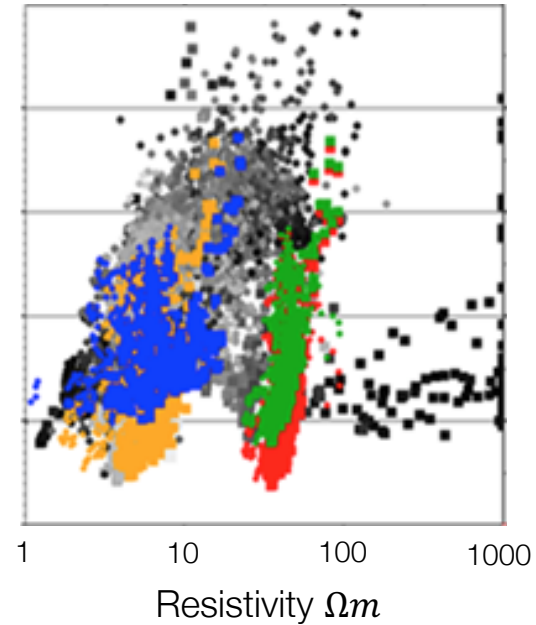
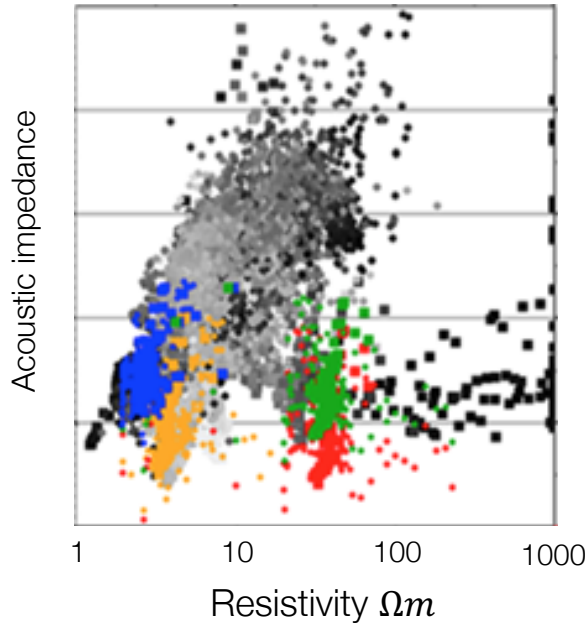
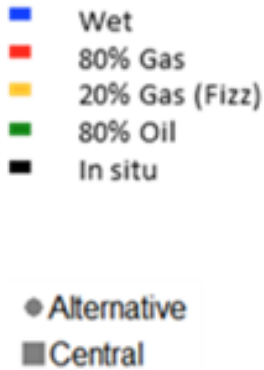


- Known hydrocarbon reservoirs within the Hoop Fault Complex, Barents Sea.
- Seismic can locate oil and gas reservoirs but cannot always determine hydrocarbon saturation (in particular fizz gas)
- Seismic, borehole and CSEM data used to characterize reservoir
  - fluid, porosity, clay content, and hydrocarbon saturation

# Properties

a) Stø Fm.

b) Nordmela Fm.

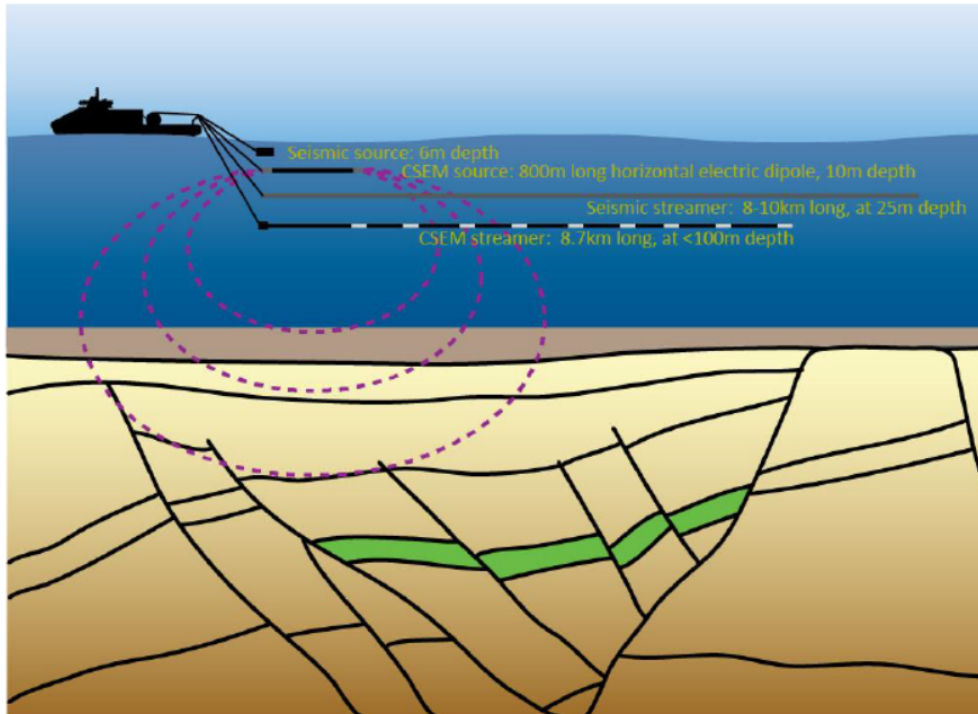


- Highly hydrocarbon-saturated reservoir (< 30% water-wet) significant resistivity
- CSEM can differentiate high from low quality reservoirs



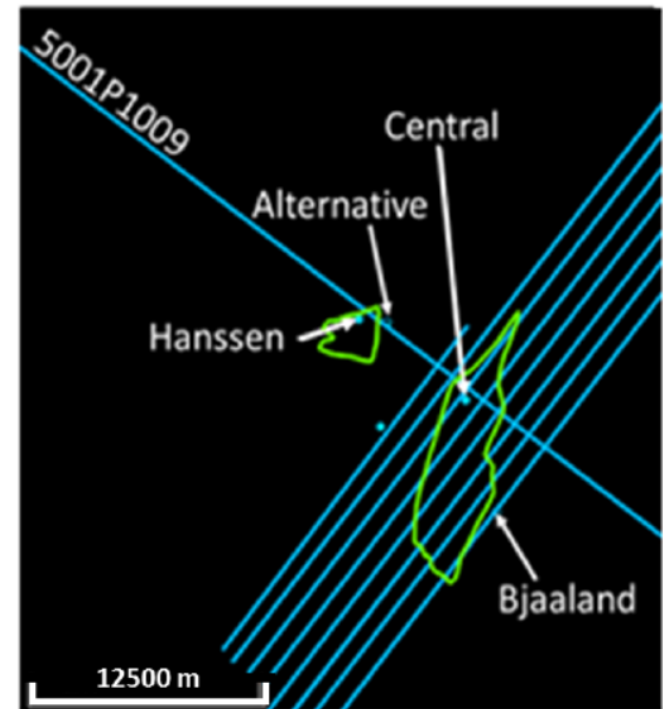
# Survey

## Towed CSEM and 2D seismic



- 6 lines of 2D seismic and towed streamer CSEM data.
- 72 receivers collected CSEM data
  - offsets from 31m to 7.8 km
- CSEM frequencies: 0.2 Hz to 3 Hz.

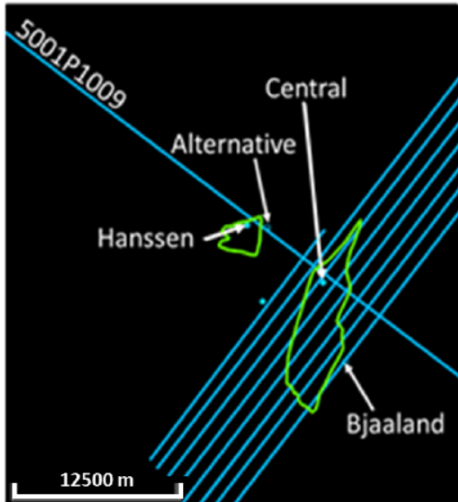
## Survey lines



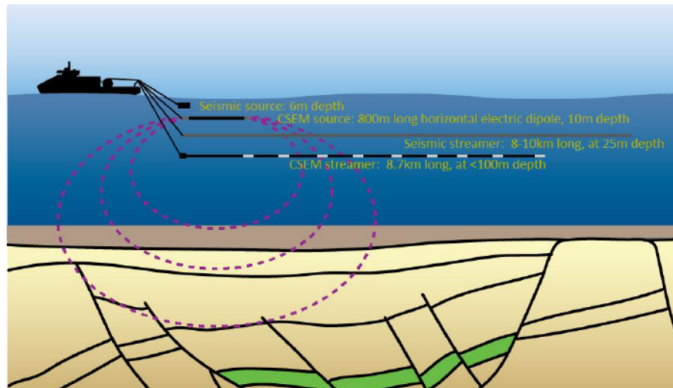
Alternative	Control well, dry
Central	Control well, productive
Hanssen	Validation well
Bjaaland	Validation well

# CSEM Data

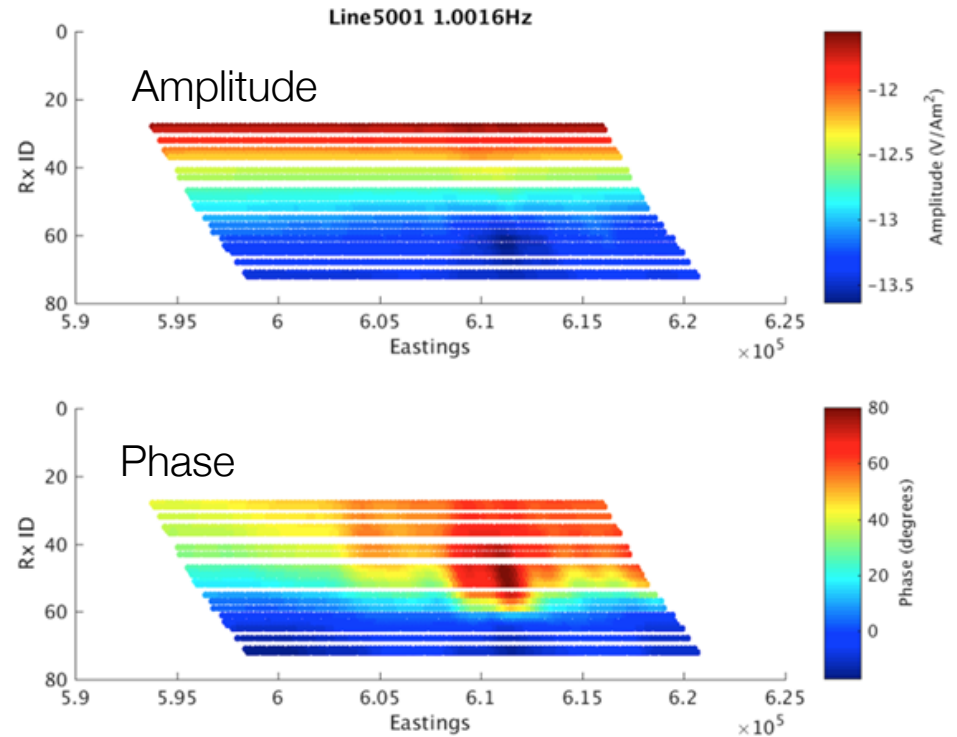
## Survey lines



## Towed-streamer EM



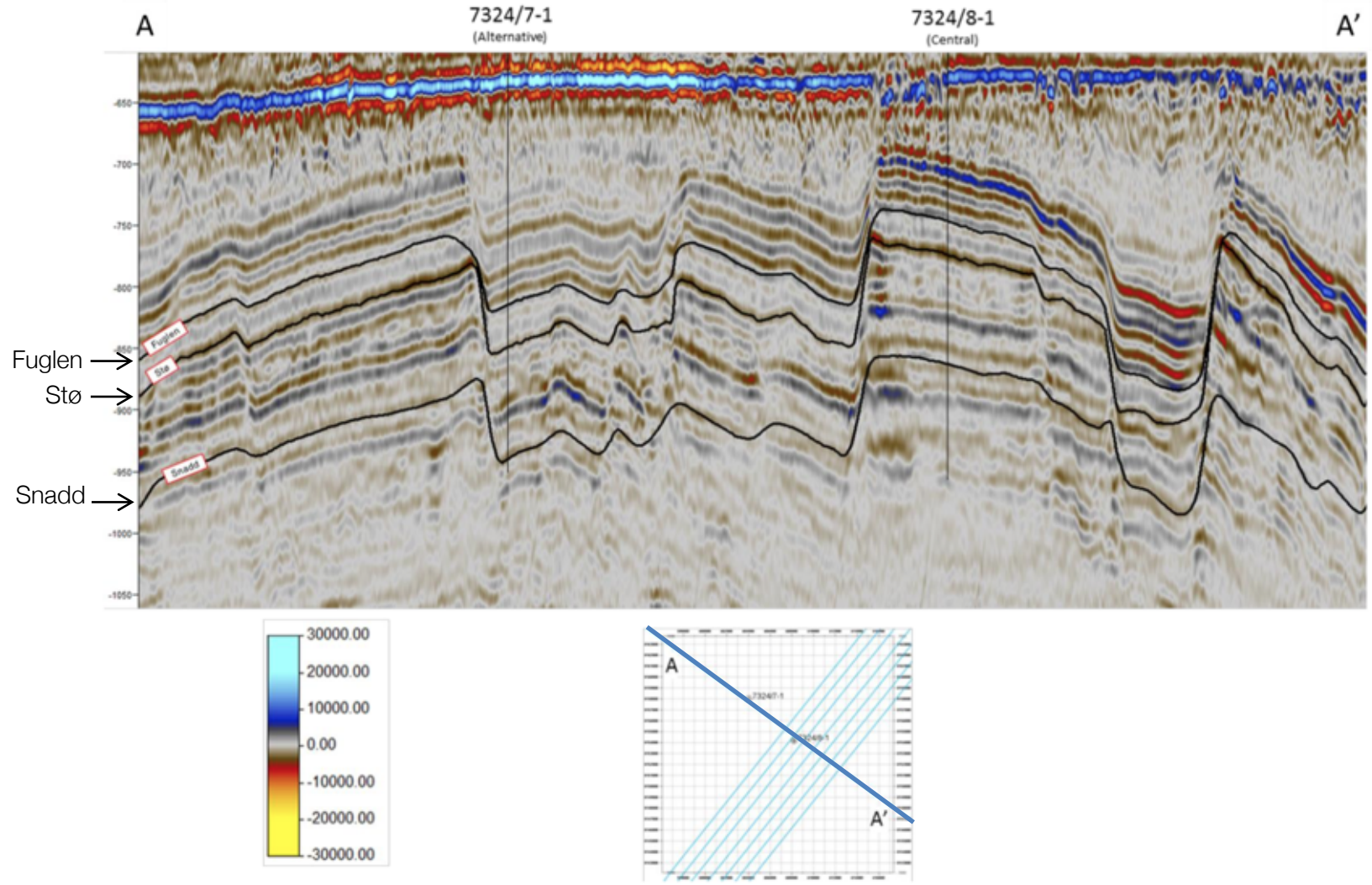
## CSEM data over central reservoir (1 Hz)



- Significant phase response over Central reservoir

# Seismic data

Seismic section: Line 5001

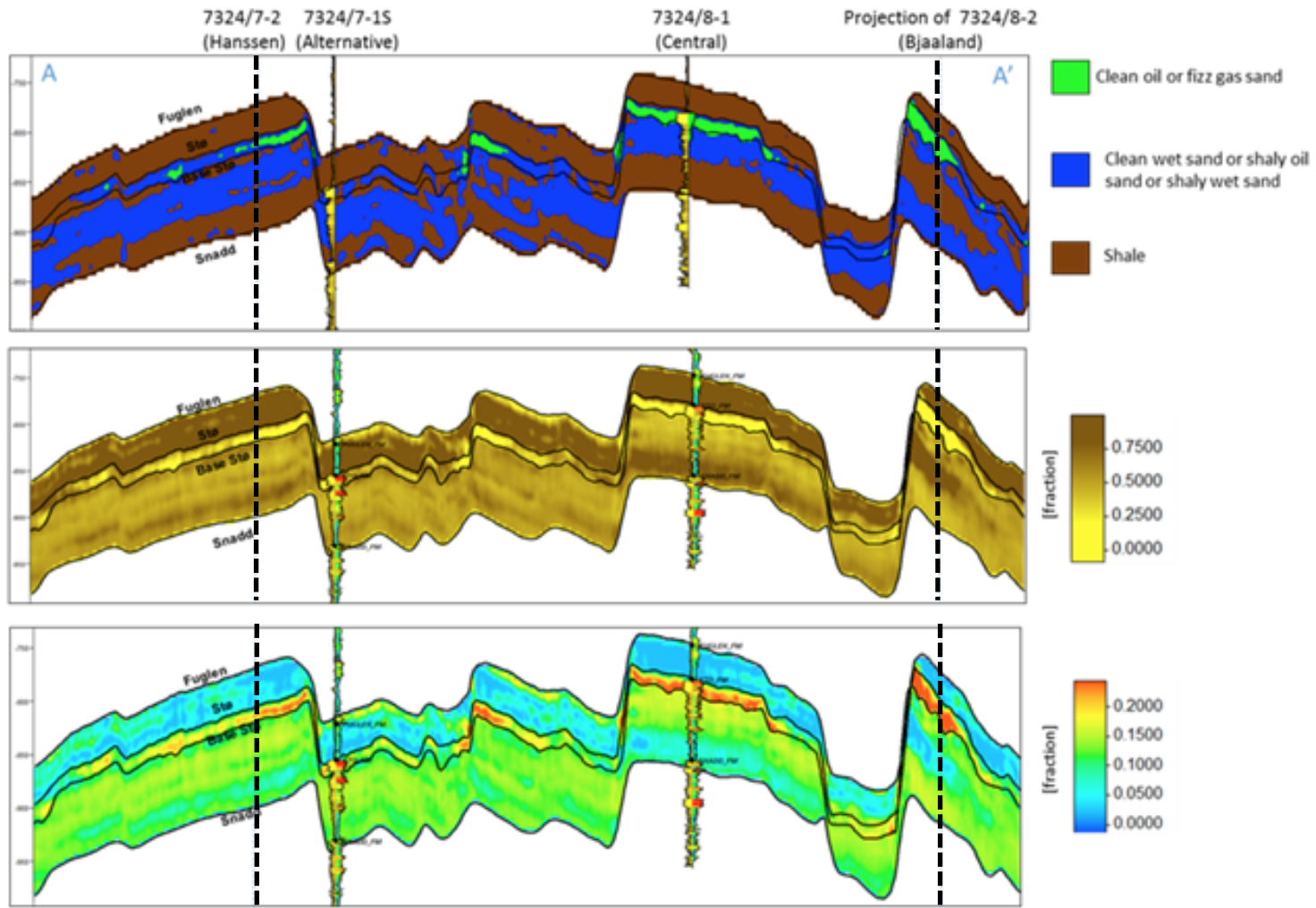


# Well-Log and Seismic Inversion

Litho-fluid  
Facies

Clay Content

Total Porosity



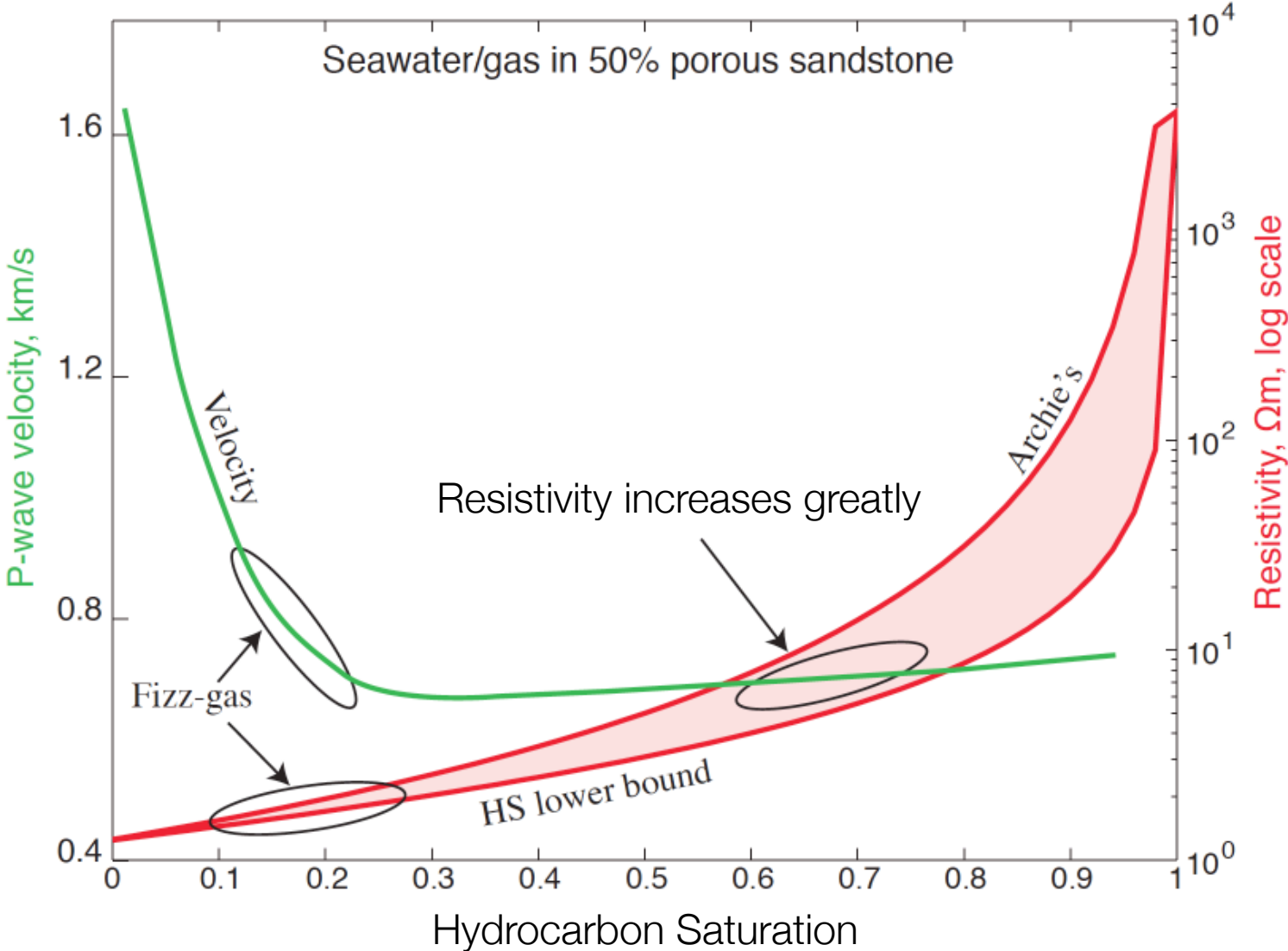
**Hanssen**  
Validation well

**Alternative**  
Control, dry

**Central**  
Control, productive

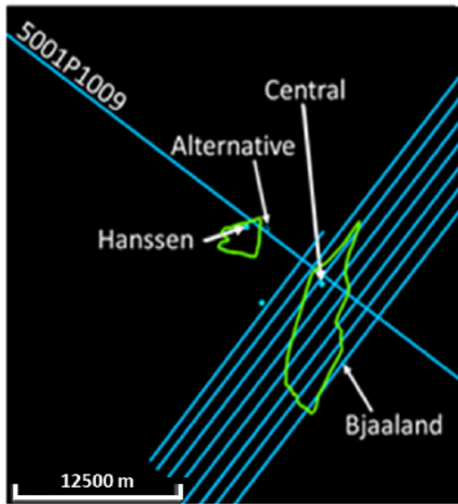
**Bjaaland**  
Validation well

# Revisiting physical properties

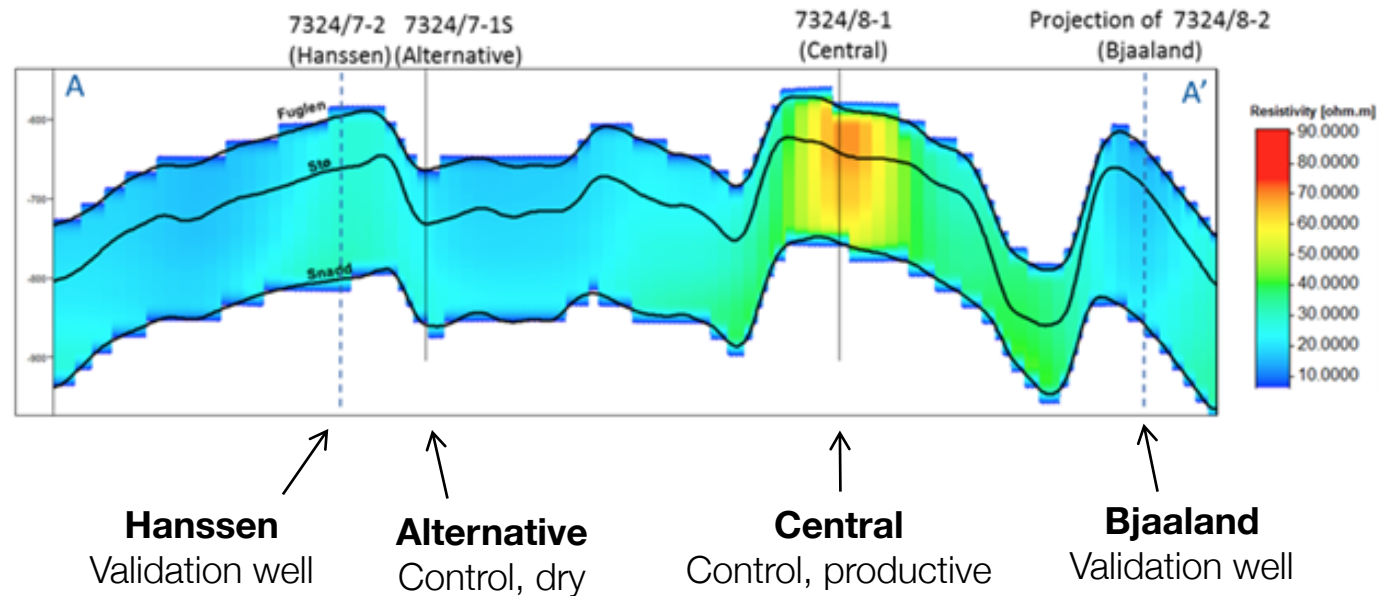


# Processing: CSEM Inversion

Survey lines



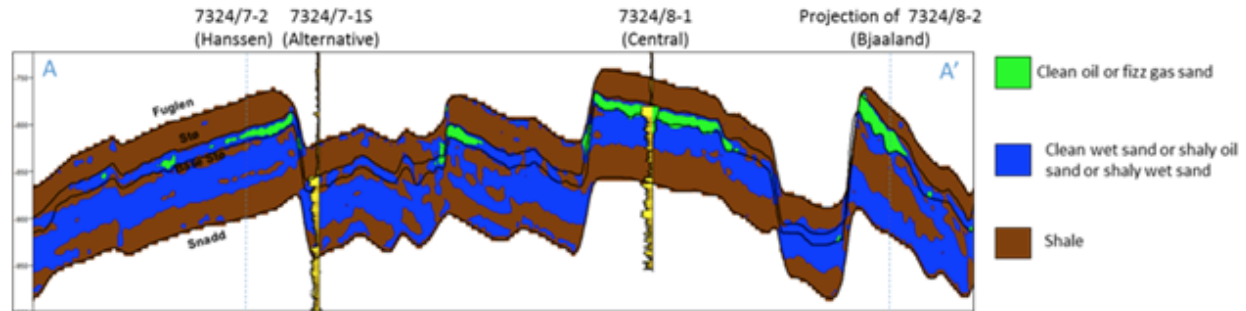
Vertical resistivity section along profile line 5001



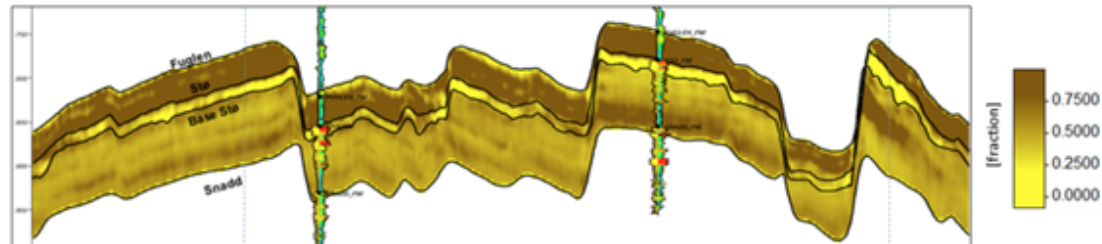
- Inversion shows strong resistor at Central and a secondary resistor at Hanssen.

# Processing: Multi-physics Approach

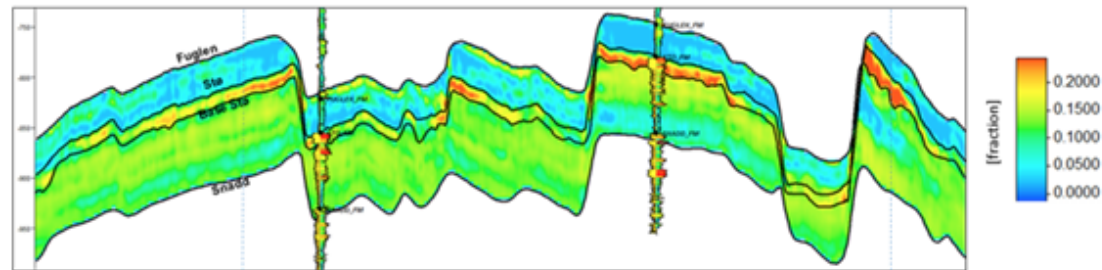
Litho-fluid  
Facies



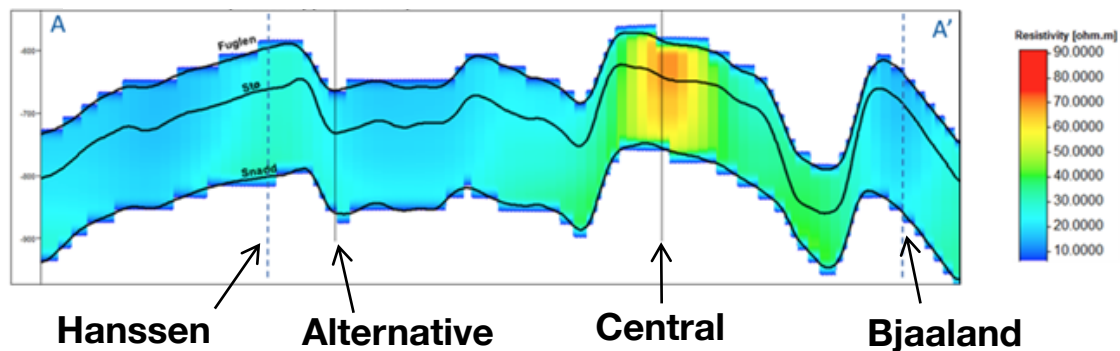
Clay Content



Total Porosity

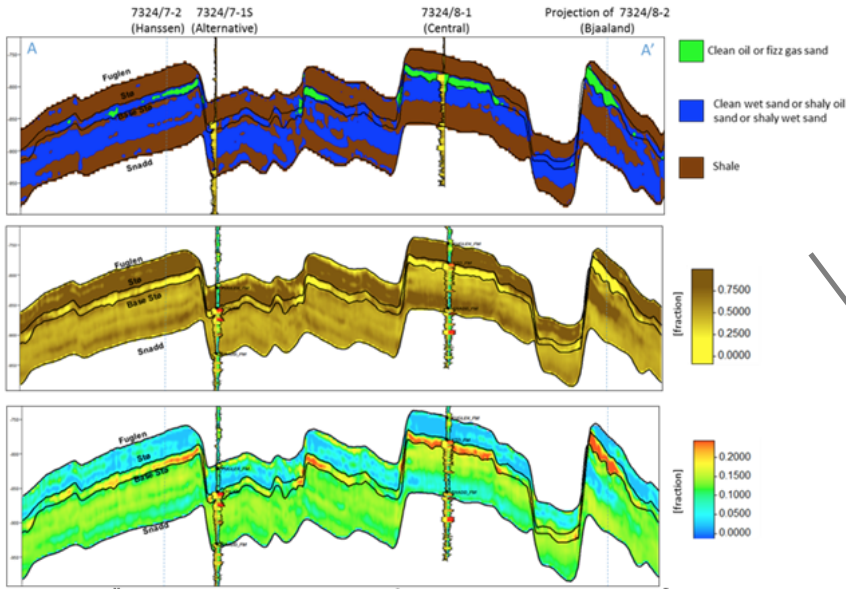


Resistivity

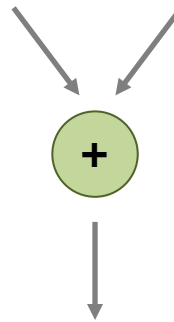
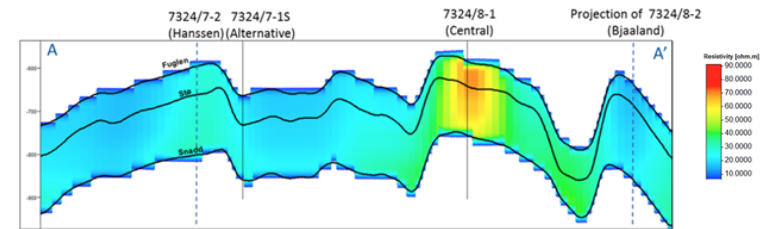


# Interpretation & Synthesis

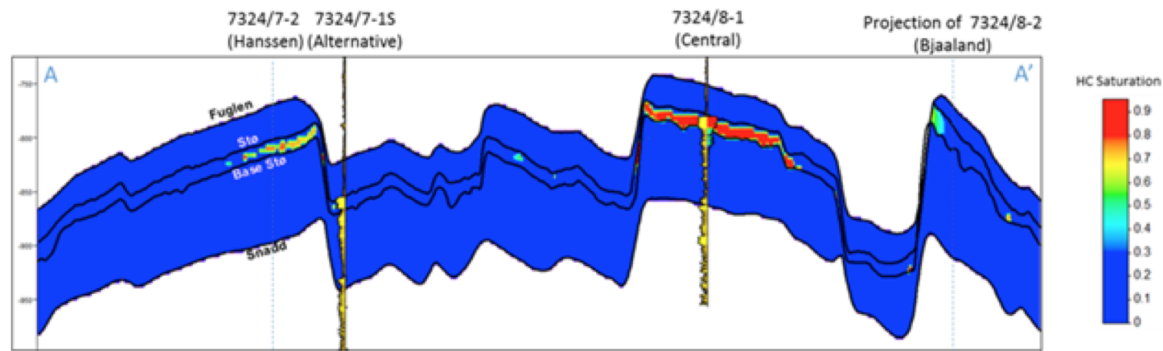
## Seismic



## EM



## Hydrocarbon saturation



**Hanssen**  
Validation well  
productive

**Alternative**  
Control, dry

**Central**  
Control, productive

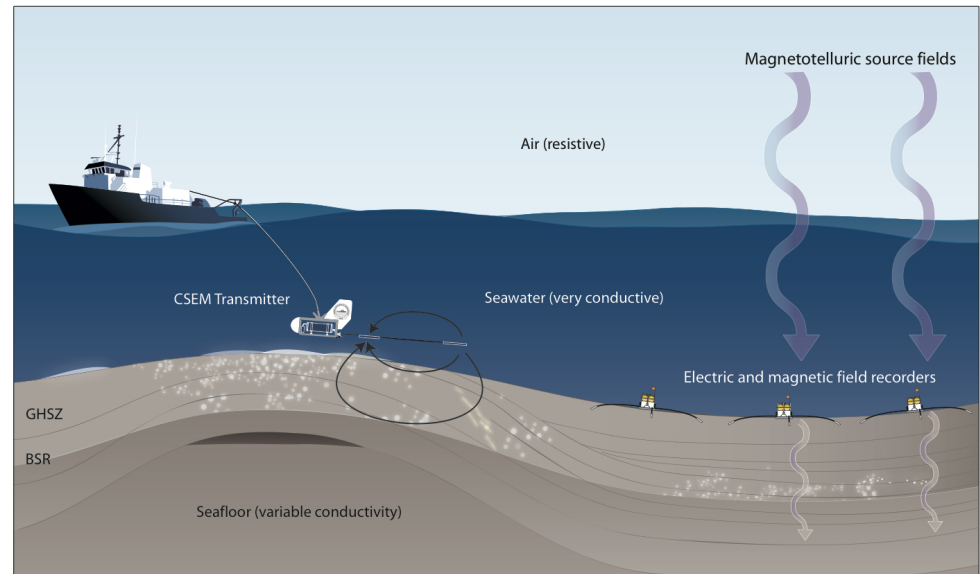
**Bjaaland**  
Validation well  
dry



# Controlled-Source Marine EM (CSEM)

# Application areas

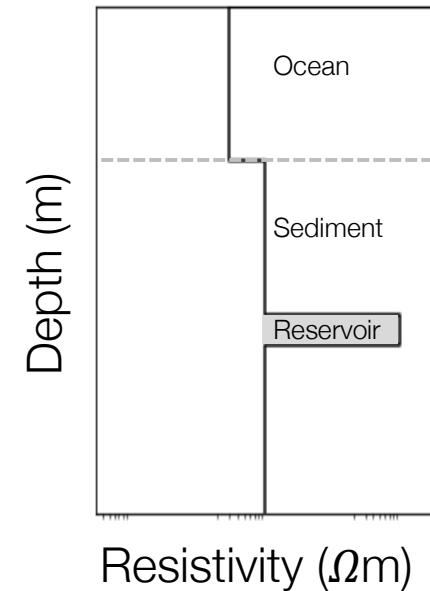
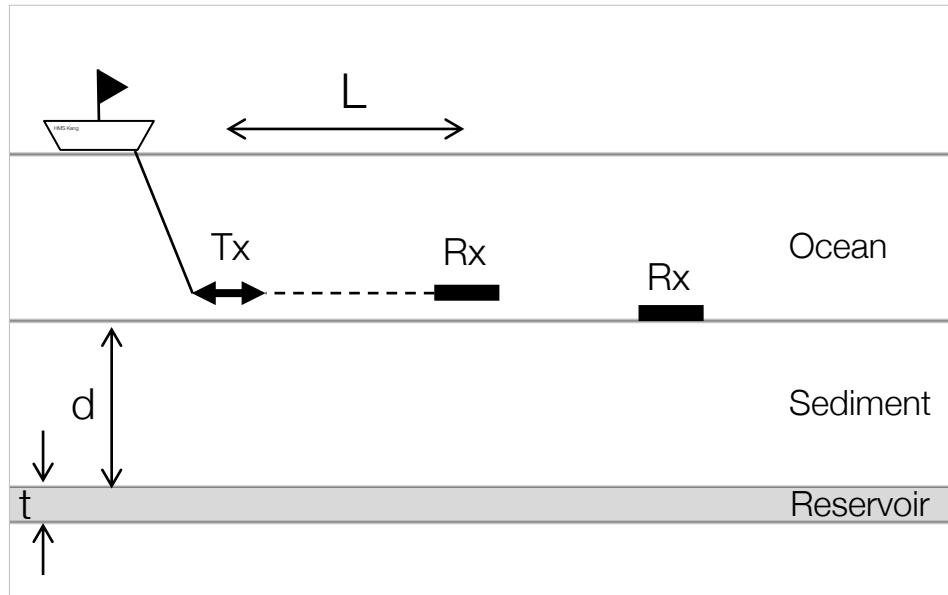
- Oil and gas
- Submarine massive sulfide (SMS)
- Methane hydrates
- Tectonic studies
- Offshore UXO
- Offshore groundwater



# Application with physical properties

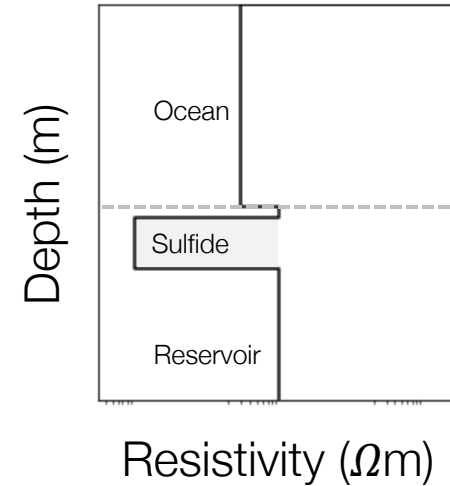
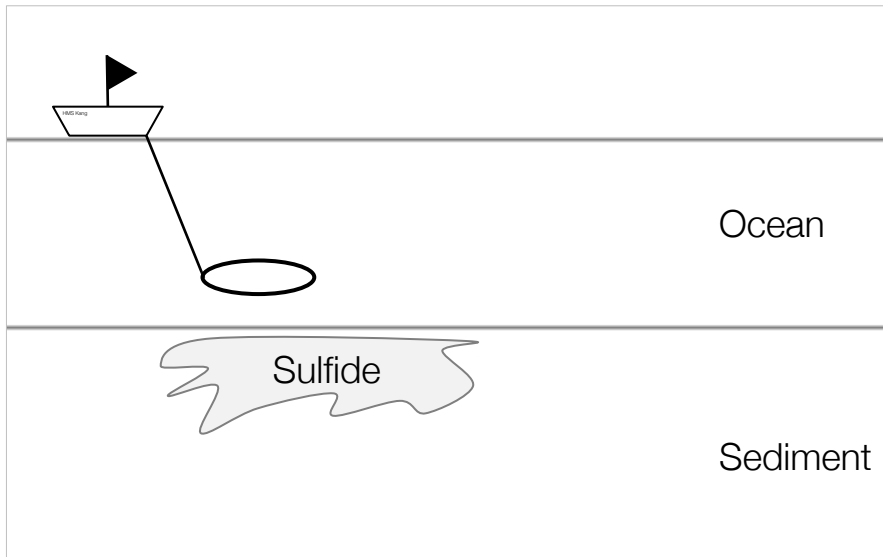
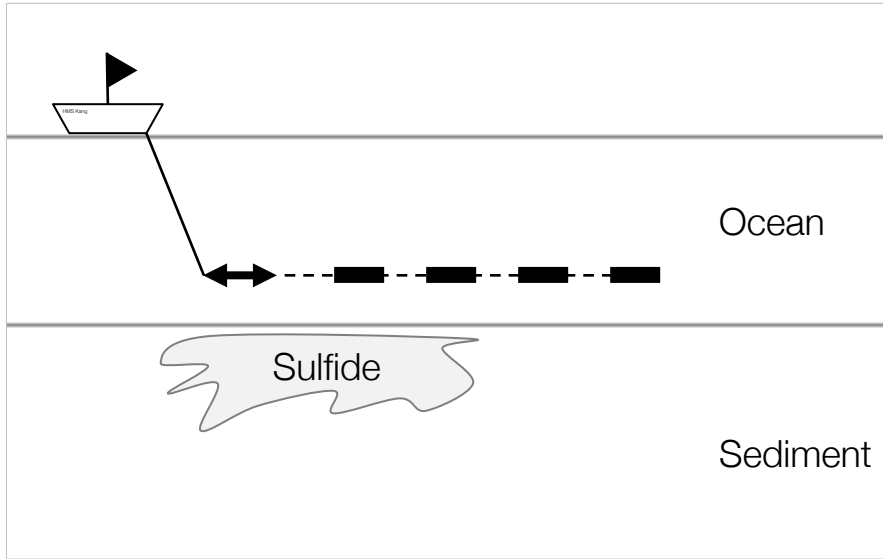
	$\rho$ ( $\Omega\text{m}$ )	$\sigma$ (S/m)
Seawater	0.25-0.31 (15-3 °C)	3.3-4
Freshwater	100-1000	0.001-0.01
Sediment	1-5	0.2-1
Hydrocarbon	~100	~0.01
Hydrate	2000 (0 °C)	0.005
Massive sulfides	0.01-1	1-100

# Resistive target: hydrocarbons



- Finding resistor: grounded source
- Deep target
  - Long offset between Tx and Rx
  - Depth of investigation  $\sim 1/3$  Tx - Rx offset

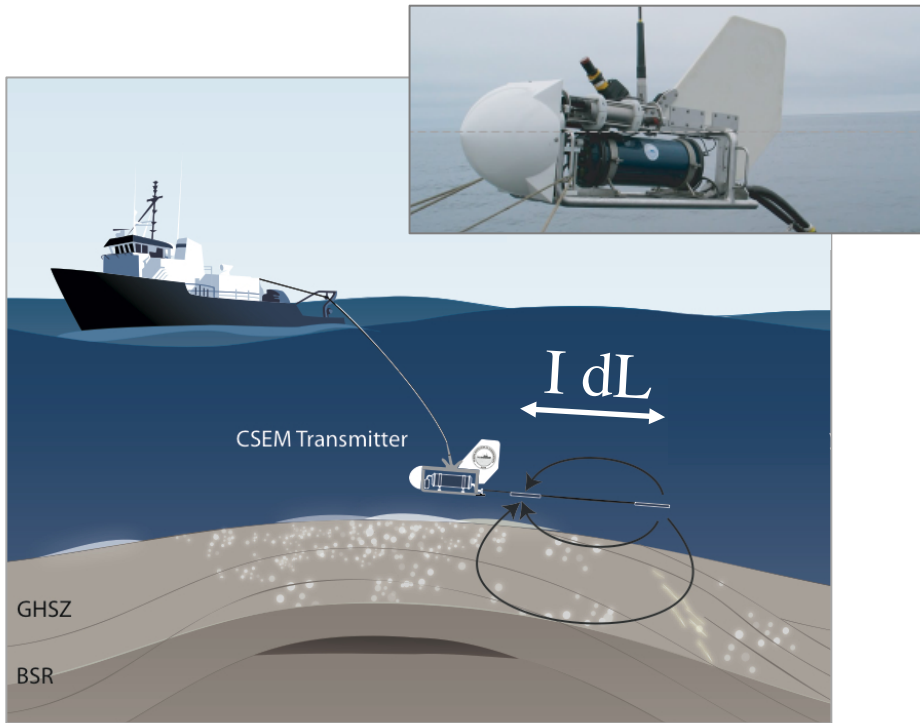
# Conductive Target: Massive sulfide



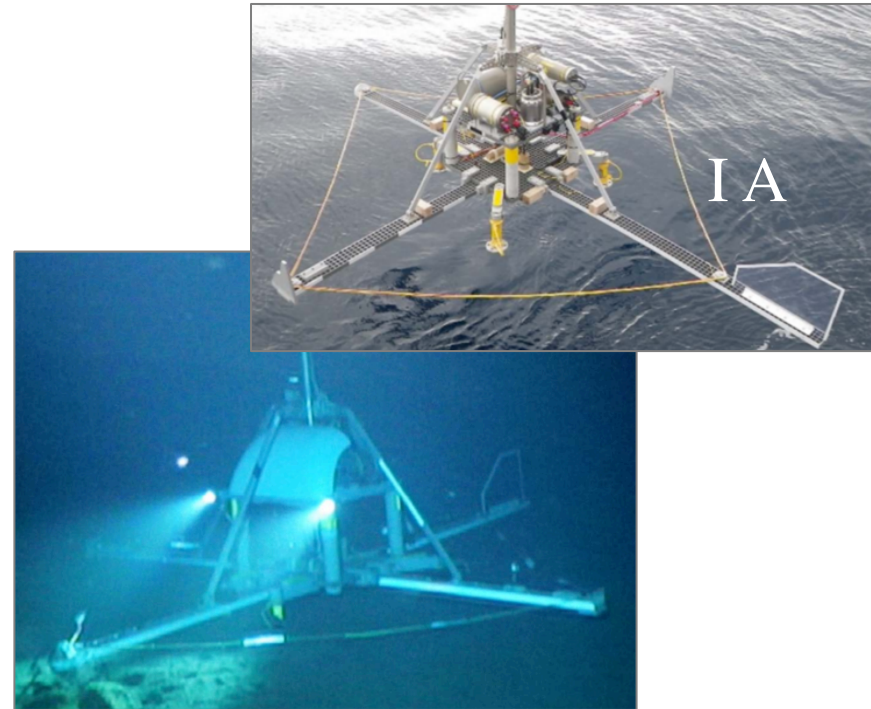
- Galvanic source
  - Towed E-field receivers
- Inductive source
  - Towed on ROV
  - $db/dt$  sensors (coil)

# Transmitters

Galvanic (Scripps: SUESI)



Inductive (Waseda Univ., GEOMAR)



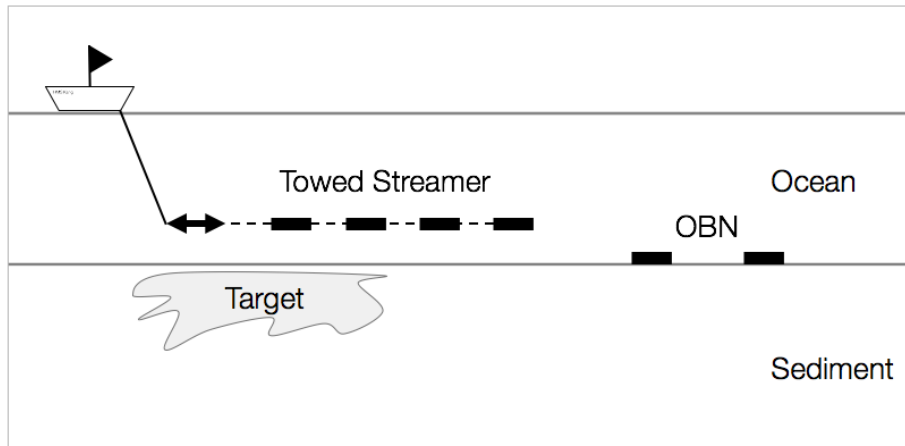
Geometric Decay  $\frac{1}{r^3}$

EM Attenuation  $\delta = 500 \sqrt{\frac{\rho}{f}}$

# Receivers

## Data

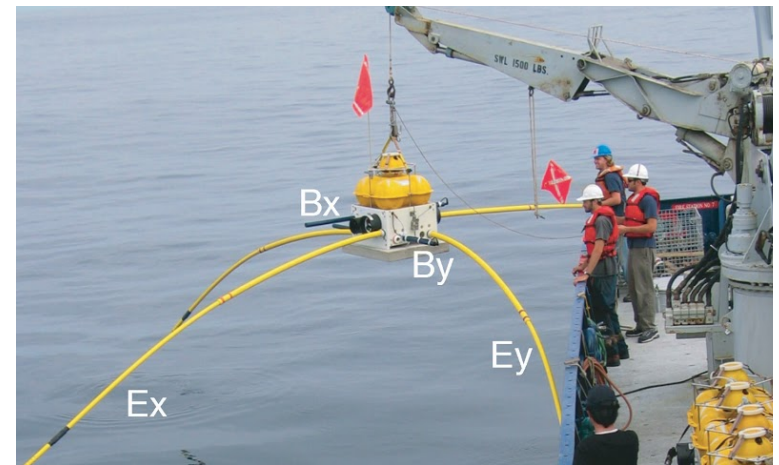
- $E_x$ ,  $E_y$ , (Recently:  $E_z$ )
- $B_x$ ,  $B_y$ ,  $B_z$



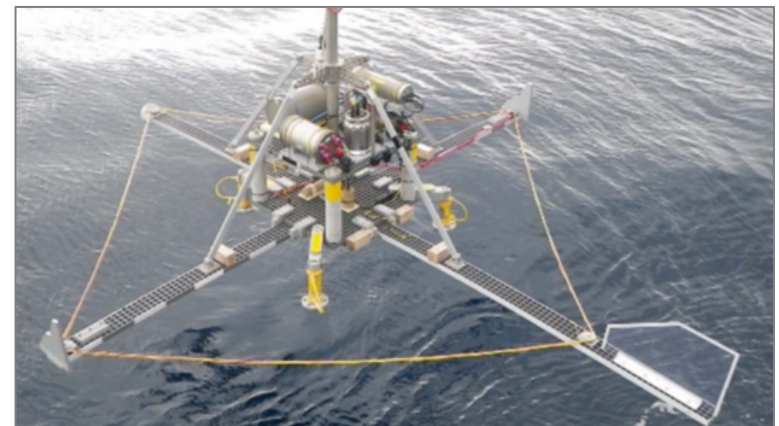
## Common Systems

- Scripps: Vulcan and Porpoise
- PGS
- EMGS

## Ocean Bottom Nodes (Scripps, EMGS)

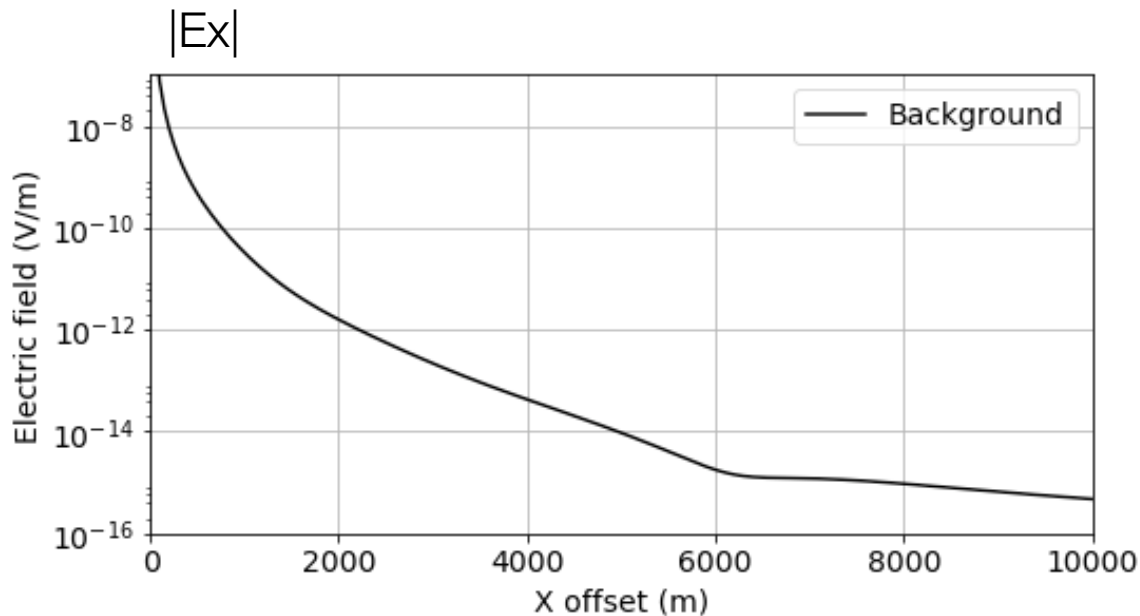
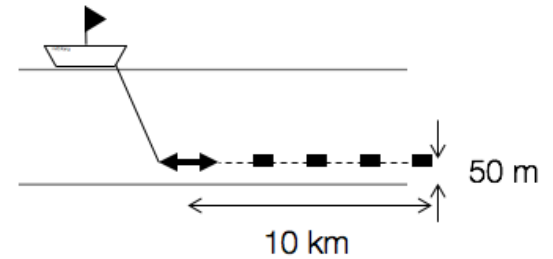


## Inductive Loop (Waseda Univ)

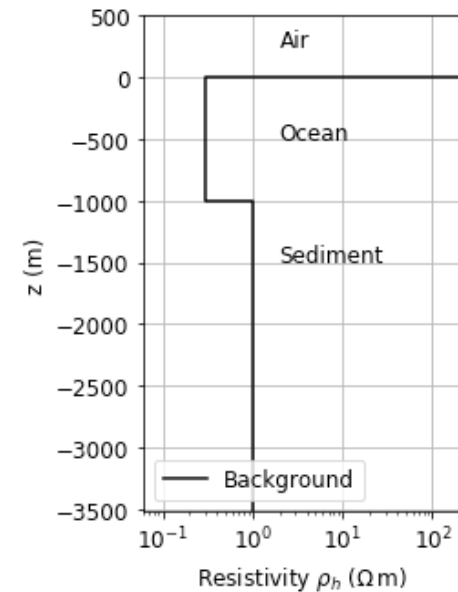


# Marine CSEM: Hydrocarbons

- Towed electric dipole streamer
  - Long offset range (500m-10 km)
  - Frequency: 0.5 Hz



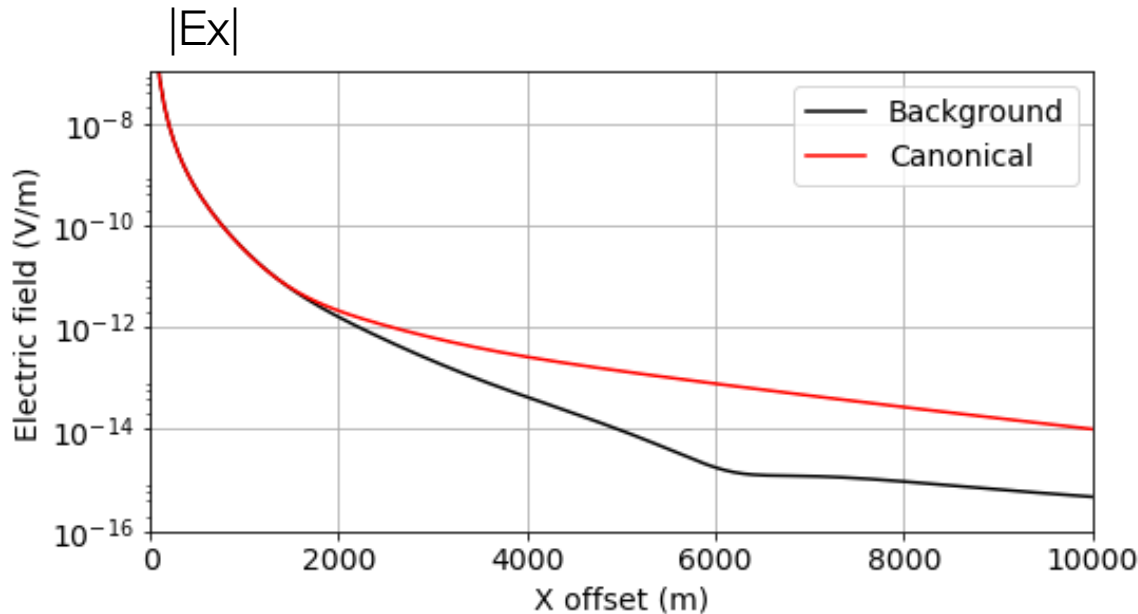
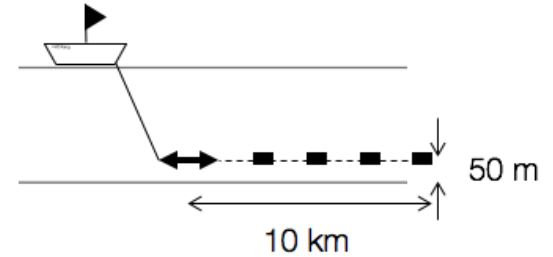
## Canonical model



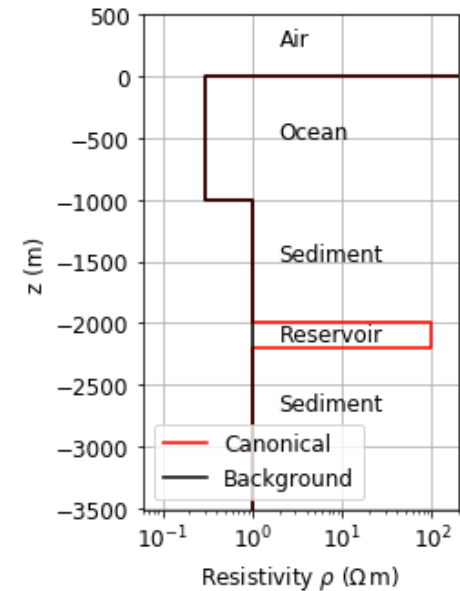


# Marine CSEM: Hydrocarbons

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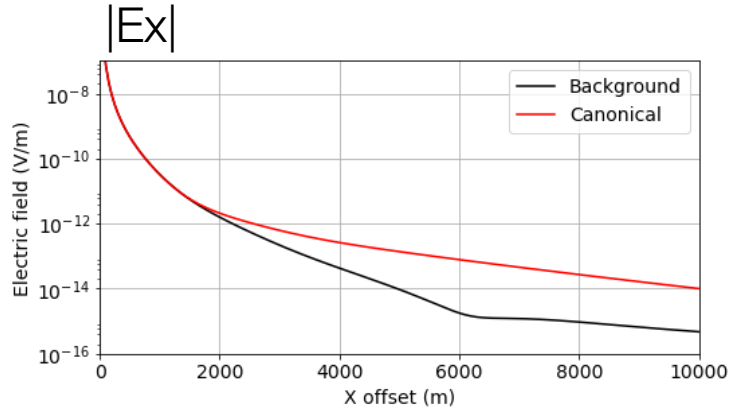
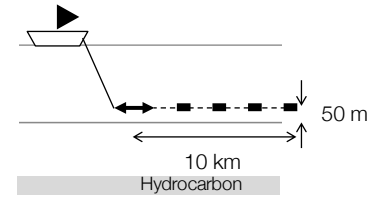


## Canonical model

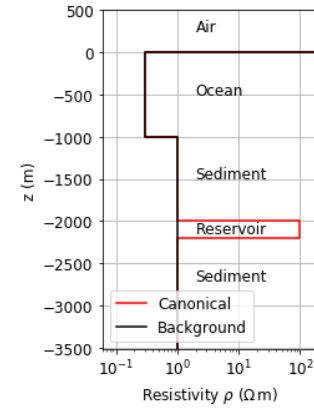


Hydrocarbon reservoir: significant signal  
How do we understand the response?

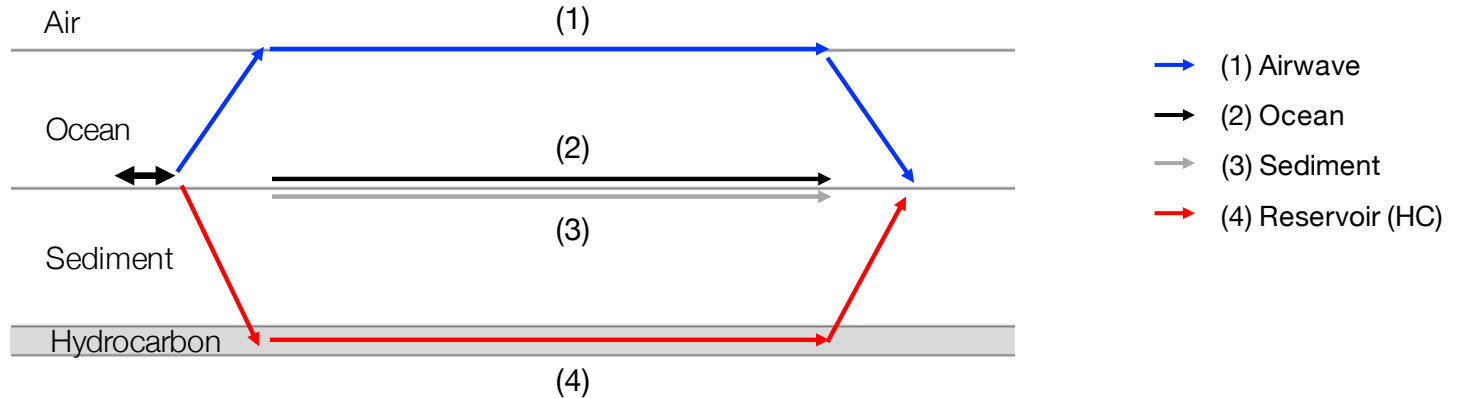
# Setup



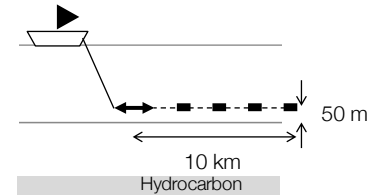
## Resistivity



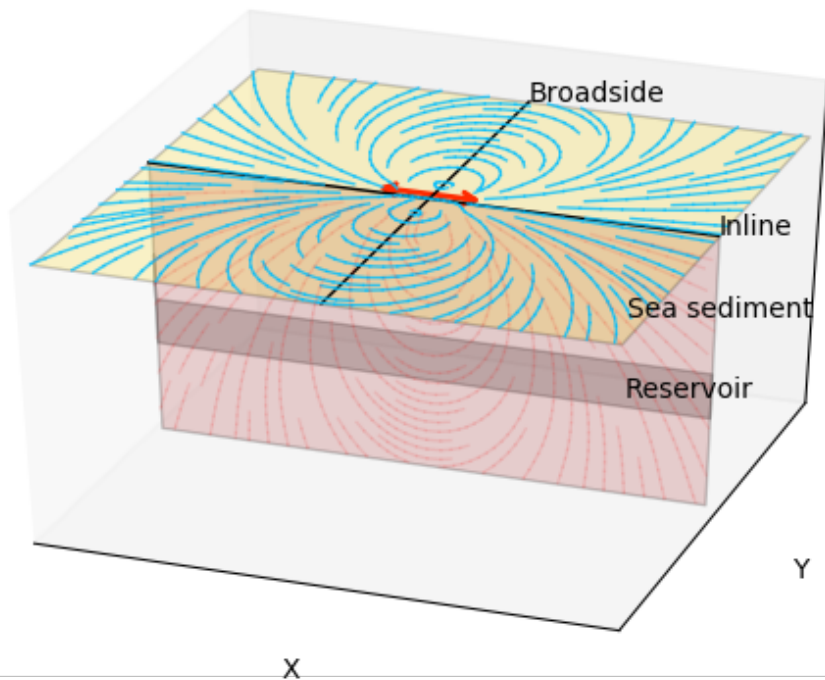
## Ray paths



# Which fields to examine?



Fields from a dipole

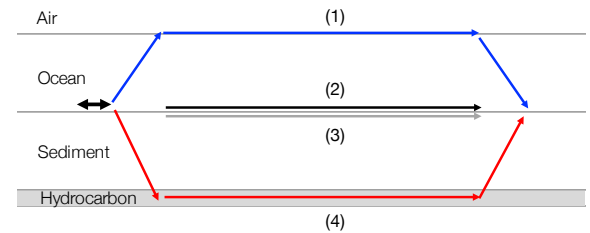


Focus on:

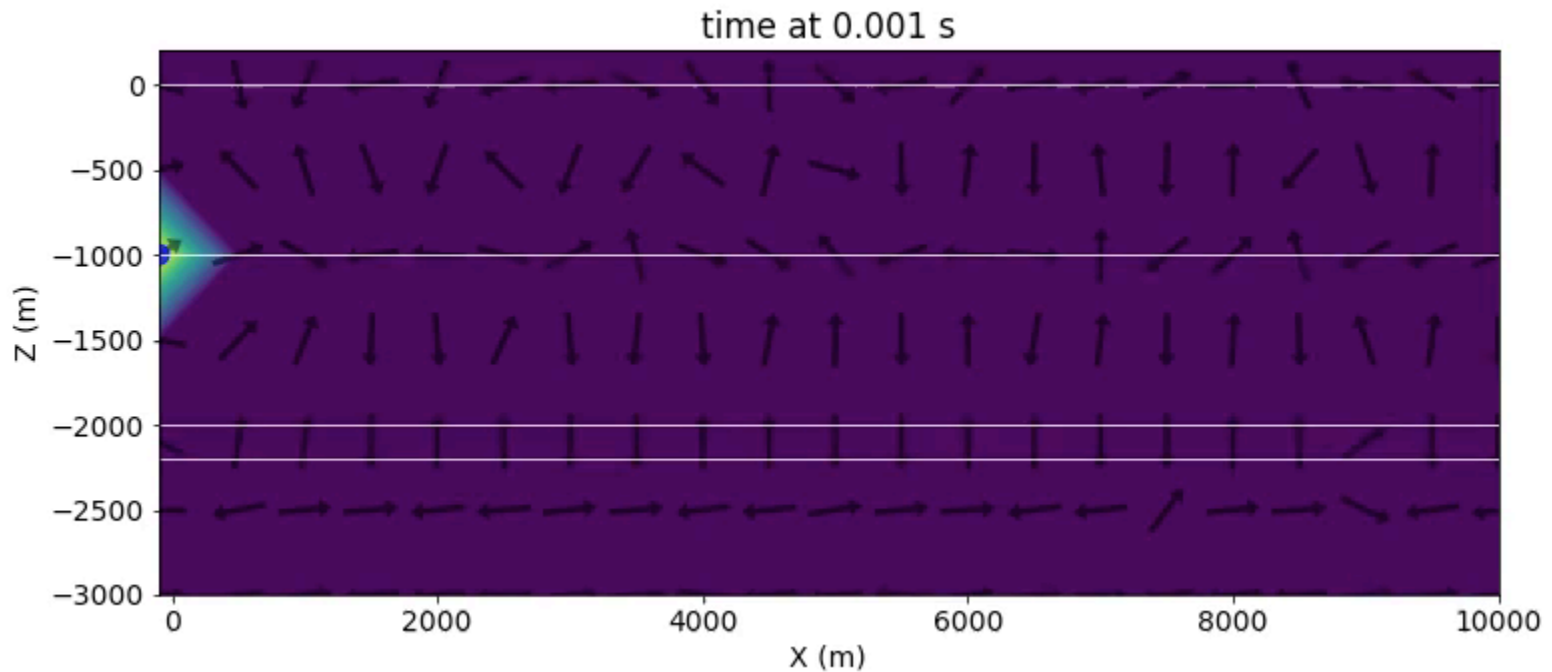
- Inline electric field
- Inline poynting vector (energy propagation)

$$\bar{\mathbf{S}} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B}$$

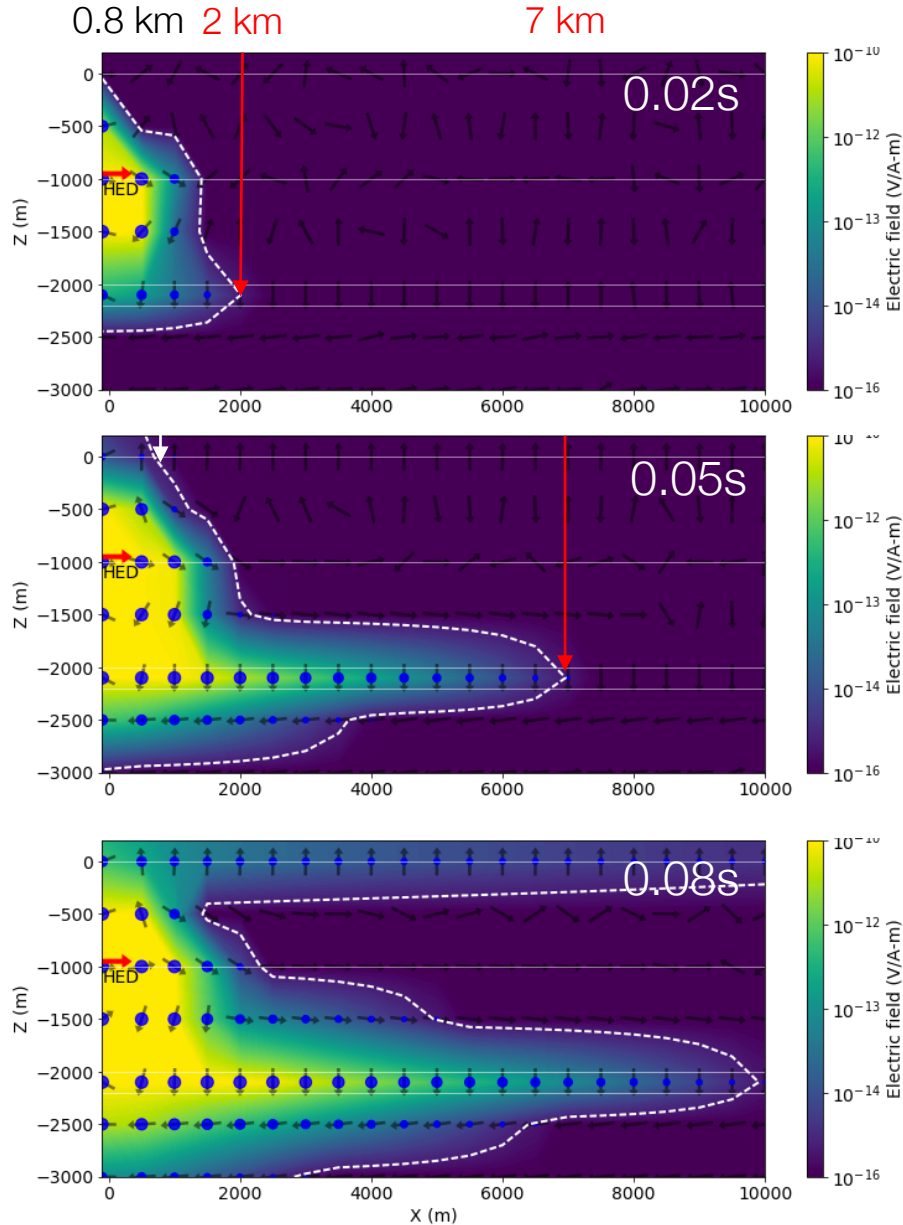
# Electric field



On XZ plane (HED source in x-direction)

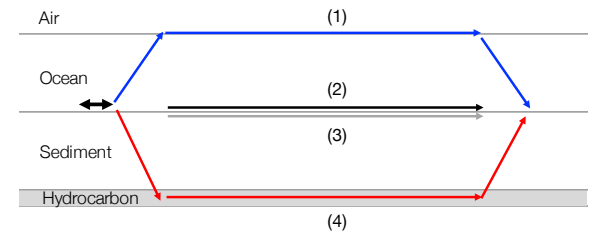


# Electric field at multiple times

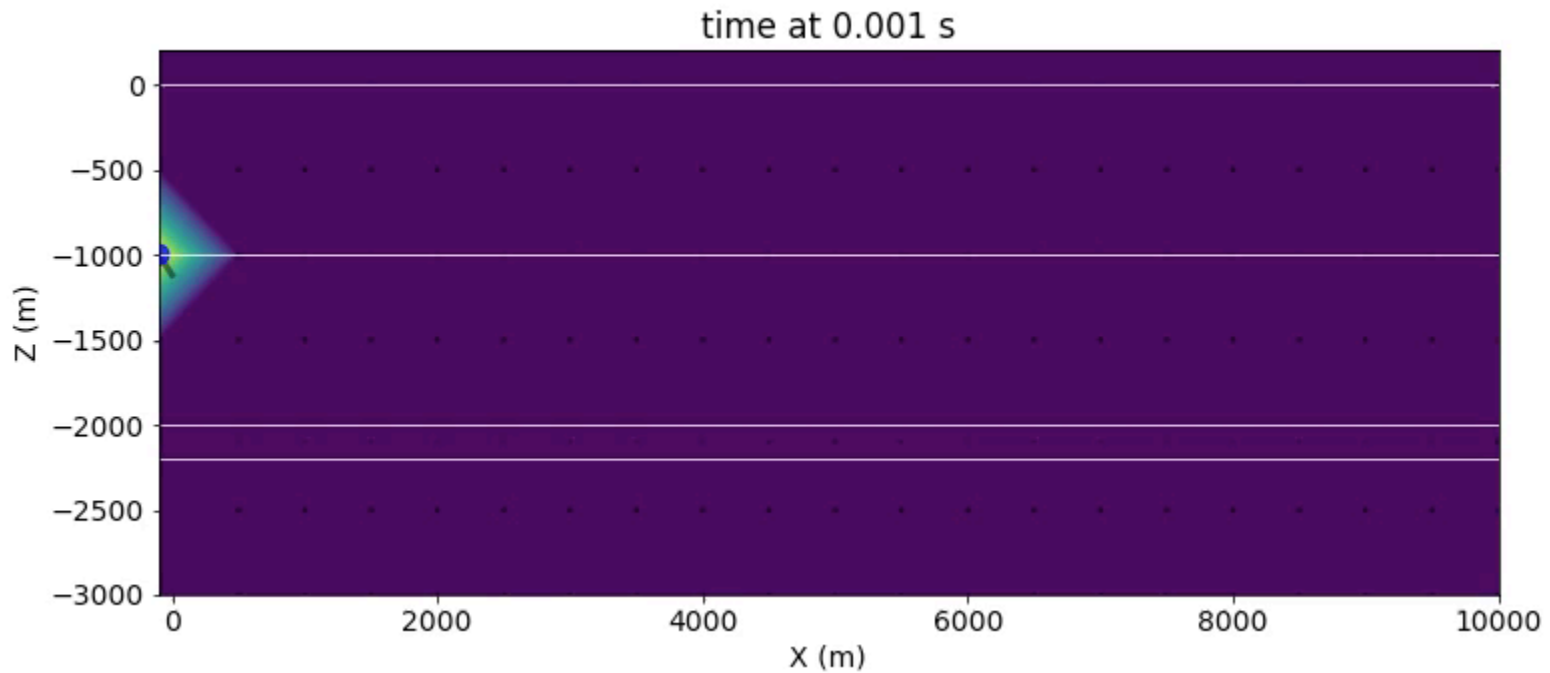


- In reservoir:  
 $5 \text{ km} / 0.03 \text{ s} = 166 \text{ km/s}$
- In air:  
 $> 10 \text{ km} / 0.03 = > 333 \text{ km/s}$
- Propagation much faster in air
- More attenuation in the reservoir

# Poynting vector



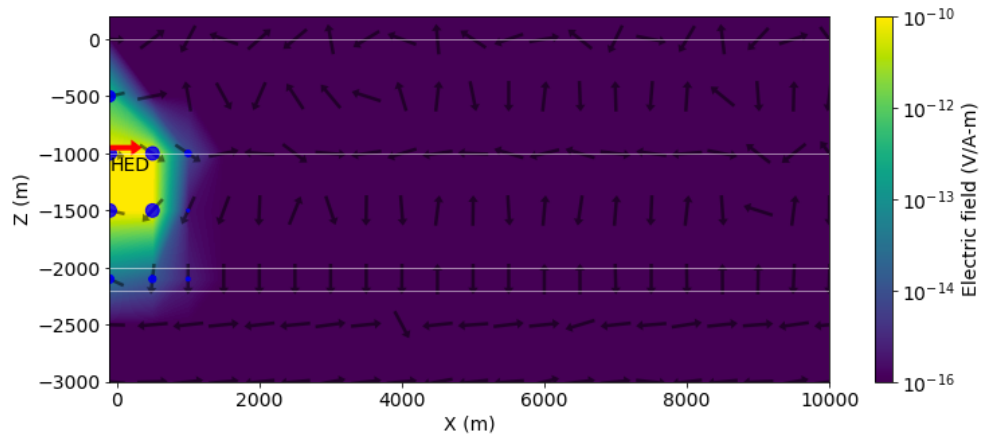
On XZ plane (HED source in x-direction)



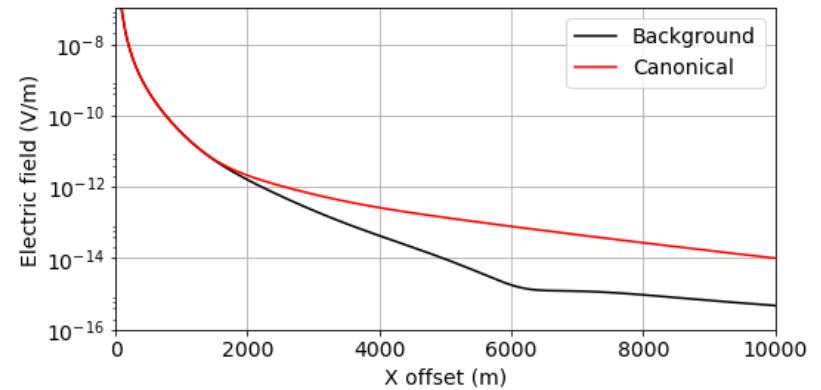
$$\text{Poynting vector: } \bar{\mathbf{S}} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B}$$

# Fields at time: 0.016s

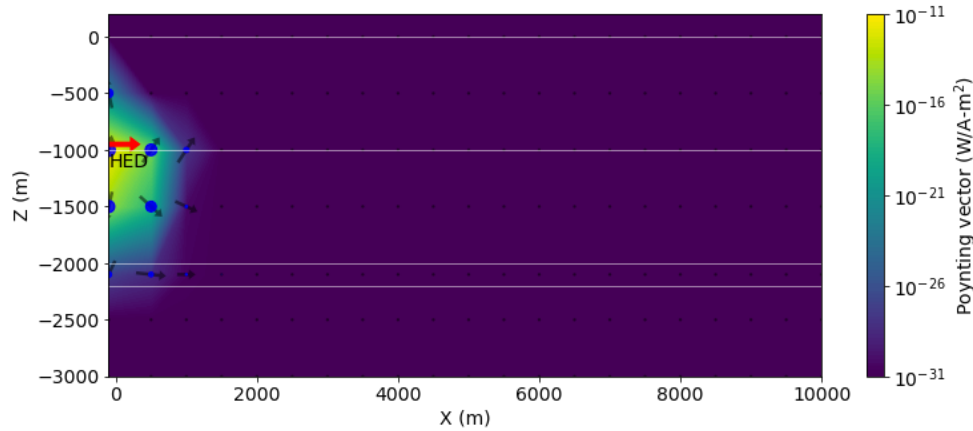
## E-field



## |Ex|



## Poynting vector

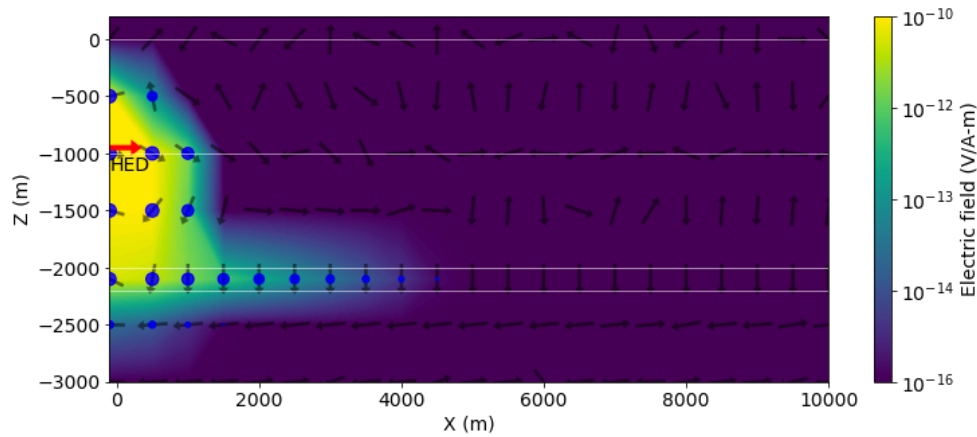


## Peak velocity

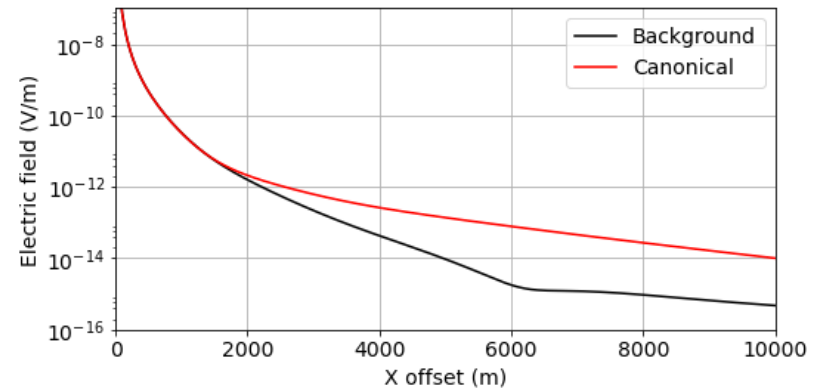
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

# Fields at time: 0.03s

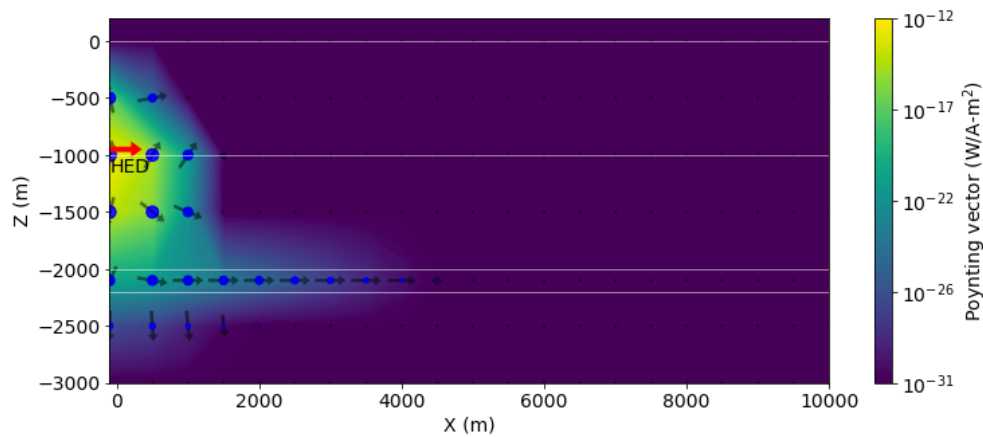
## E-field



## |Ex|



## Poynting vector



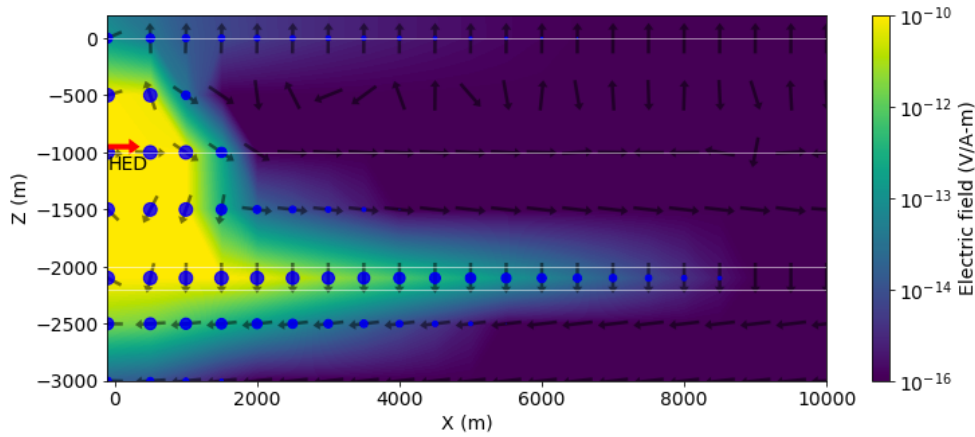
## Peak velocity

$$v = \sqrt{\frac{\rho}{2\mu t}}$$

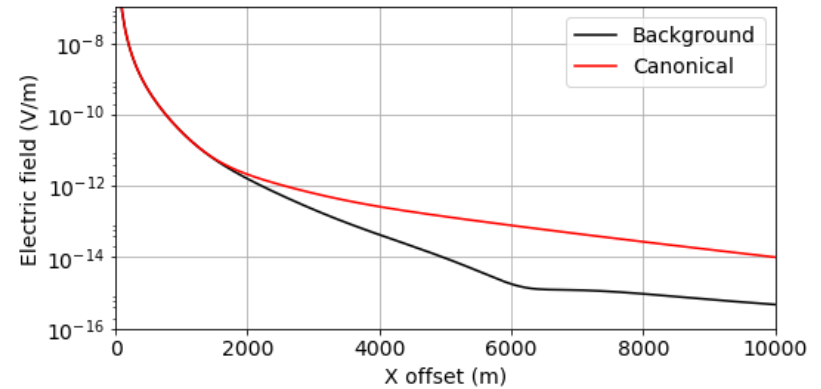


# Fields at time: 0.08s

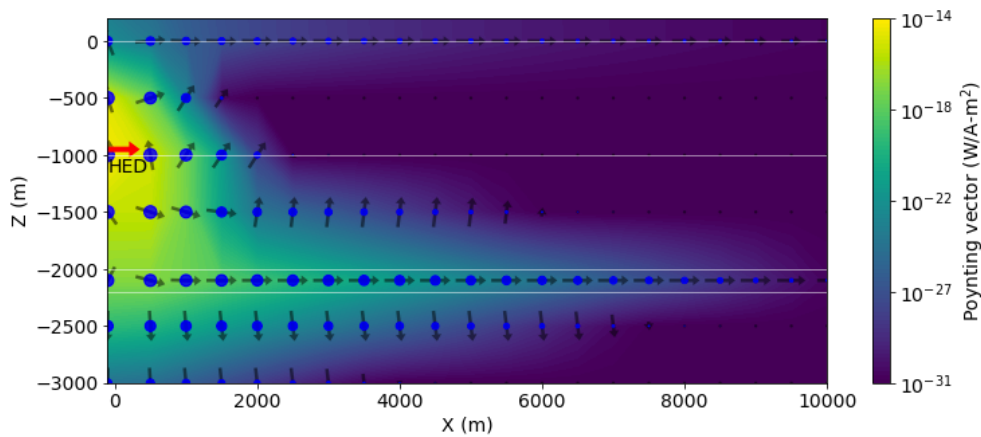
## E-field



## |Ex|



## Poynting vector

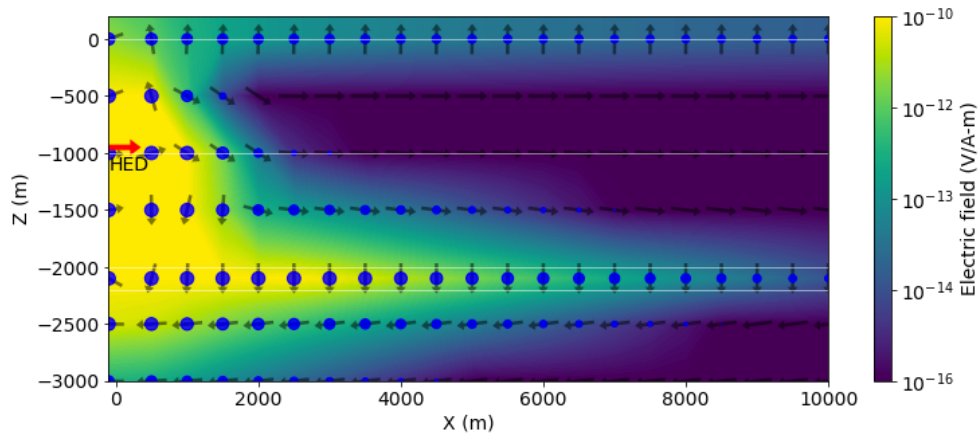


## Peak velocity

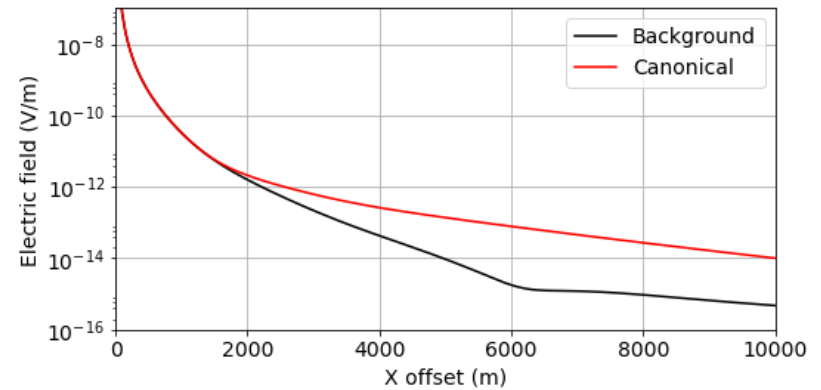
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

# Fields at time: 0.10s

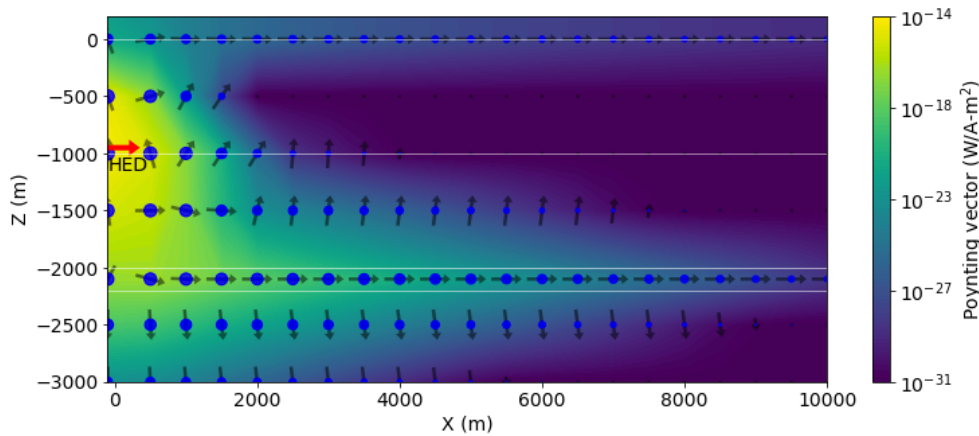
## E-field



## $|E_x|$



## Poynting vector

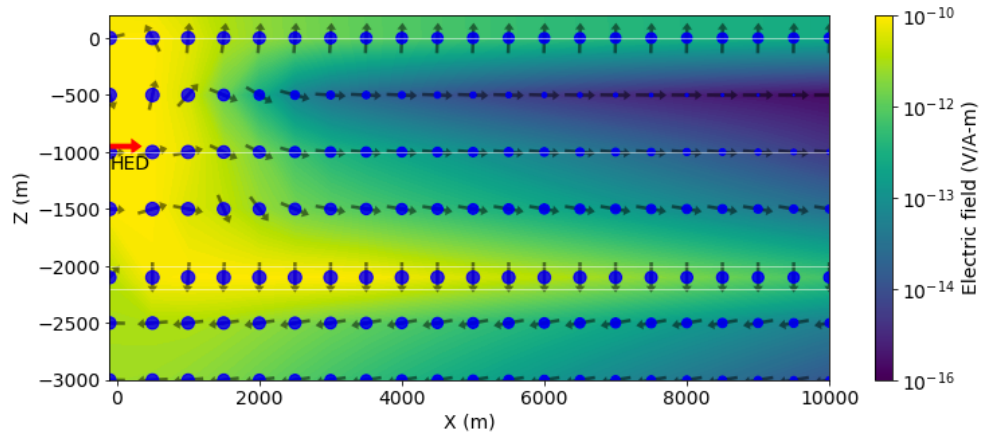


## Peak velocity

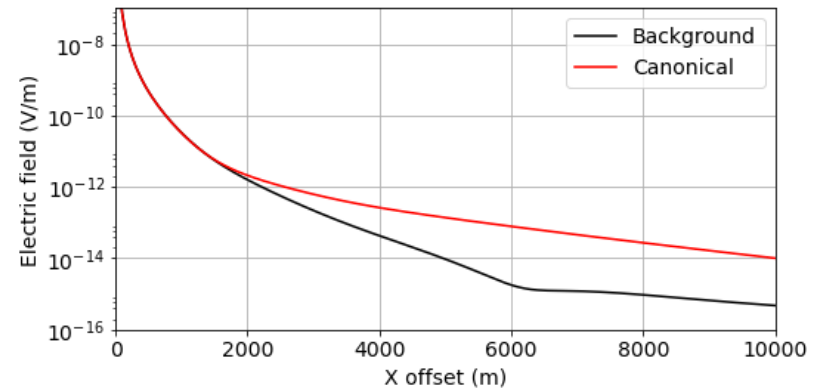
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

# Fields at time: 0.32s

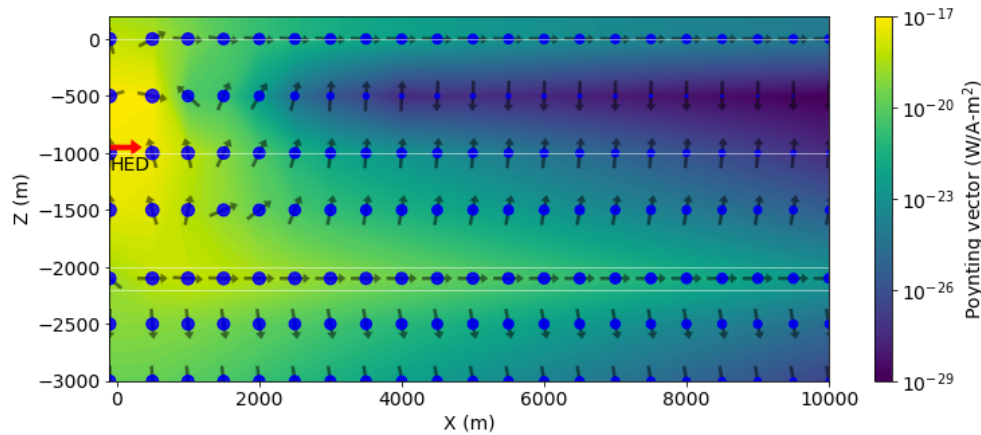
## E-field



## |Ex|



## Poynting vector

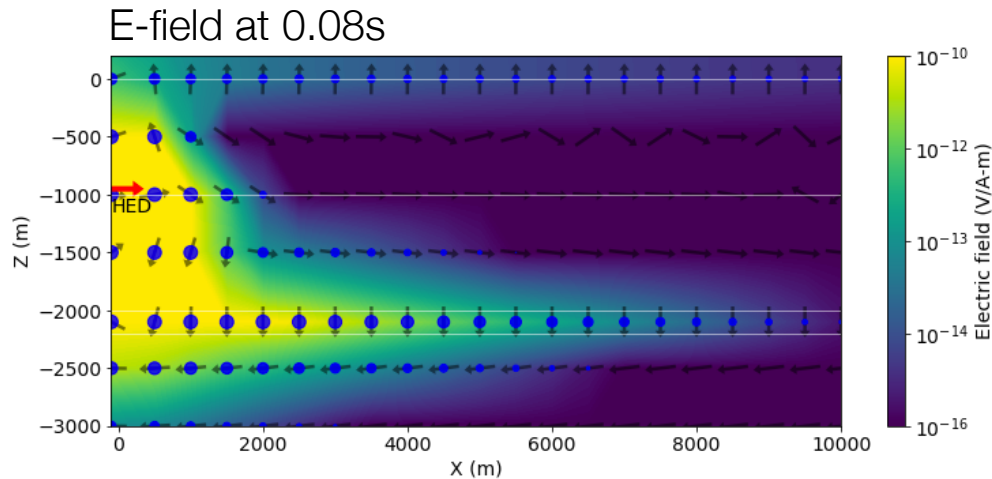


## Peak velocity

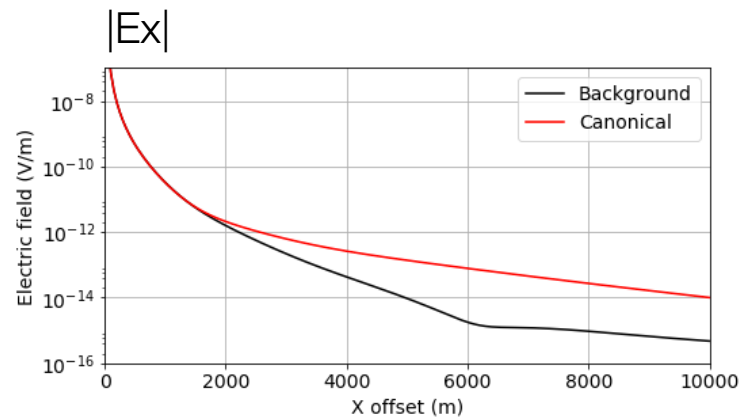
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

# Amplitude vs offset

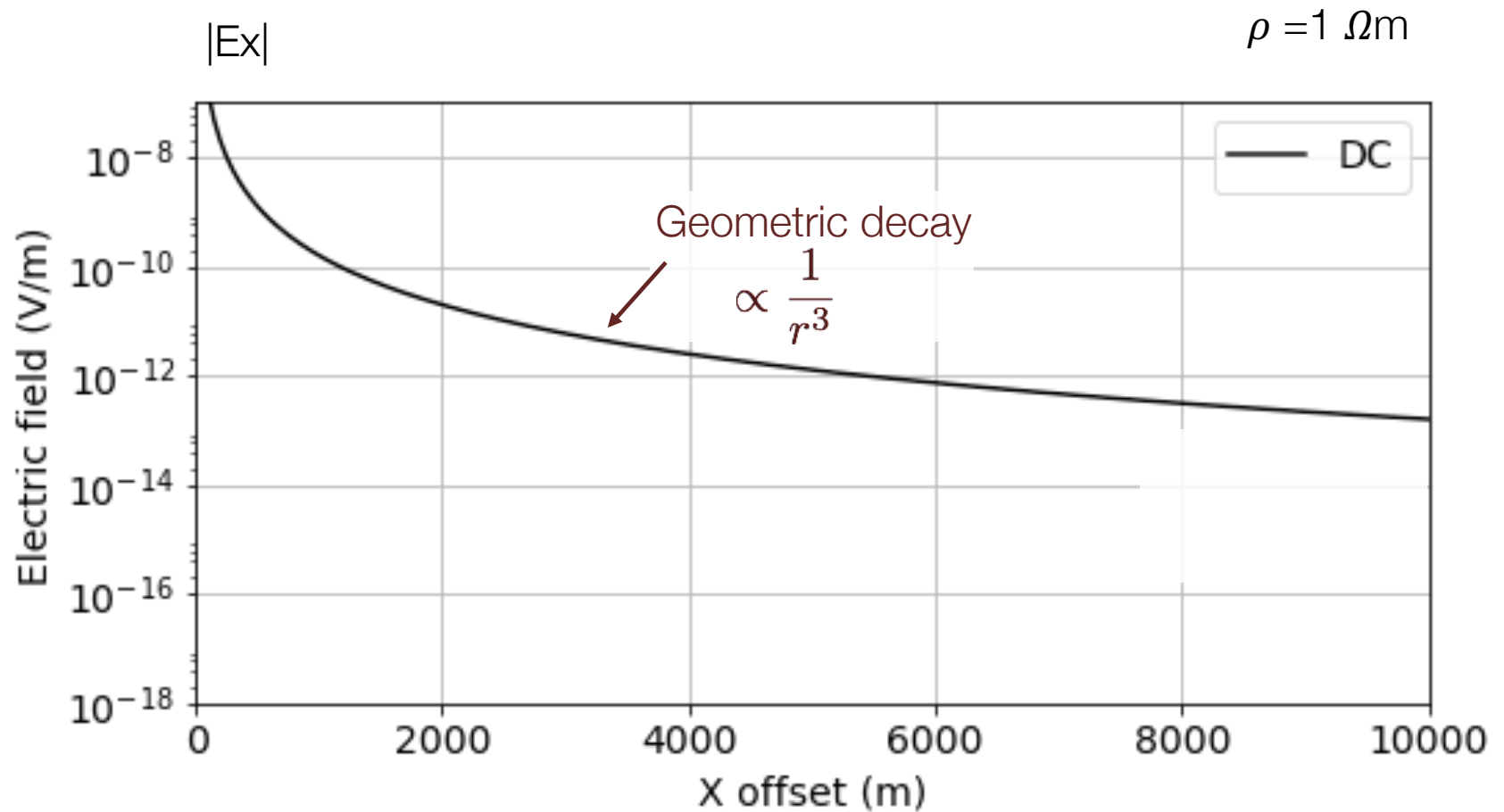
- Time snapshots tell us about
  - where energy is travelling
  - something about propagation speed



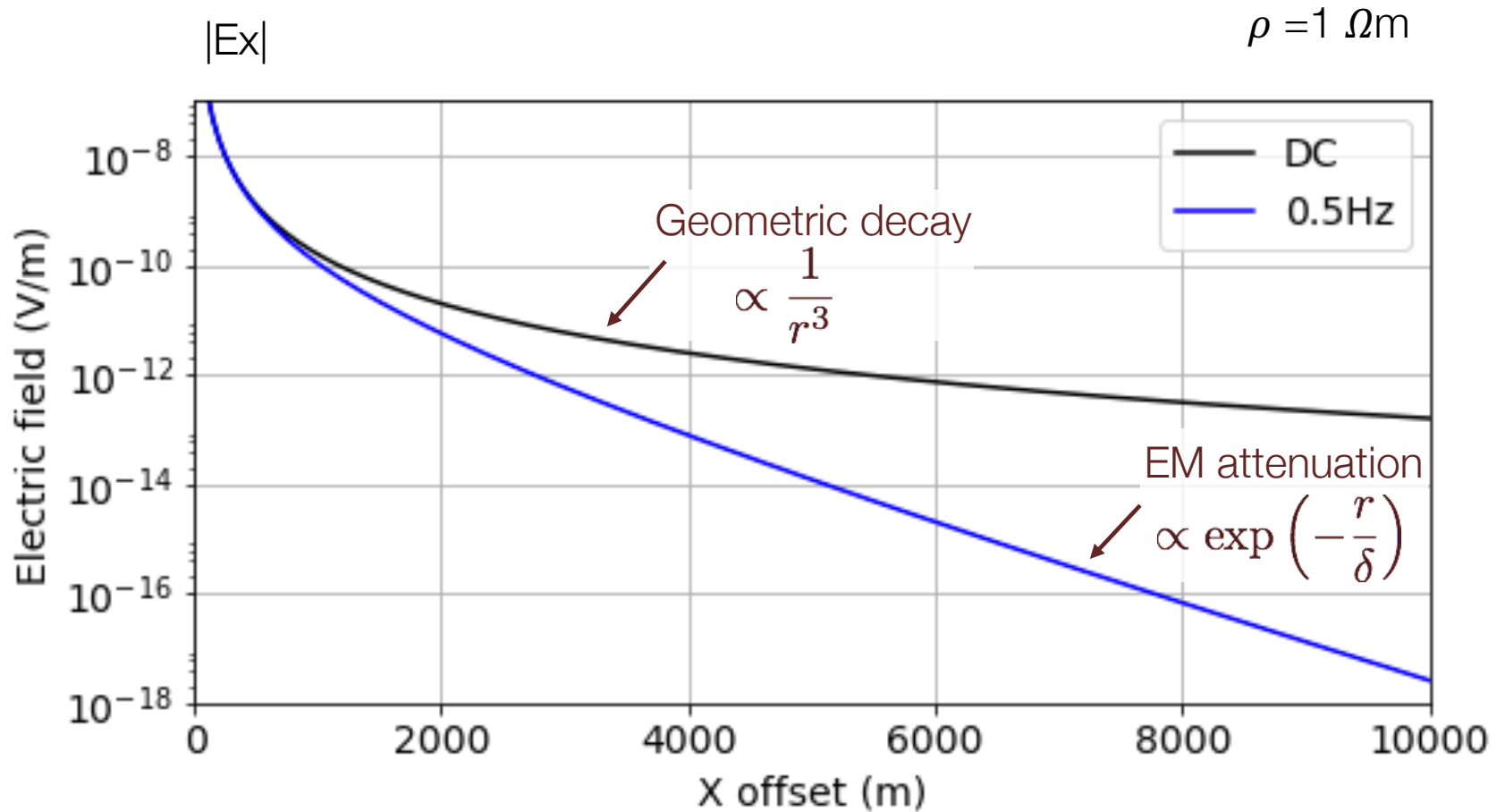
- What about amplitudes?
- Work in frequency domain



# Amplitude: Electric dipole in a wholespace

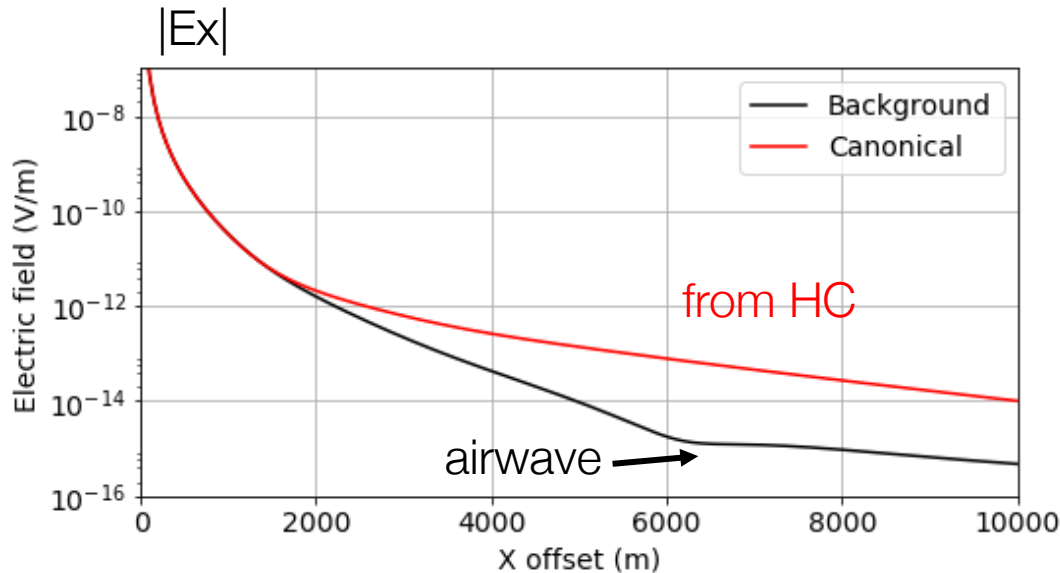
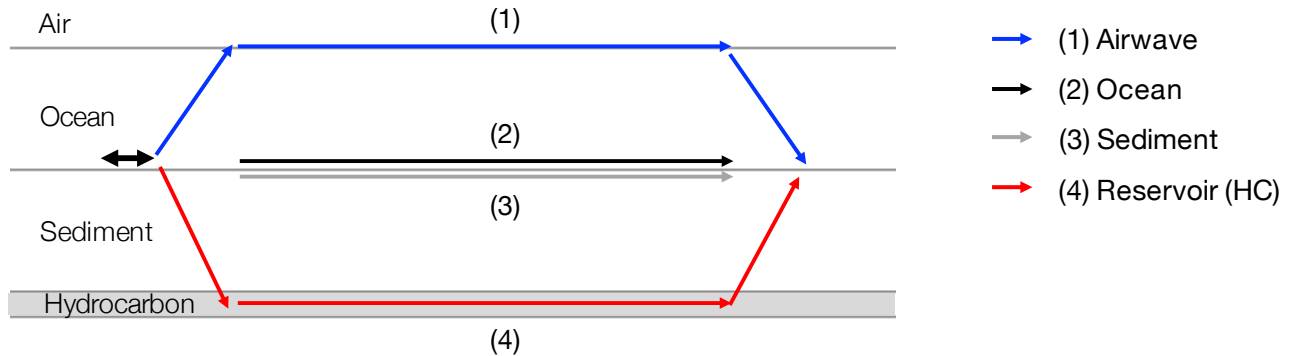


# Amplitude: Electric dipole in a wholespace



# Amplitude vs Offset

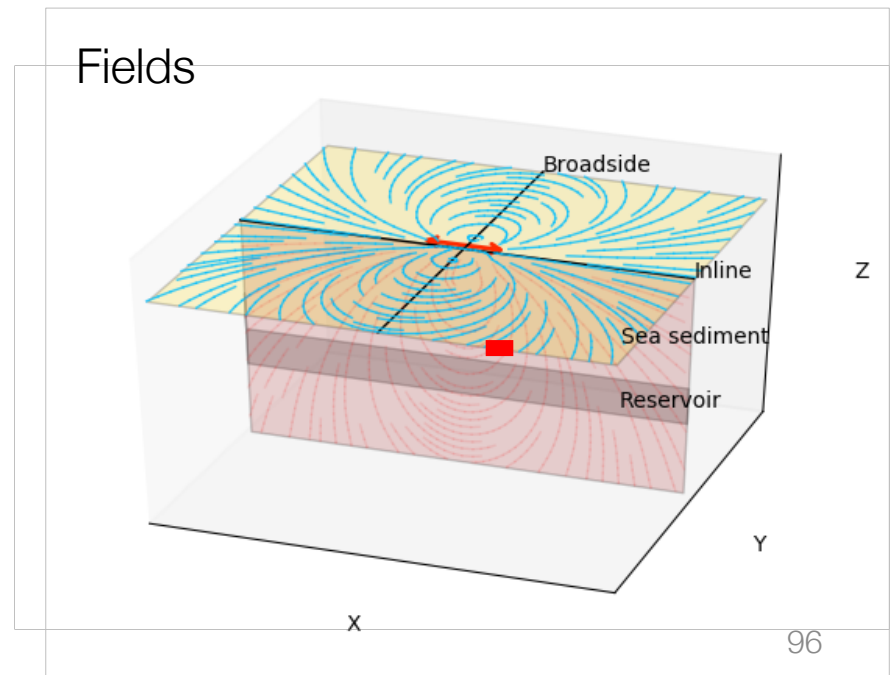
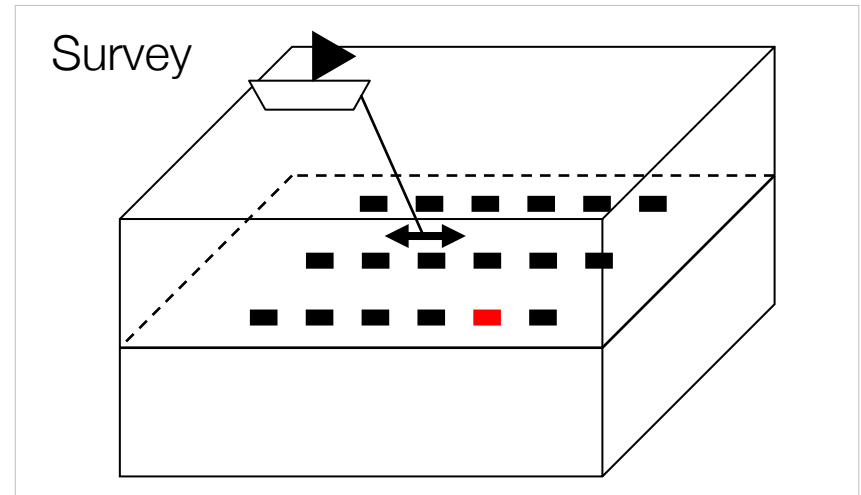
Ray paths



- Short offset (<2km):
  - geometric decay ( $1/r^3$ )
- Intermediate offset (2-6 km):
  - skin effects + HC
- Large offset (6-10 km):
  - airwave + HC

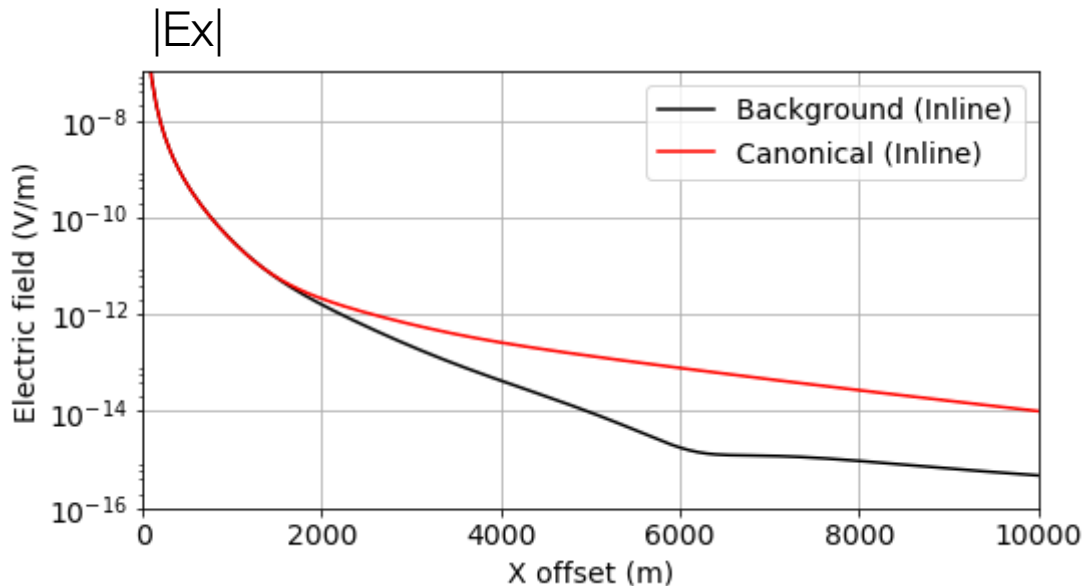
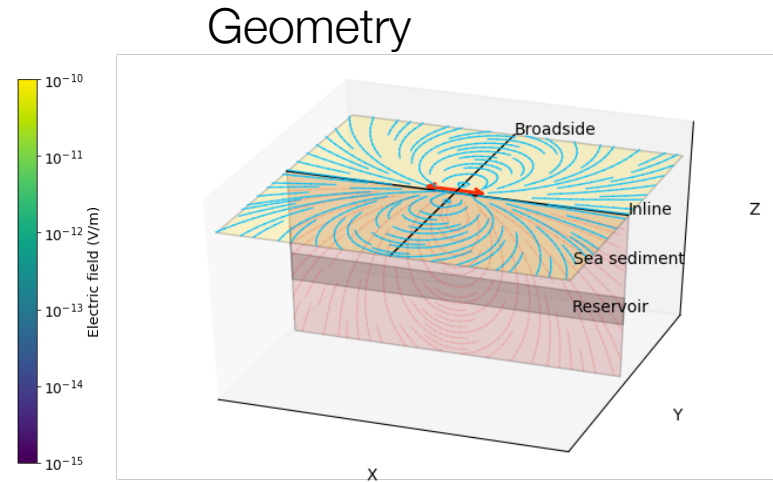
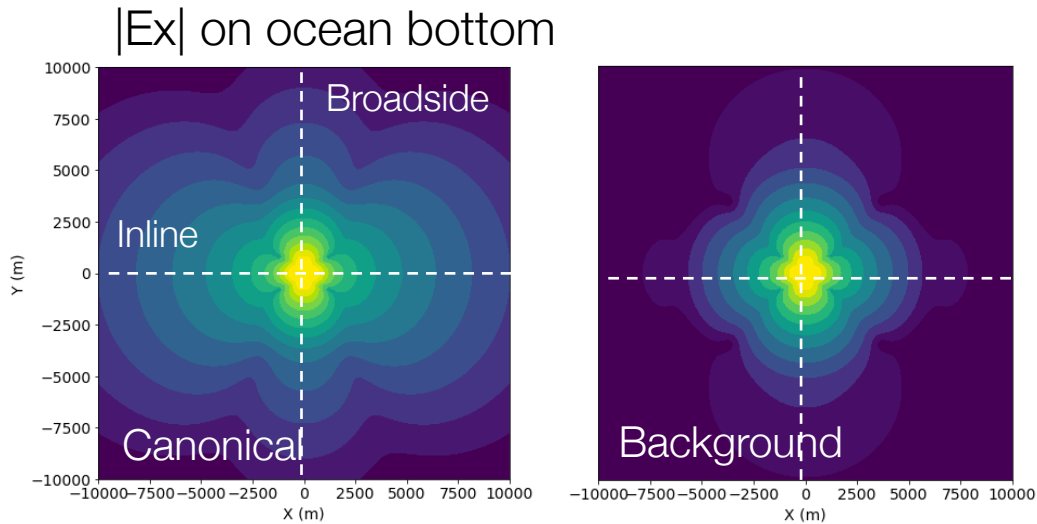
# General CSEM

- Fields are 3D: All three components exists
  - $E_x$ ,  $E_y$ ,  $E_z$
  - $B_x$ ,  $B_y$ ,  $B_z$
- Inline ( $E_x$ ,  $E_z$ ,  $B_y$ )
  - Electric field crosses the HC layer boundary
  - Galvanic dominates
- Broadside ( $E_x$ ,  $B_y$ ,  $B_z$ )
  - No vertical electric field (no charge build up)
  - Inductive dominates



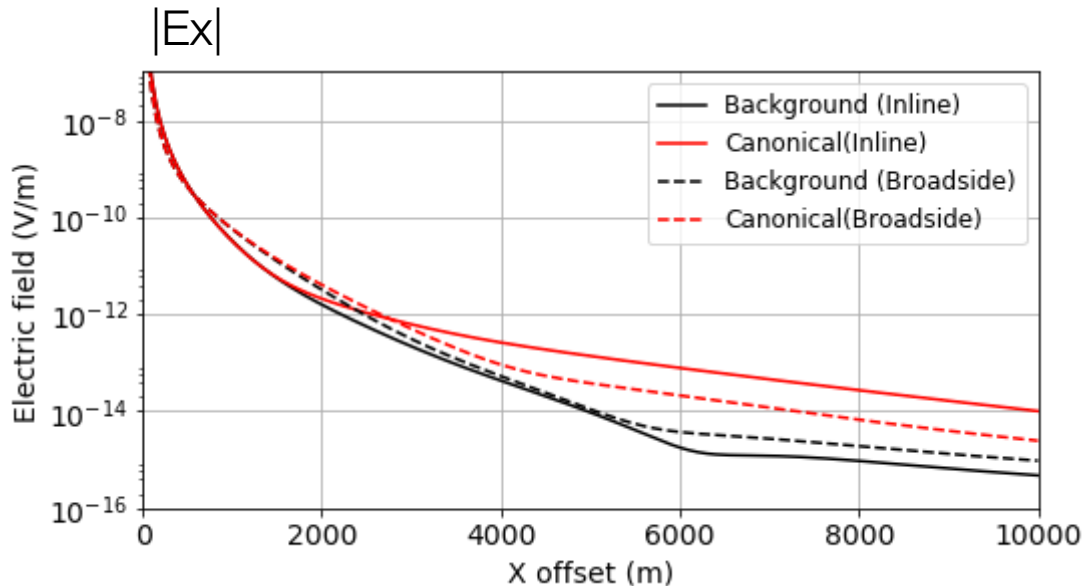
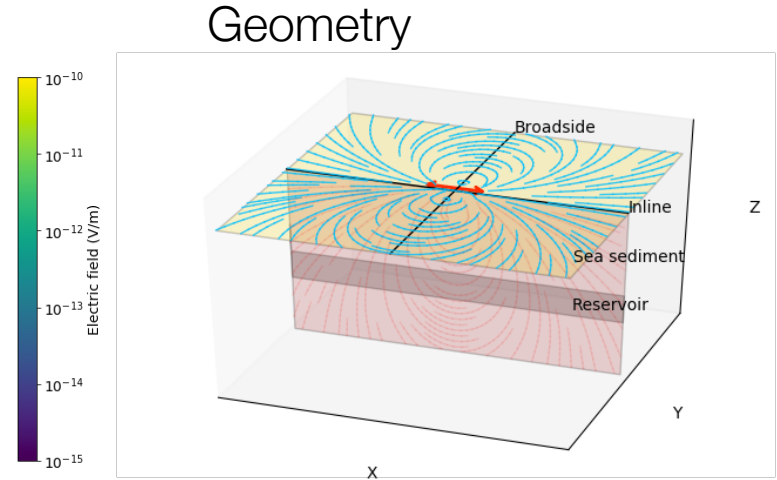
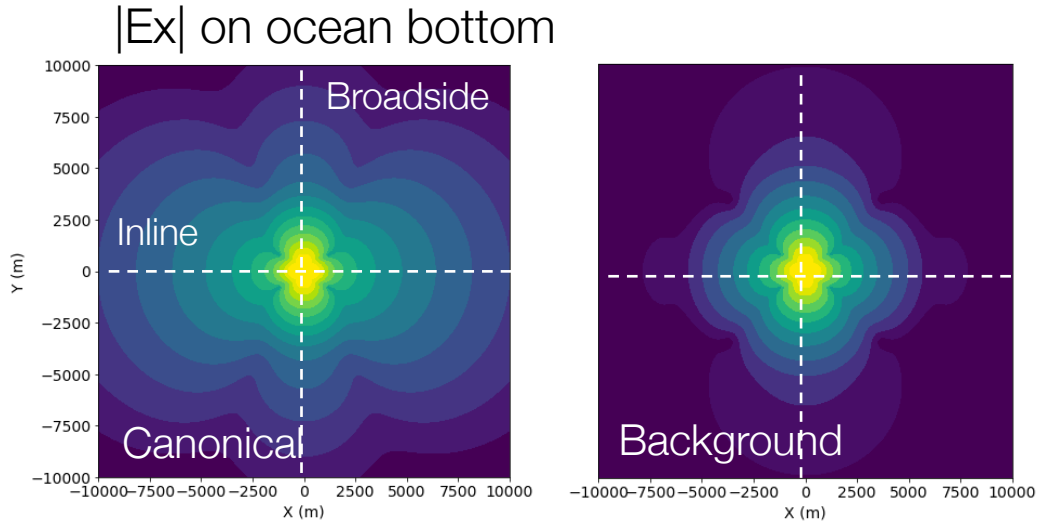


# Measured data: inline and broadside



- Inline  $|E_x|$ 
  - Significant signal from reservoir

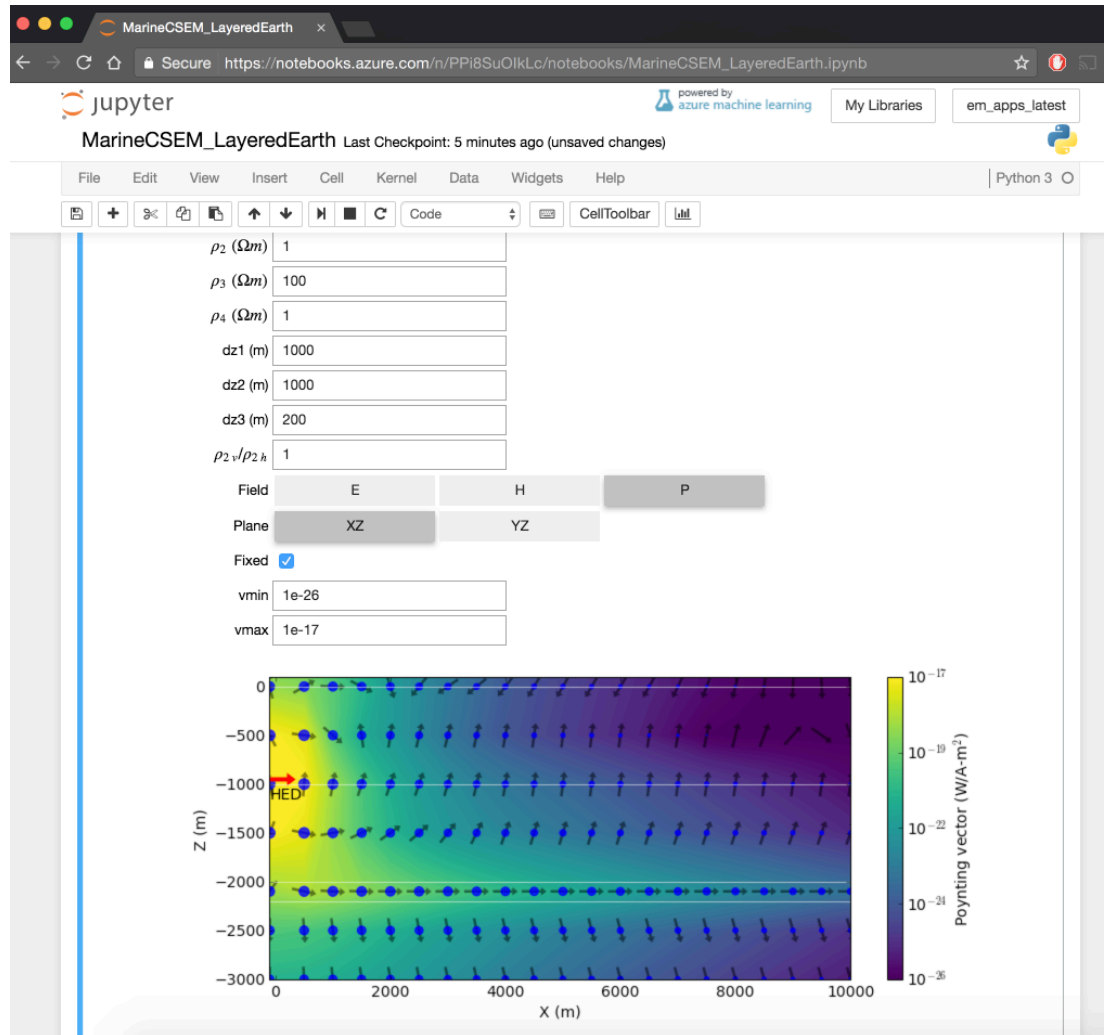
# Measured data: inline and broadside



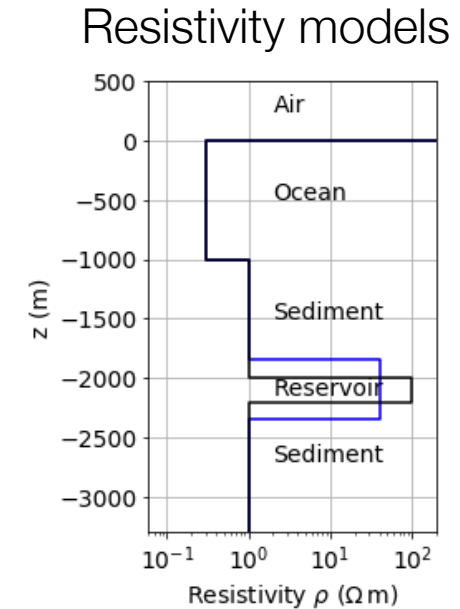
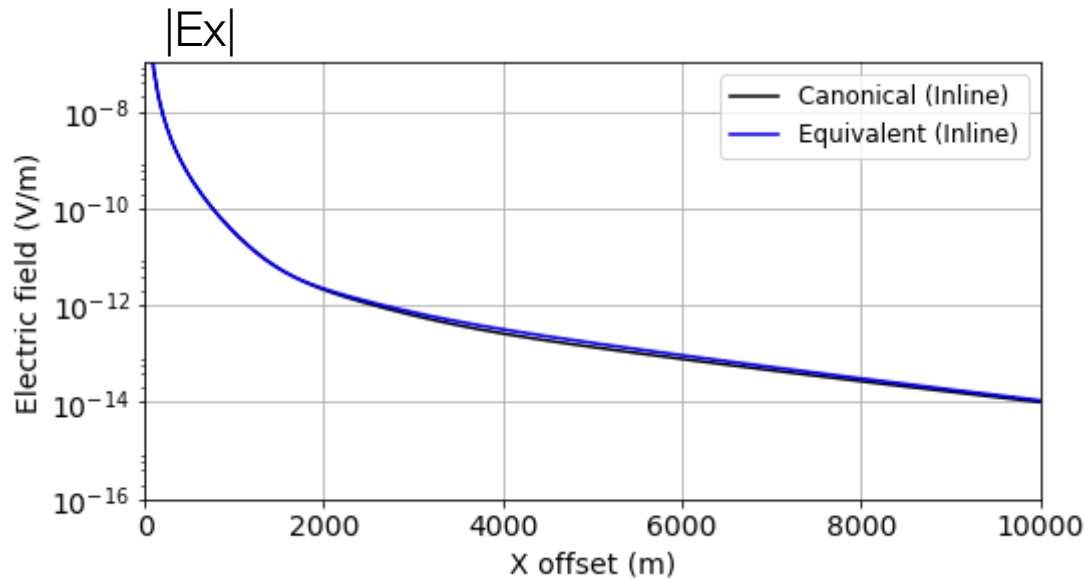
- Inline  $|E_x|$ 
  - Significant signal from reservoir
- Broadside  $|E_x|$ 
  - Anomaly is smaller than inline

# Marine CSEM App

- Simulate Marine CSEM
  - 4 layers
  - E, H Fields
  - Poynting vector

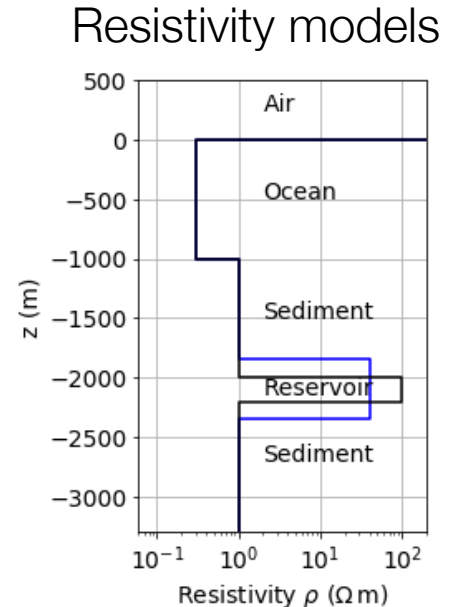
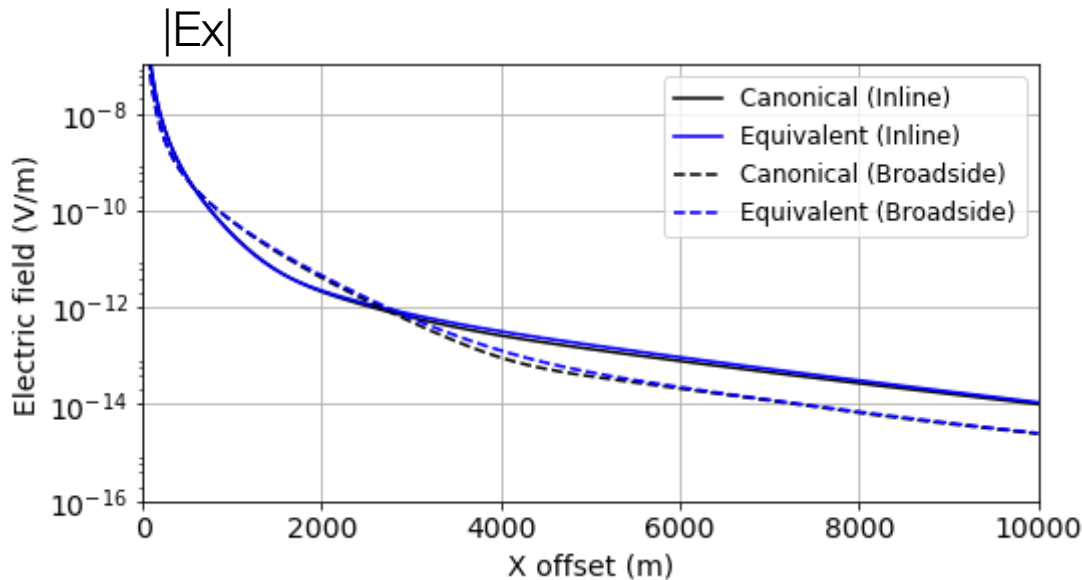


# Equivalence: resistivity-thickness product



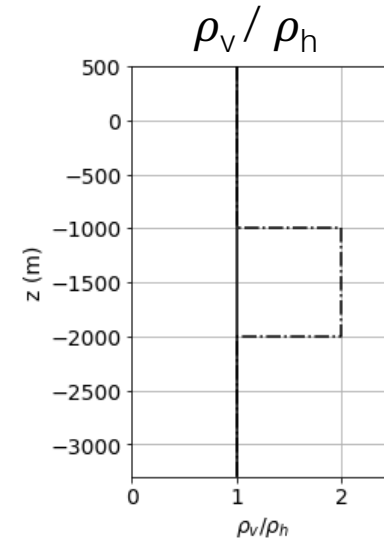
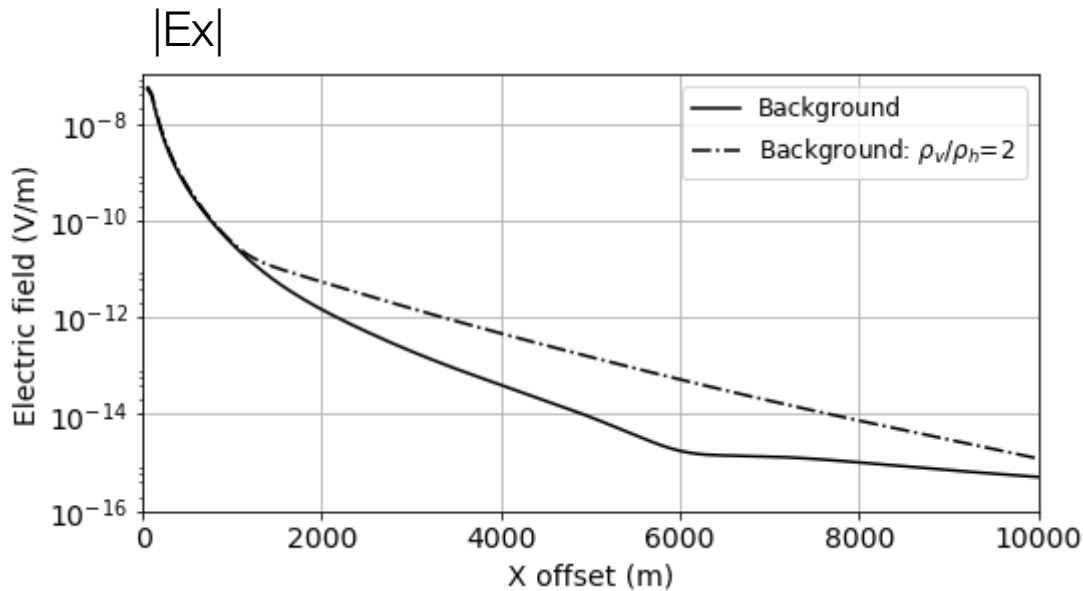
- Electric fields are sensitive to resistivity-thickness product
- Reduce non-uniqueness with better data coverage, more components, other information (e.g. seismic)

# Equivalence: resistivity-thickness product

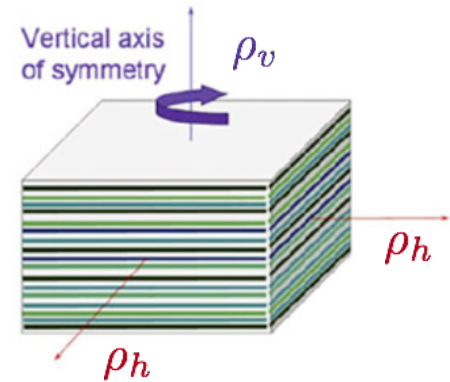


- Electric fields are sensitive to resistivity-thickness product
- Reduce non-uniqueness with better data coverage, more components, other information (e.g. seismic)

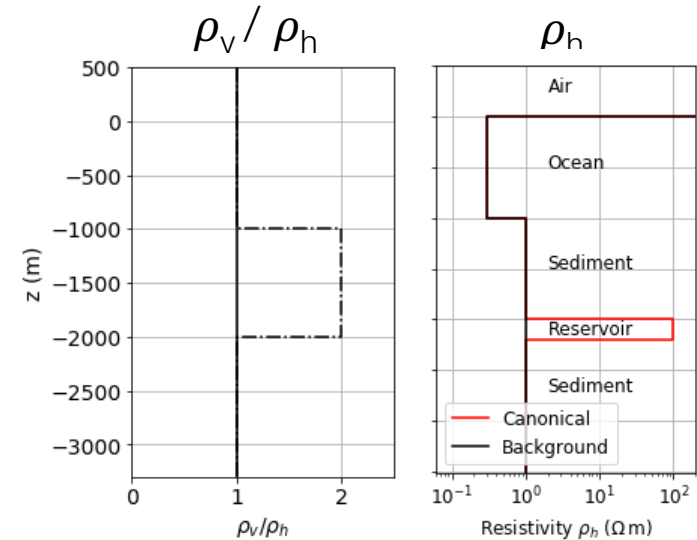
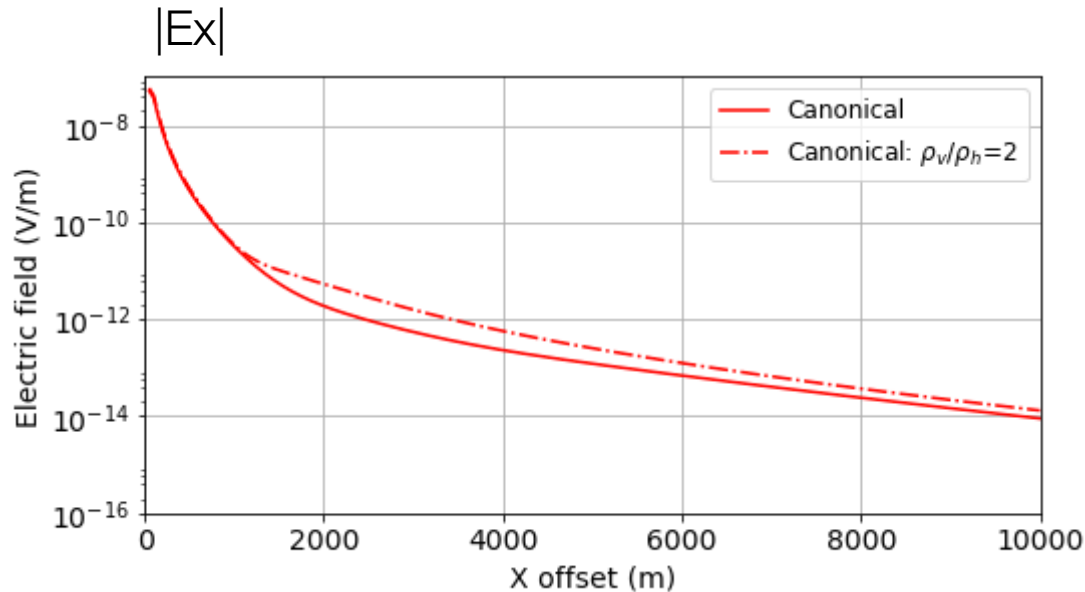
# Anisotropy



- Sediment could have vertical anisotropy
- $\rho_v > \rho_h$  :  $|E_x|$  larger at far offsets

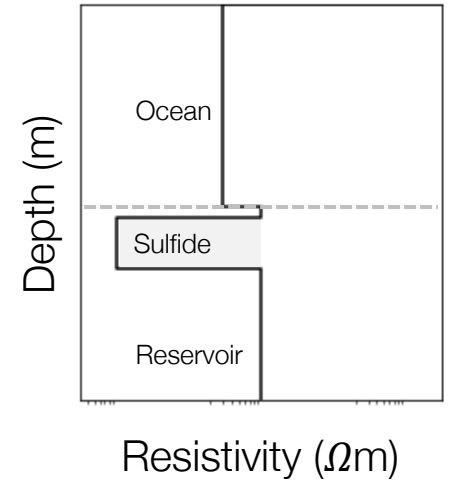
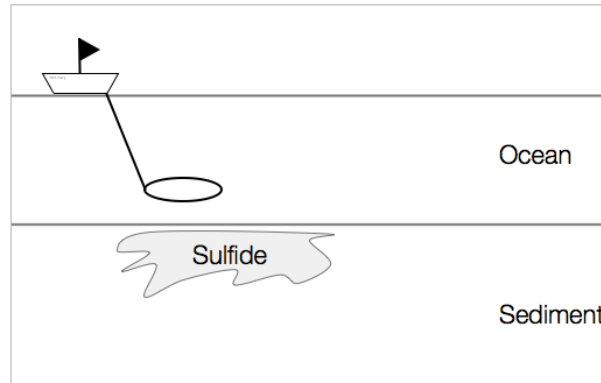
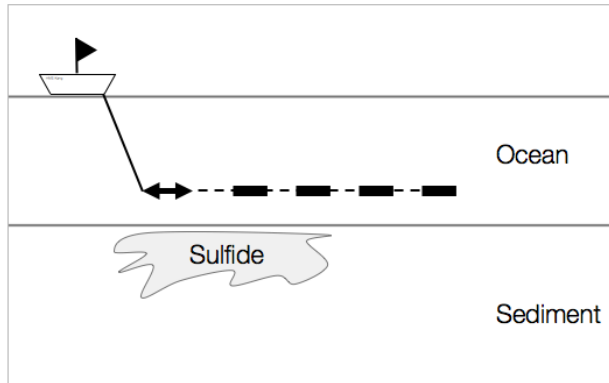


# Anisotropy



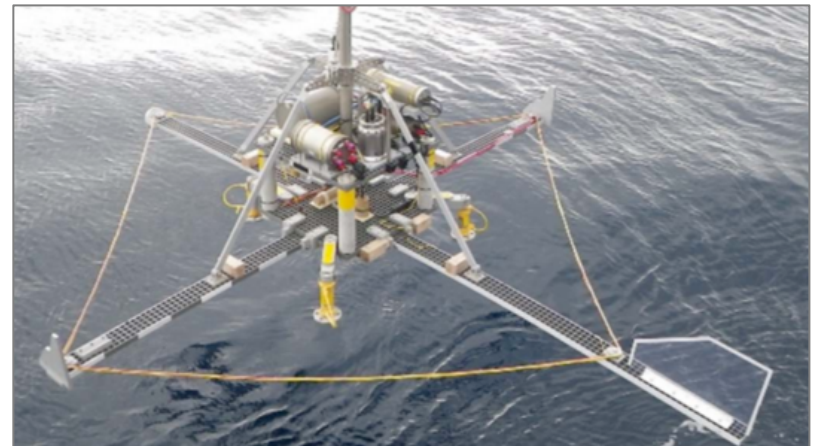
- Significant impact to signal from reservoir
  - need to account for this when interpreting marine CSEM data

# Finding conductors



Source: towed

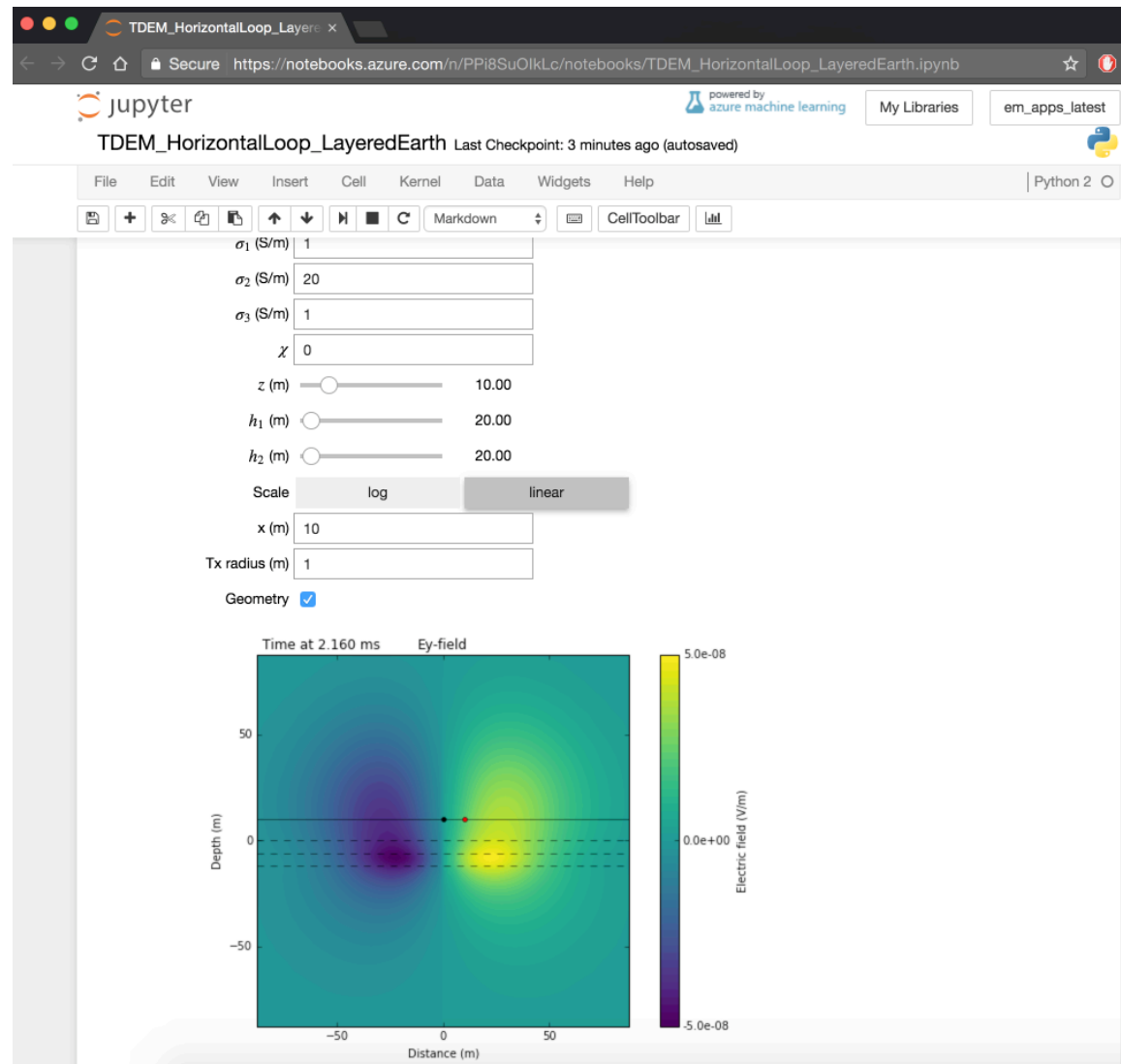
- Galvanic source
- Inductive source
- Receivers: (towed)
  - E-field
  - B-field





# TDEM Horizontal Loop App

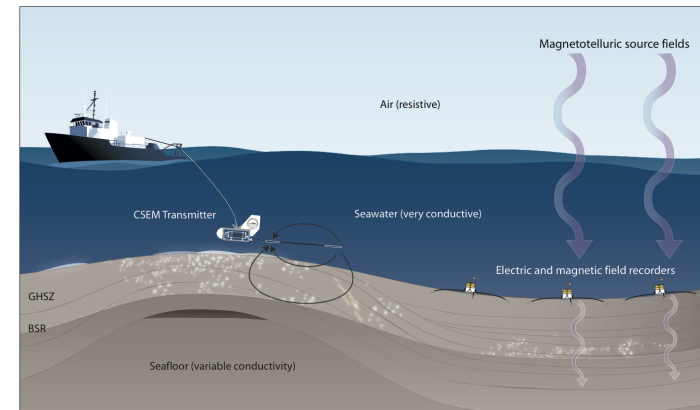
- TDEM
  - 4 layers
  - Fields, currents
  - Plot time decays



# Summary

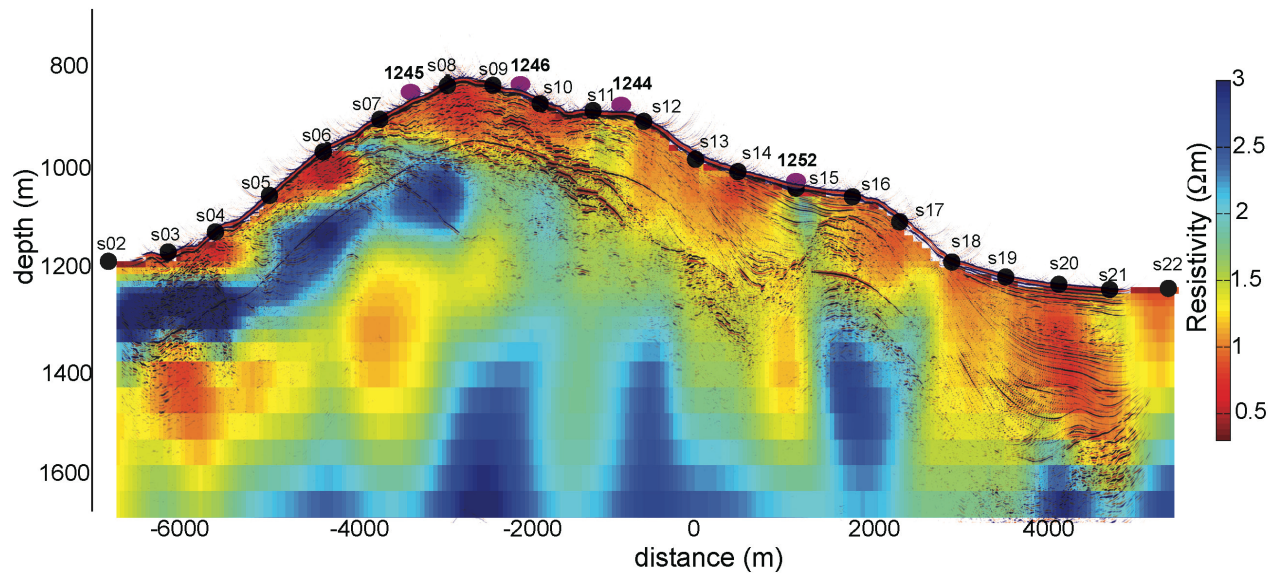
- Generic CSEM survey
- Wave and energy propagation
- Transmitters: galvanic or inductive
- Receivers: E-field, B-field: fixed or moving
- Canonical hydrocarbon example
- Useful for finding conductors or resistors
  - Hydrocarbons
  - Gas hydrate
  - Sea floor massive sulfides
  - Sea floor UXO
  - Near surface geologic structure
  - Fresh water aquifers

Case History: Gas Hydrates

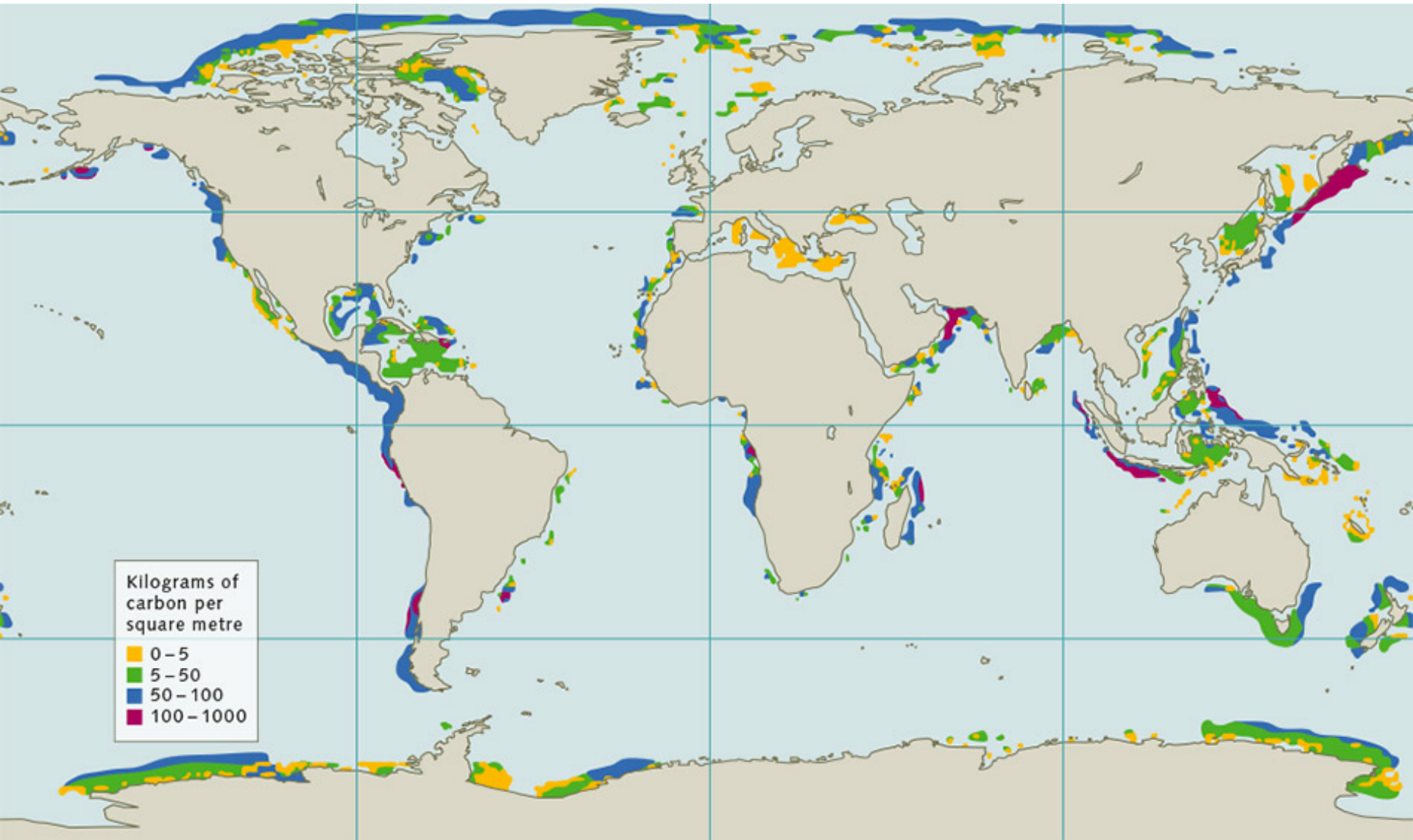


# Case History: Hydrate Ridge offshore Oregon, USA

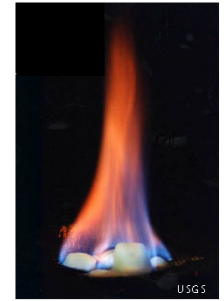
Weitemeyer et al. 2011



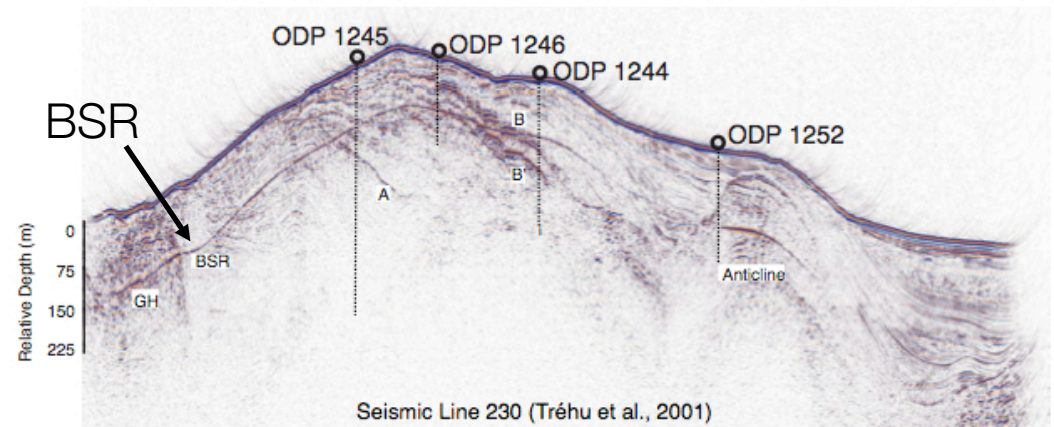
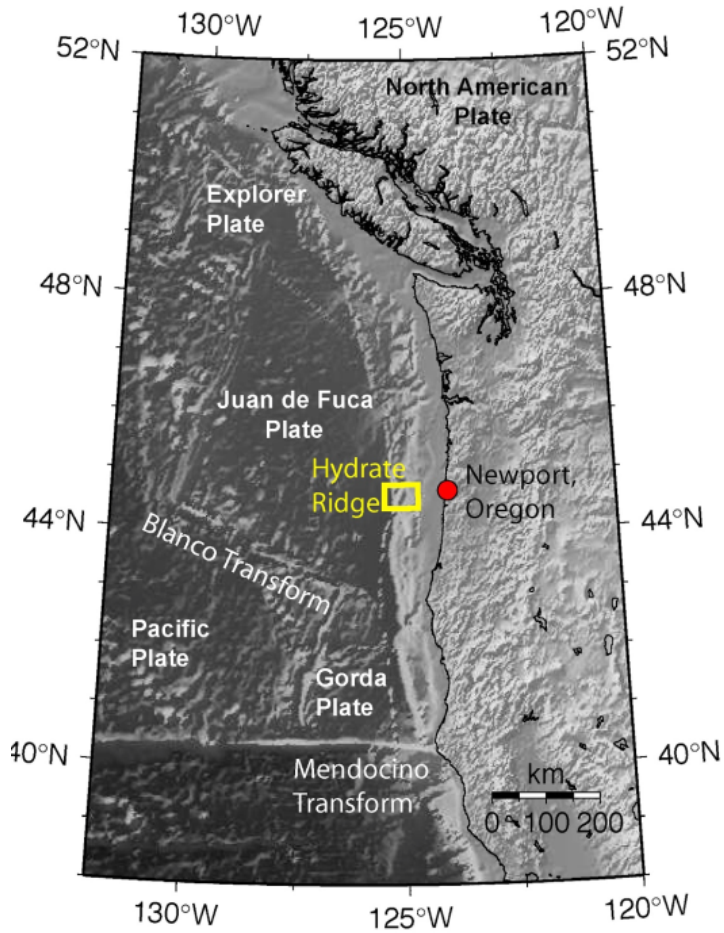
# Methane Hydrates



# Setup



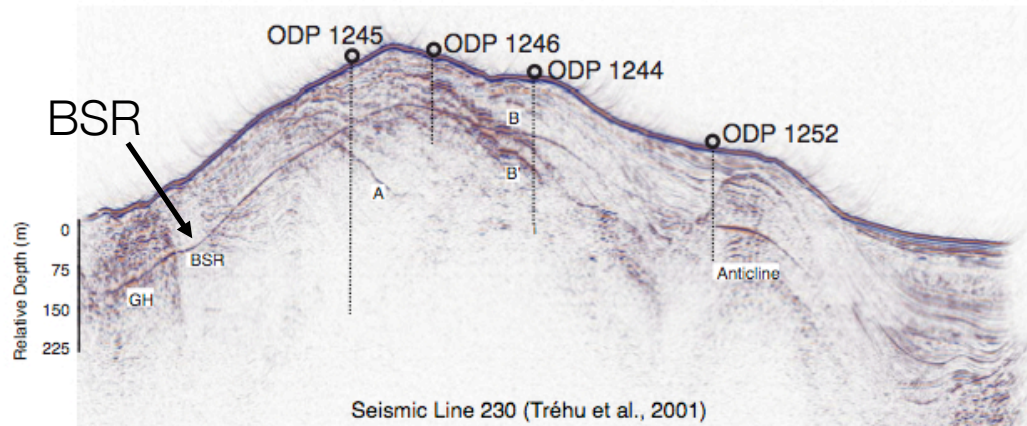
## Hydrate Ridge, offshore Oregon



- On the accretionary complex of the Cascadia subduction zone
- Bottom simulating reflector (BSR)
  - Obtained from seismic reflection data
  - Acoustic impedance contrast between hydrate and free gas

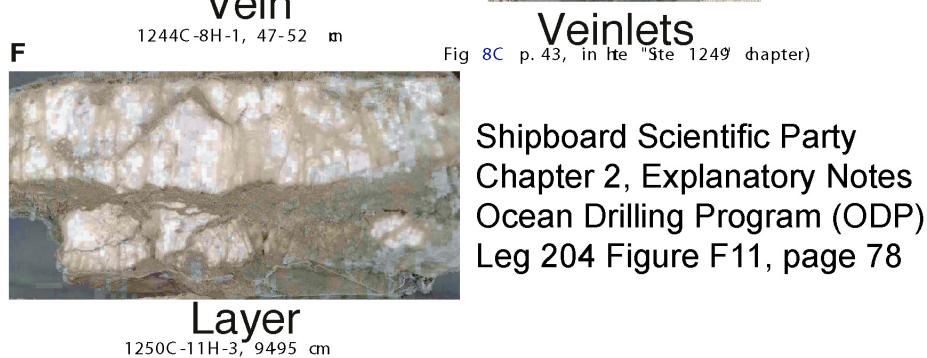
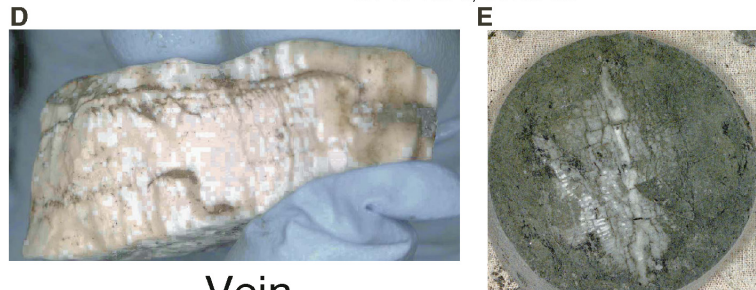
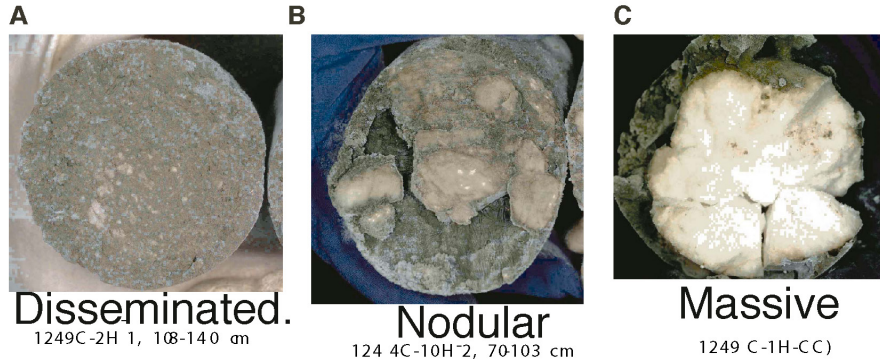
# Questions

- Can existing marine CSEM techniques be adapted to map methane hydrates?
- Can resistive regions identified by CSEM be corroborated with other geophysical and geological data?



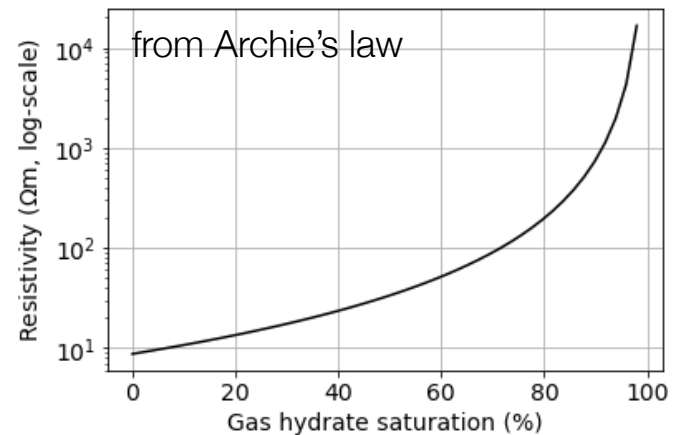
# Properties

## Types of hydrate



	Resistivity ( $\Omega\text{m}$ )
Seawater	0.25-0.31 (15-3°C)
Freshwater	100-1000
Sediment	1-5
CH <sub>4</sub> hydrate	20,000 (at 0°C)
Basement	~10-20

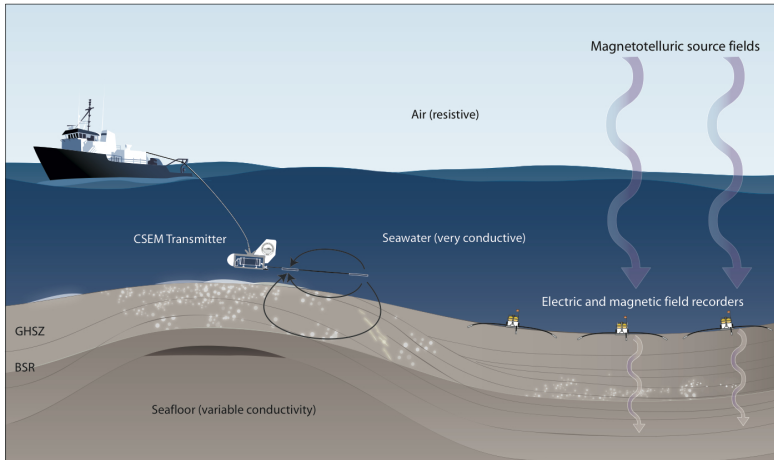
## Resistivity vs. Hydrate saturation



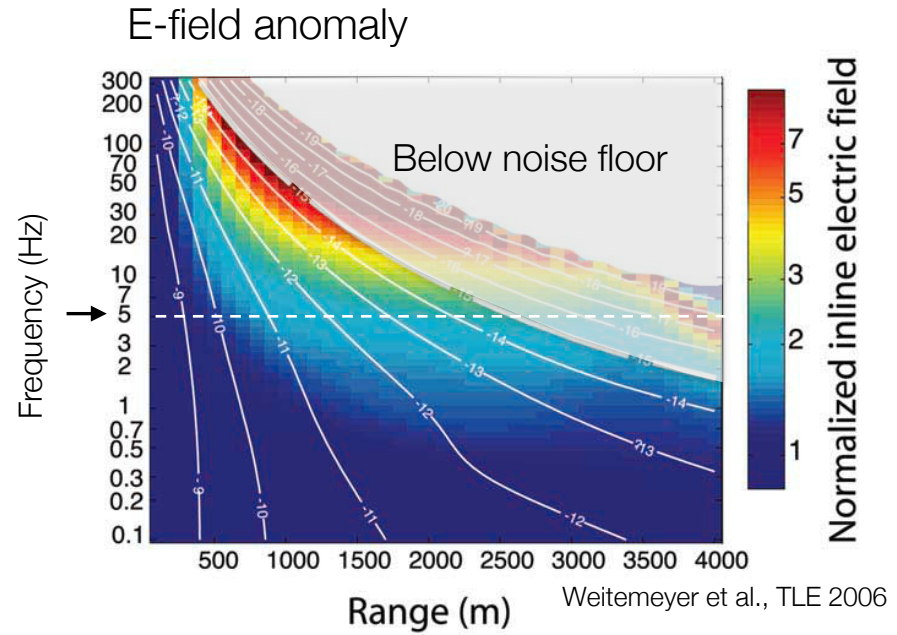
Shipboard Scientific Party  
Chapter 2, Explanatory Notes  
Ocean Drilling Program (ODP)  
Leg 204 Figure F11, page 78

# Survey design

## Marine CSEM survey

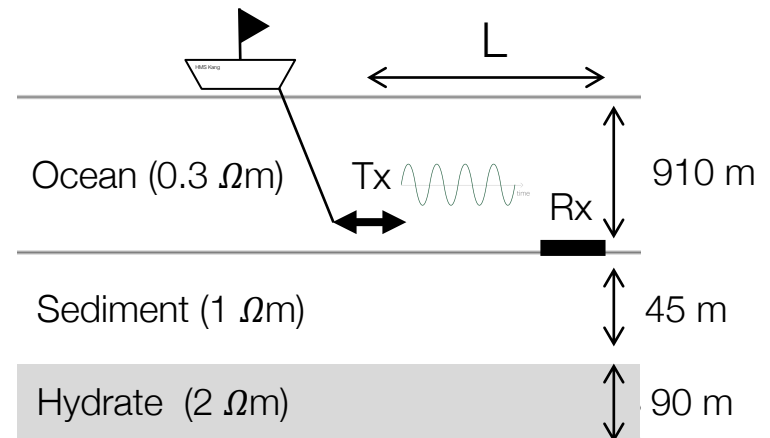


Weitemeyer et al., TLE 2006



Weitemeyer et al., TLE 2006

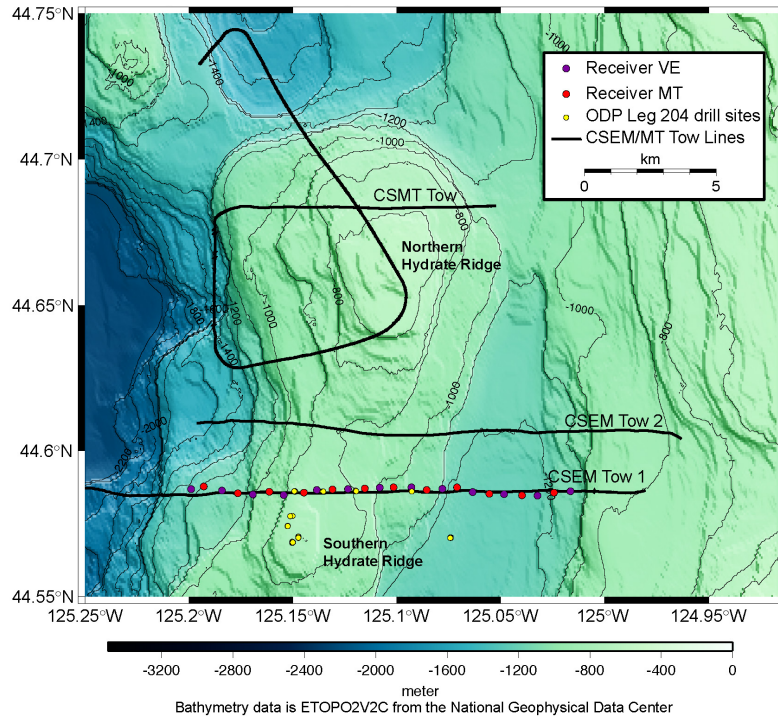
- Tx frequency: 5 Hz
- Range of offset: 0 - 3 km
- Noise level:  $10^{-15}$  V/A-m<sup>2</sup>



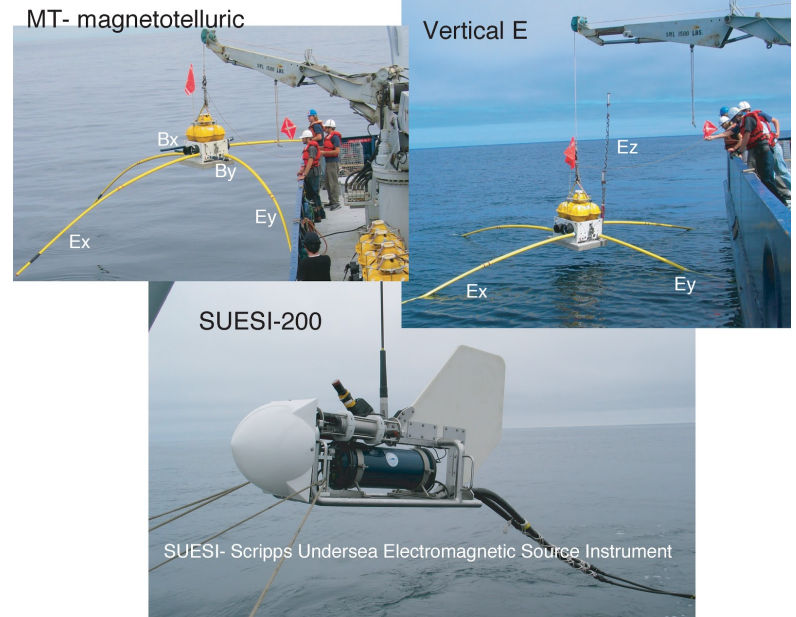


# Survey

## Geometry



## Transmitter and receivers

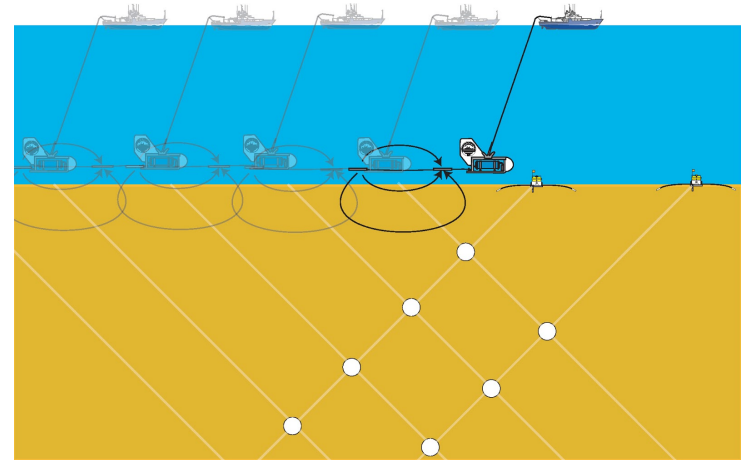
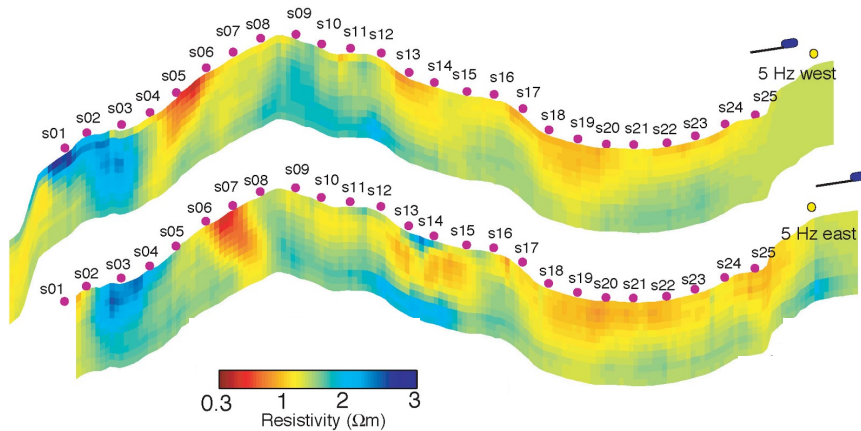


from Weitemeyer 2008 PhD Thesis

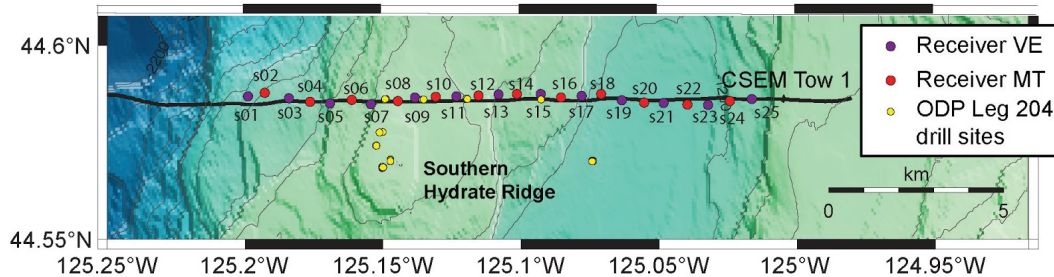
- CSEM (5Hz)
  - Receivers deployed on ocean bottom (MT and Ez)
  - 2 tow lines
- CSMT (0.1 Hz)
  - Tow line further away from receivers

# Processing: pseudo-section

Pseudo-section (apparent resistivity)



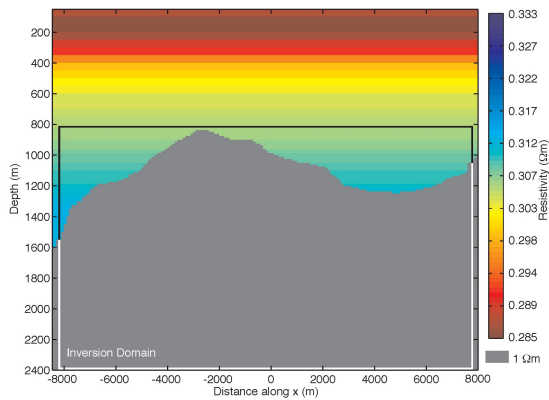
Survey geometry



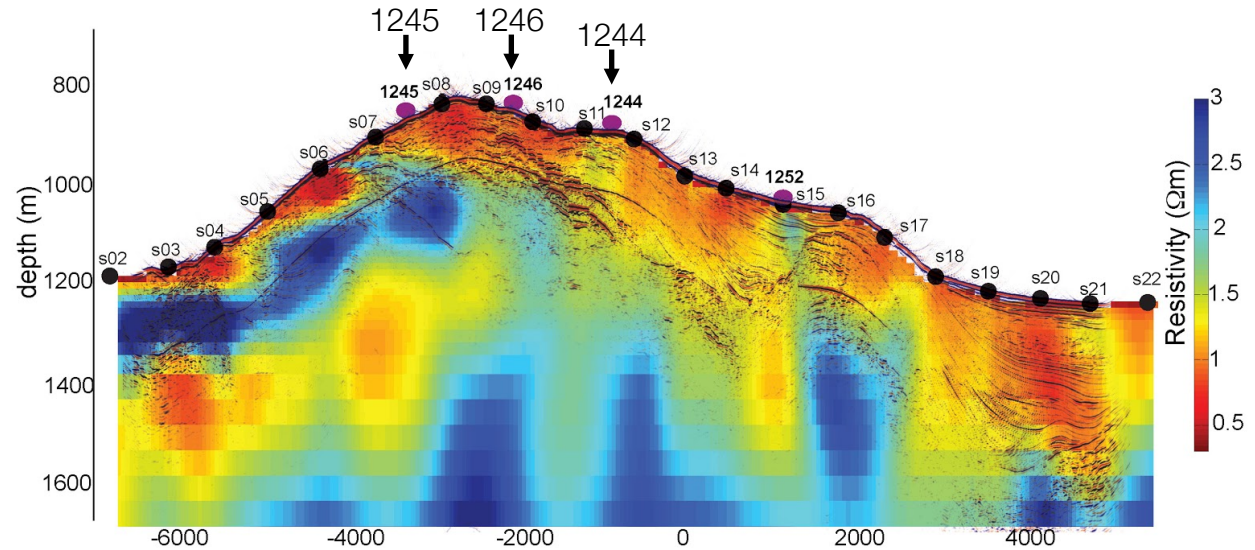
- pseudo-section:
  - fixed ocean resistivity
  - find effective subsea resistivity

# Processing: 2.5D inversion

Initial model

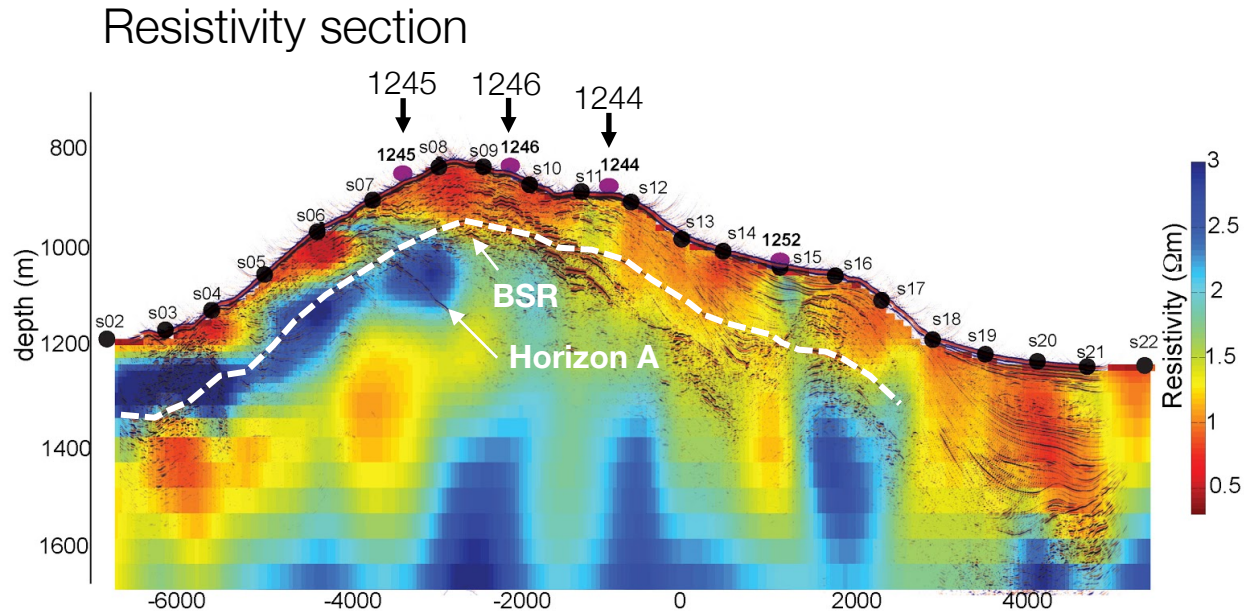


Resistivity section



- Variable ocean  $\sigma$ 
  - assign conductivity from CTD data (conductivity, temperature, depth)
- Significant near surface resistivity structure on the west
- Seismic image overlaid on the resistivity

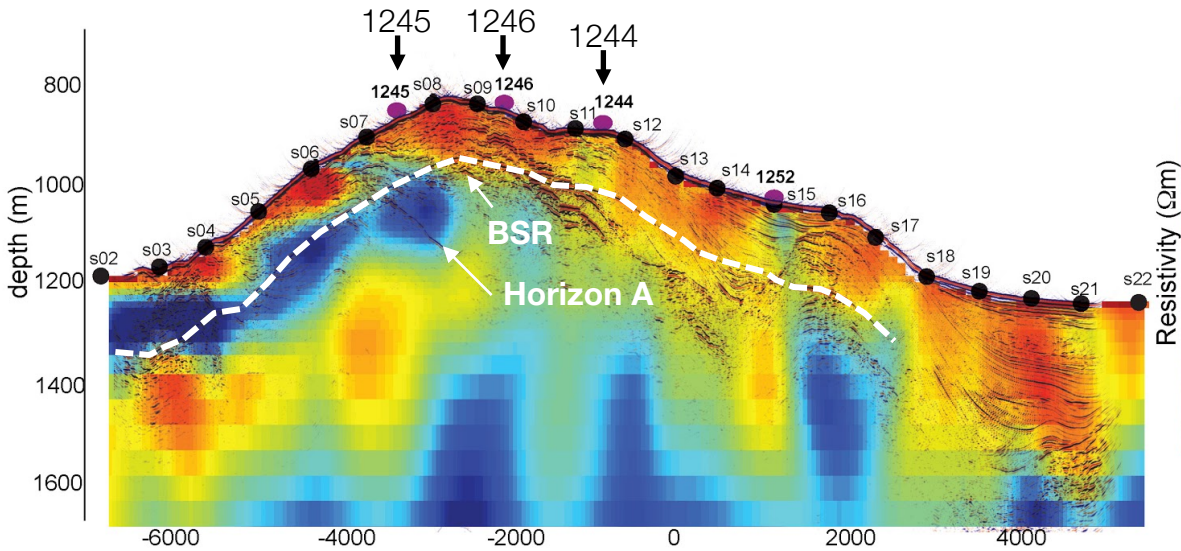
# Interpretation: 2.5D inversion



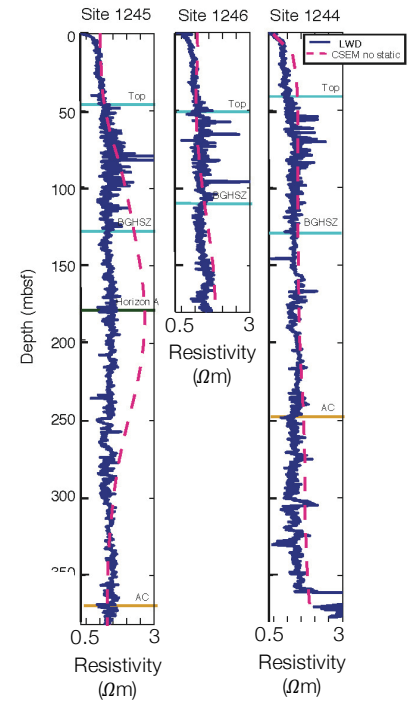
- Resistors are imaged near BSR
- Hydrate stability
  - Above BSR: hydrate
  - Below BSR: free gas

# Interpretation / Synthesis

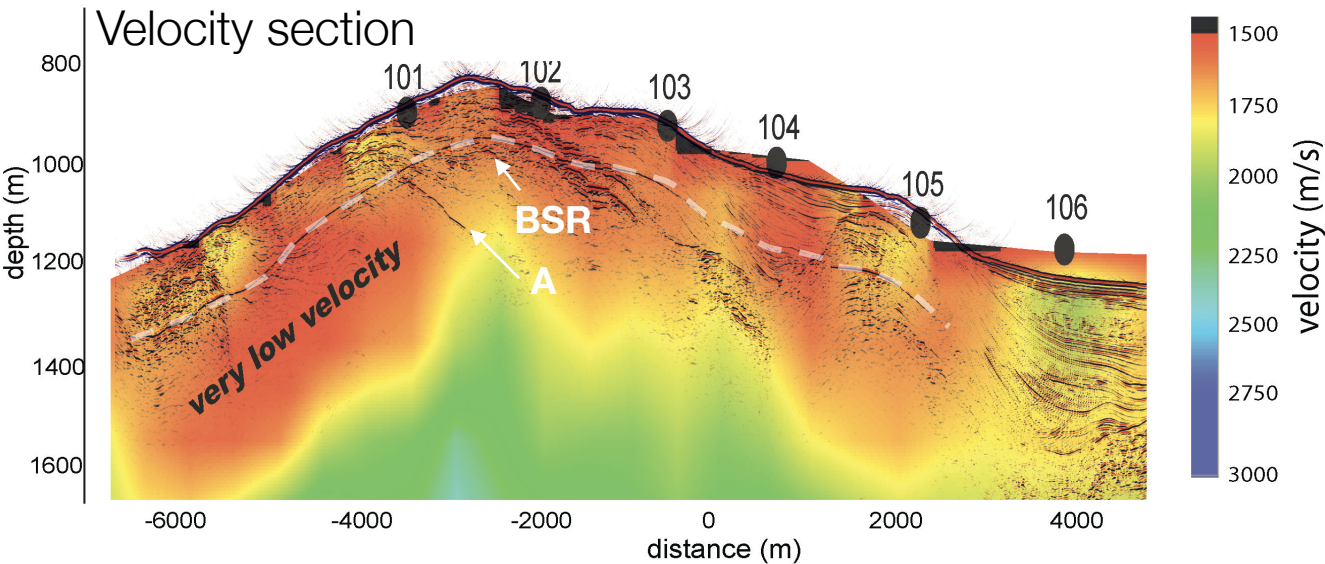
## Resistivity section



## Well-logs



## Velocity section



Hydrate	$\rho$	$V_p$
Free gas	High	Low
Solid	High	High

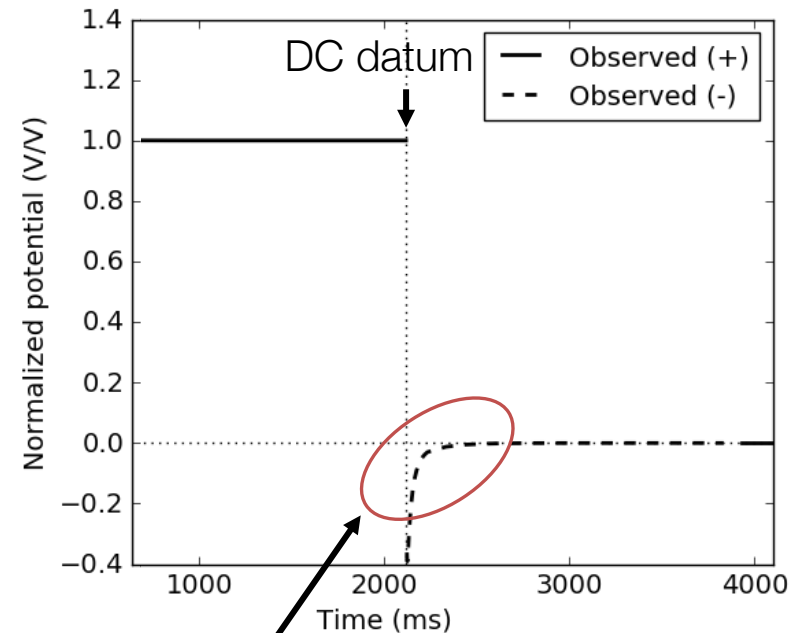
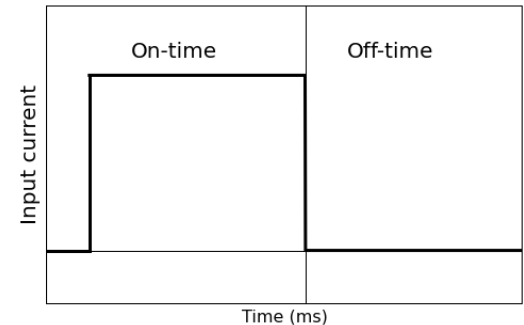
# Additional Material

- DC / EM Inversion tutorial

# DC/EM Inversion

# DC/EM: Goals

- Standard DCR time domain waveform
- Compare:
  - Inversions from DC data
  - Inversions from EM data
- Illustrate the value of data which is often discarded
- Numerical example from a gradient array

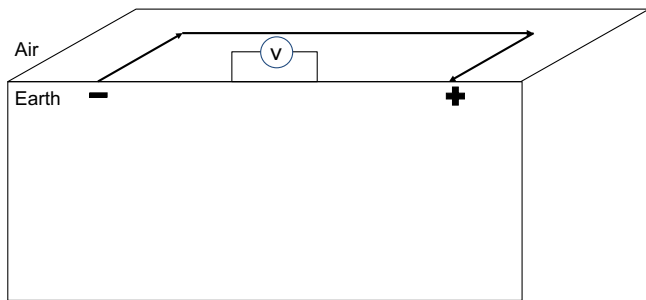
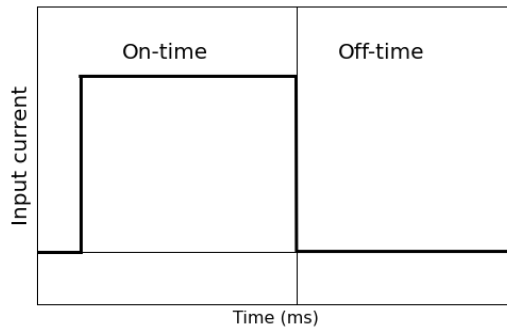


EM portion  
Generally considered noise

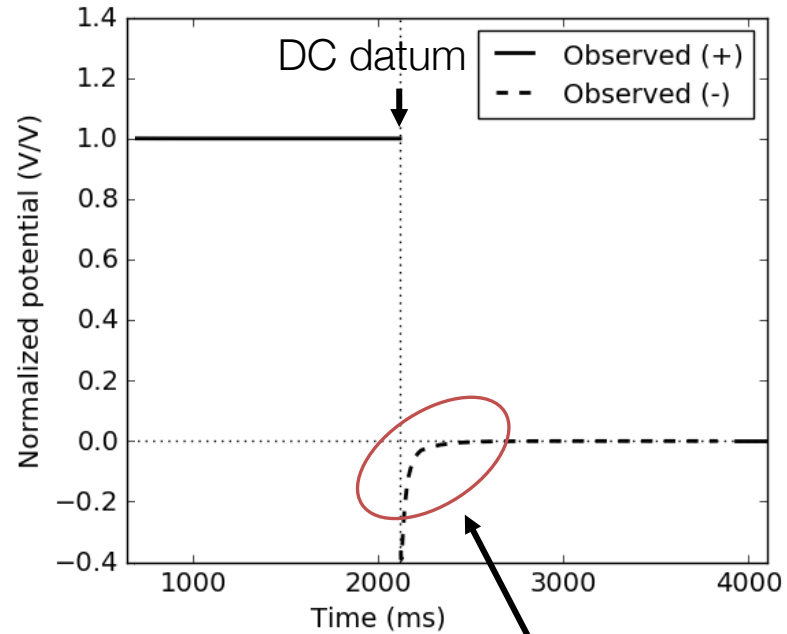


# Survey and Data

## Transmitter



## Measured Voltage



EM portion  
Generally considered noise

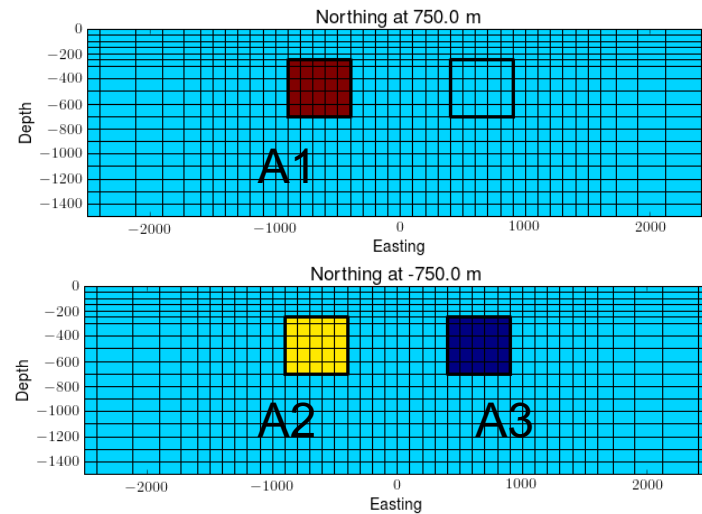
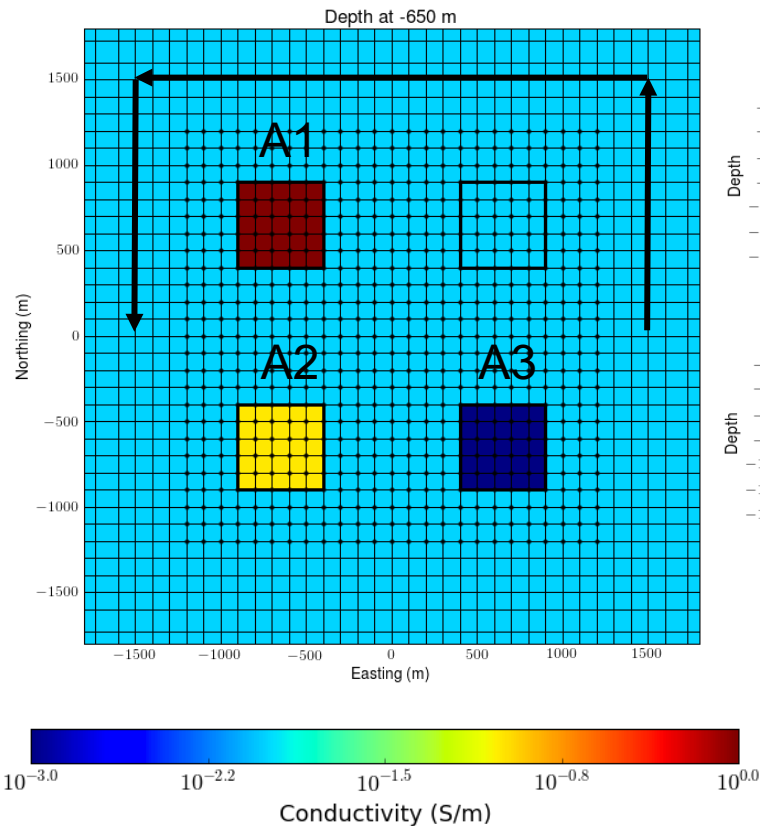
# Gradient array

- Model

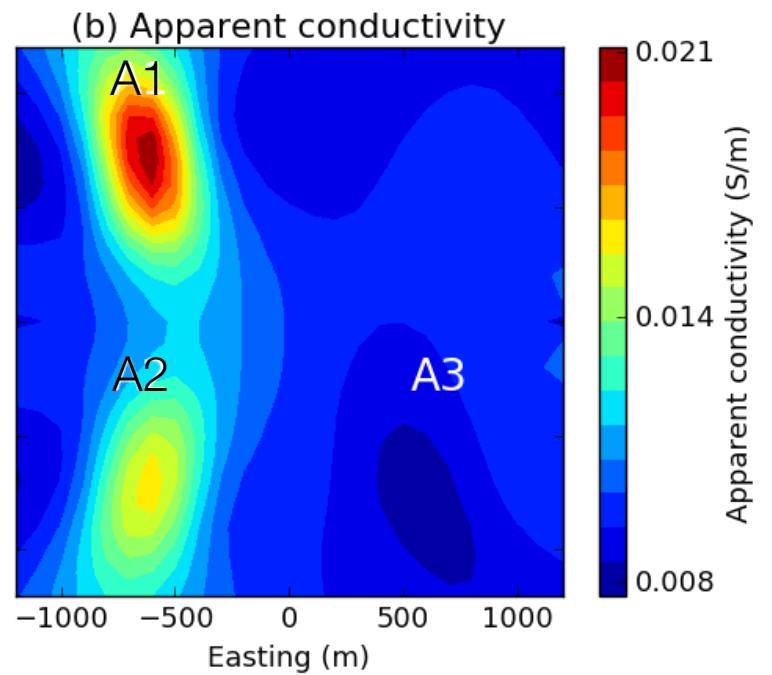
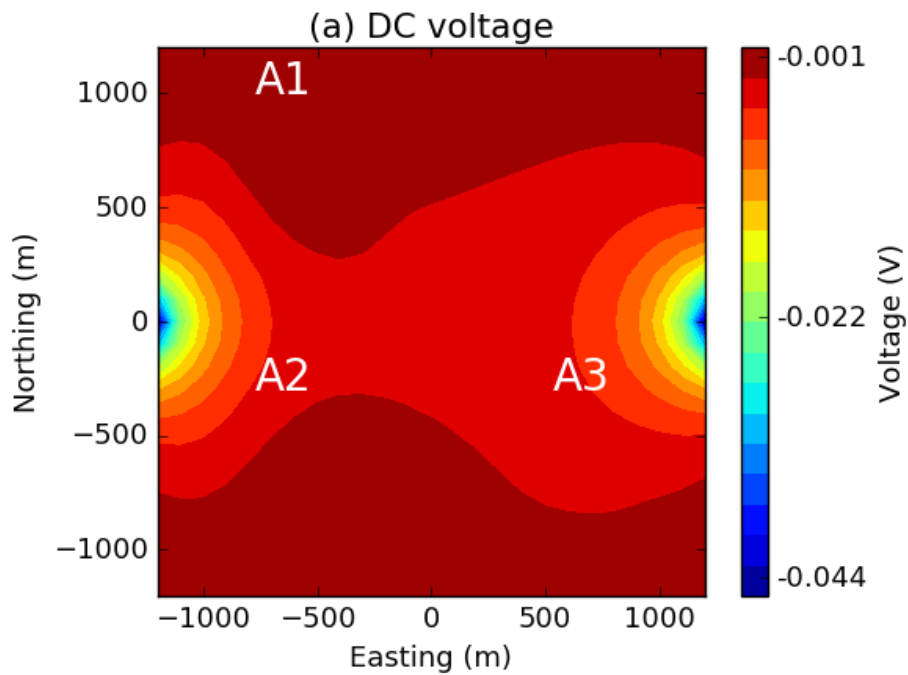
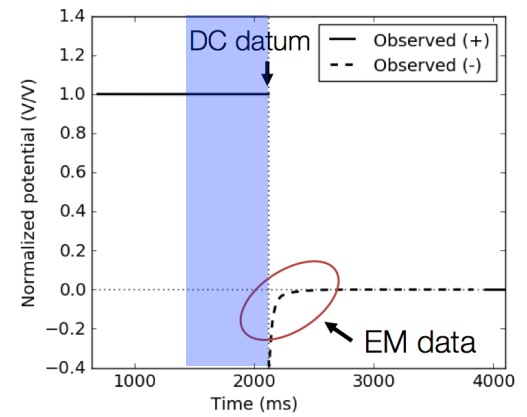
- A1: high conductivity
- A2: moderate conductivity
- A3: resistive

- Survey

- 200m bi-pole (625 data)
- times: 1-600ms

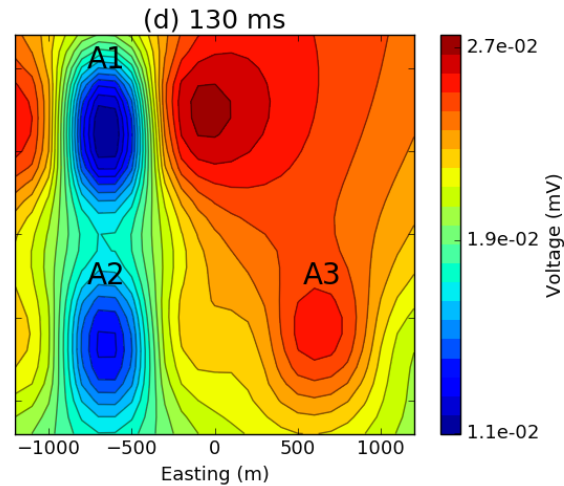
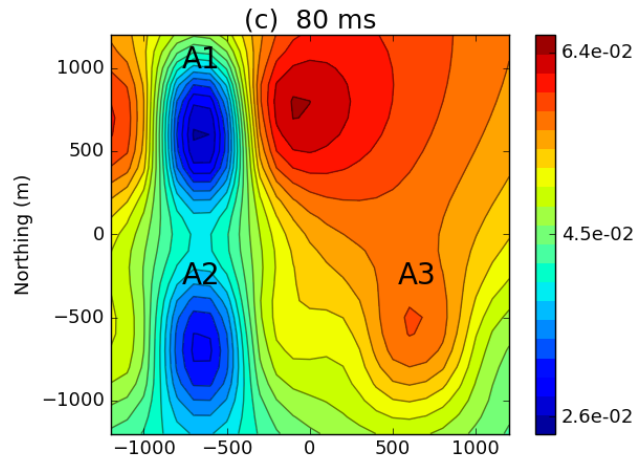
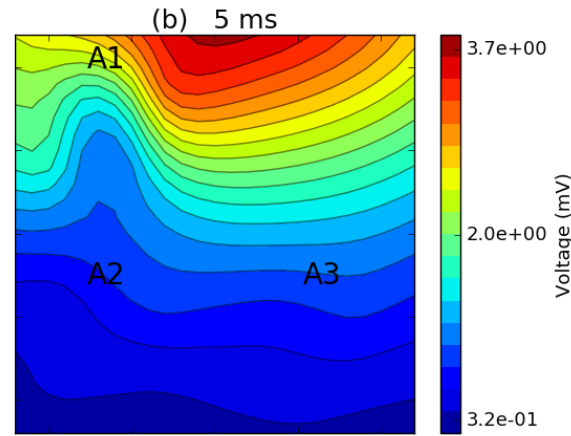
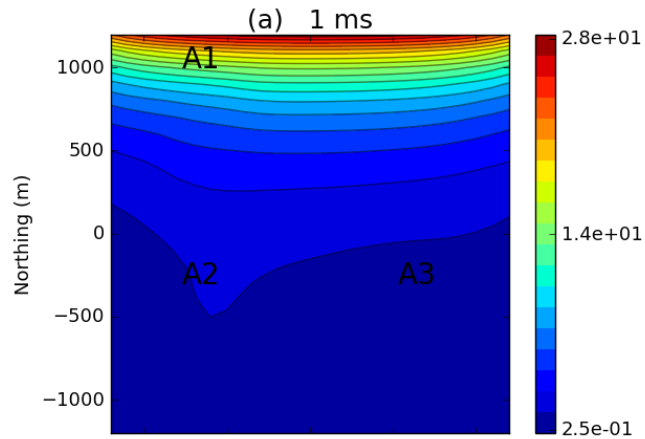
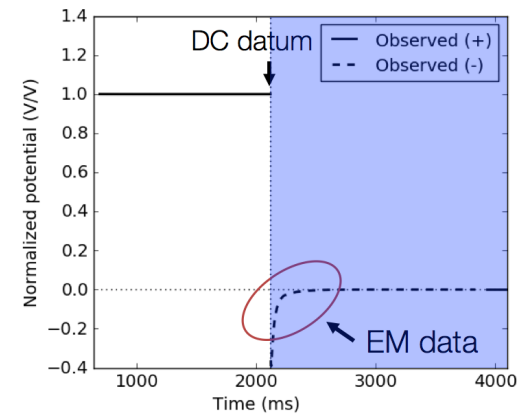


# DC data



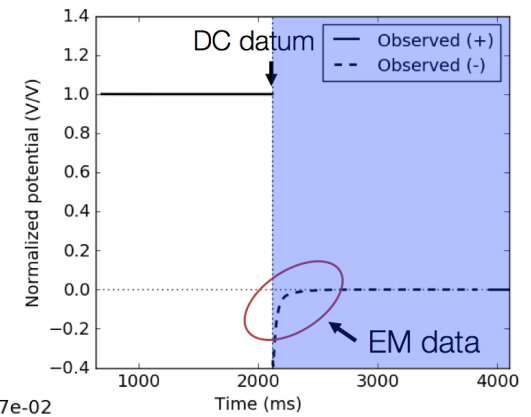
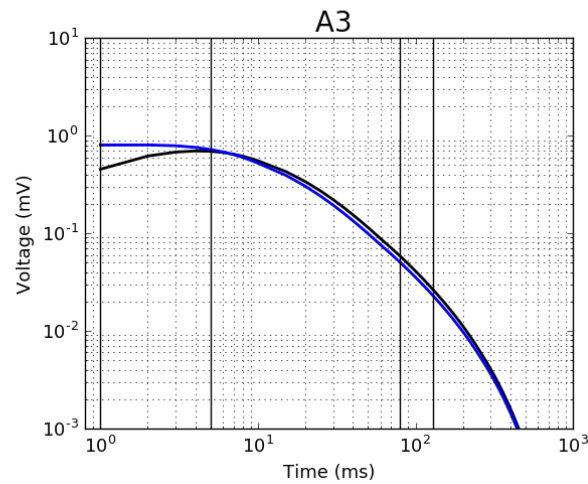
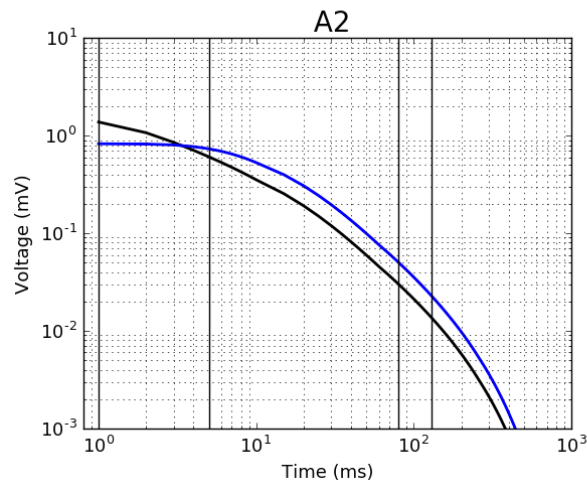
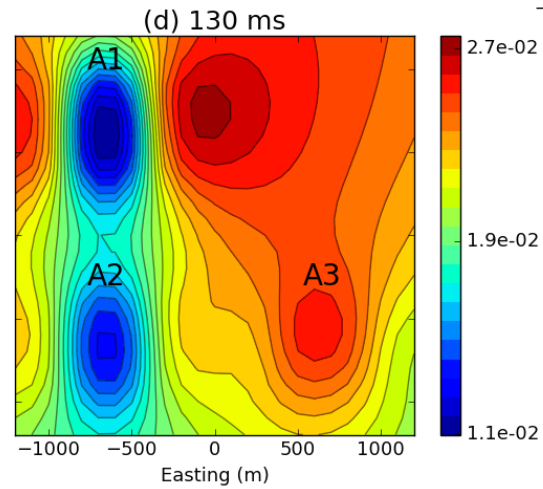
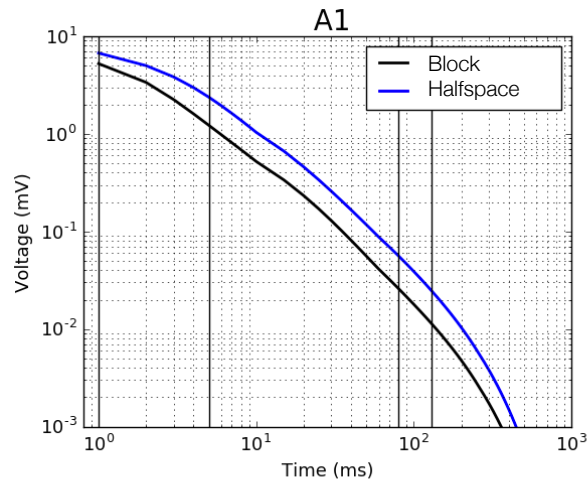
# Off-time data

- TDEM data



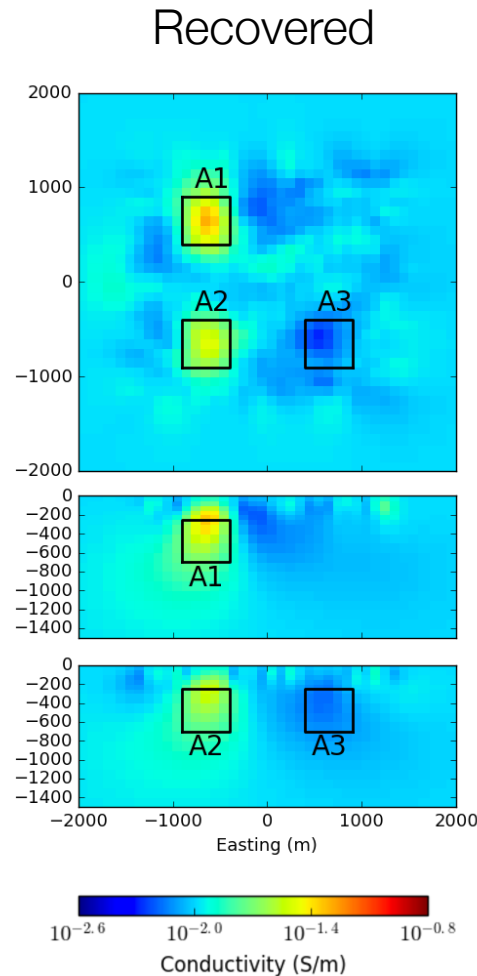
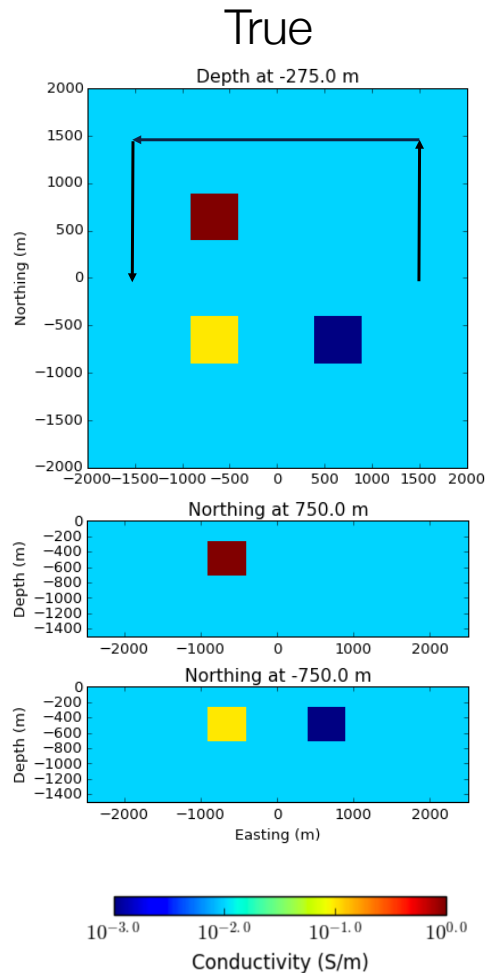
# Off-time data

- $E_x$  Decay curves at A1-A3

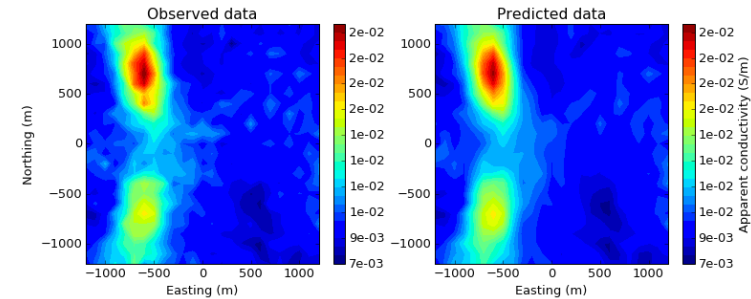


# DC inversion

- Recovered 3D conductivity



## Apparent conductivity

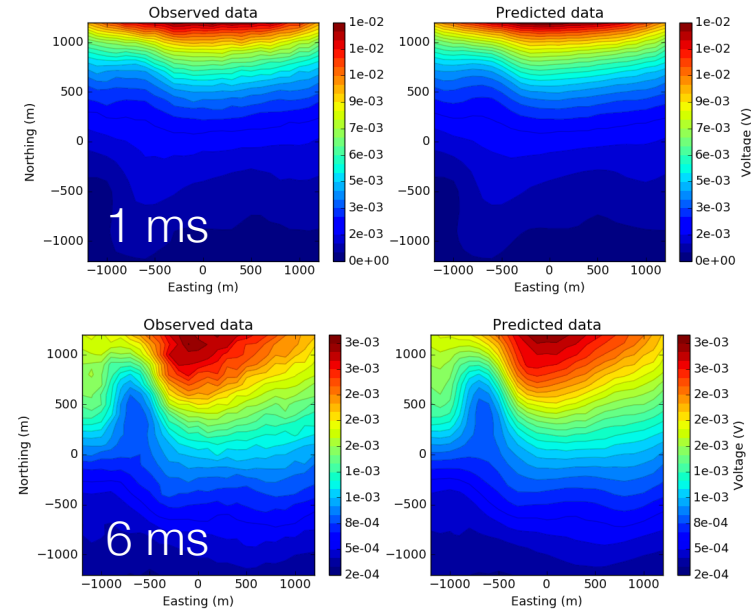
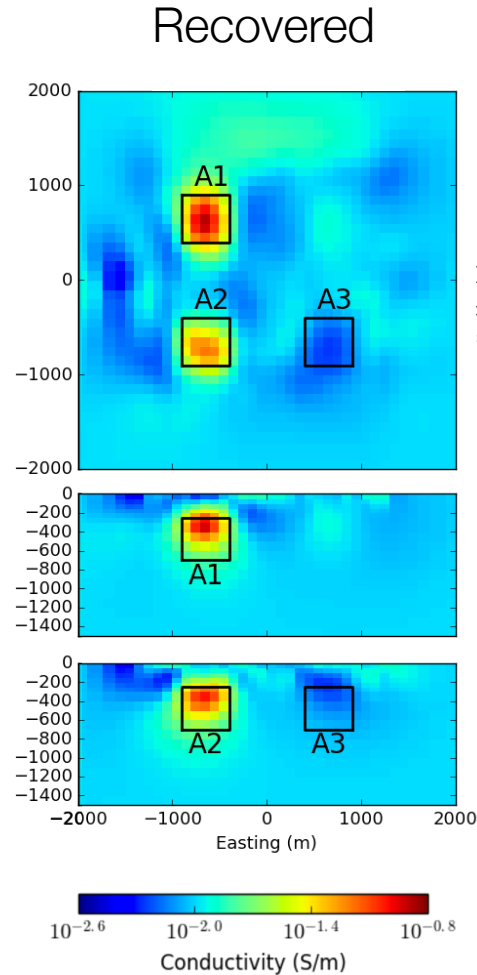
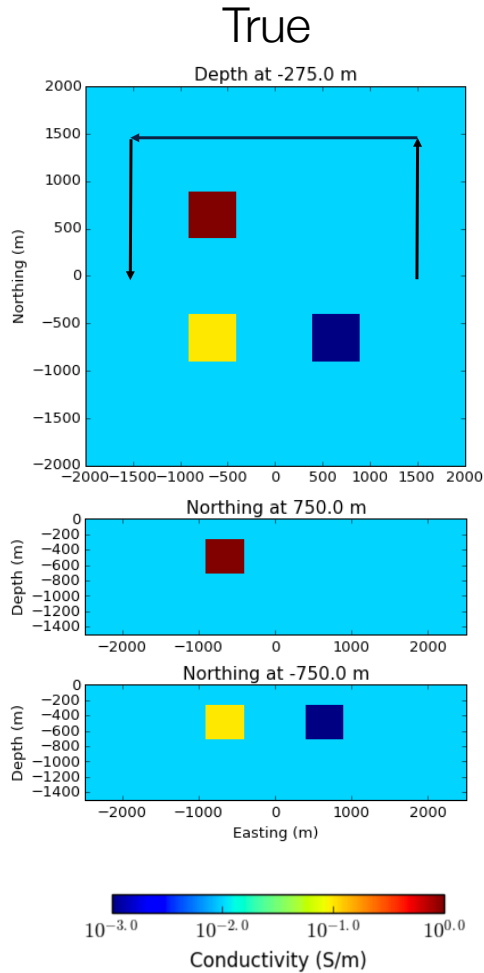


- Depth weighting
  - Compensate for high sensitivity near surface (similar to mag.)

$$\frac{1}{(z - z_0)^3}$$

# EM inversion

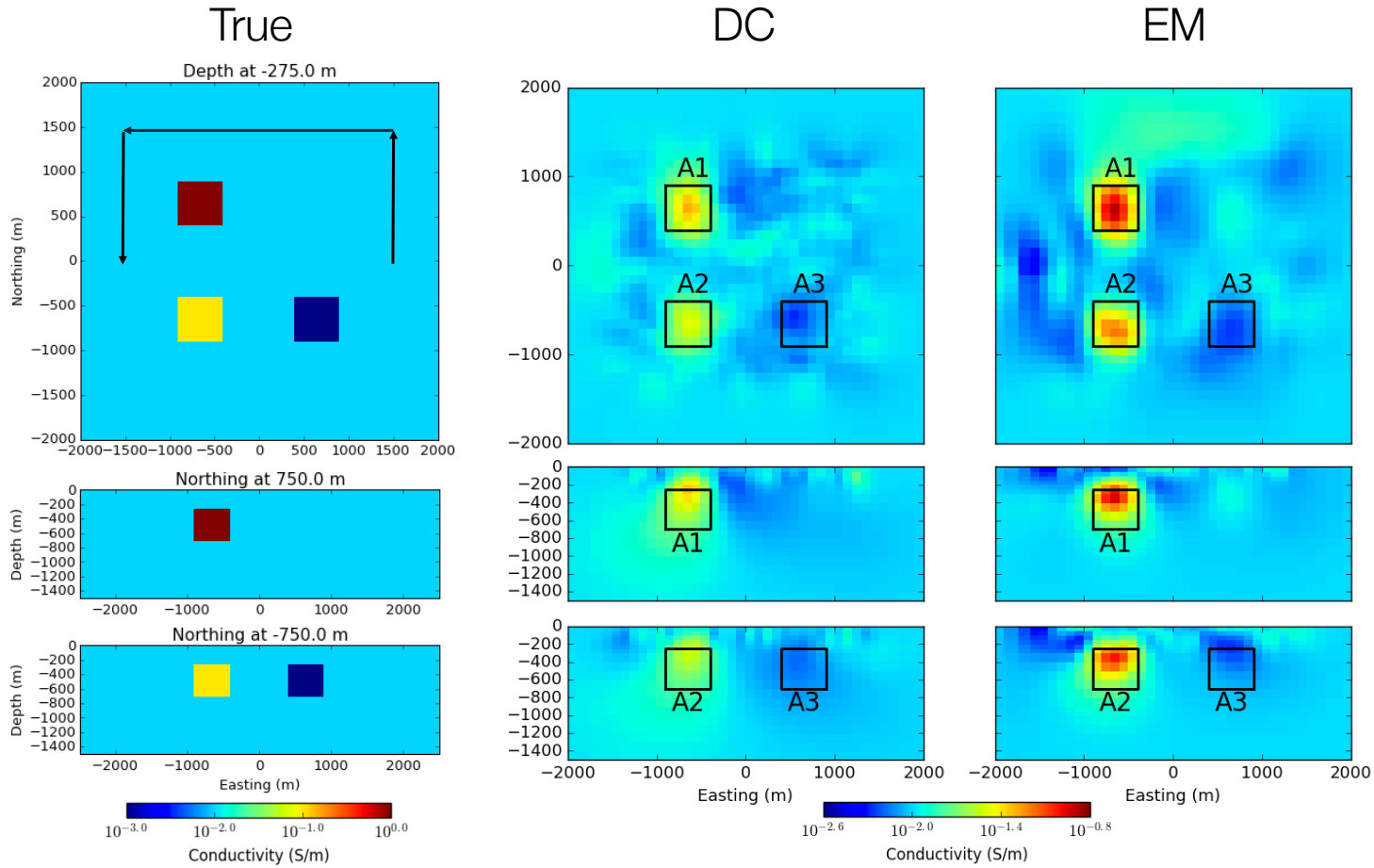
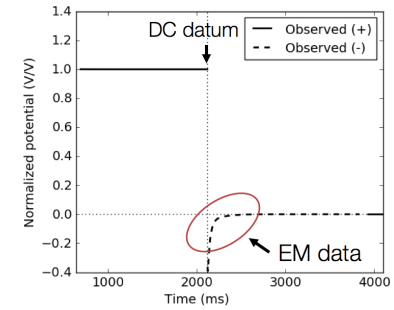
- Recovered 3D conductivity



- No depth weighting

# Conductivity models

- True, DC, and TEM conductivities



EM data contain signal



# End of Grounded Sources

