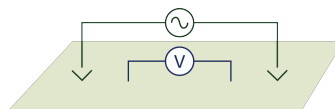


EM: Grounded Sources

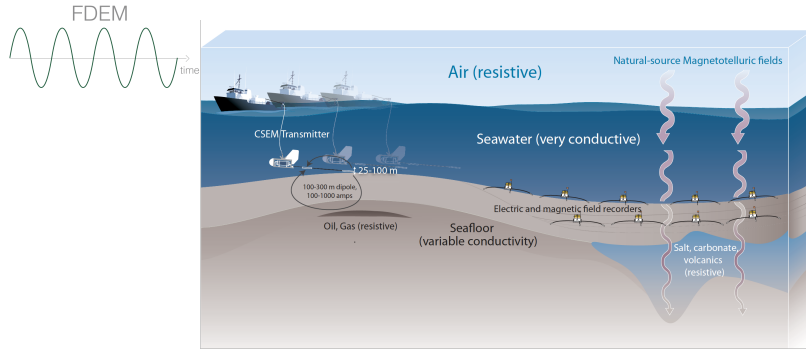


Outline

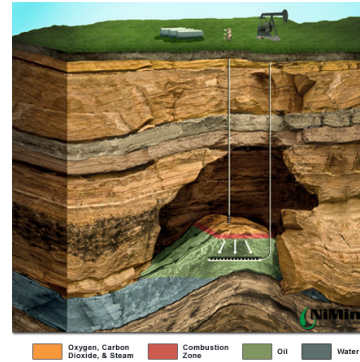
- Basic experiment
- TDEM: Electric dipole in a whole space
- FDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets
- Resistive Targets
- Marine EM: Overview
- Case History: Methane hydrates

Motivational examples

Marine EM for hydrocarbon



Oil and Gas (EOR)

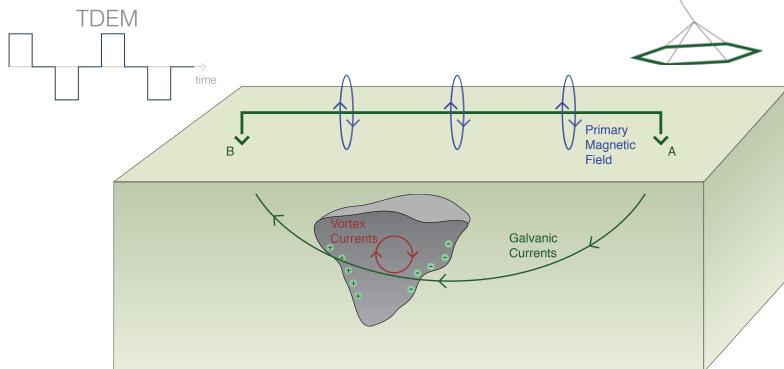


Methane hydrates



Galvanic source TEM

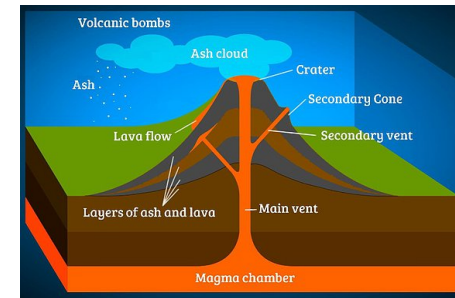
- LoTEM (ground)
- HeliSAM (Rx on the air)
- GREATEM (Rx on the air)



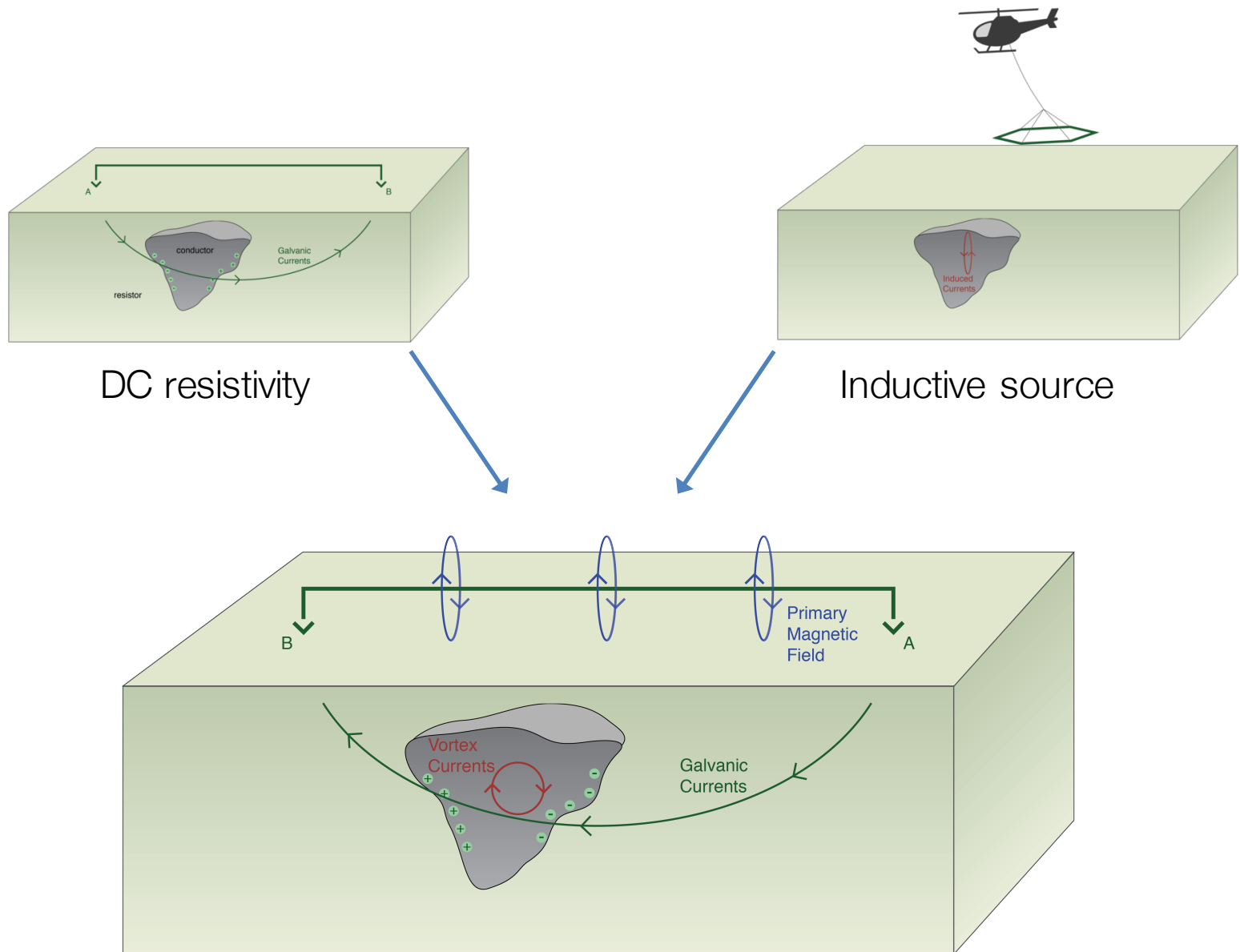
Minerals



Volcanoes

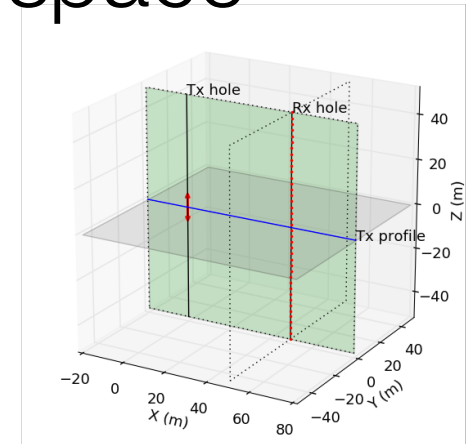


Basic experiment

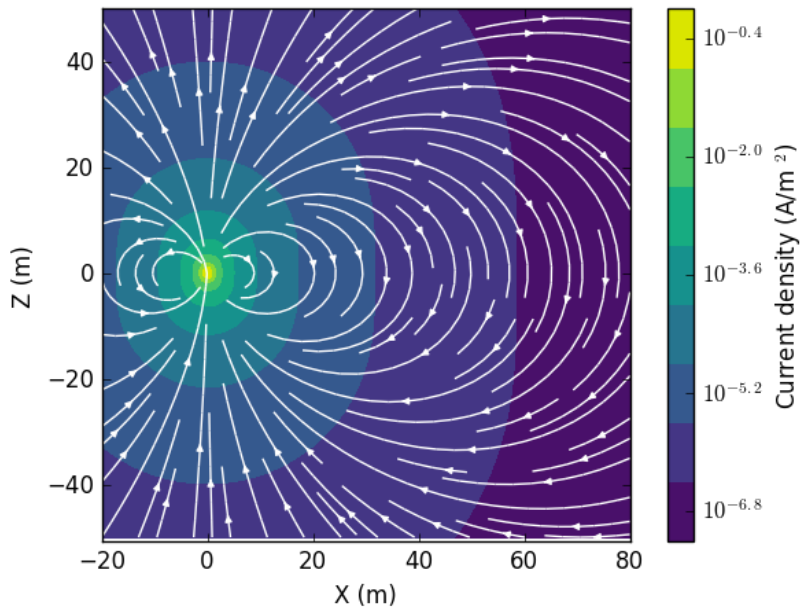


Electric Dipole in a whole space

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



DC current density

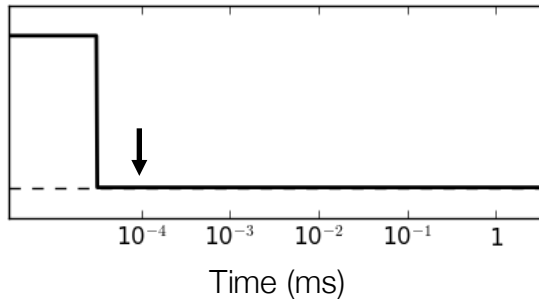


$$\mathbf{E}_{DC}(\mathbf{r}) = \frac{1}{4\pi\sigma|\mathbf{r}|^3} \left(\frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m} \right)$$

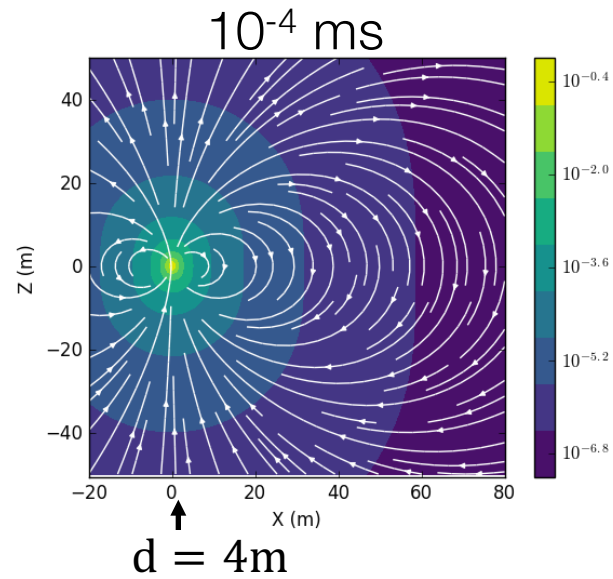
$$\mathbf{J}_{DC}(\mathbf{r}) = \frac{1}{4\pi|\mathbf{r}|^3} \left(\frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m} \right)$$

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

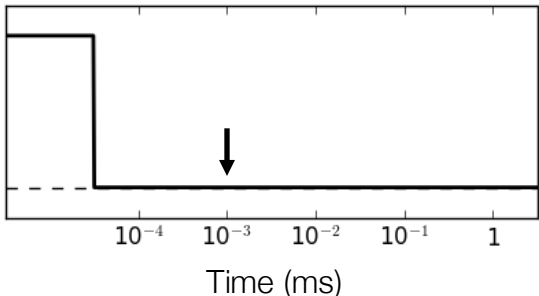
Electric Dipole in a whole space: TDEM



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

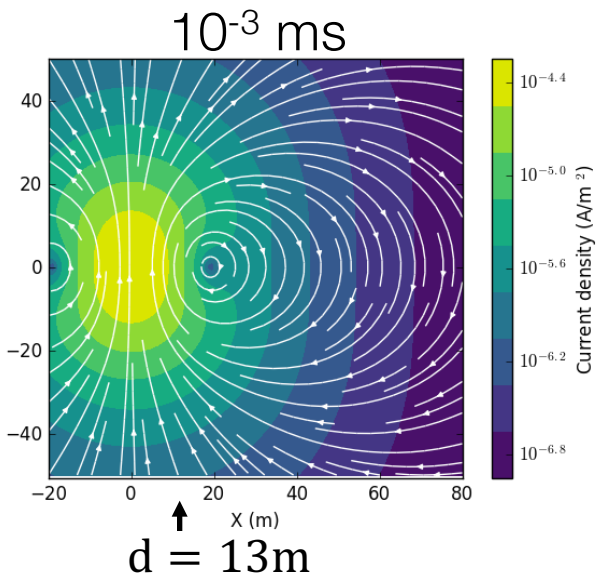
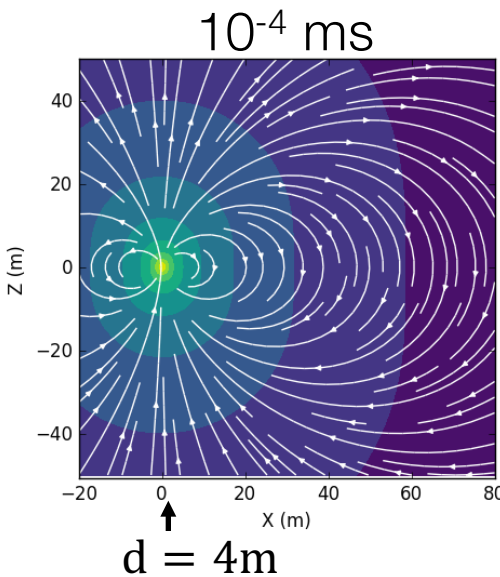


Electric Dipole in a whole space: TDEM



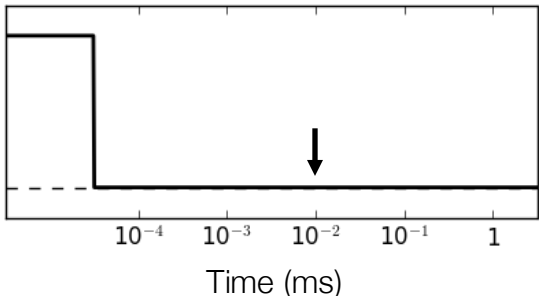
Diffusion distance

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

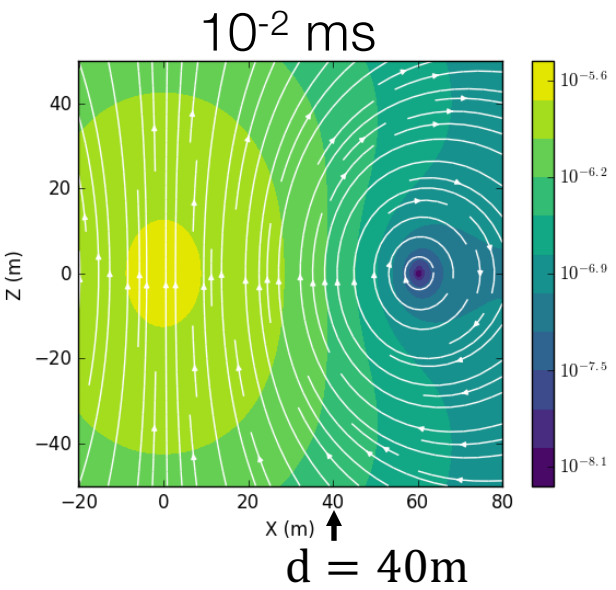
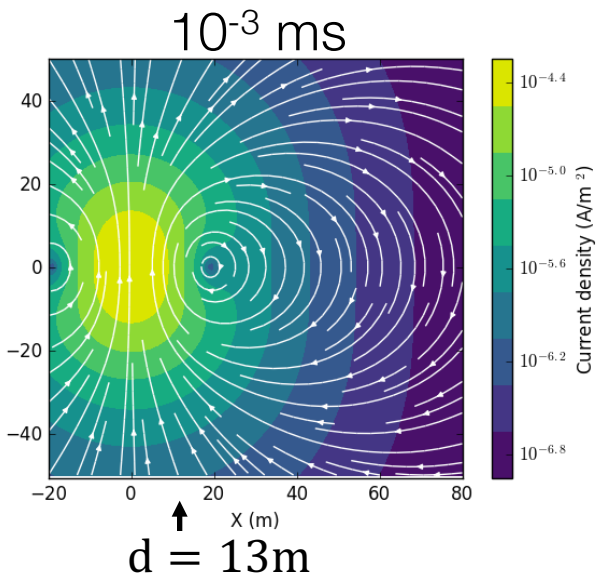
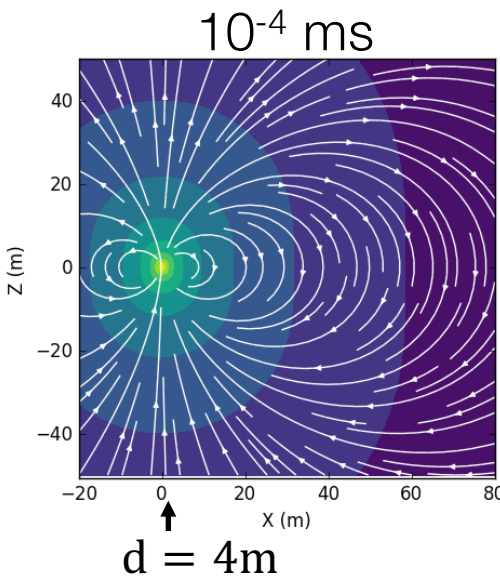


Current density (A/m²)

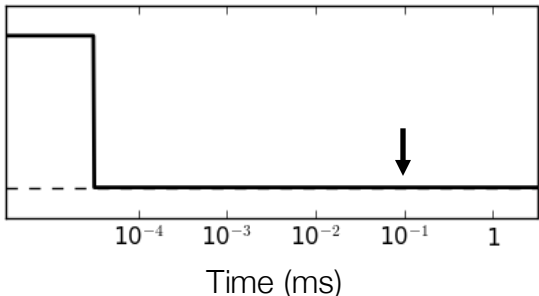
Electric Dipole in a whole space: TDEM



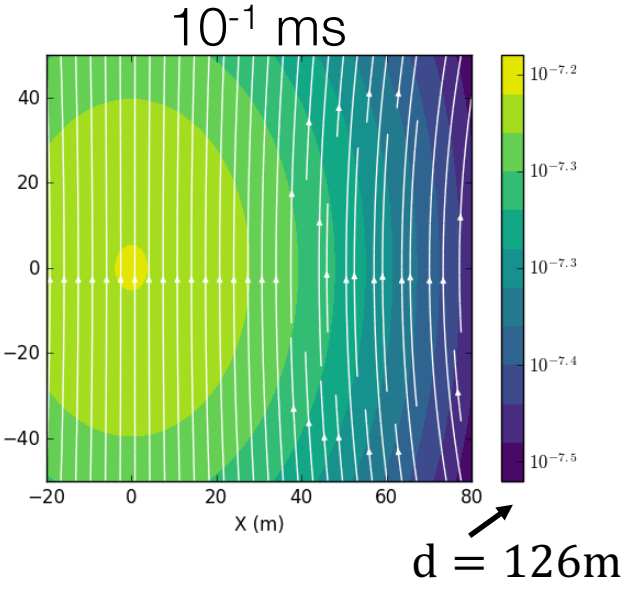
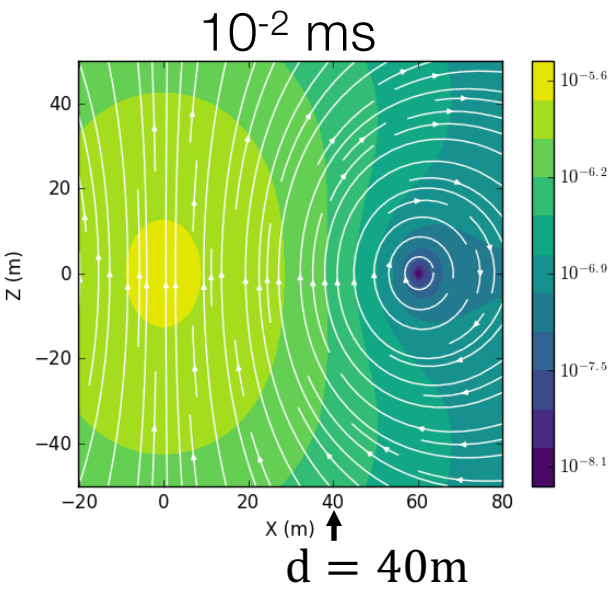
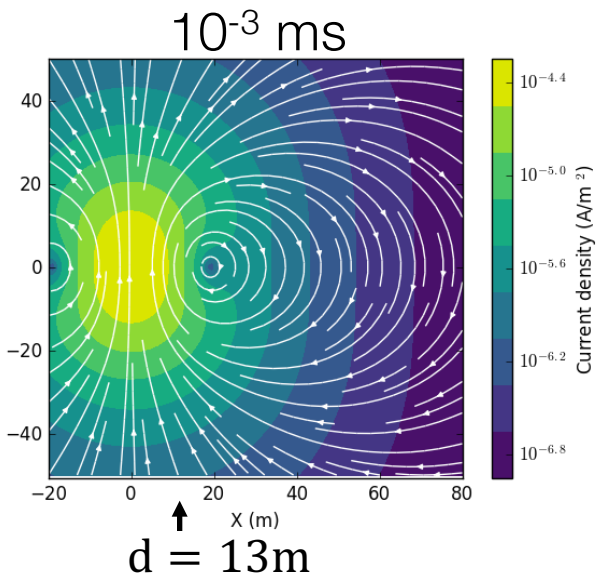
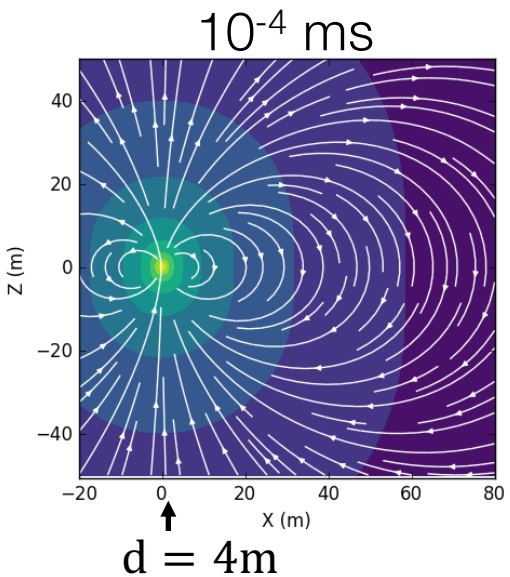
Diffusion distance $d = \sqrt{\frac{2t}{\mu\sigma}}$



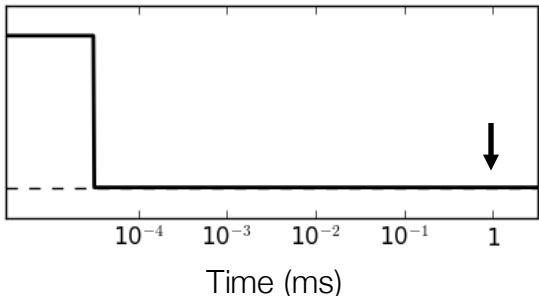
Electric Dipole in a whole space: TDEM



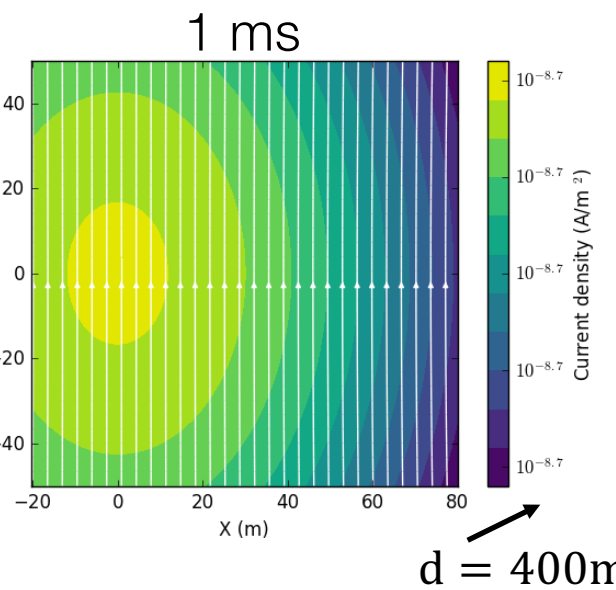
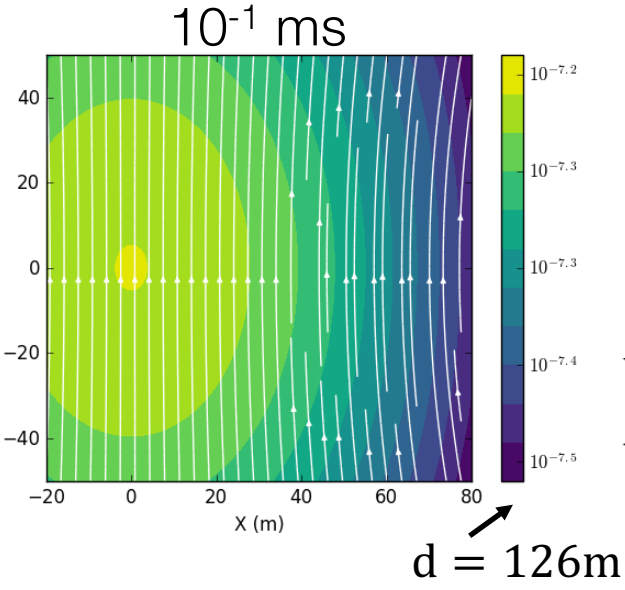
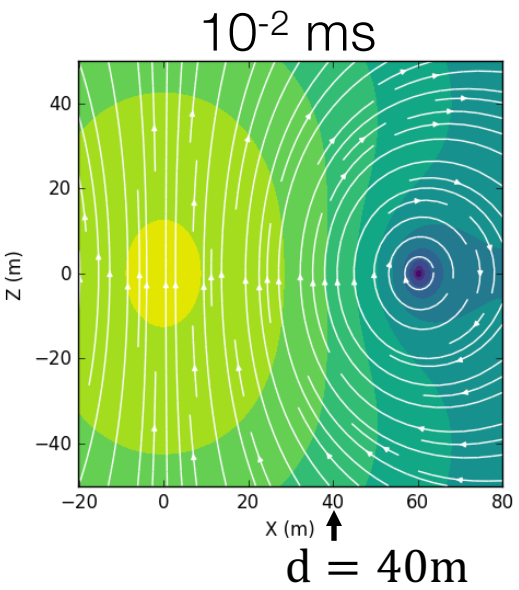
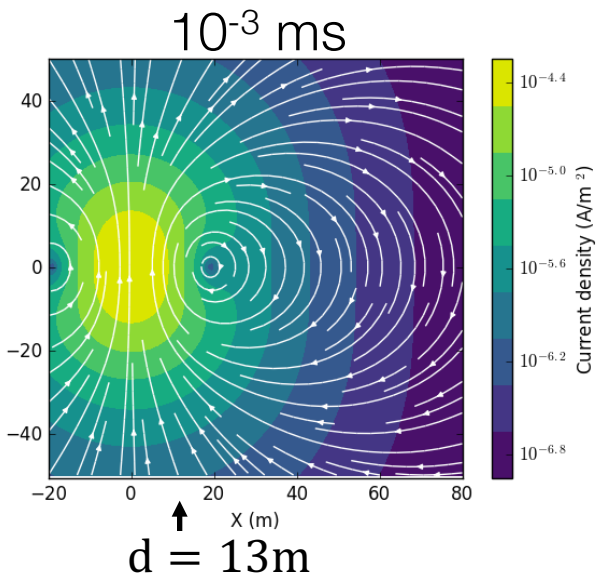
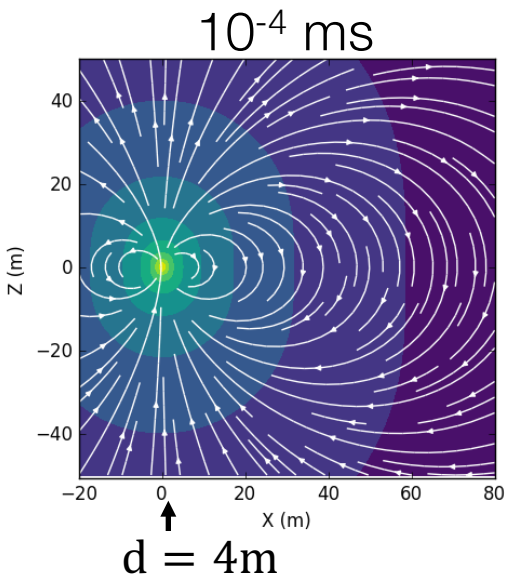
Diffusion distance $d = \sqrt{\frac{2t}{\mu\sigma}}$



Electric Dipole in a whole space: TDEM

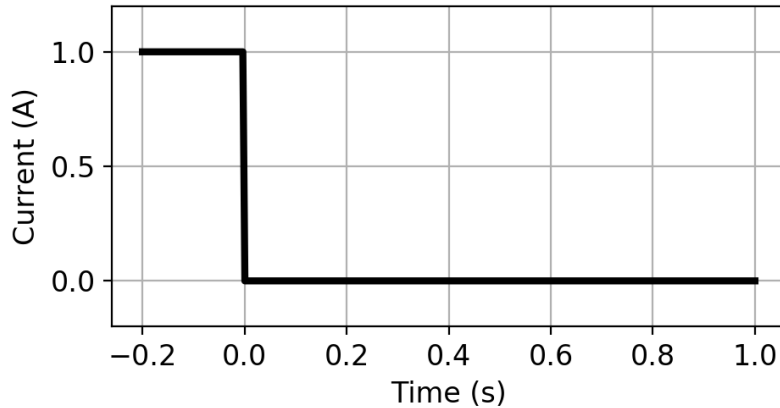


Diffusion distance $d = \sqrt{\frac{2t}{\mu\sigma}}$



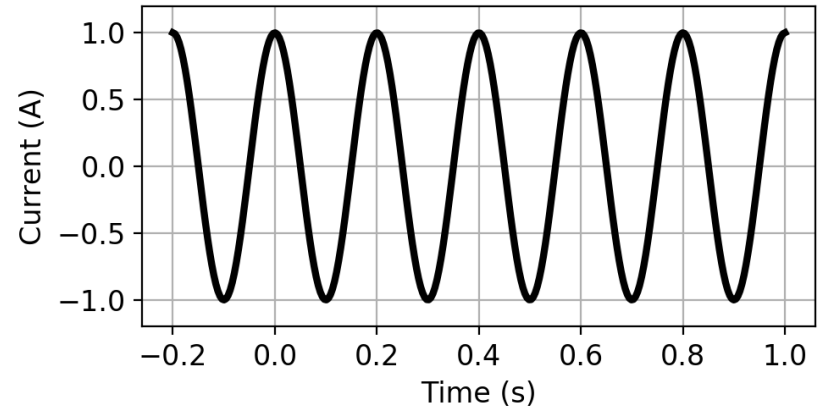
TDEM vs. FDEM

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

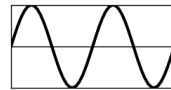
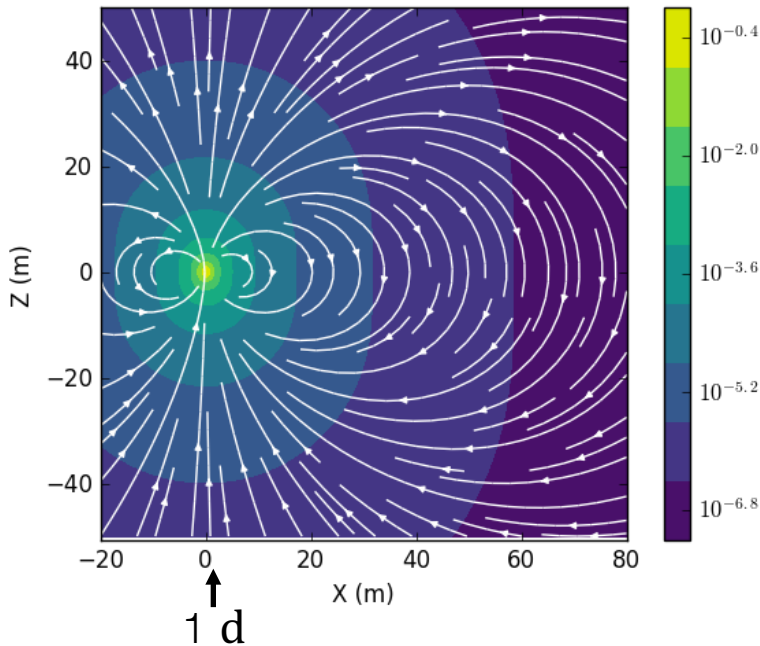
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

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

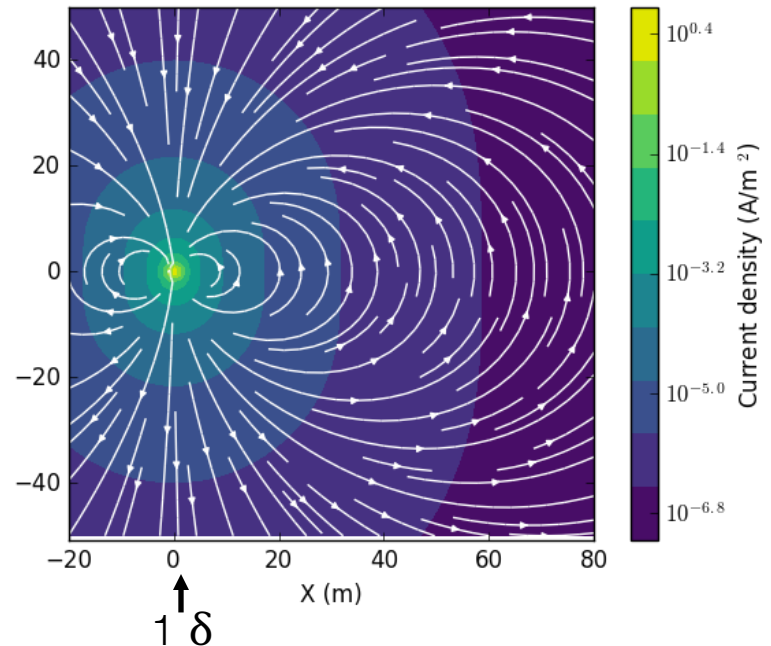
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



j



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



Electric Dipole in a whole space: FDEM

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

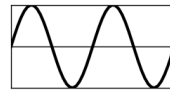
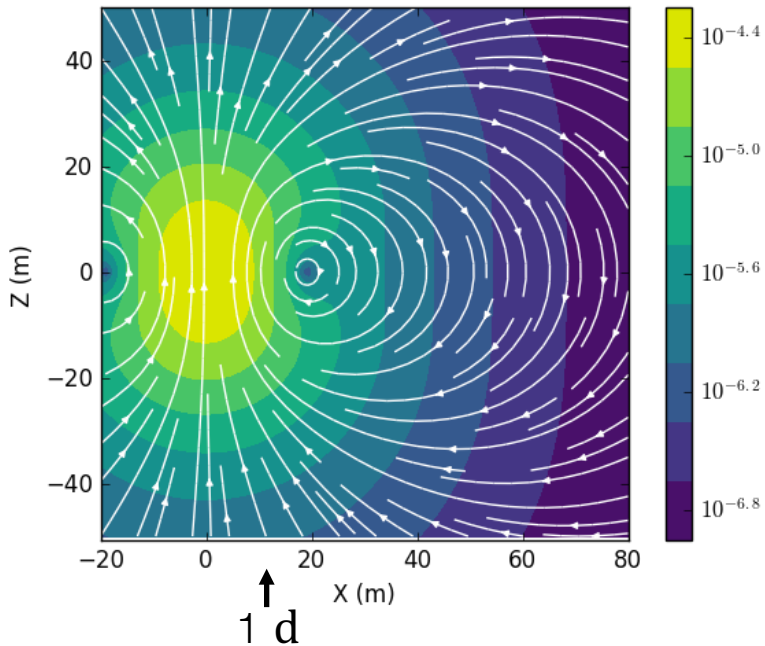
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

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

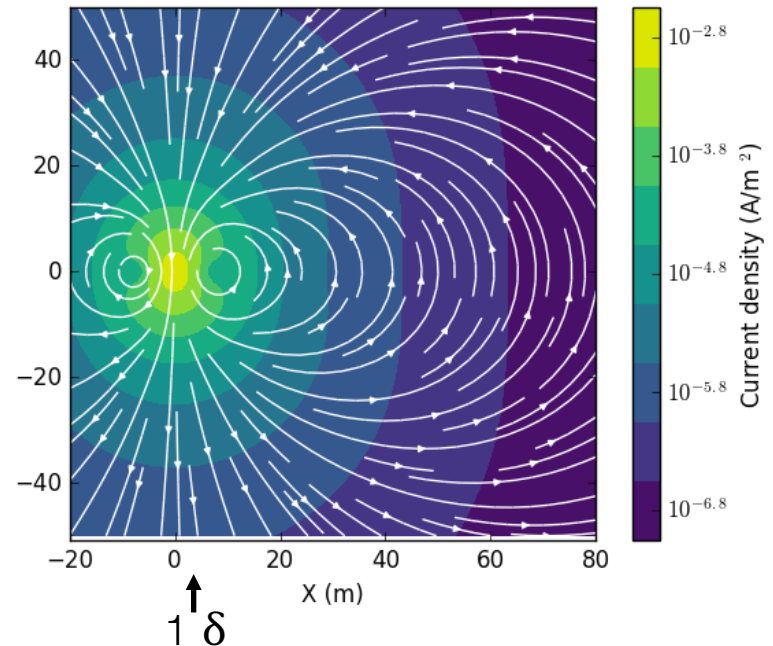
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



j



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



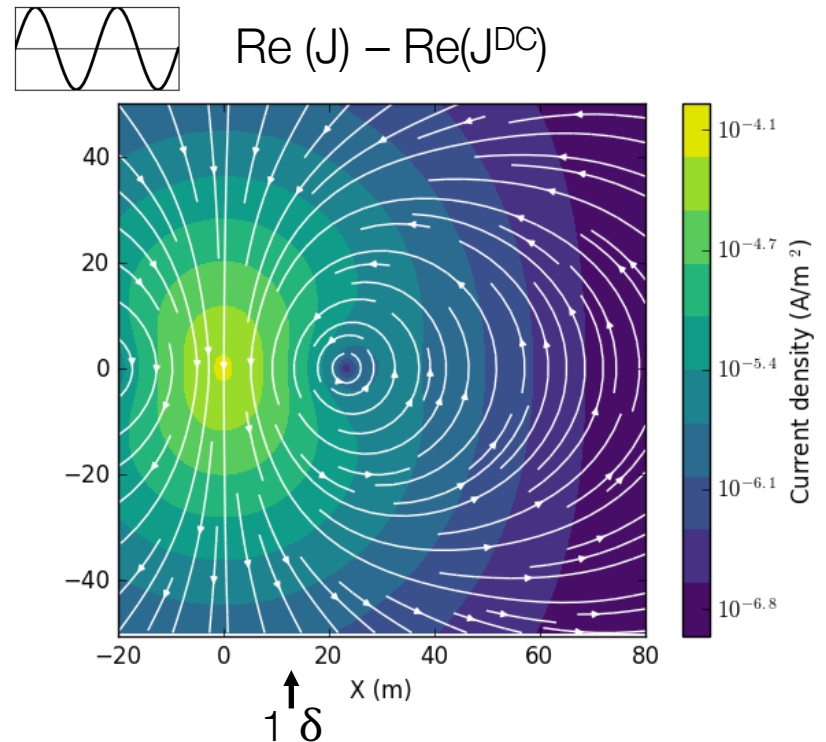
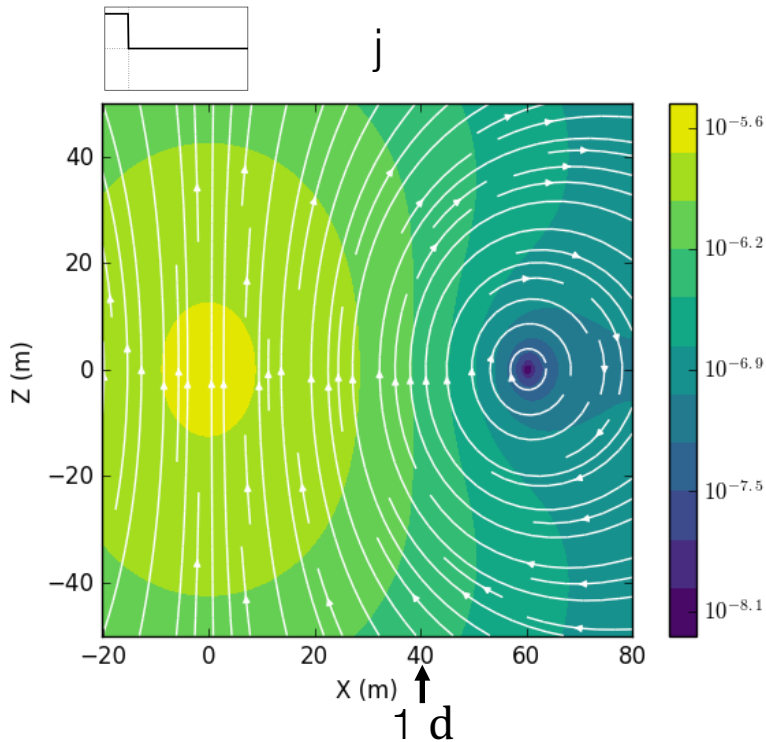
Electric Dipole in a whole space: FDEM

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

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

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

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



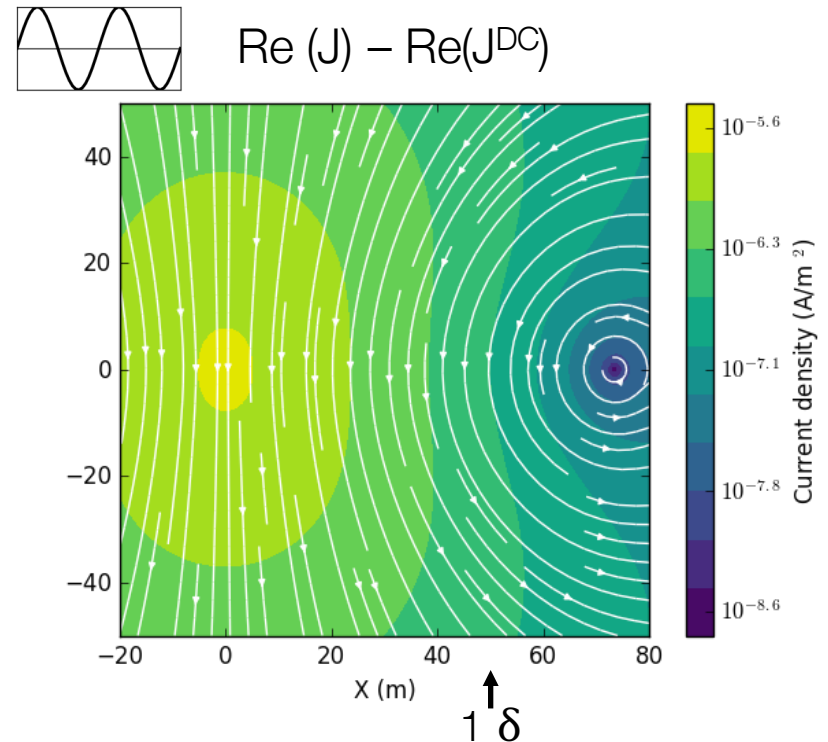
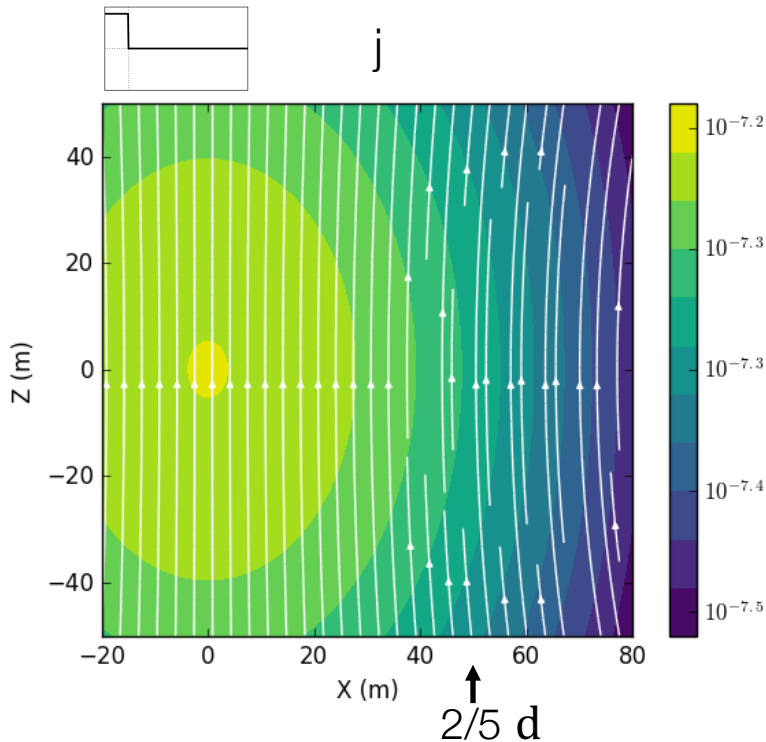
Electric Dipole in a whole space: FDEM

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

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

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

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



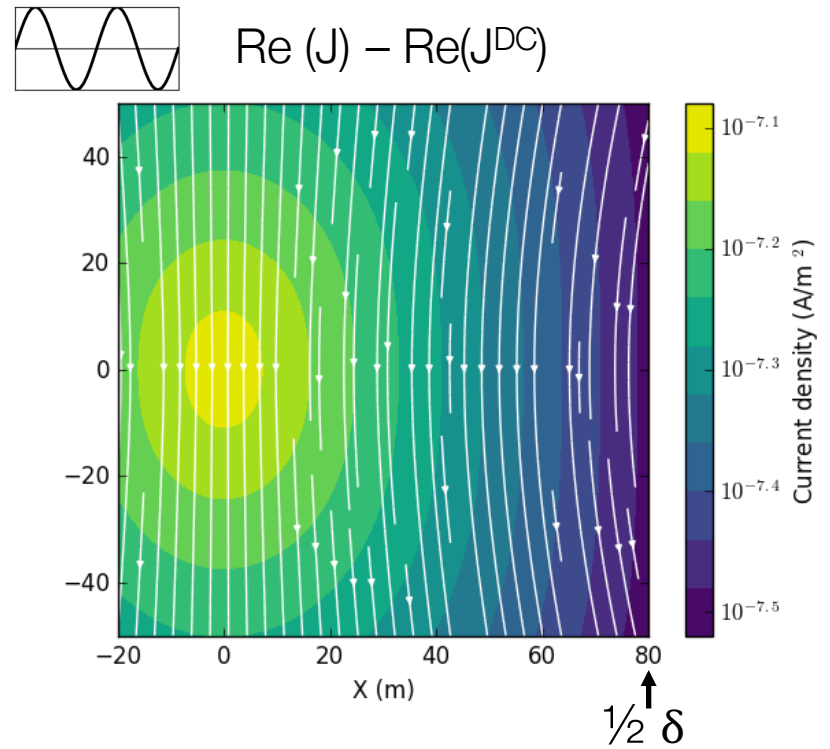
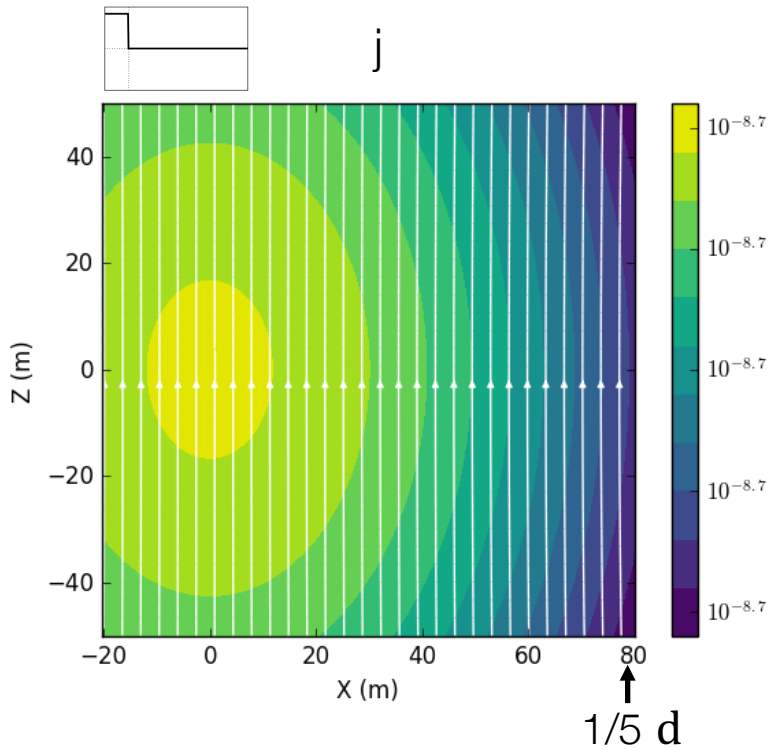
Electric Dipole in a whole space: FDEM

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

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

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

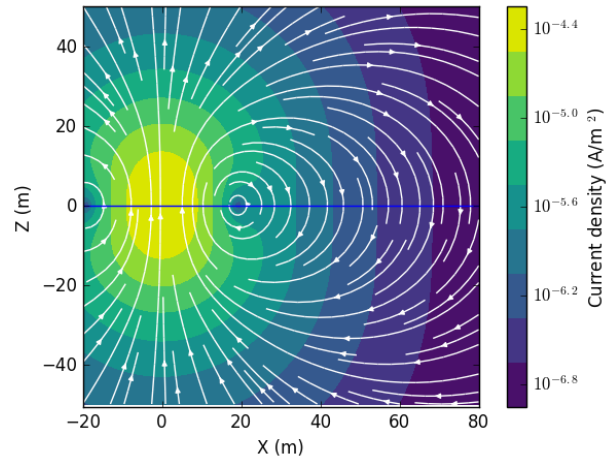
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



Summary: Dipole in a whole space

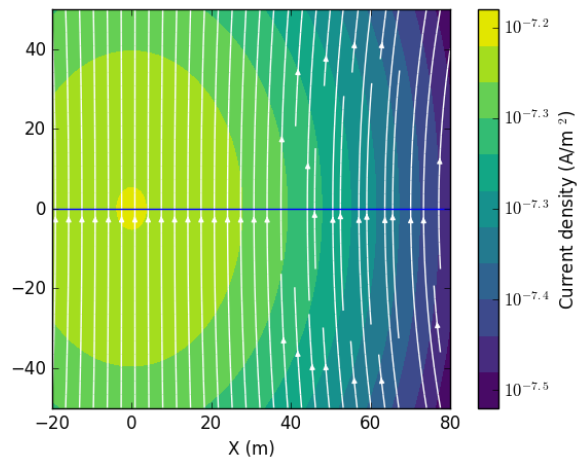
Currents diffuse into the earth

Early time
High frequency



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

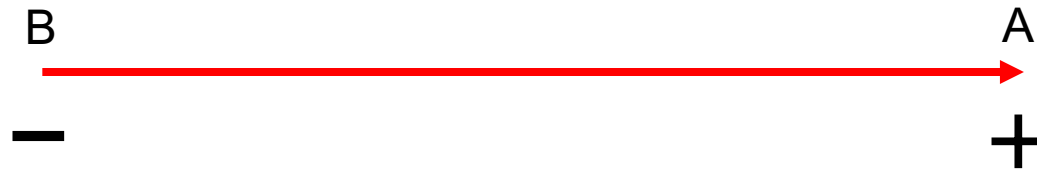
Late time
Low frequency



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

Bipole Sources

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

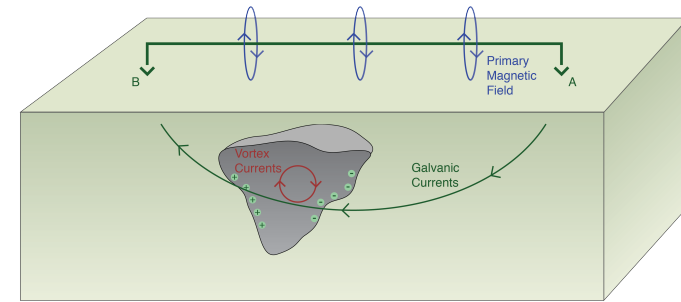


- Crooked line (horse shoe)



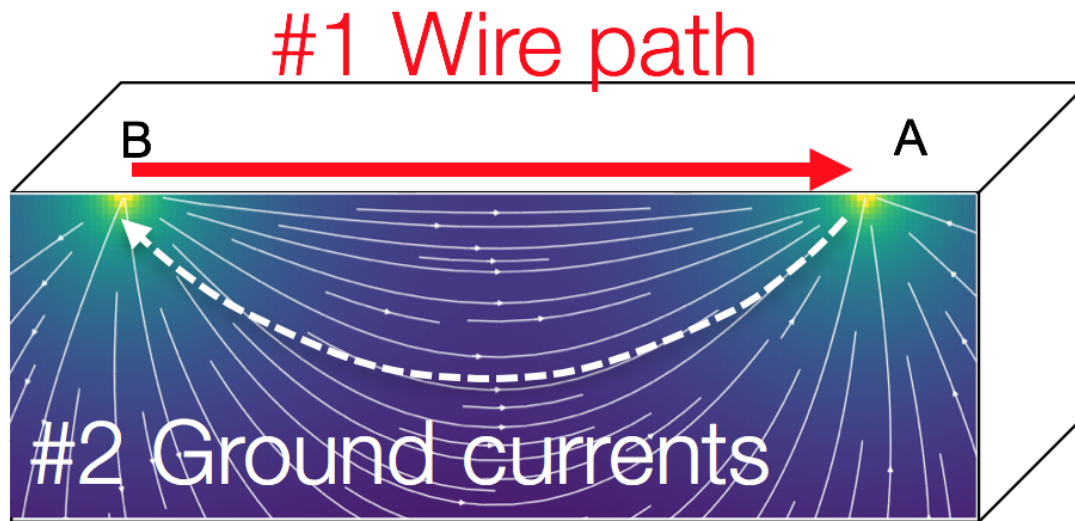
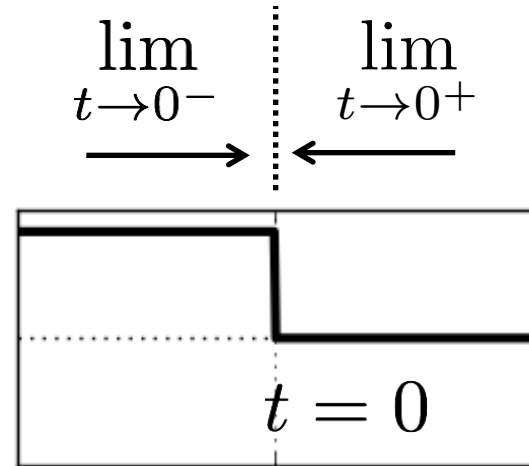
Grounded Sources: On the surface

- 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



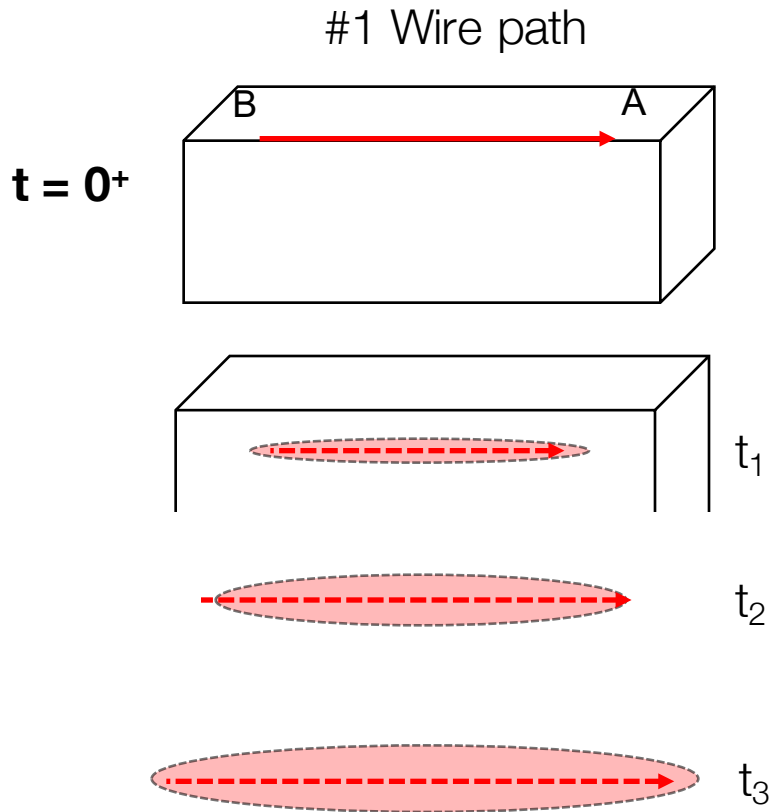
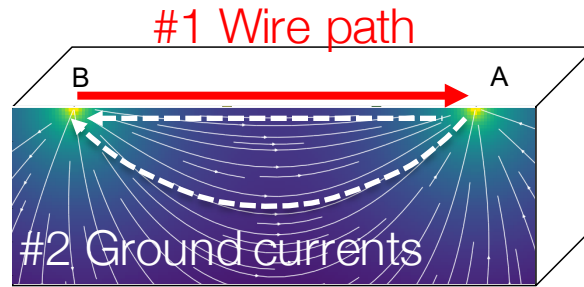
Currents: Grounded System

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



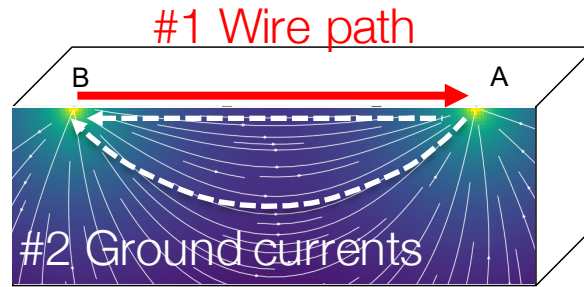
What happens when we shut the system off?

Currents: Grounded System

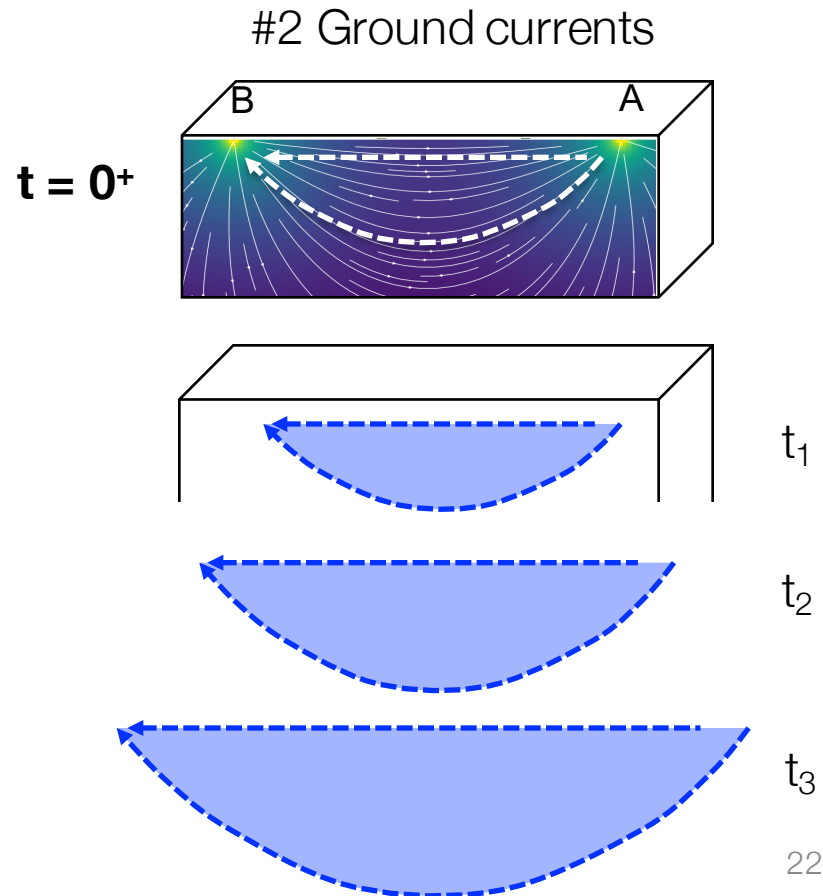


- Immediately after shut off: image current at the surface
- Successive time: currents diffuse downwards and outwards

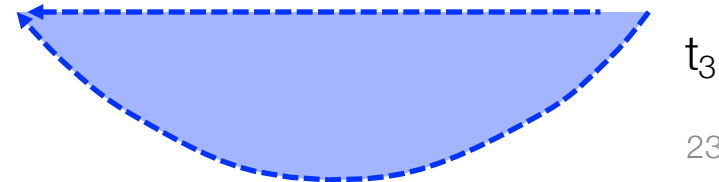
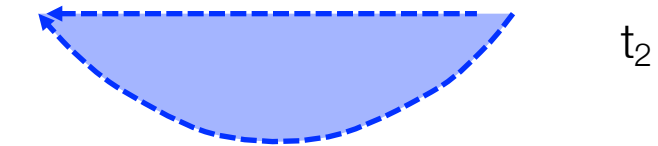
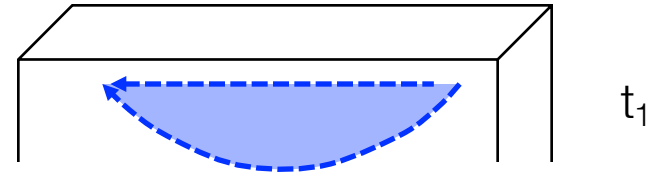
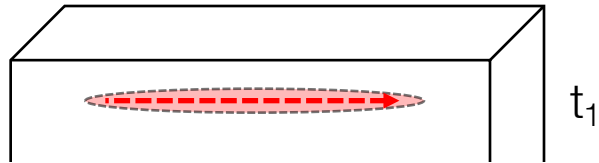
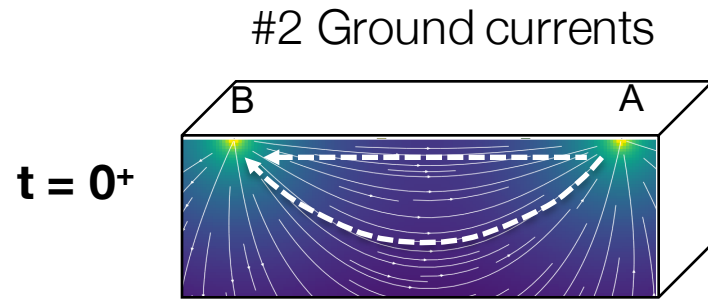
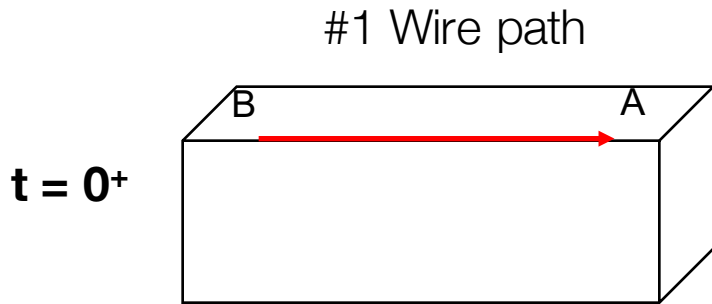
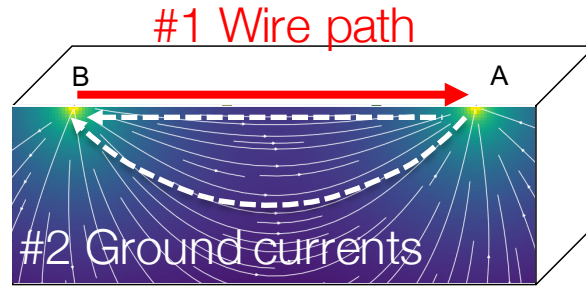
Currents: Grounded System



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

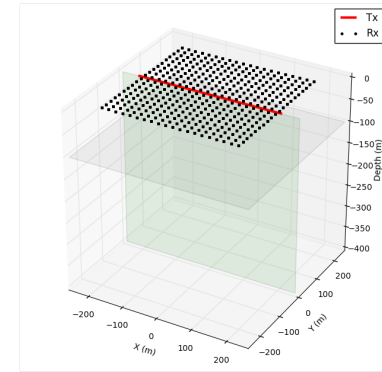


Currents: Grounded System

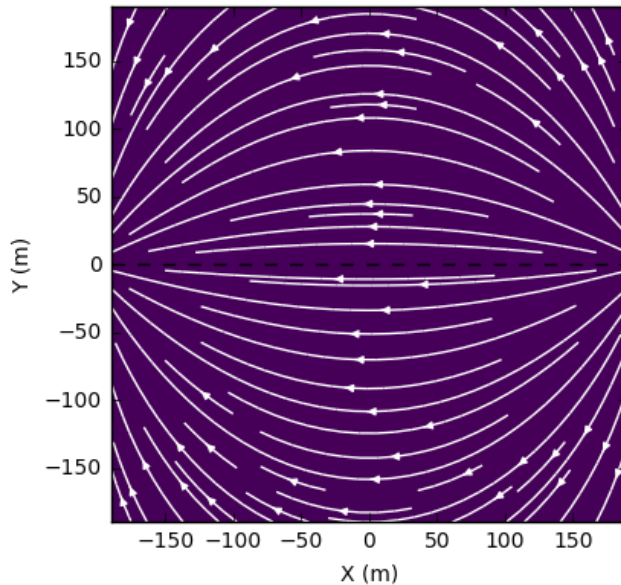


Grounded Source: Halfspace Currents

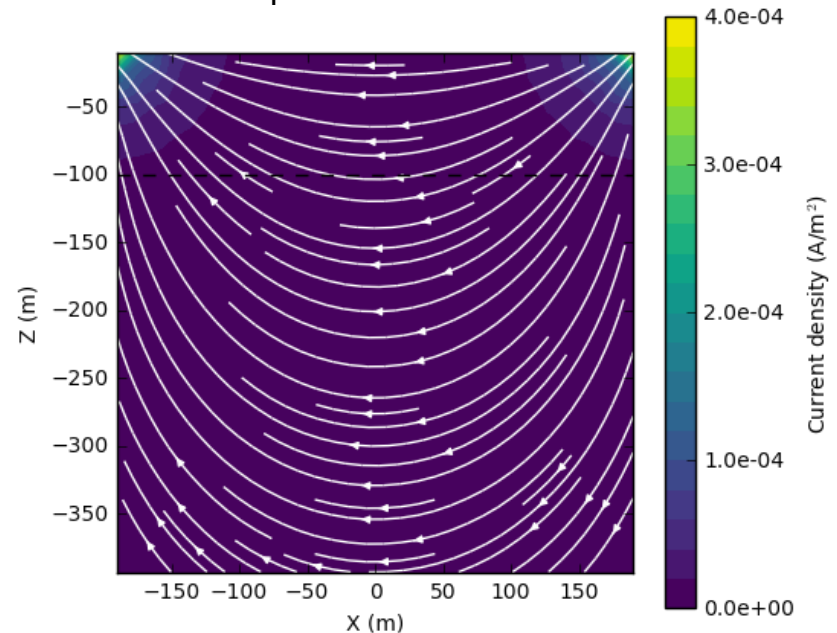
- Parameters:
 - halfspace (0.01 S/m)
 - $t=0^-$, steady state



XY plane at Z=-100 m

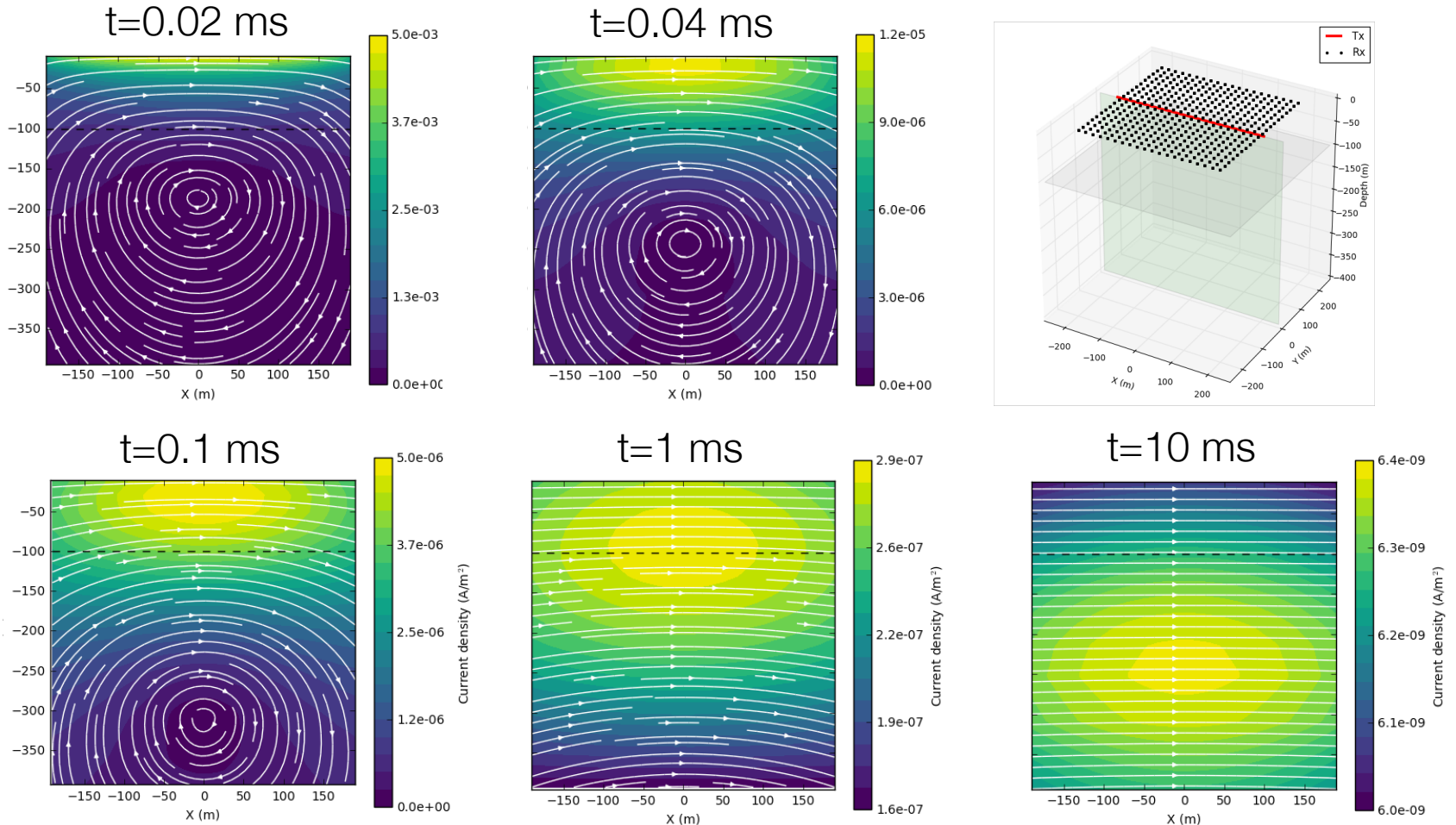


XZ plane at Y=0 m



Grounded Source: Halfspace currents

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

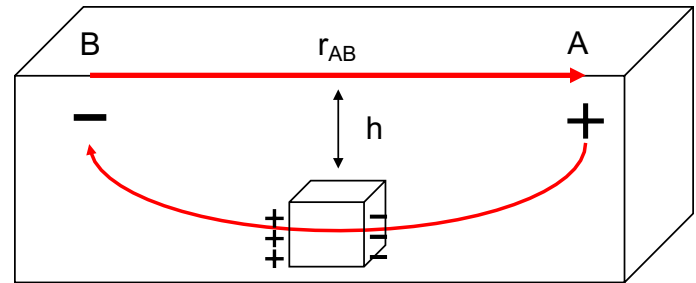


Grounded sources: with a target

- Block in a halfspace

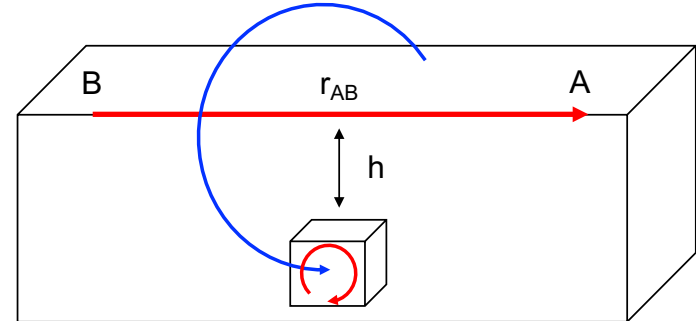
- DC

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



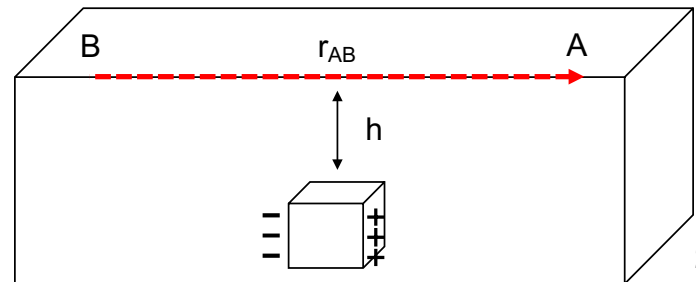
- Vortex currents

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



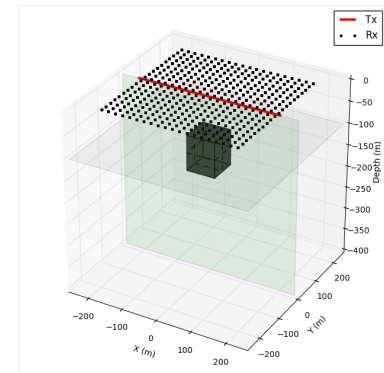
- Galvanic currents

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

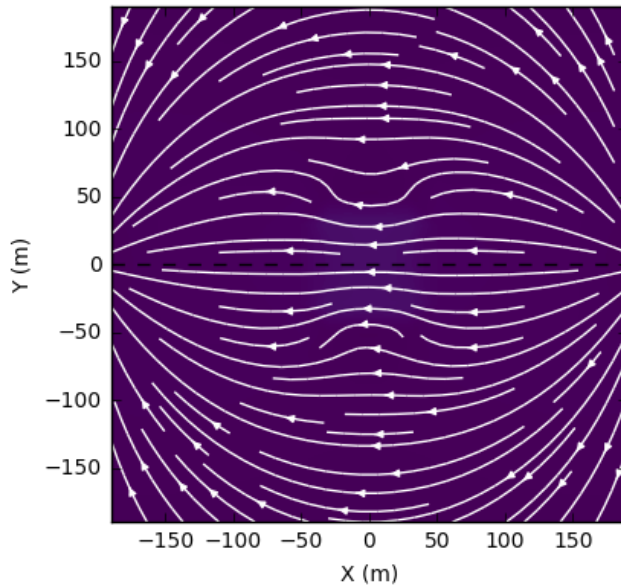


Conductor: currents

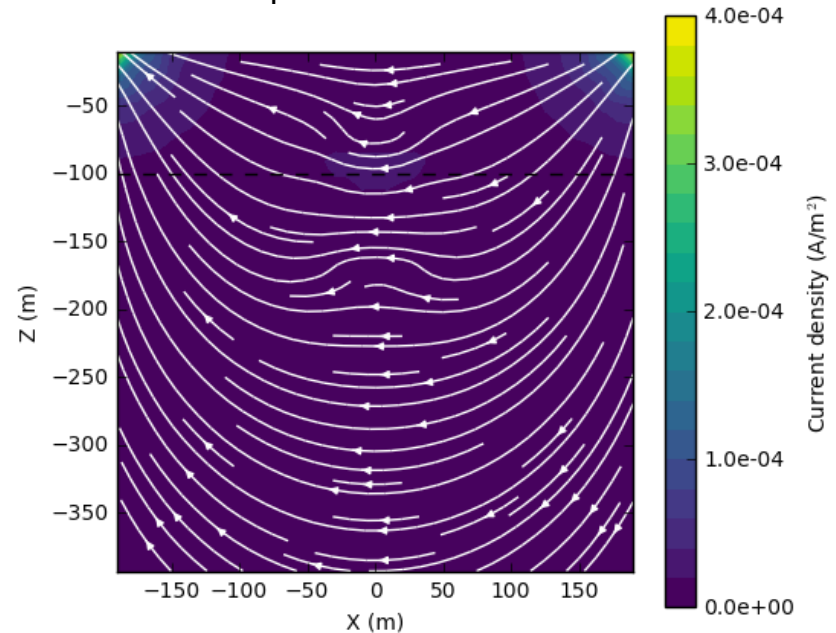
- Grounded wire
 - A conductor (1S/m) in a halfspace (0.01 S/m)
 - $t=0^-$, steady state



XY plane at Z=-100 m

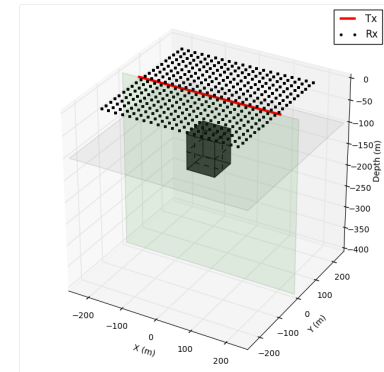


XZ plane at Y=0 m

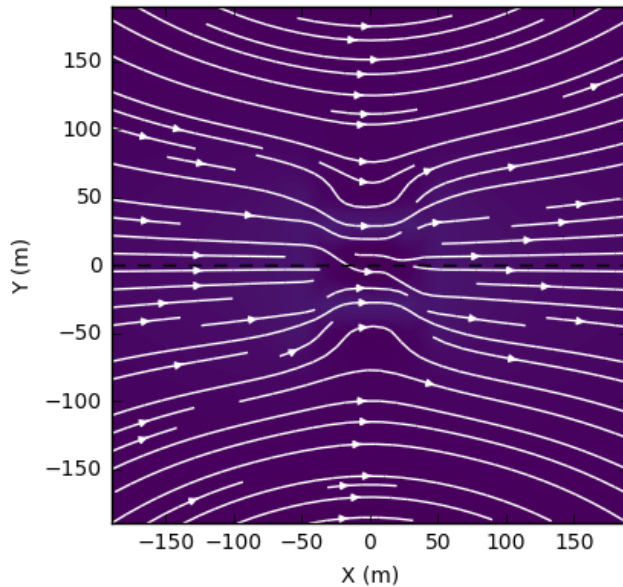


Conductor: currents

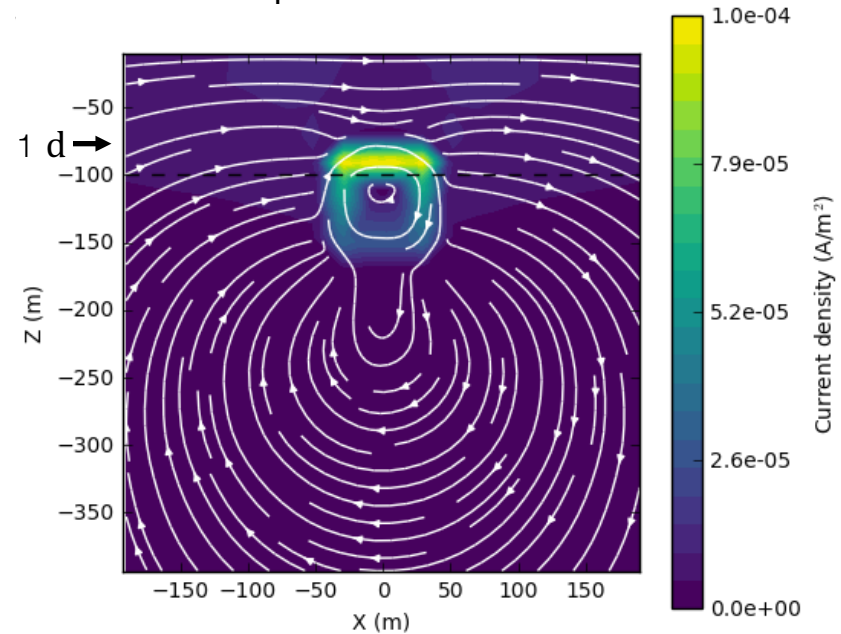
- Grounded wire
 - A conductor (1S/m) in a halfspace (0.01 S/m)
 - **0.04** ms, $d = 80$ m



XY plane at Z=-100 m

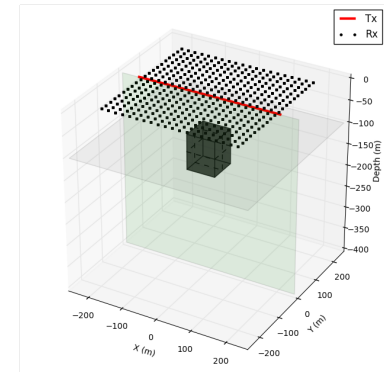


XZ plane at Y=0 m

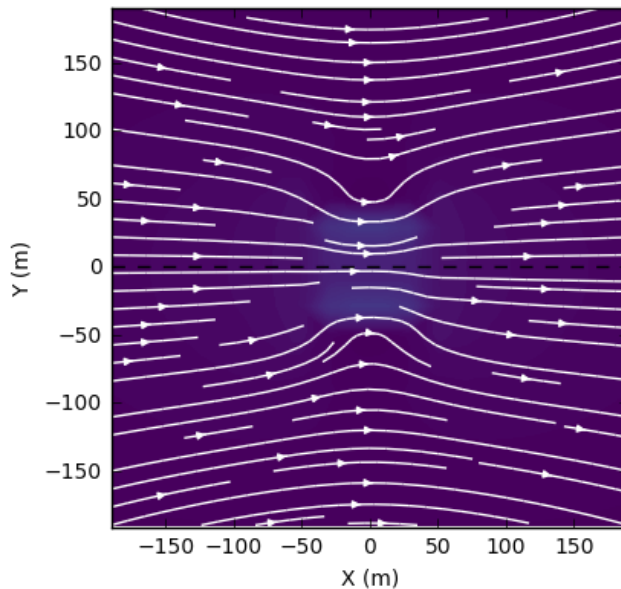


Conductor: currents

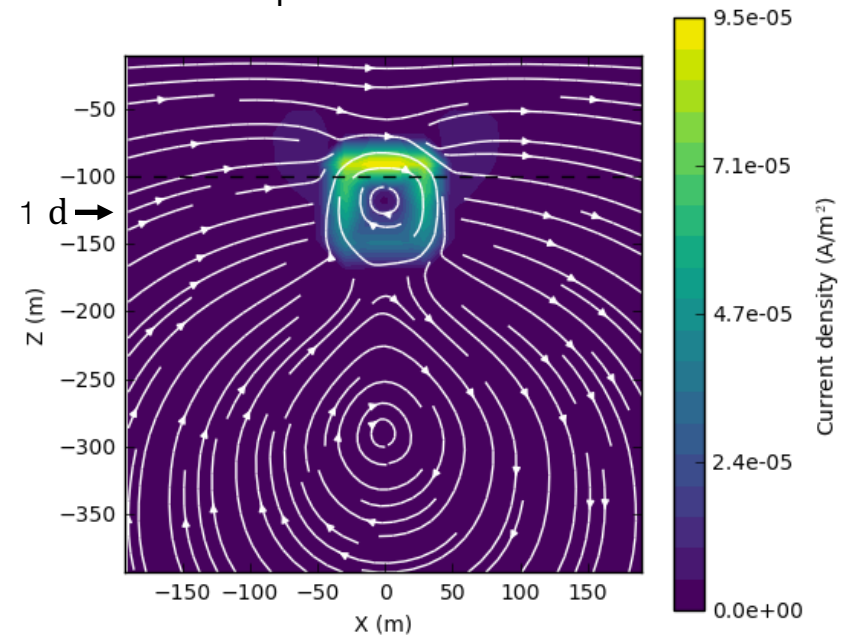
- Grounded wire
 - A conductor (1S/m) in a halfspace (0.01 S/m)
 - **0.1** ms, $d = 126$ m



XY plane at Z=-100 m

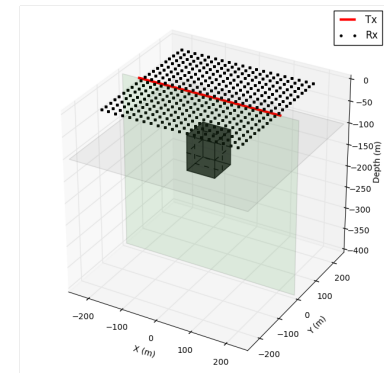


XZ plane at Y=0 m

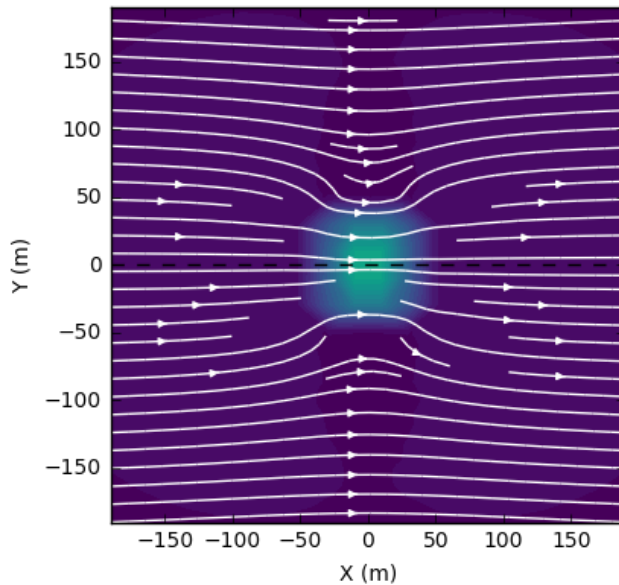


Conductor: currents

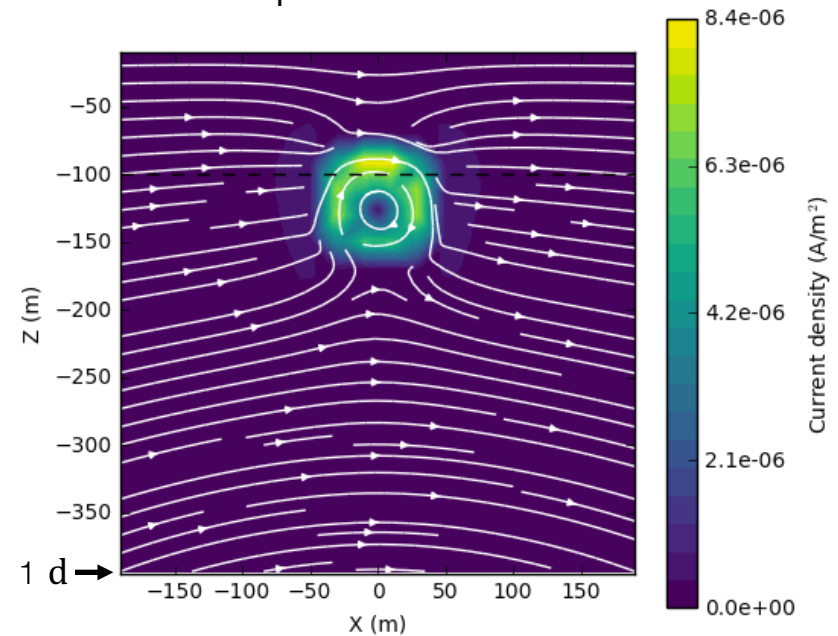
- Grounded wire
 - A conductor (1S/m) in a halfspace (0.01 S/m)
 - 1 ms, $d = 400$ m



XY plane at $Z = -100$ m

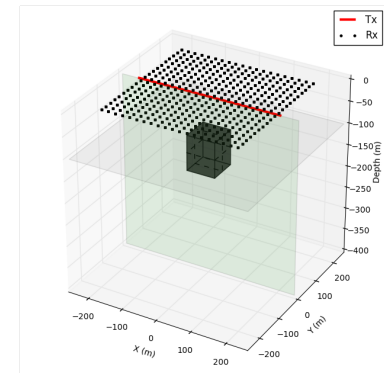


XZ plane at $Y = 0$ m

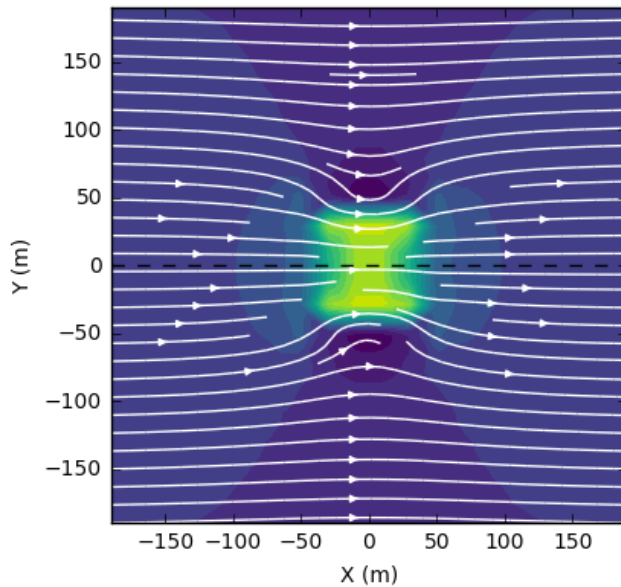


Conductor: currents

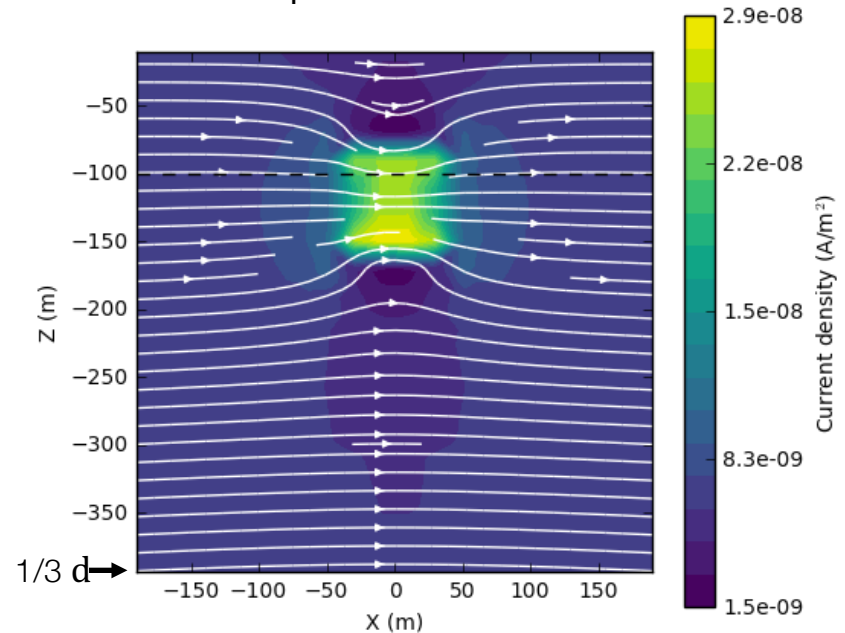
- Grounded wire
 - A conductor (1S/m) in a halfspace (0.01 S/m)
 - **10** ms, $d = 1270$ m



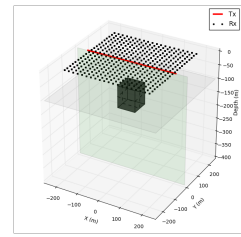
XY plane at $Z=-100$ m



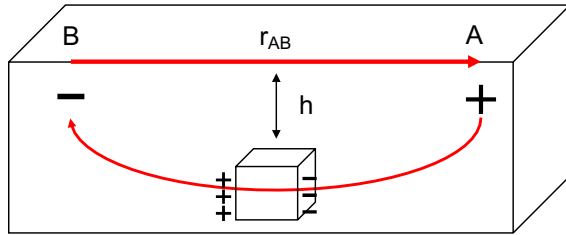
XZ plane at $Y=0$ m



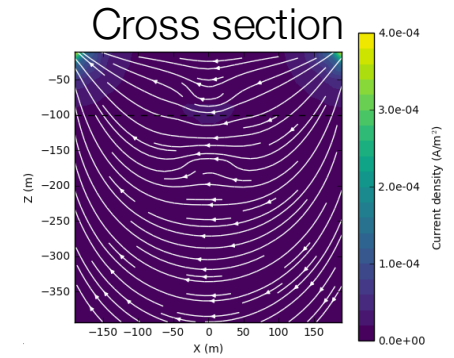
Conductor: currents



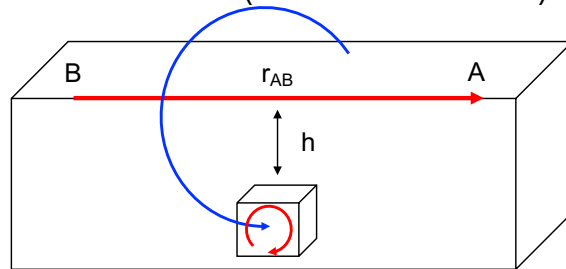
Steady State (galvanic current)



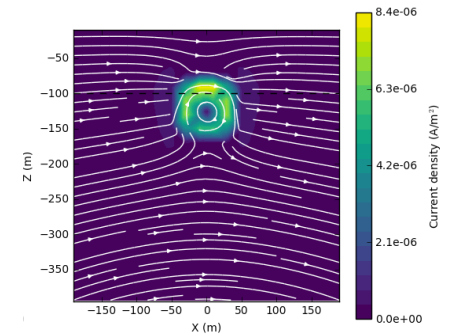
Galvanic current
 $t = 0^-$



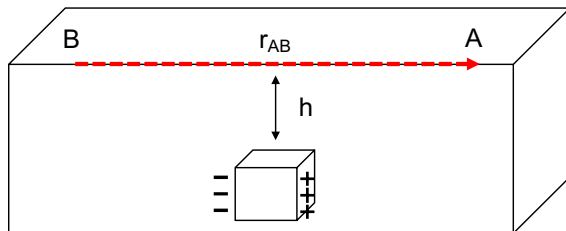
EM induction (vortex current)



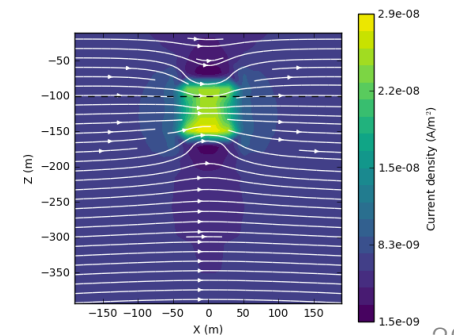
Vortex current
 $t = 1 \text{ ms}$



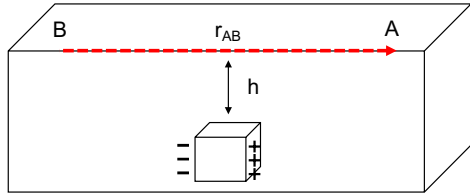
EM induction (galvanic current)



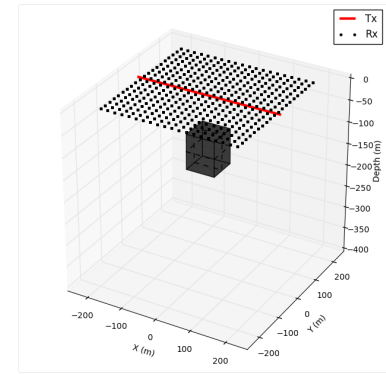
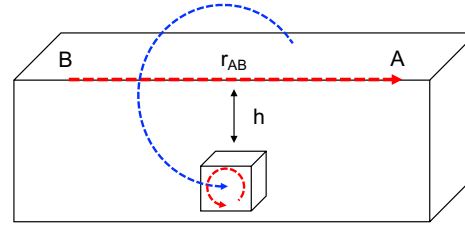
Galvanic current
 $t = 10 \text{ ms}$



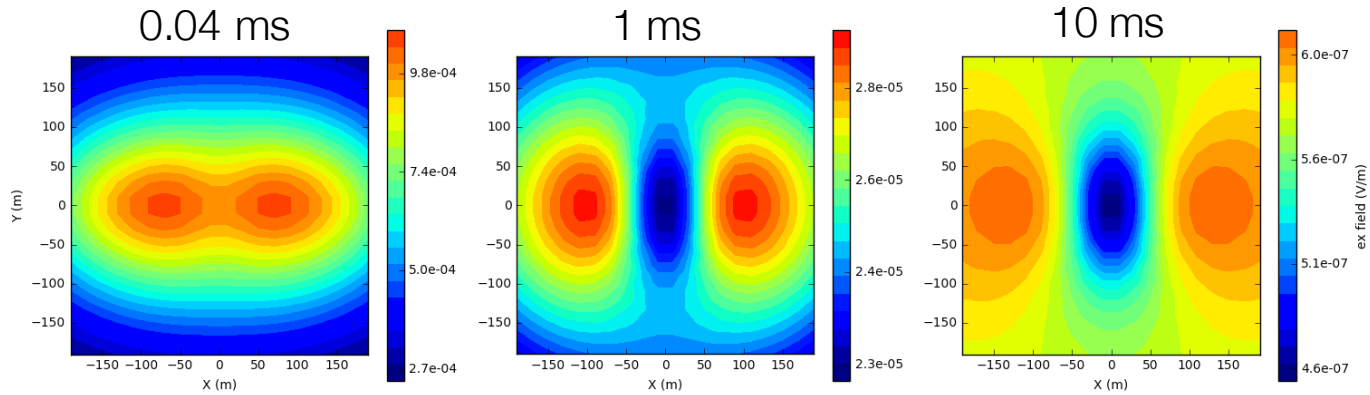
Data: e_x field



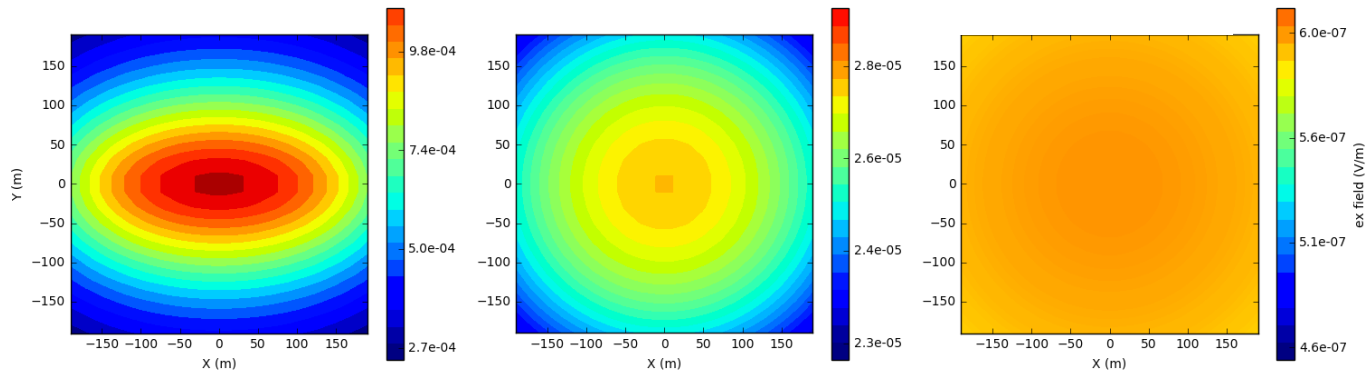
+



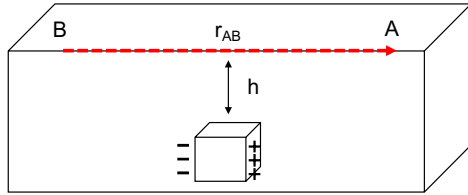
Conductor



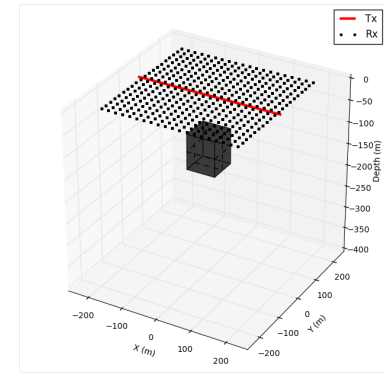
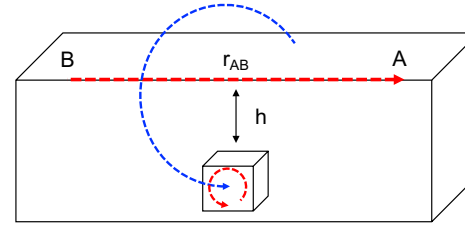
Halfspace



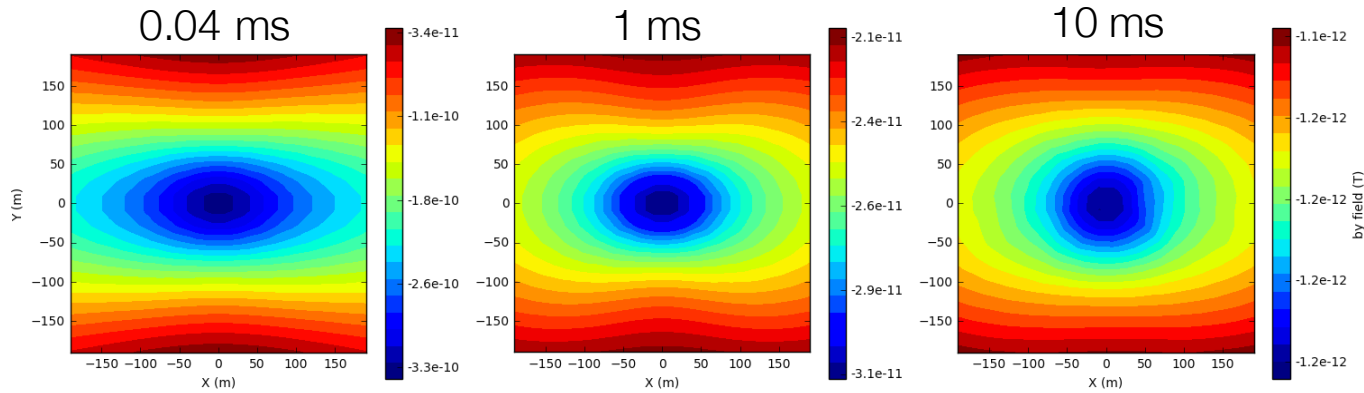
Data: b_y field



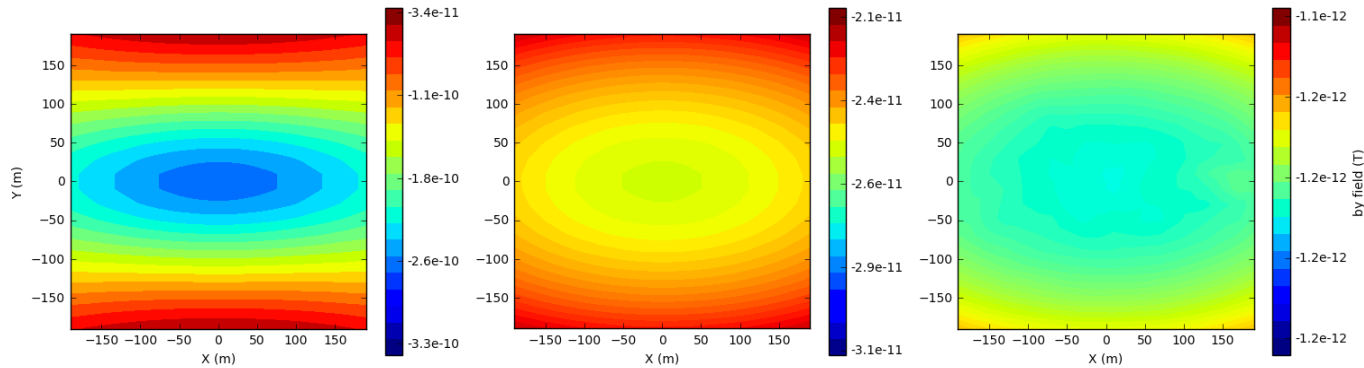
+



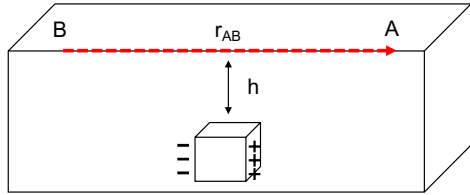
Conductor



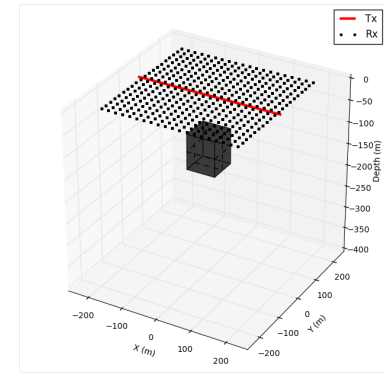
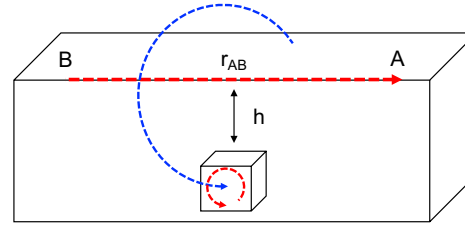
Halfspace



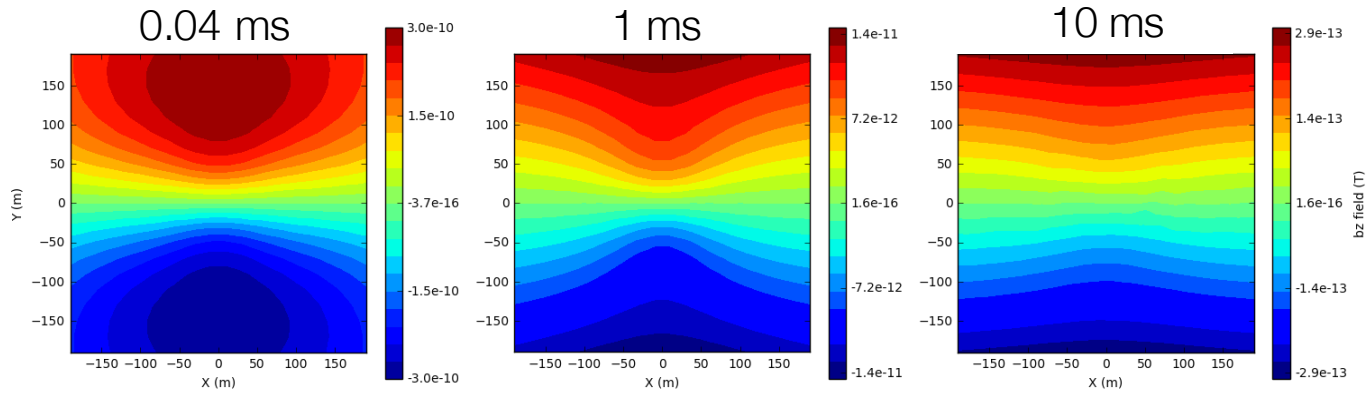
Data: b_z field



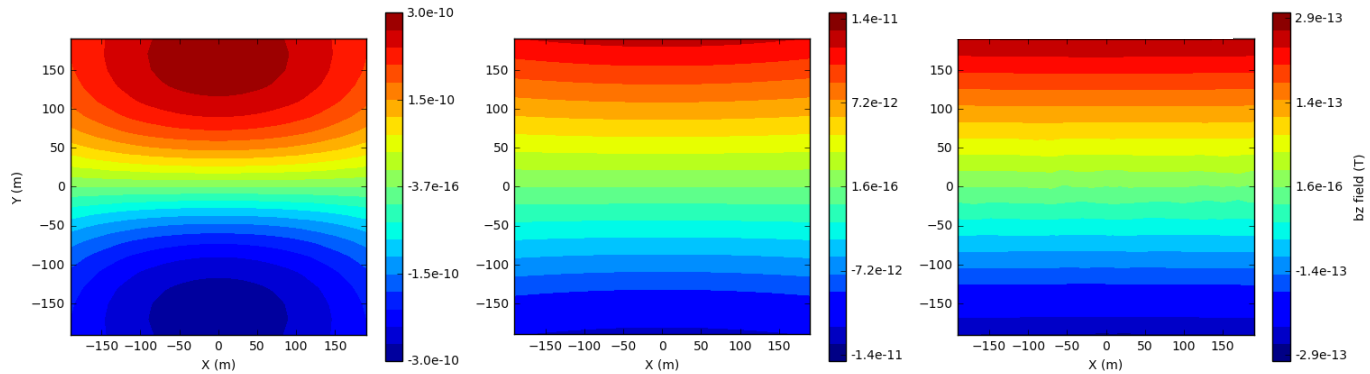
+



Conductor

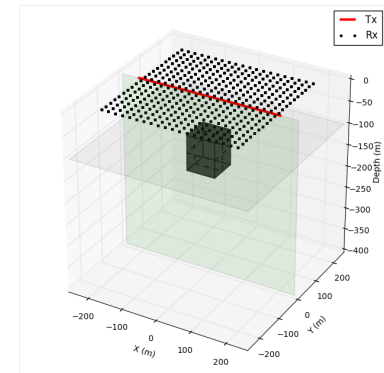


Halfspace

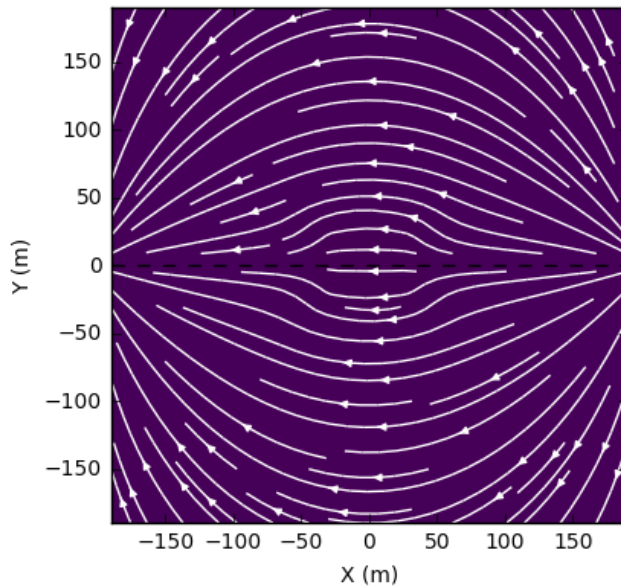


Resistor: currents

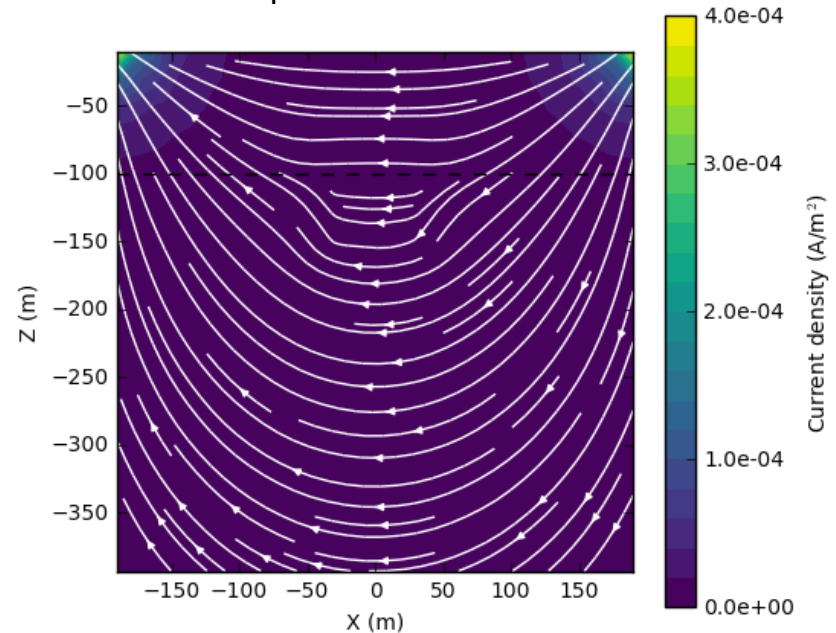
- Grounded wire
 - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
 - $t=0^-$, steady state



XY plane at Z=-100 m

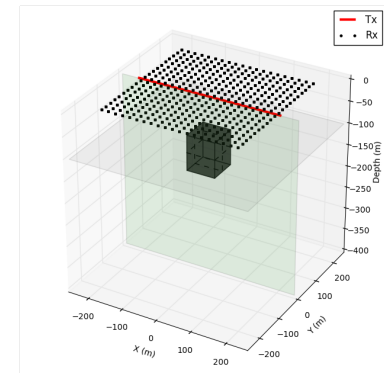


XZ plane at Y=0 m

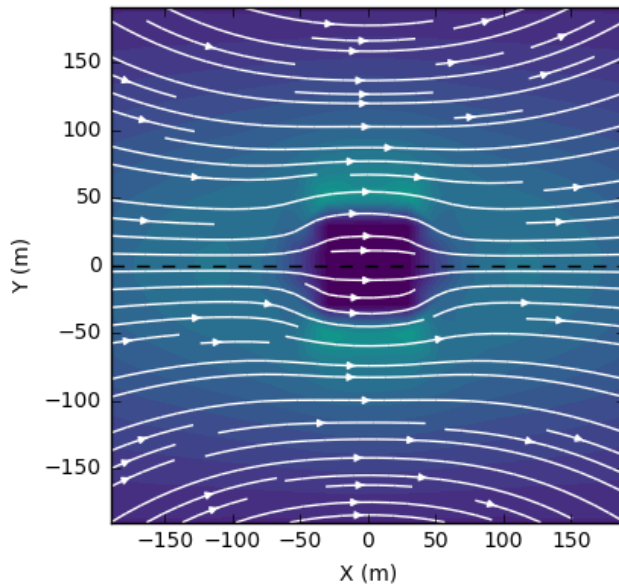


Resistor: currents

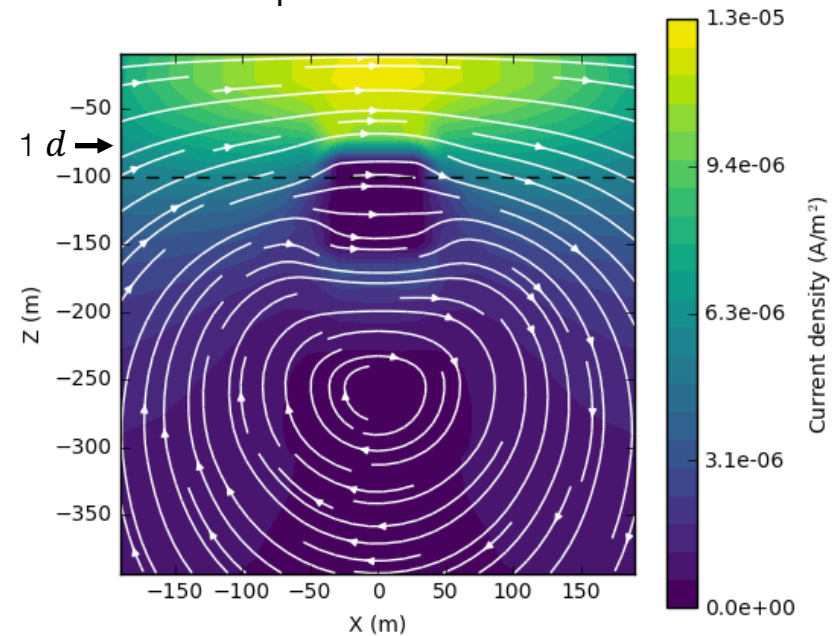
- Grounded wire
 - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
 - **0.04** ms, $d = 80$ m



XY plane at $Z = -100$ m

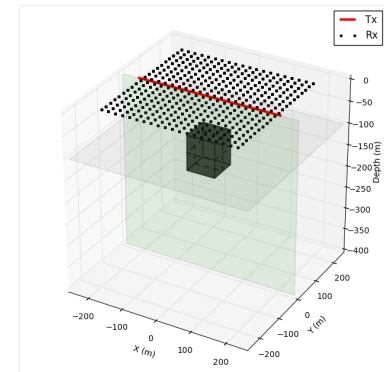


XZ plane at $Y = 0$ m

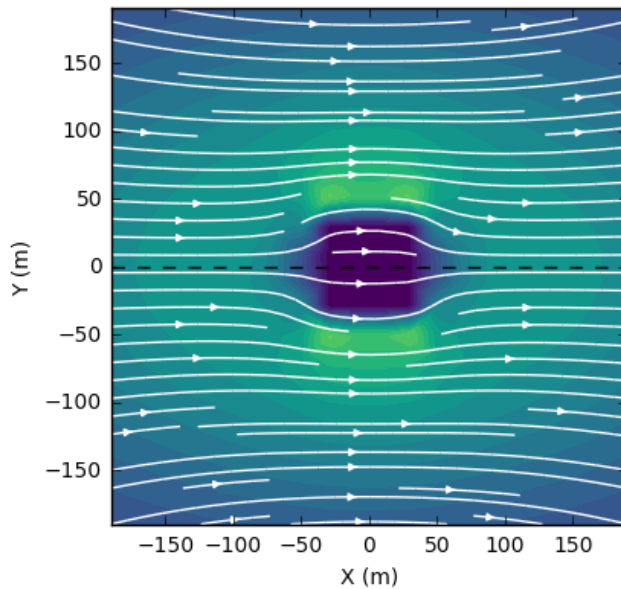


Resistor: currents

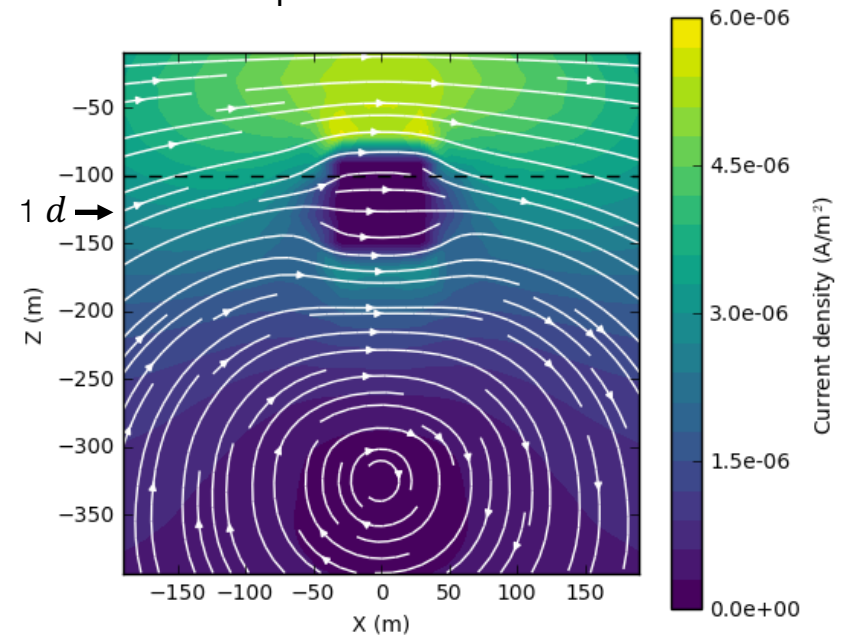
- Grounded wire
 - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
 - **0.1** ms, $d = 126$ m



XY plane at $Z = -100$ m

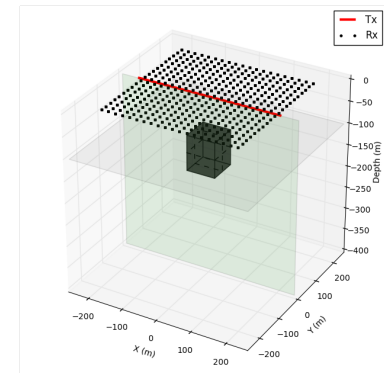


XZ plane at $Y = 0$ m

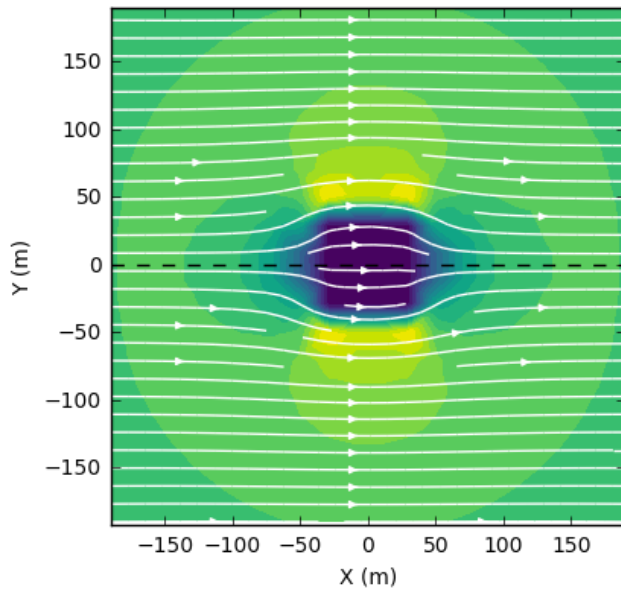


Resistor: currents

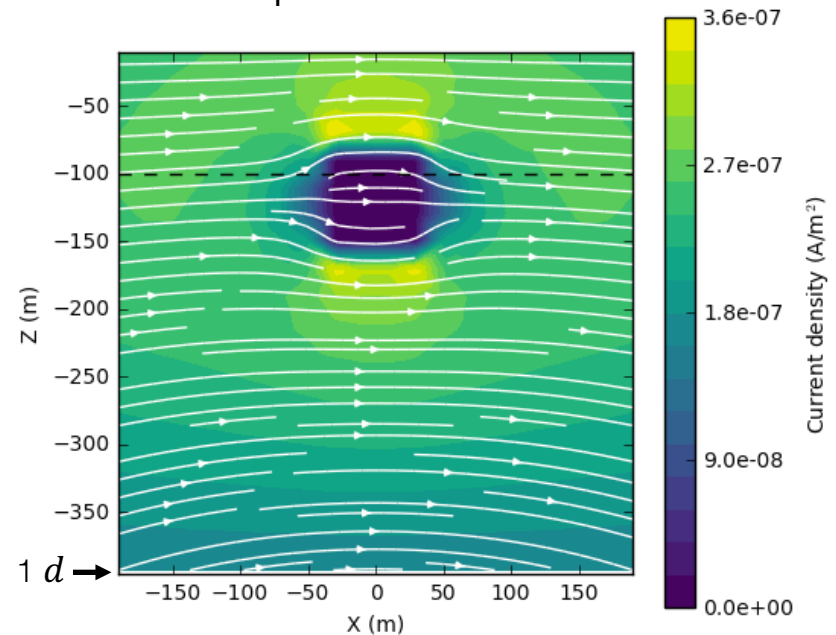
- Grounded wire
 - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
 - **1** ms, $d = 400$ m



XY plane at $Z = -100$ m

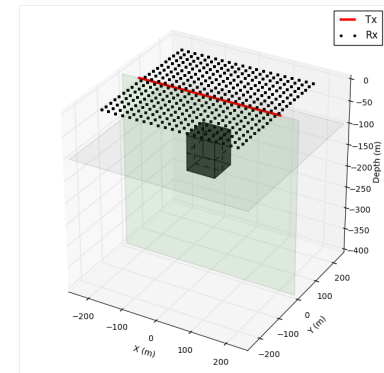


XZ plane at $Y = 0$ m

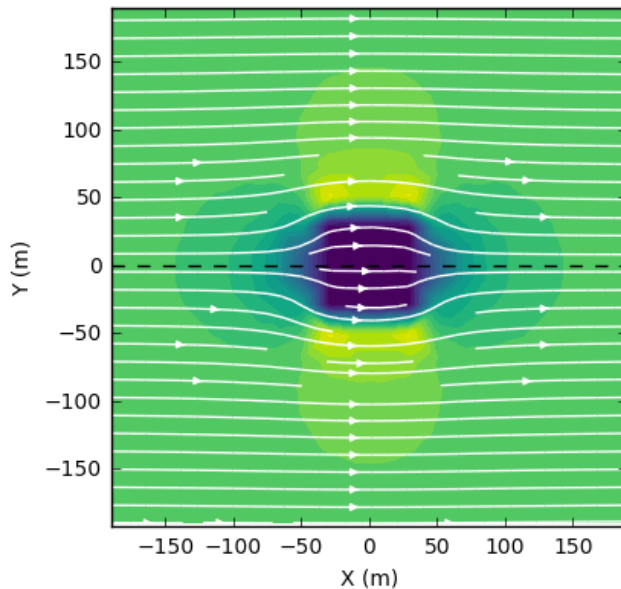


Resistor: currents

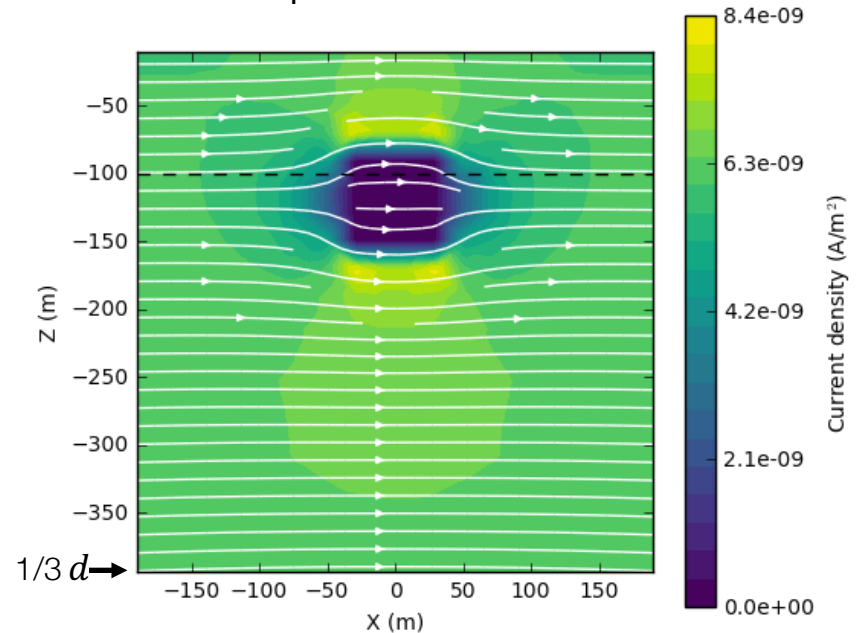
- Grounded wire
 - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
 - **10** ms, $d = 1270$ m



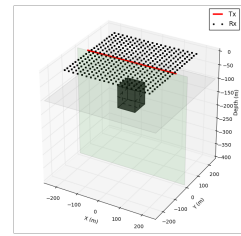
XY plane at $Z = -100$ m



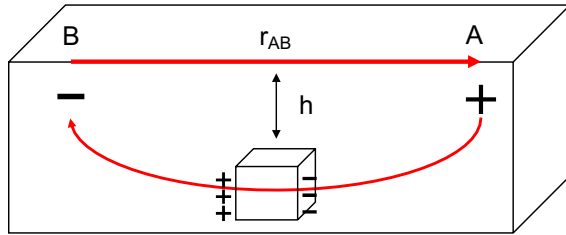
XZ plane at $Y = 0$ m



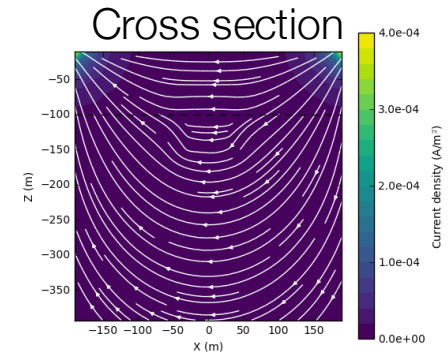
Resistor: currents



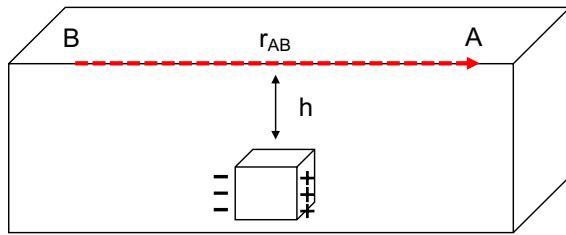
DC (galvanic current)



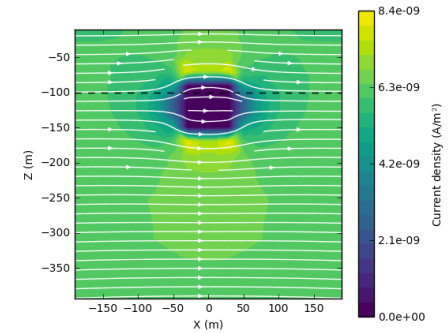
Galvanic current
 $t = 0^-$



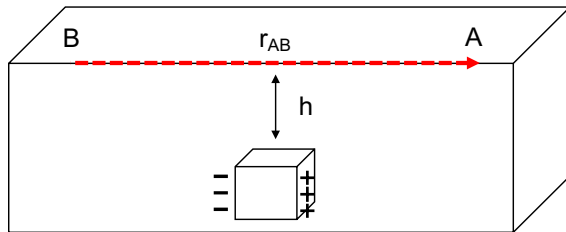
EM induction (galvanic current)



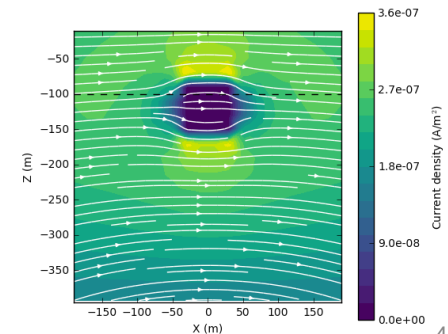
Galvanic current
 $t = 1 \text{ ms}$



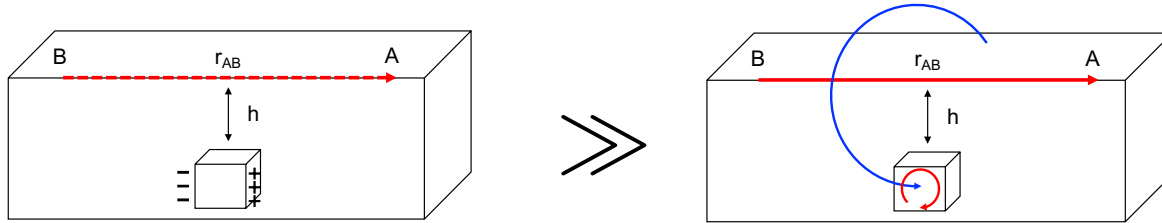
EM induction (galvanic current)



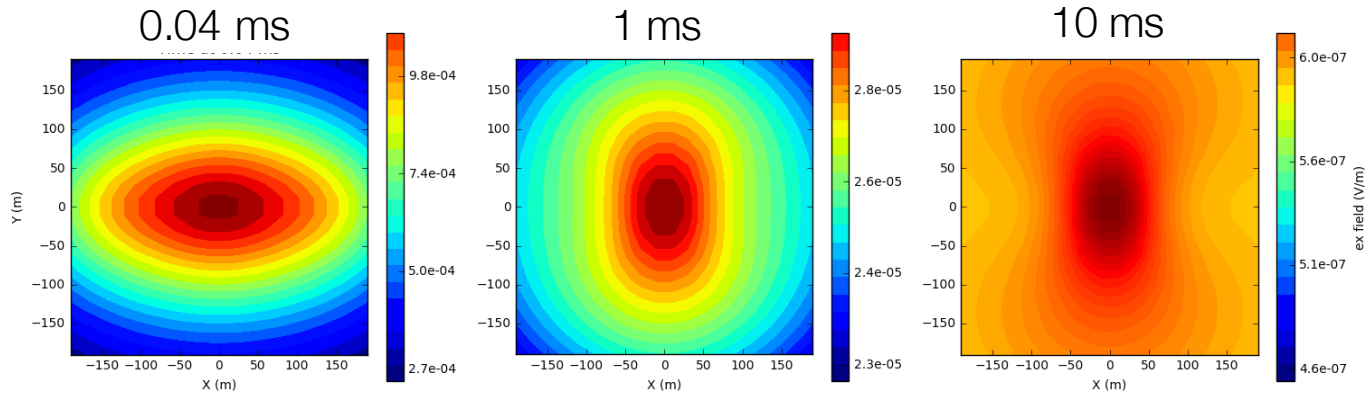
Galvanic current
 $t = 10 \text{ ms}$



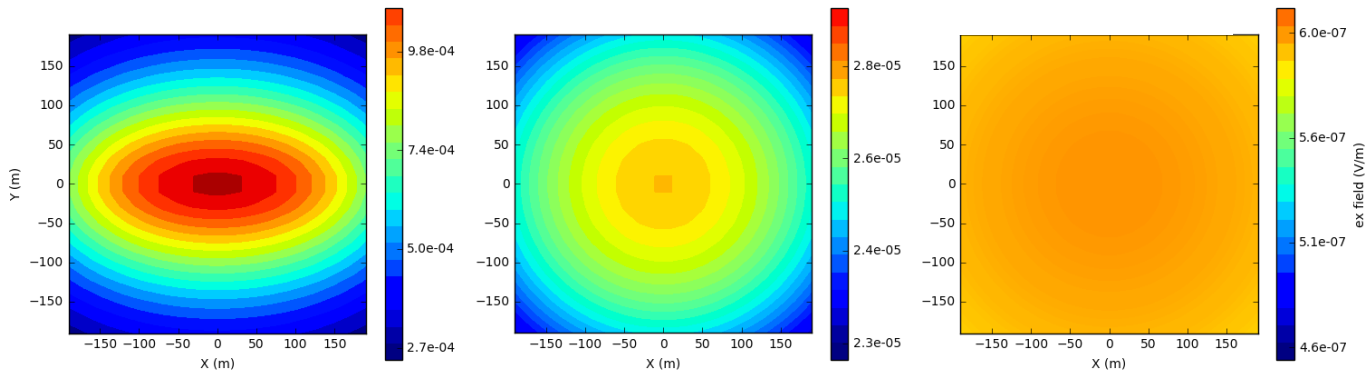
Data: e_x field



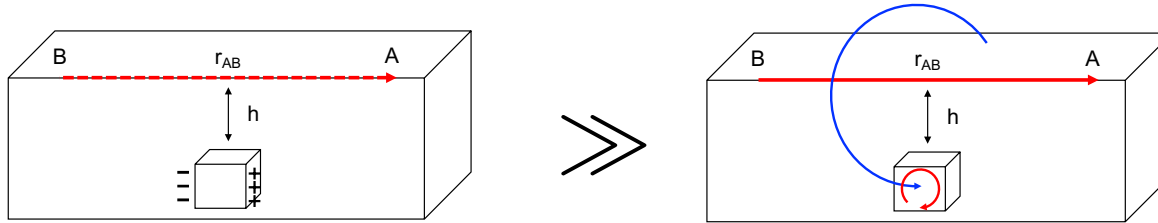
Resistor



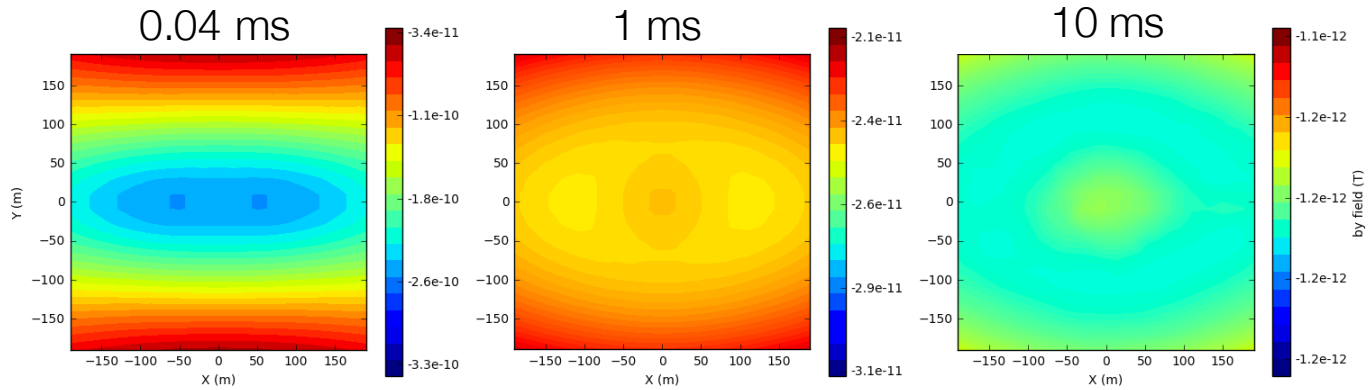
Halfspace



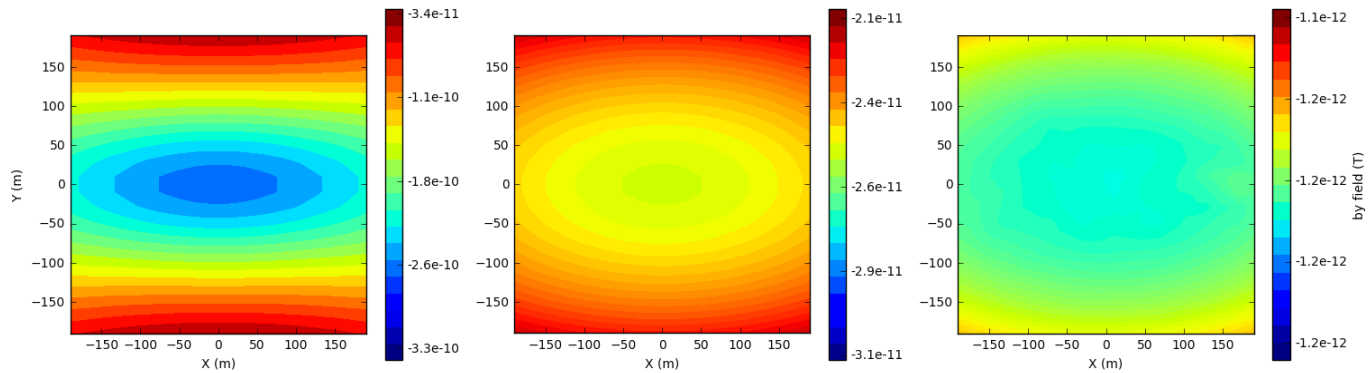
Data: b_y field



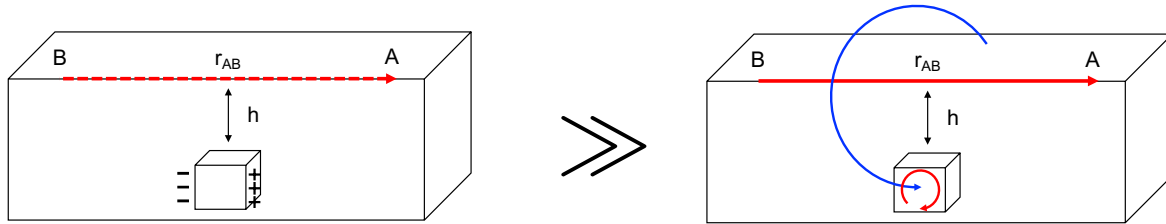
Resistor



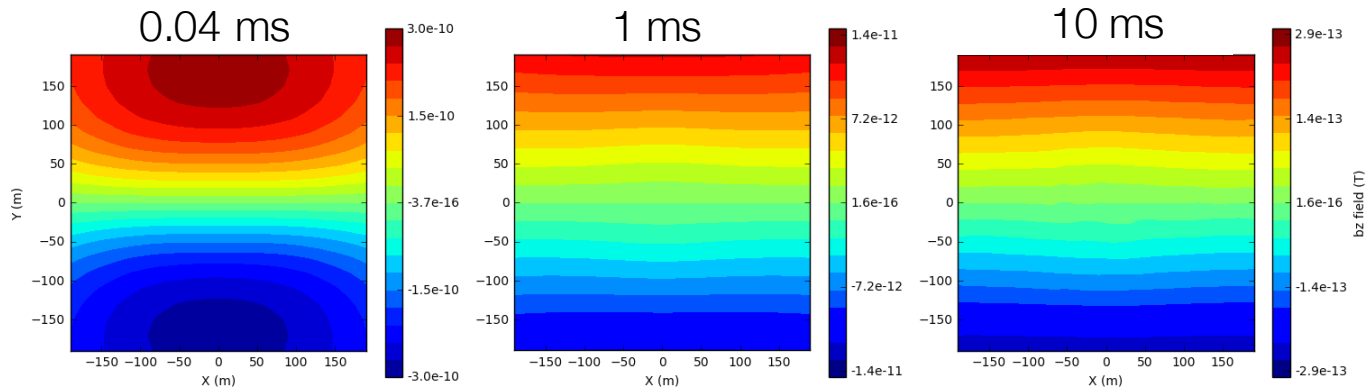
Halfspace



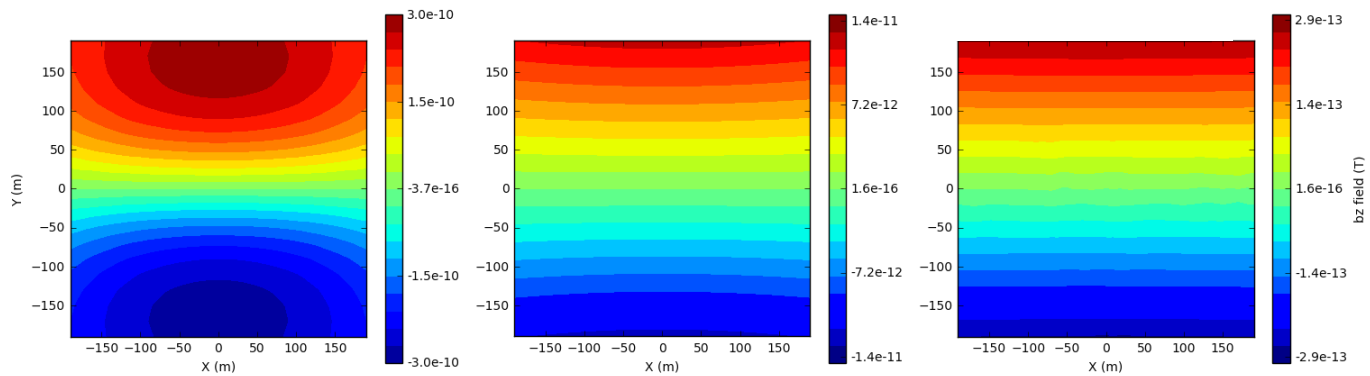
Data: b_z field



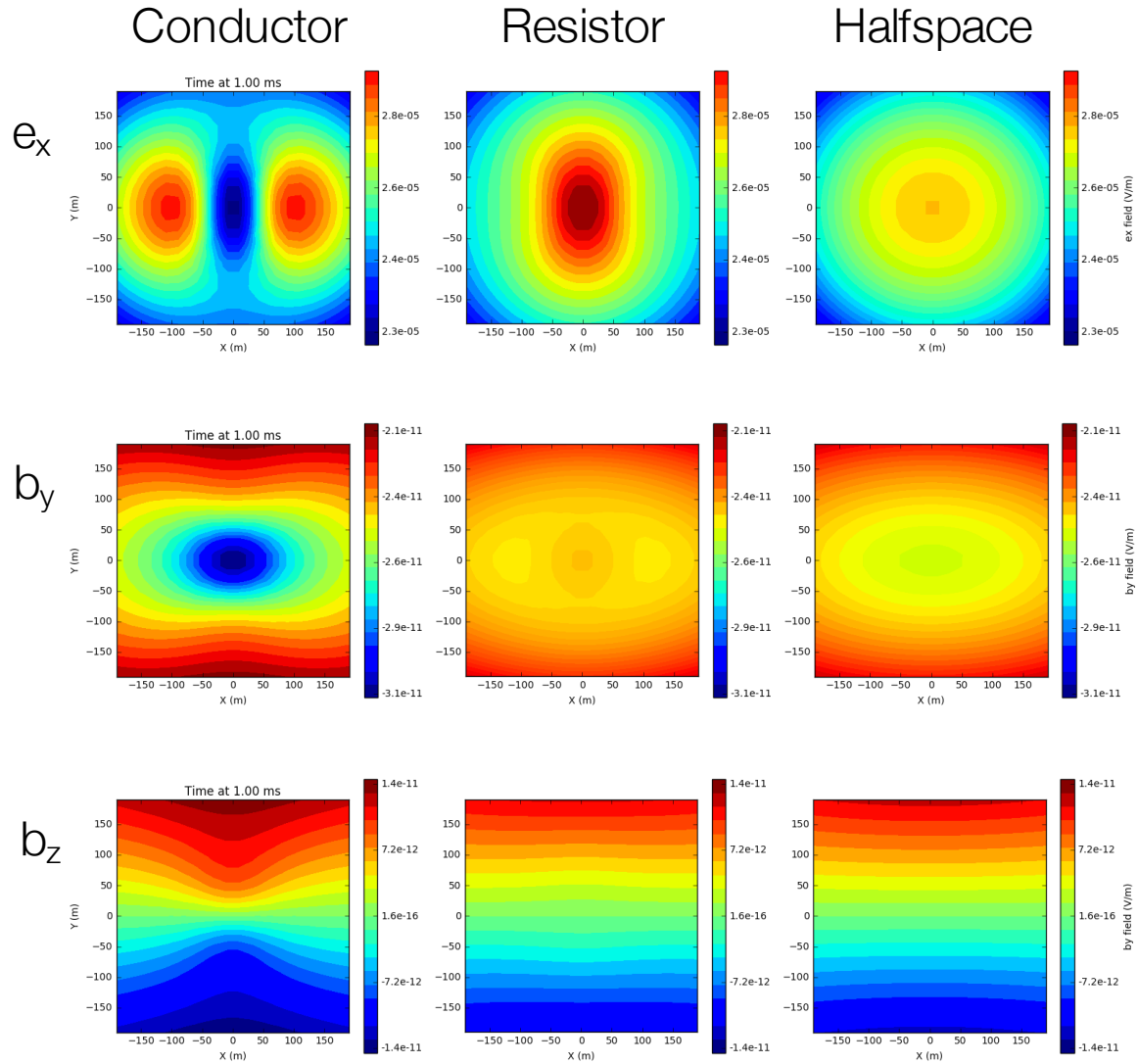
Resistor



Halfspace

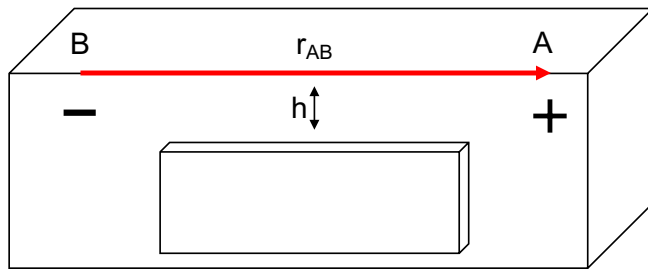


Data summary

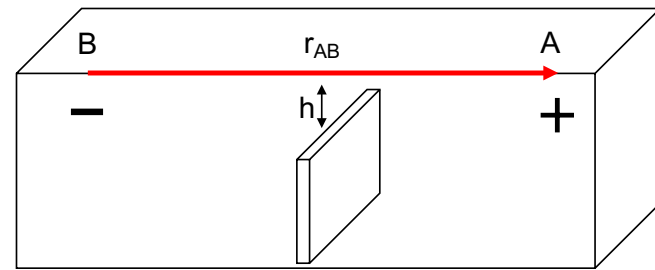


Geometric Complexities

- 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

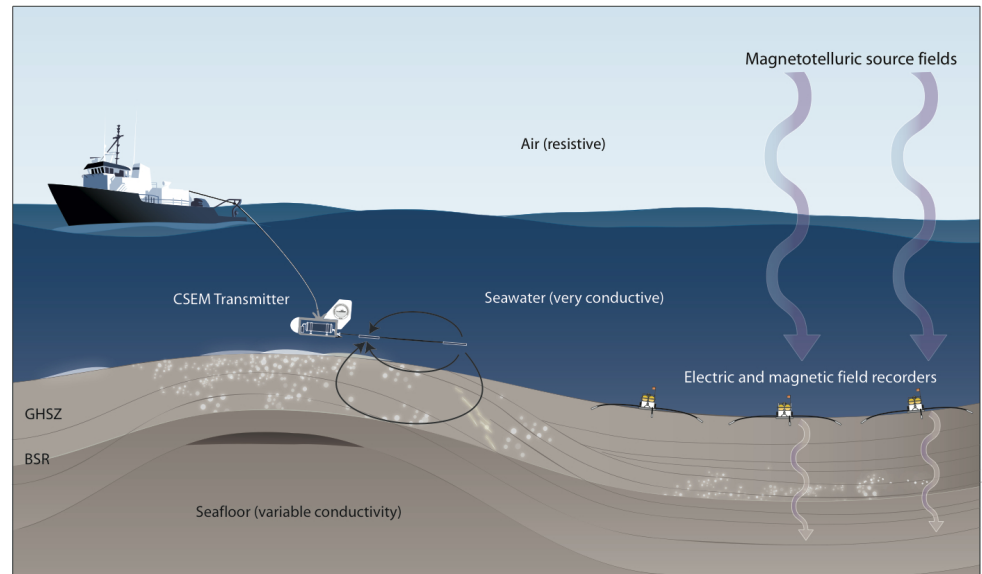
- Questions

- Marine CSEM: Overview
- Case history: Methane Hydrates

Controlled-Source Marine EM (CSEM)

Application areas

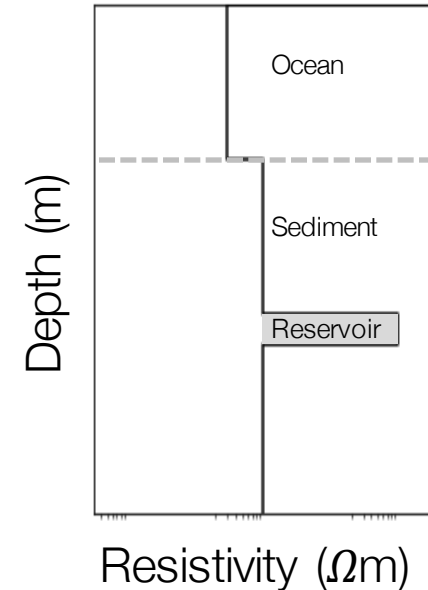
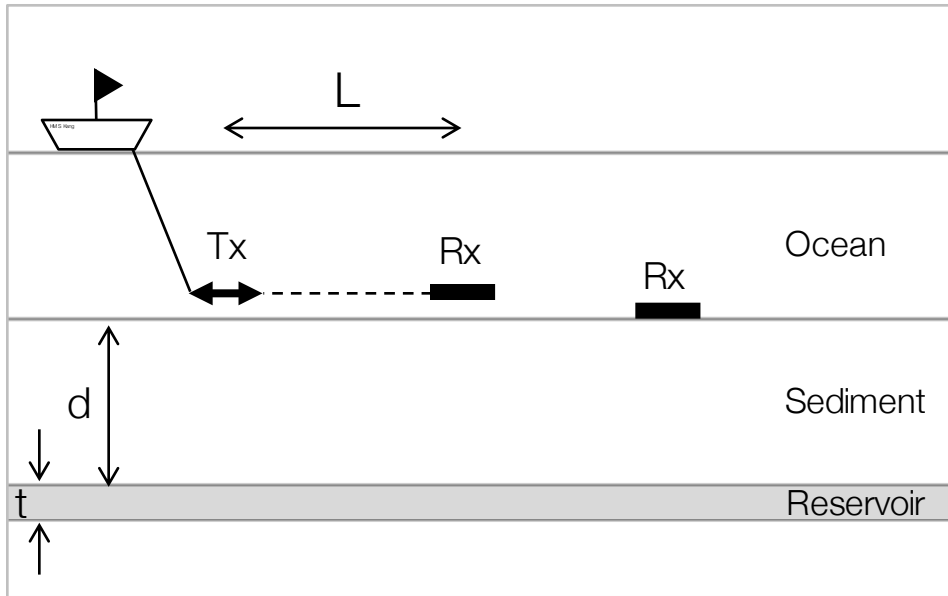
- Oil and gas
- Submarine massive sulfide (SMS)
- Methane hydrates
- Tectonic studies
- Offshore UXO
- Offshore groundwater



Application with physical properties

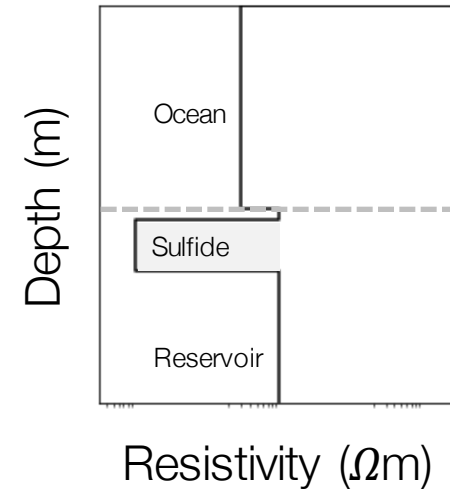
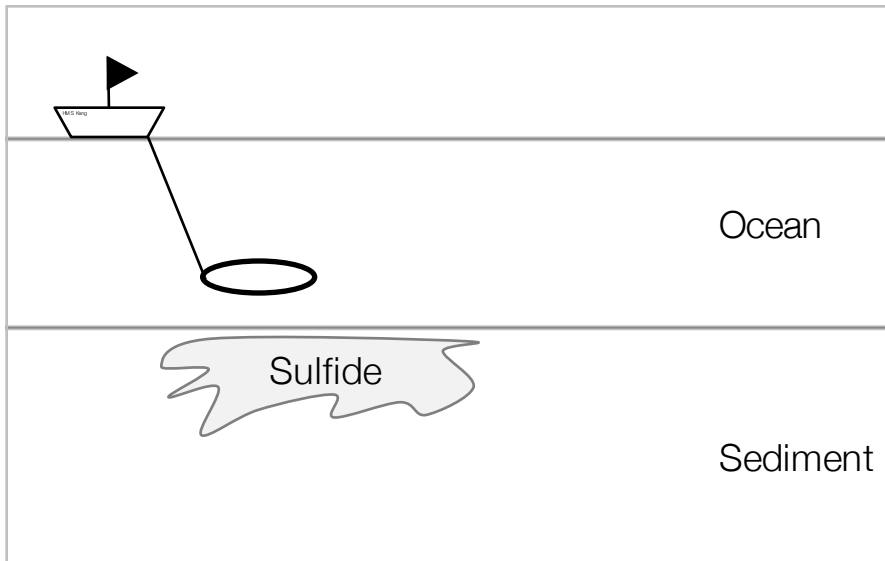
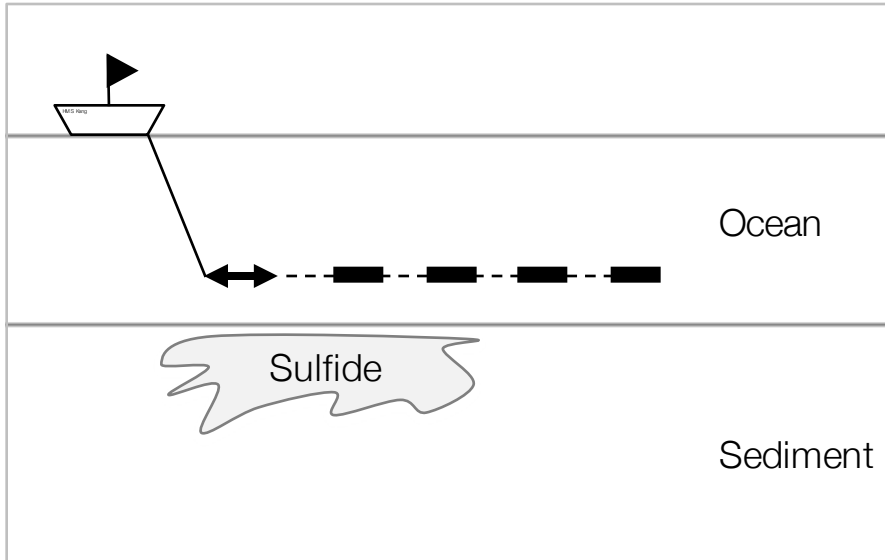
	ρ (Ωm)	σ (S/m)
Seawater	0.25-0.31 (15-3 °C)	3.3-4
Freshwater	100-1000	0.001-0.01
Sediment	1-5	0.2-1
Hydrocarbon	~100	~0.01
Hydrate	2000 (0 °C)	0.005
Massive sulfides	0.01-1	1-100

Resistive target: hydrocarbons



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

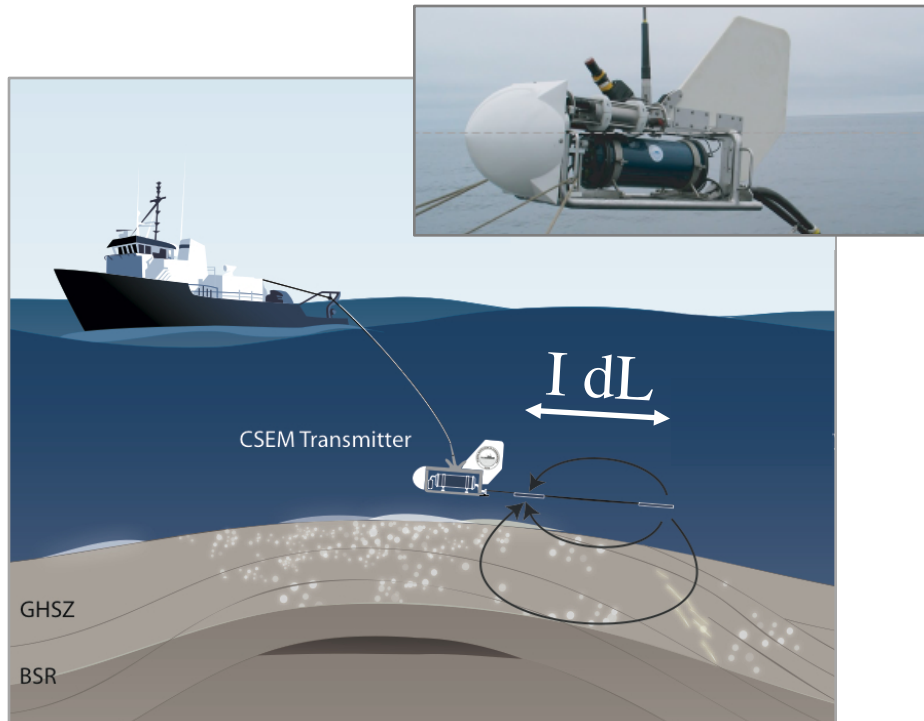
Conductive Target: Massive sulfide



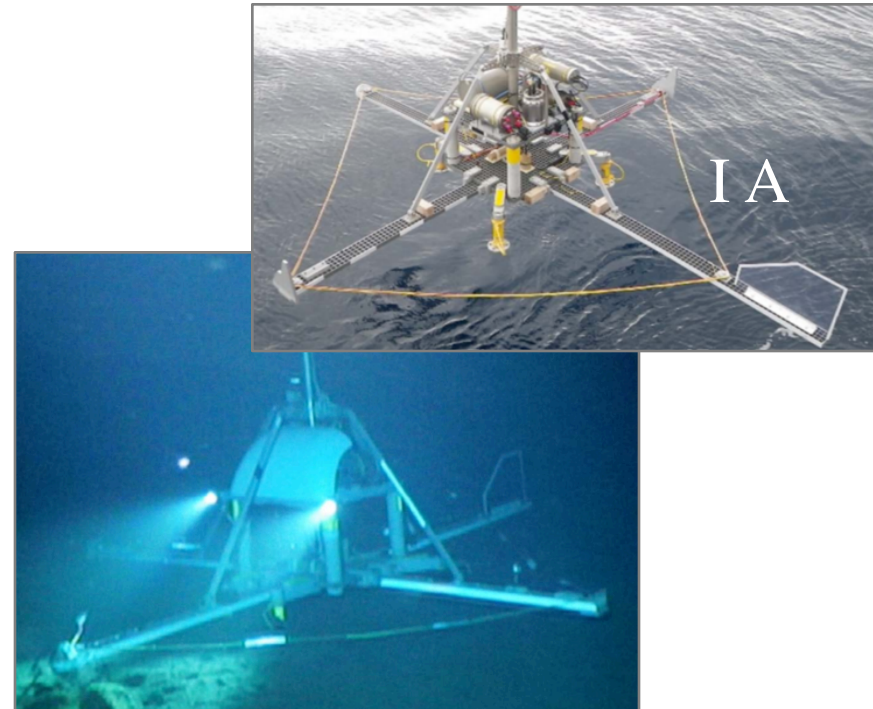
- Galvanic source
 - Towed E-field receivers
- Inductive source
 - Towed on ROV
 - db/dt sensors (coil)

Transmitters

Galvanic (Scripps: SUESI)



Inductive (Waseda Univ., GEOMAR)



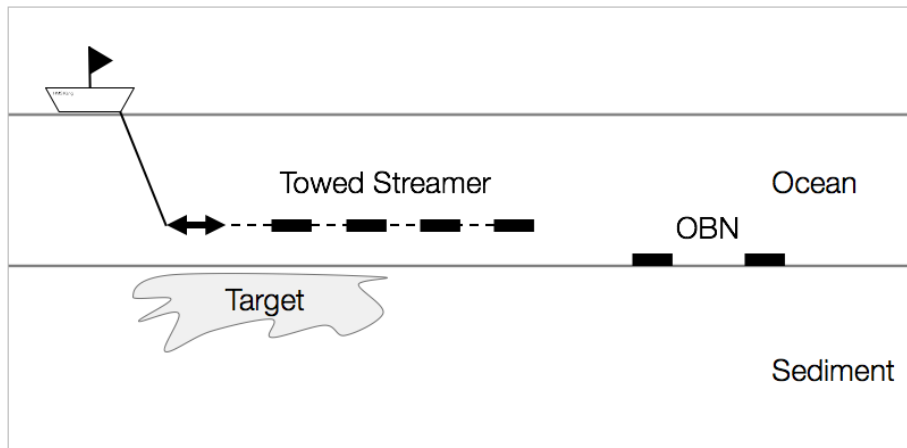
Geometric Decay $\frac{1}{r^3}$

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

Receivers

Data

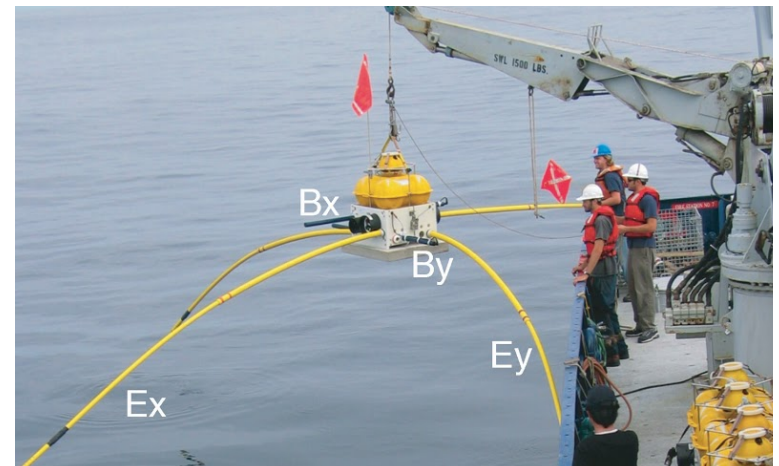
- E_x , E_y , (Recently: E_z)
- B_x , B_y , B_z



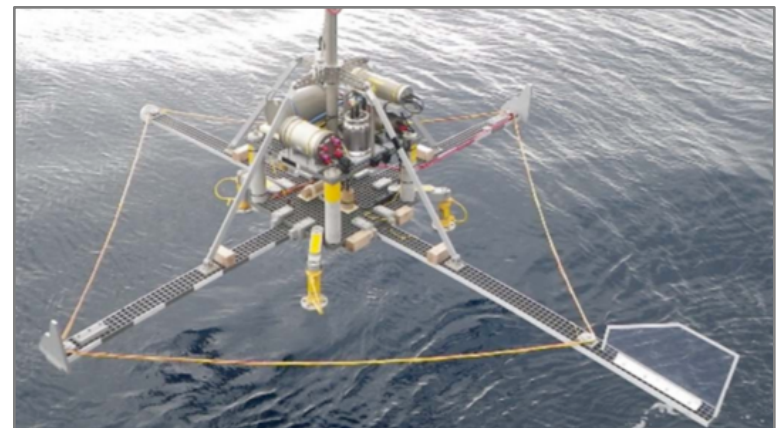
Common Systems

- Scripps: Vulcan and Porpoise
- PGS
- EMGS

Ocean Bottom Nodes (Scripps, EMGS)

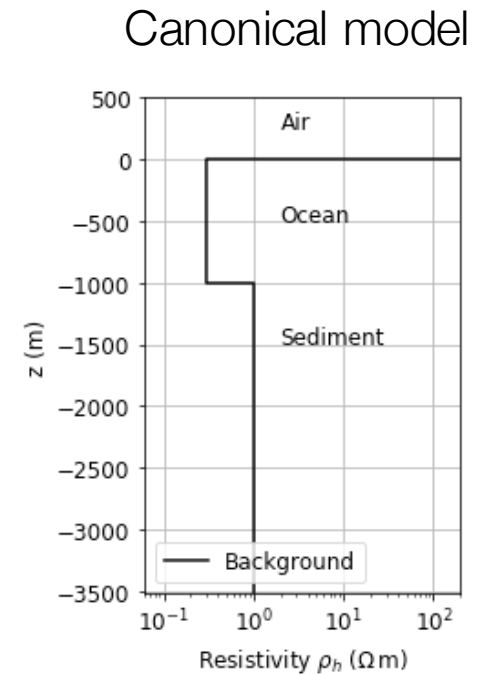
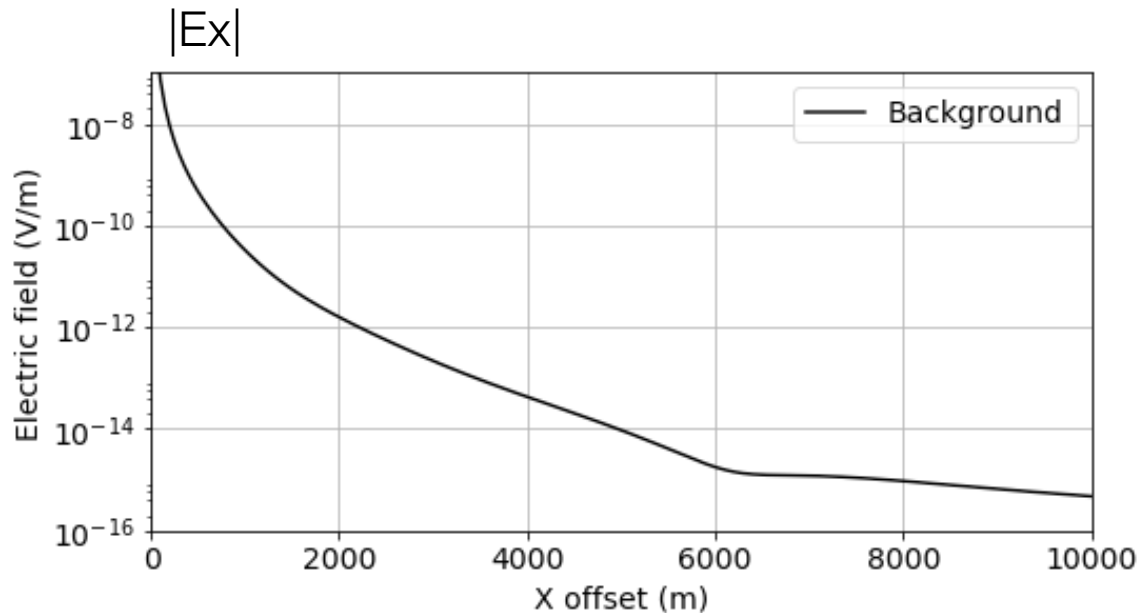
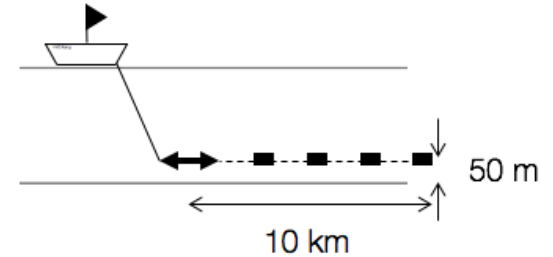


Inductive Loop (Waseda Univ)



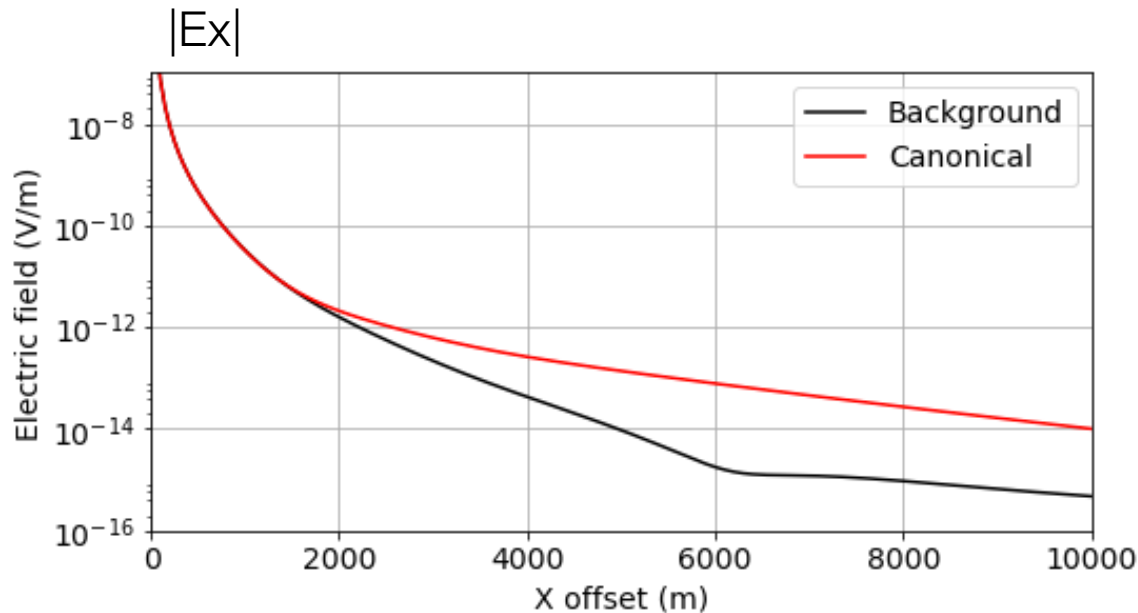
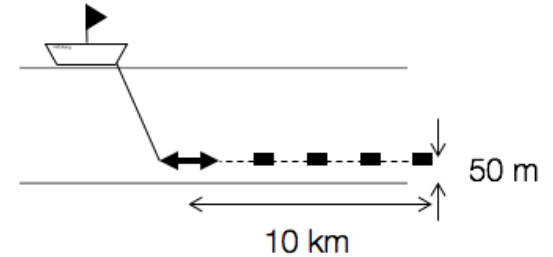
Marine CSEM: Hydrocarbons

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

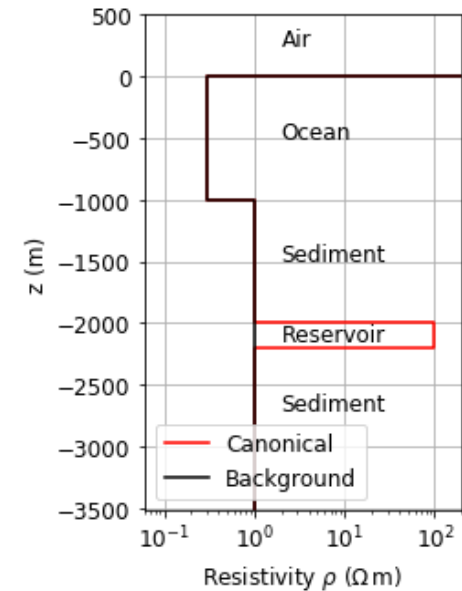


Marine CSEM: Hydrocarbons

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

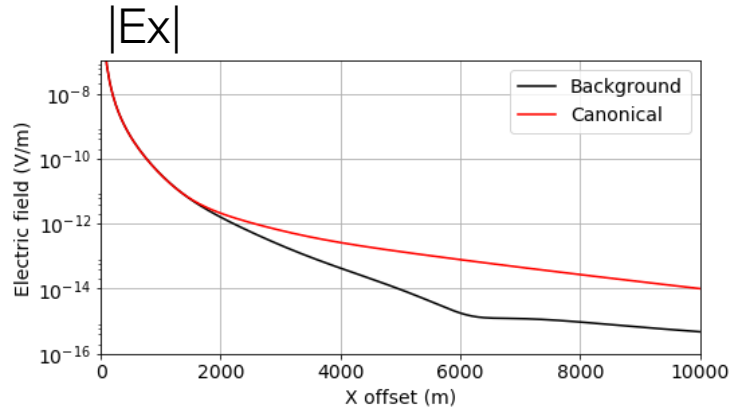
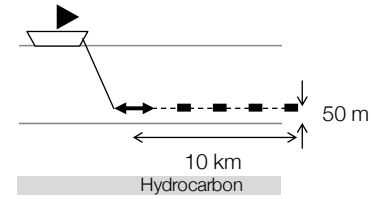


Canonical model

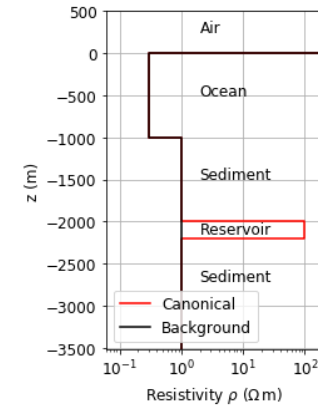


Hydrocarbon reservoir: significant signal
How do we understand the response?

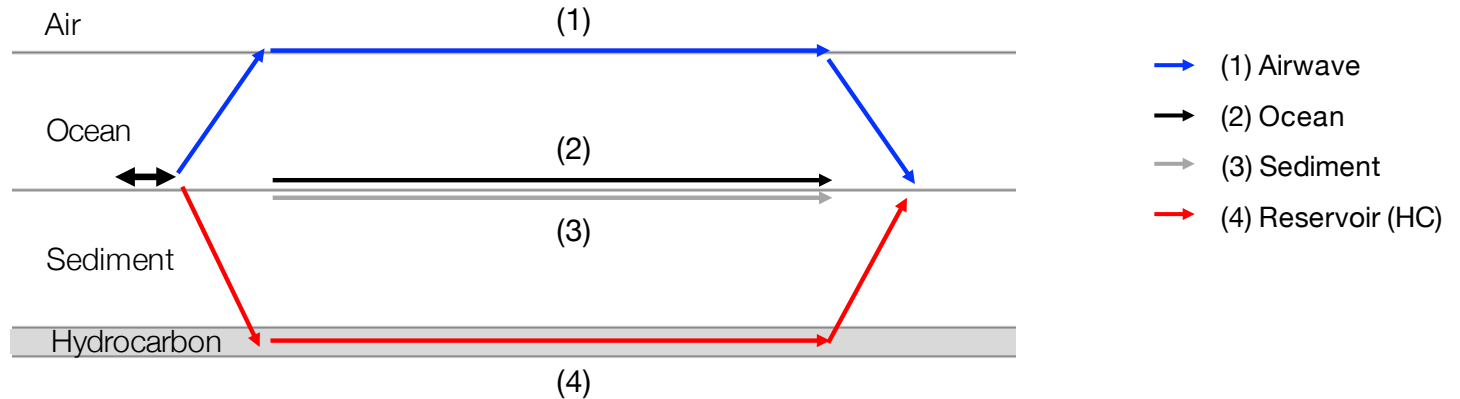
Setup



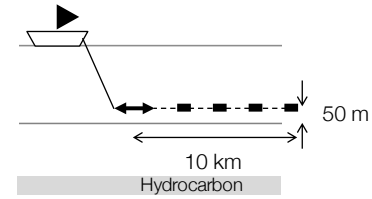
Resistivity



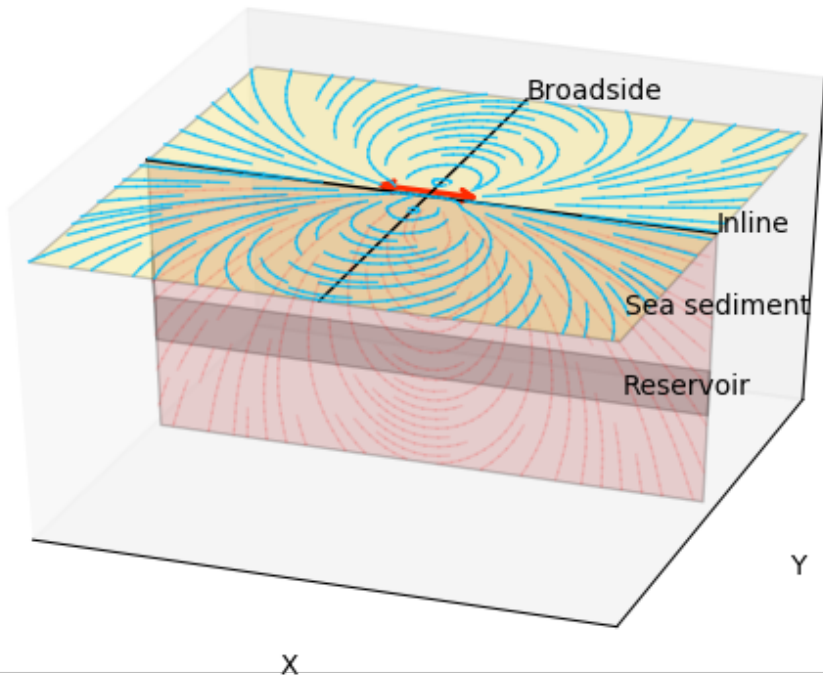
Ray paths



Which fields to examine?



Fields from a dipole

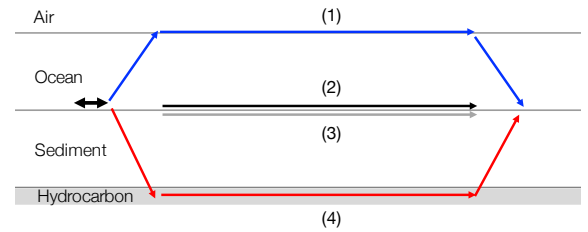


Focus on:

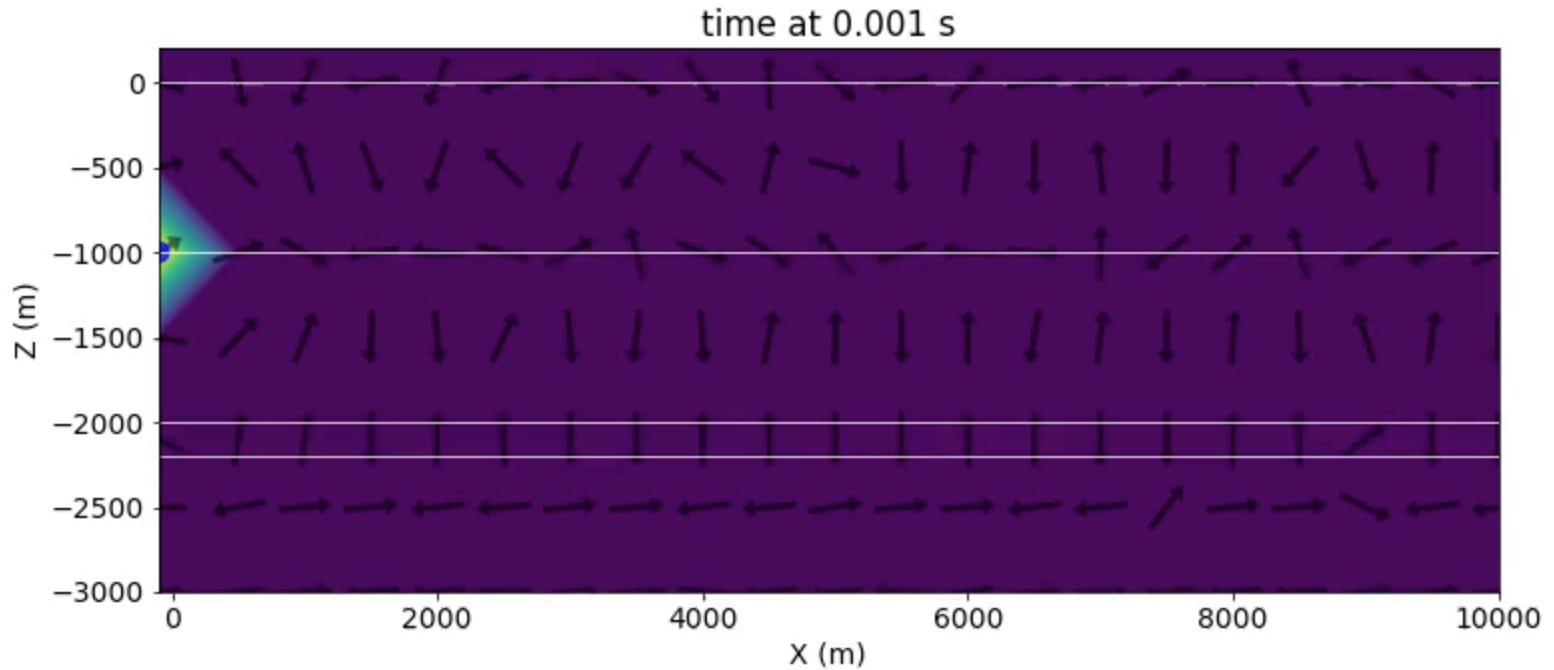
- Inline electric field
- Inline poynting vector (energy propagation)

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

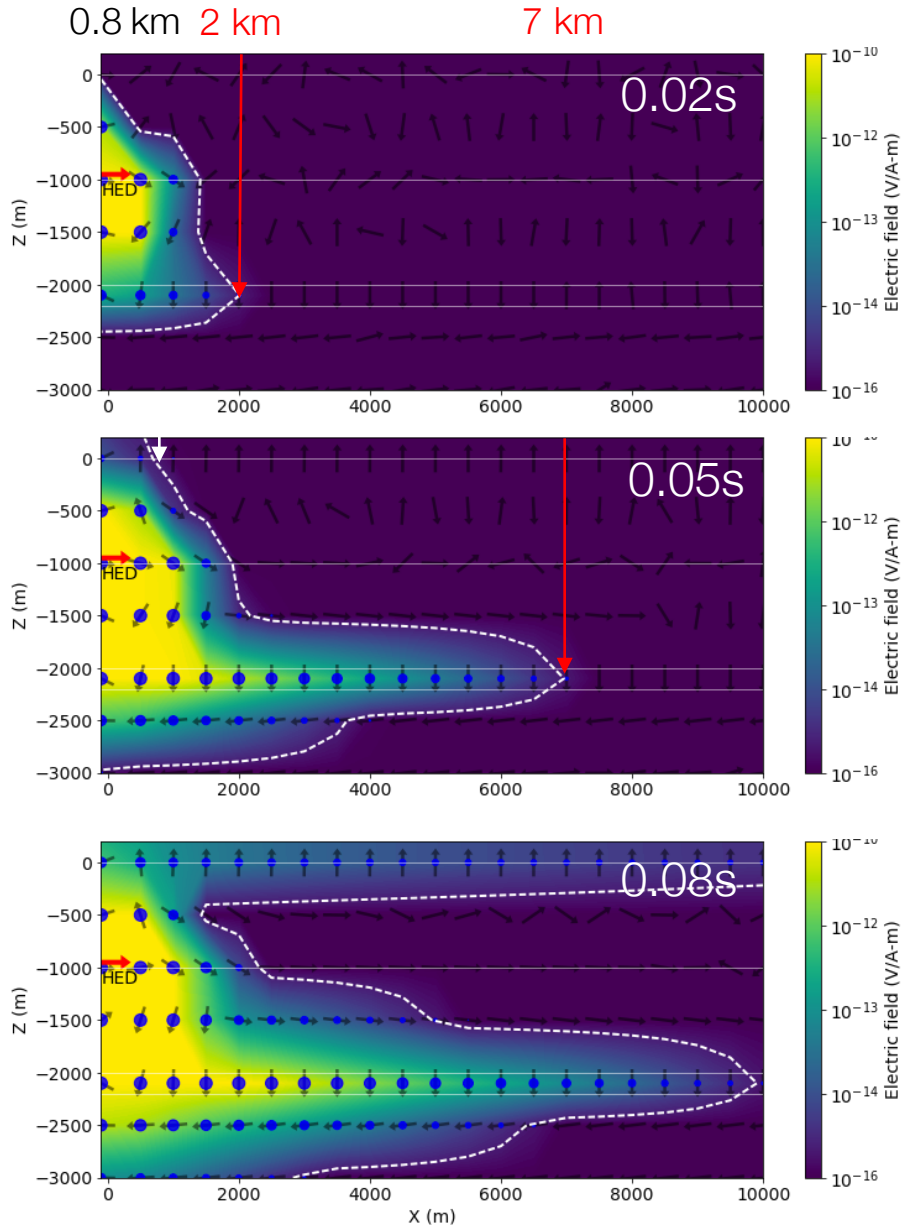
Electric field



On XZ plane (HED source in x-direction)

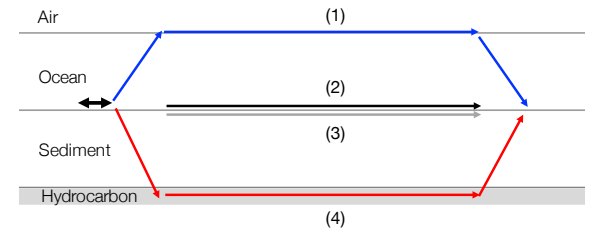


Electric field at multiple times

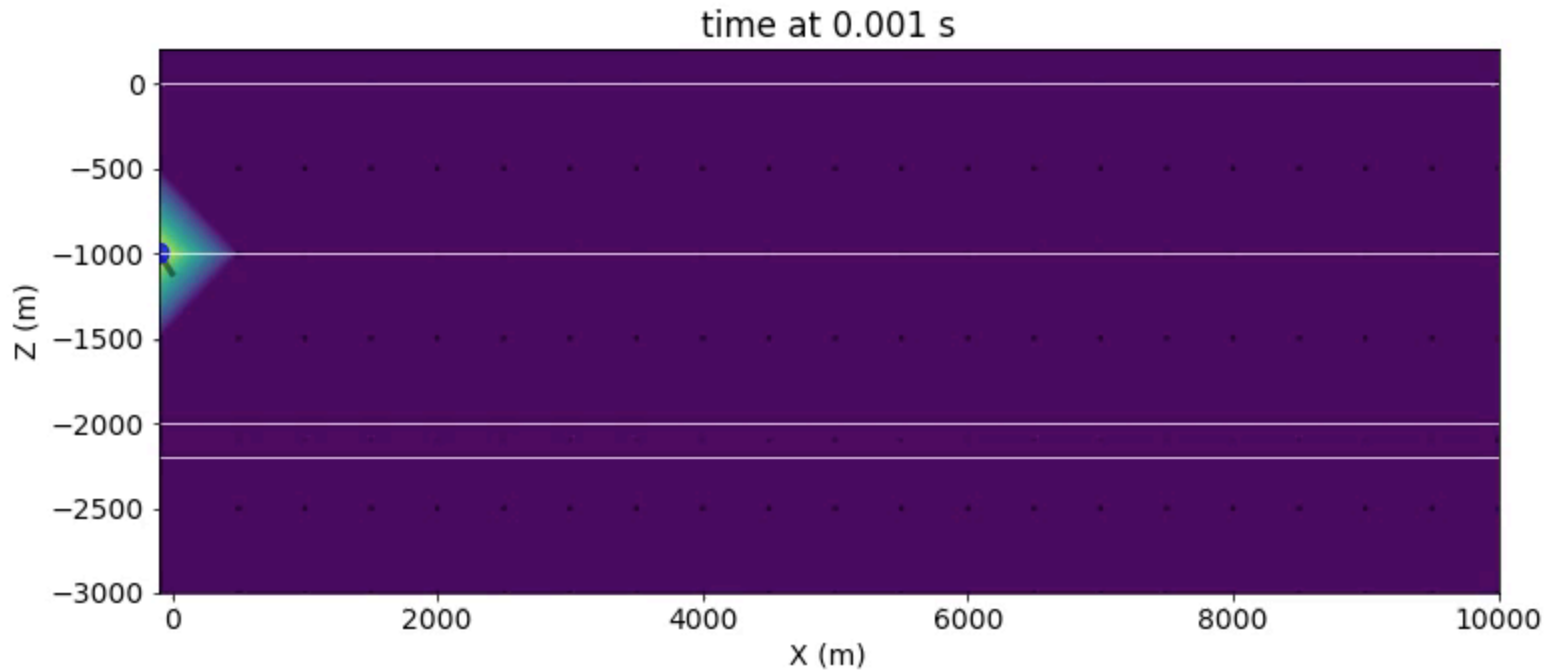


- In reservoir:
 $5 \text{ km} / 0.03\text{s} = 166\text{km/s}$
- In air:
 $>10\text{km} / 0.03 = > 333 \text{ km/s}$
- Propagation much faster in air
- More attenuation in the reservoir

Poynting vector



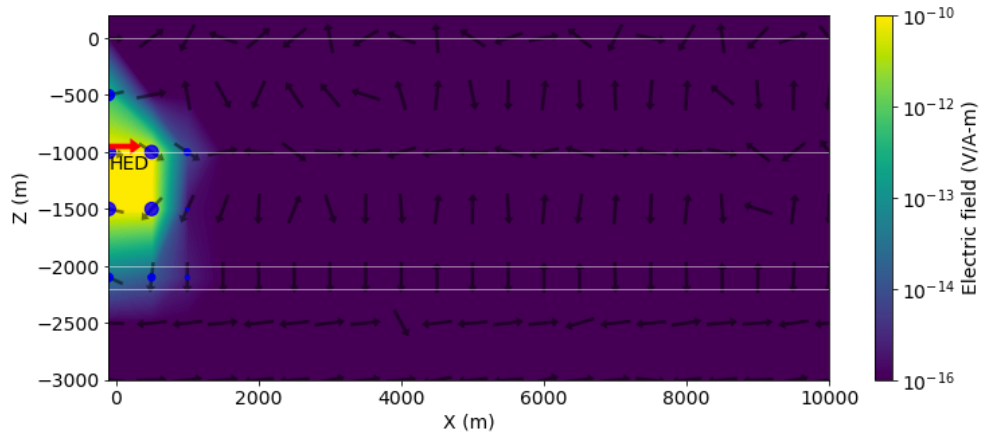
On XZ plane (HED source in x-direction)



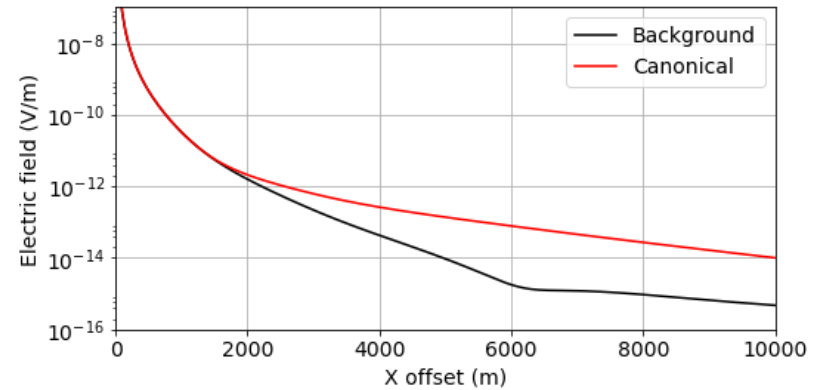
$$\text{Poynting vector: } \bar{\mathbf{S}} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B}$$

Fields at time: 0.016s

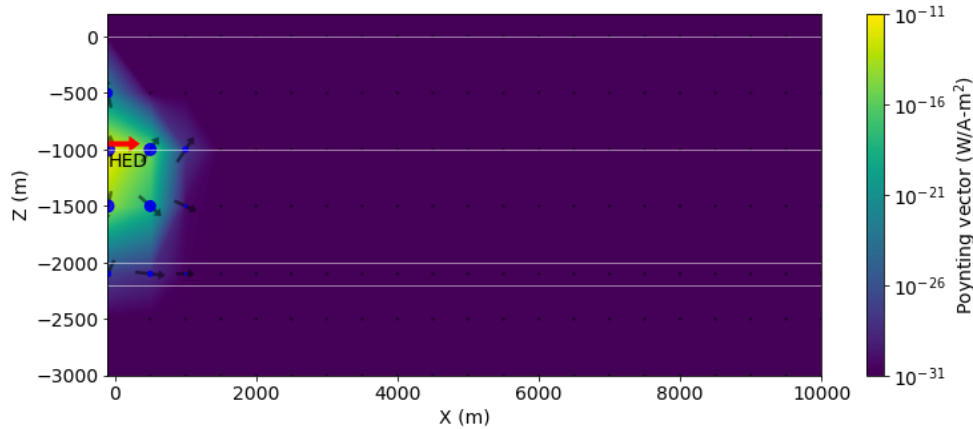
E-field



|Ex|



Poynting vector

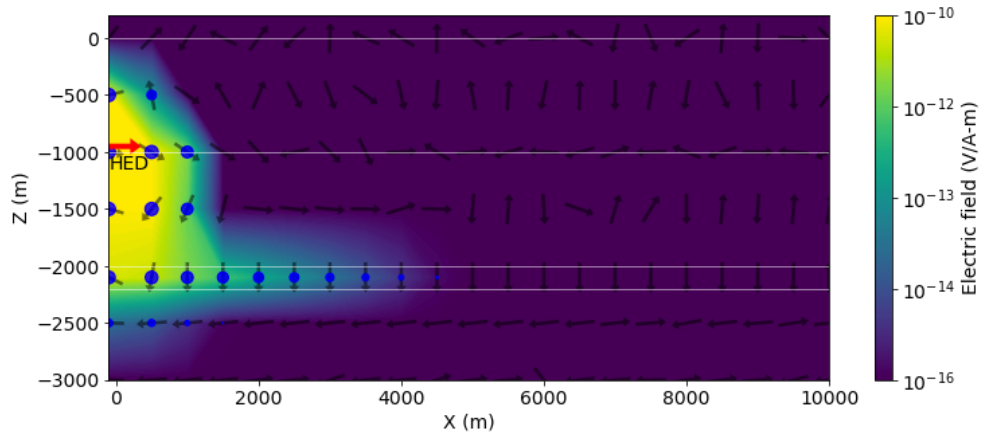


Peak velocity

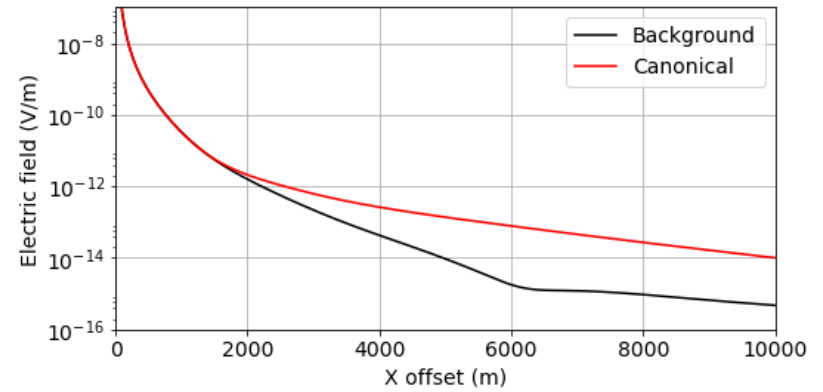
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

Fields at time: 0.03s

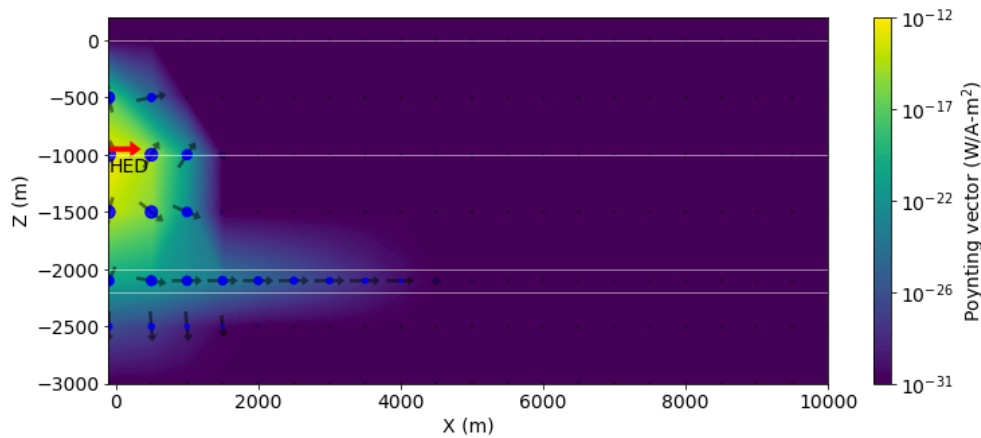
E-field



|Ex|



Poynting vector

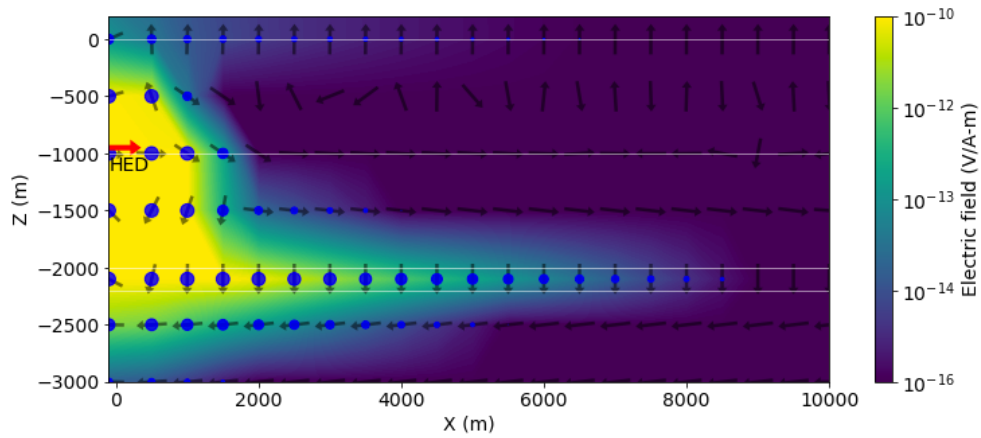


Peak velocity

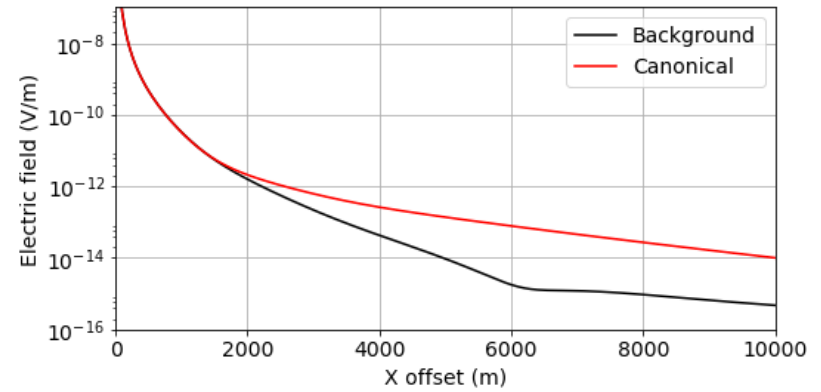
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

Fields at time: 0.08s

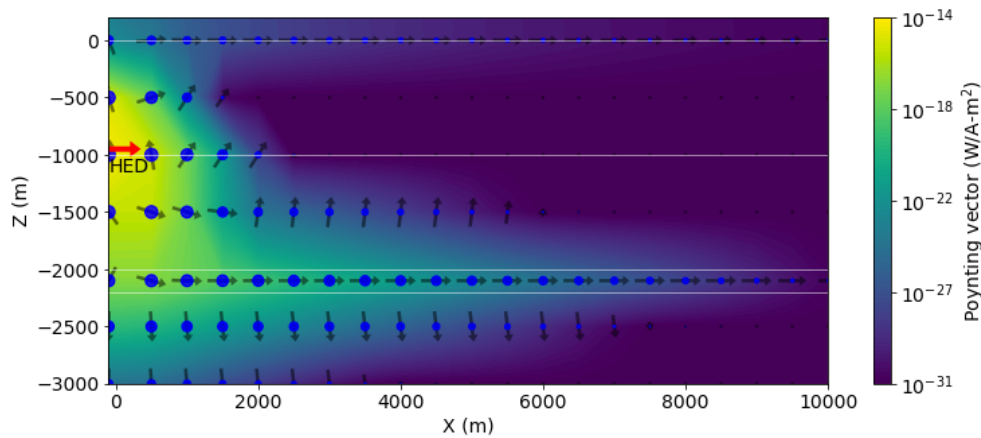
E-field



|Ex|



Poynting vector

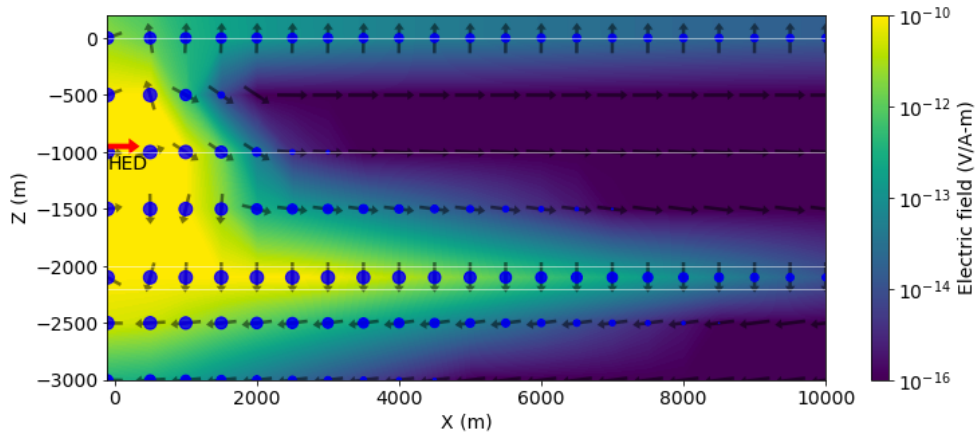


Peak velocity

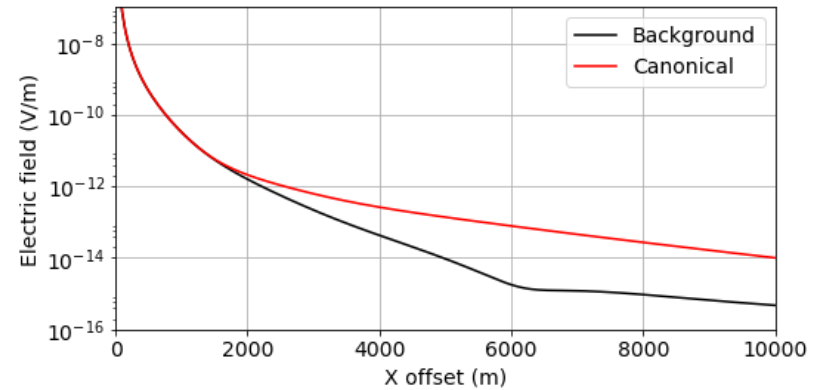
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

Fields at time: 0.10s

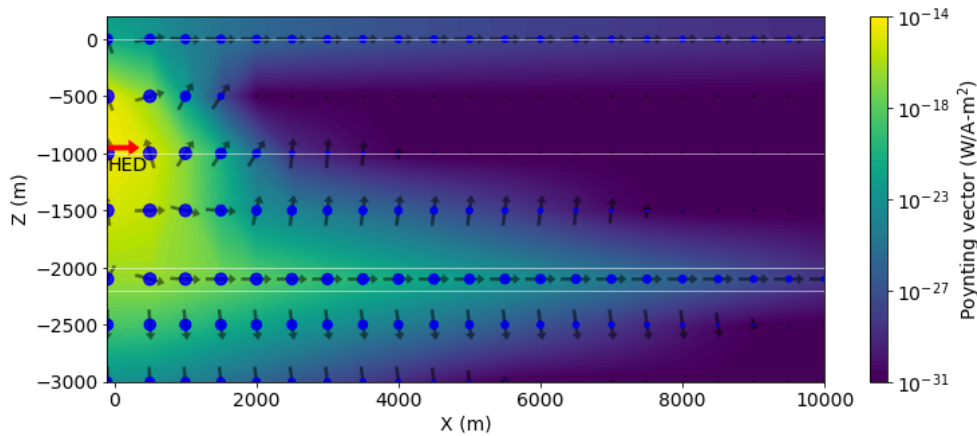
E-field



|Ex|



Poynting vector

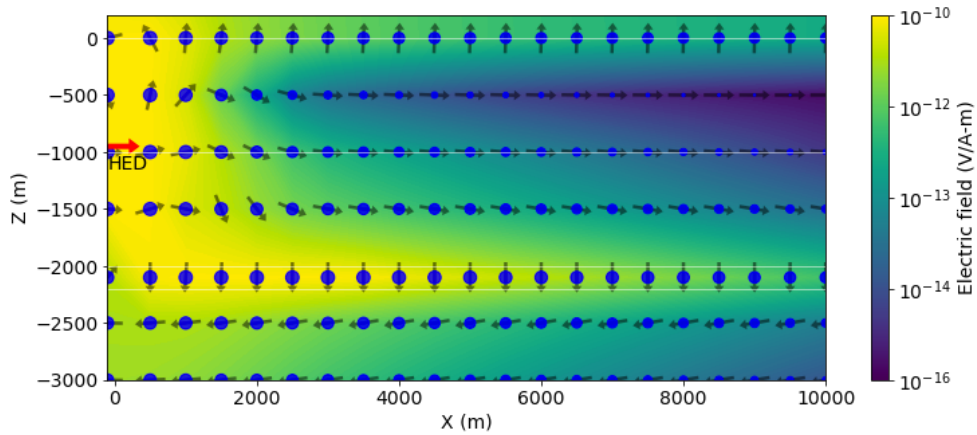


Peak velocity

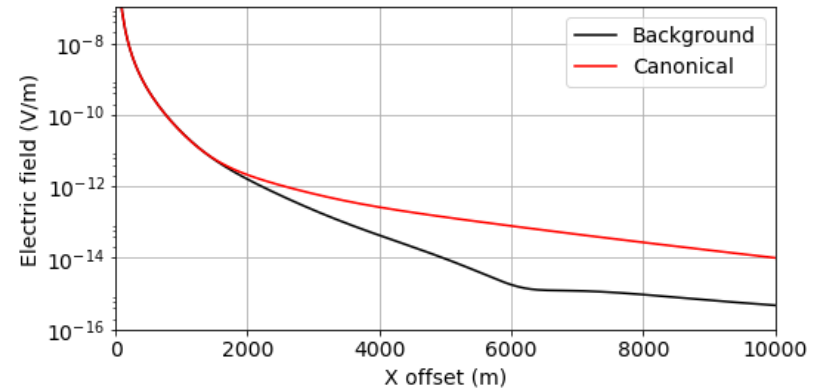
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

Fields at time: 0.32s

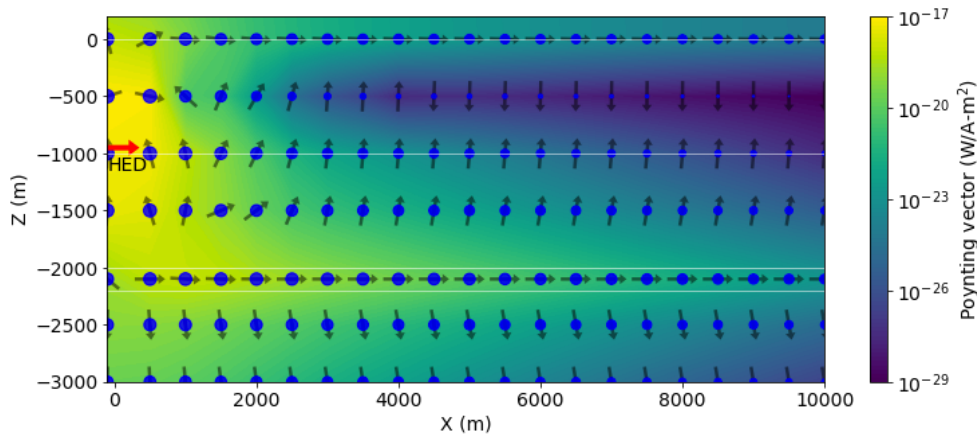
E-field



|Ex|



Poynting vector

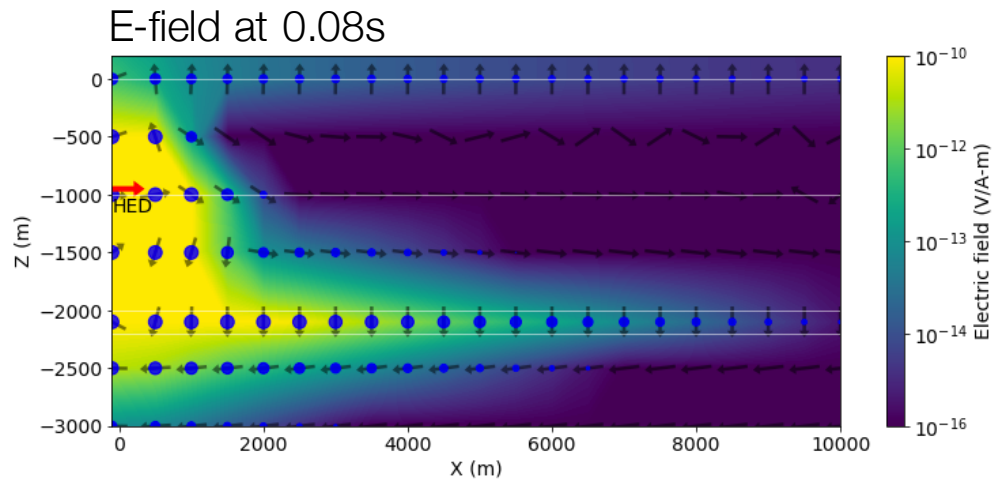


Peak velocity

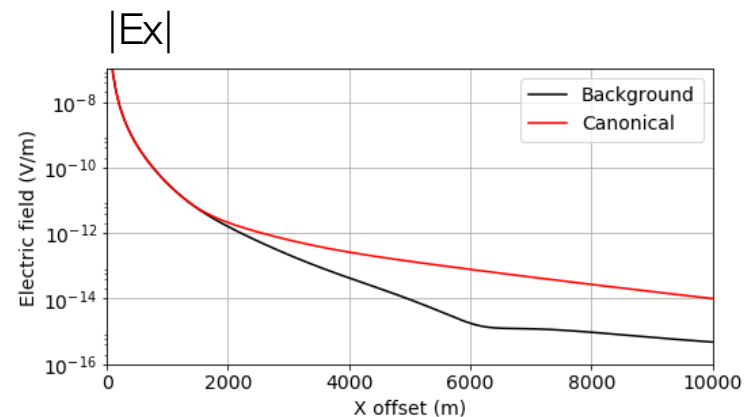
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

Amplitude vs offset

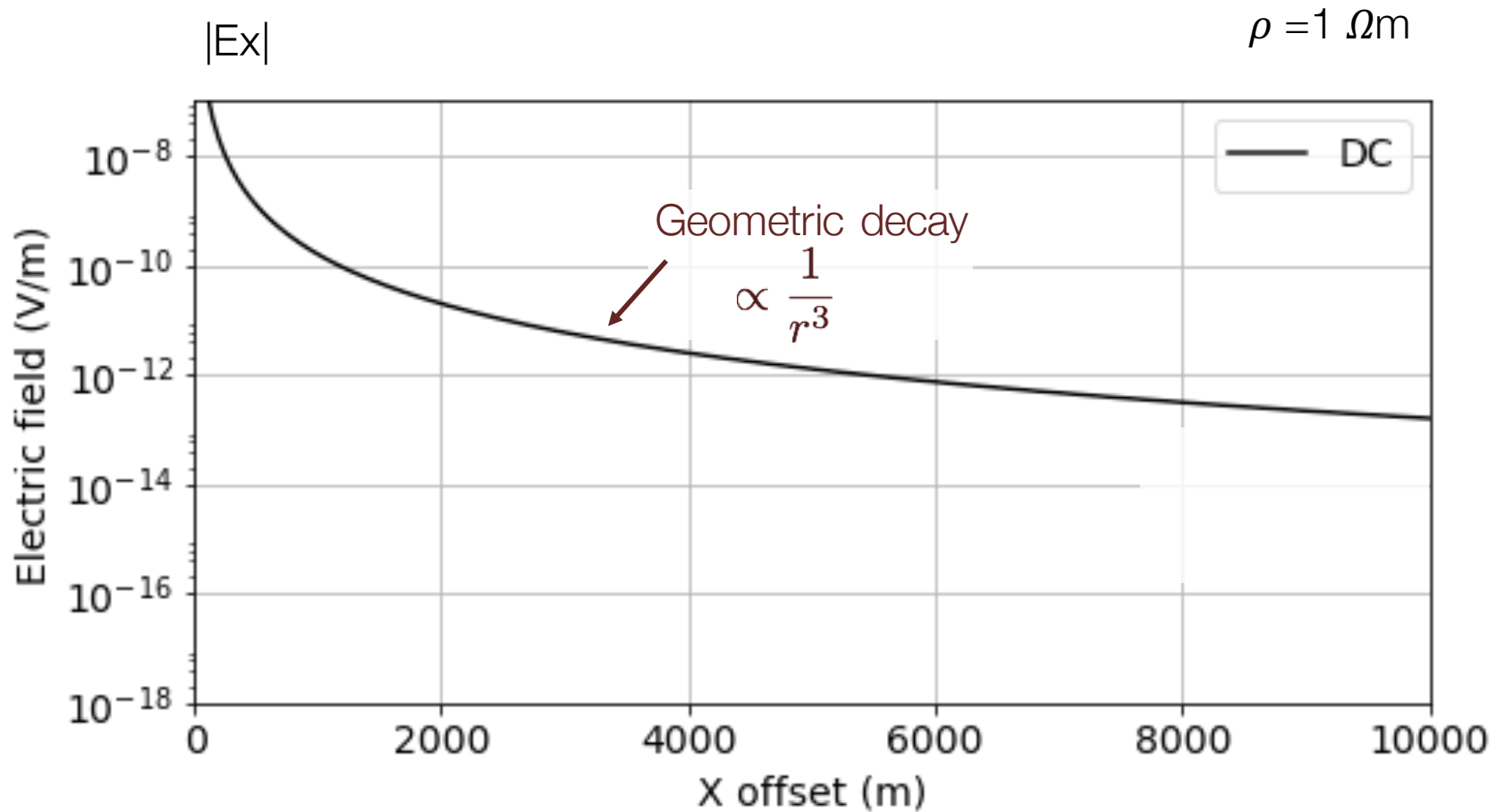
- Time snapshots tell us about
 - where energy is travelling
 - something about propagation speed



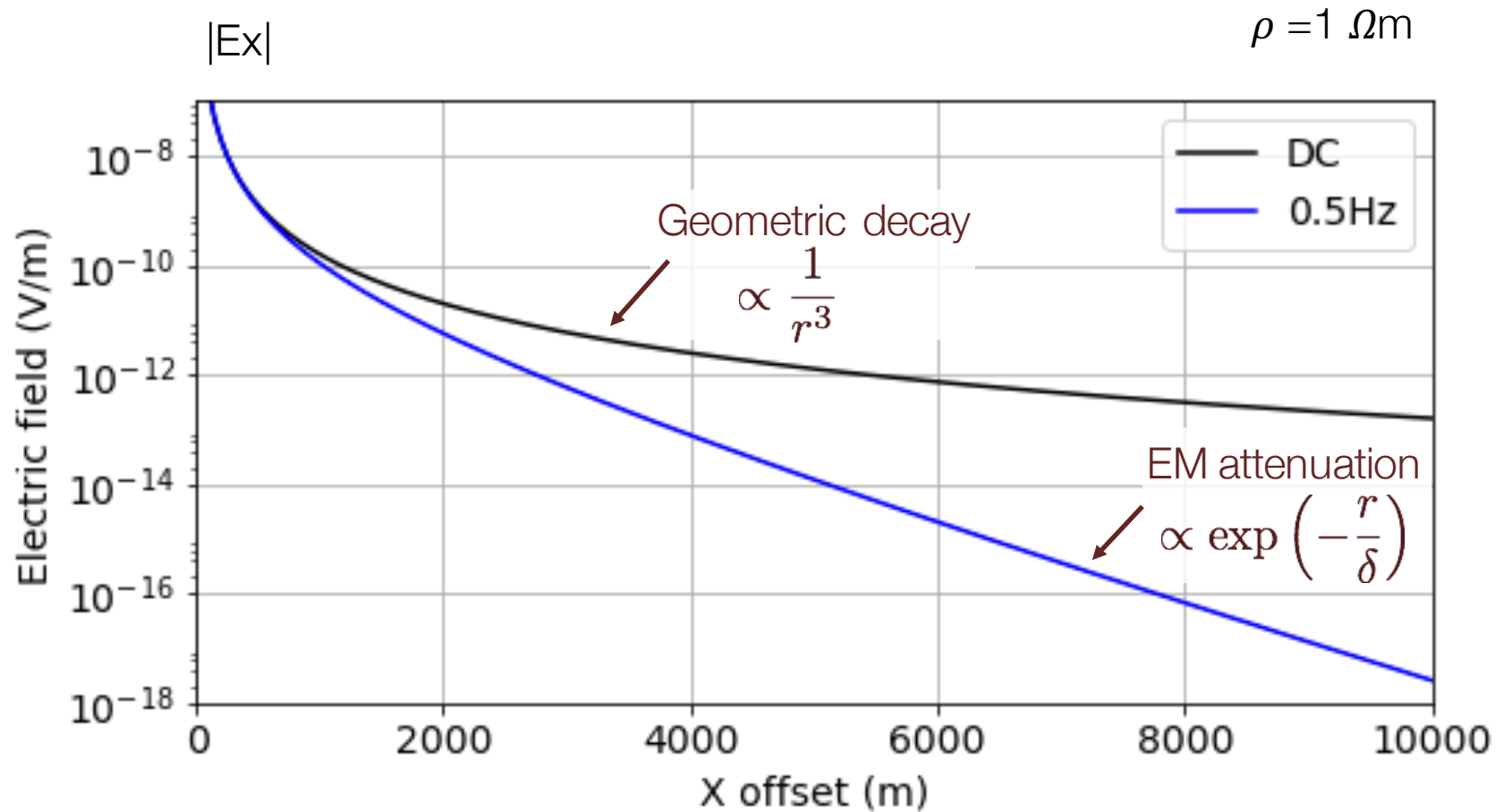
- What about amplitudes?
- Work in frequency domain



Amplitude: Electric dipole in a wholespace

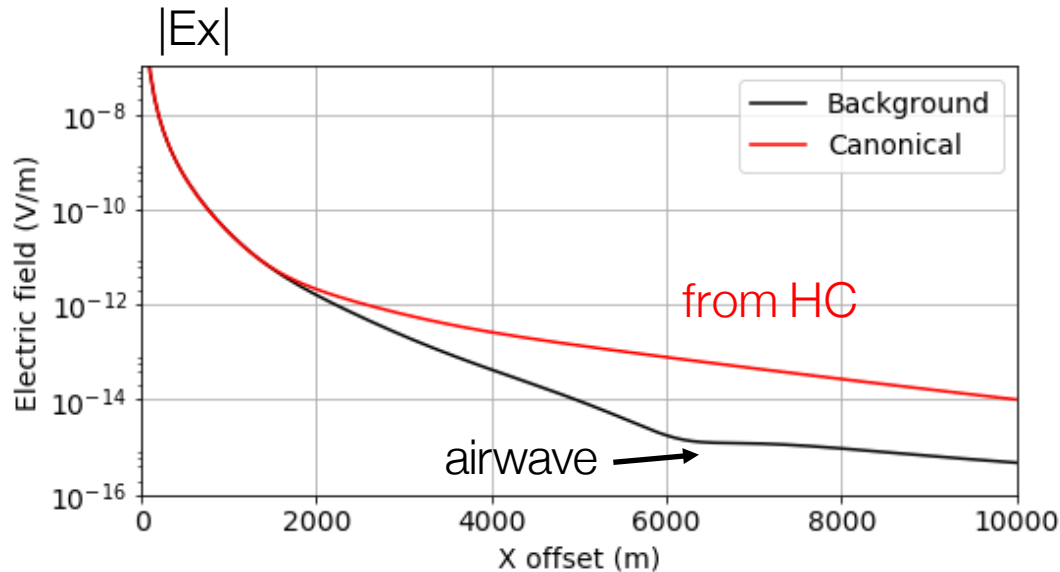
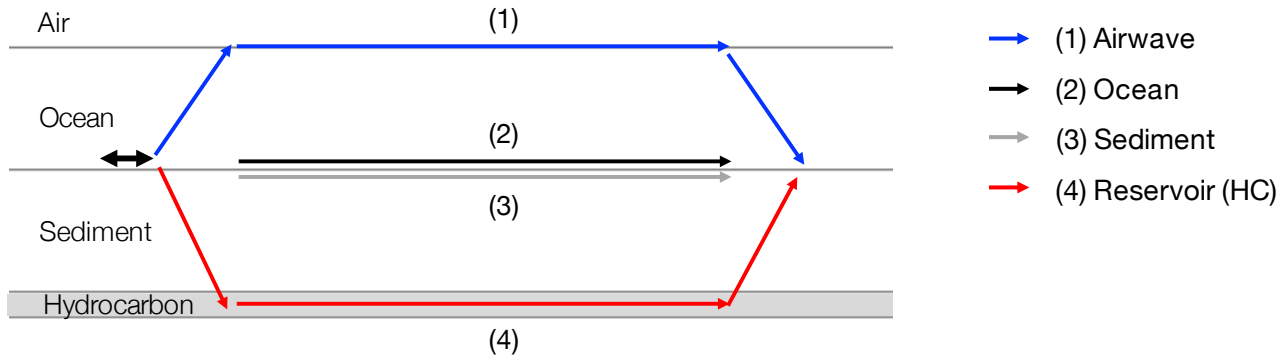


Amplitude: Electric dipole in a wholespace



Amplitude vs Offset

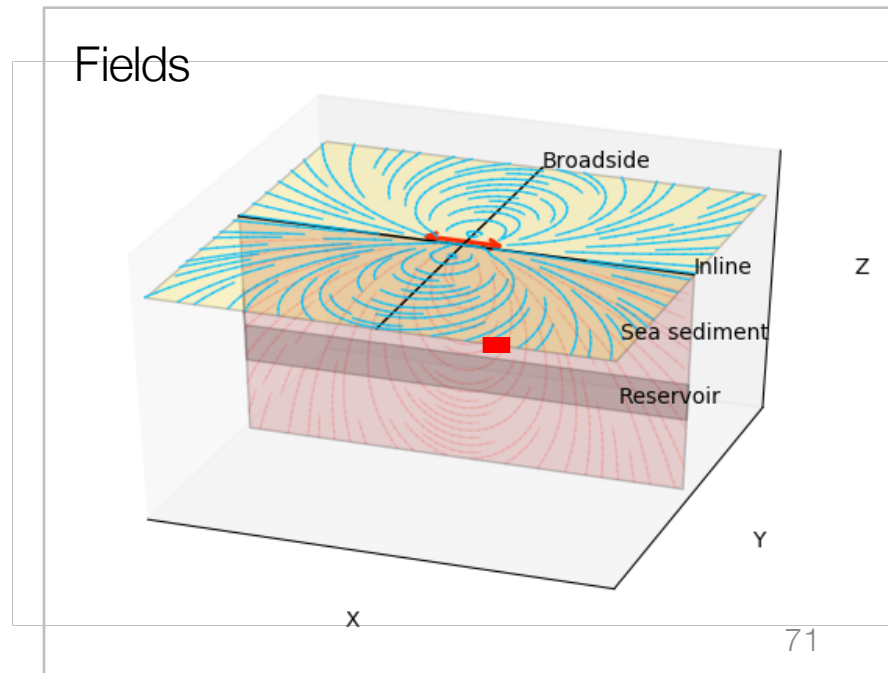
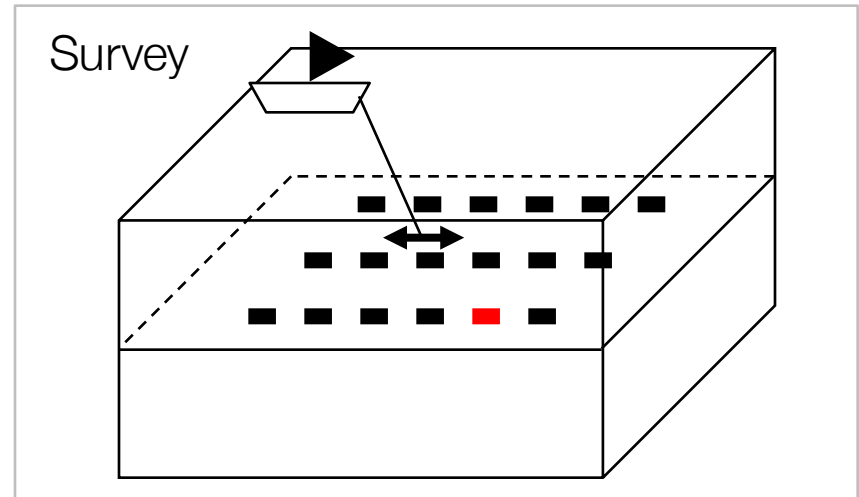
Ray paths



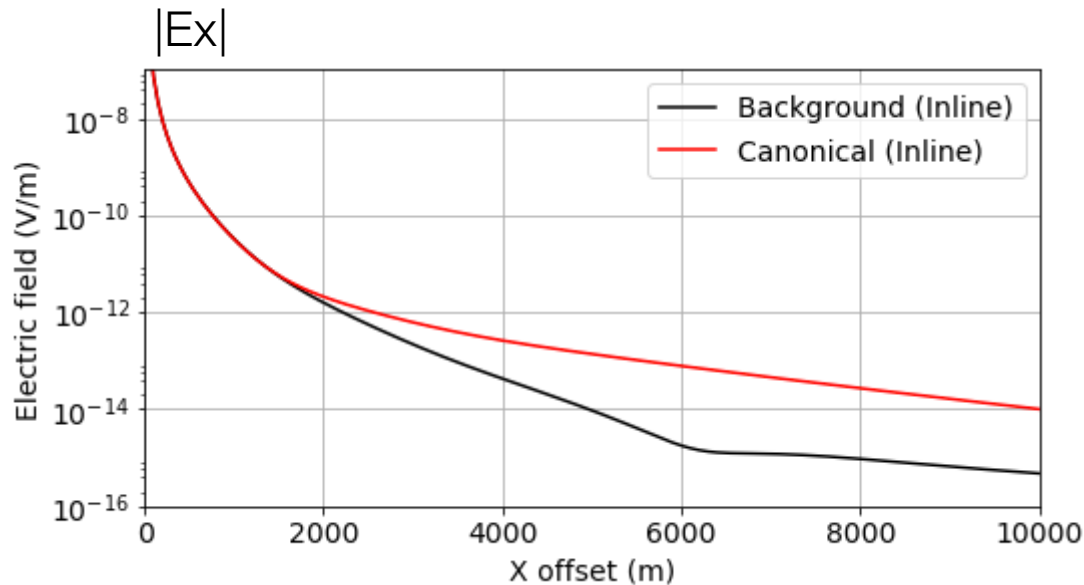
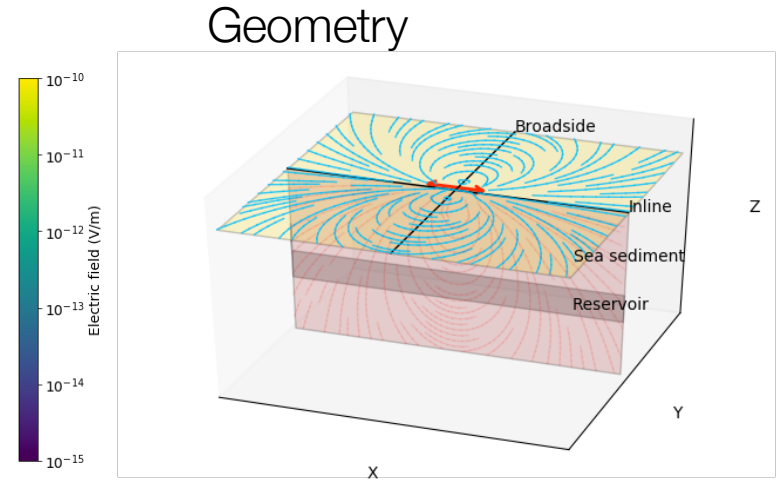
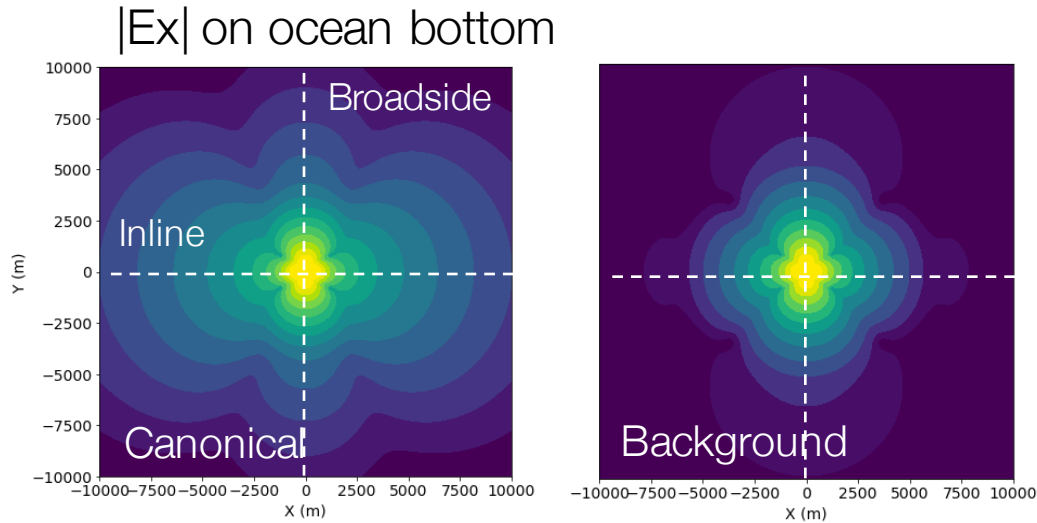
- Short offset (<2km):
 - geometric decay ($1/r^3$)
- Intermediate offset (2-6 km):
 - skin effects + HC
- Large offset (6-10 km):
 - airwave + HC

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



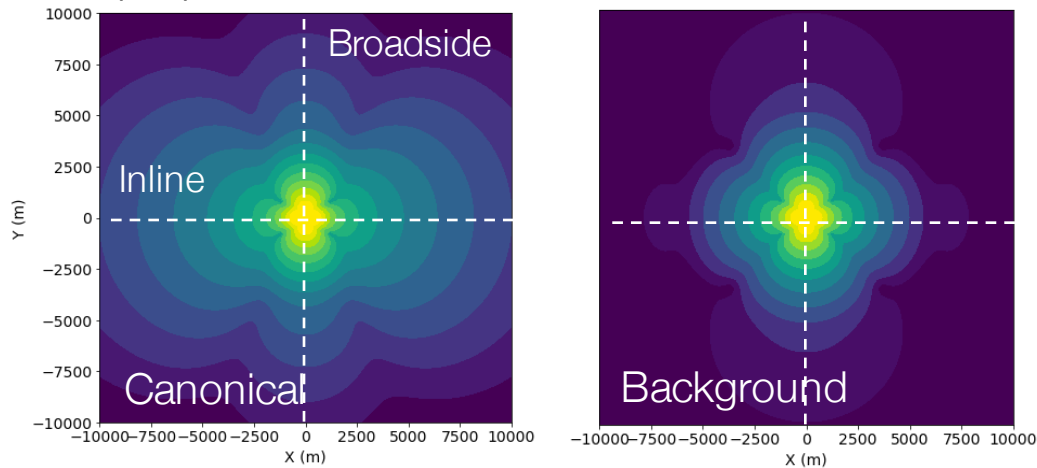
Measured data: inline and broadside



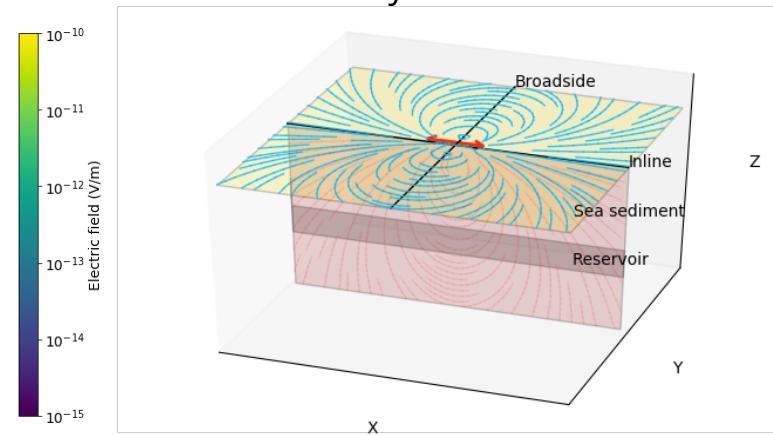
- Inline $|E_x|$
 - Significant signal from reservoir

Measured data: inline and broadside

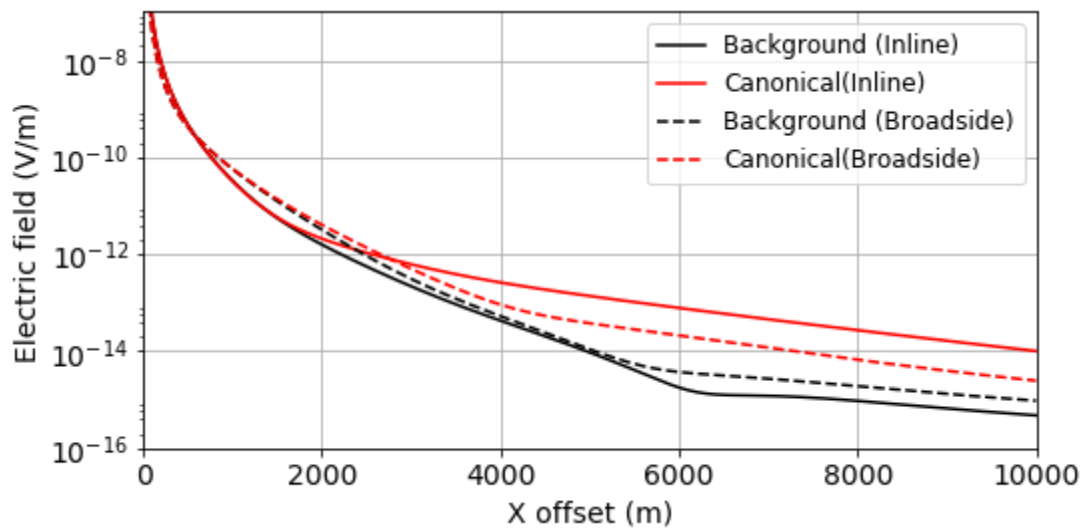
$|E_x|$ on ocean bottom



Geometry



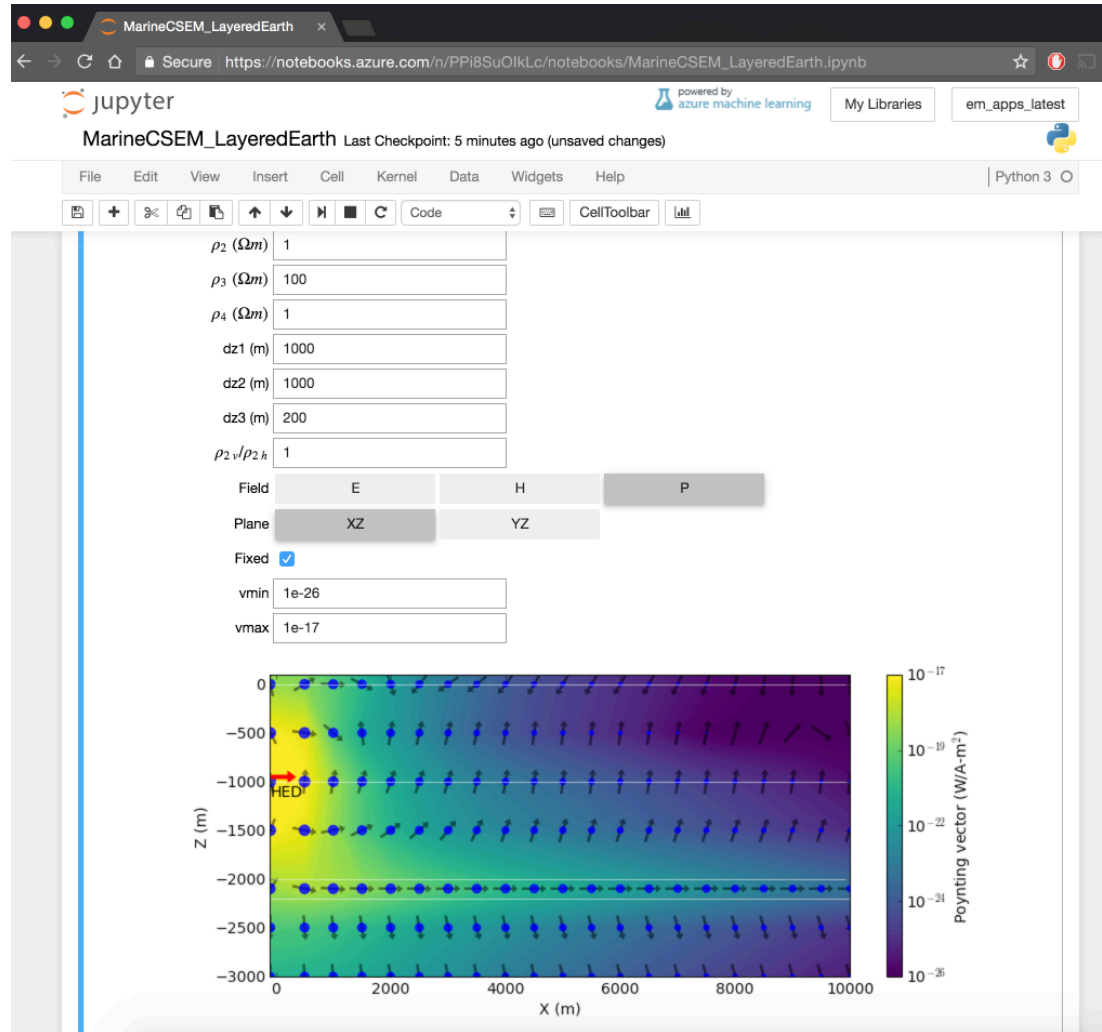
$|E_x|$



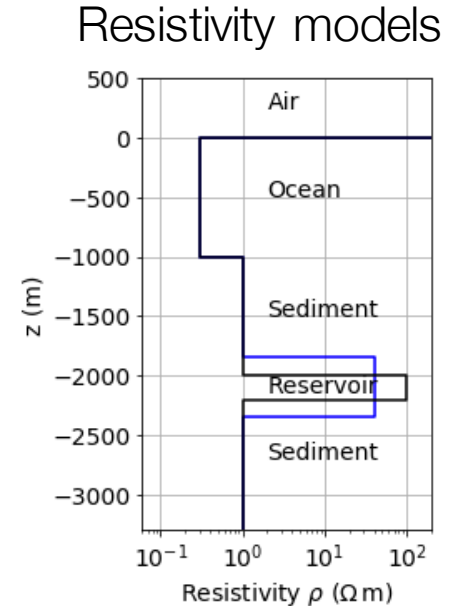
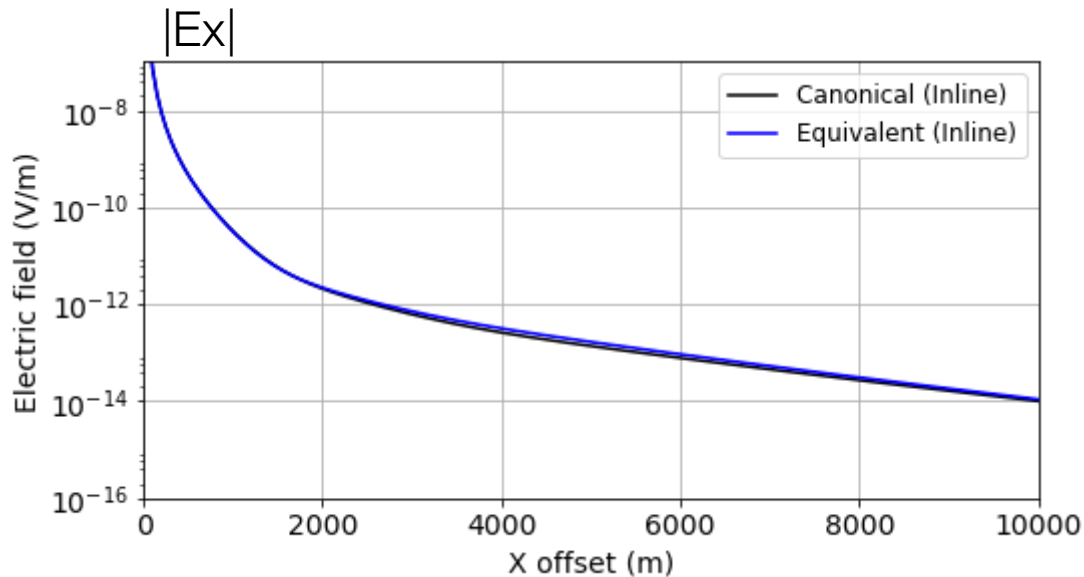
- Inline $|E_x|$
 - Significant signal from reservoir
- Broadside $|E_x|$
 - Anomaly is smaller than inline

Marine CSEM App

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

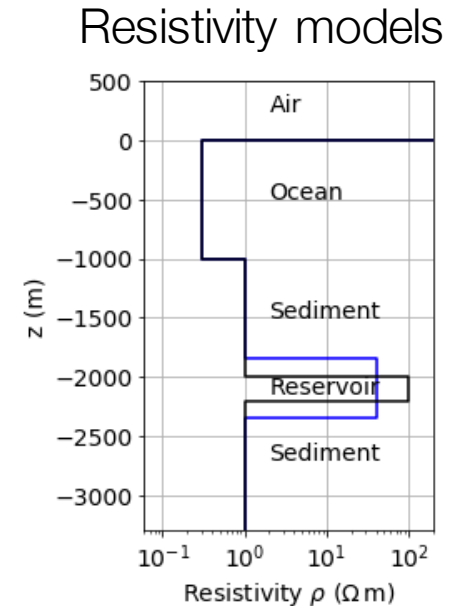
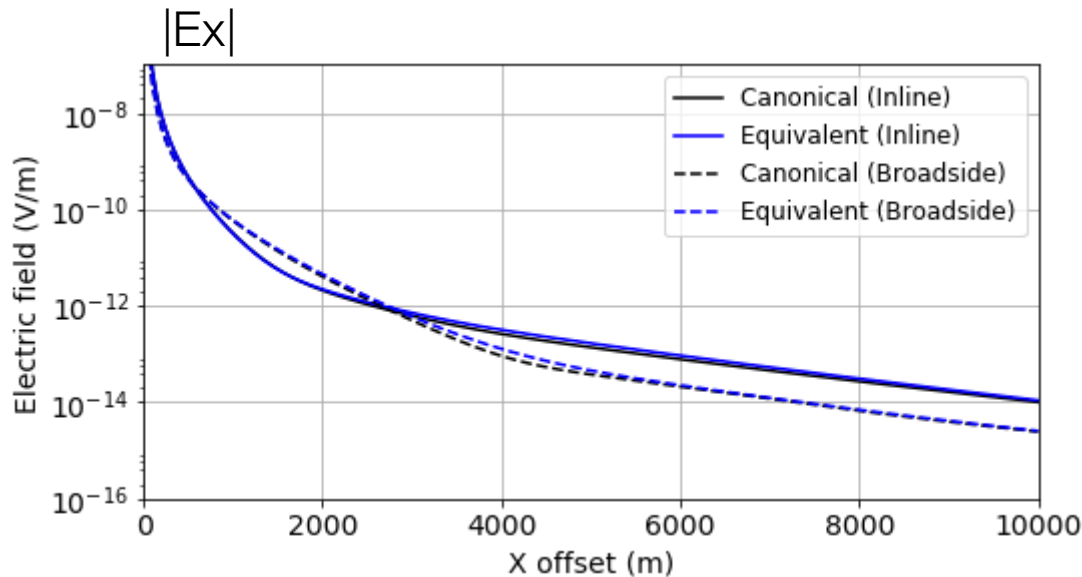


Equivalence: resistivity-thickness product



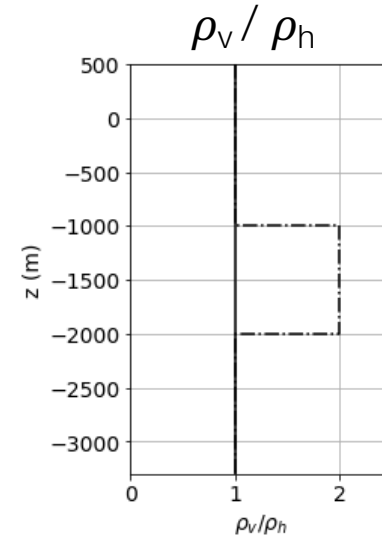
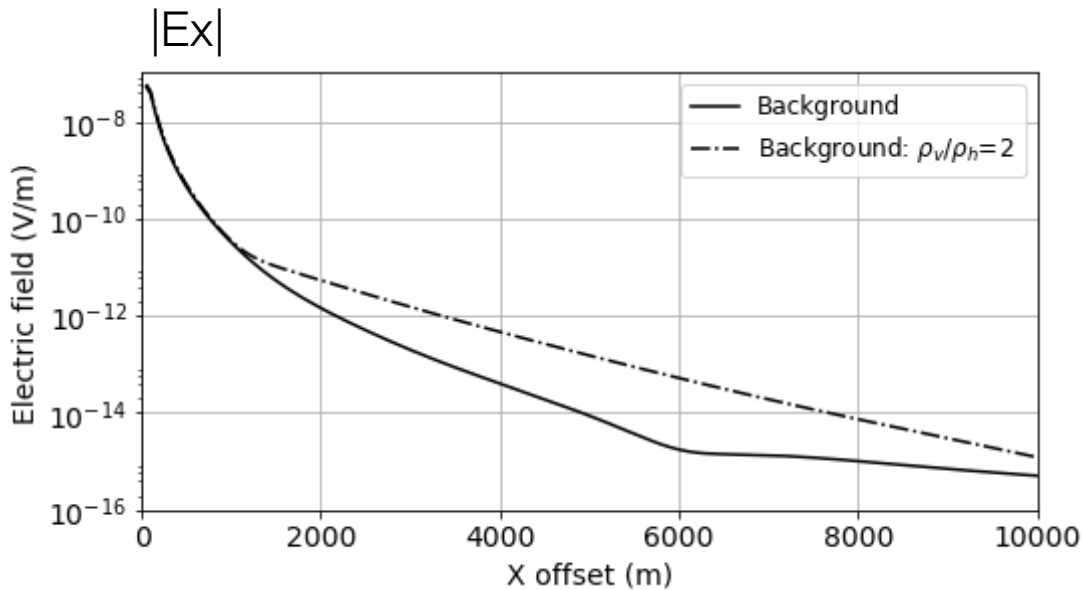
- Electric fields are sensitive to resistivity-thickness product
- Reduce non-uniqueness with better data coverage, more components, other information (e.g. seismic)

Equivalence: resistivity-thickness product

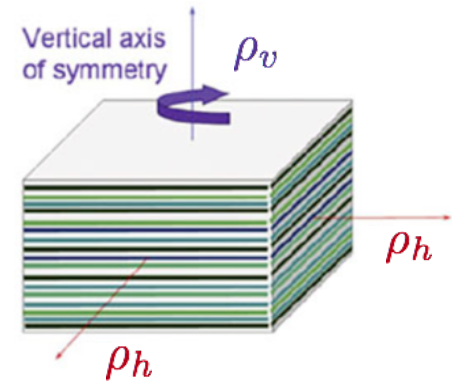


- Electric fields are sensitive to resistivity-thickness product
- Reduce non-uniqueness with better data coverage, more components, other information (e.g. seismic)

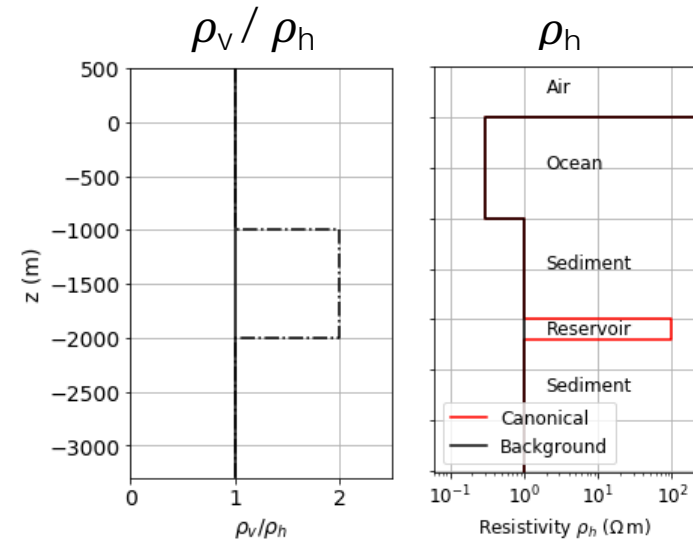
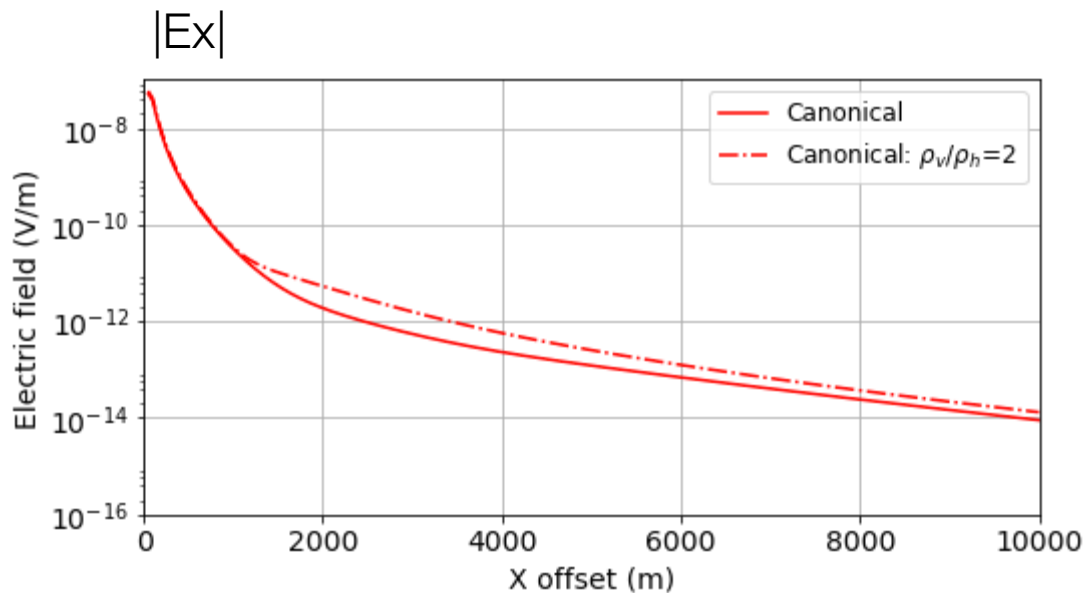
Anisotropy



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

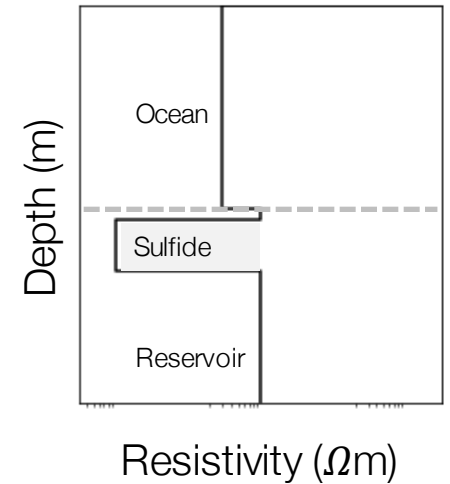
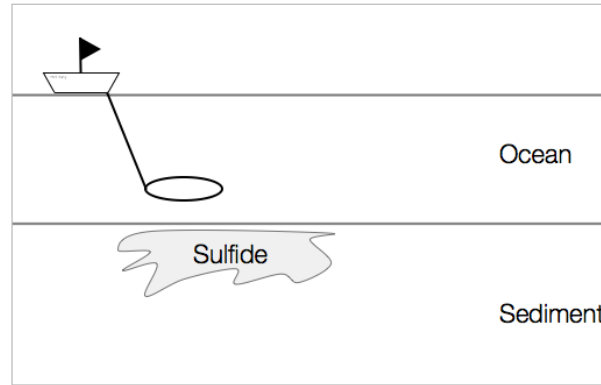
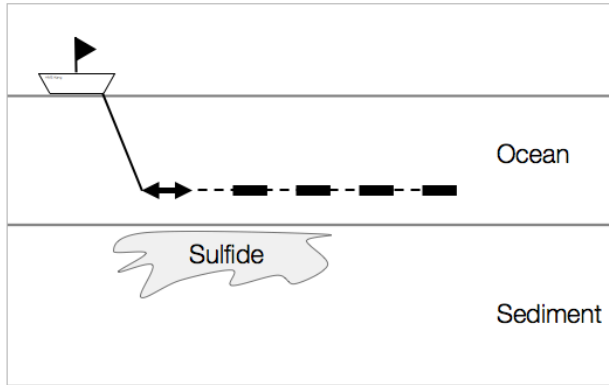


Anisotropy



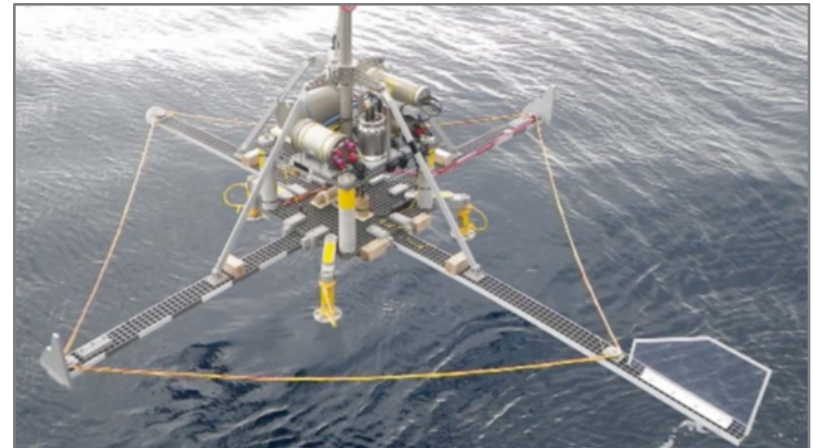
- Significant impact to signal from reservoir
 - need to account for this when interpreting marine CSEM data

Finding conductors



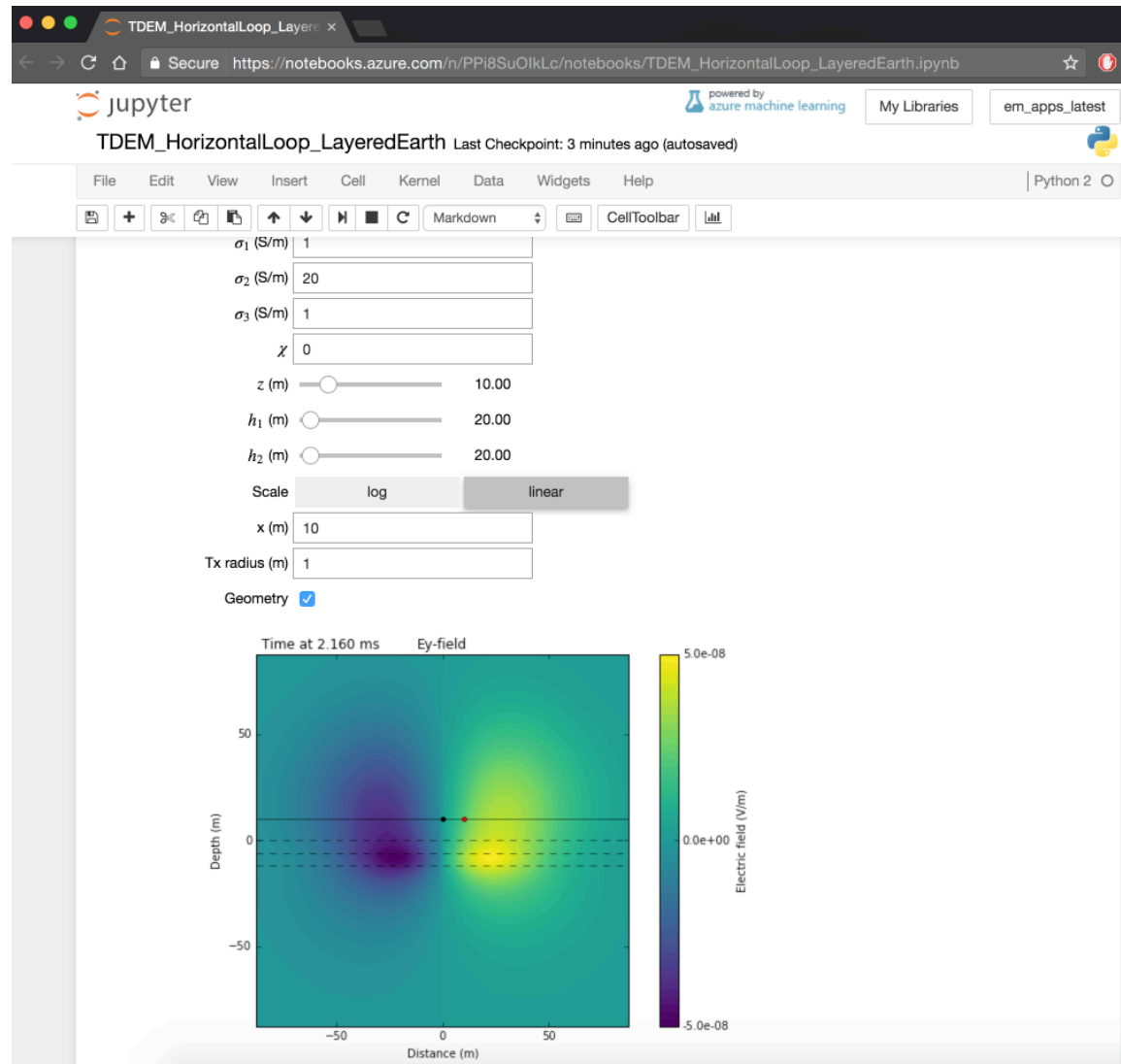
Source: towed

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



TDEM Horizontal Loop App

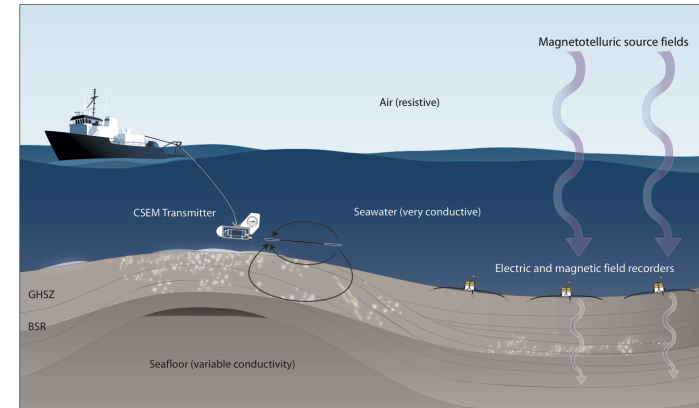
- TDEM
 - 4 layers
 - Fields, currents
 - Plot time decays



Summary

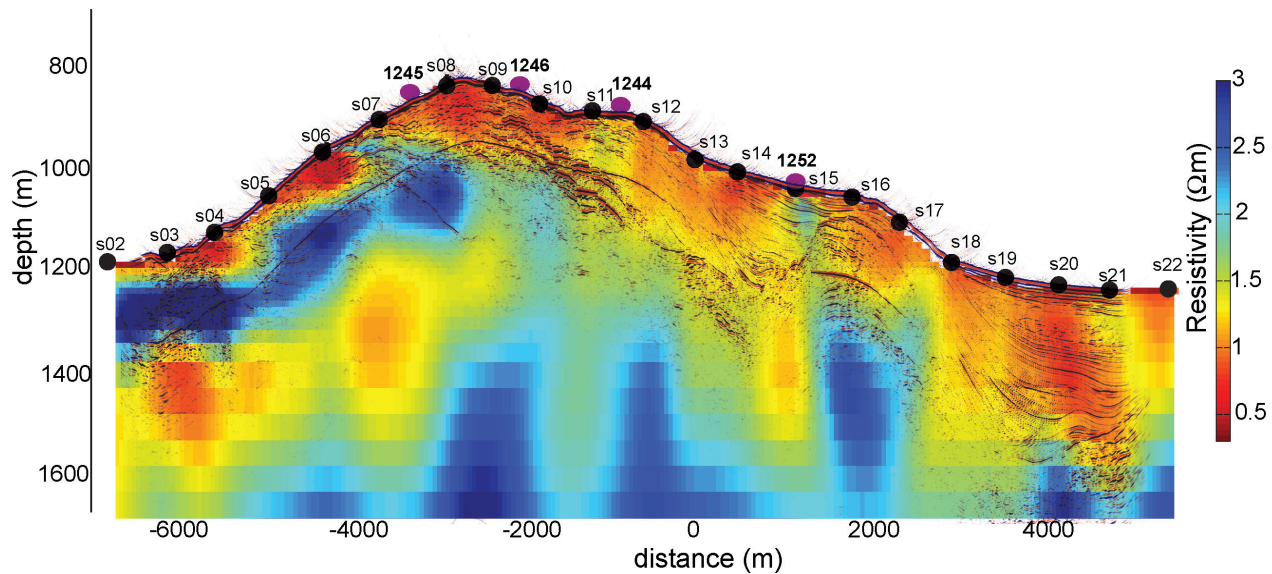
- Generic CSEM survey
- Wave and energy propagation
- Transmitters: galvanic or inductive
- Receivers: E-field, B-field: fixed or moving
- Canonical hydrocarbon example
- Useful for finding conductors or resistors
 - Hydrocarbons
 - Gas hydrate
 - Sea floor massive sulfides
 - Sea floor UXO
 - Near surface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

Case History: Gas Hydrates



Case History: Hydrate Ridge offshore Oregon, USA

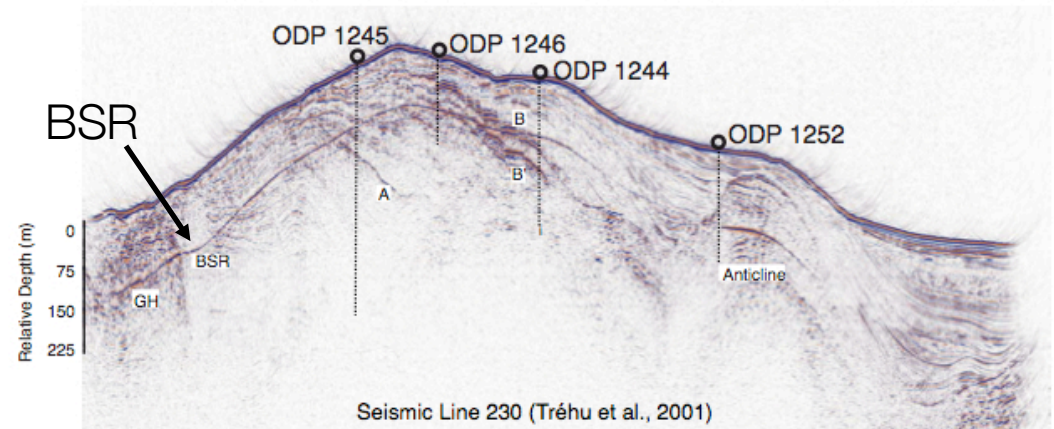
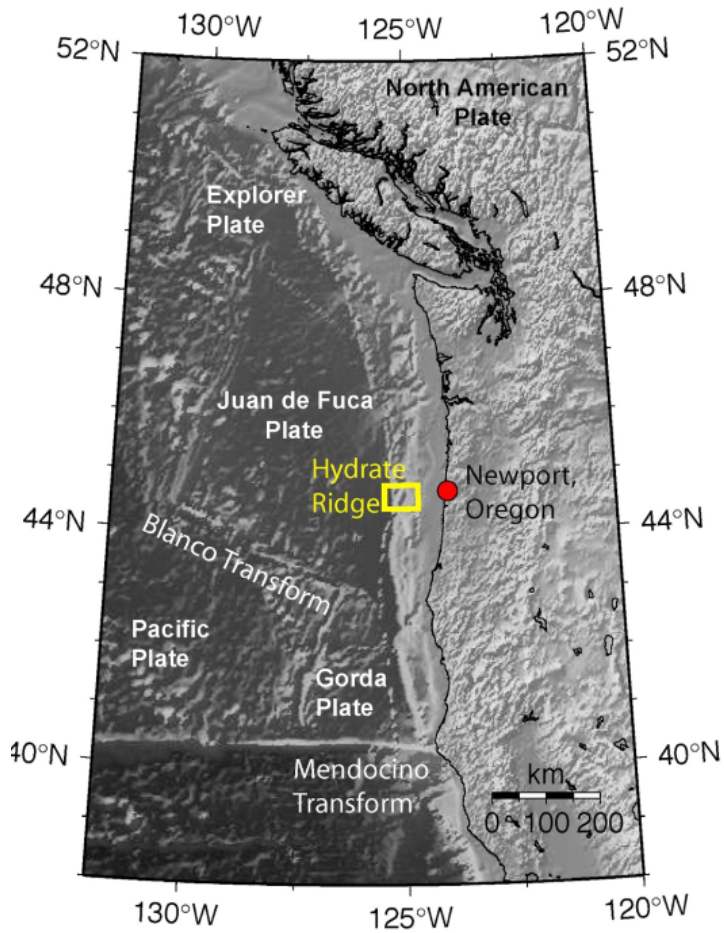
Weitemeyer et al. 2011



Setup



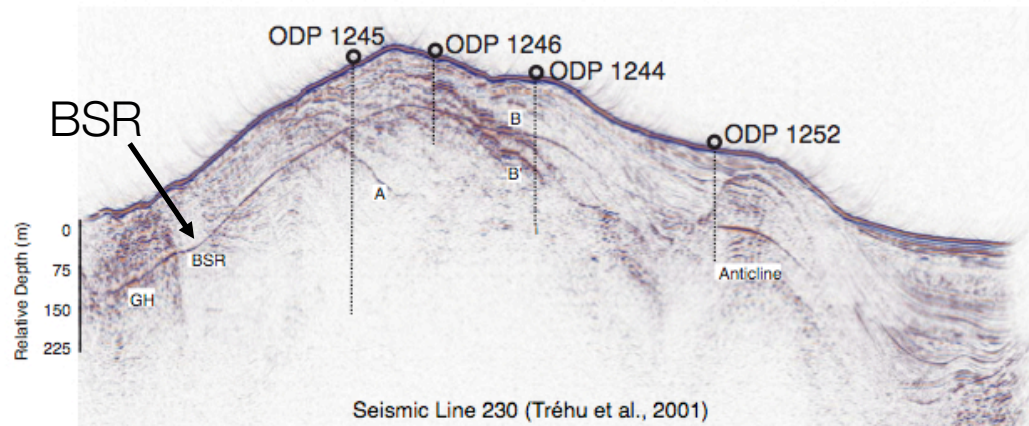
Hydrate Ridge, offshore Oregon



- 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?



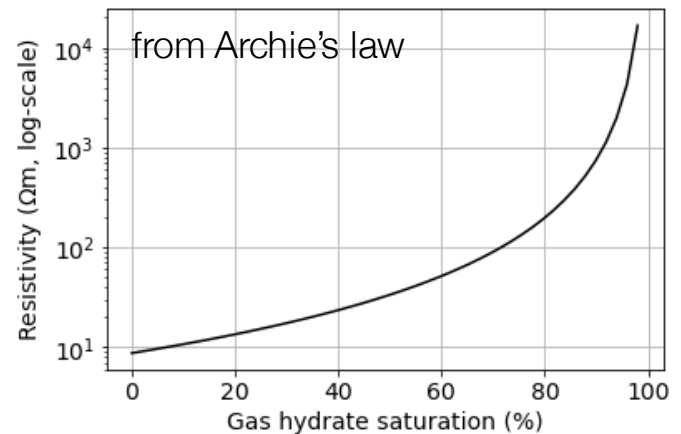
Properties

Types of hydrate



	Resistivity (Ωm)
Seawater	0.25-0.31 (15-3°C)
Freshwater	100-1000
Sediment	1-5
CH ₄ hydrate	20,000 (at 0°C)
Basement	~10-20

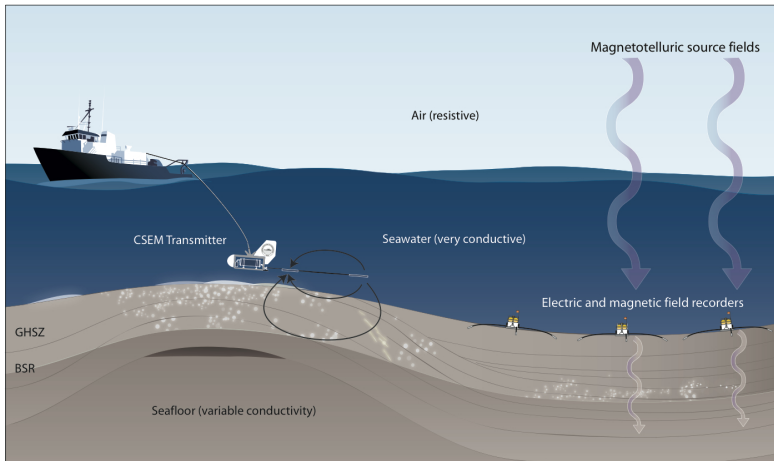
Resistivity vs. Hydrate saturation



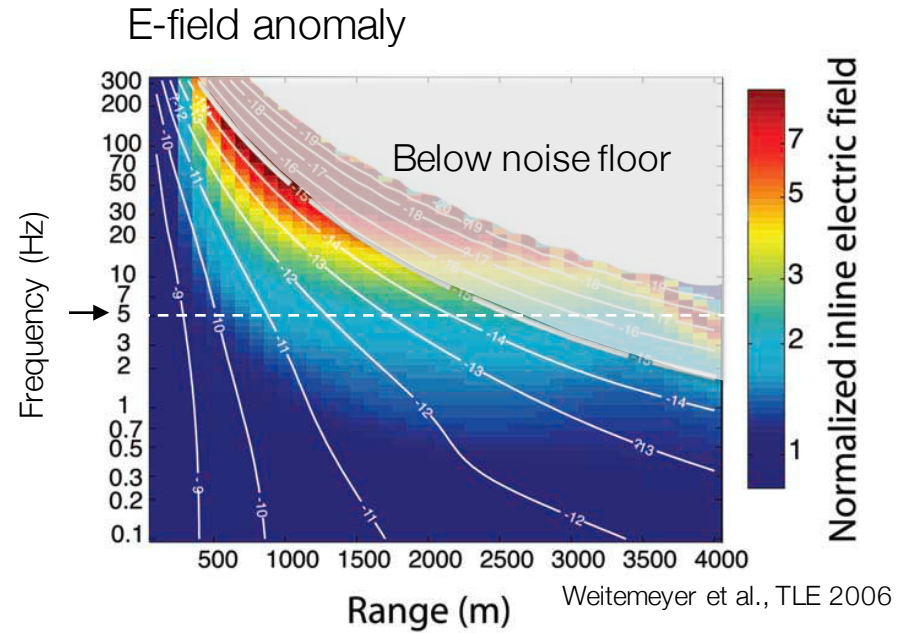
Shipboard Scientific Party
Chapter 2, Explanatory Notes
Ocean Drilling Program (ODP)
Leg 204 Figure F11, page 78

Survey design

Marine CSEM survey

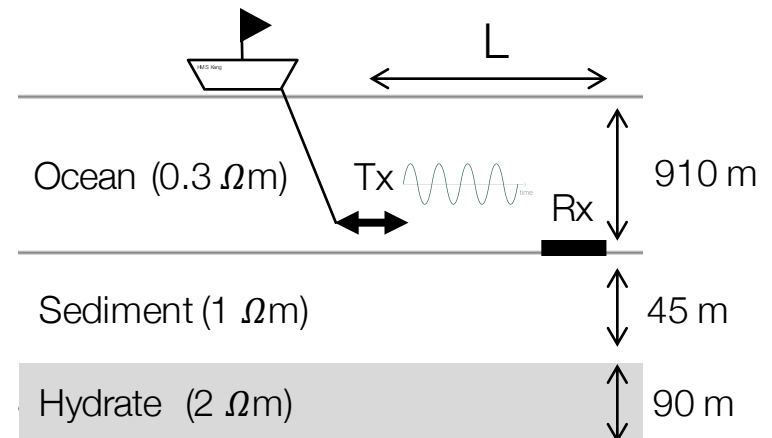


Weitemeyer et al., TLE 2006



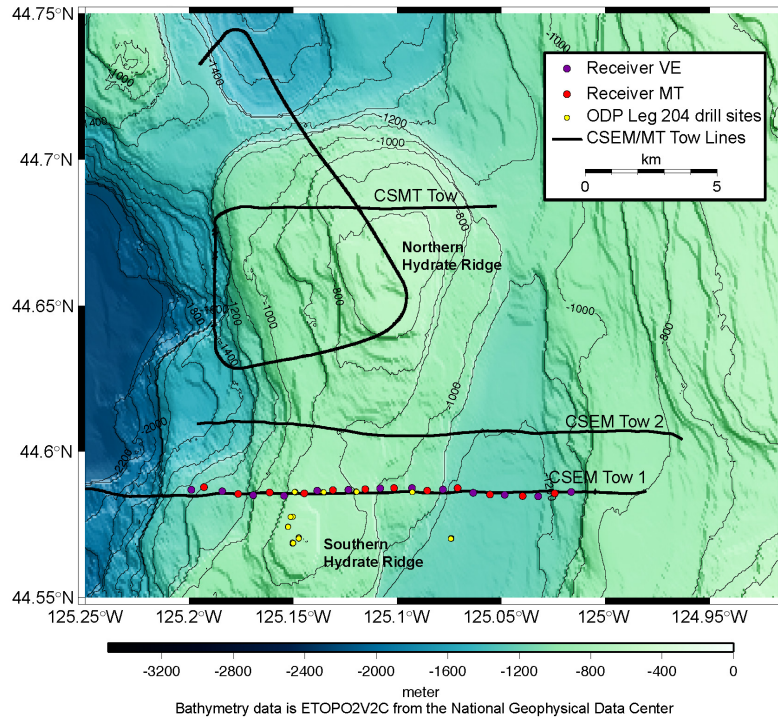
Weitemeyer et al., TLE 2006

- Tx frequency: 5 Hz
- Range of offset: 0 - 3 km
- Noise level: 10^{-15} V/A-m²

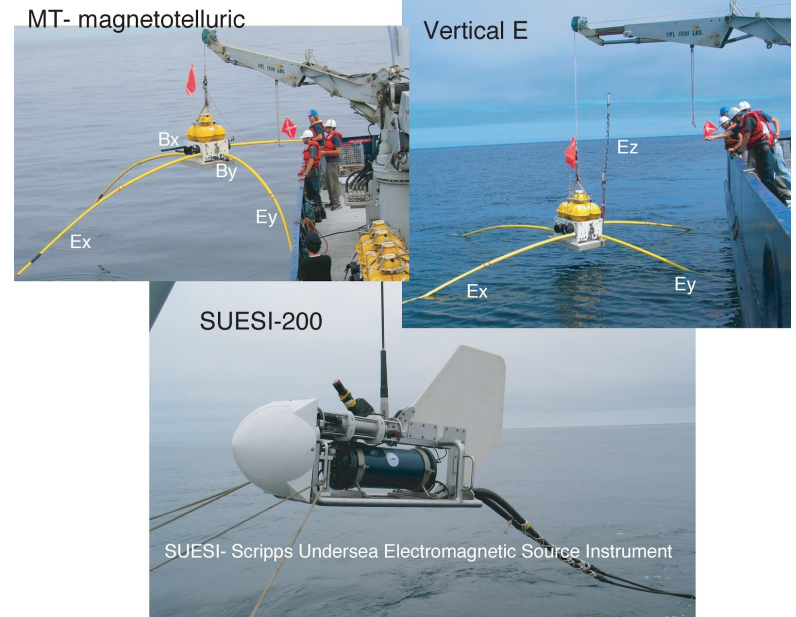


Survey

Geometry



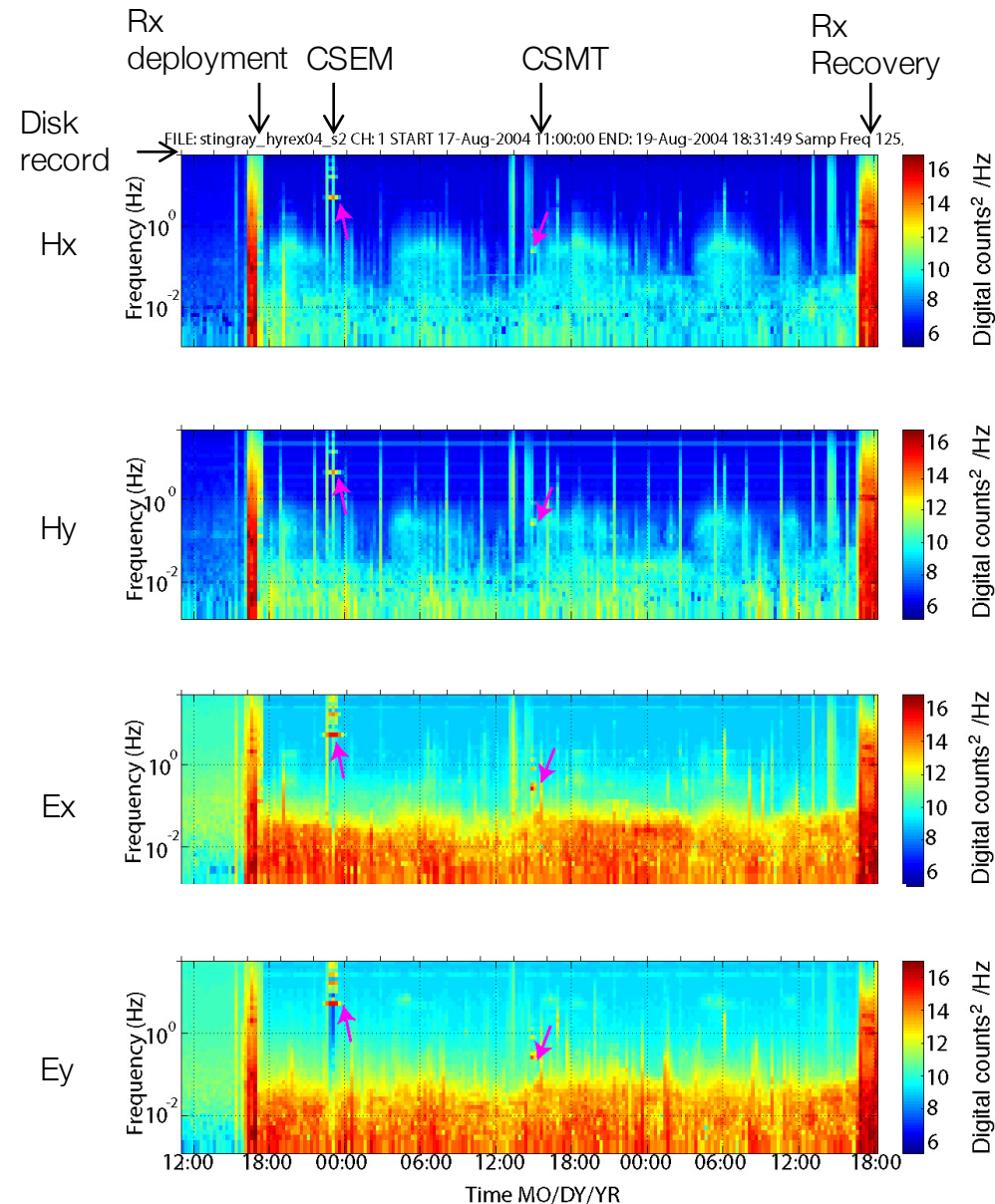
Transmitter and receivers



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

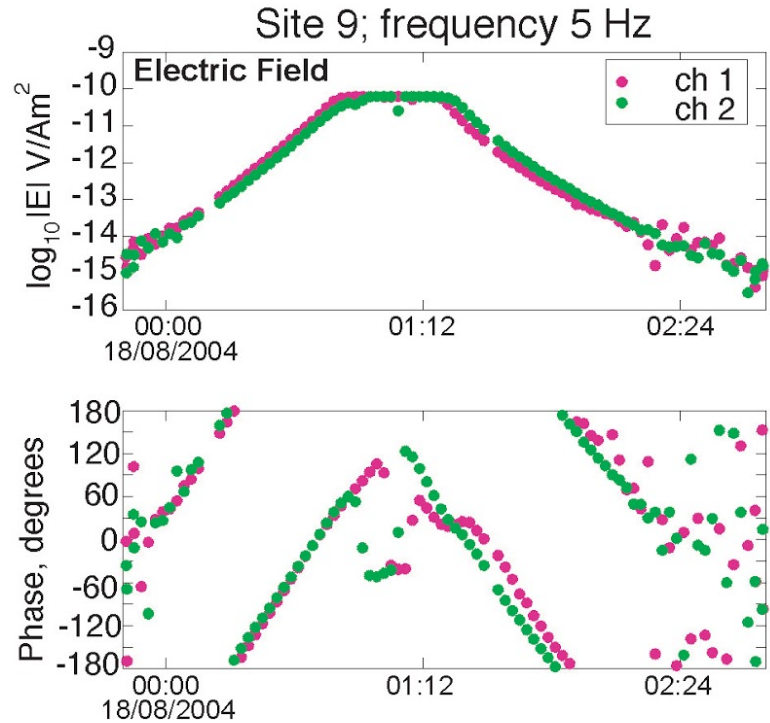
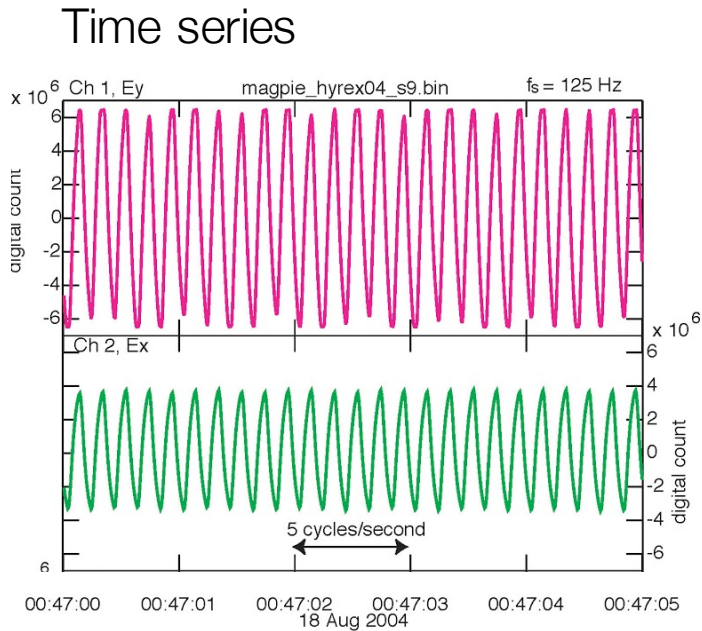
Data: spectrogram



- Disk recording generates noise
- Diurnal variation in H-fields
- Low frequency MT signals (<0.1Hz) in both E and H-fields
 - Ocean: low pass filter
- CSEM: 5Hz
 - Odd harmonics: 15, 25, 35 Hz
- CSMT: 0.1 Hz
 - Odd harmonics: 0.3, 0.5, 0.7 Hz

Processing: amplitude and phase

Amplitude & phase vs. transmission time (offset)

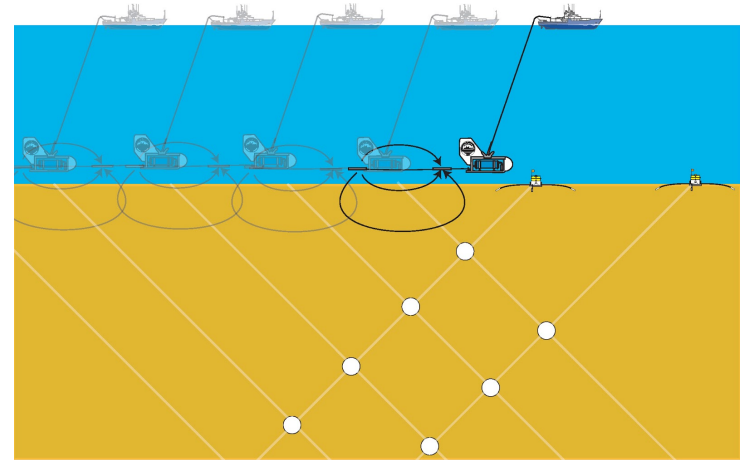
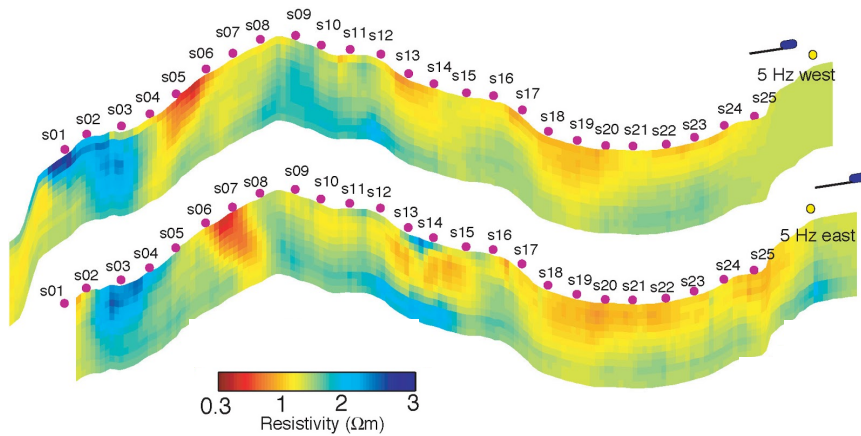


← ~6.7 km →

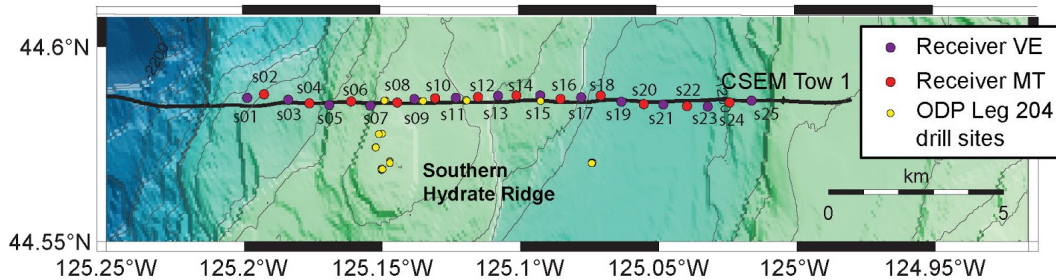
Tow speed:
~1.5 knot (1.852 km/h)

Processing: pseudo-section

Pseudo-section (apparent resistivity)



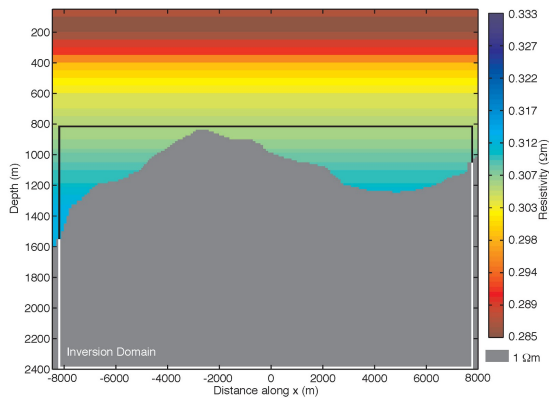
Survey geometry



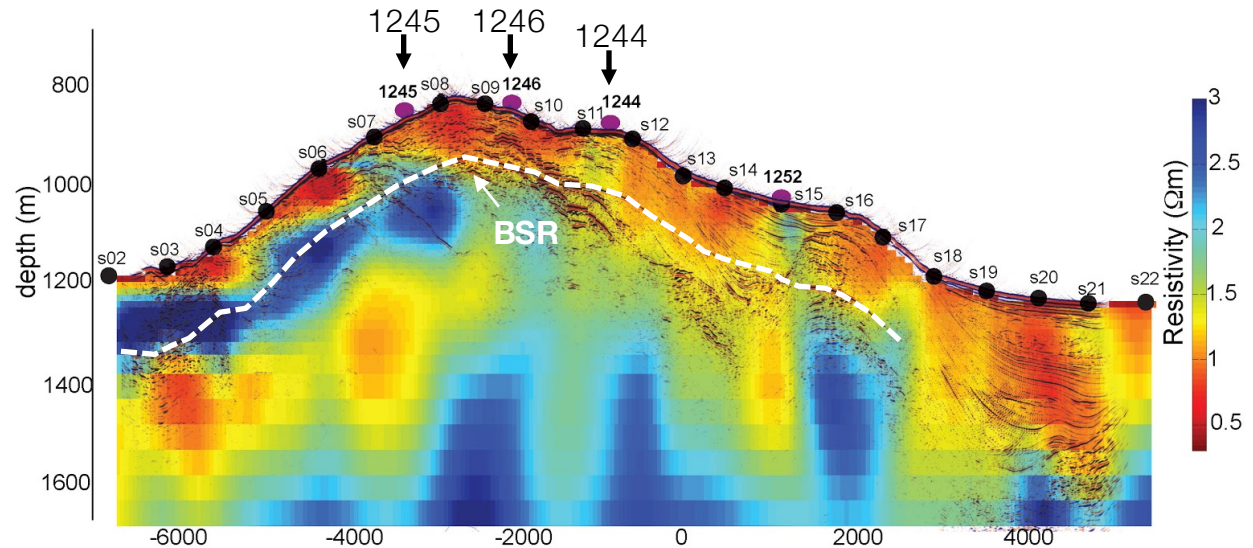
- pseudo-section:
 - fixed ocean resistivity
 - find effective subsea resistivity

Processing: 2.5D inversion

Initial model



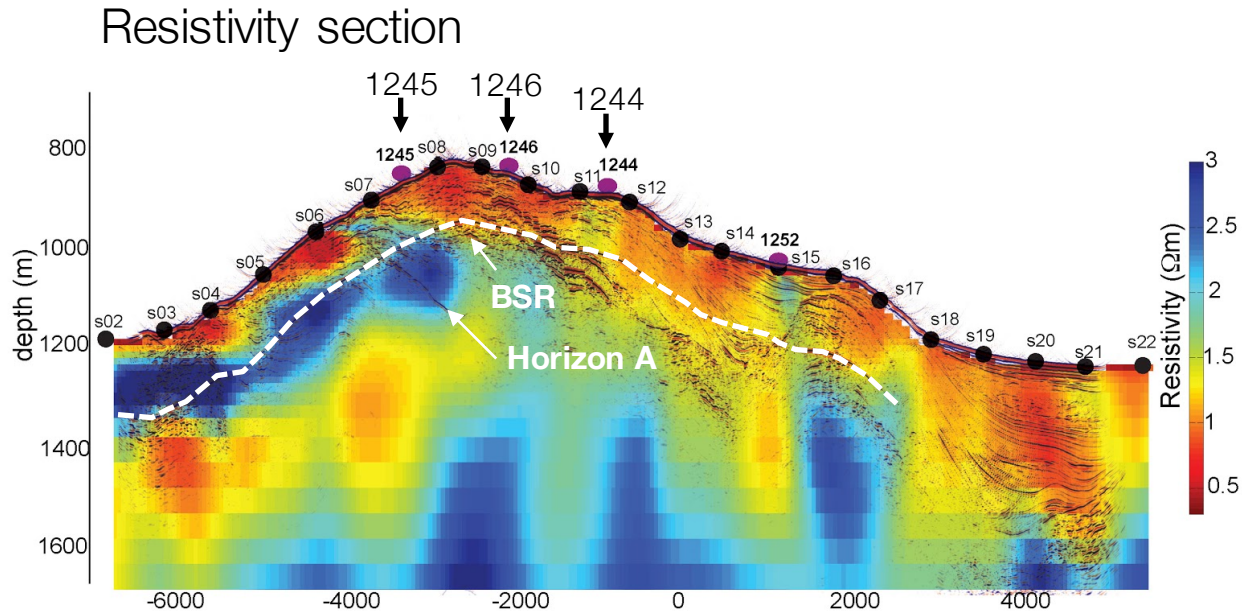
Resistivity section



- Variable ocean σ
 - assign conductivity from CTD data (conductivity, temperature, depth)

- Resistors are imaged near BSR

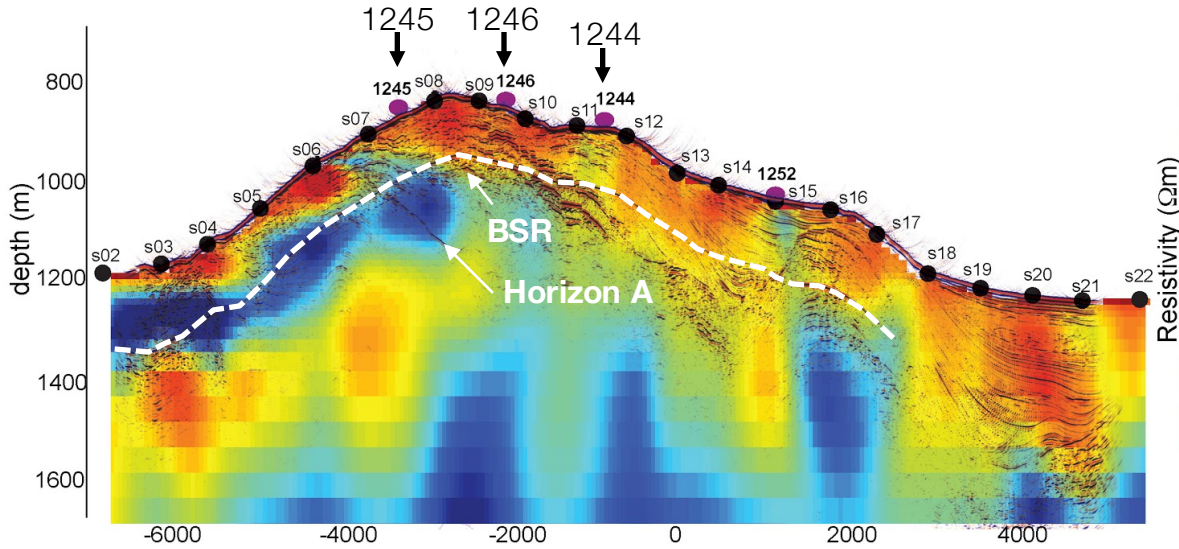
Interpretation: 2.5D inversion



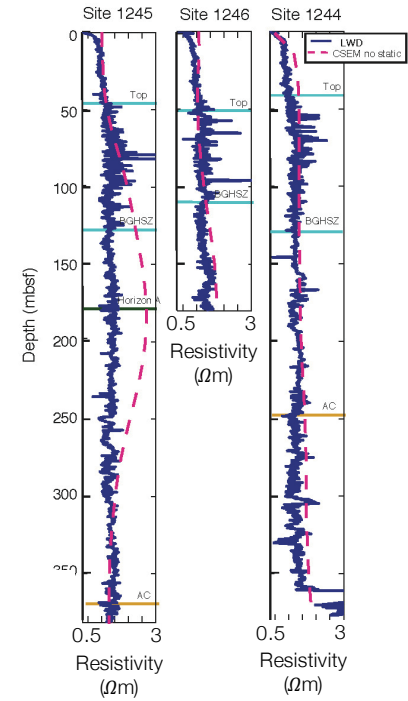
- Resistors are imaged near BSR
- Hydrate stability
 - Above BSR: hydrate
 - Below BSR: free gas

Interpretation / Synthesis

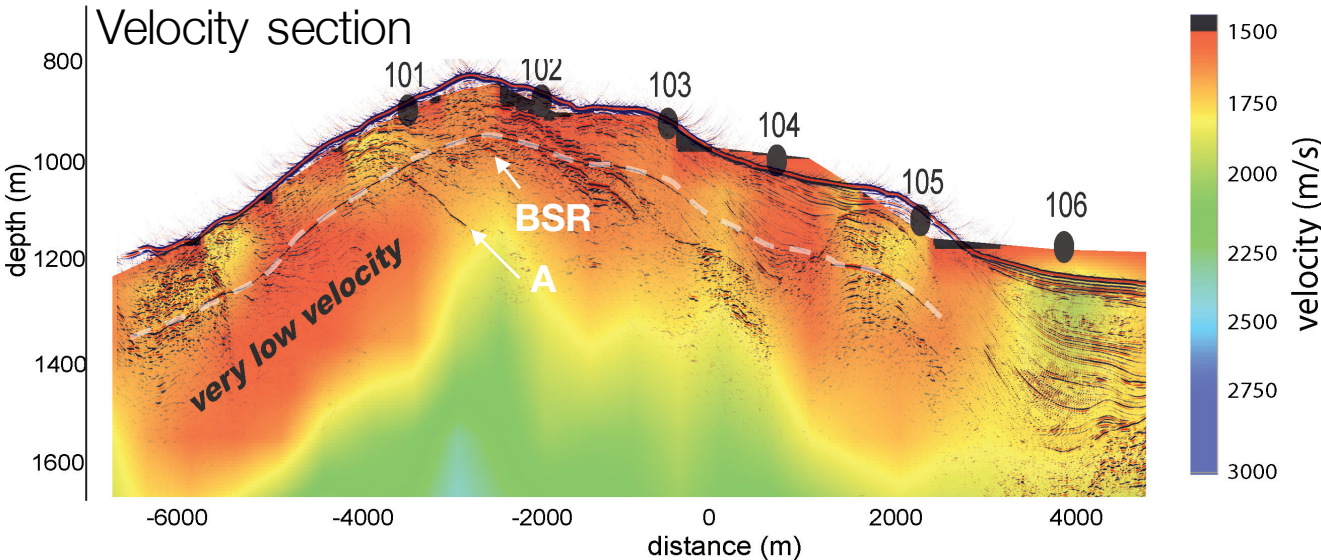
Resistivity section



Well-logs



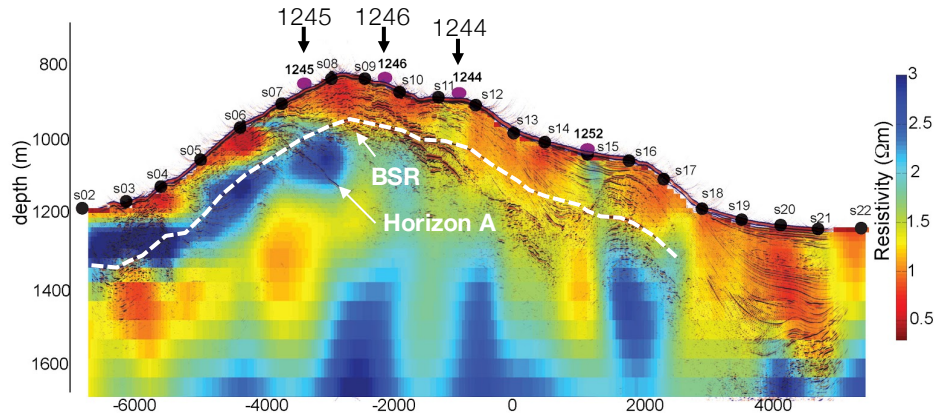
Velocity section



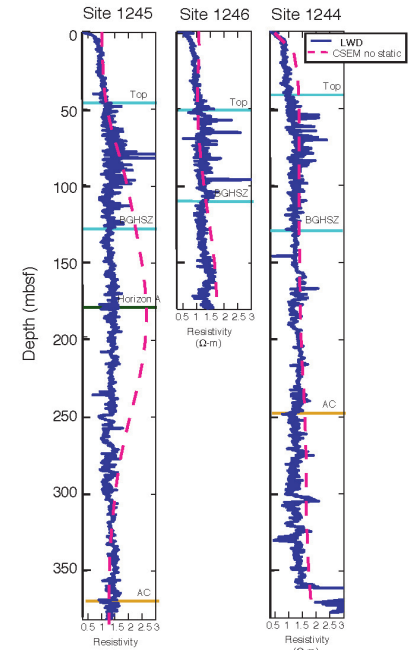
Hydrate	ρ	V_p
Free gas	High	Low
Solid	High	High

Synthesis: hydrate concentration

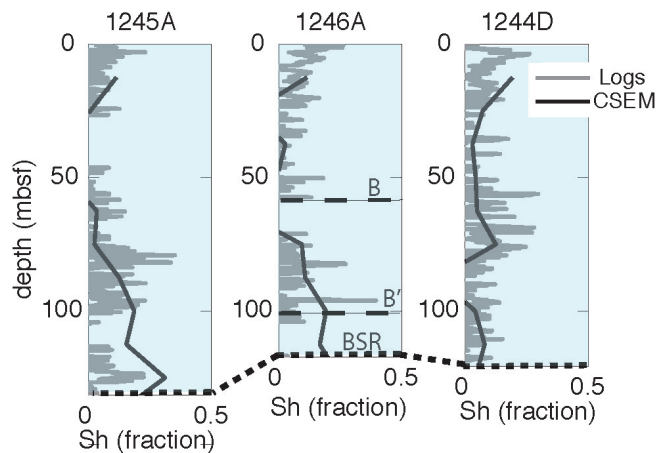
Resistivity section (from CSEM)



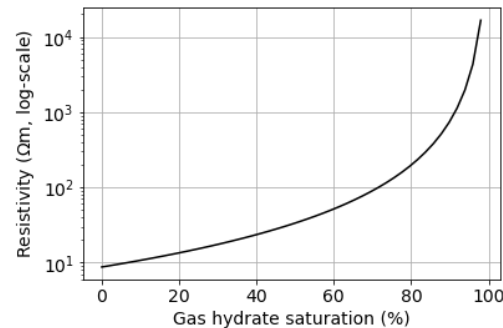
Well-logs



Computed hydrate concentration



Resistivity vs. Hydrate saturation



Archie's law:

$$S_w = (aR_w / \phi^m R_t)^{1/n}$$

$$S_h = 1 - S_w$$

R_w : formation water res.

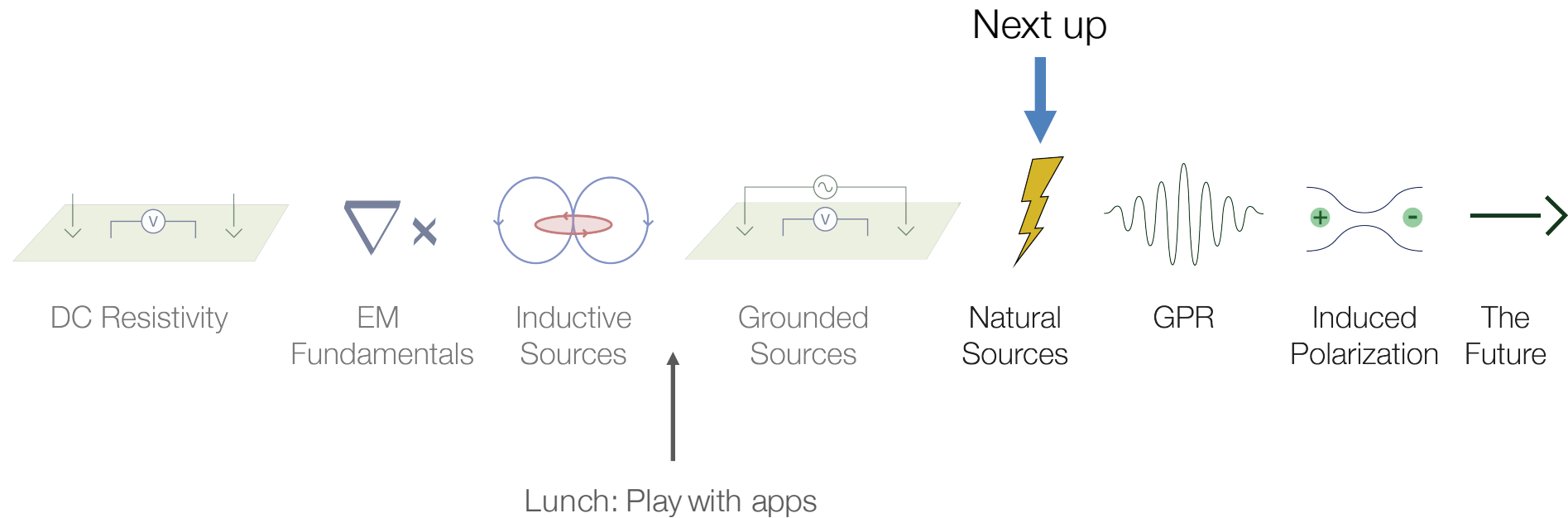
R_t : formation res.

ϕ : porosity

$a=1, m=2.8, n=1.9$

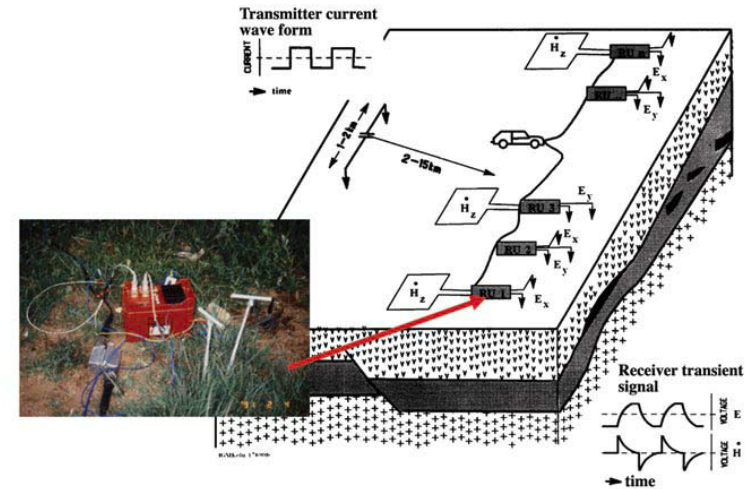
(from ODP Leg 204 report)

End of Grounded Sources

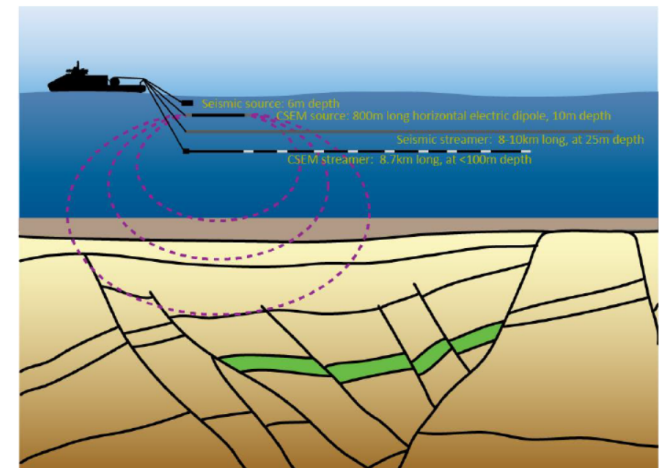


Grounded sources: two examples

- Land EM
 - Large offset time domain system
 - Looking for sediments below basalts



- Marine EM (towed Tx, Rx array)
 - Multiple transmitters, frequencies
 - Looking for a resistive target

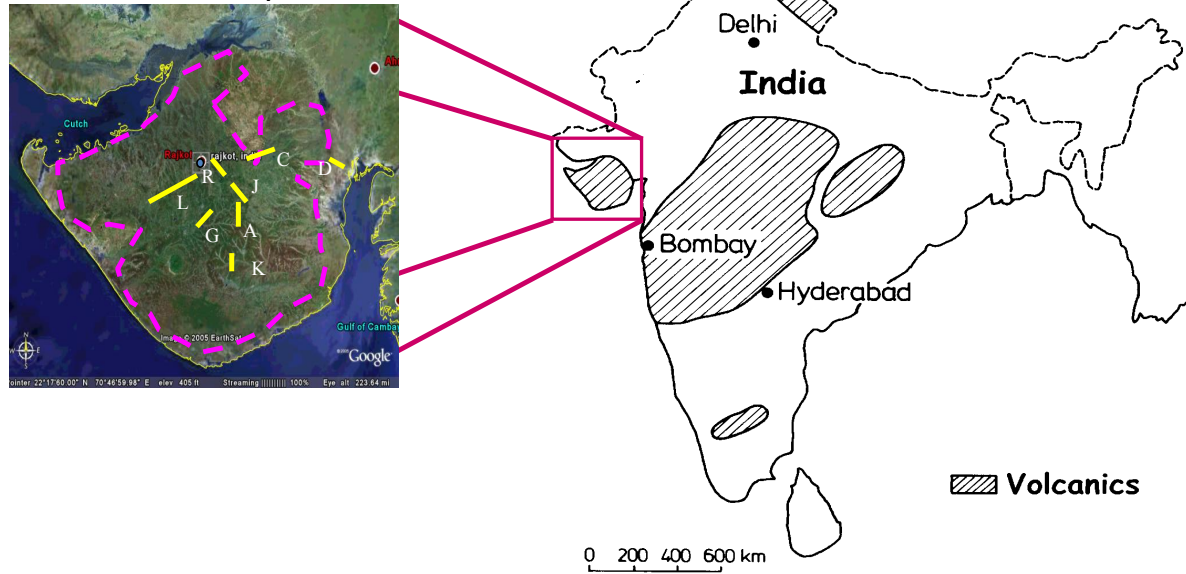


Case History: Mesozoic sediments beneath Deccan traps, India

Strack and Pandey, 2007

Setup

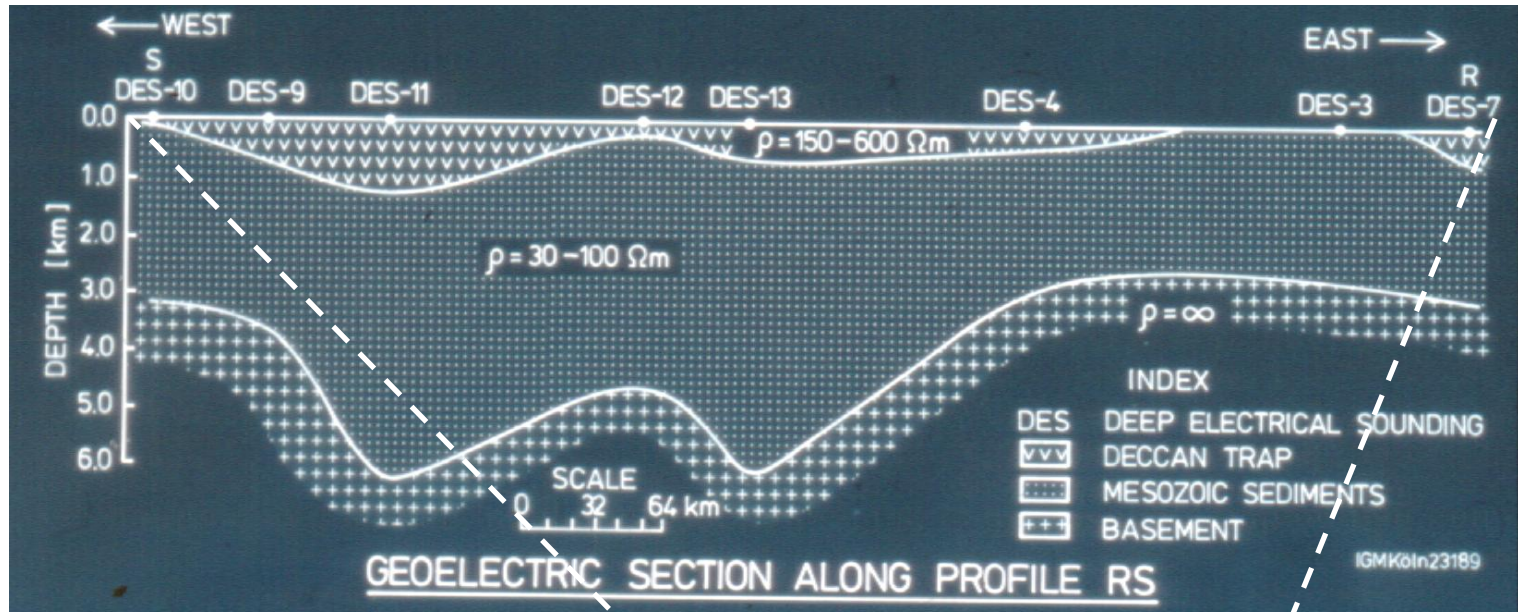
Location map



- Trap basalts (onshore)
 - flat lying basalt layers fed by fissures
- Complex geology (offshore)
- Challenging for Seismic
- Find Mesozoic sediments and then look for reservoirs

Previous DCR survey (ONGC)

Resistivity section



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

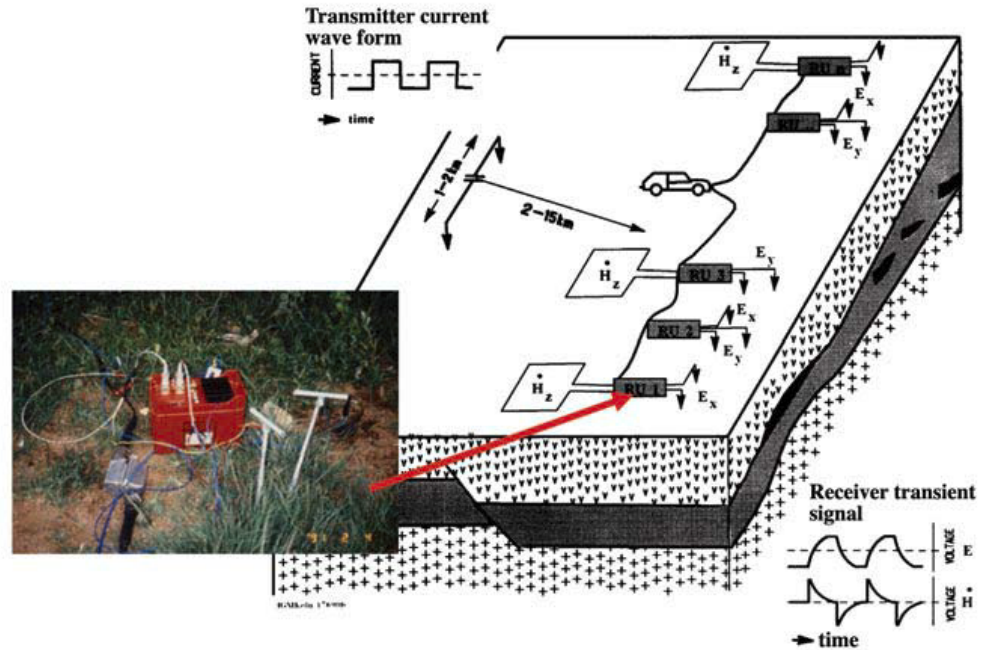


Survey

Map

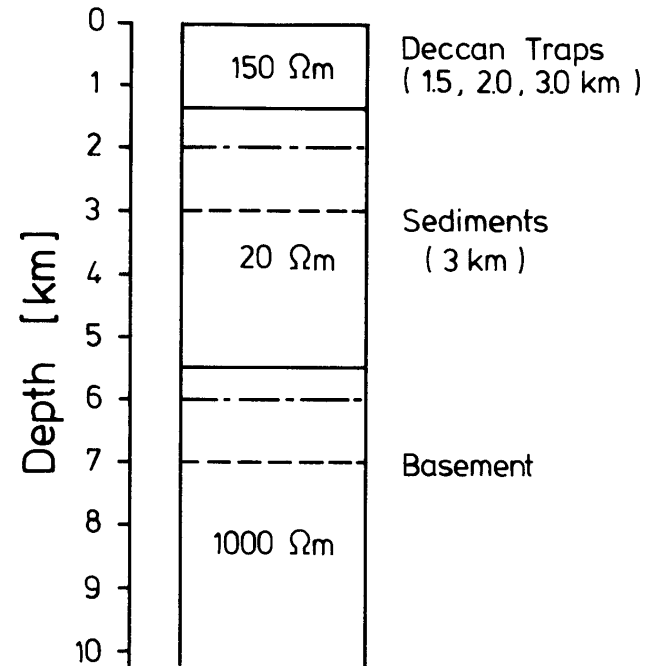
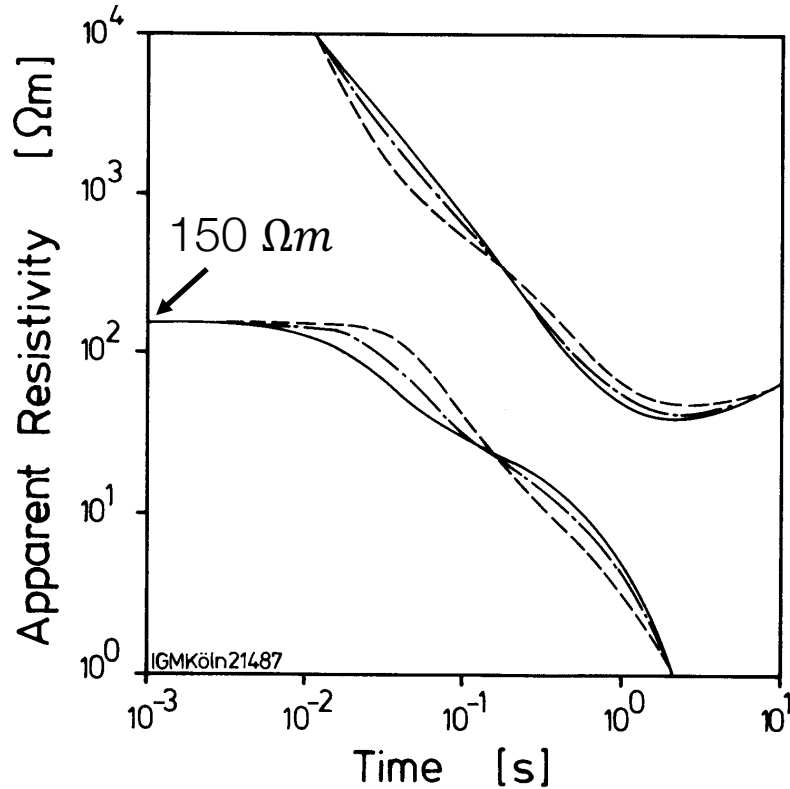


Long offset time domain EM (LOTEM)



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

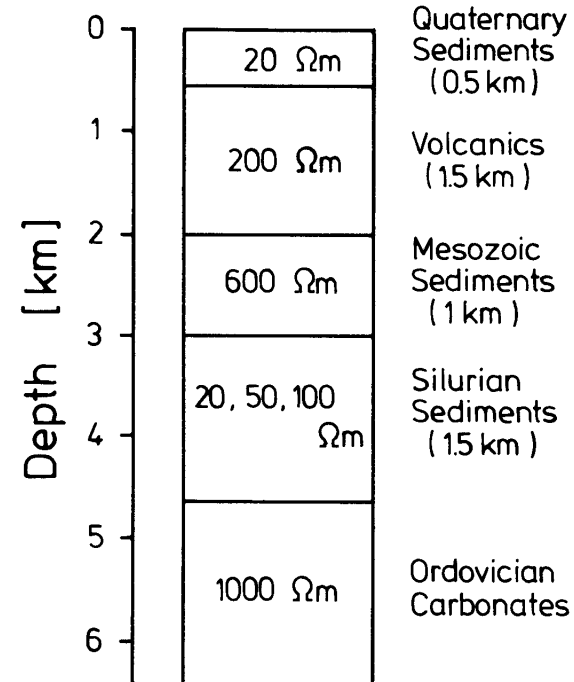
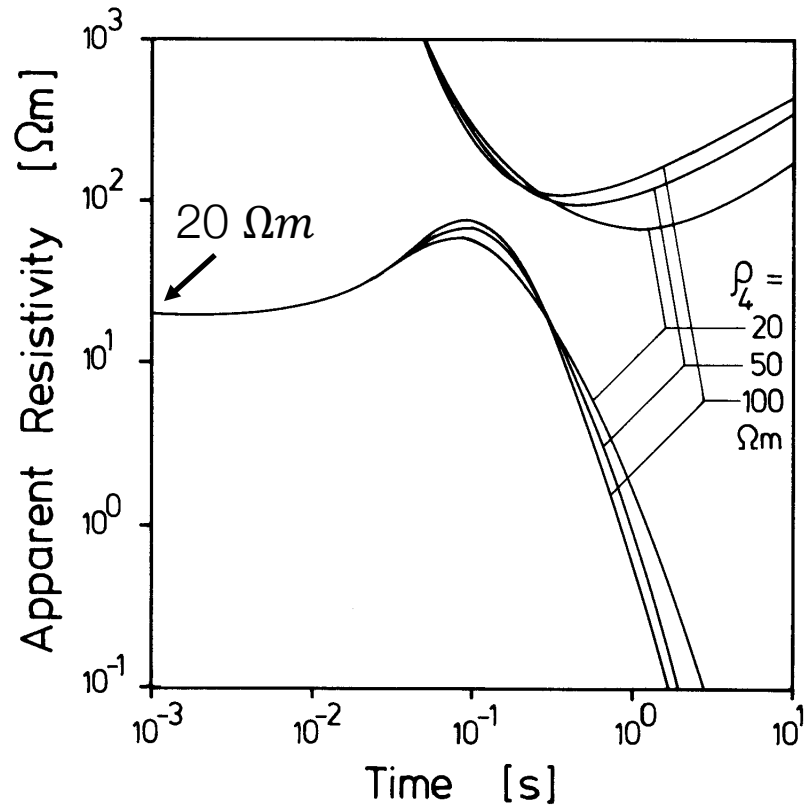
Survey design: basalt thickness



Varied : 1st layer thickness
Offset : 10 km

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

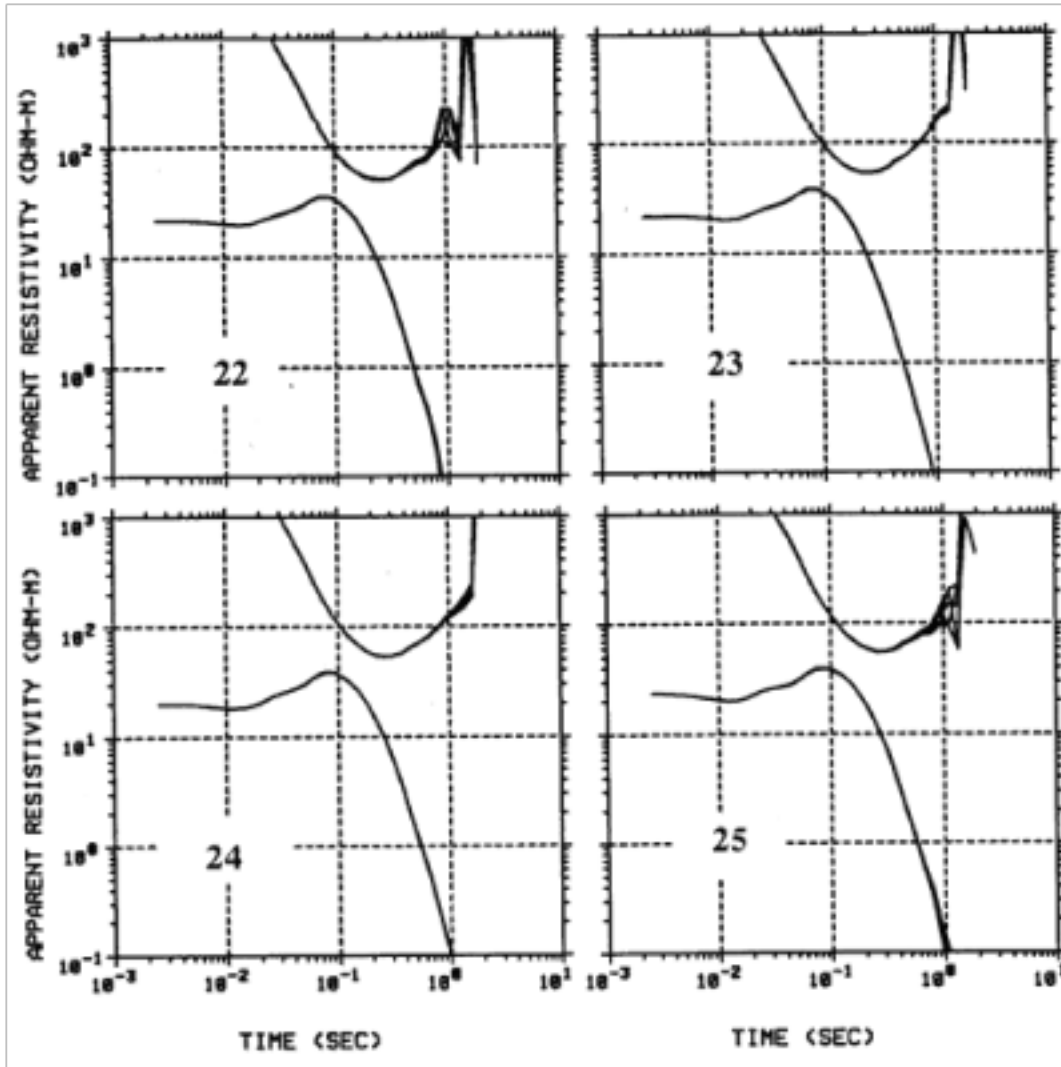
Survey design: sediment resistivity



Varied : 4 th layer resistivity
Offset : 9 km

- Apparent resistivity changes with varying resistivity of Silurian Sediments

Data



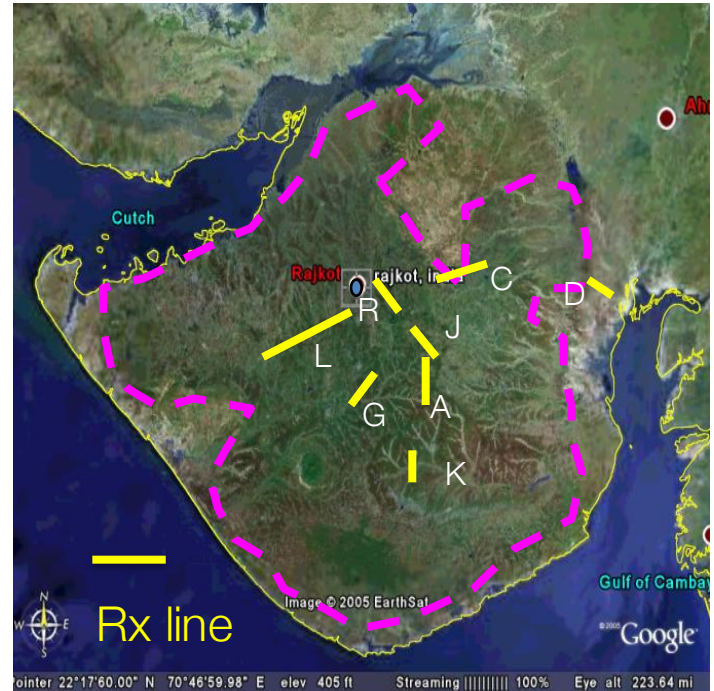
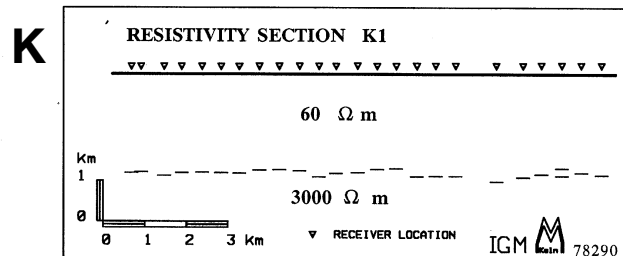
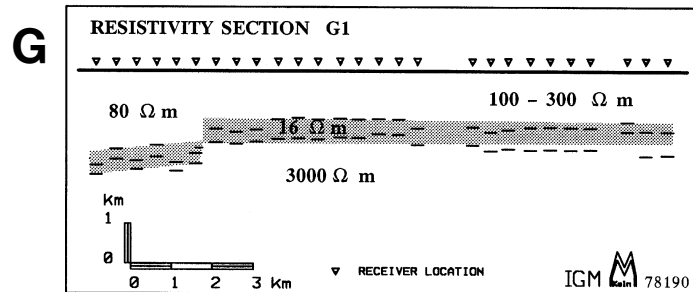
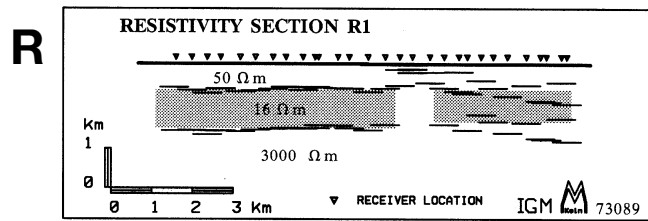
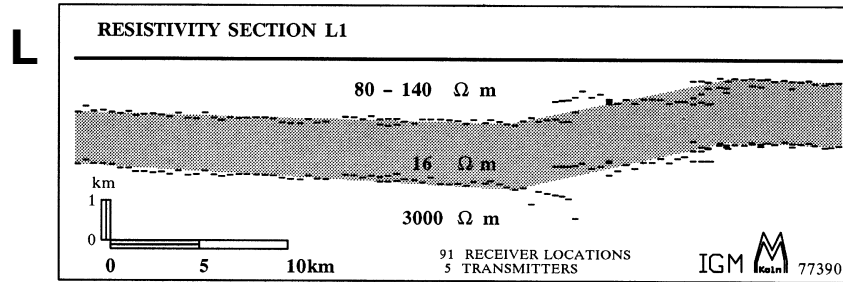
- Stacked data
- Time range: 1ms-10s
- High S/N ratio until 1s
- Similar to synthetic data

Processing

1D inversions (stitched)

Location map

Thickness decreases

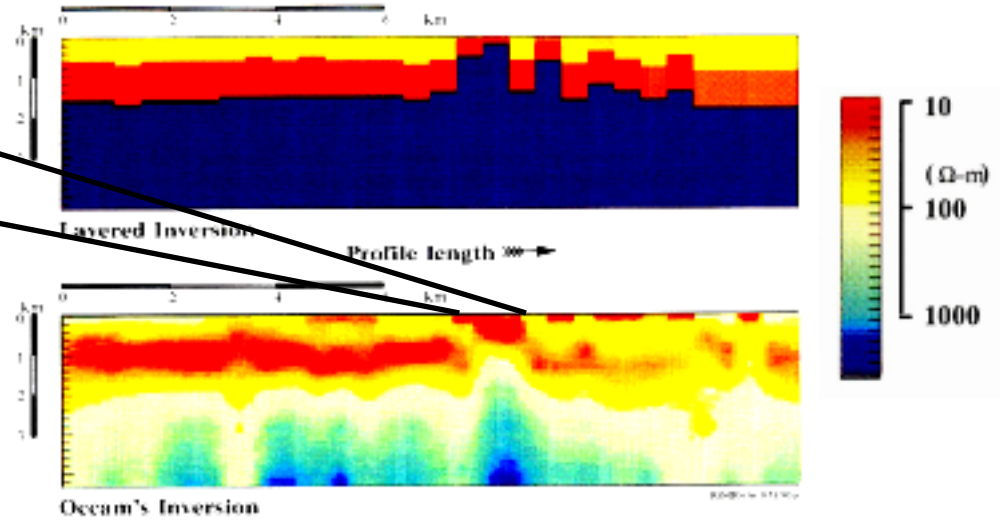


The sediment thickness:

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

Interpretation: dyke. Profile **R**

Surface outcrop

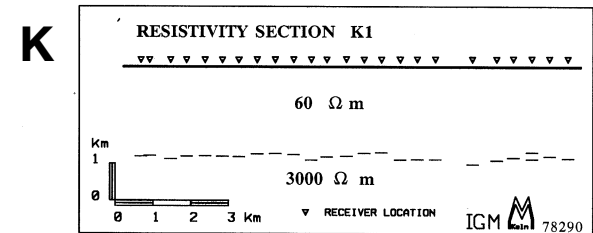
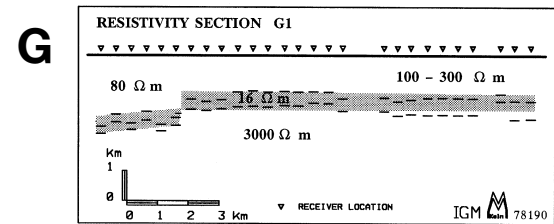
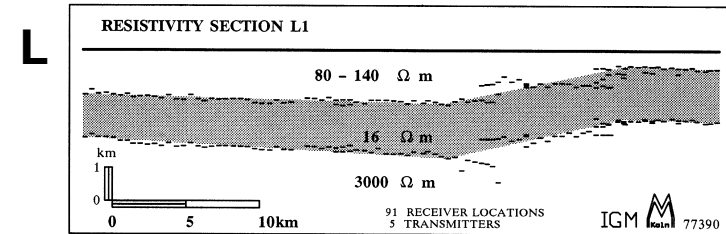
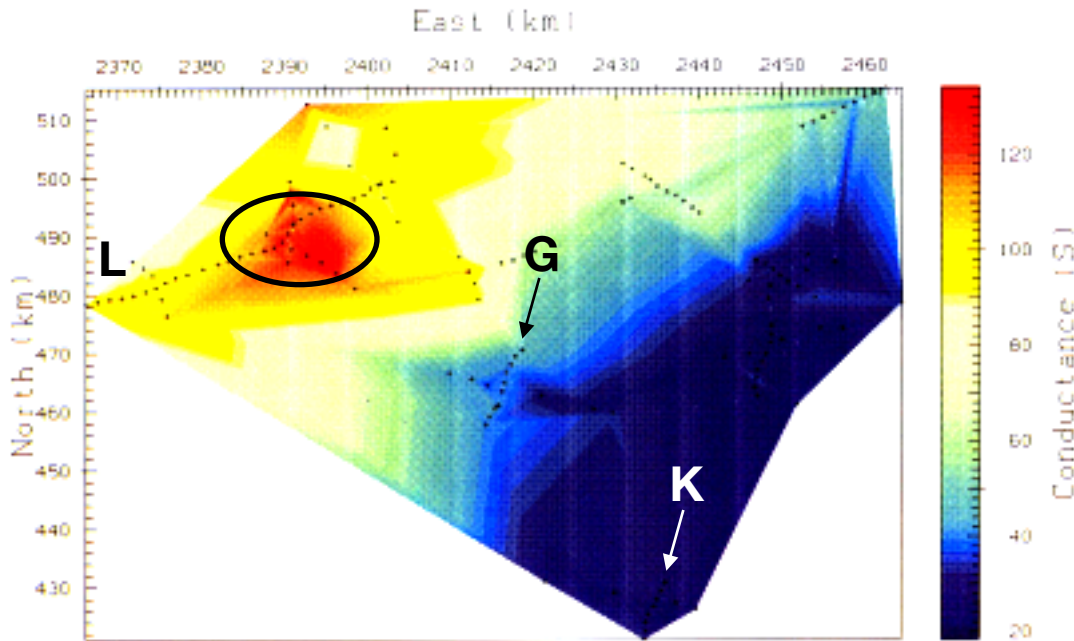


Extended view

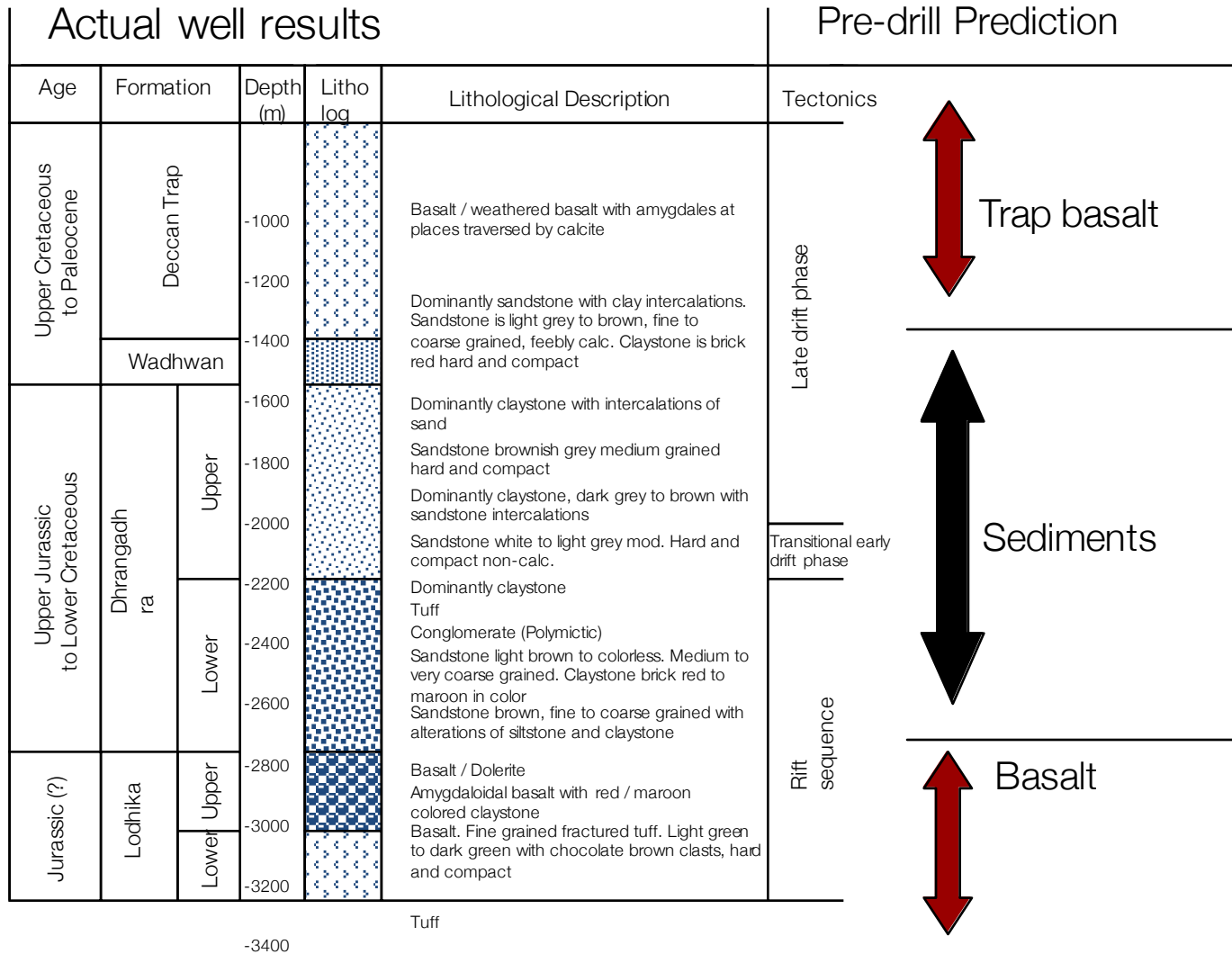


Dyke is a resistor

Interpretation: sediment conductance and drill target



Synthesis

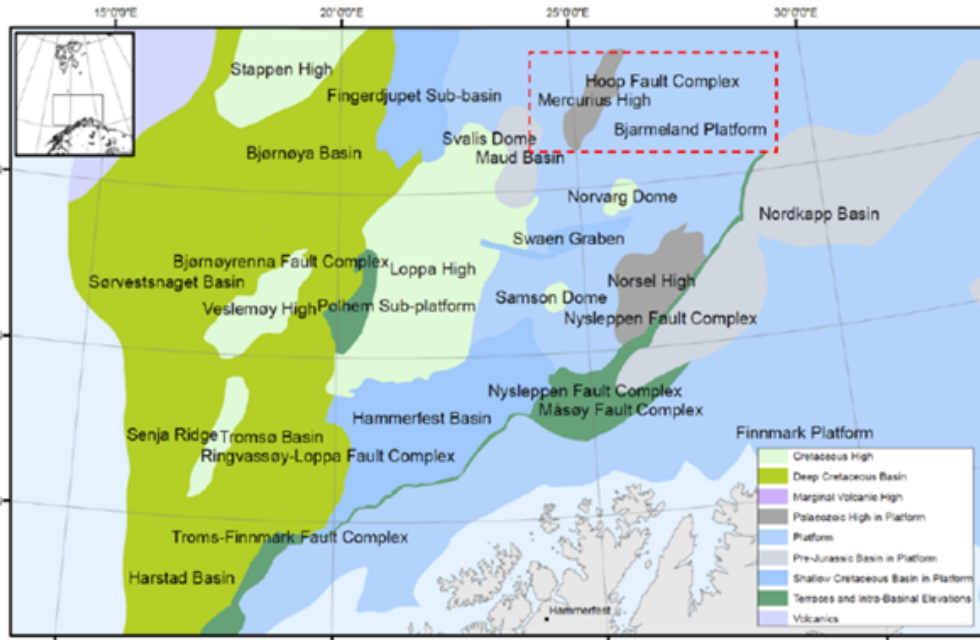


Case History: Barents Sea

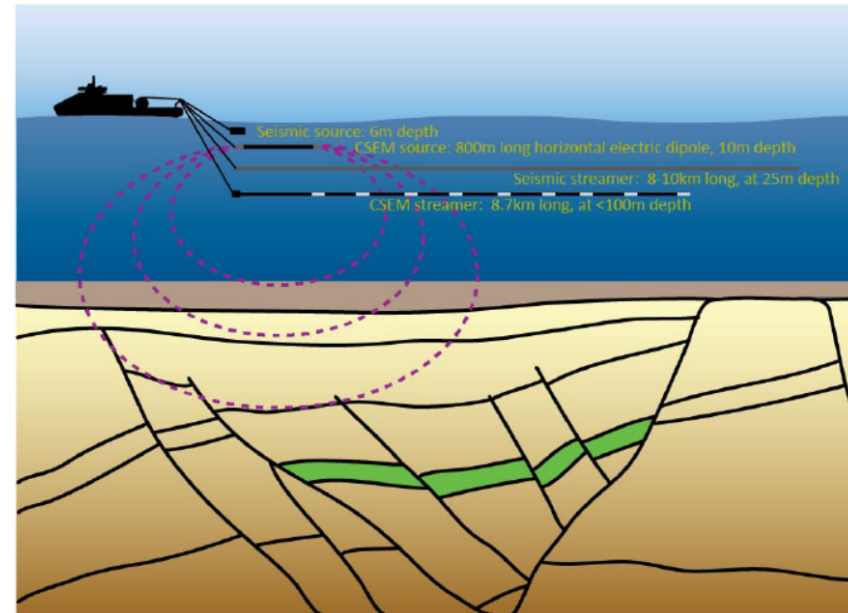
Alvarez et al., 2016. Rock Solid Images

Setup

Hoop Fault Complex, Barents Sea

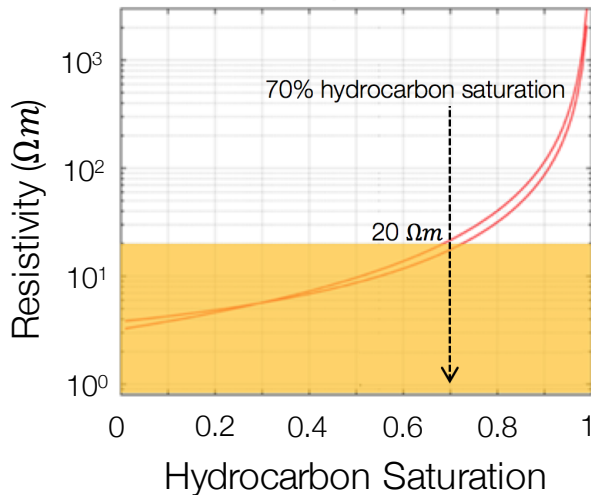
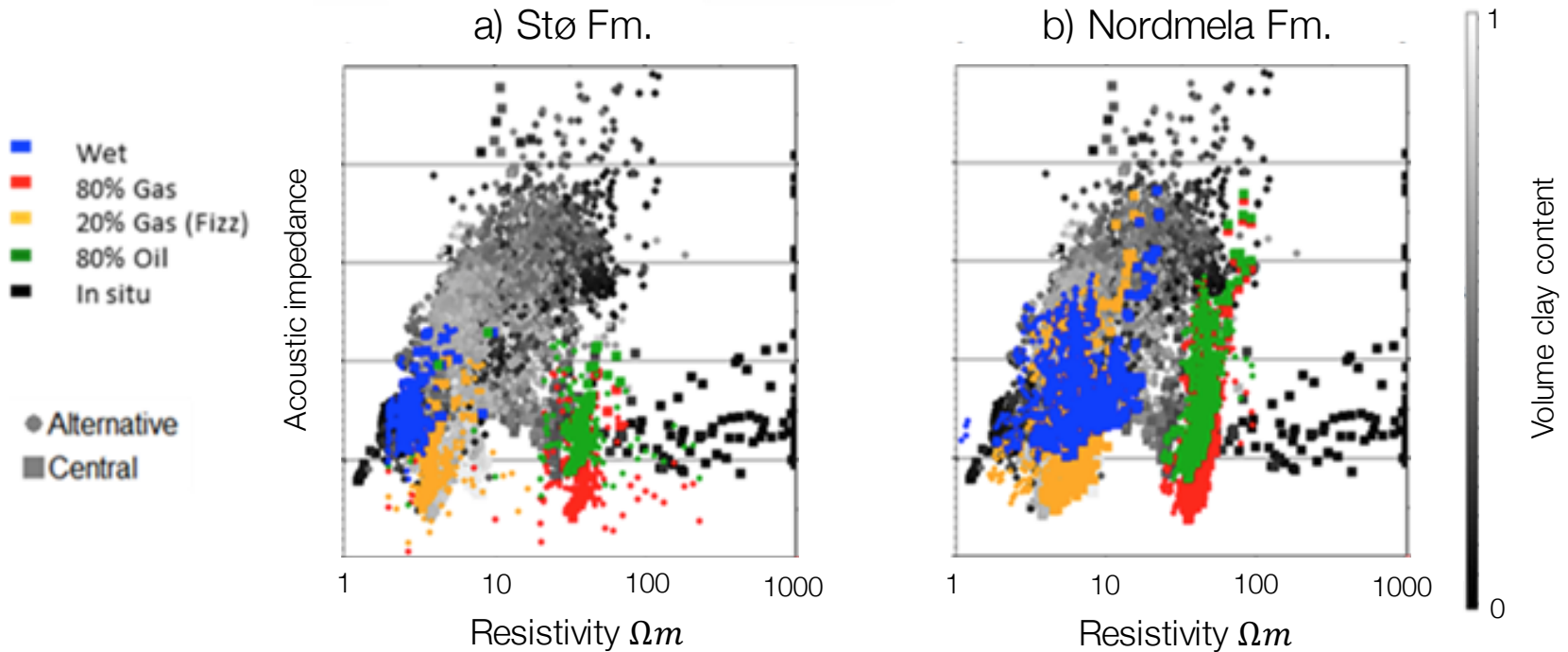


Marine CSEM



- 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

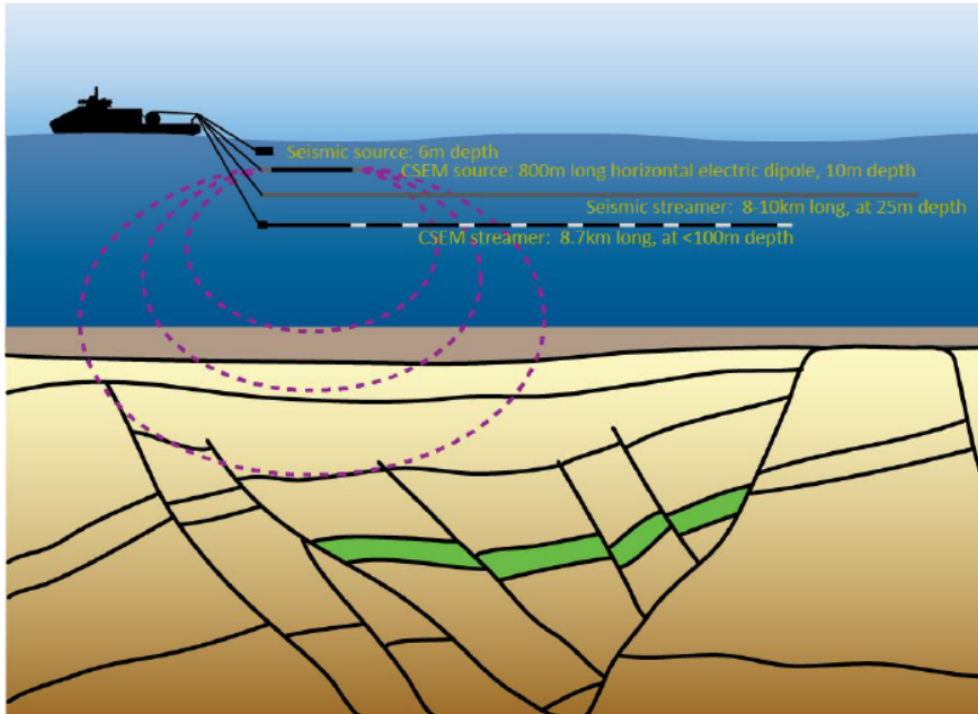
Properties



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

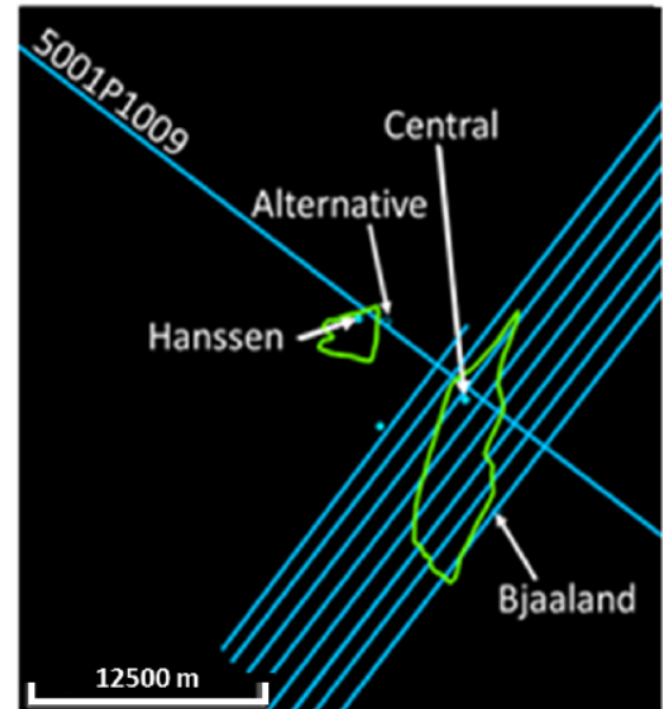
Survey

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.

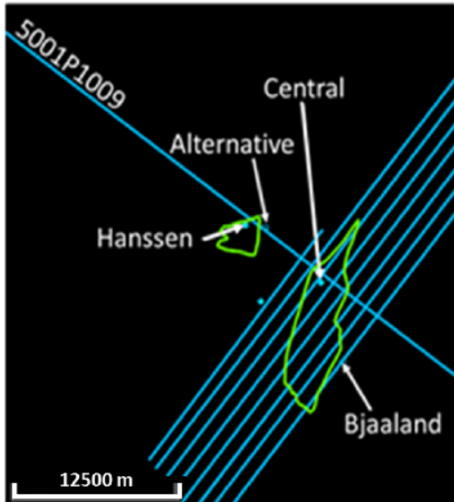
Survey lines



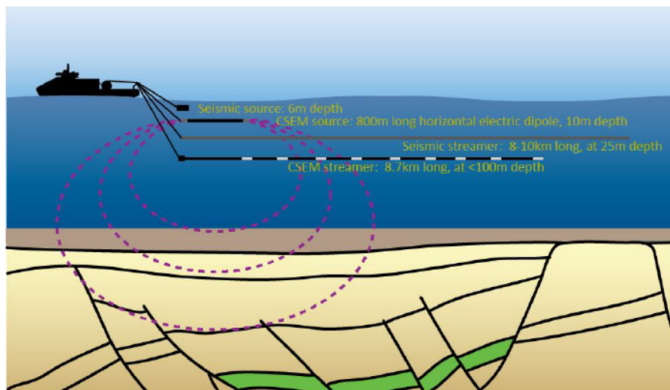
Alternative	Control well, dry
Central	Control well, productive
Hanssen	Validation well
Bjaaland	Validation well

CSEM Data

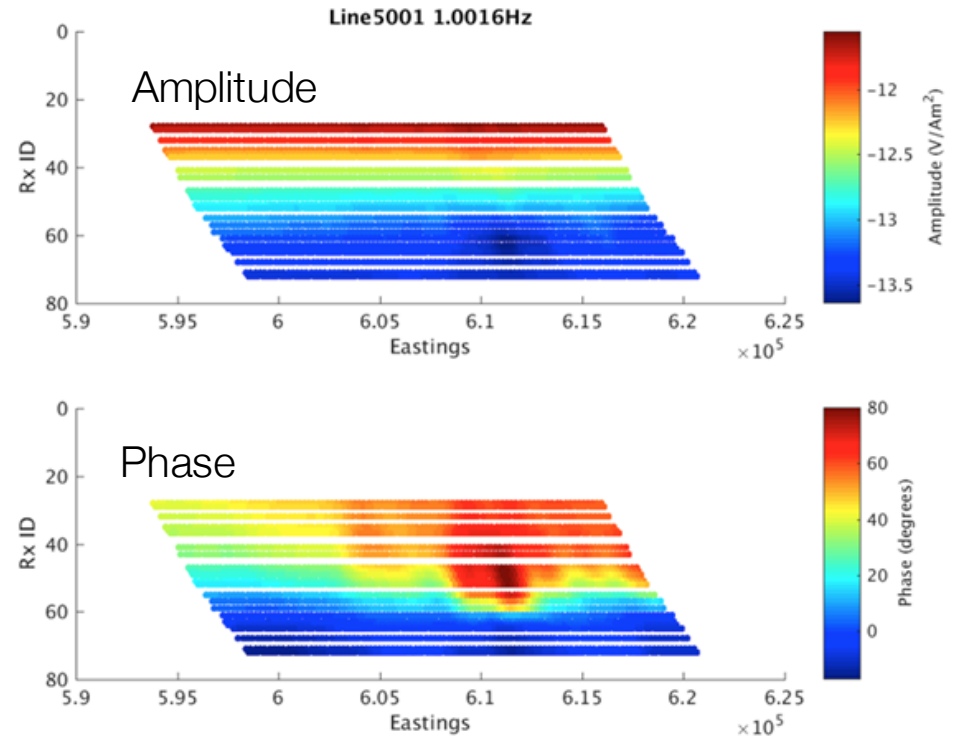
Survey lines



Towed-streamer EM



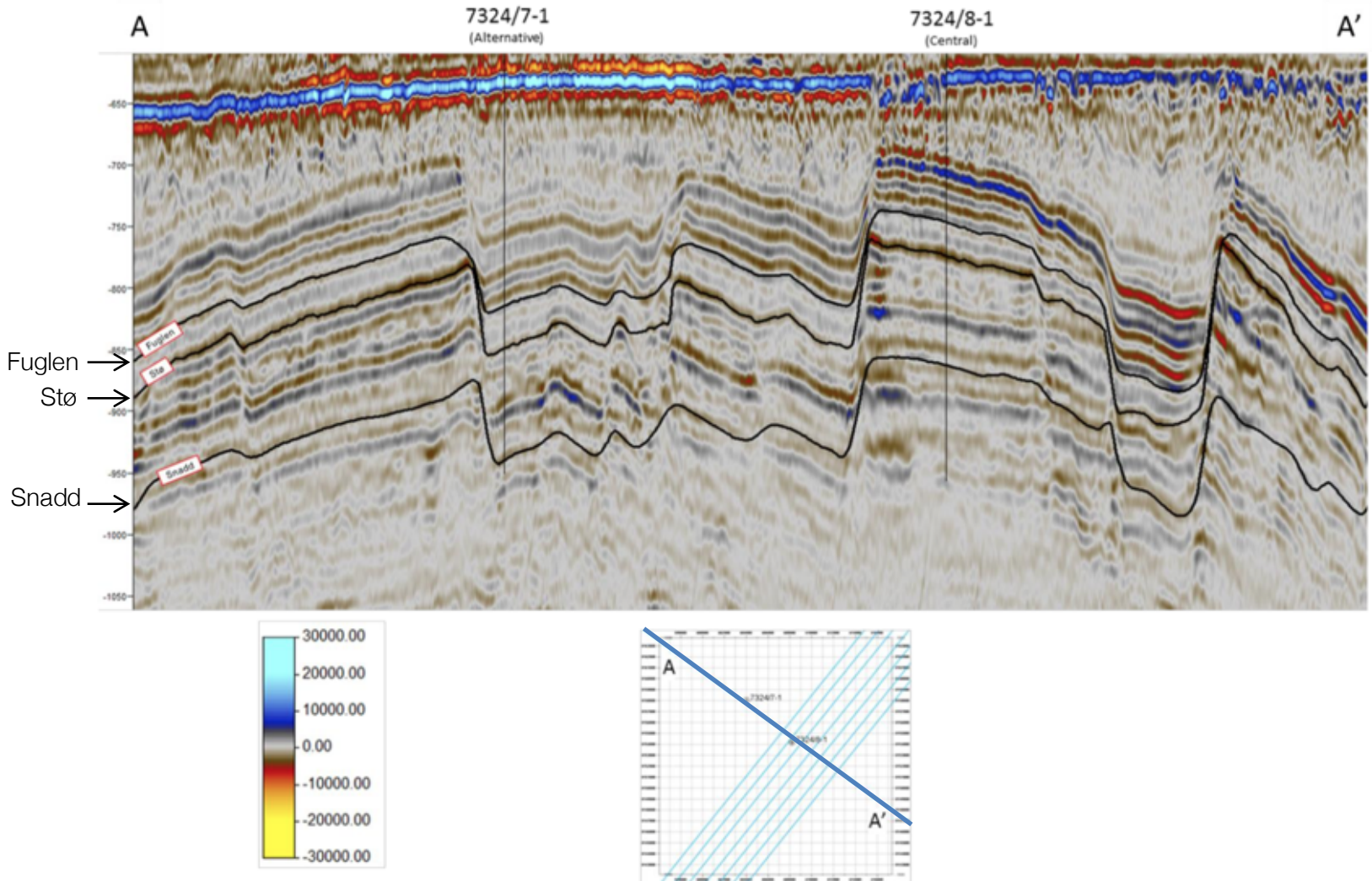
CSEM data over central reservoir (1 Hz)



- Significant phase response over Central reservoir

Seismic data

Seismic section: Line 5001

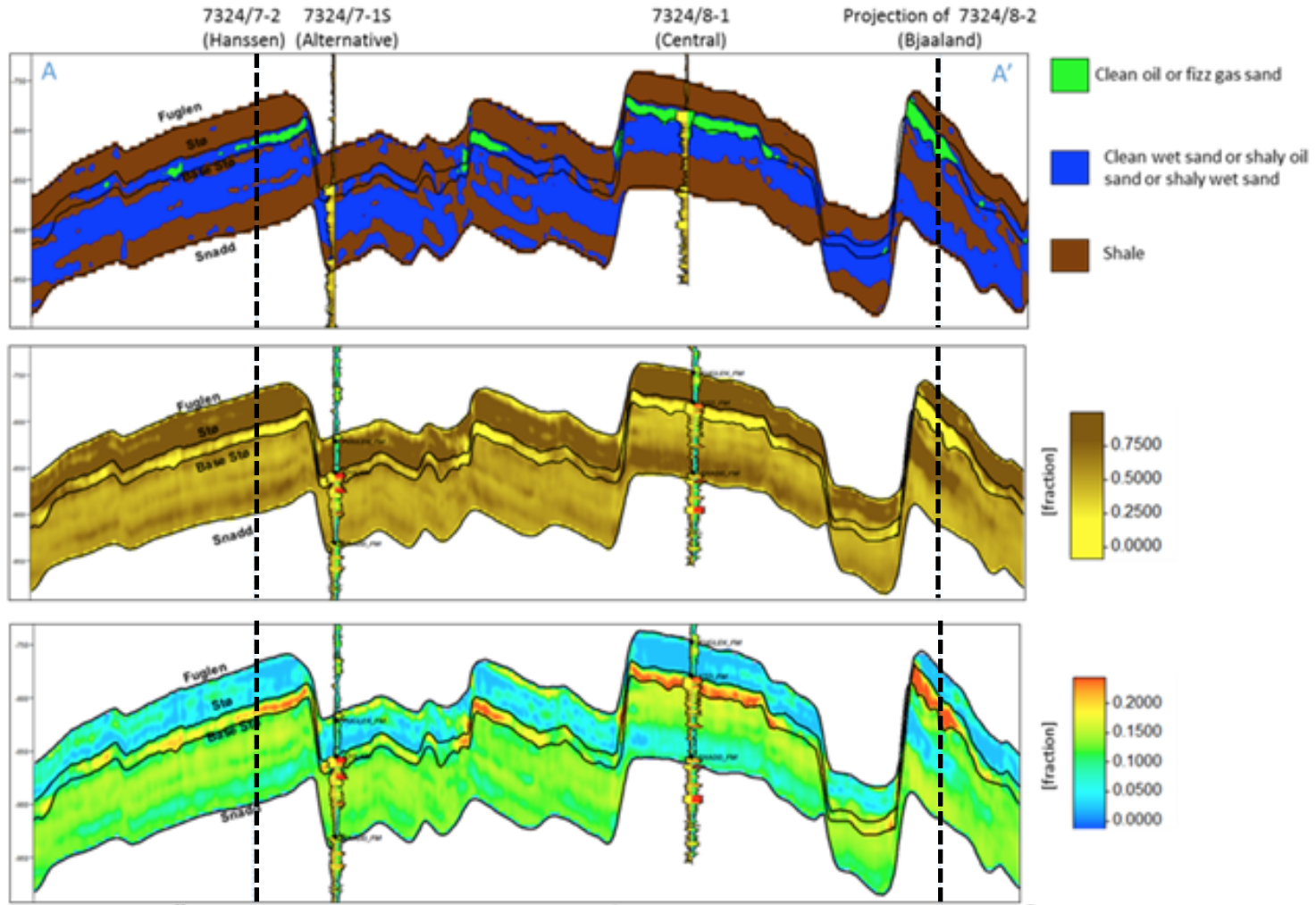


Well-Log and Seismic Inversion

Litho-fluid
Facies

Clay Content

Total Porosity



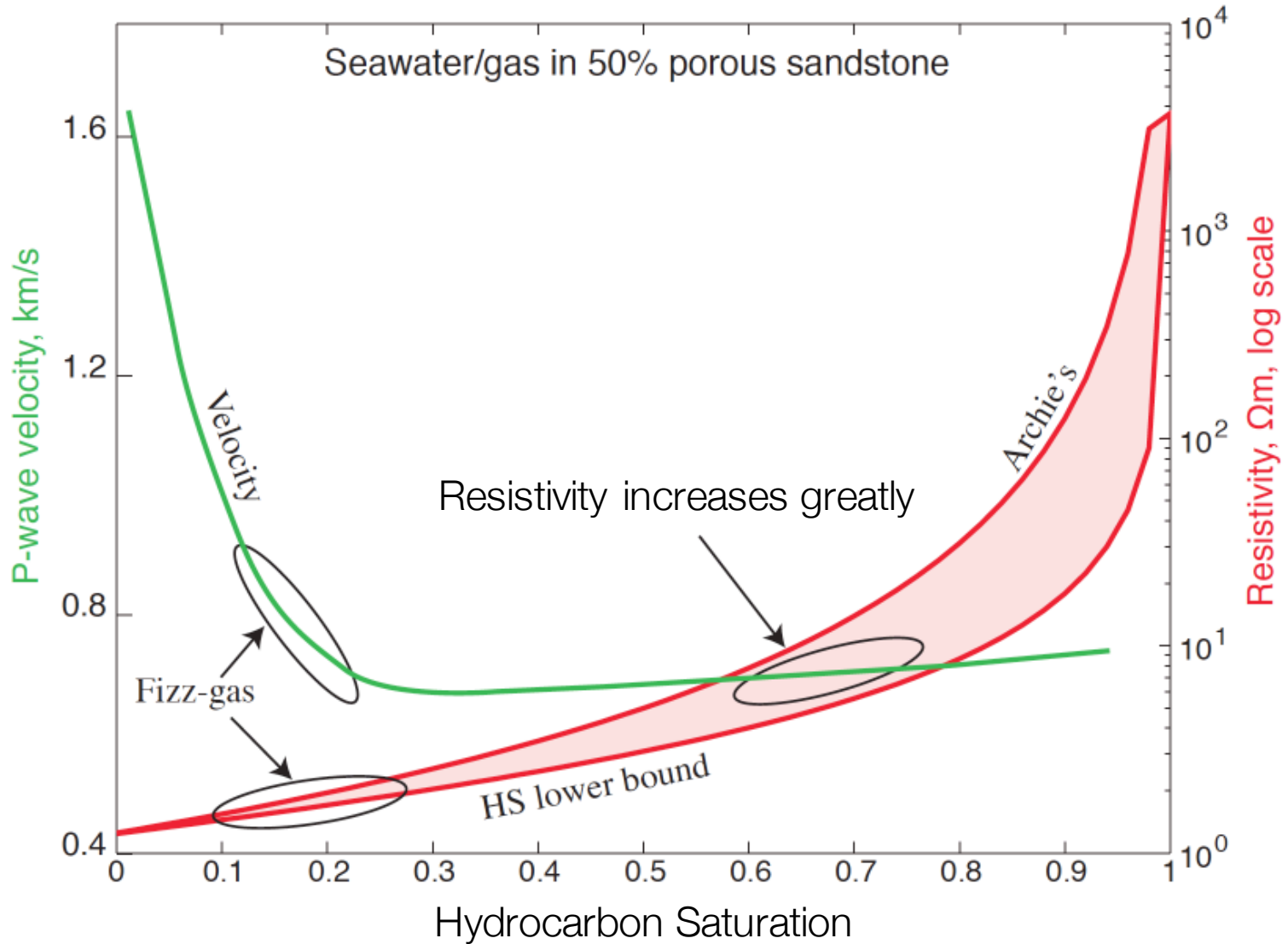
Hanssen
Validation well

Alternative
Control, dry

Central
Control, productive

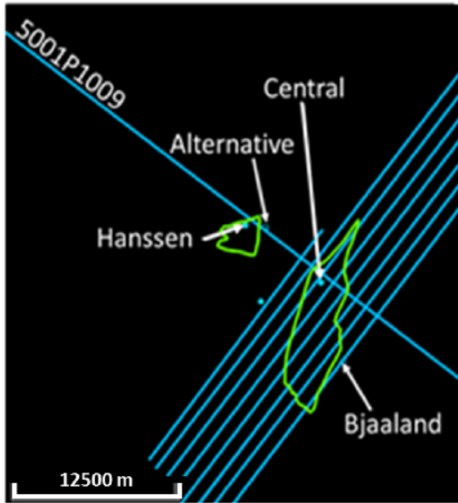
Bjaaland
Validation well

Revisiting physical properties

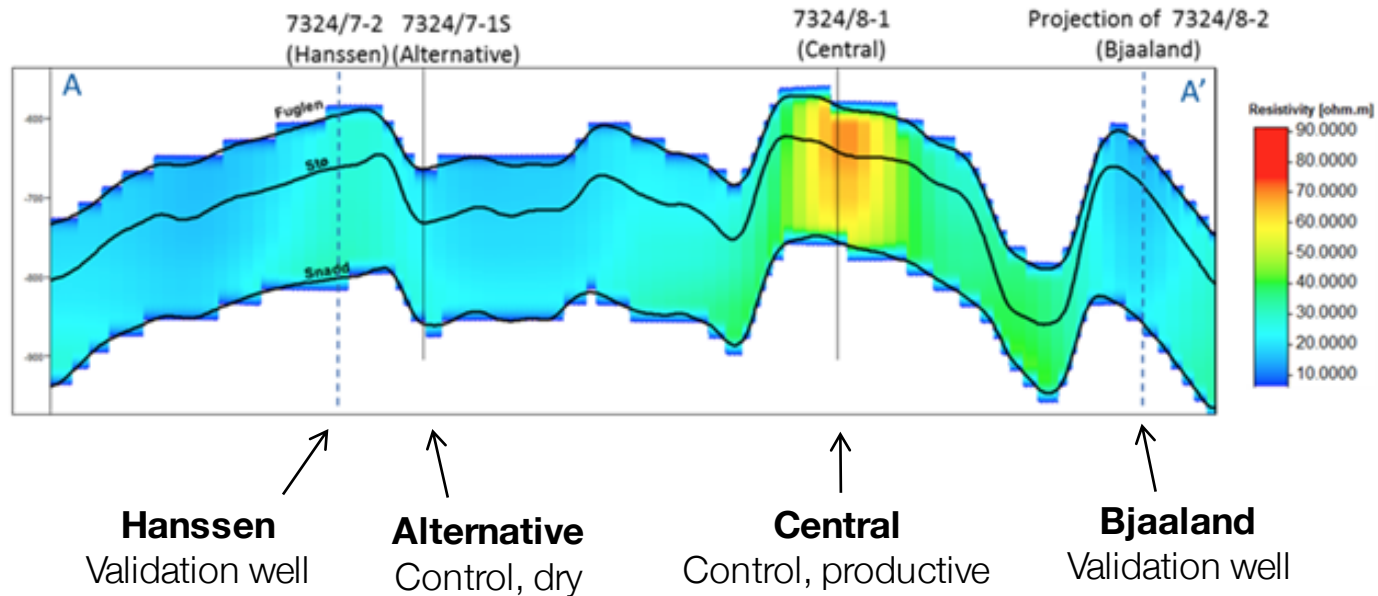


Processing: CSEM Inversion

Survey lines



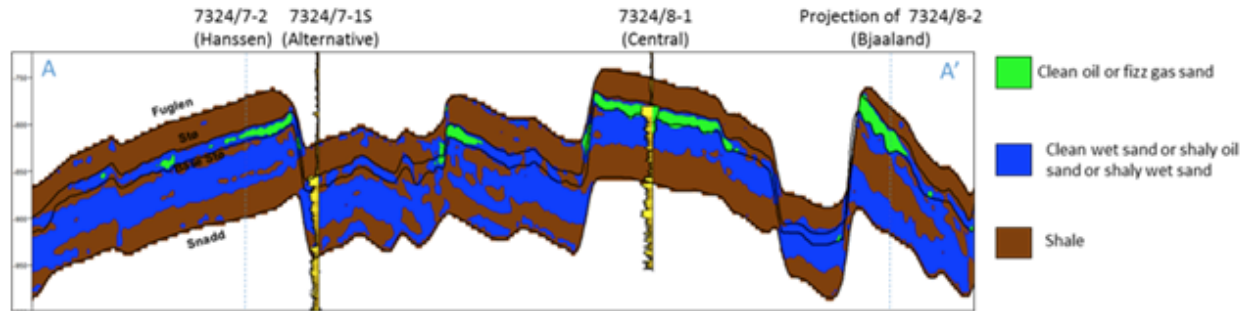
Vertical resistivity section along profile line 5001



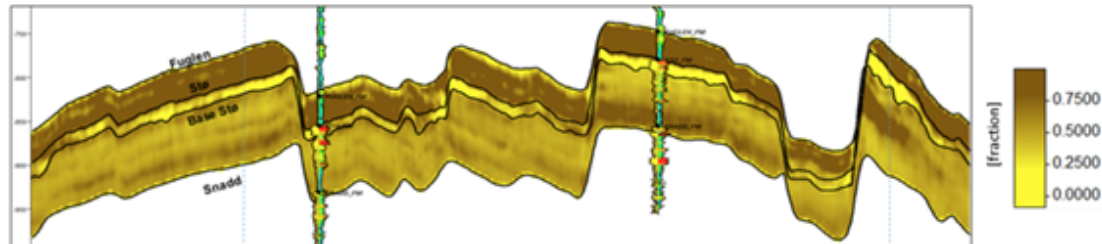
- Inversion shows strong resistor at Central and a secondary resistor at Hanssen.

Processing: Multi-physics Approach

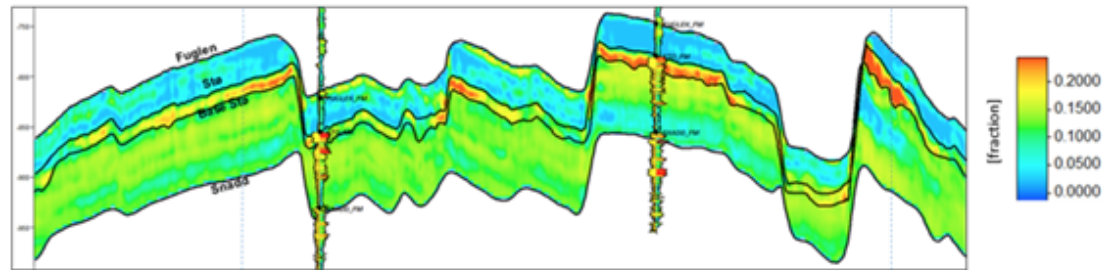
Litho-fluid
Facies



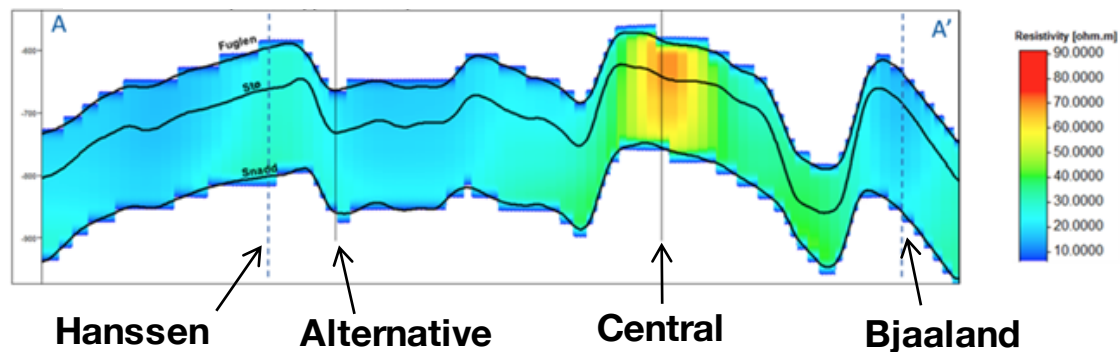
Clay Content



Total Porosity

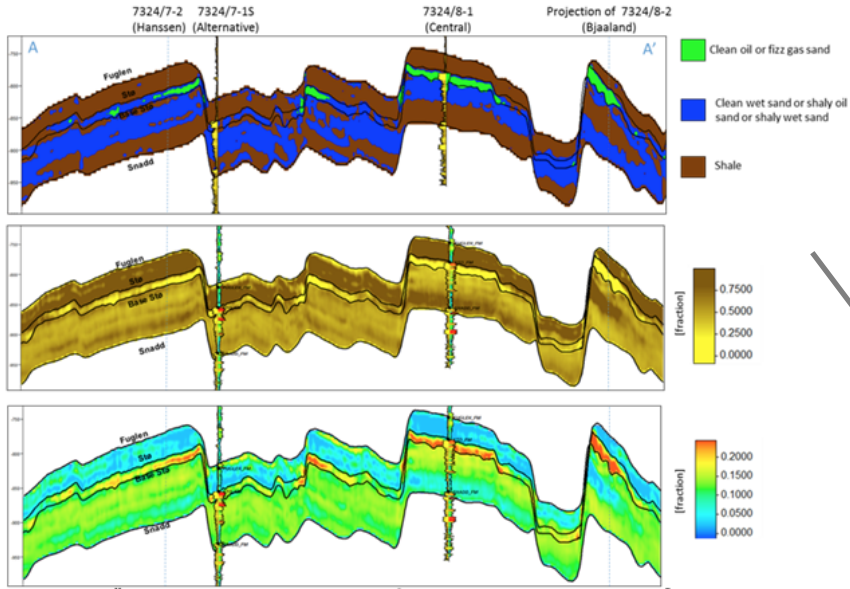


Resistivity

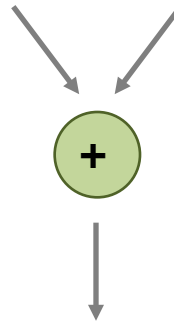
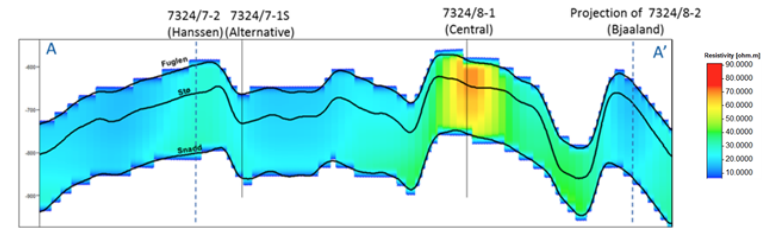


Interpretation & Synthesis

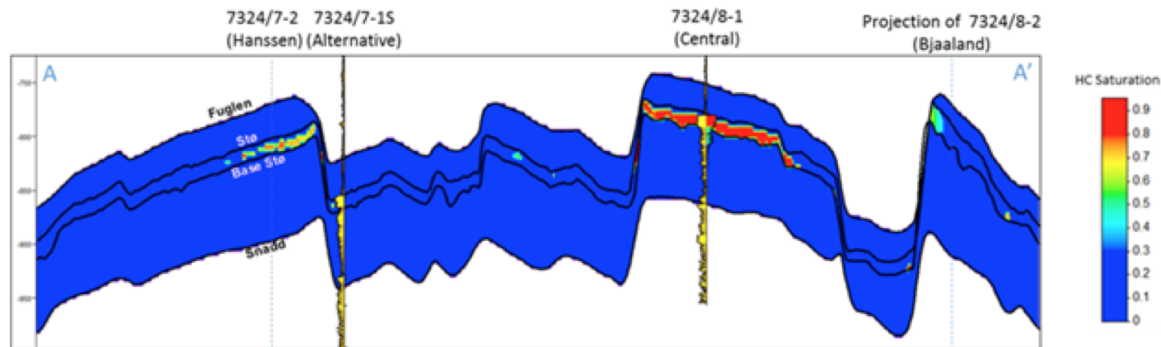
Seismic



EM



Hydrocarbon saturation



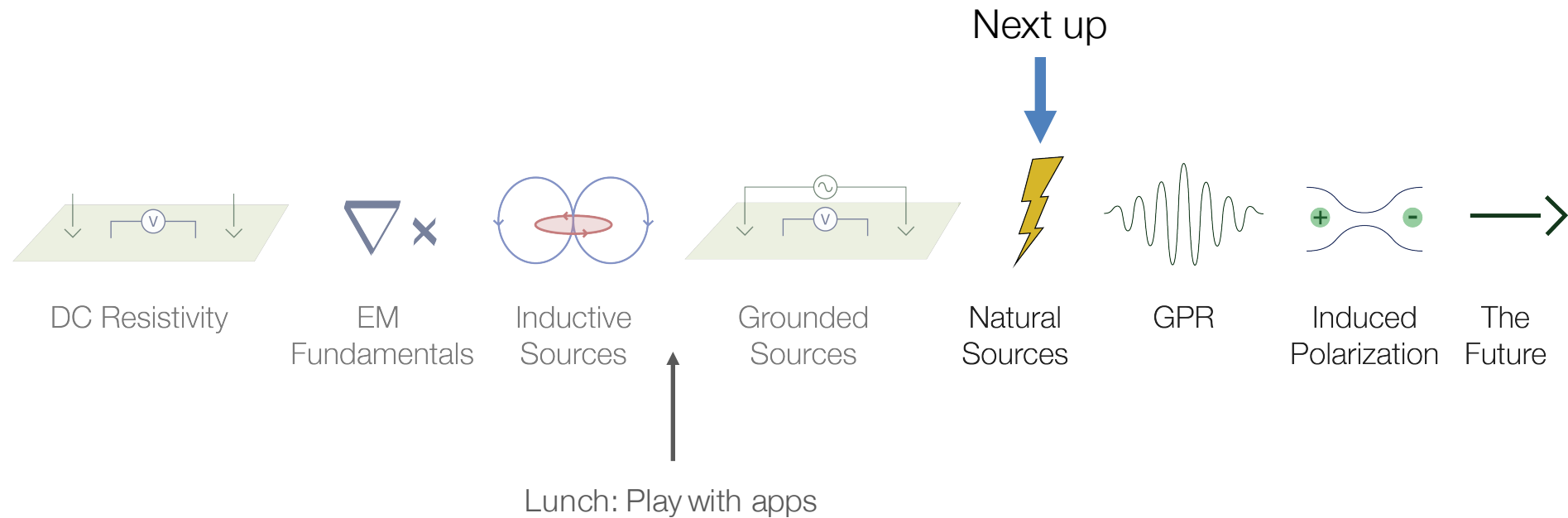
Hanssen
Validation well
productive

Alternative
Control, dry

Central
Control, productive

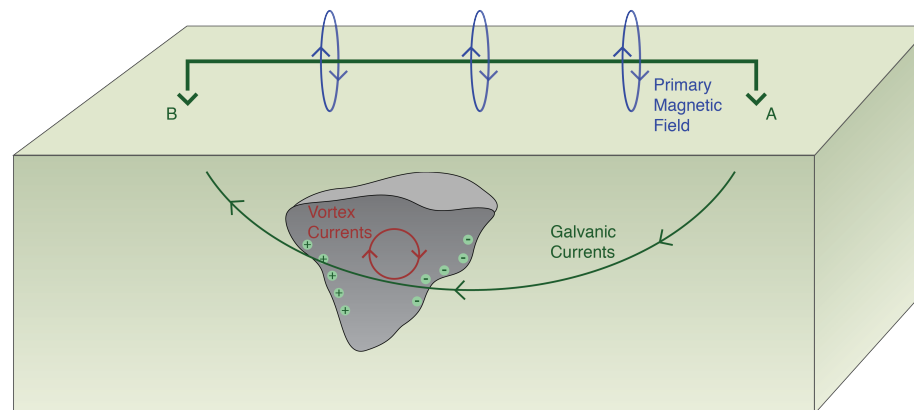
Bjaaland
Validation well
dry

End of Grounded Sources



Summary

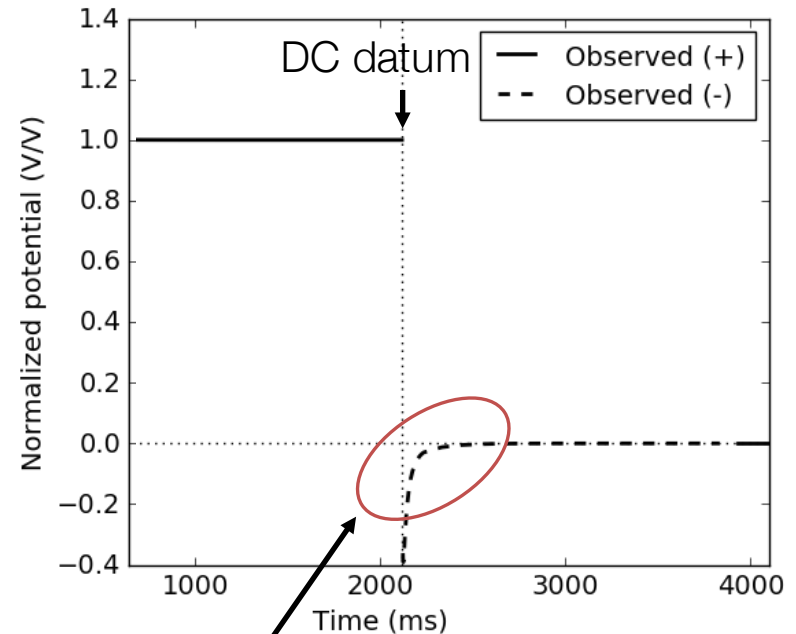
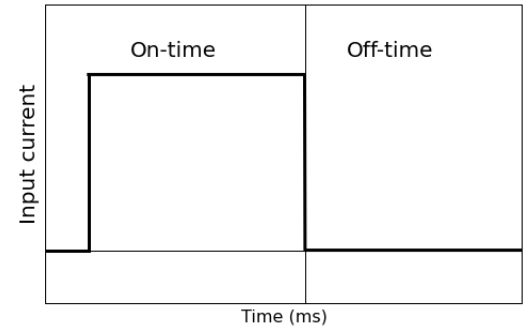
- Basic experiment
- FDEM: Electric dipole in a whole space
- TDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets: currents and data
- Resistive Targets: currents and data
- Case History: India. Basalt
- Case History: Barents Sea



DC/EM Inversion

DC/EM: Goals

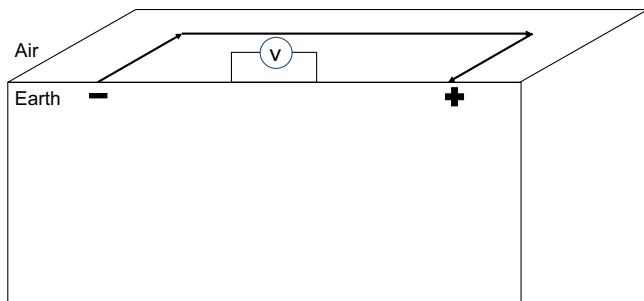
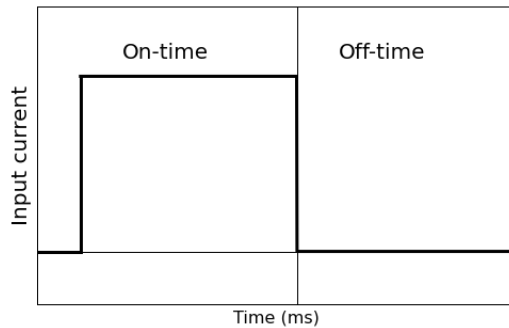
- Standard DCR time domain waveform
- Compare:
 - Inversions from DC data
 - Inversions from EM data
- Illustrate the value of data which is often discarded
- Numerical example from a gradient array



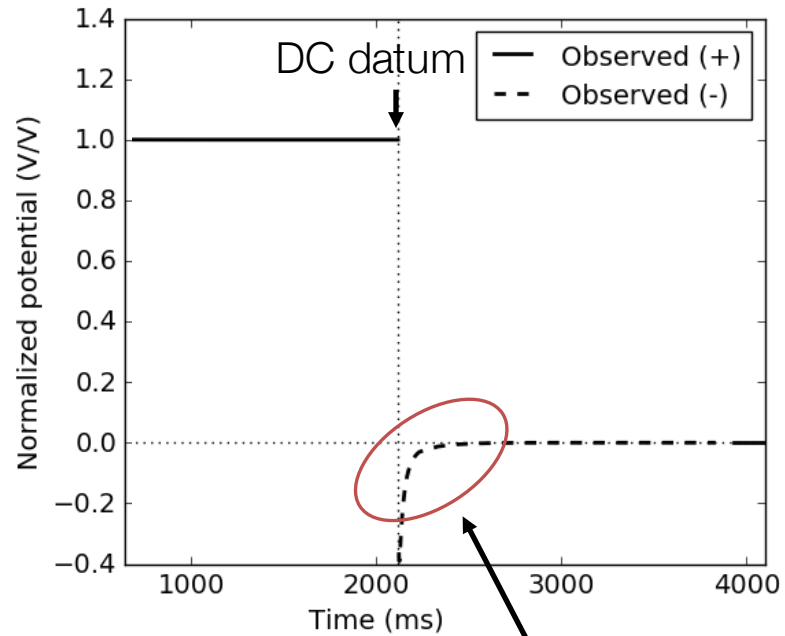
EM portion
Generally considered noise

Survey and Data

Transmitter



Measured Voltage



EM portion
Generally considered noise

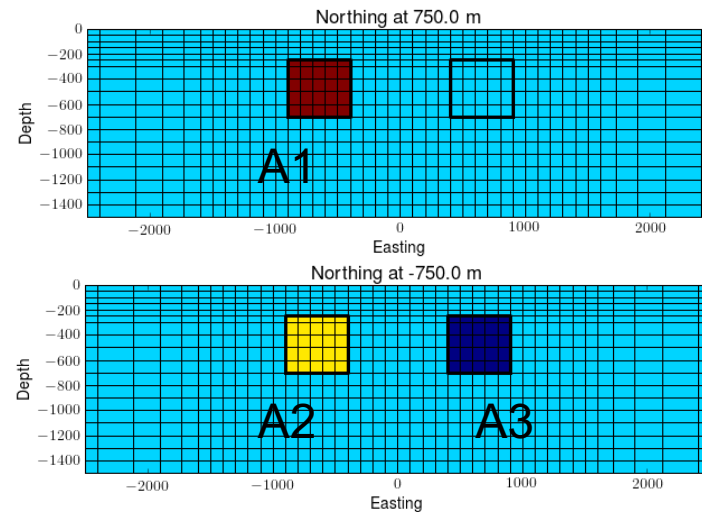
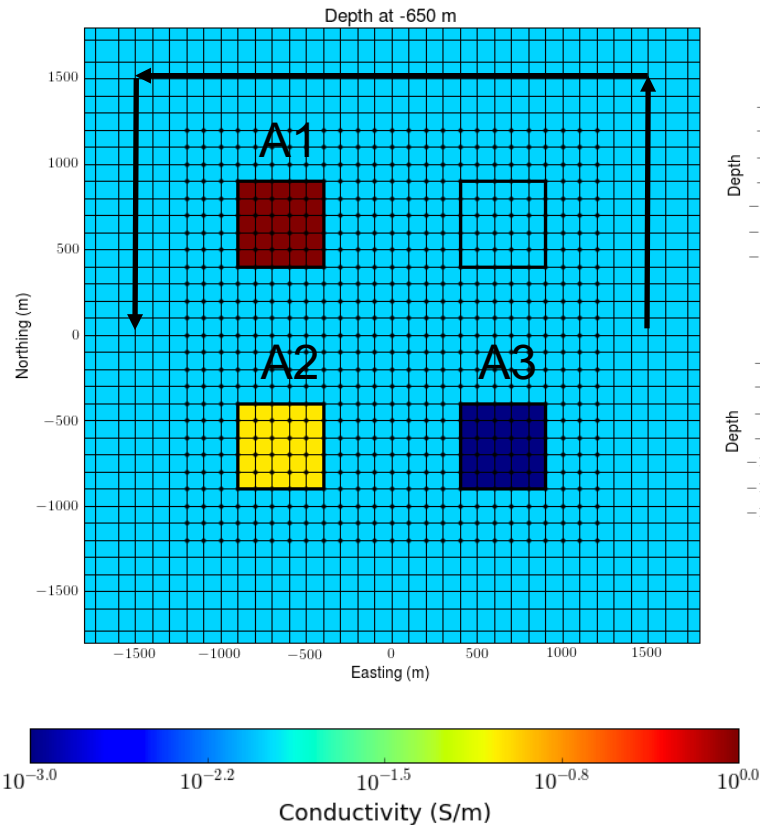
Gradient array

- Model

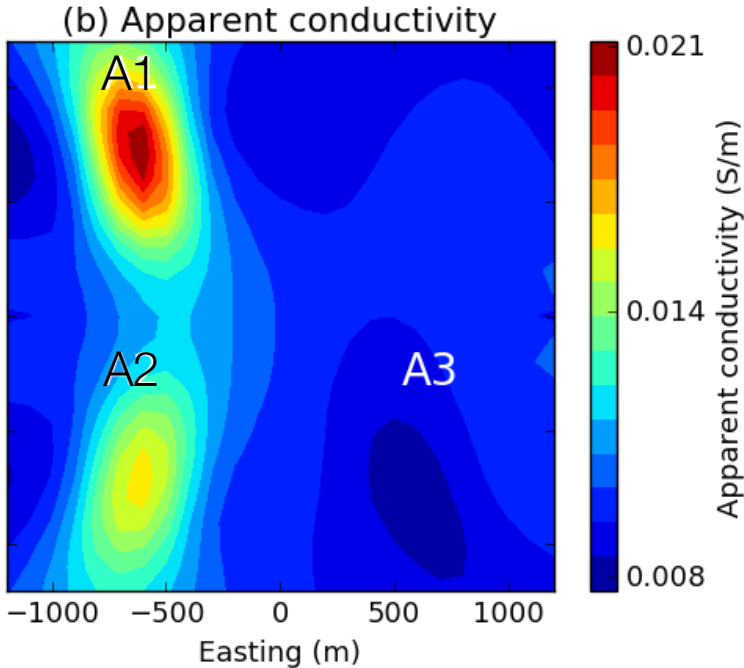
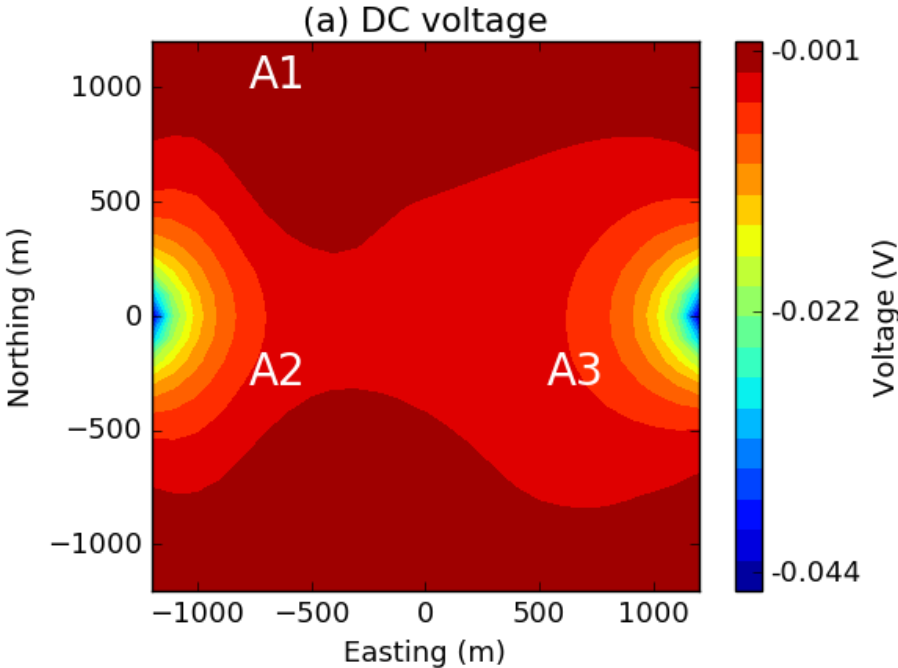
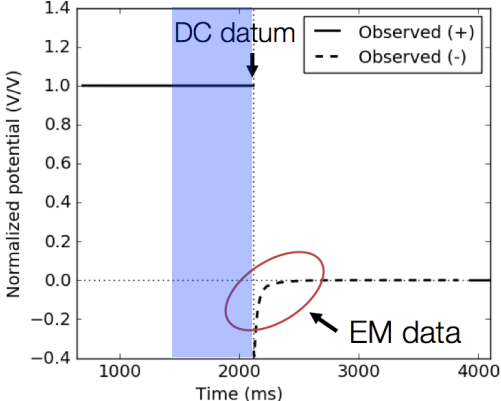
- A1: high conductivity
- A2: moderate conductivity
- A3: resistive

- Survey

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

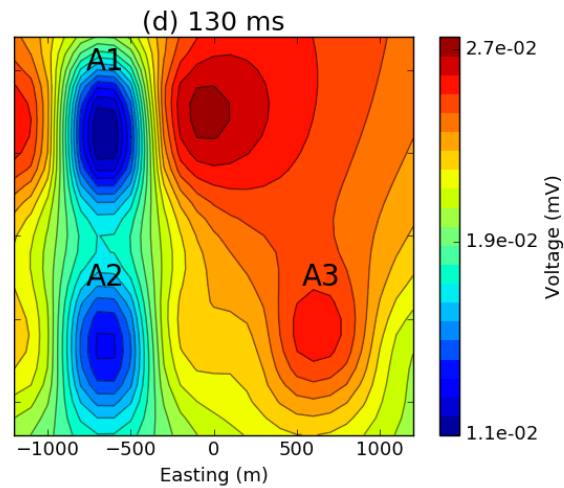
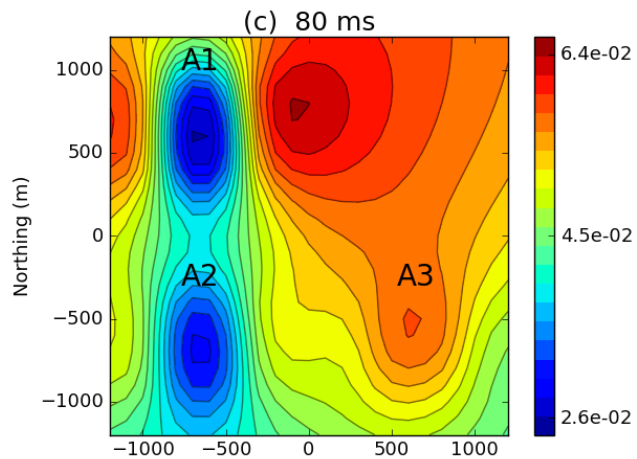
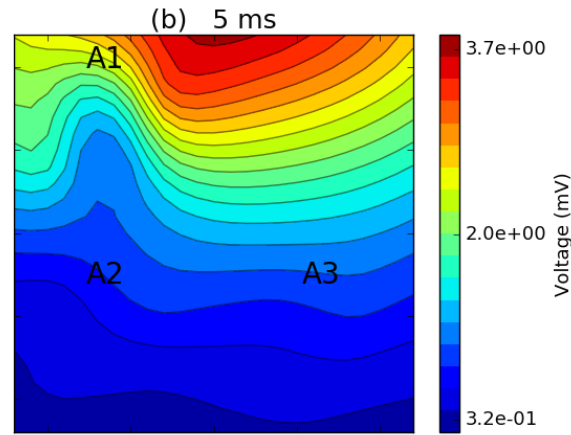
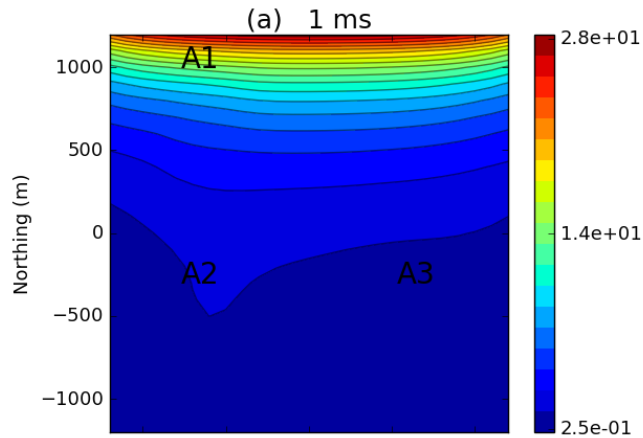
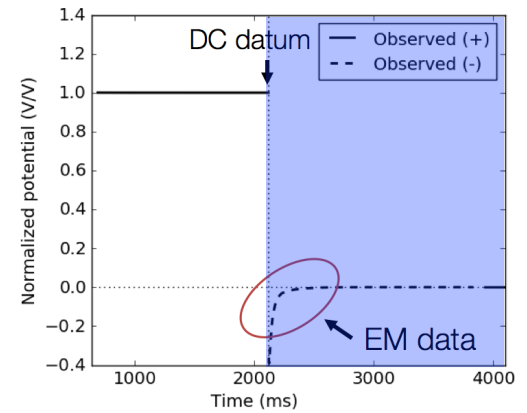


DC data



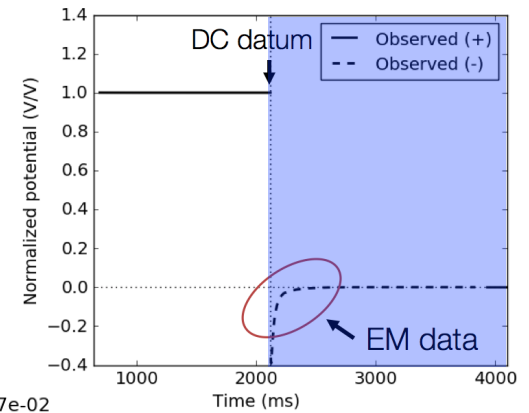
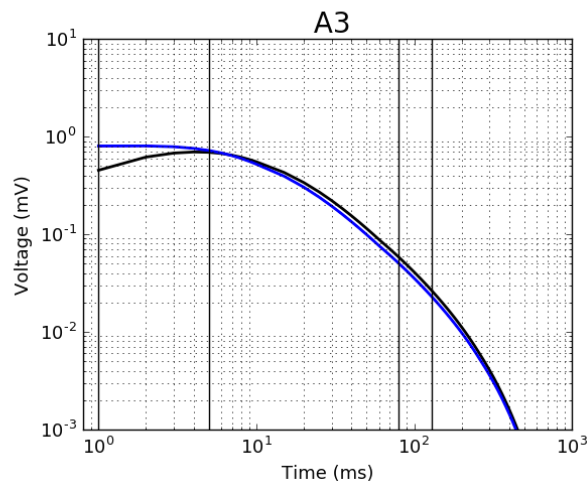
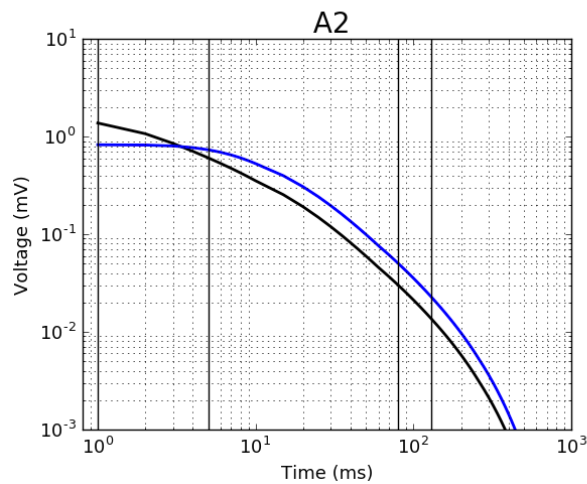
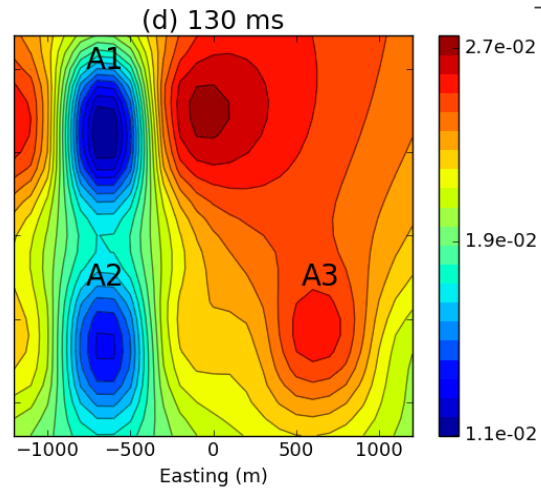
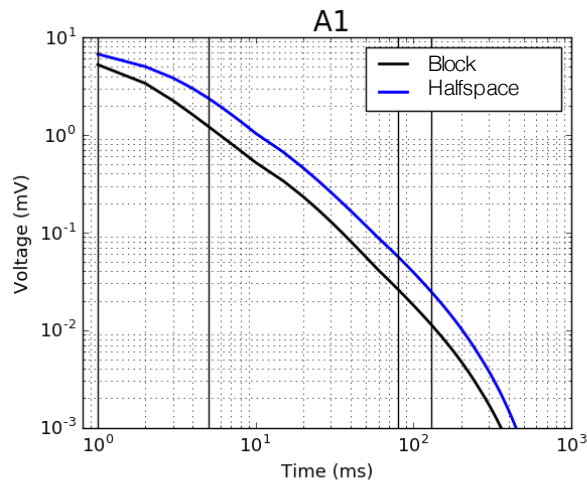
Off-time data

- TDEM data



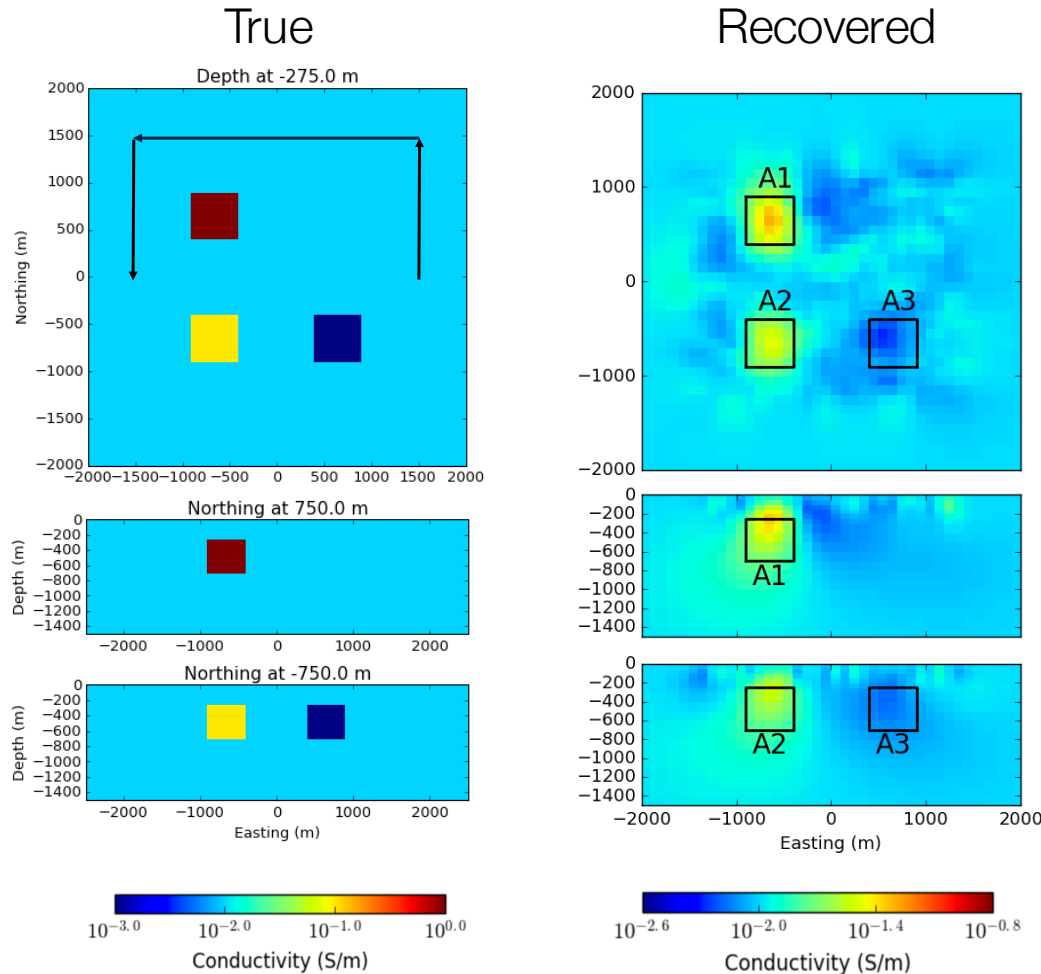
Off-time data

- E_x Decay curves at A1-A3

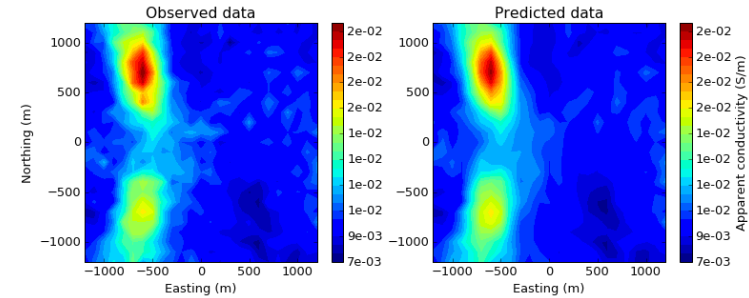


DC inversion

- Recovered 3D conductivity



Apparent conductivity

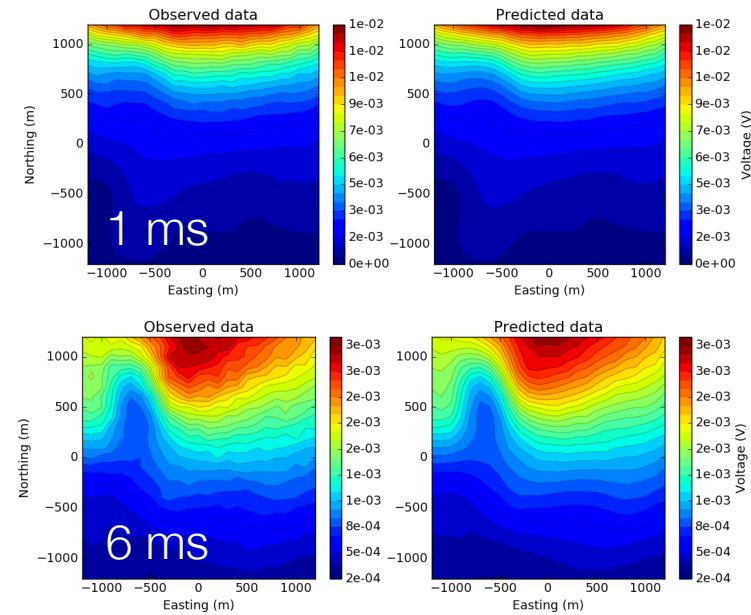
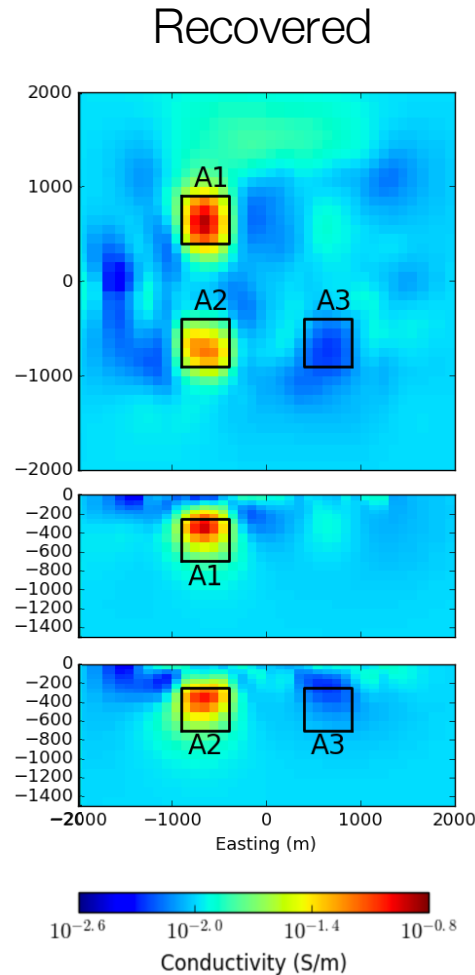
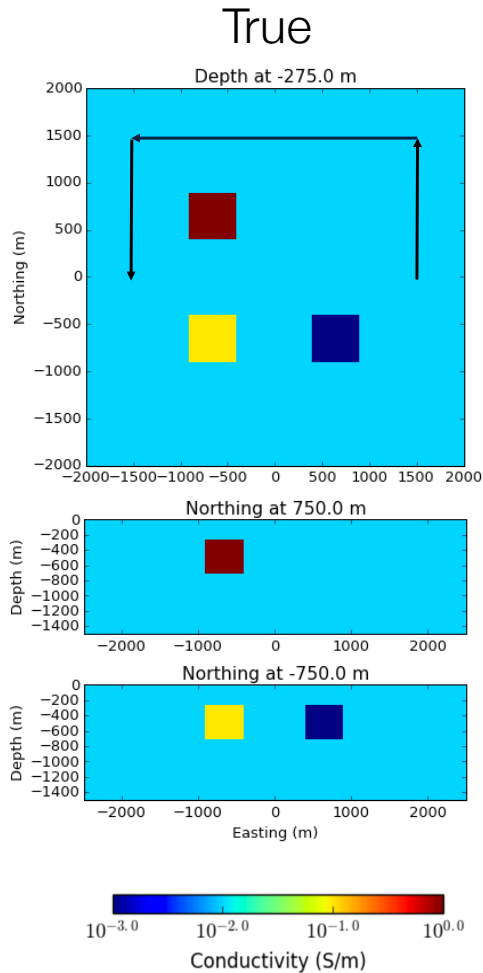


- Depth weighting
 - Compensate for high sensitivity near surface (similar to mag.)

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

EM inversion

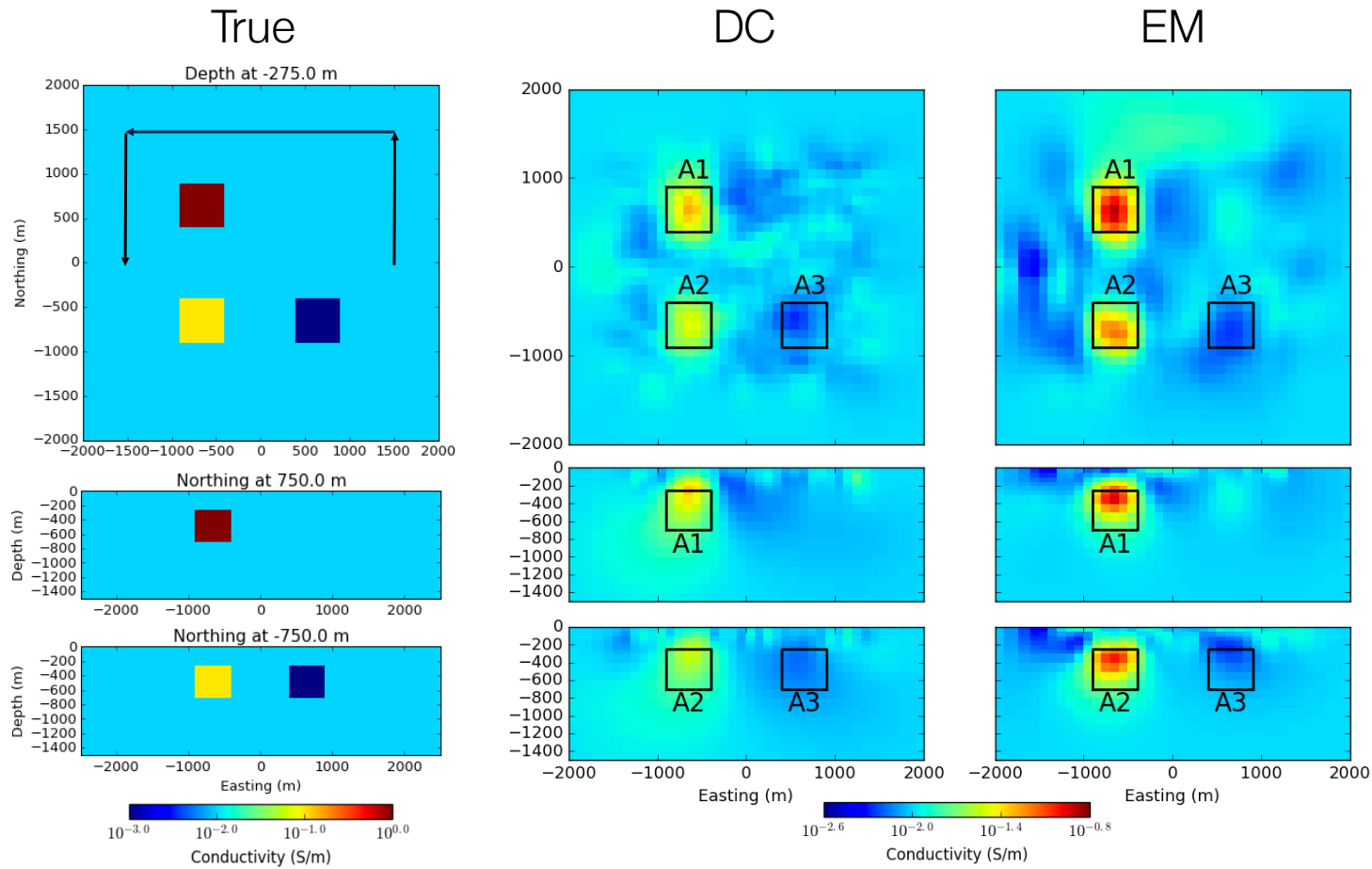
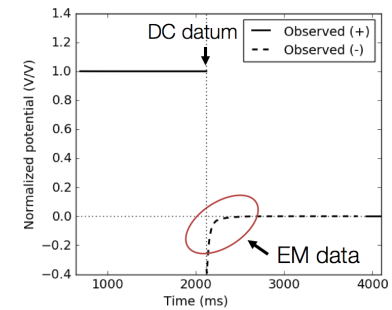
- Recovered 3D conductivity



- No depth weighting

Conductivity models

- True, DC, and TEM conductivities



EM data contain signal