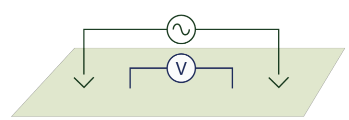
EM: Grounded Sources

DISC

2017

Electromagnetics
Fundamentals and Applications

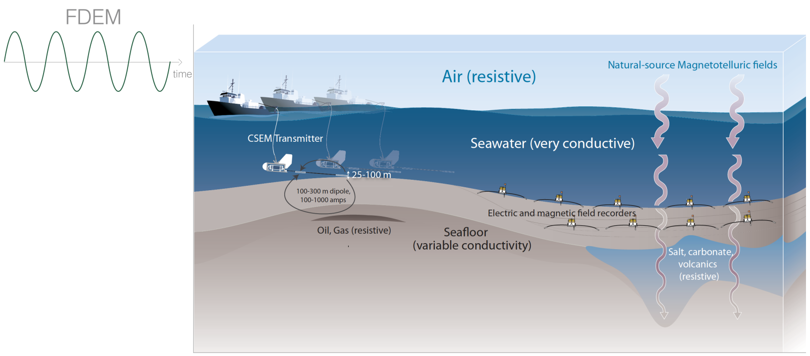


Outline

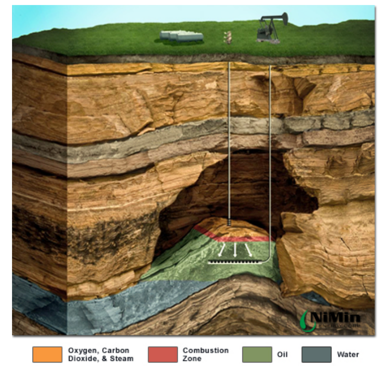
- Basic experiment
- TDEM: Electric dipole in a whole space
- FDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets
- Resistive Targets
- Case History: Deccan Traps
- Case History: Offshore Hydrocarbon De-risking
- Marine CSEM: Overview
- Case History: Methane hydrates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

Motivational examples

Marine EM for hydrocarbon



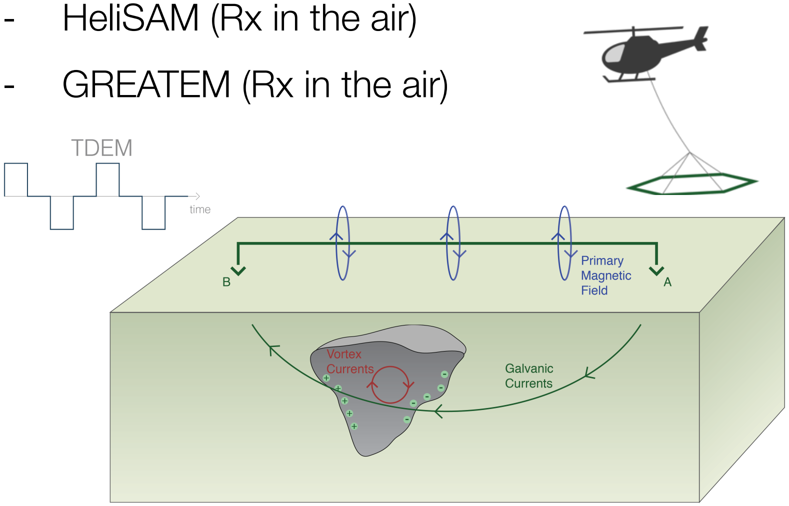
Oil and Gas (EOR)



Methane hydrates

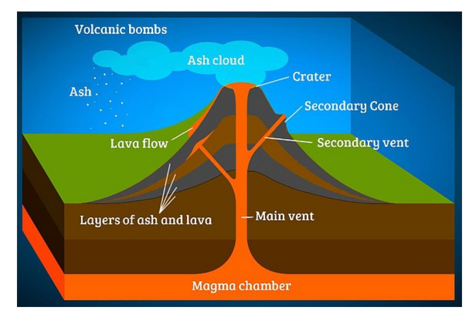
Galvanic source TEM

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

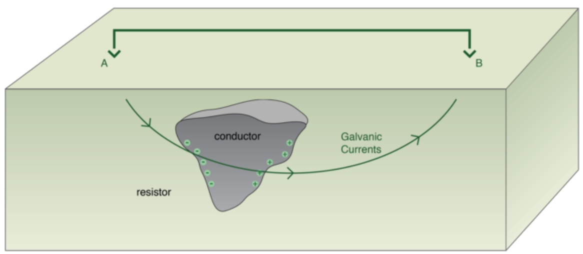


Minerals

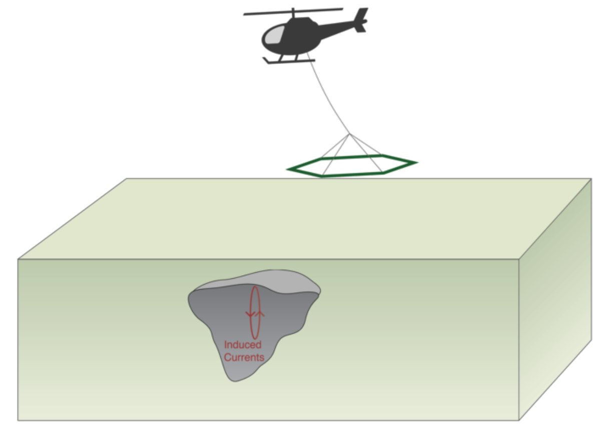
Volcanoes



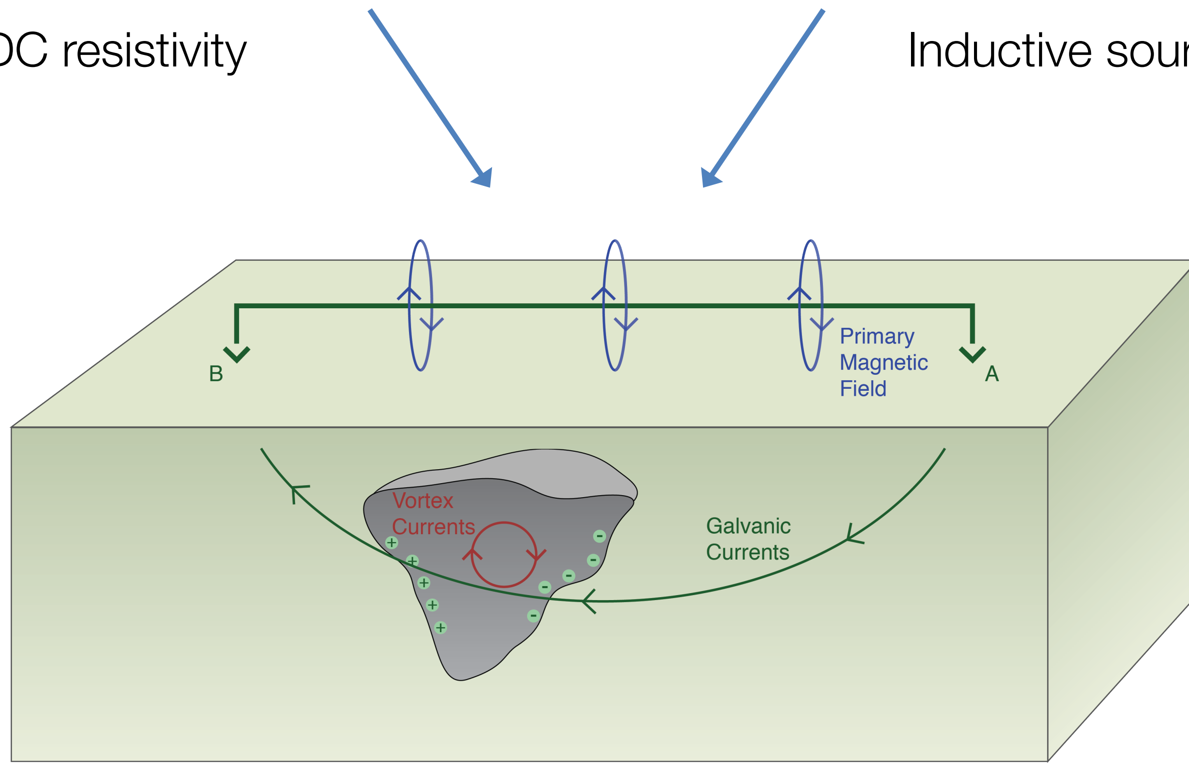
Basic experiment



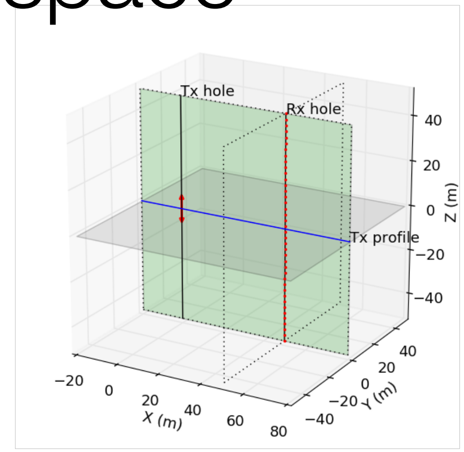
DC resistivity



Inductive source

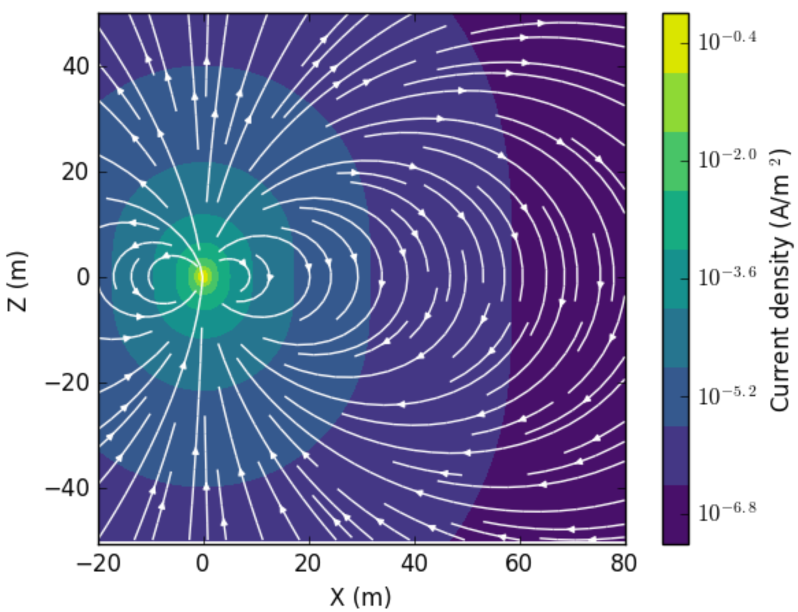


Electric Dipole in a whole space



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

DC current density

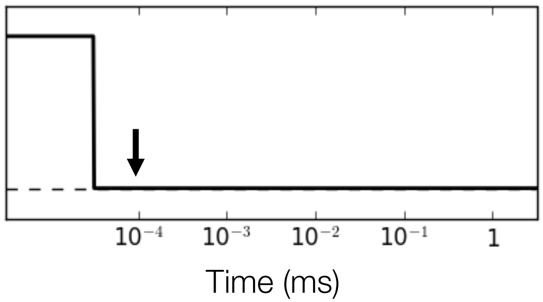


$$\mathbf{E}_{DC}(\mathbf{r}) = \frac{1}{4\pi\sigma|\mathbf{r}|^3}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m}\right)$$

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

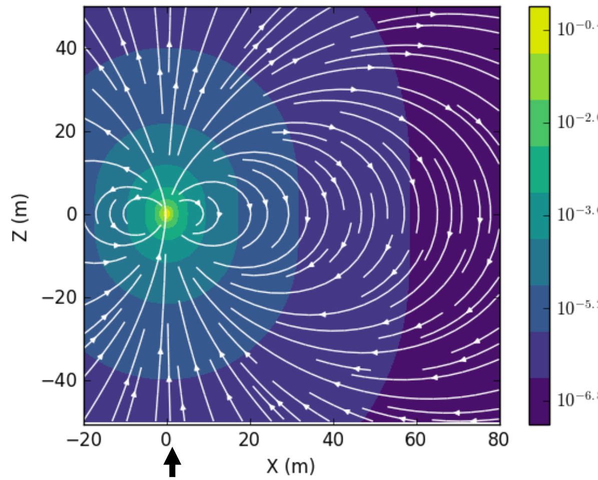
- Geometric decay: $1/r^3$
- Current path is geometric for homogeneous earth
- Electric field is dependent upon σ

Electric Dipole in a whole space: TDEM



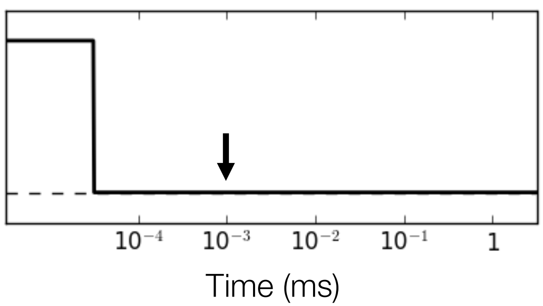
Diffusion distance $d = \sqrt{\frac{2t}{\mu\sigma}}$

10^{-4} ms



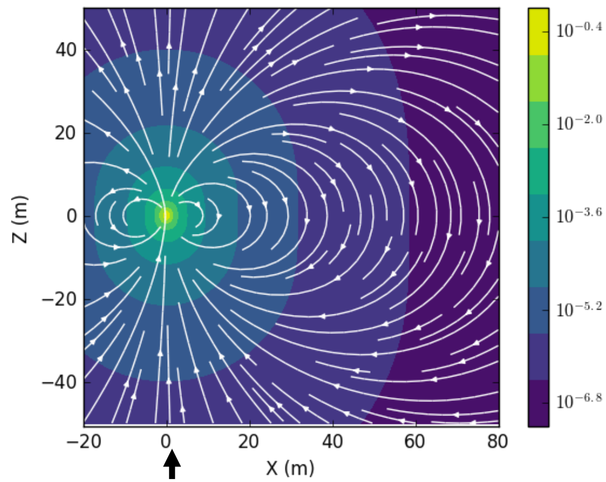
d = 4m

Electric Dipole in a whole space: TDEM



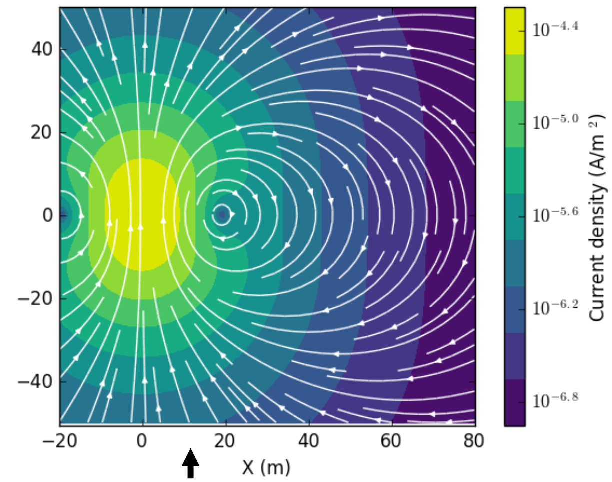
Diffusion distance $d = \sqrt{\frac{2t}{\mu\sigma}}$

10^{-4} ms



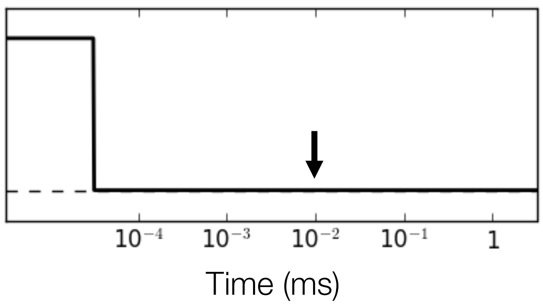
d = 4m

10^{-3} ms



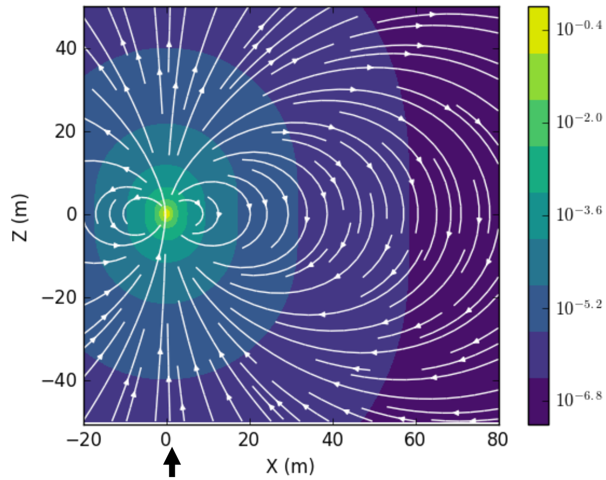
d = 13m

Electric Dipole in a whole space: TDEM



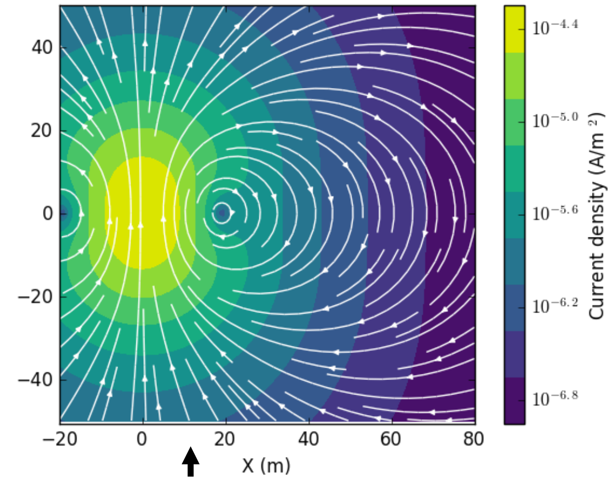
Diffusion distance $$d = \sqrt{\frac{2t}{\mu\sigma}}$$

10^{-4} ms



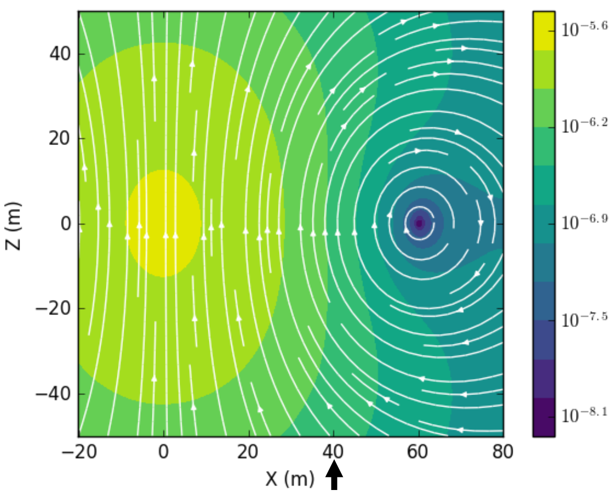
d = 4m

10^{-3} ms



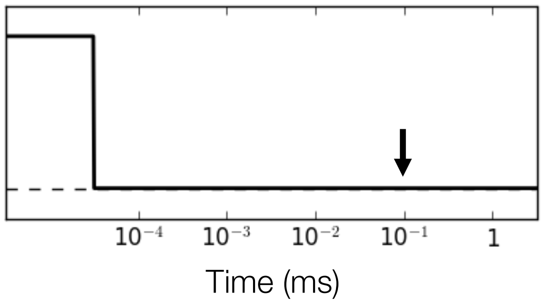
d = 13m

10^{-2} ms



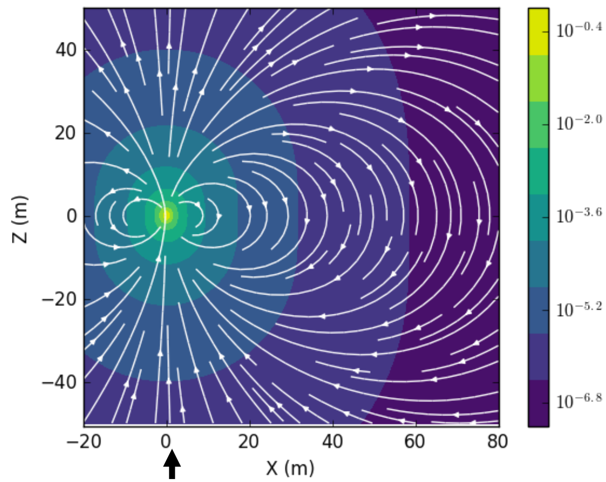
d = 40m

Electric Dipole in a whole space: TDEM



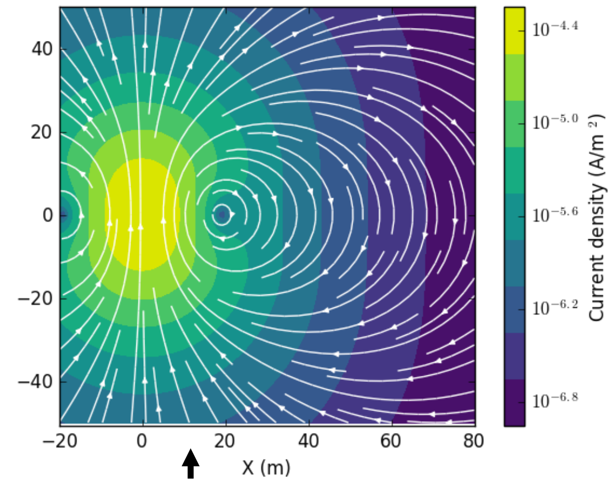
Diffusion distance $$d = \sqrt{\frac{2t}{\mu\sigma}}$$

10^{-4} ms



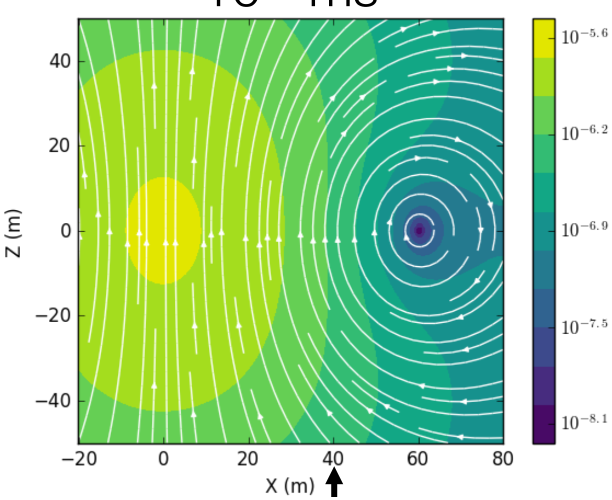
d = 4m

10^{-3} ms



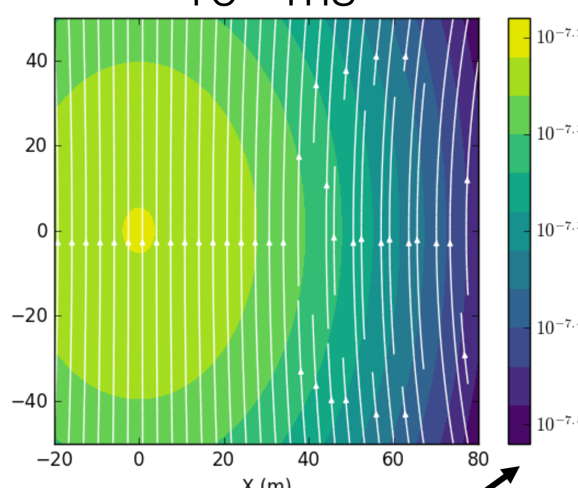
d = 13m

10^{-2} ms



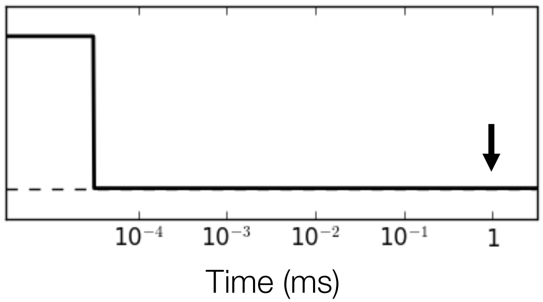
d = 40m

10^{-1} ms



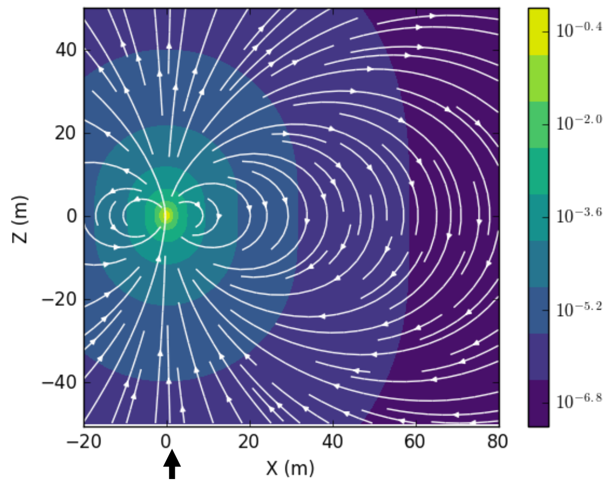
d = 126m

Electric Dipole in a whole space: TDEM



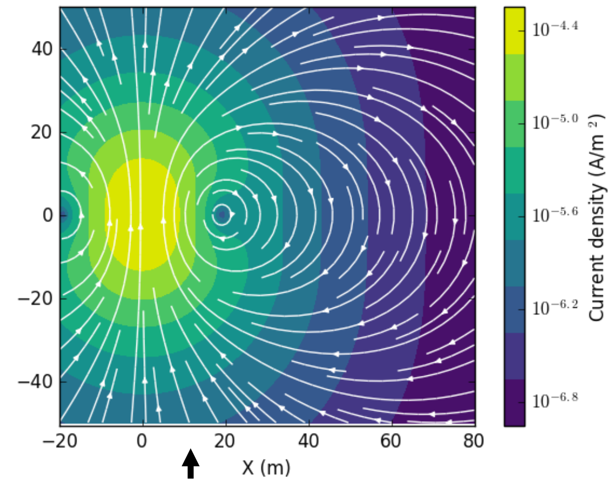
Diffusion distance $d = \sqrt{\frac{2t}{\mu\sigma}}$

10^{-4} ms



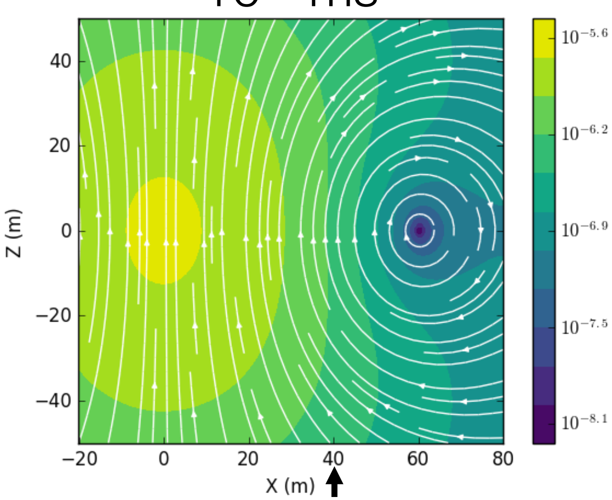
d = 4m

10^{-3} ms



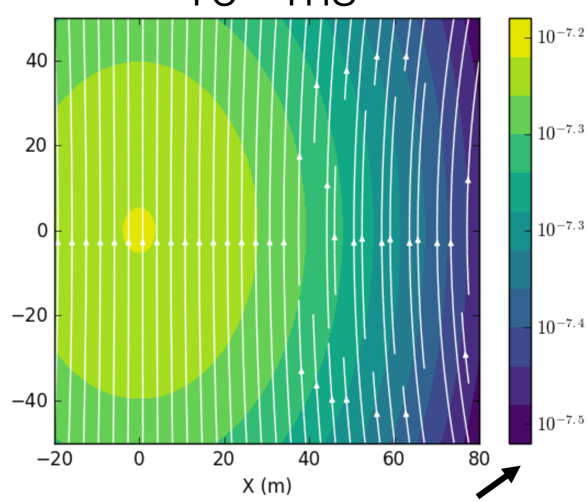
d = 13m

10^{-2} ms



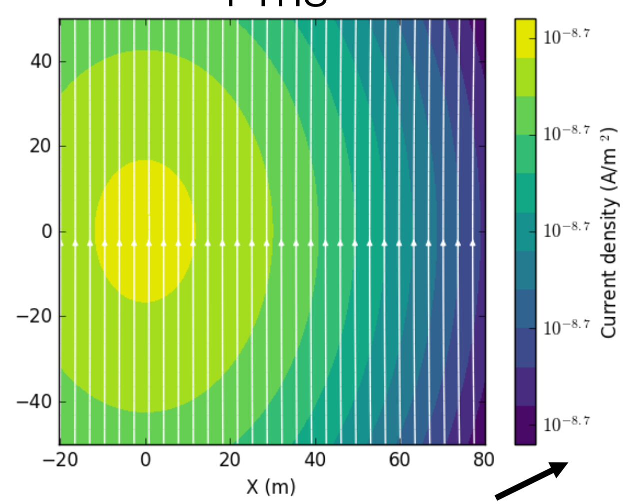
d = 40m

10^{-1} ms



d = 126m

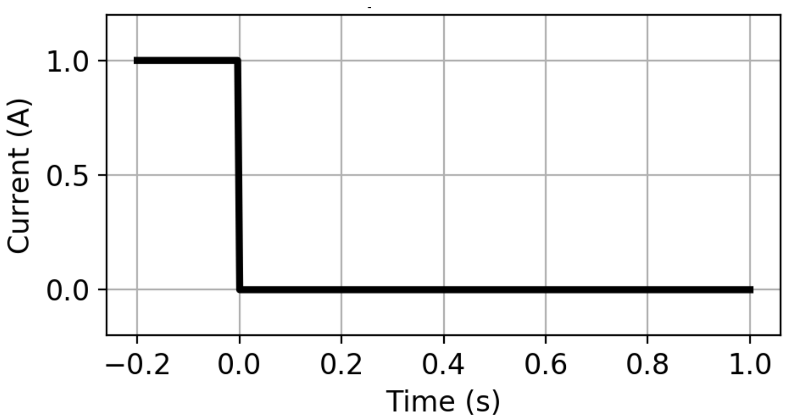
1 ms



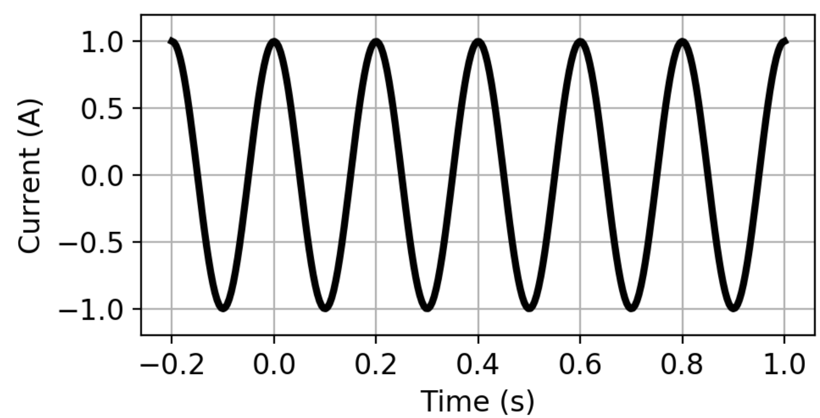
d = 400m

TDEM vs. FDEM

Step-off



Harmonic



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

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

Electric Dipole in a whole space: FDEM

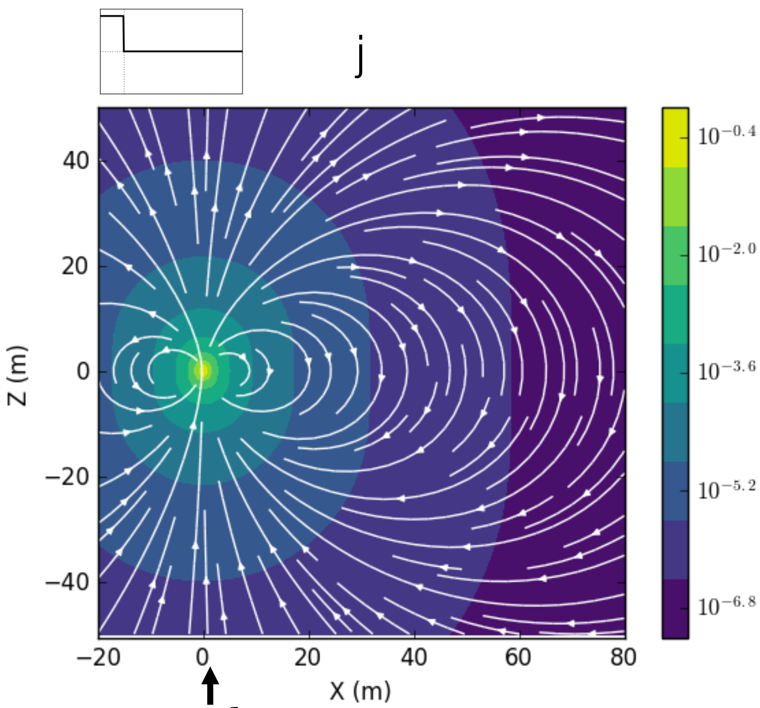
t=10^{-4} ms, $\mathbf{d}$ = 4 m

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

f=10^{4} kHz, δ = 2 m

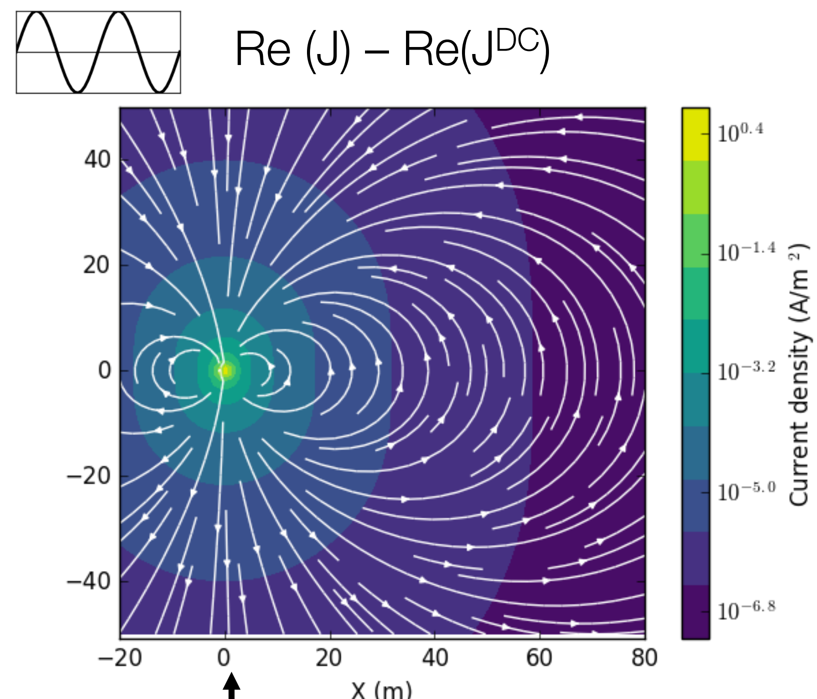
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

j



1 d

Re (J) – Re(J^{DC})



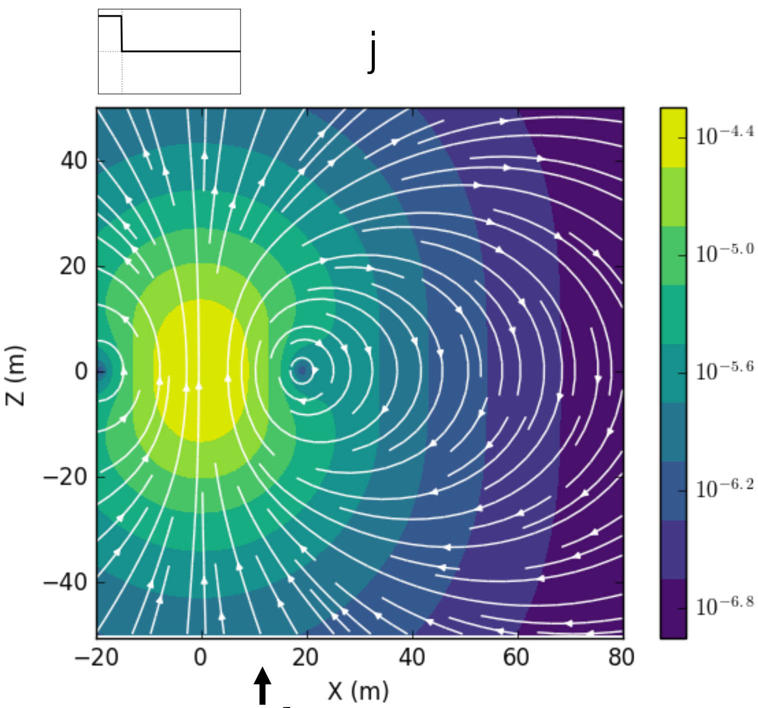
1 δ

Electric Dipole in a whole space: FDEM

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

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

j

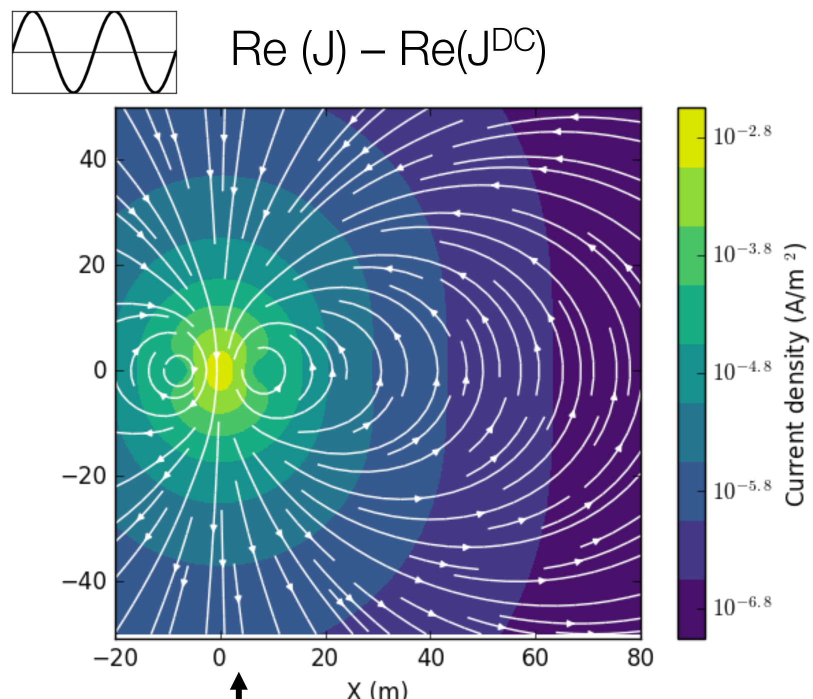


1 d

f=10^3 kHz, δ = 5 m

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

Re (J) – Re(J^{DC})



1 δ

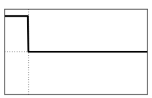
Electric Dipole in a whole space: FDEM

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

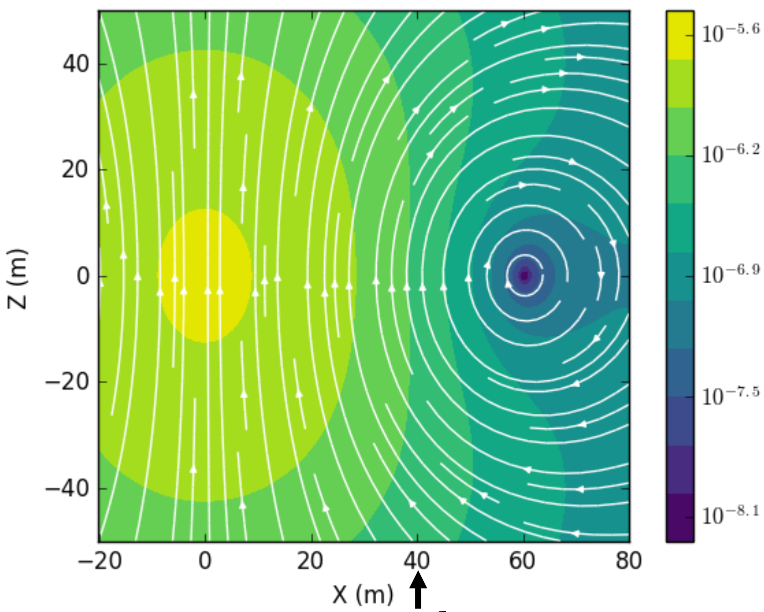
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

f=10^{2} kHz, **δ** = 16 m

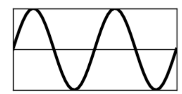
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



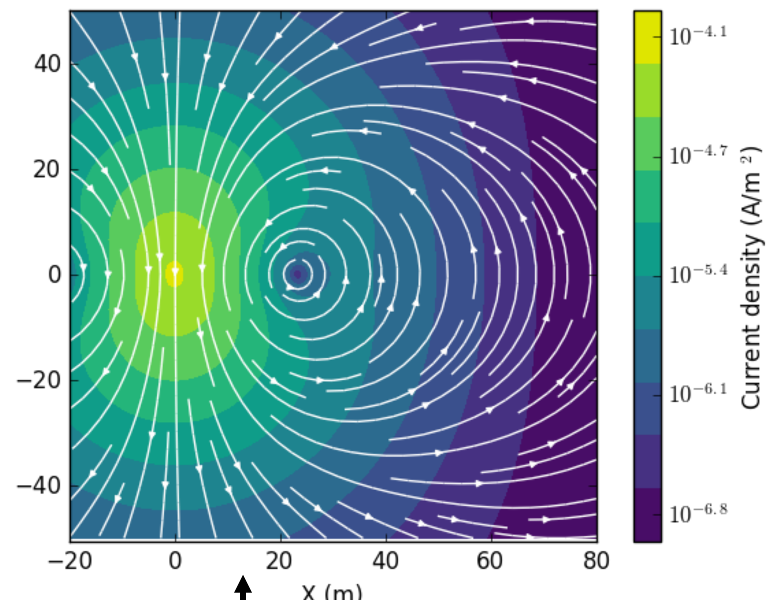
j



1 d



Re (J) – Re(J^{DC})



1 δ

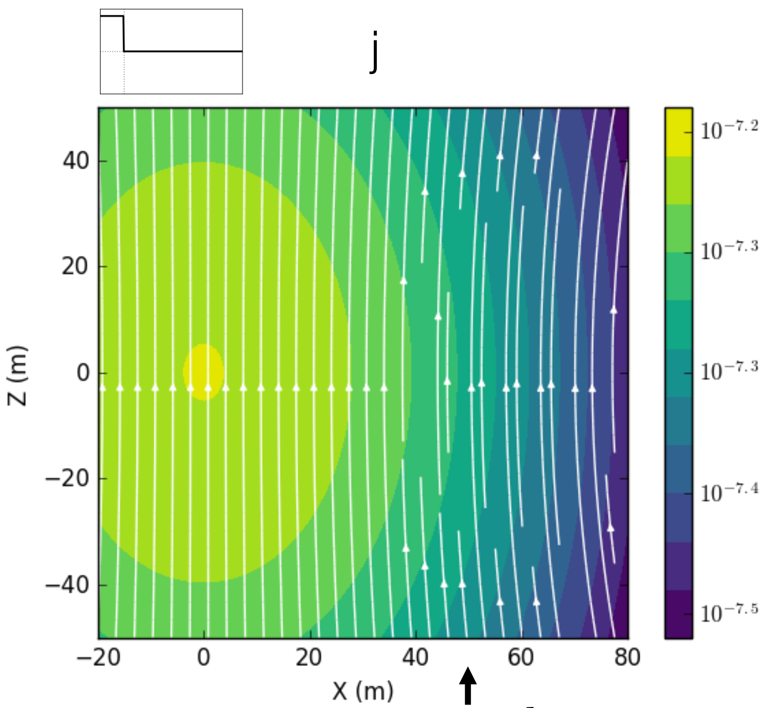
Electric Dipole in a whole space: FDEM

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

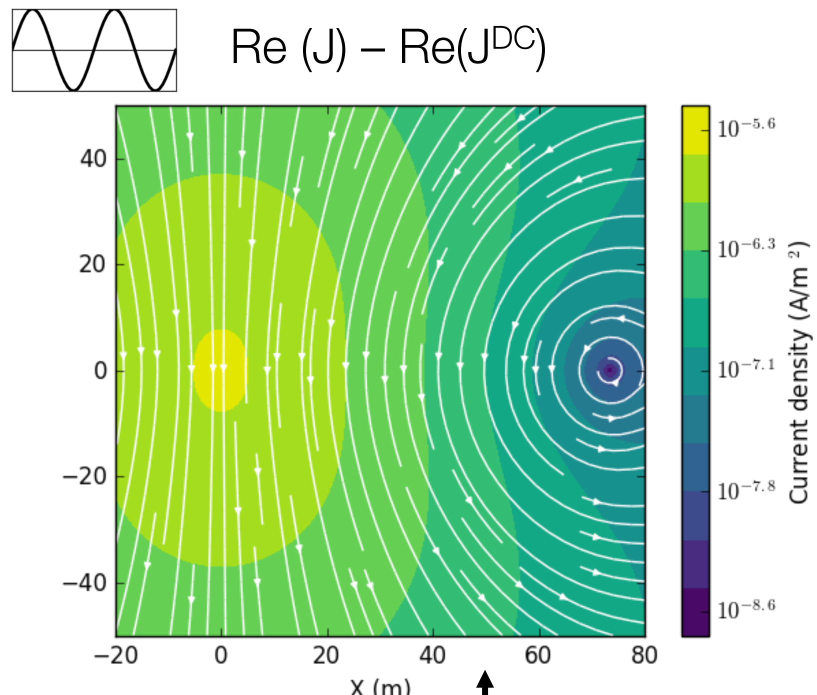
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

f=10^{1} kHz, **δ** = 50 m

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



2/5 **d**



1 **δ**

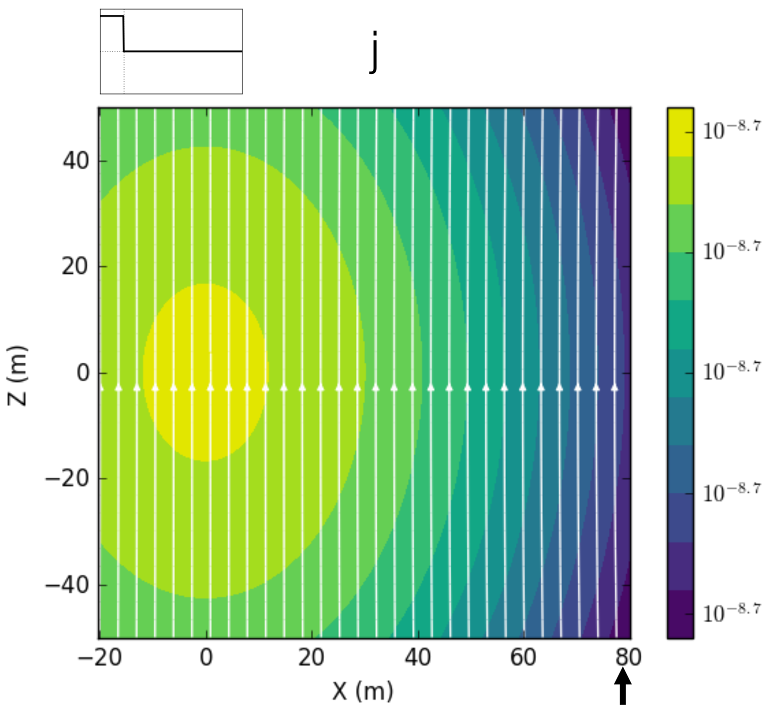
Electric Dipole in a whole space: FDEM

t=1 ms, **d** = 400m

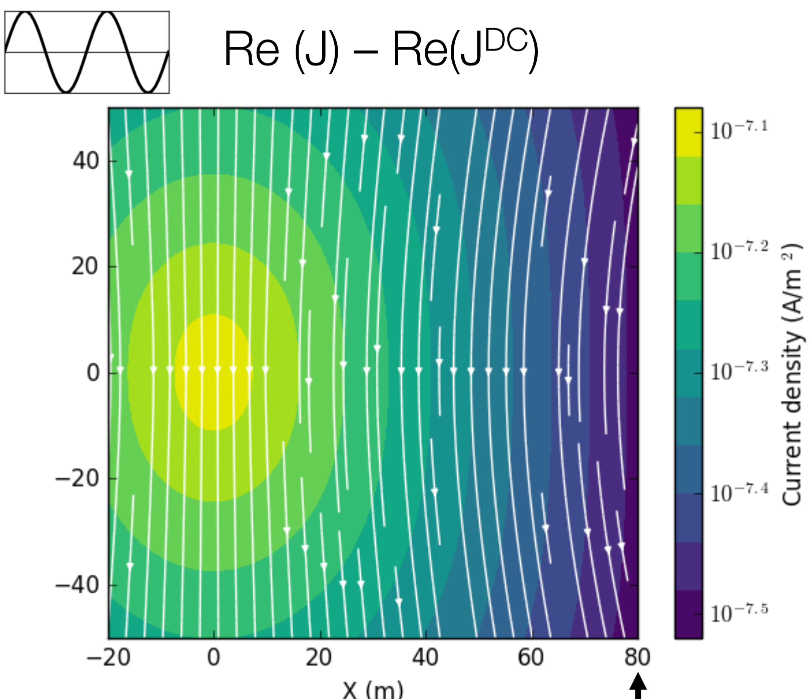
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

f=1 kHz, δ = 160 m

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



1/5 **d**

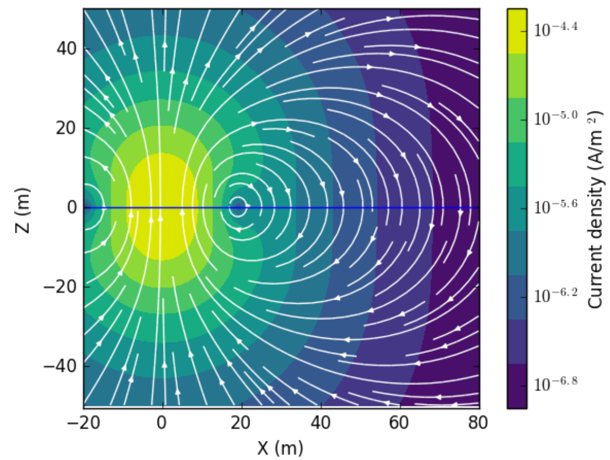


½ δ

Summary: Dipole in a whole space

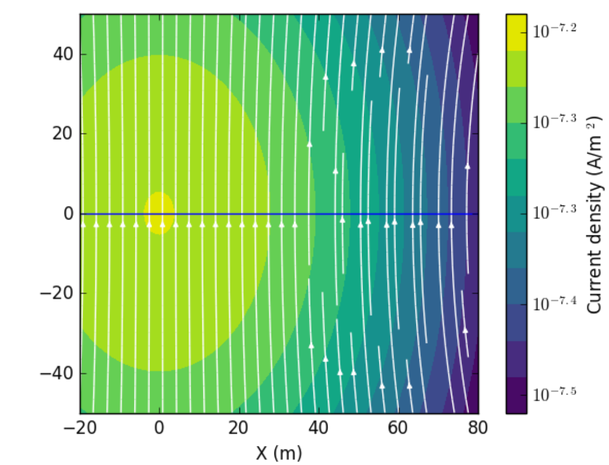
Currents diffuse into the earth

Early time
High frequency



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

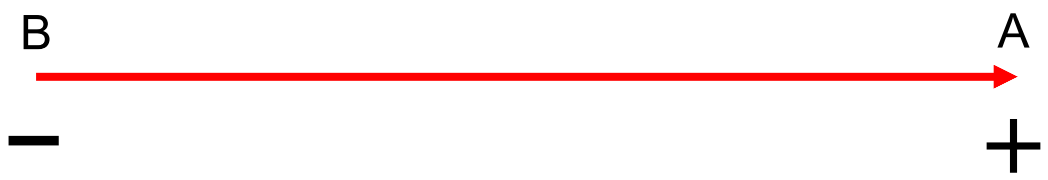
Late time
Low frequency



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

Bipole Sources

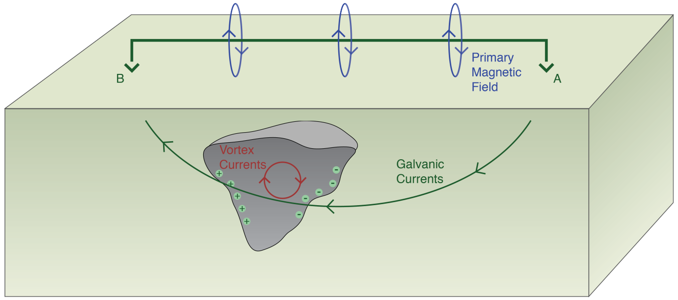
- Extended line sources
  - Grounded term (**galvanic**) + wire path (**inductive**)
  - Straight line



  - Crooked line (horse shoe)

Grounded Sources: On the surface

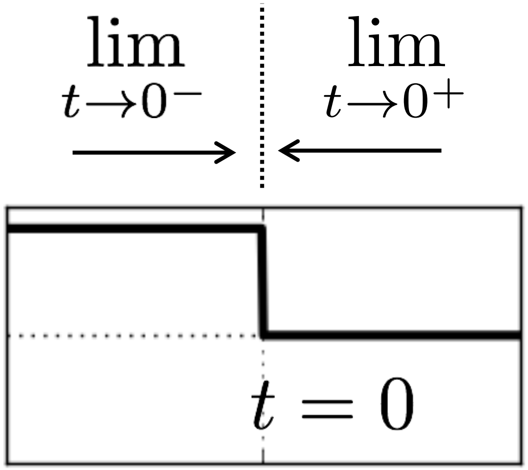
- Ability to detect target depends on
  - Geometry, conductivity of target & host
  - Geometry of TX
  - Frequency or time
  - Fields and components measured
    - e, b, db/dt
  - Location of Tx and Rx with respect to the target

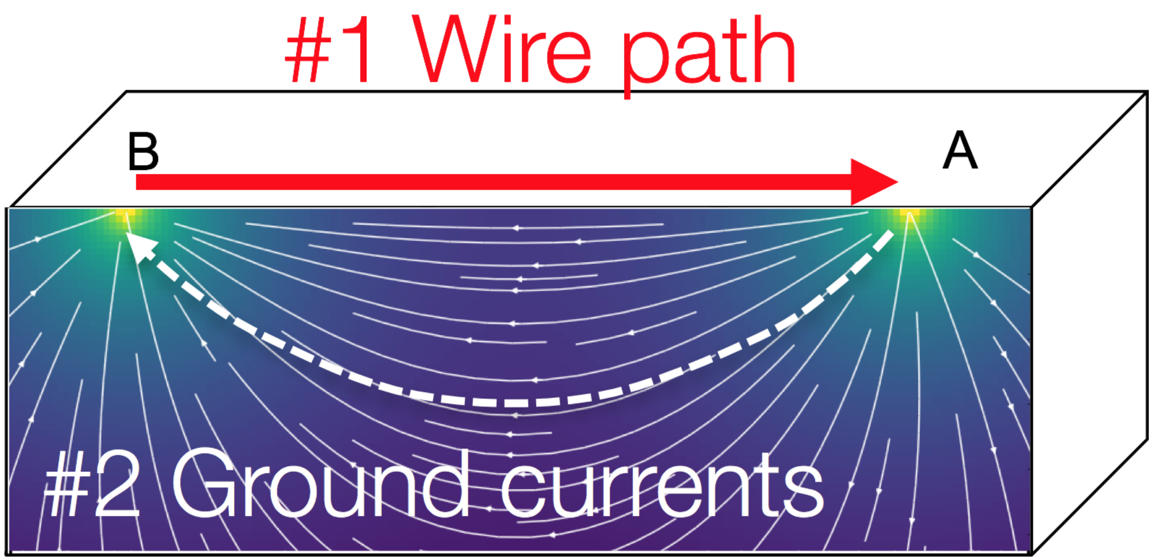


- Lots of variables…
  - Use an example to highlight important concepts

Currents: Grounded System

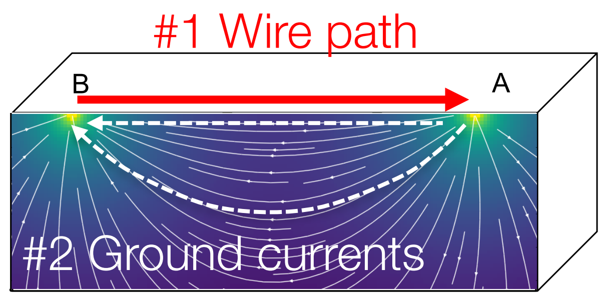
- $t = 0^-$ Steady state
- $t = 0$ Shut off current
- $t = 0^+$ Off-time

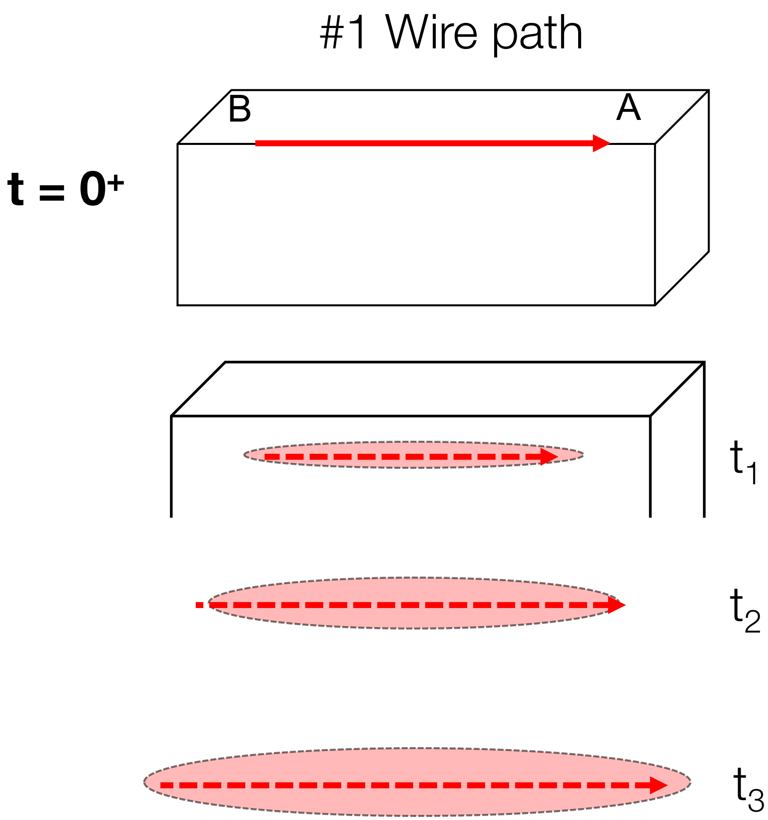




What happens when we shut the system off?

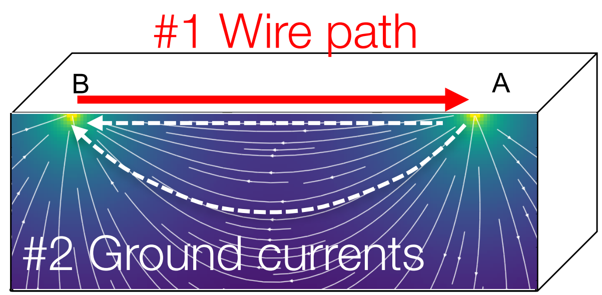
Currents: Grounded System





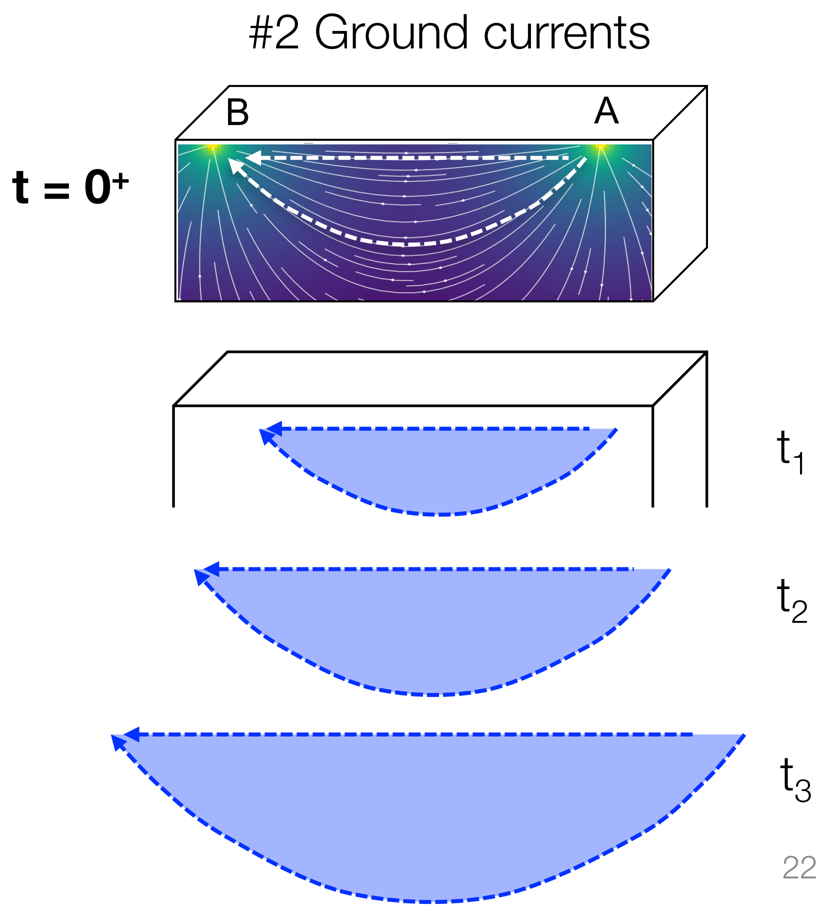
- Immediately after shut off: image current at the surface
- Successive time: currents diffuse downwards and outwards

Currents: Grounded System

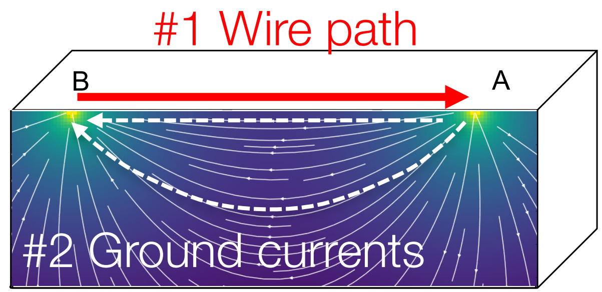


- Immediately after shut off: ground currents are still there

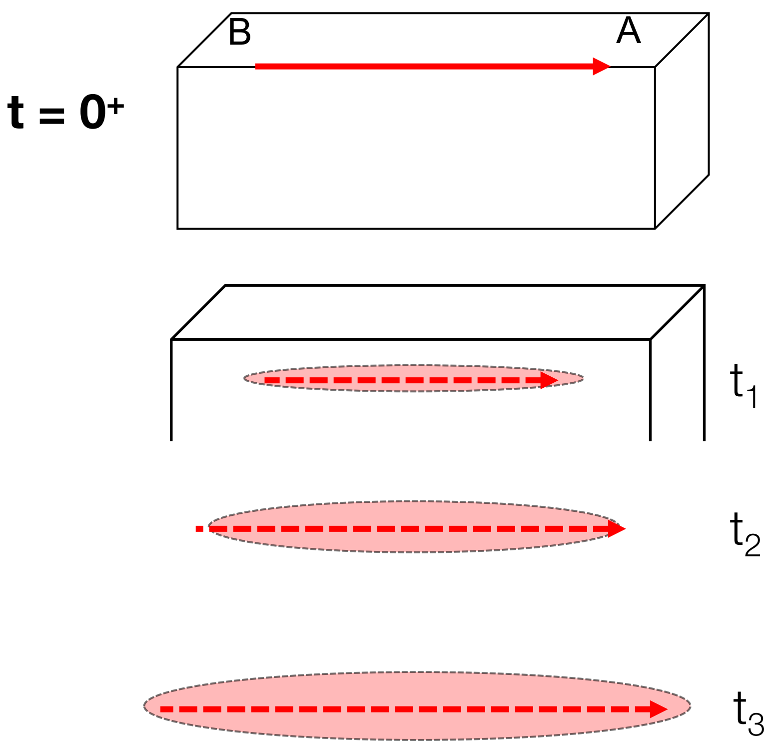
- Successive time: currents diffuse downwards and outwards



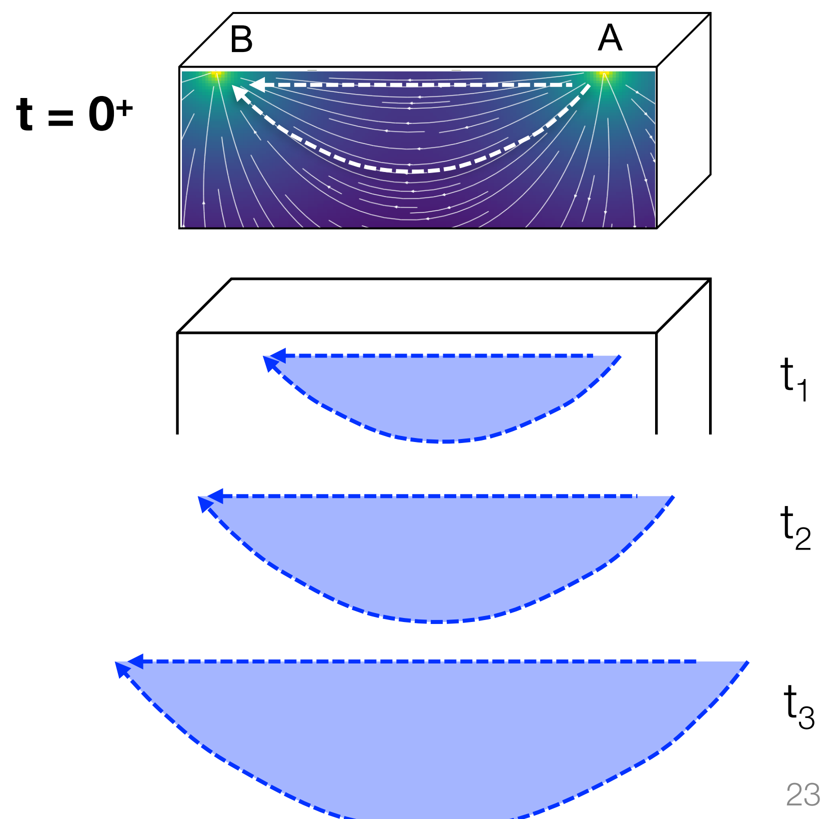
Currents: Grounded System



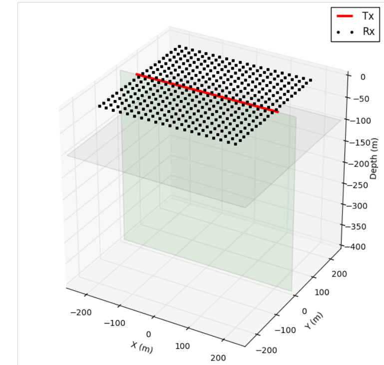
#1 Wire path



#2 Ground currents

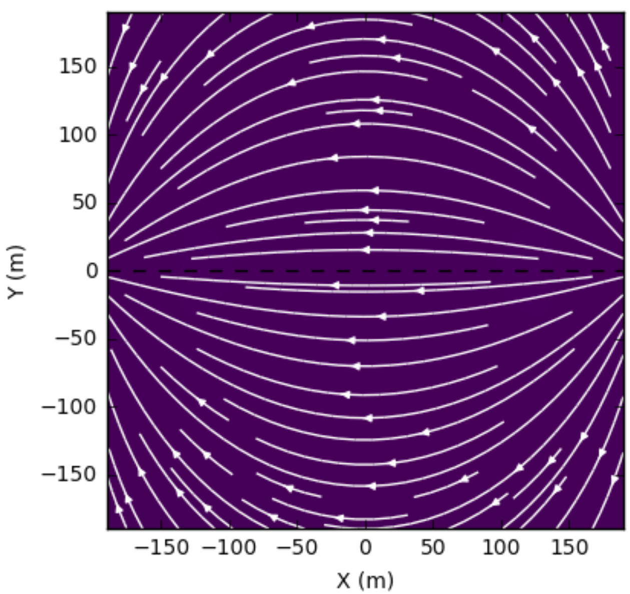


Grounded Source: Halfspace Currents

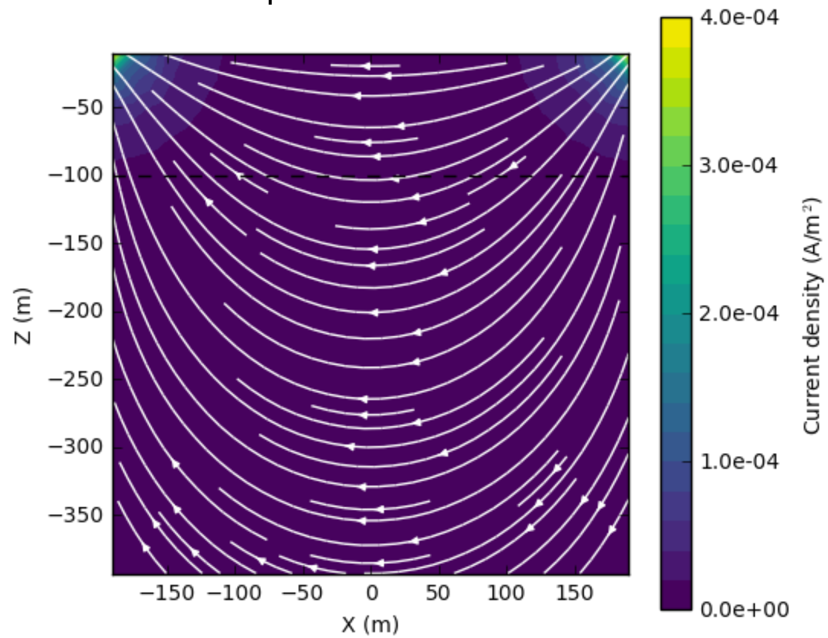


- Parameters:
  - halfspace (0.01 S/m)
  - **t=0$^-$**, steady state

XY plane at Z=-100 m

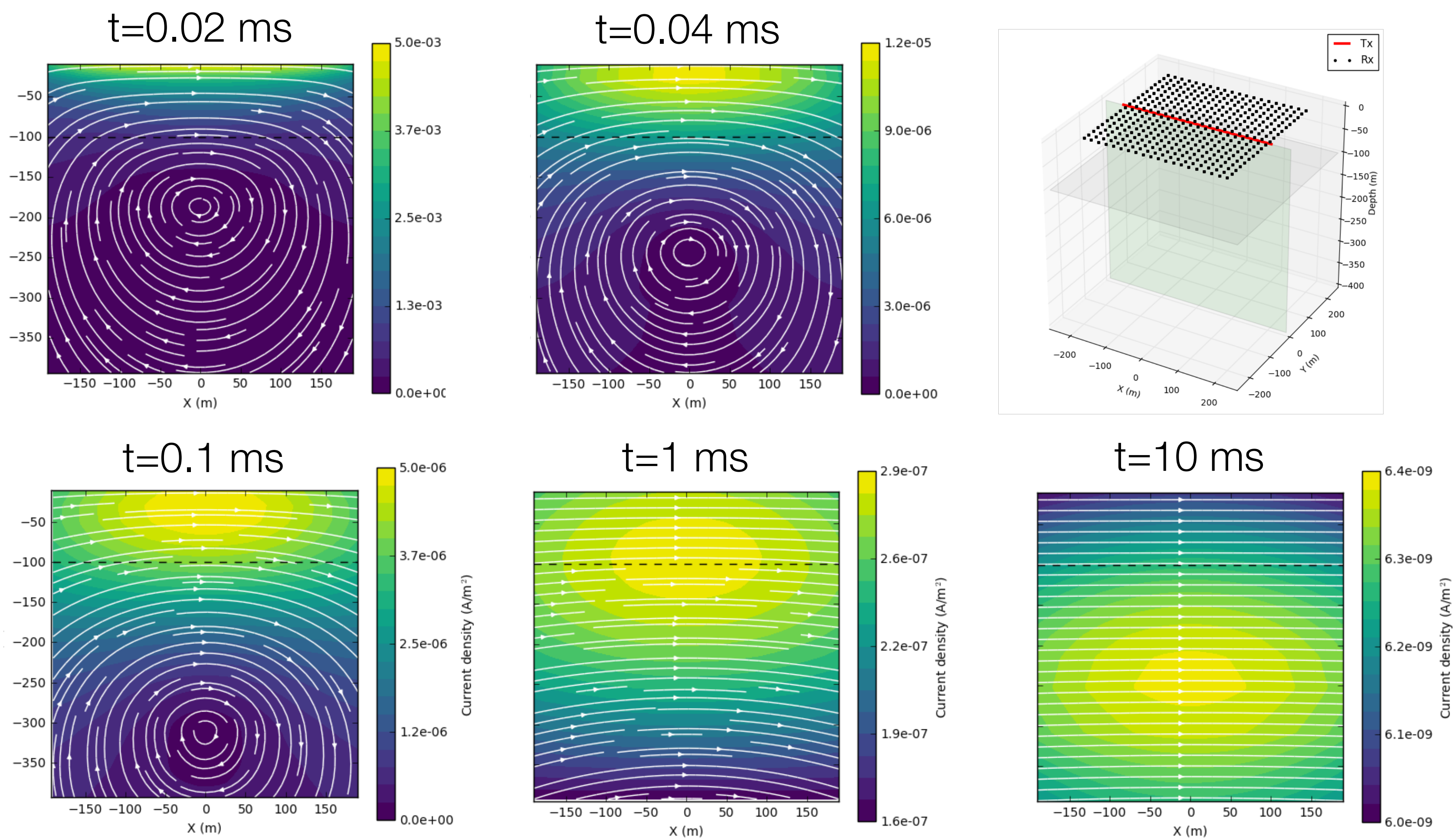


XZ plane at Y=0 m



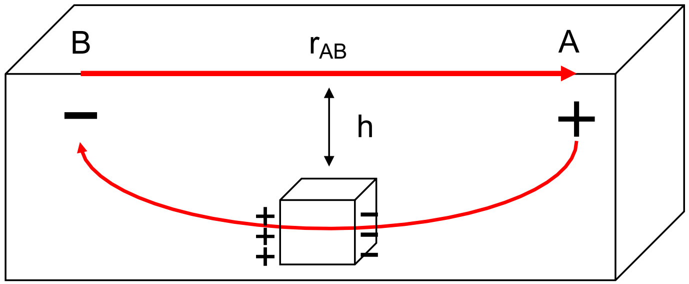
Grounded Source: Halfspace currents

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

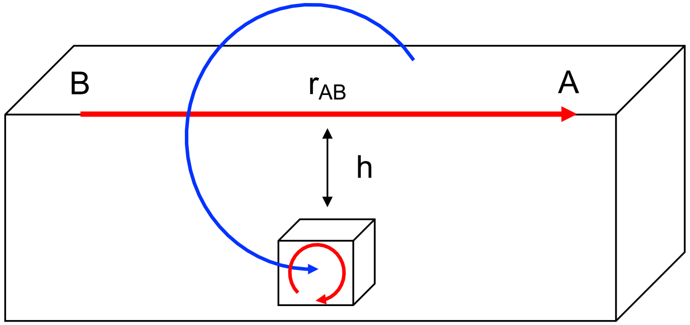


Grounded sources: with a target

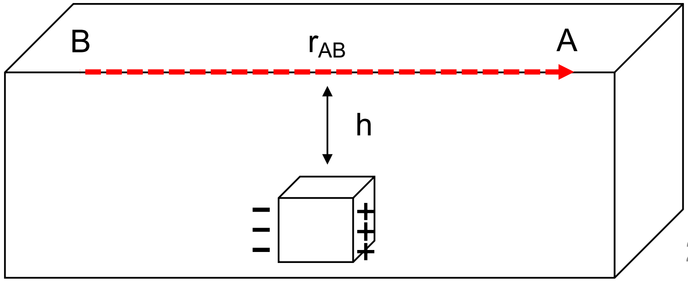
- Block in a halfspace
  - DC
    - Good coupling if h < r_{AB}



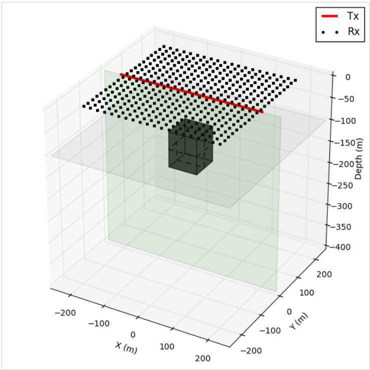
  - Vortex currents
    - Good coupling (magnetic fields)
    - Good signal for conductor
    - Resistor more difficult



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

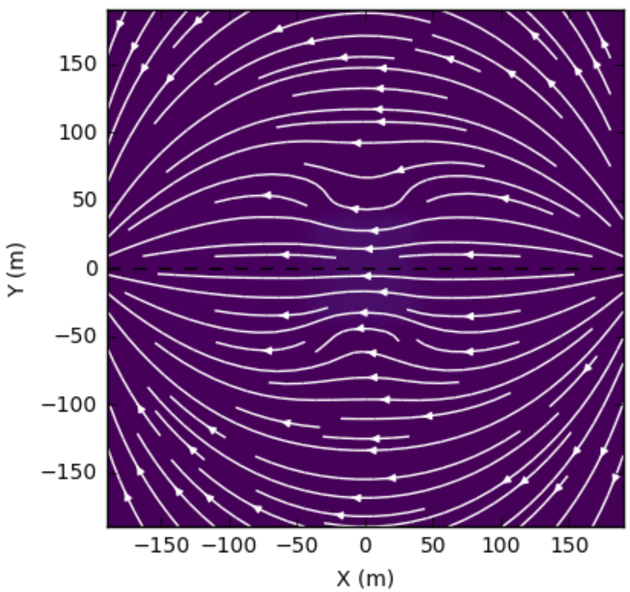


Conductor: currents

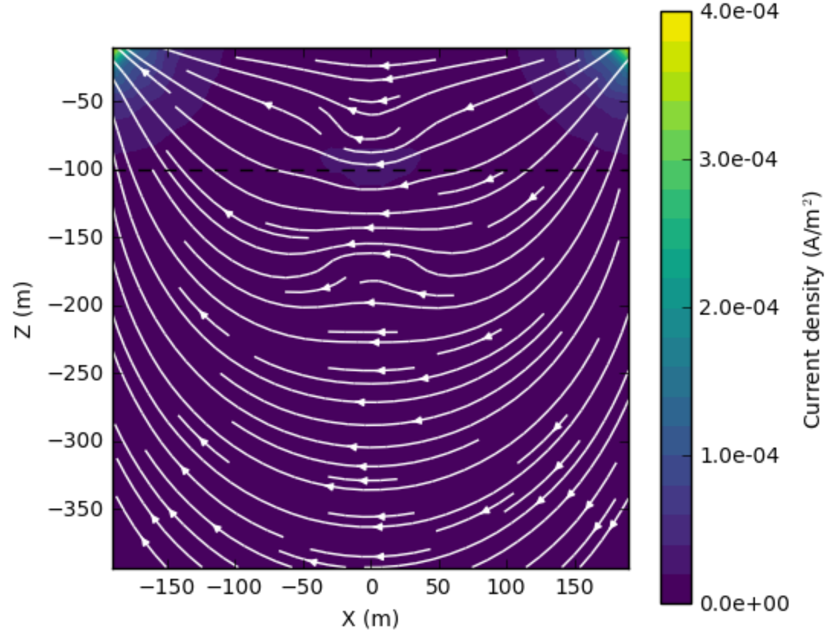


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **t=0$^-$**, steady state

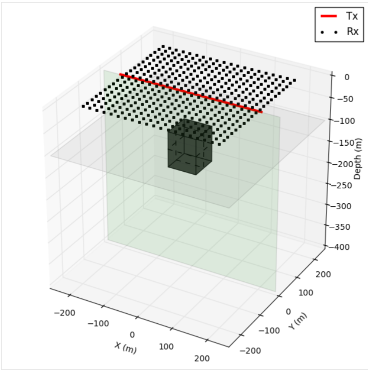
XY plane at Z=-100 m



XZ plane at Y=0 m

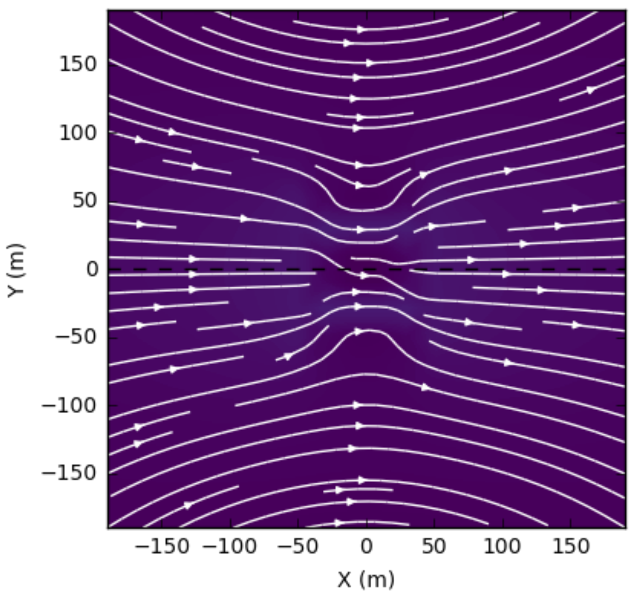


Conductor: currents

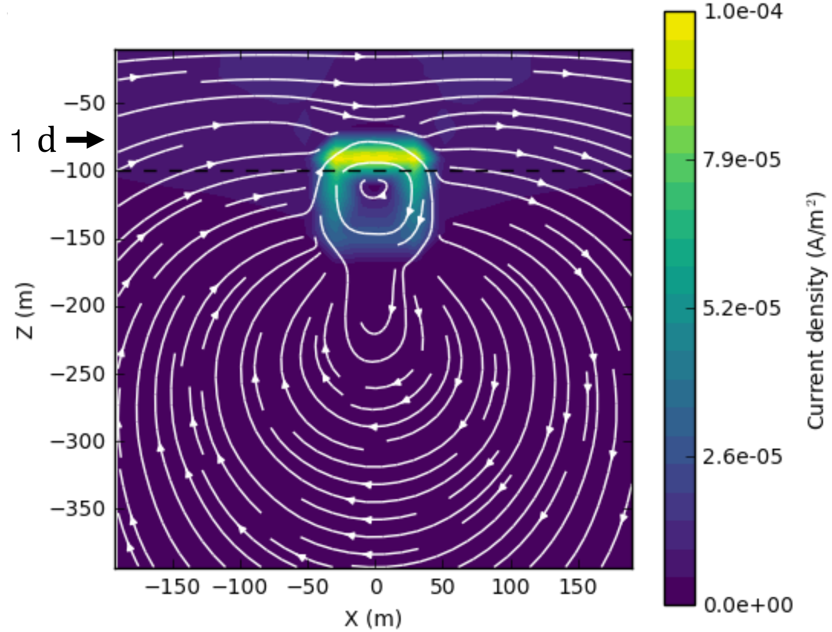


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **0.04** ms, d = 80 m

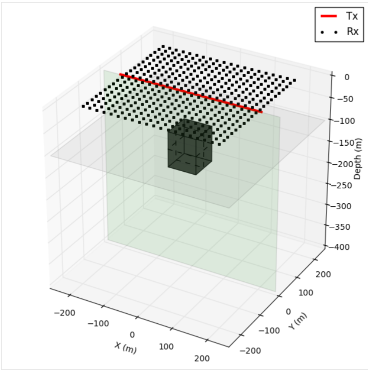
XY plane at Z=-100 m



XZ plane at Y=0 m

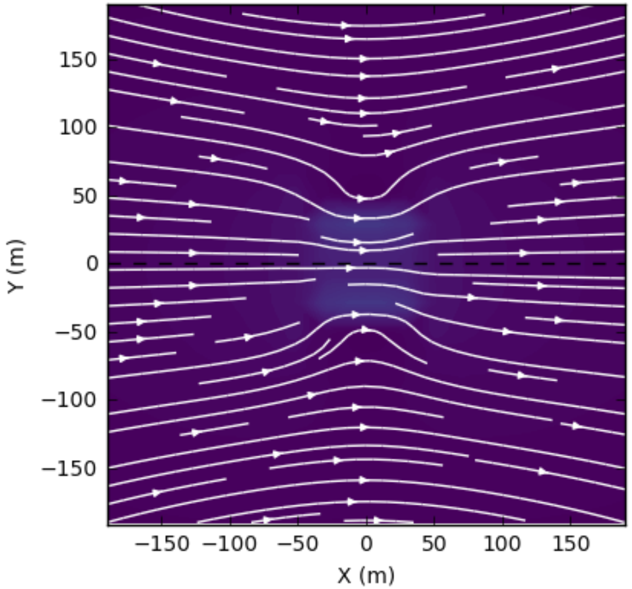


Conductor: currents

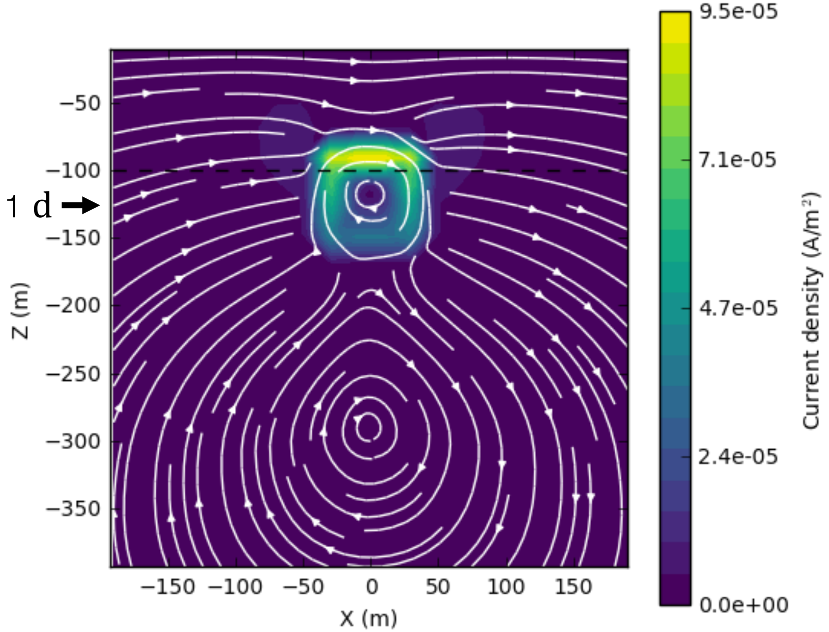


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **0.1** ms, d = 126 m

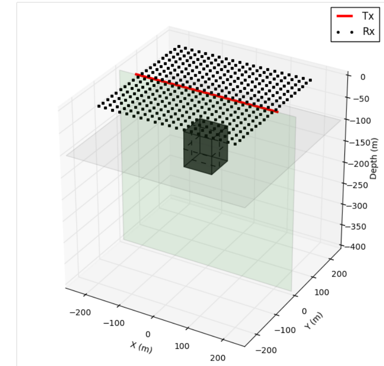
XY plane at Z=-100 m



XZ plane at Y=0 m

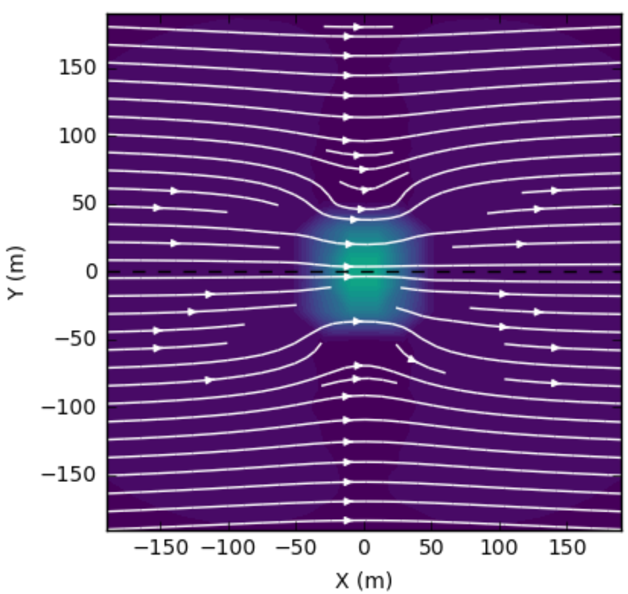


Conductor: currents

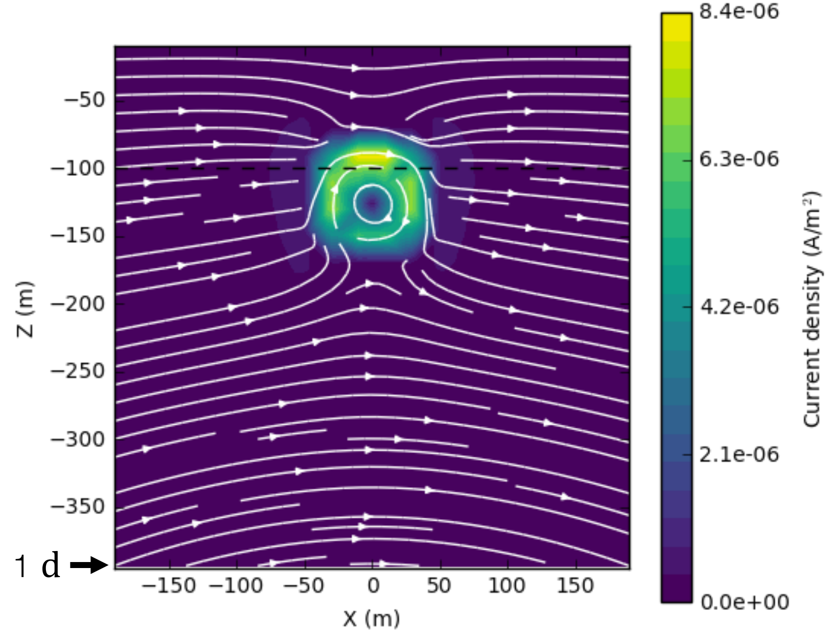


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - 1 ms, d = 400 m

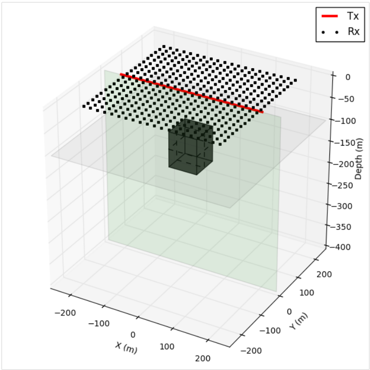
XY plane at Z=-100 m



XZ plane at Y=0 m

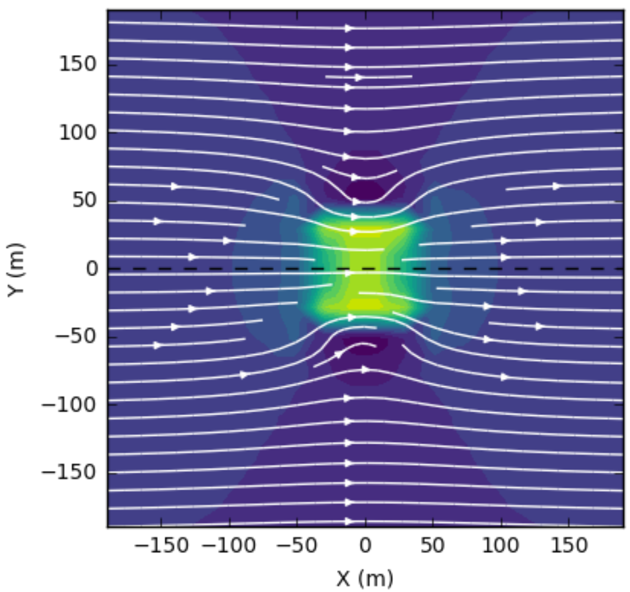


Conductor: currents

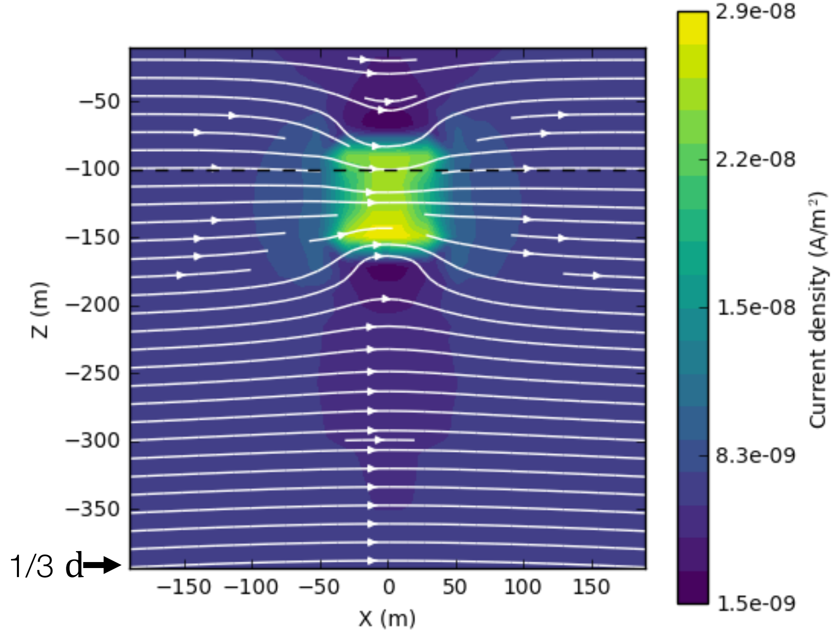


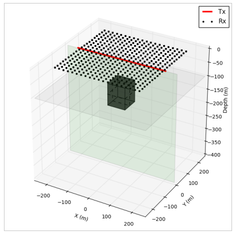
- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **10** ms, d = 1270 m

XY plane at Z=-100 m



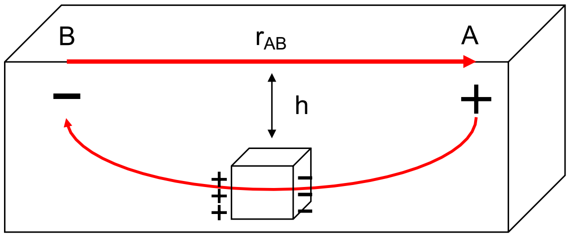
XZ plane at Y=0 m





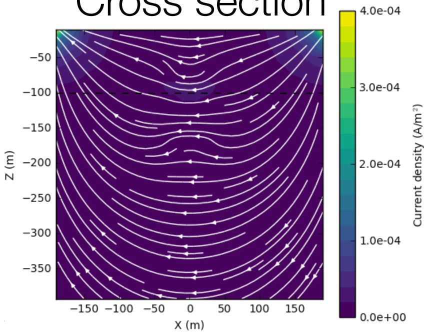
Conductor: currents

Steady State (galvanic current)

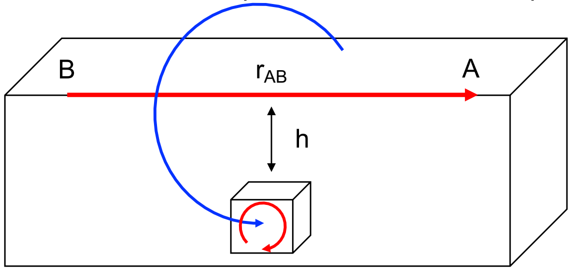


Galvanic current
$t = 0^-$

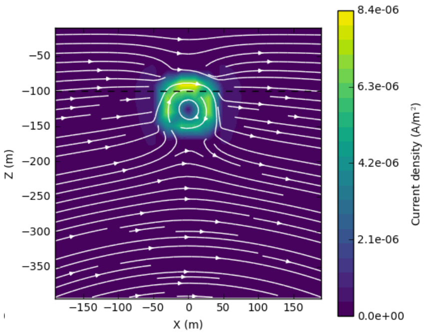
Cross section



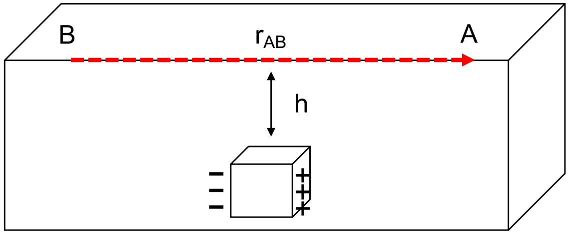
EM induction (vortex current)



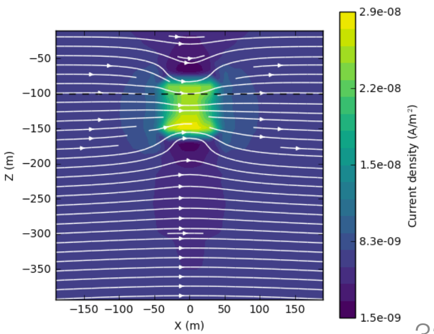
Vortex current
t = 1 ms



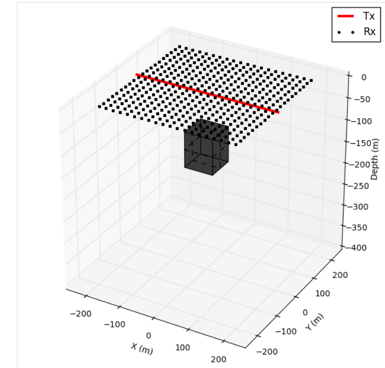
EM induction (galvanic current)

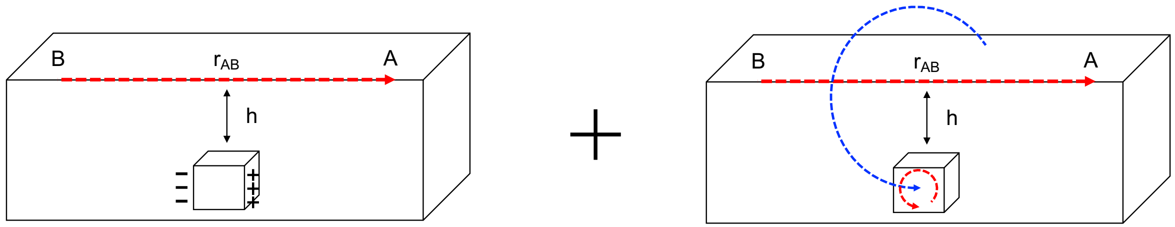


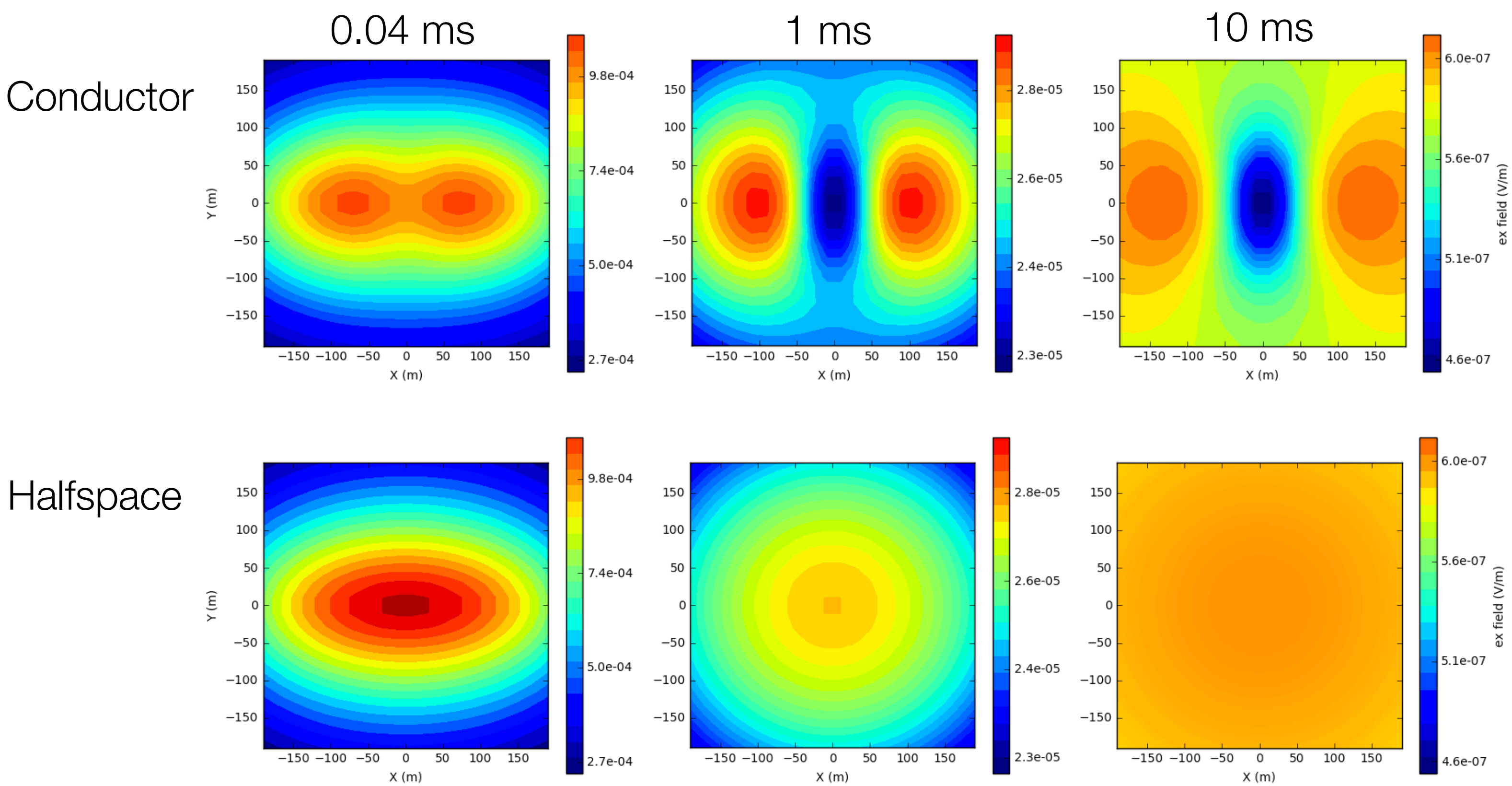
Galvanic current
t = 10 ms



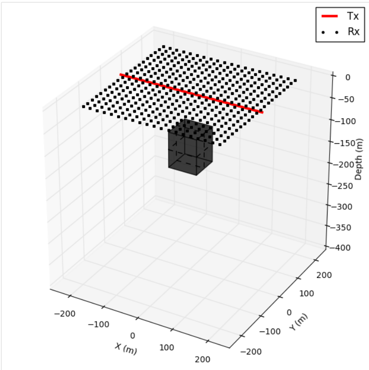
Data: e_x field

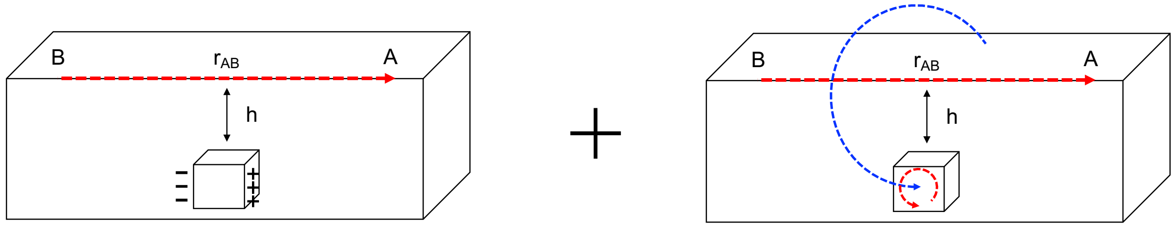


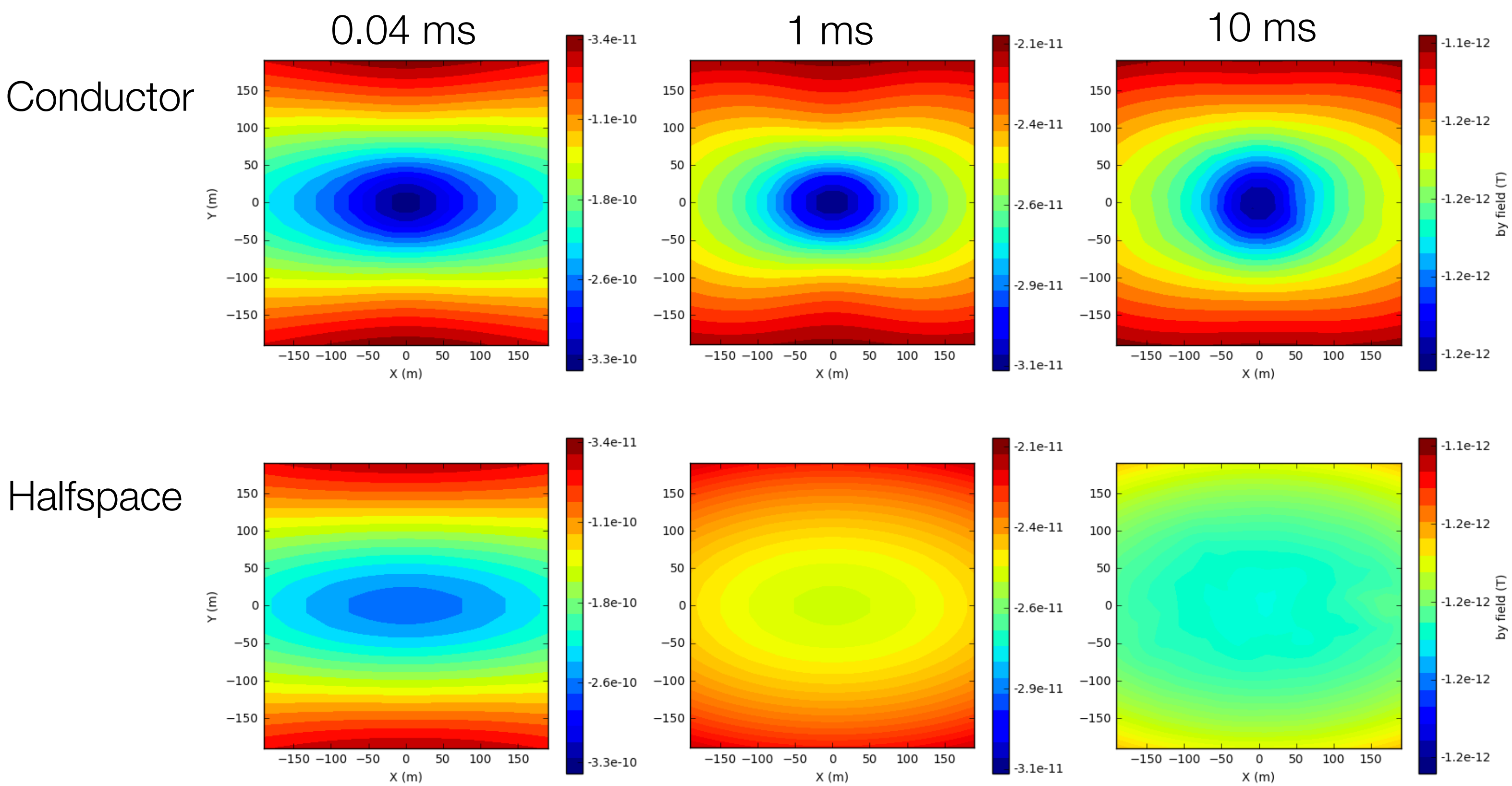




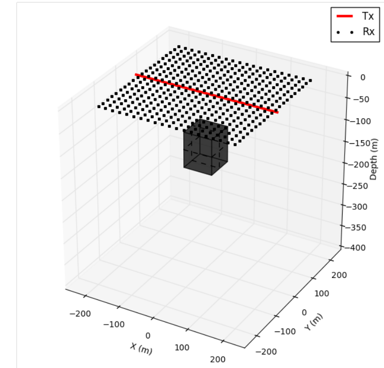
Data: b_y field

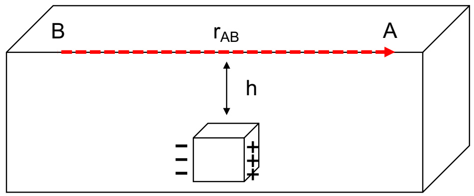




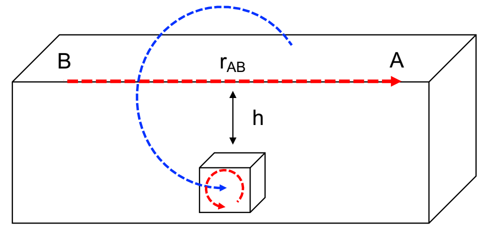


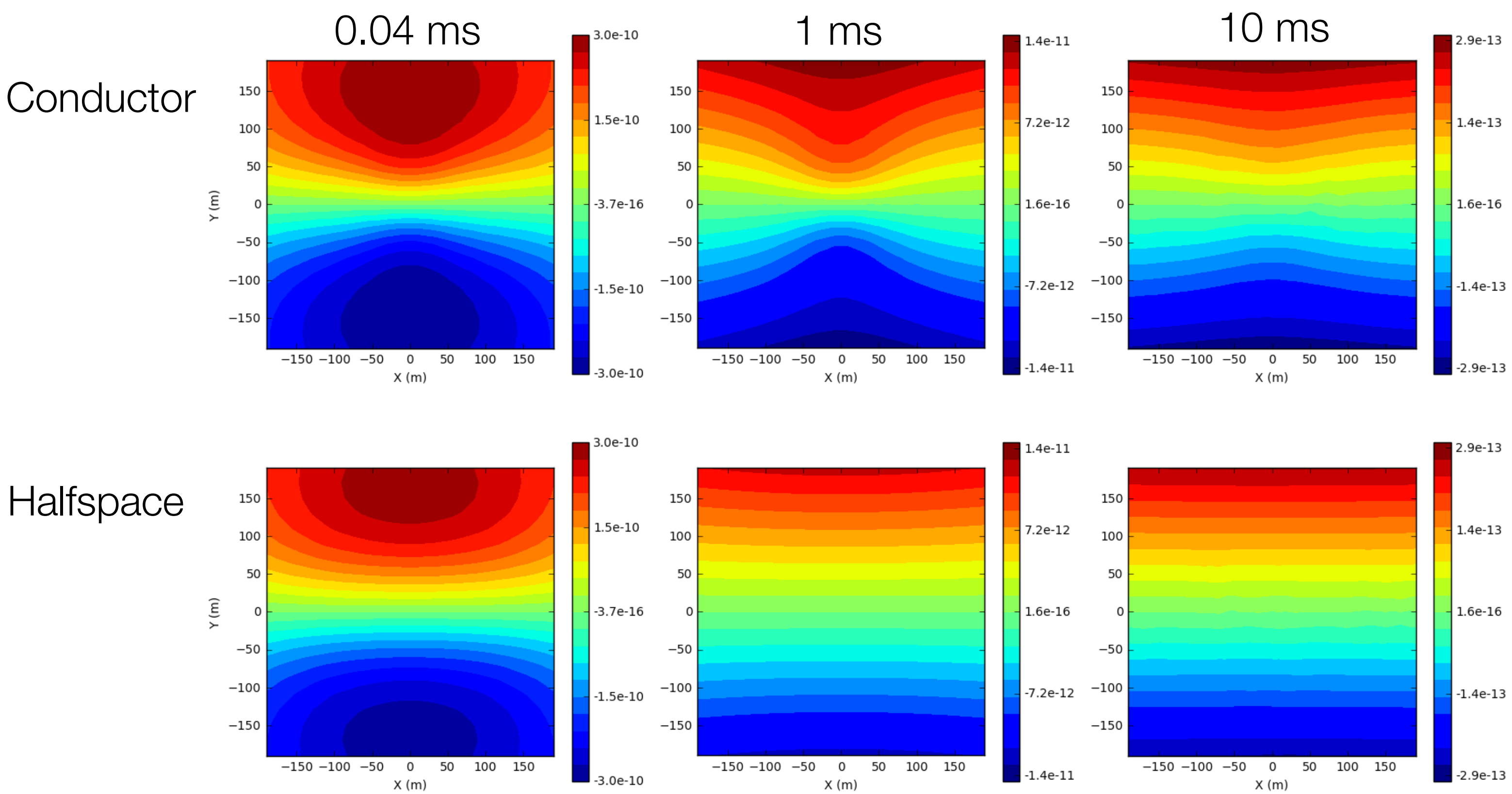
Data: b_z field



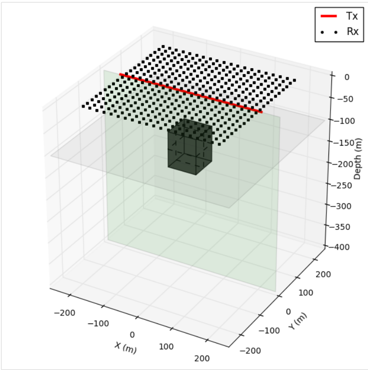


+





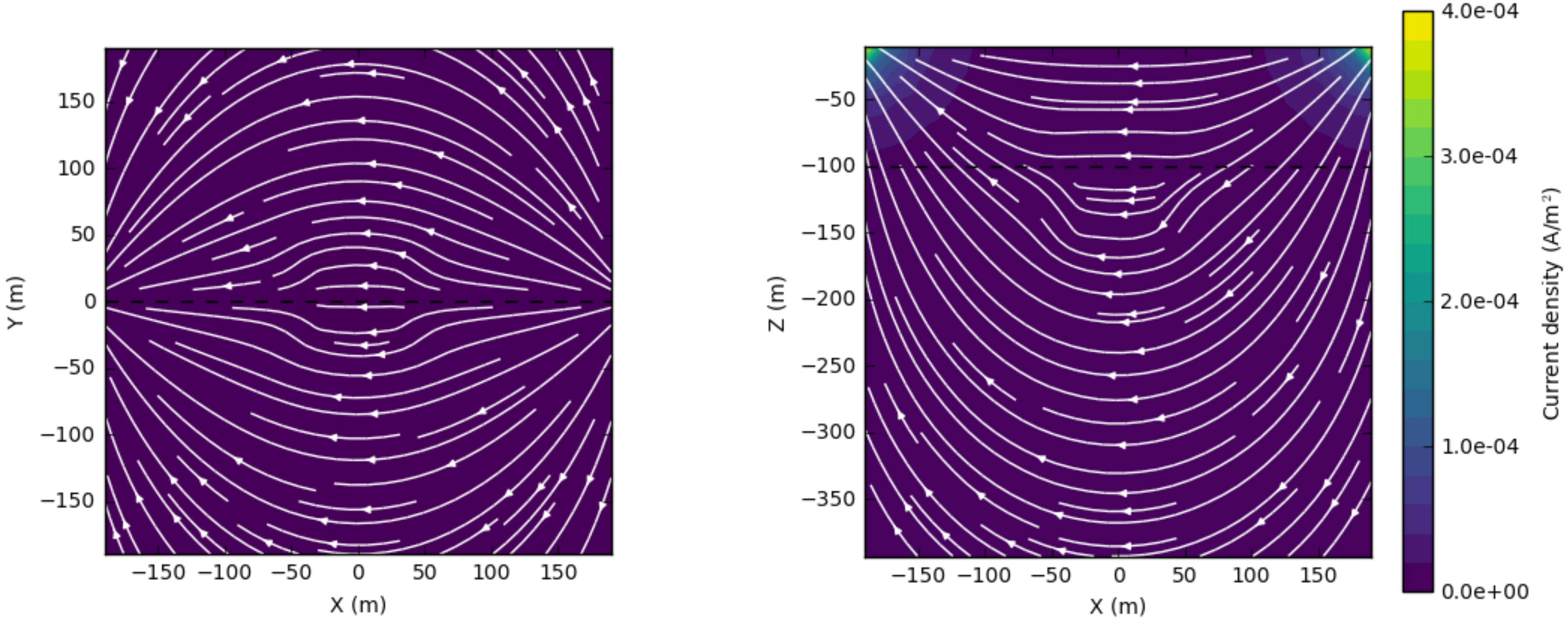
Resistor: currents



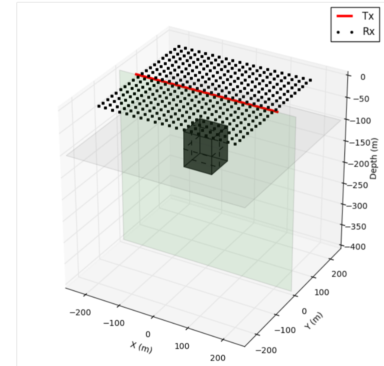
- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **t=0⁻**, steady state

XY plane at Z=-100 m

XZ plane at Y=0 m

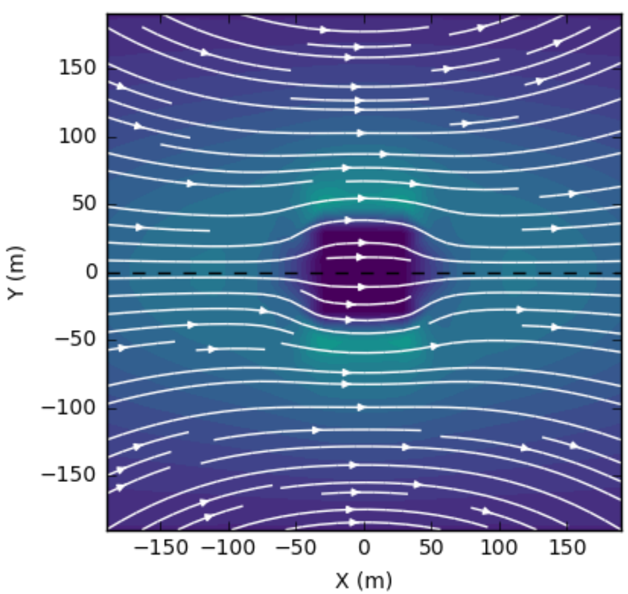


Resistor: currents

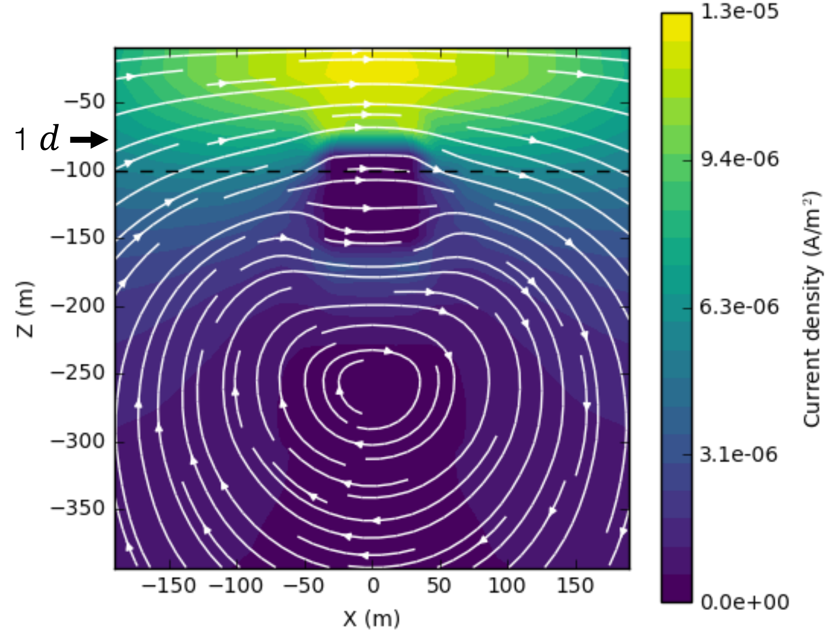


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **0.04** ms, d = 80 m

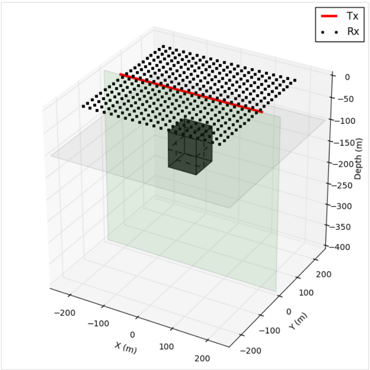
XY plane at Z=-100 m



XZ plane at Y=0 m



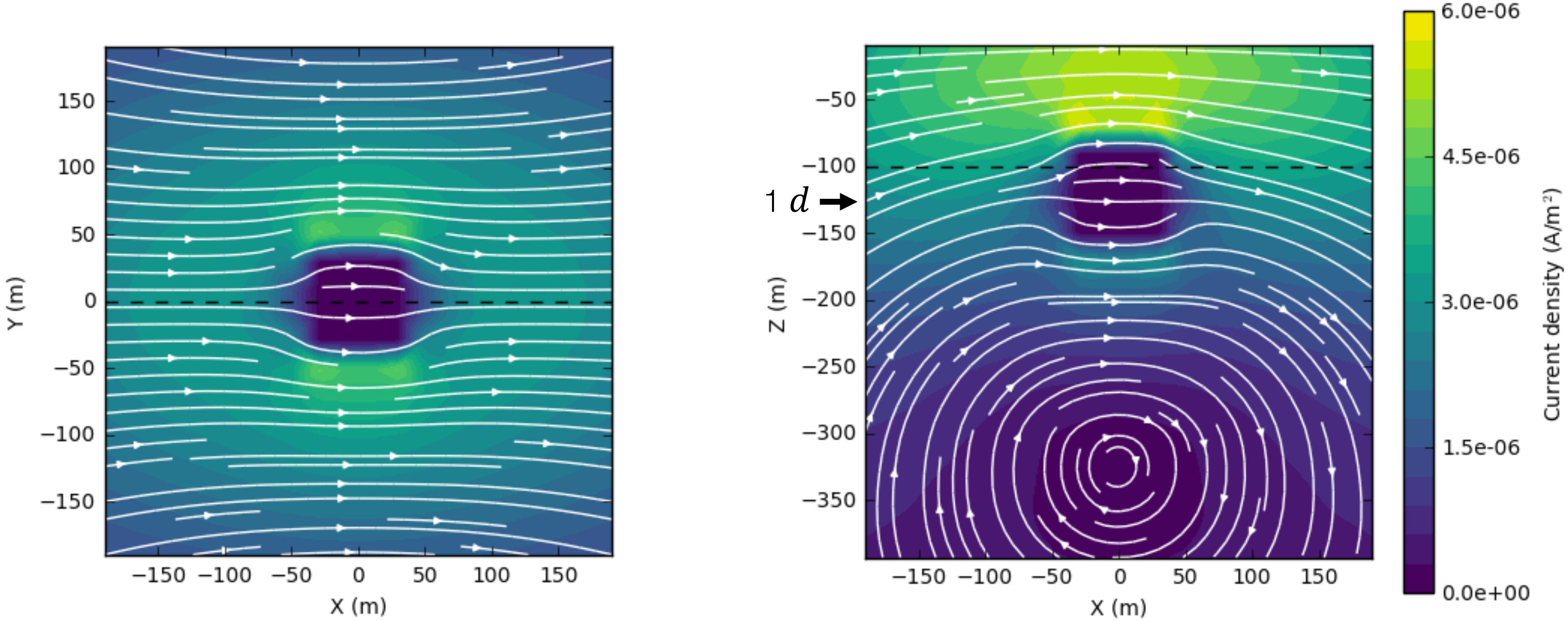
Resistor: currents



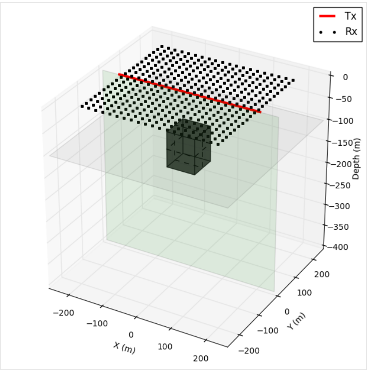
- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **0.1** ms, d = 126 m

XY plane at Z=-100 m

XZ plane at Y=0 m



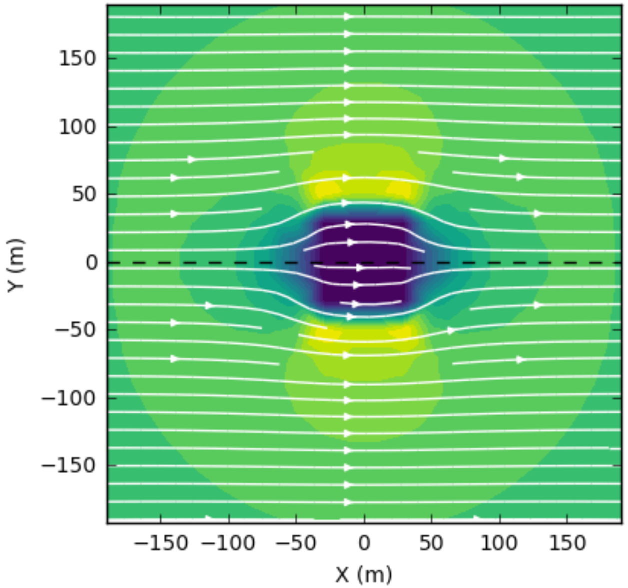
Resistor: currents

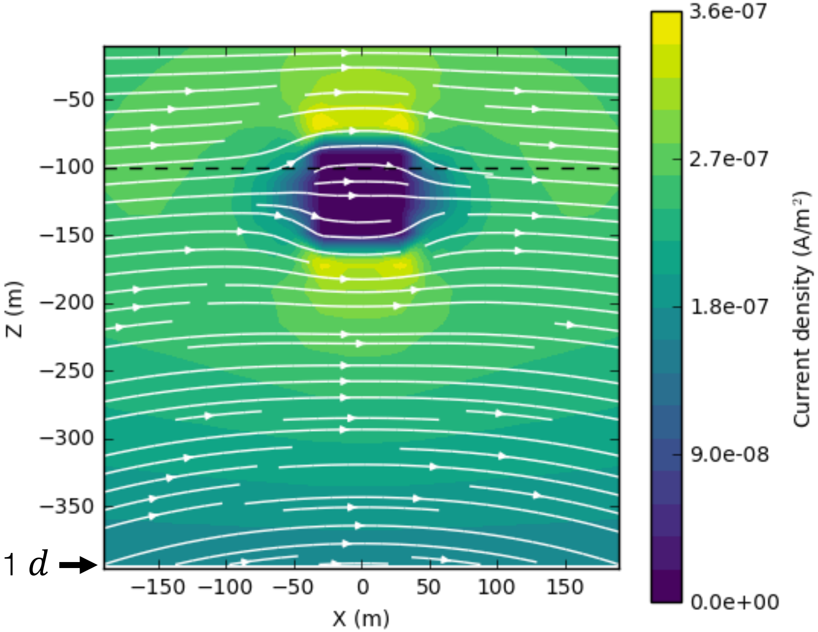


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **1** ms, d = 400 m

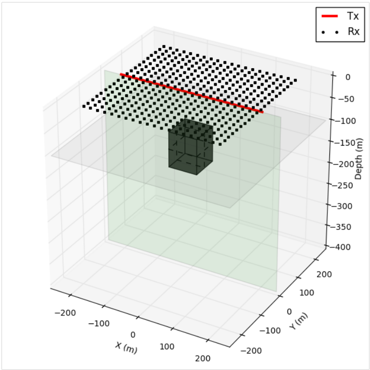
XY plane at Z=-100 m

XZ plane at Y=0 m





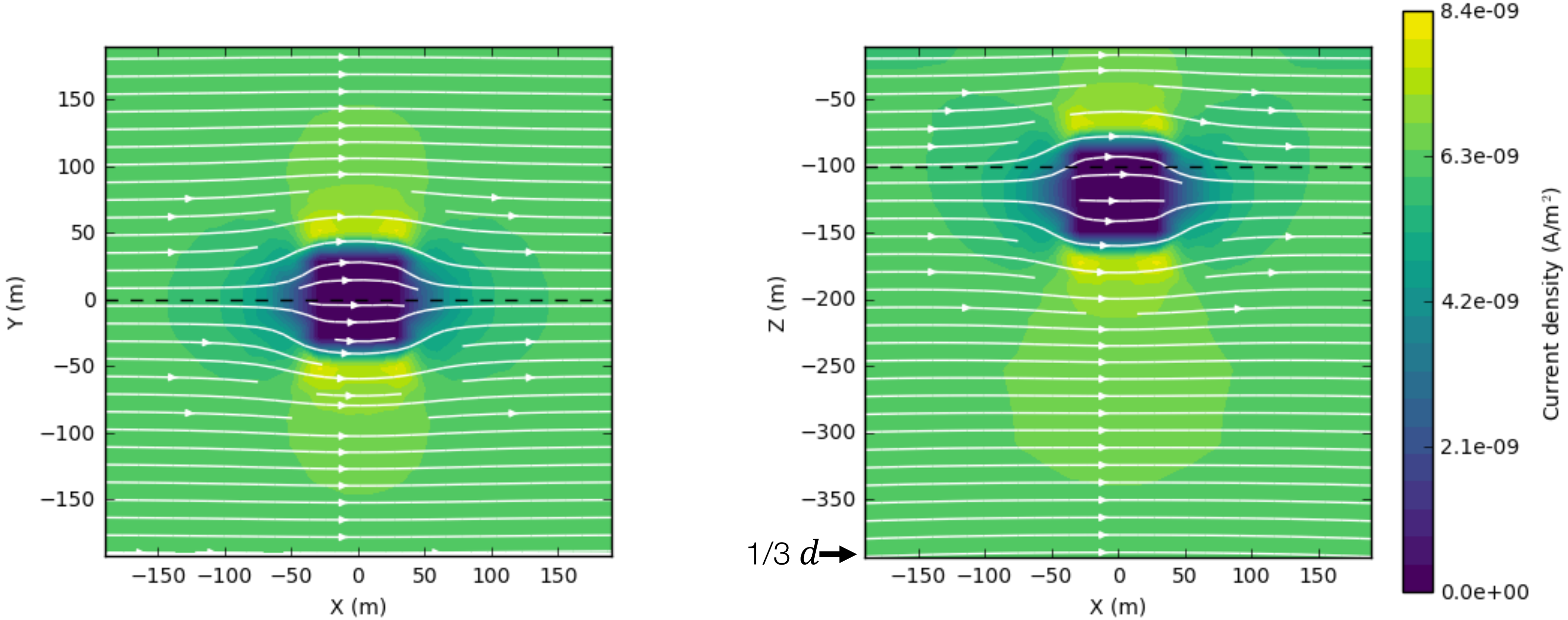
Resistor: currents

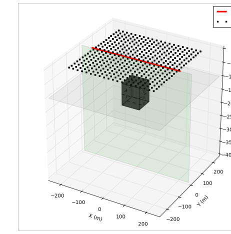


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **10** ms, d = 1270 m

XY plane at Z=-100 m

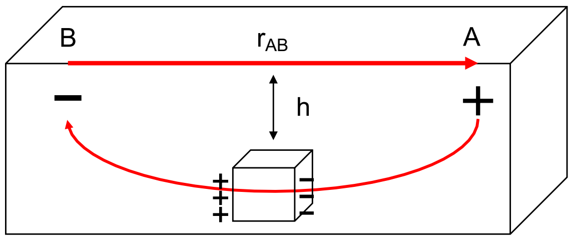
XZ plane at Y=0 m





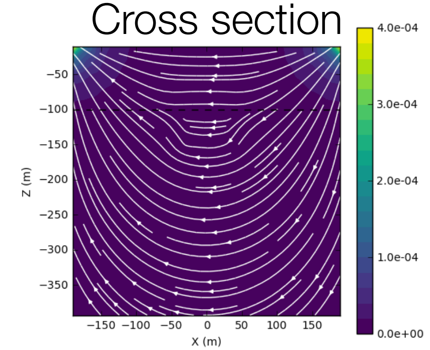
Resistor: currents

DC (galvanic current)

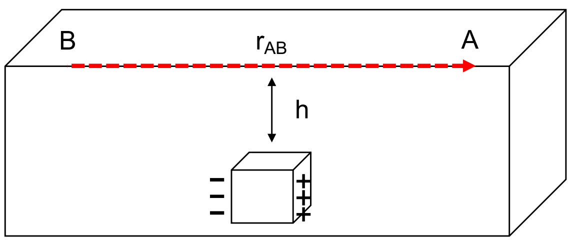


Galvanic current
$t = 0^-$

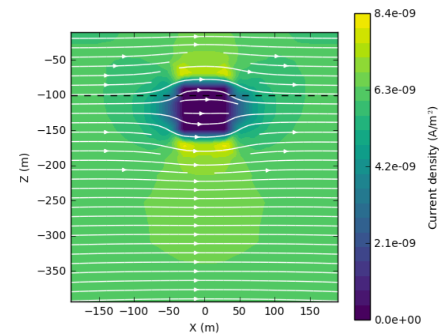
Cross section



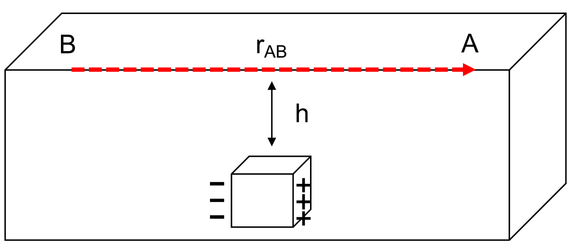
EM induction (galvanic current)



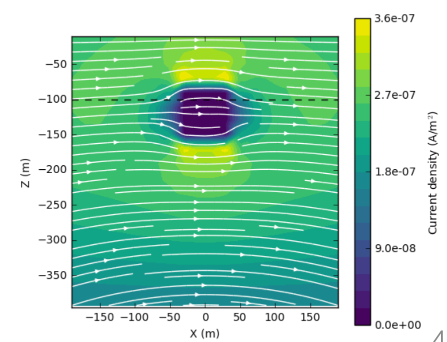
Galvanic current
t = 1 ms



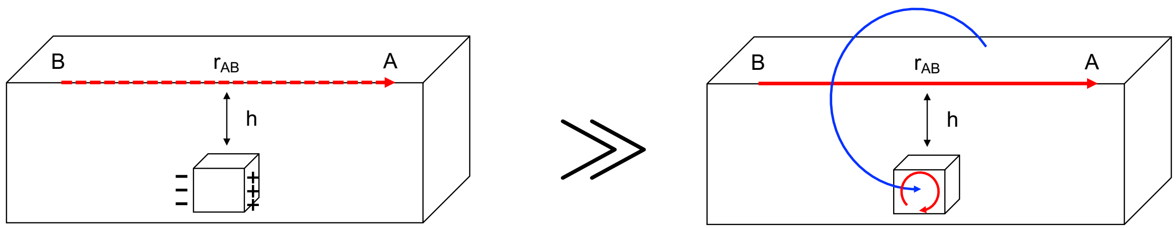
EM induction (galvanic current)

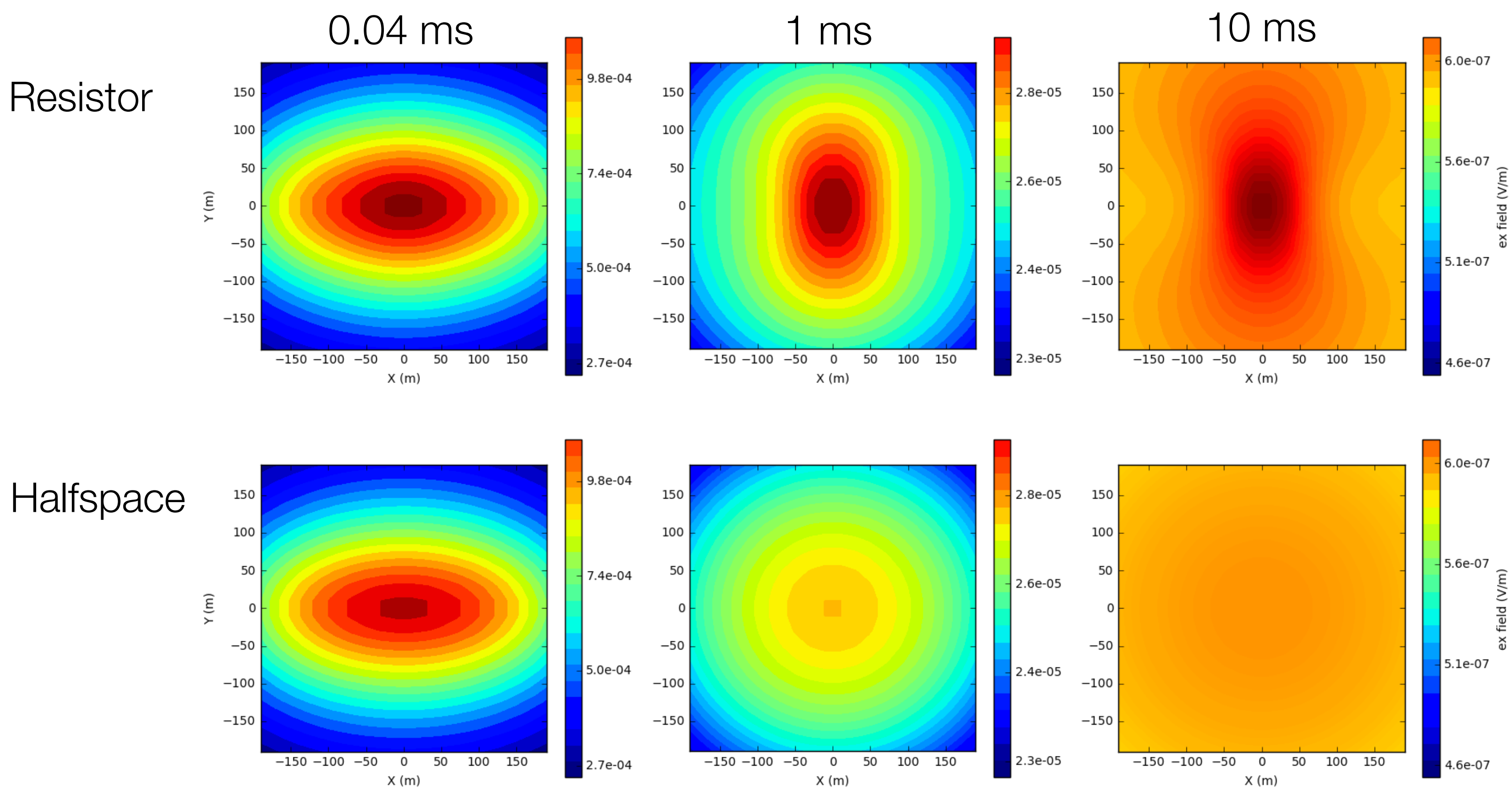


Galvanic current
t = 10 ms

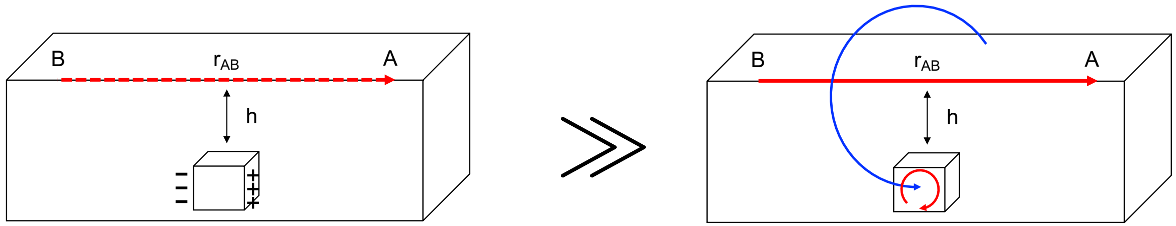


Data: e_x field



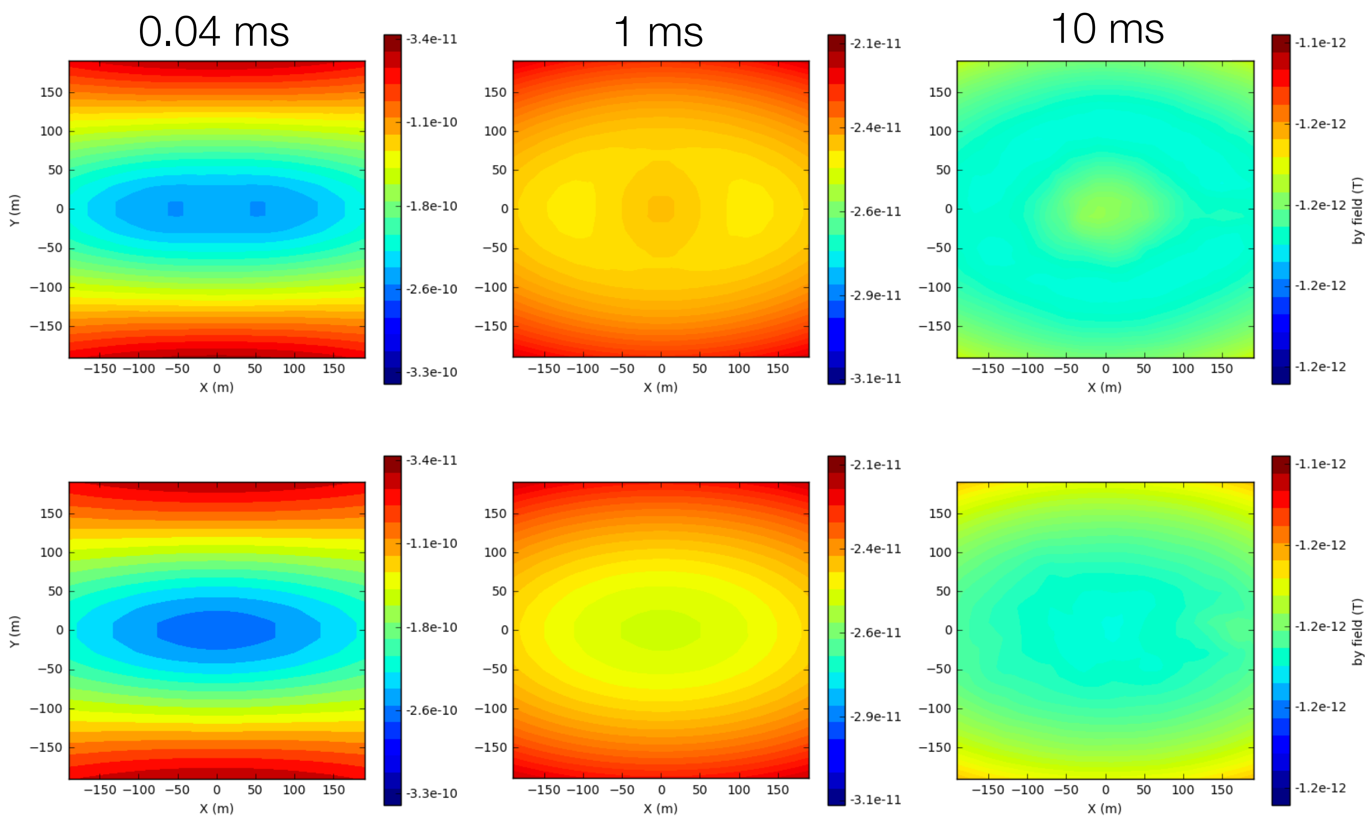


Data: b_y field

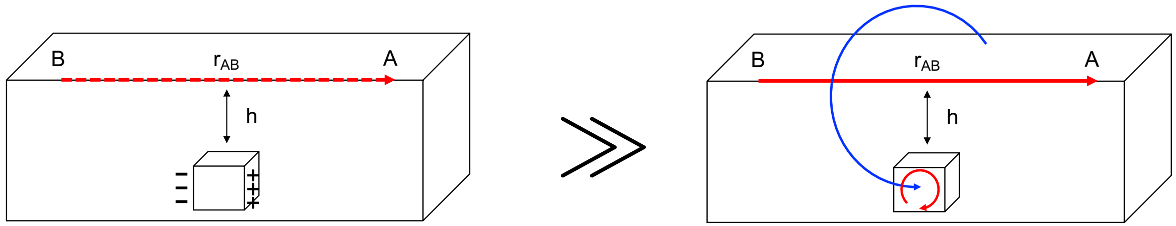


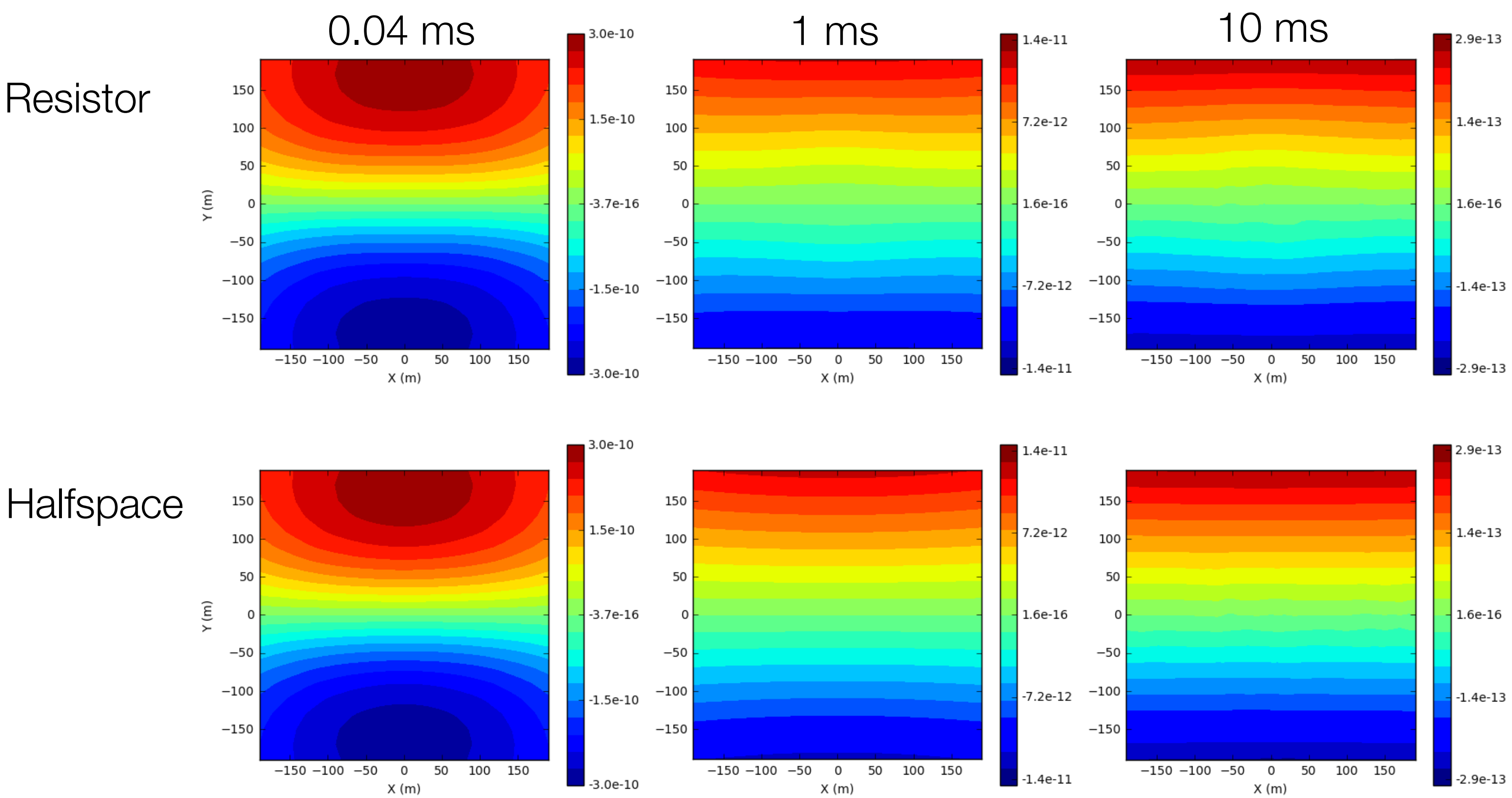
Resistor

Halfspace



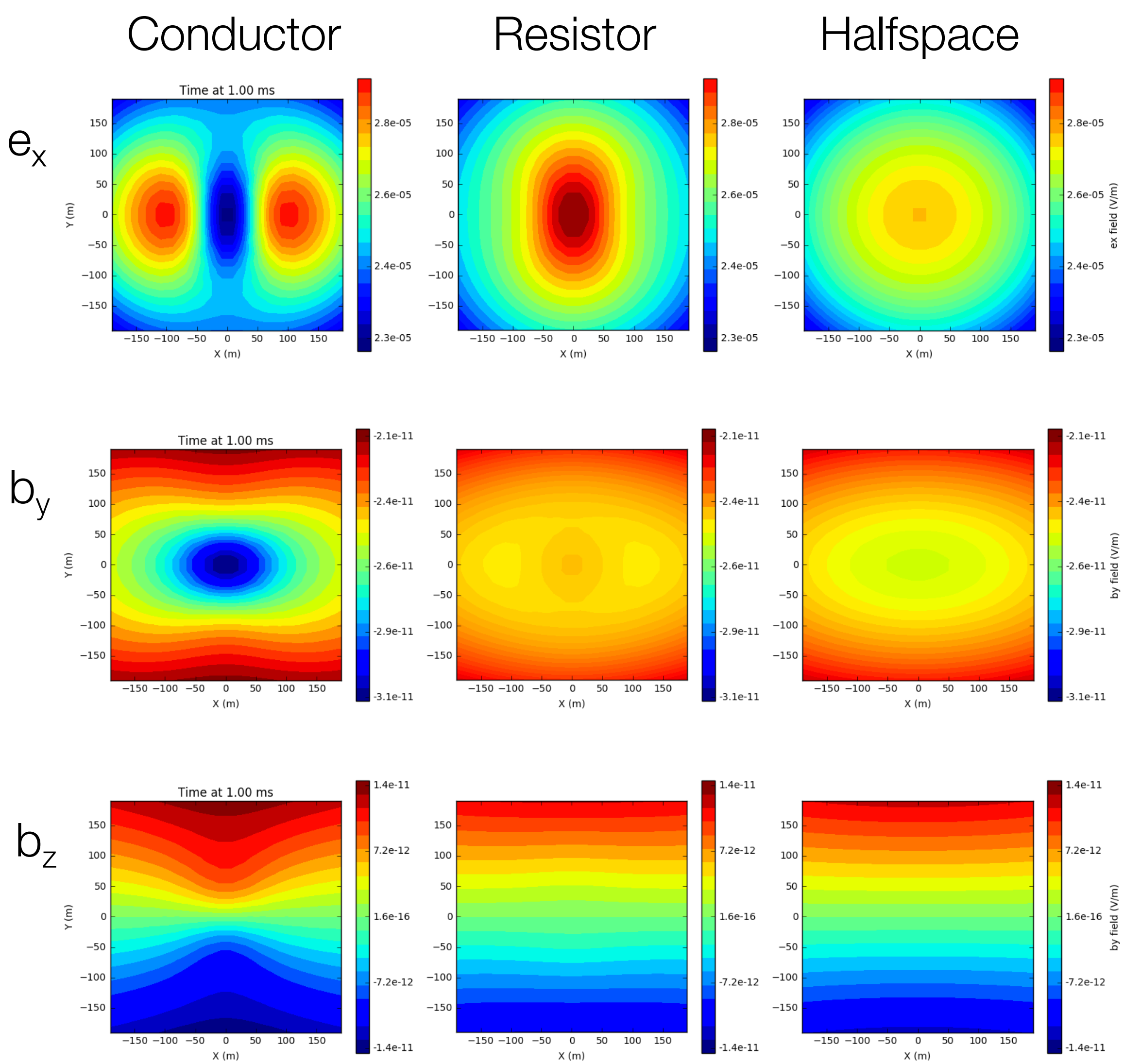
Data: b_z field





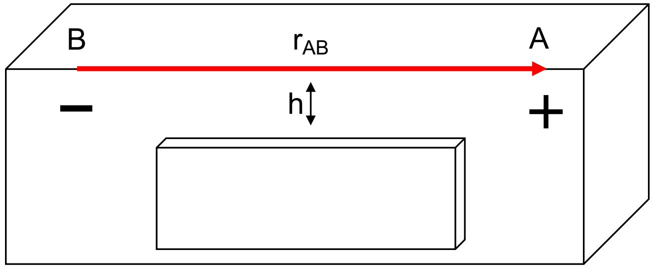
t = 1ms

Data summary

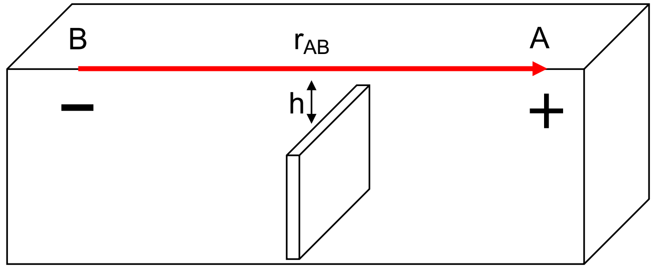


Geometric Complexities

- Coupling: Back to finding thin plates…



- DCR: good coupling
- EM: good coupling



- DCR: poor coupling
- EM: poor coupling

- Arbitrary target requires multiple excitation directions
- Forward simulations necessary

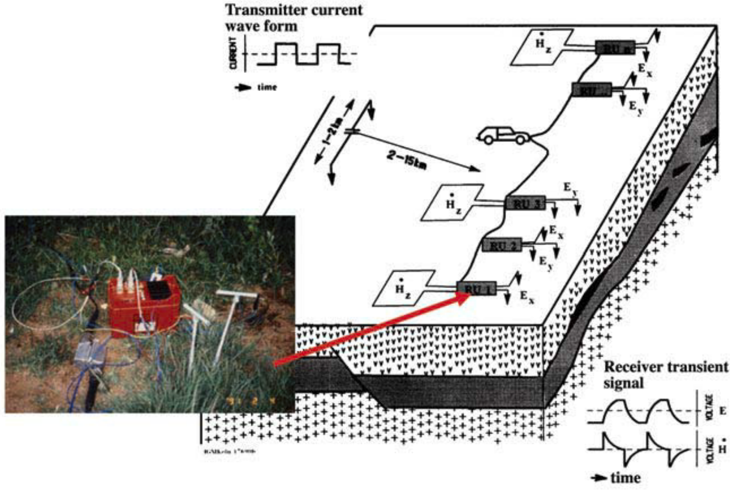
Grounded Sources: Summary

- Basic experiment
- TDEM: Electric dipole in a whole space
- FDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets
- Resistive Targets

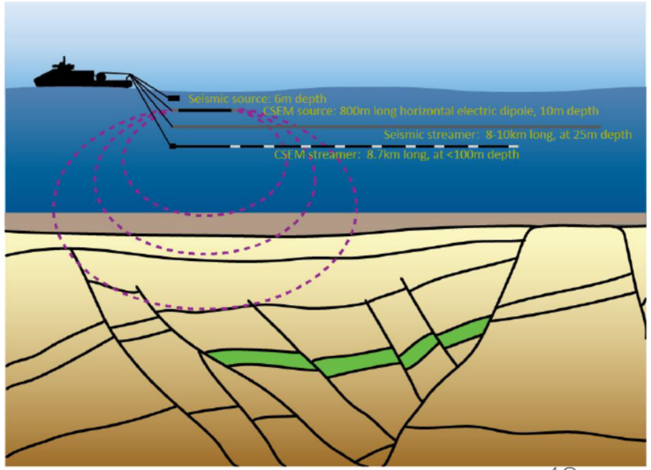
- Case History: Deccan Traps
- Case History: Offshore Hydrocarbon De-risking
- Marine CSEM: Overview
- Case History: Methane hydrates
- DC/EM Inversion

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

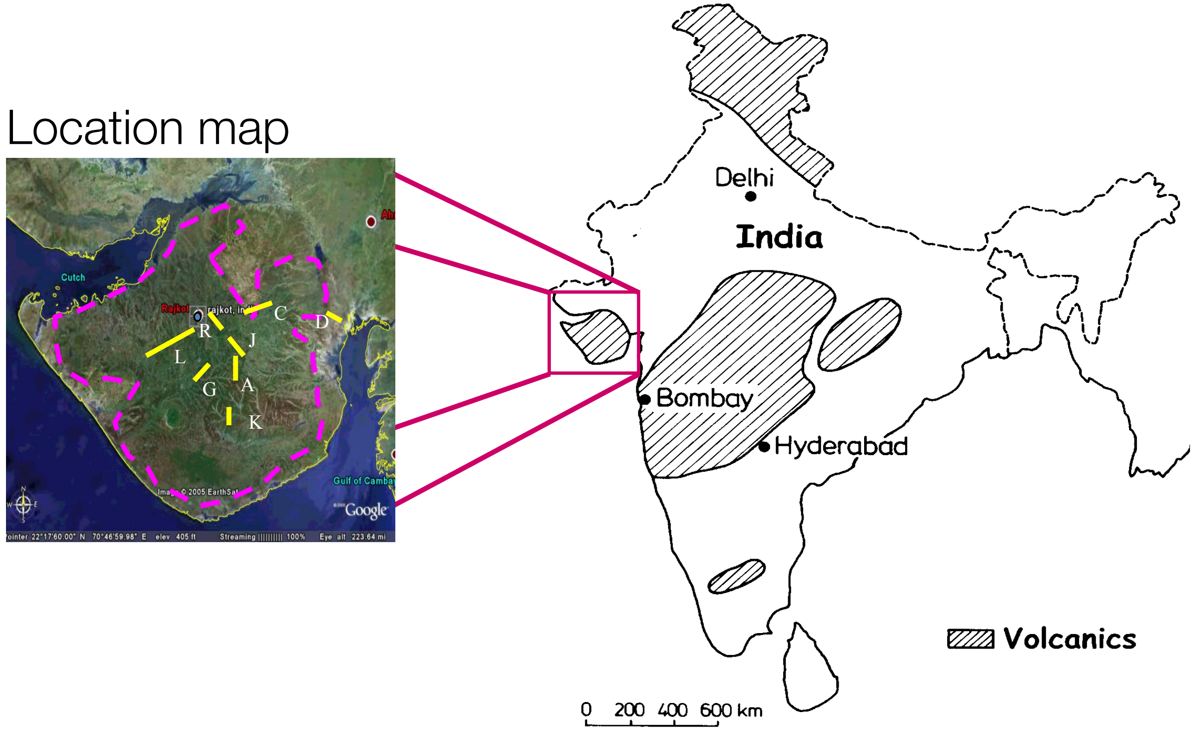


Case History: Mesozoic sediments beneath Deccan traps, India

Strack and Pandey, 2007

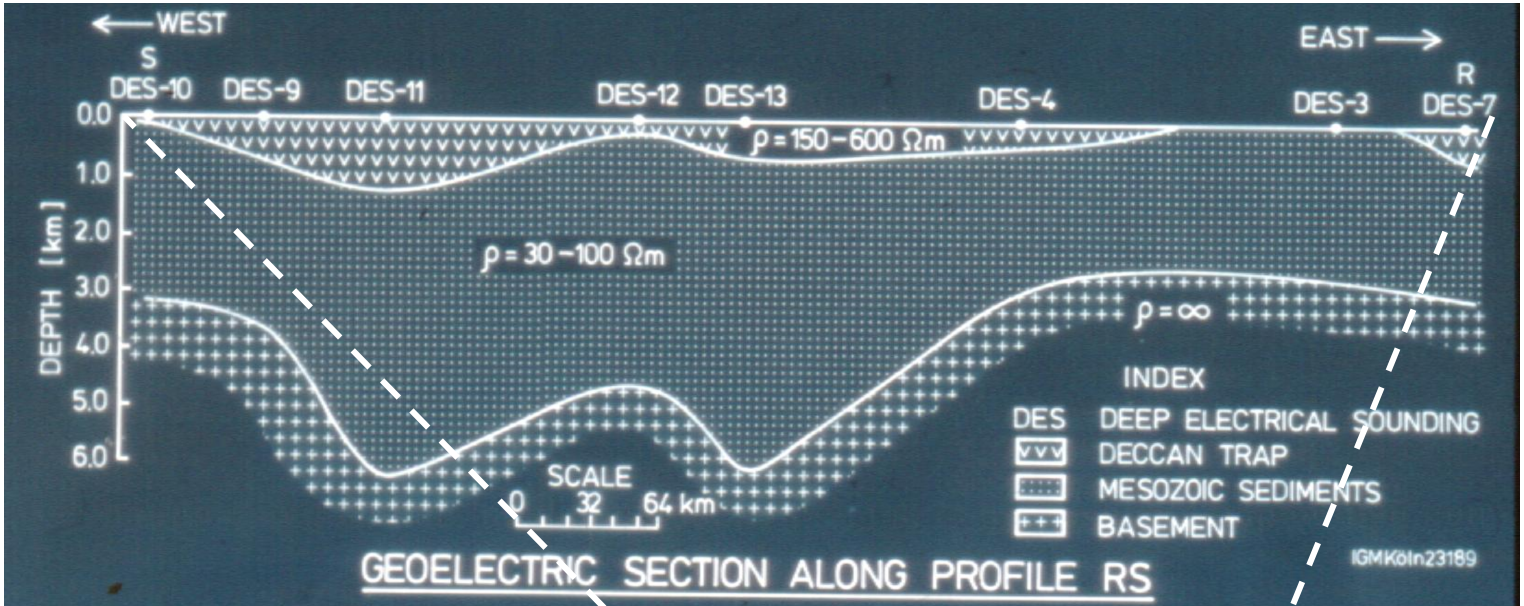
Setup

Location map



Previous DCR survey (ONGC)

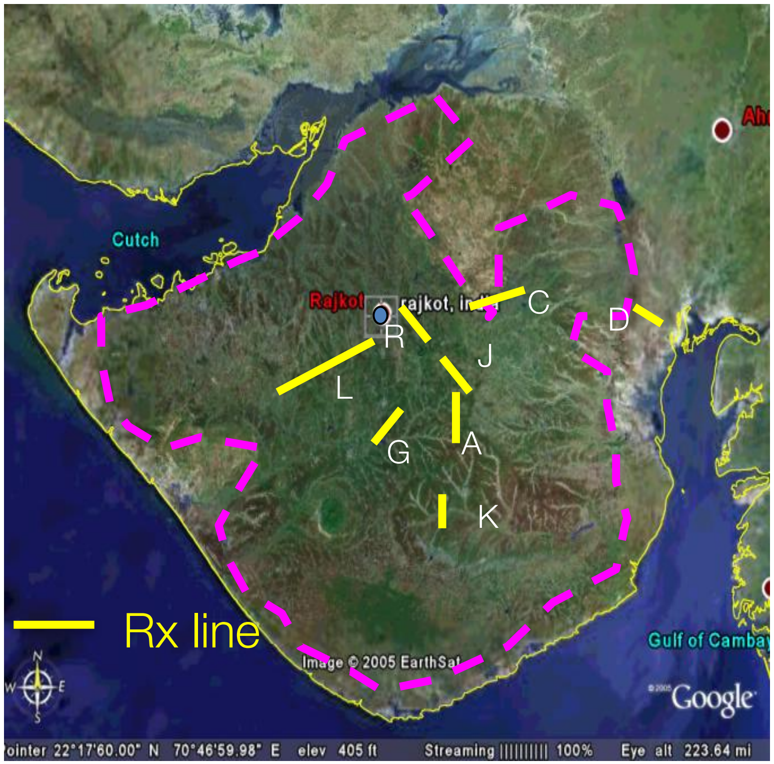
Resistivity section



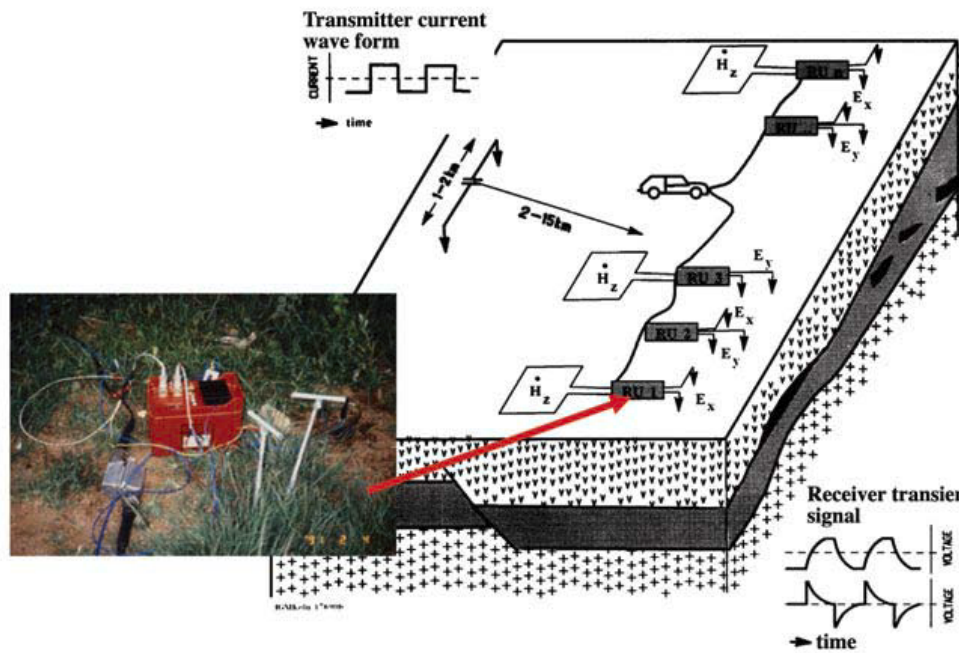
- Sediments exist but unclear where and how thick. Interpretation weak

Survey

Map

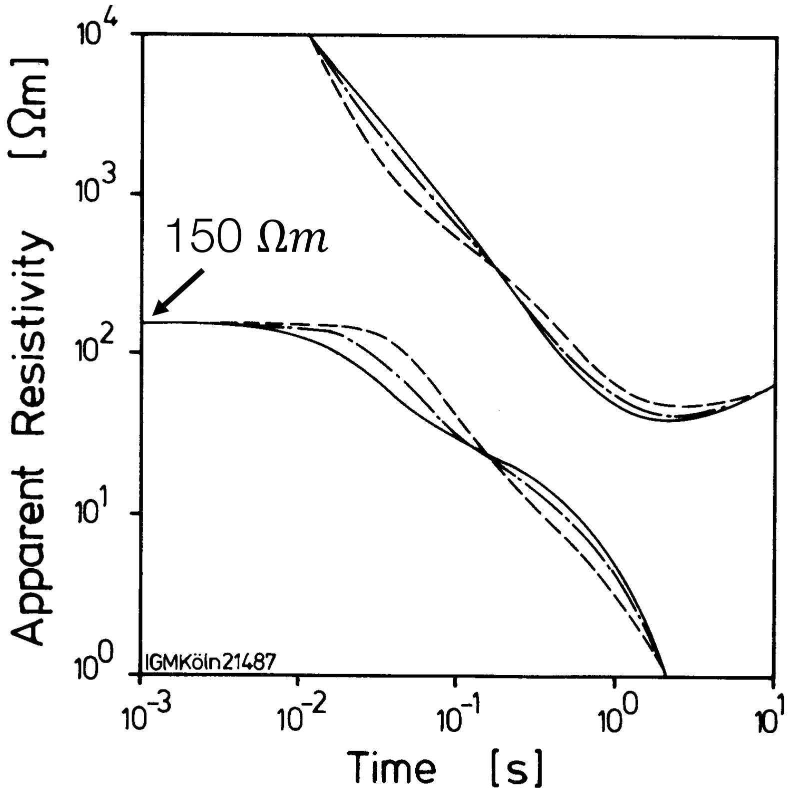


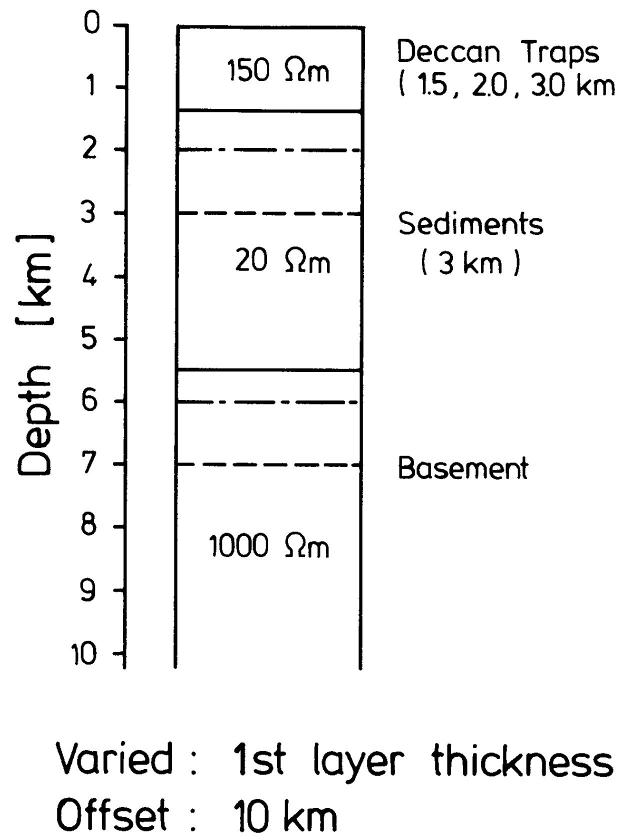
Long offset time domain EM (LOTEM)



- Rx component: Ex, Ey, and Hz
- # of Tx: 10
- Tx current: 400 A (full-duty cycle)

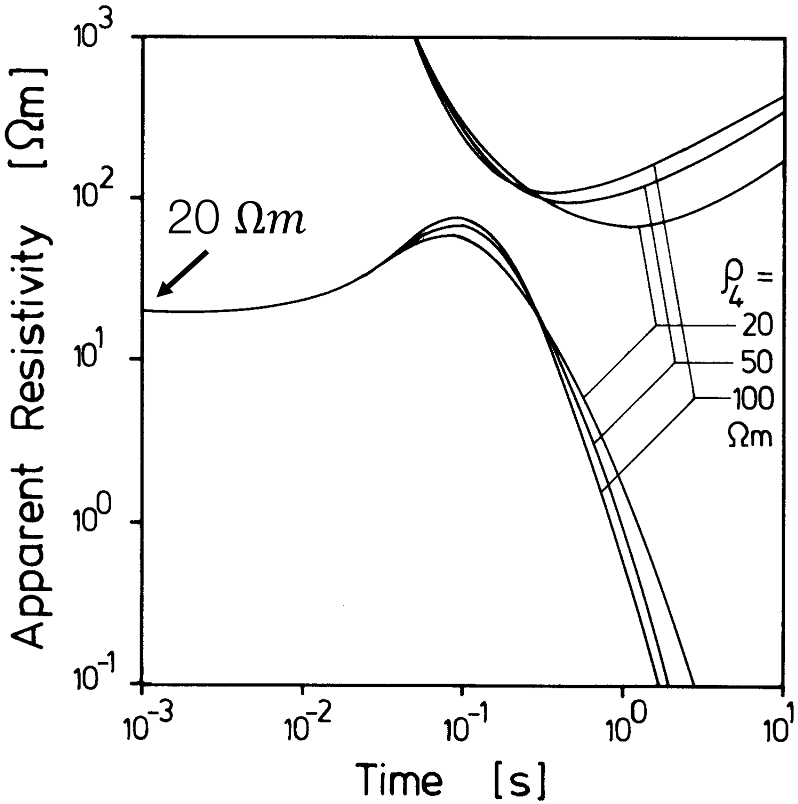
Survey design: basalt thickness

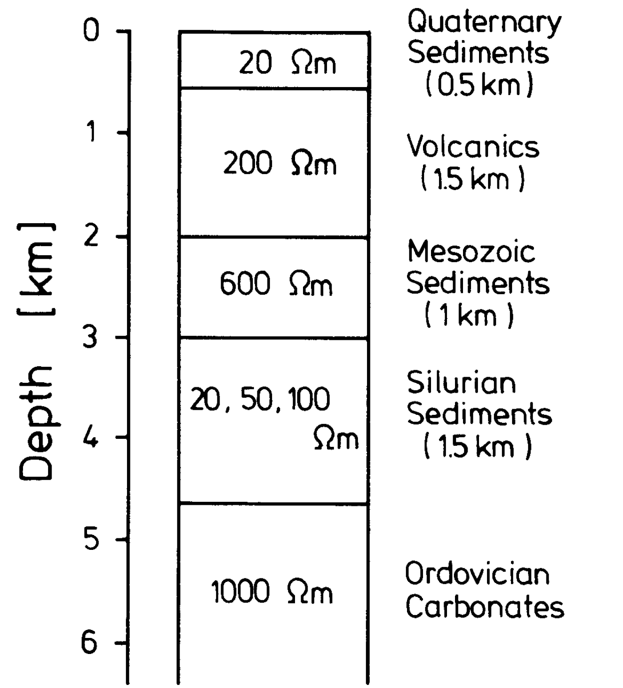




- Apparent resistivity changes with varying thickness of Deccan Traps: 1.5, 2 and 3 km

Survey design: sediment resistivity

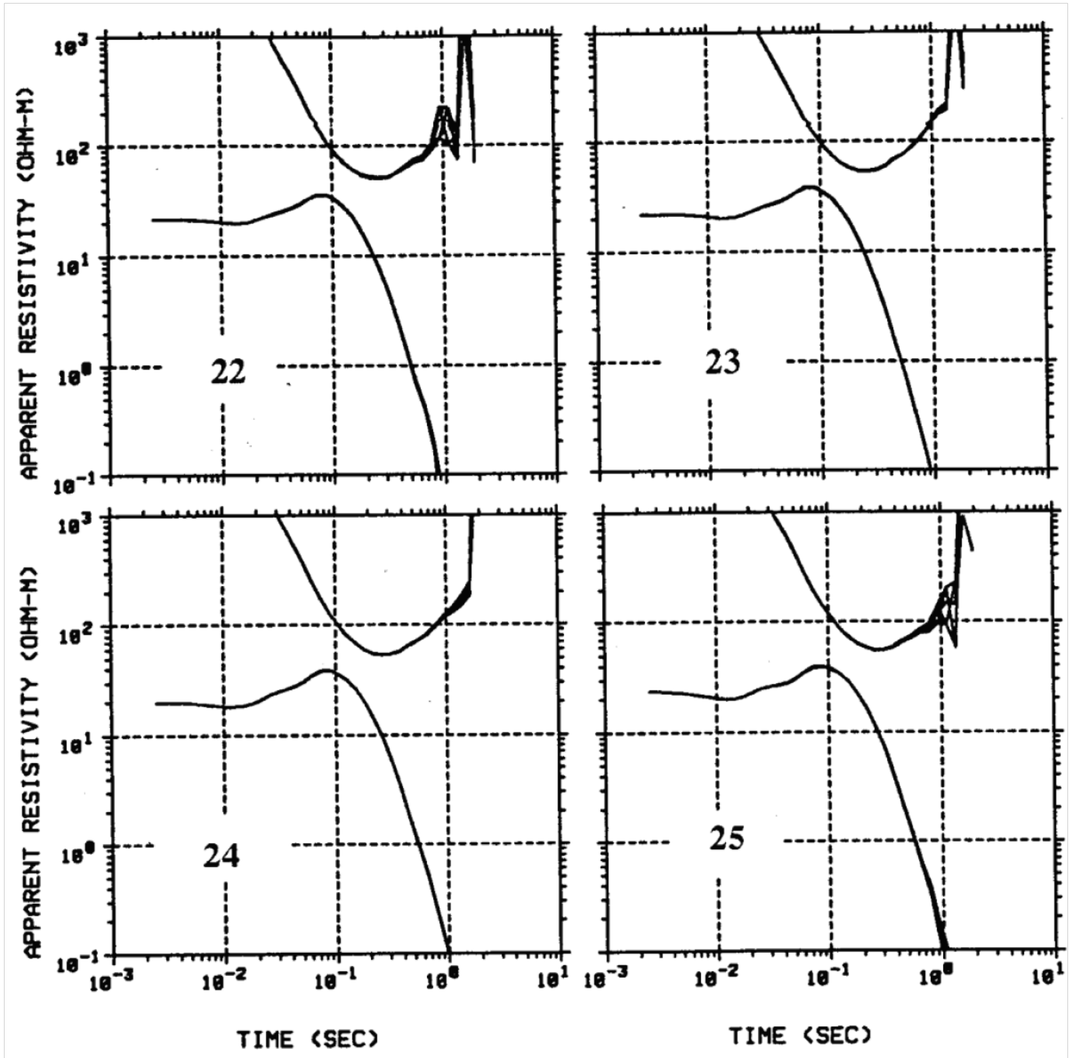




Varied : 4 th layer resistivity
Offset : 9 km

- Apparent resistivity changes with varying resistivity of Silurian Sediments

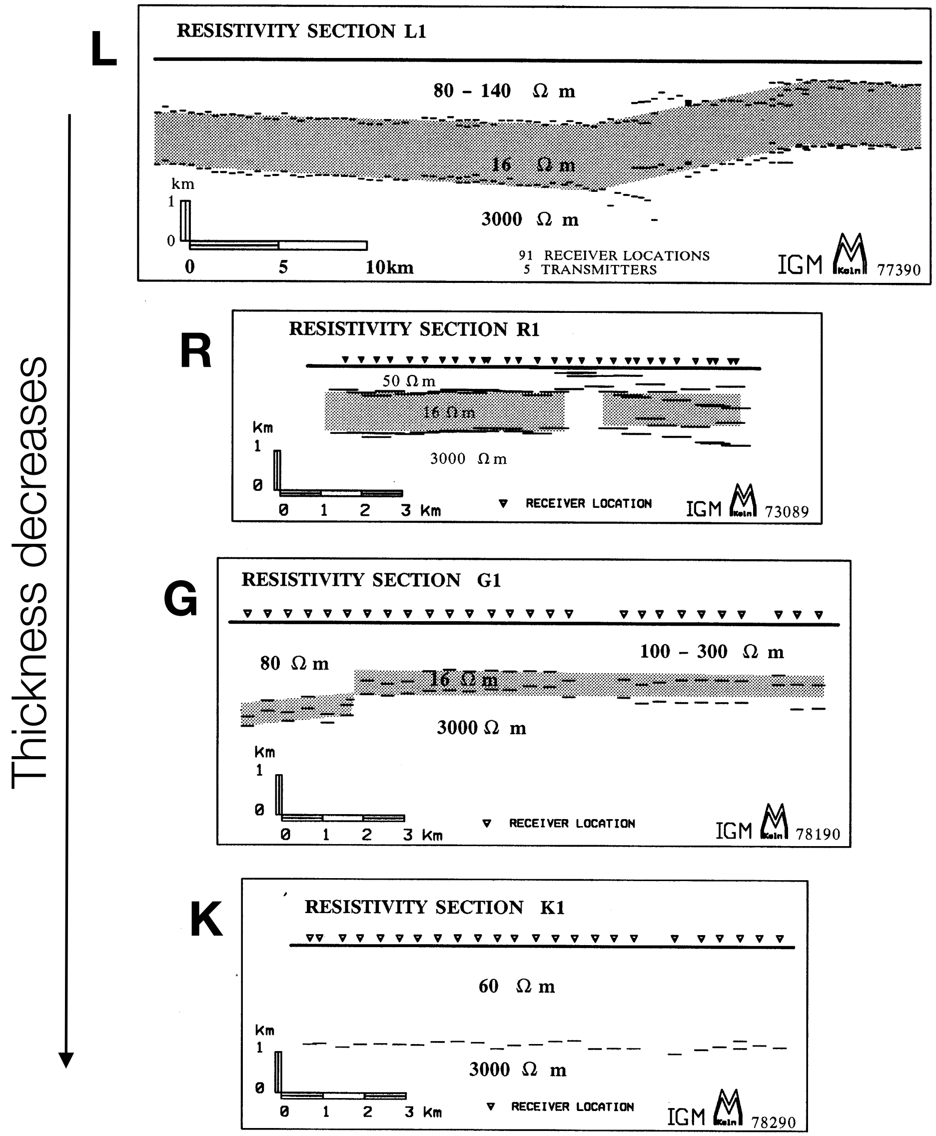
Data



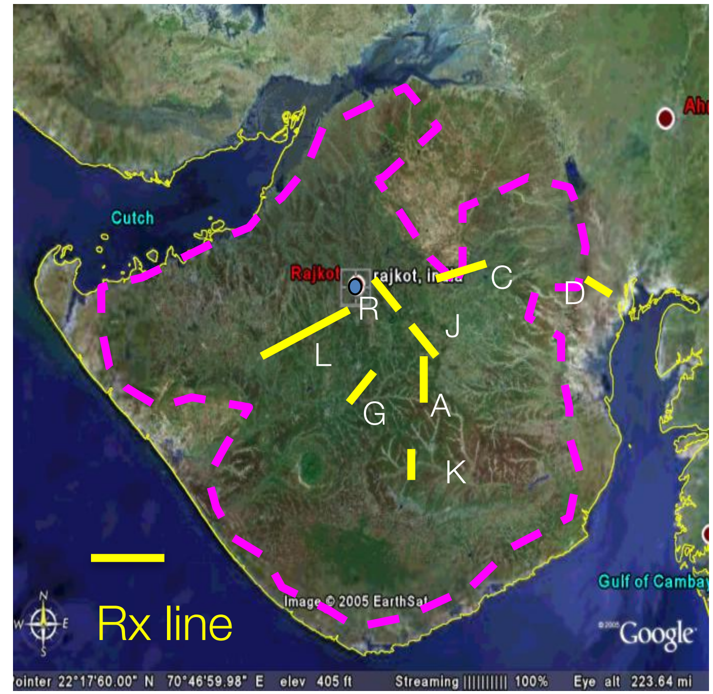
- Stacked data
- Time range: 1ms-10s
- High S/N ratio until 1s
- Similar to synthetic data

Processing

1D inversions (stitched)



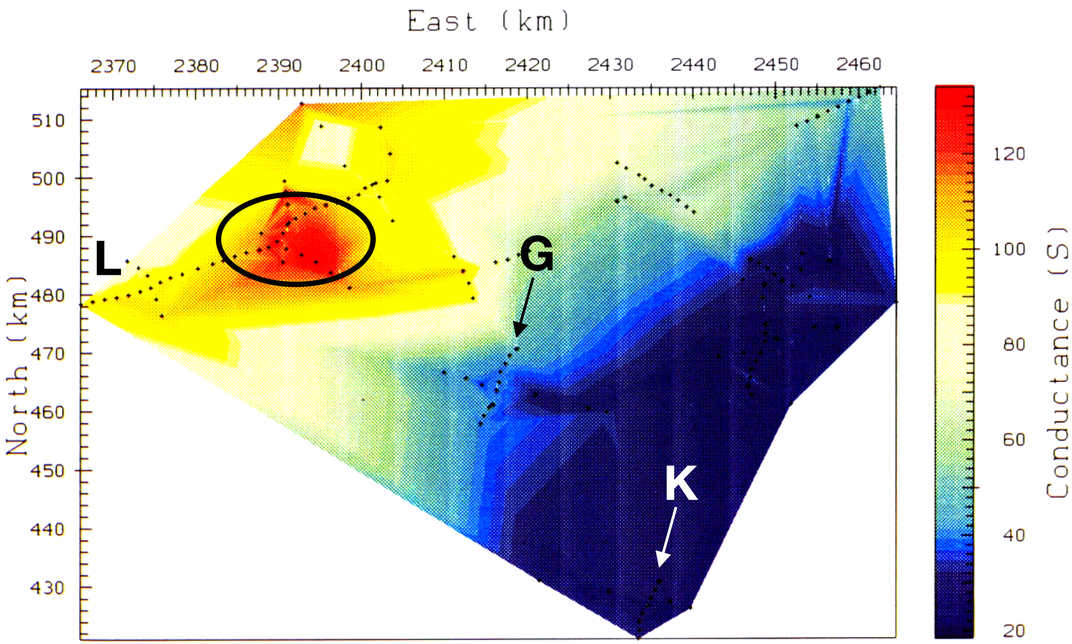
Location map



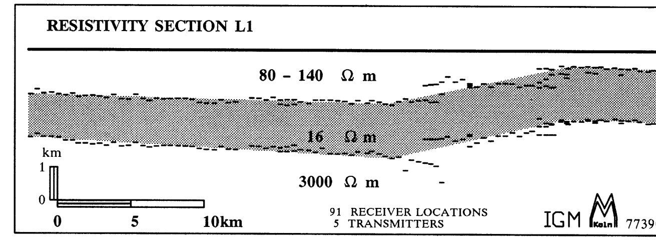
The sediment thickness:

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

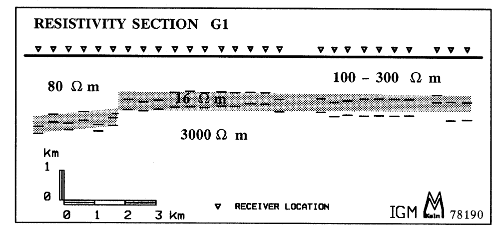
Interpretation:
sediment conductance and drill target



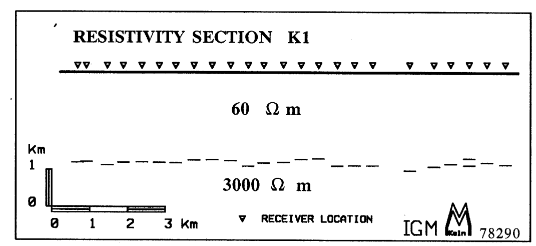
L



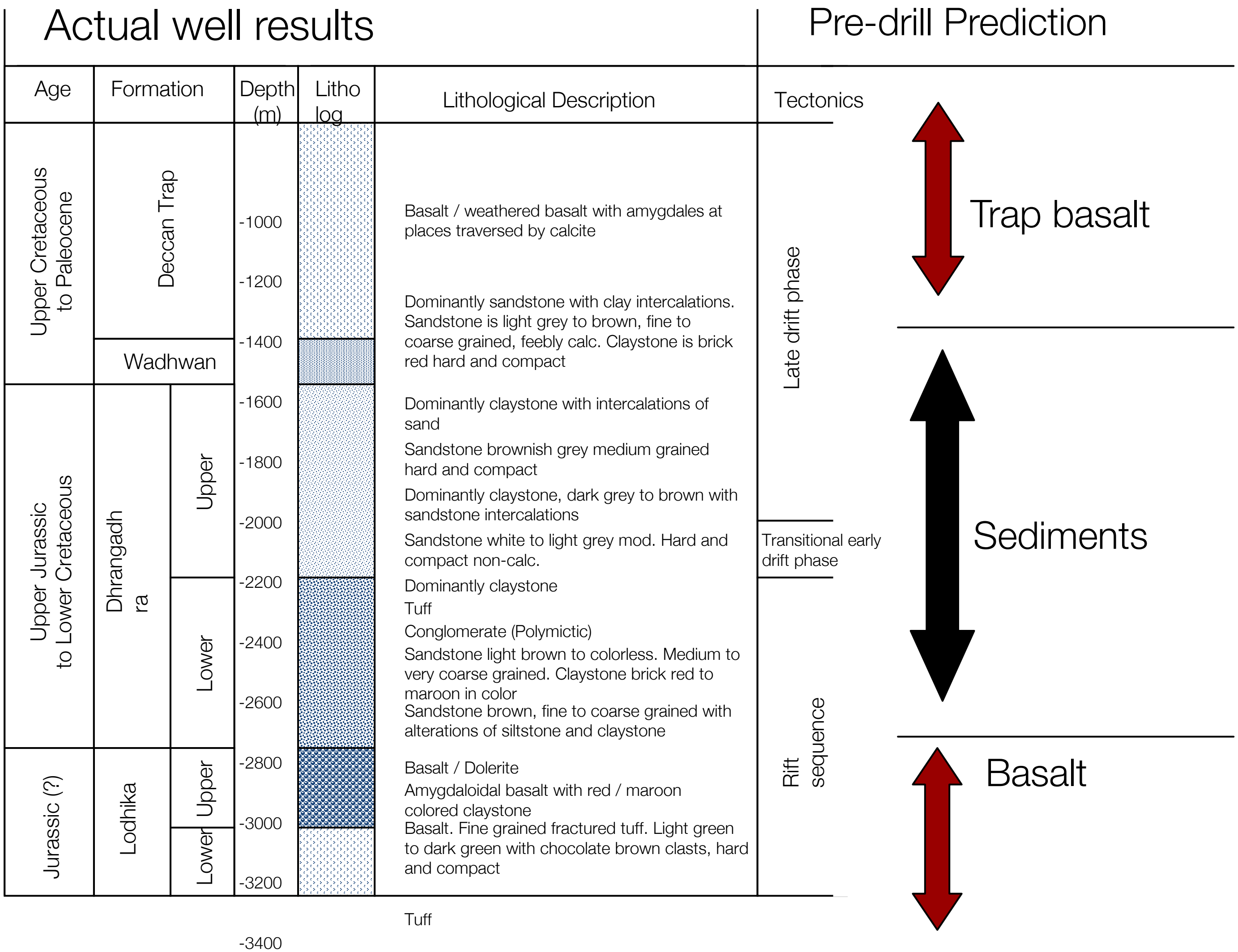
G



K



Synthesis



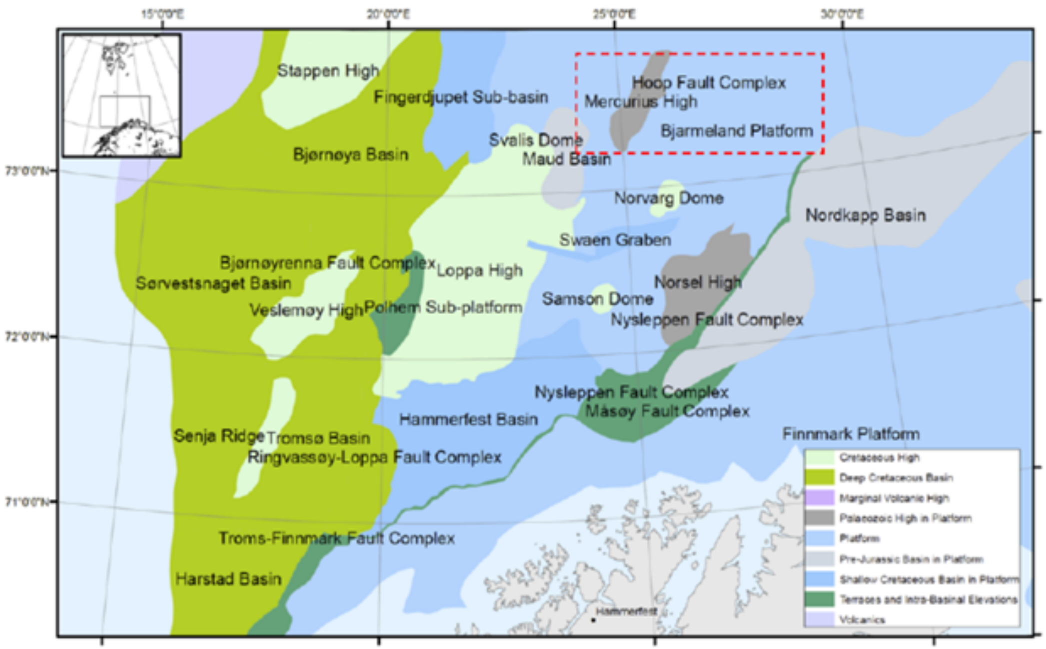
Actual well results
Pre-drill Prediction
Age
Formation
Depth (m)
Litho log
Lithological Description
Tectonics
Upper Cretaceous to Paleocene
Deccan Trap
Wadhwan
Upper Jurassic to Lower Cretaceous
Dhrangadhra
Upper
Lower
Jurassic (?)
Lodhika
Upper
Lower
-1000
-1200
-1400
-1600
-1800
-2000
-2200
-2400
-2600
-2800
-3000
-3200
-3400
Basalt / weathered basalt with amygdales at places traversed by calcite
Dominantly sandstone with clay intercalations. Sandstone is light grey to brown, fine to coarse grained, feebly calc. Claystone is brick red hard and compact
Dominantly claystone with intercalations of sand
Sandstone brownish grey medium grained hard and compact
Dominantly claystone, dark grey to brown with sandstone intercalations
Sandstone white to light grey mod. Hard and compact non-calc.
Dominantly claystone
Tuff
Conglomerate (Polymictic)
Sandstone light brown to colorless. Medium to very coarse grained. Claystone brick red to maroon in color
Sandstone brown, fine to coarse grained with alterations of siltstone and claystone
Basalt / Dolerite
Amygdaloidal basalt with red / maroon colored claystone
Basalt. Fine grained fractured tuff. Light green to dark green with chocolate brown clasts, hard and compact
Tuff
Late drift phase
Transitional early drift phase
Rift sequence
Trap basalt
Sediments
Basalt

Case History: Barents Sea

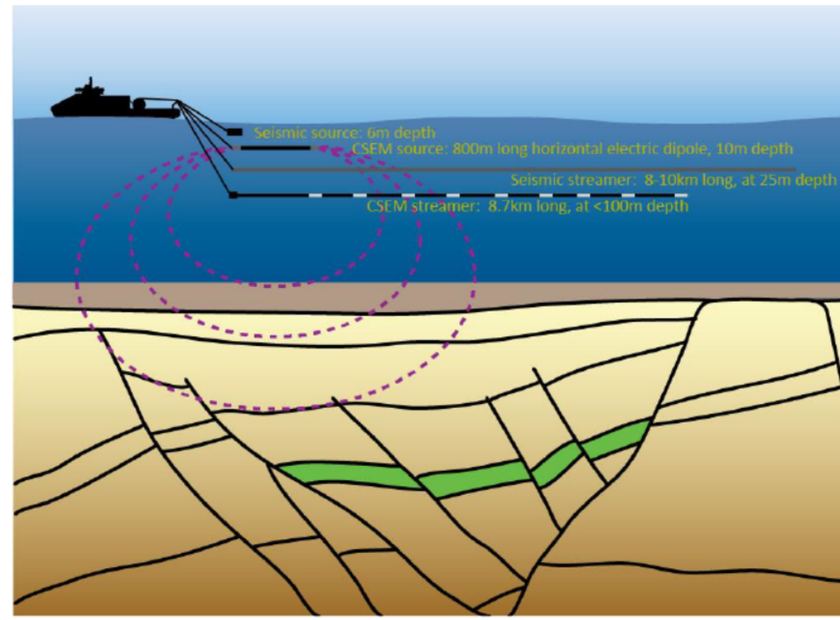
Alvarez et al., 2016. Rock Solid Images

Setup

Hoop Fault Complex, Barents Sea

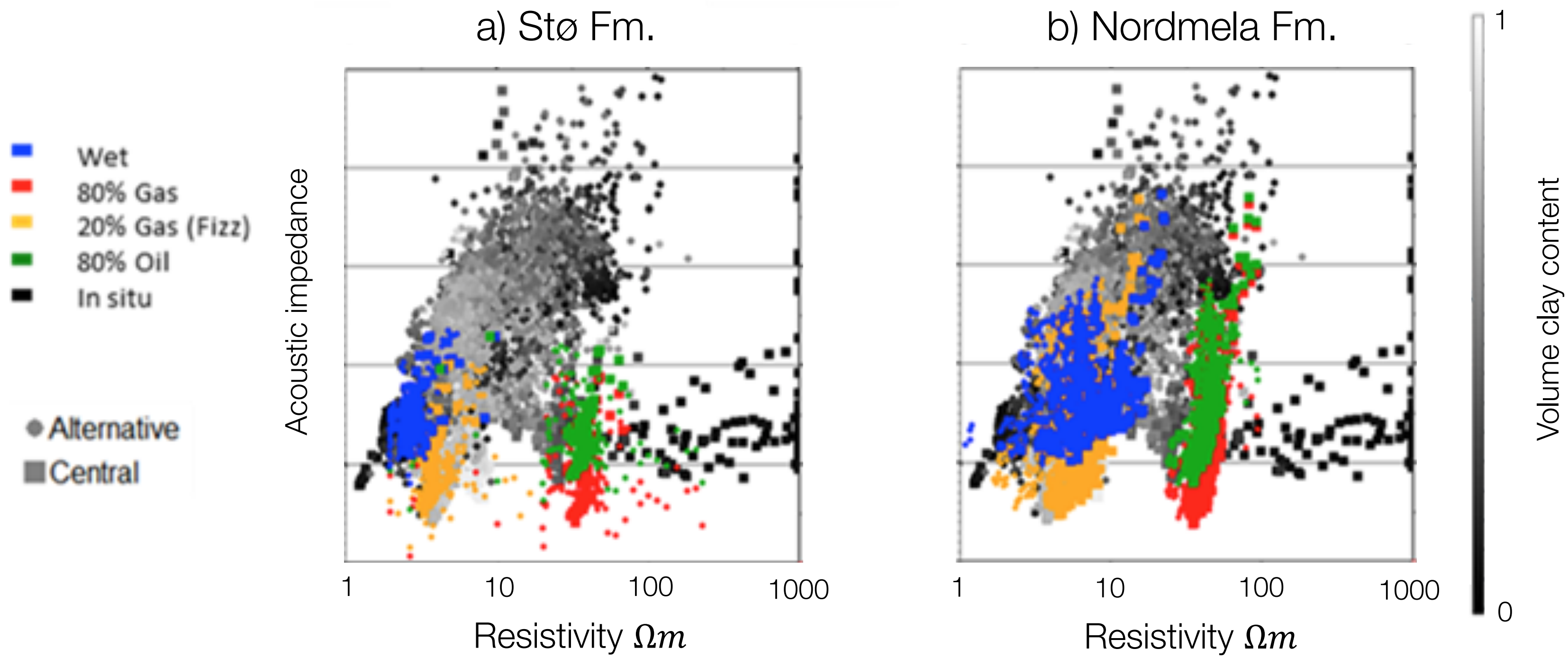


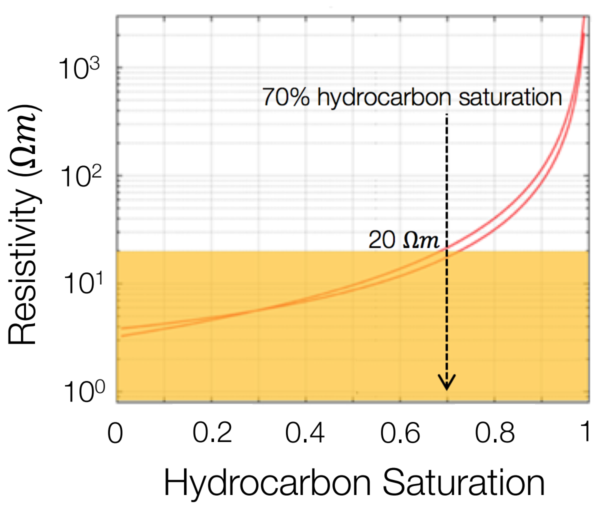
Marine CSEM



- 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

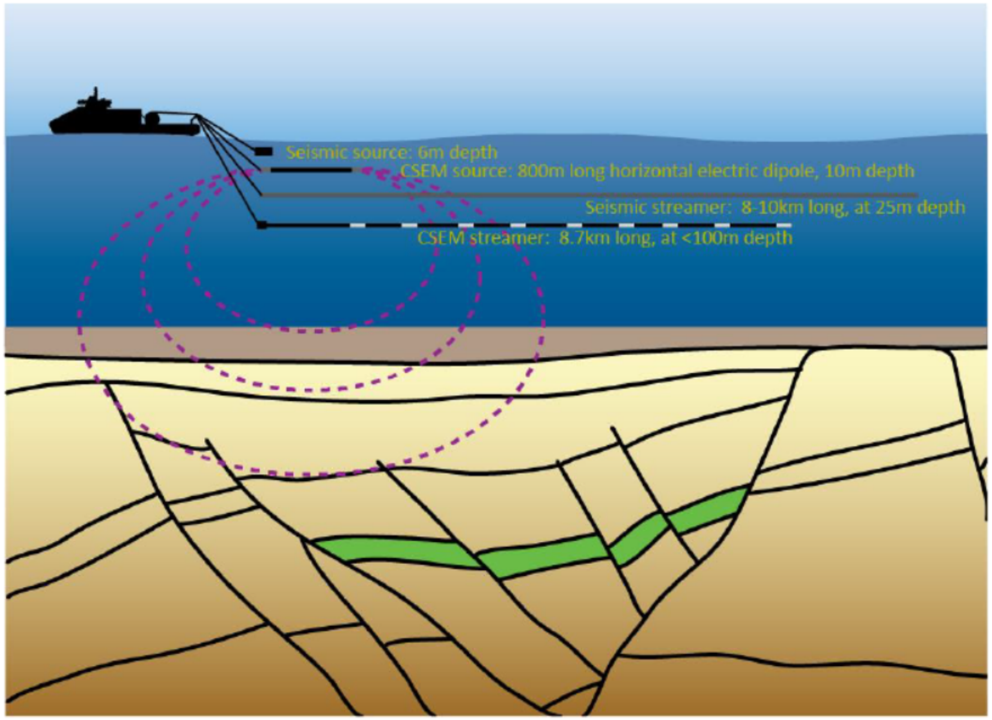




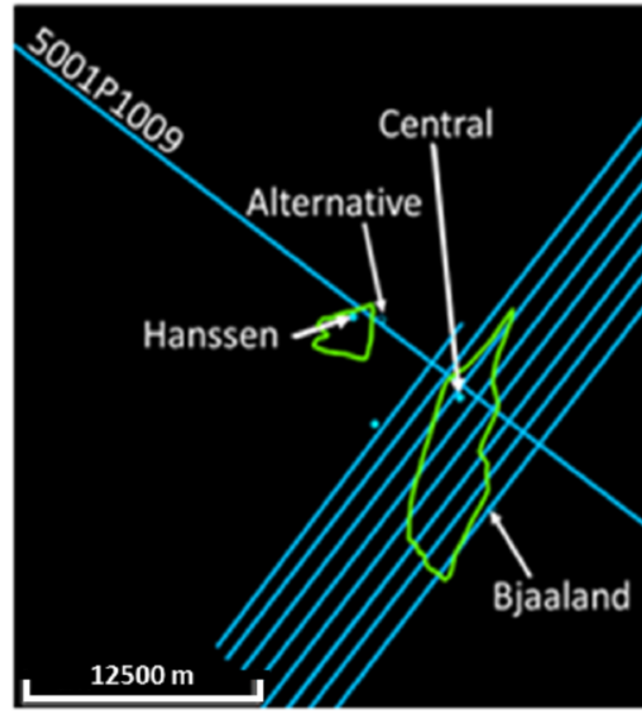
- Highly hydrocarbon-saturated reservoir (< 30% water-wet) significant resistivity
- CSEM can differentiate high from low quality reservoirs

Survey

Towed CSEM and 2D seismic



Survey lines

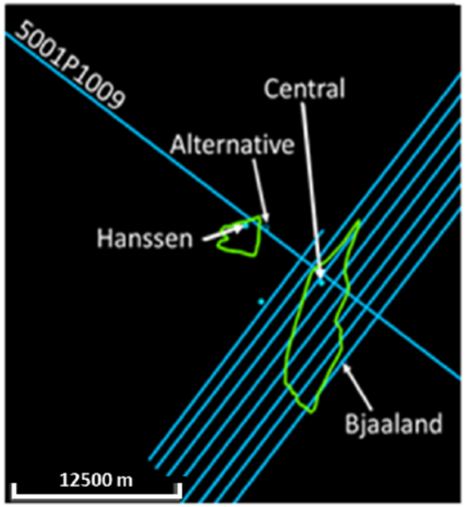


- 6 lines of 2D seismic and towed streamer CSEM data.
- 72 receivers collected CSEM data
  - offsets from 31m to 7.8 km
- CSEM frequencies: 0.2 Hz to 3 Hz.

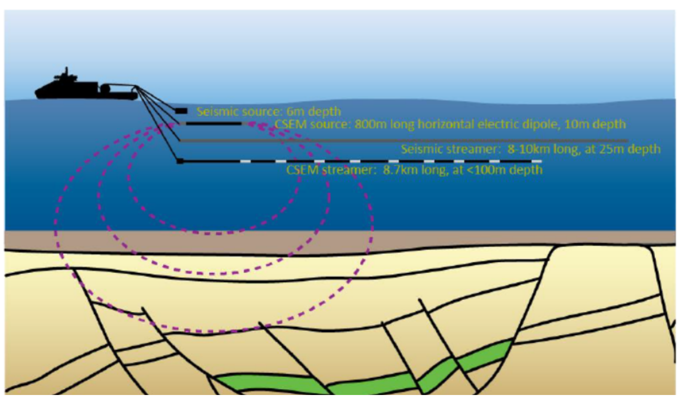
Alternative	Control well, dry
Central	Control well, productive
Hanssen	Validation well
Bjaaland	Validation well

CSEM Data

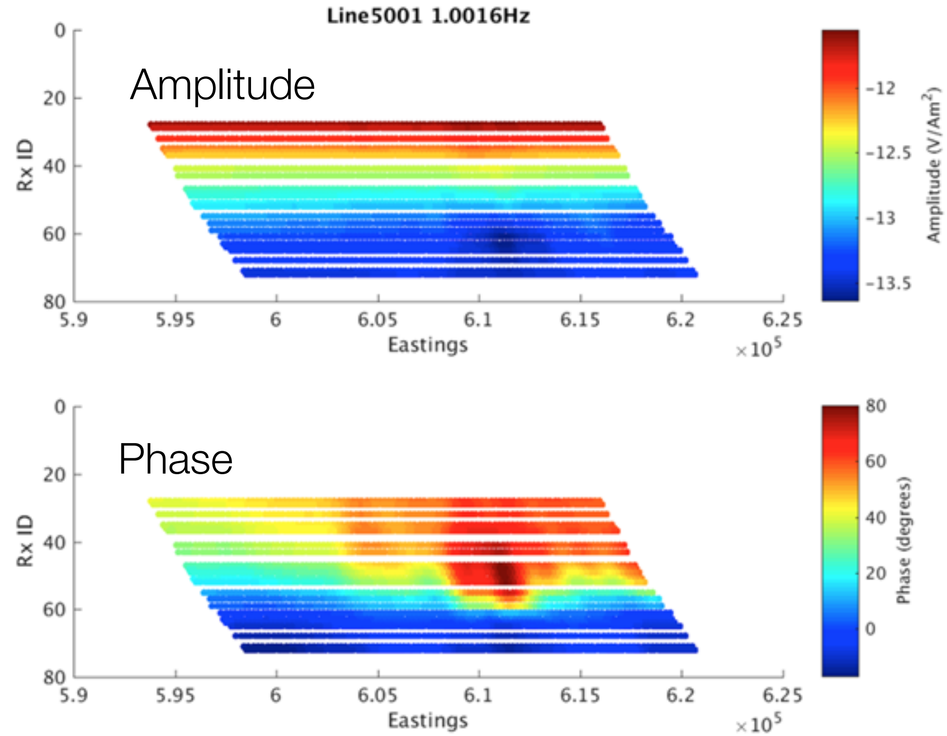
Survey lines



Towed-streamer EM



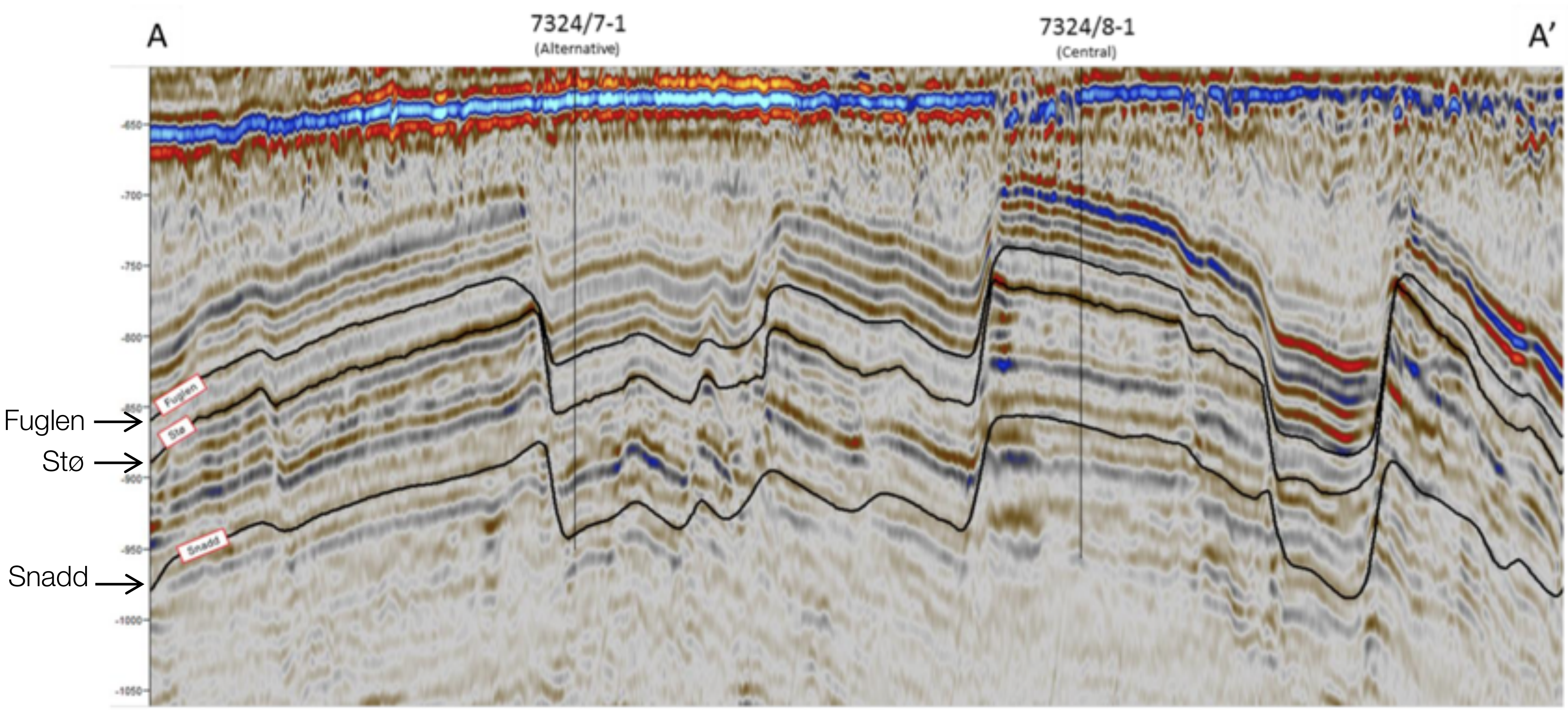
CSEM data over central reservoir (1 Hz)

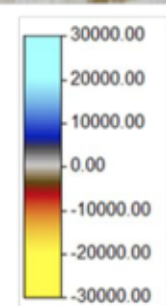


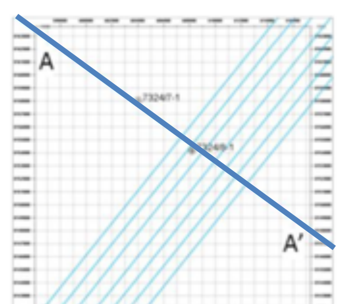
- Significant phase response over Central reservoir

Seismic data

Seismic section: Line 5001





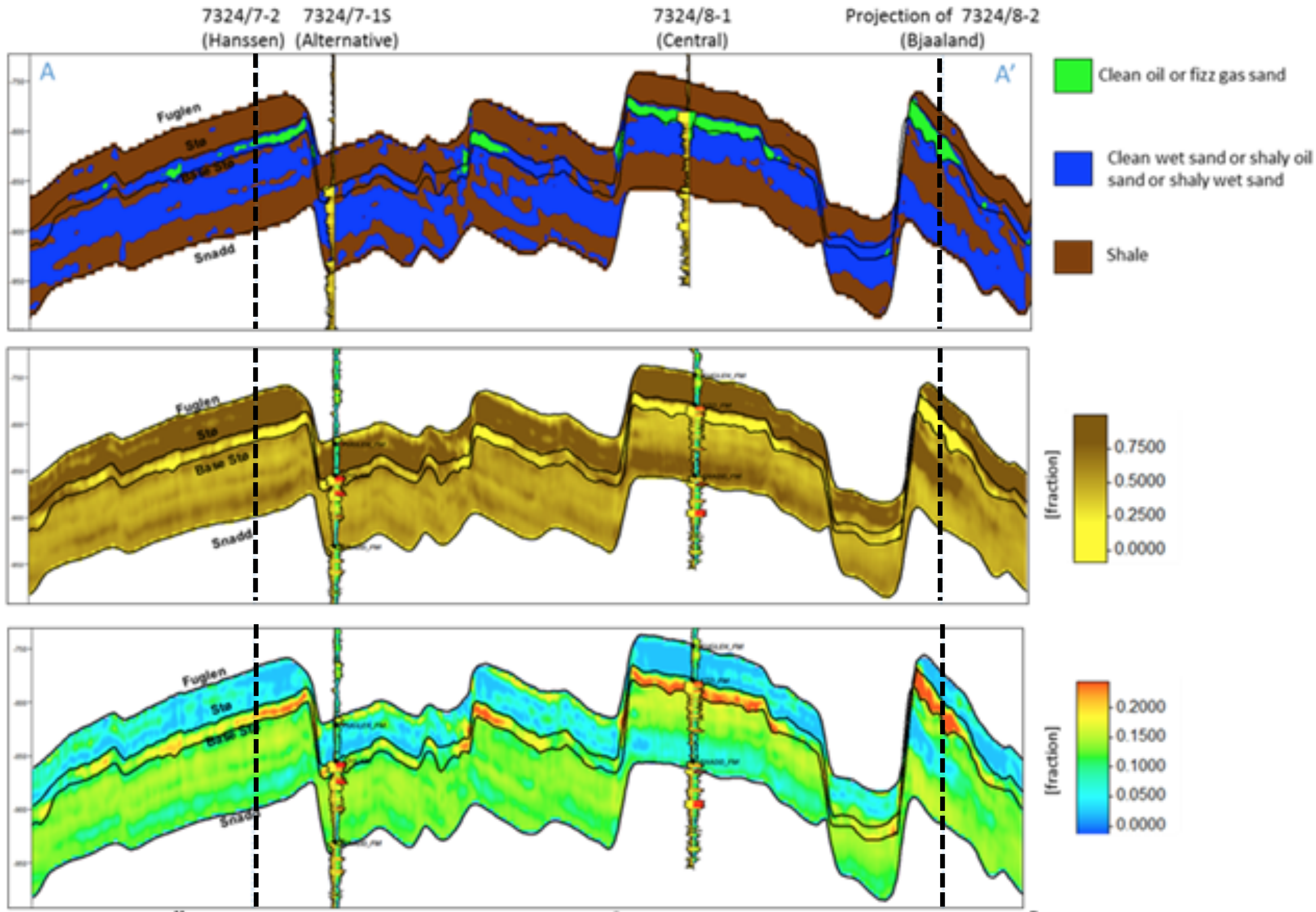


Well-Log and Seismic Inversion

Litho-fluid Facies

Clay Content

Total Porosity



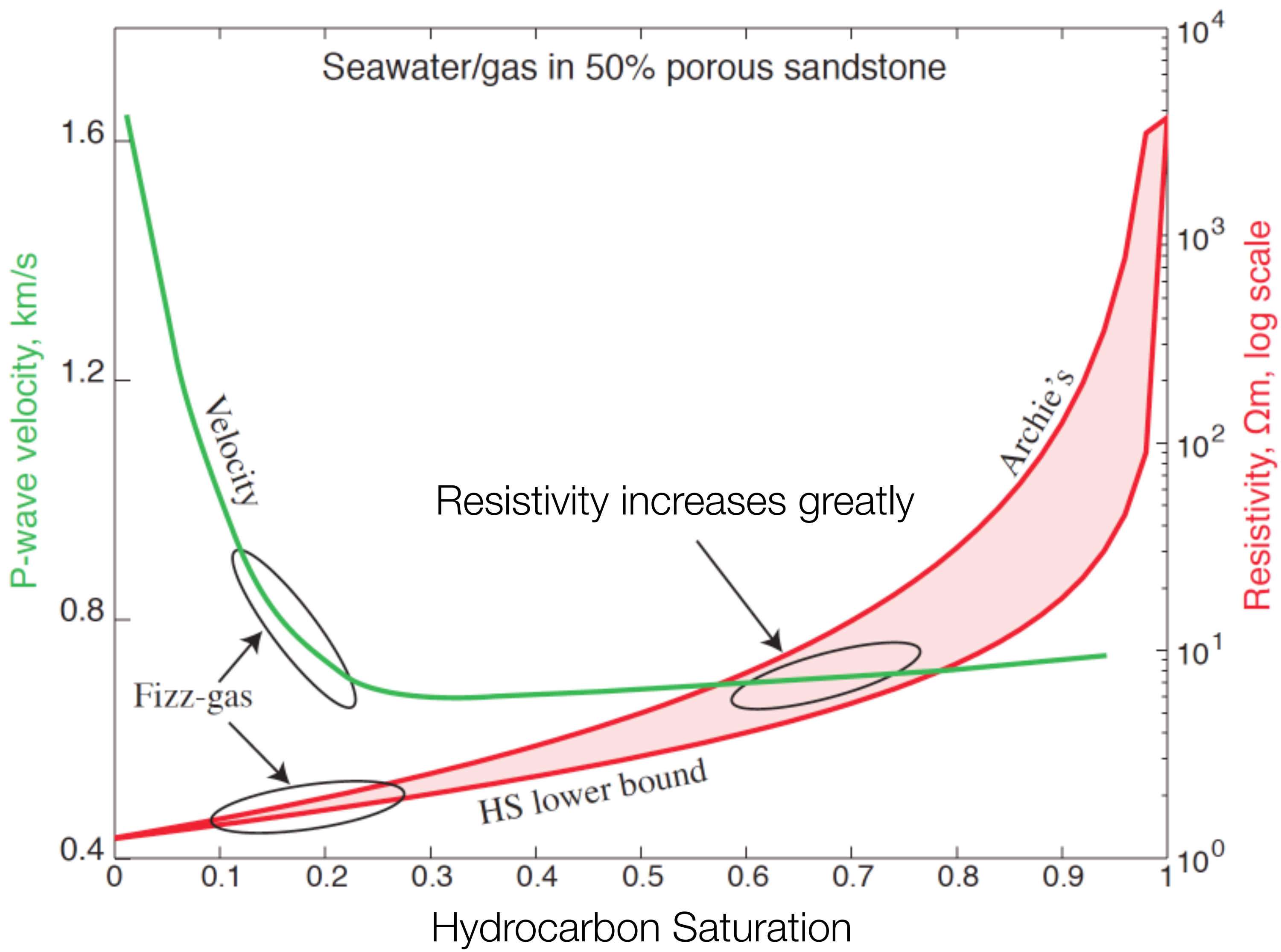
Hanssen
Validation well

Alternative
Control, dry

Central
Control, productive

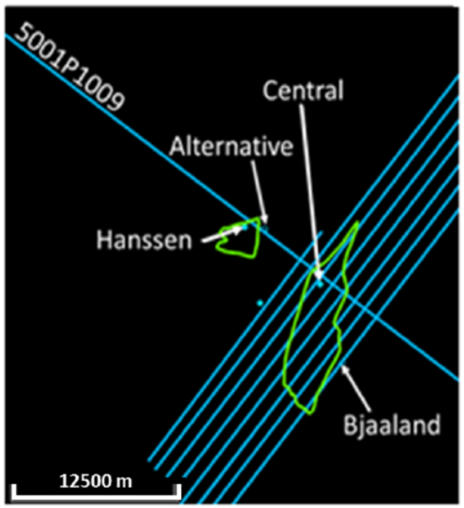
Bjaaland
Validation well

Revisiting physical properties

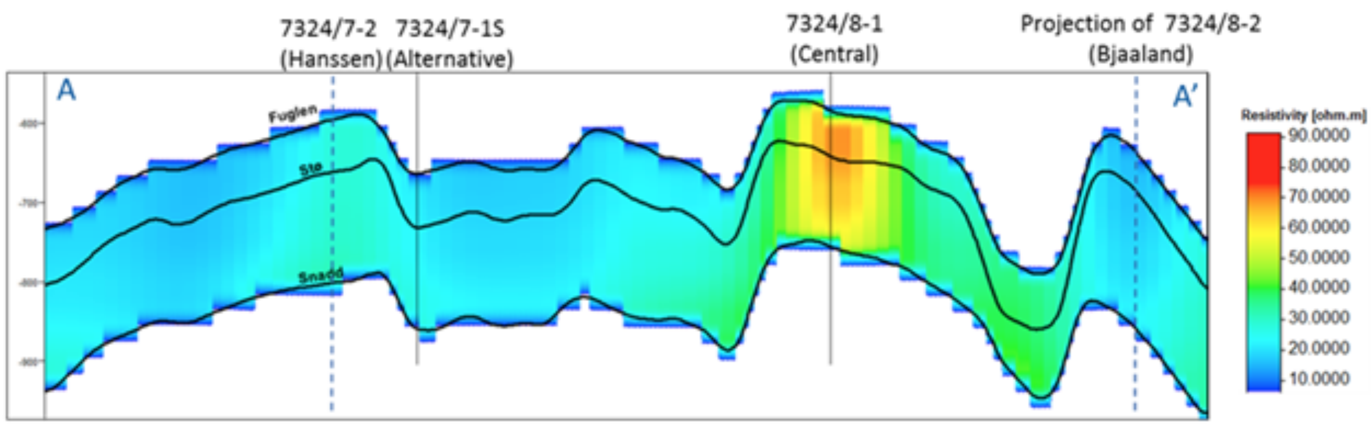


Processing: CSEM Inversion

Survey lines



Vertical resistivity section along profile line 5001



Hanssen
Validation well

Alternative
Control, dry

Central
Control, productive

Bjaaland
Validation well

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

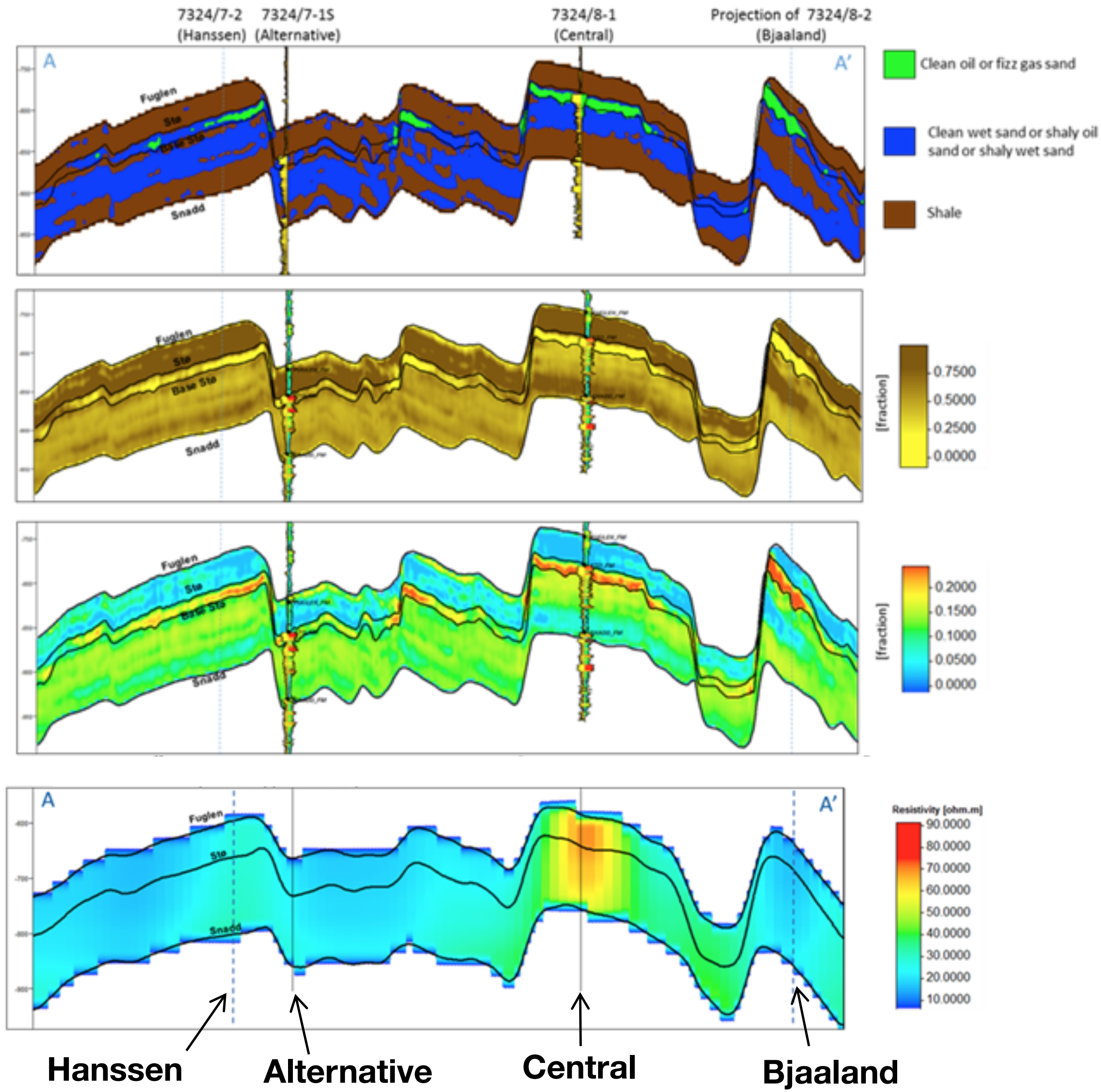
Processing: Multi-physics Approach

Litho-fluid Facies

Clay Content

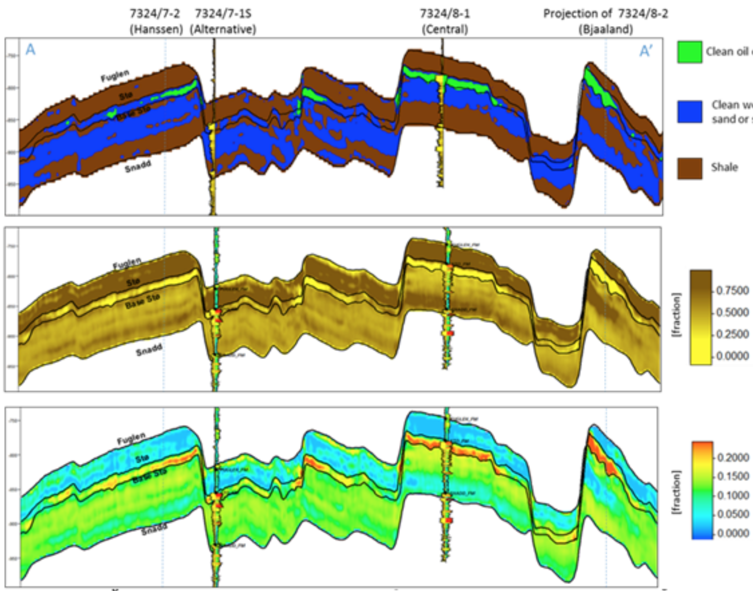
Total Porosity

Resistivity

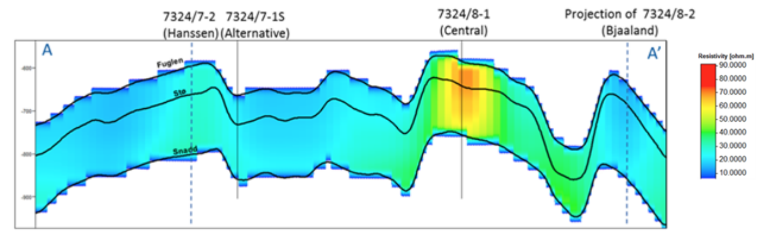


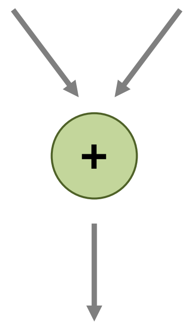
Interpretation & Synthesis

Seismic

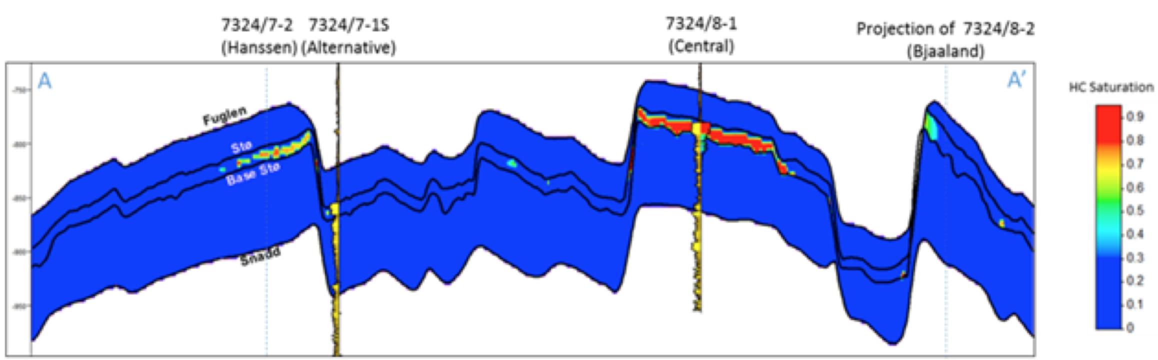


EM





Hydrocarbon saturation



Hanssen
Validation well productive

Alternative
Control, dry

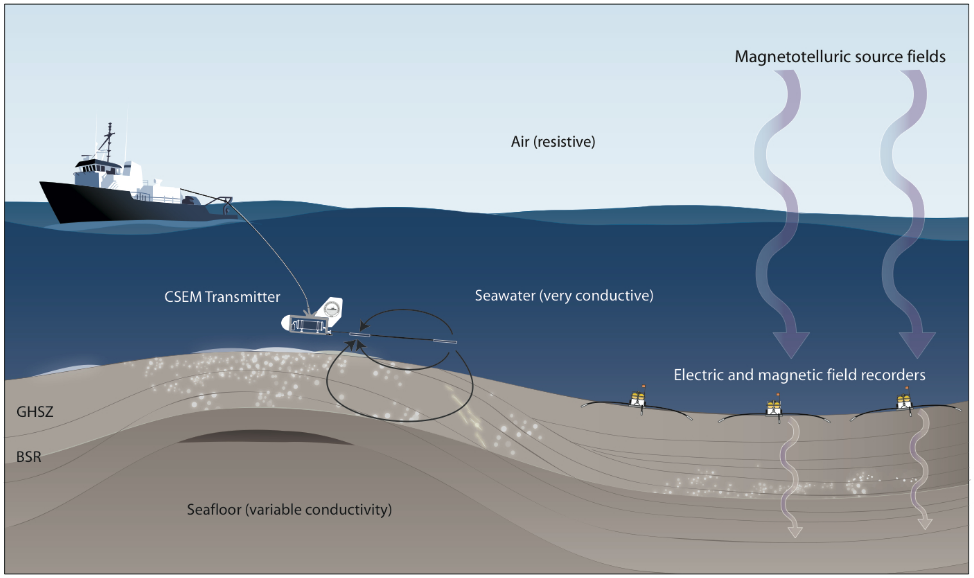
Central
Control, productive

Bjaaland
Validation well dry

Controlled-Source Marine EM (CSEM)

Application areas

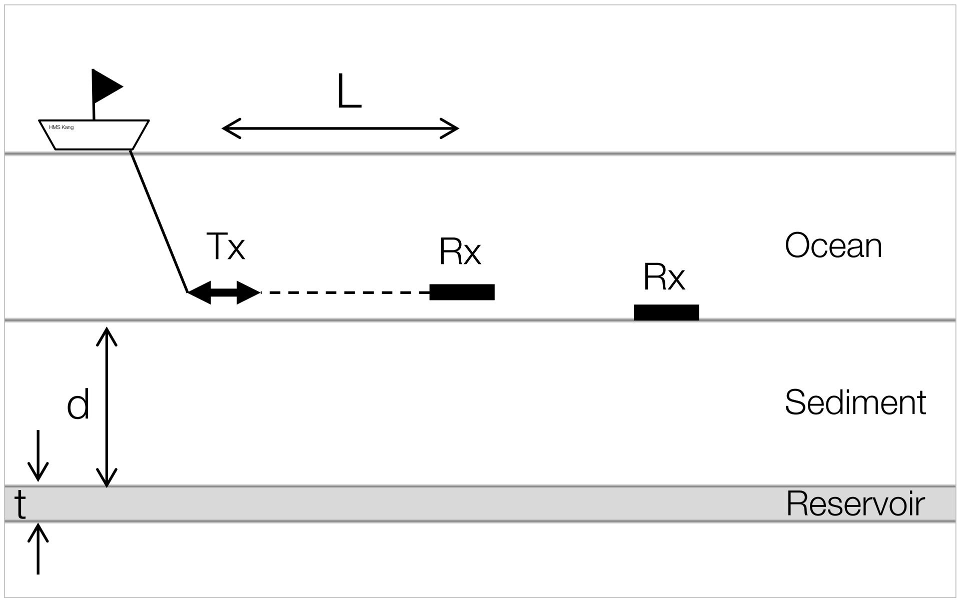
- Oil and gas
- Submarine massive sulfide (SMS)
- Methane hydrates
- Tectonic studies
- Offshore UXO
- Offshore groundwater

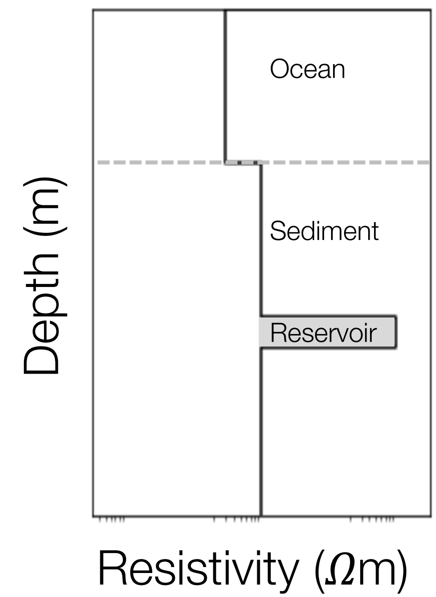


Application with physical properties

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

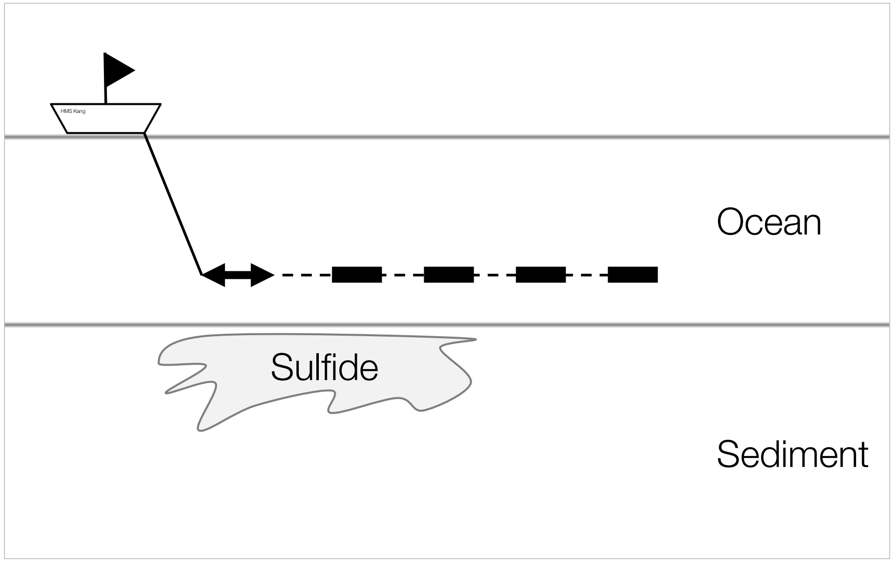
Resistive target: hydrocarbons

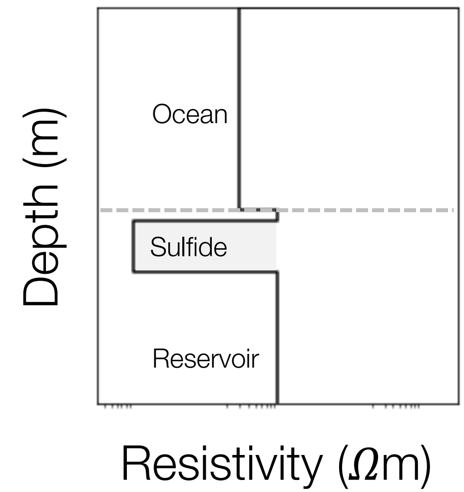


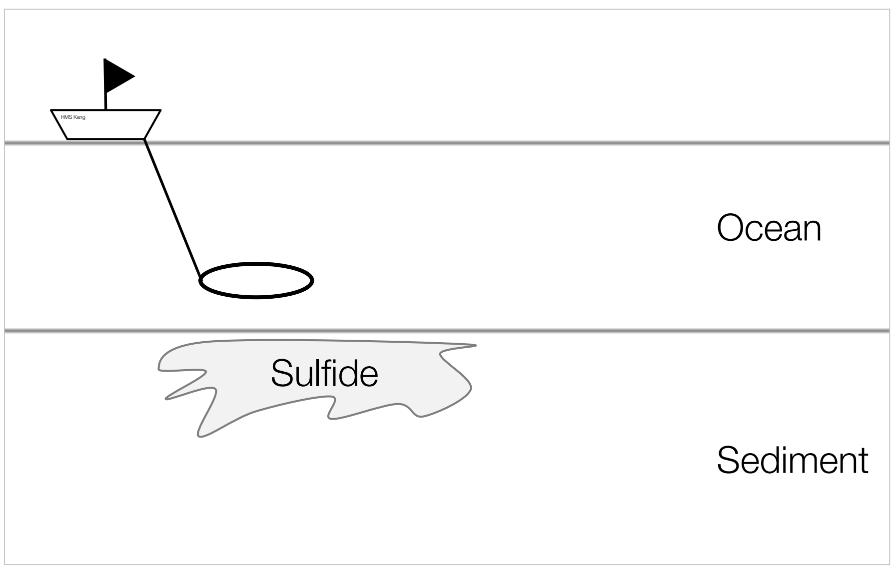


- Finding resistor: grounded source
- Deep target
  - Long offset between Tx and Rx
  - Depth of investigation ~1/3 Tx - Rx offset

Conductive Target: Massive sulfide



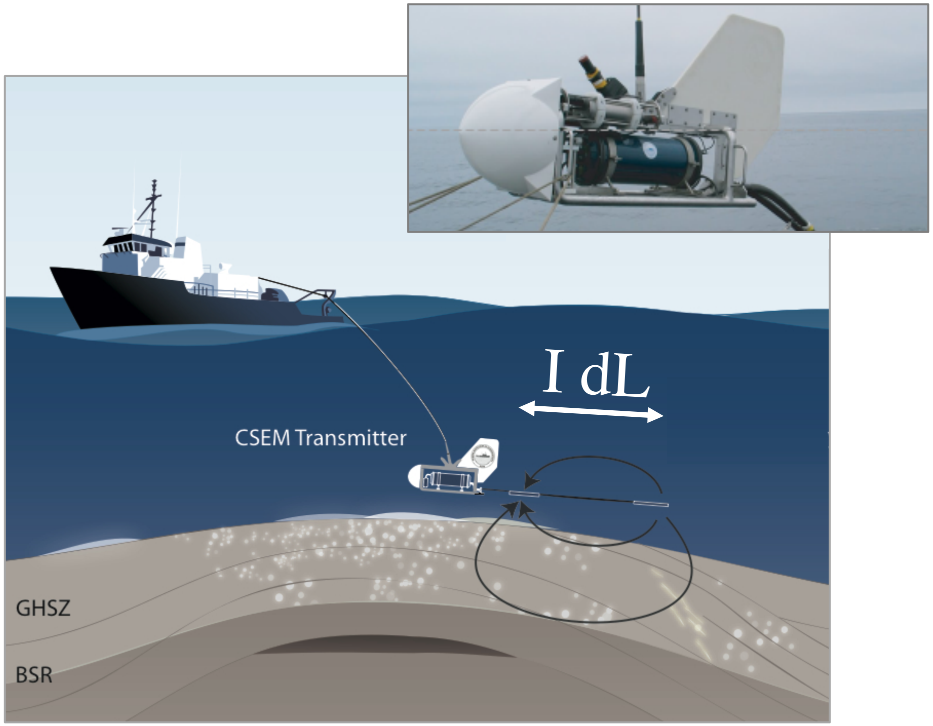




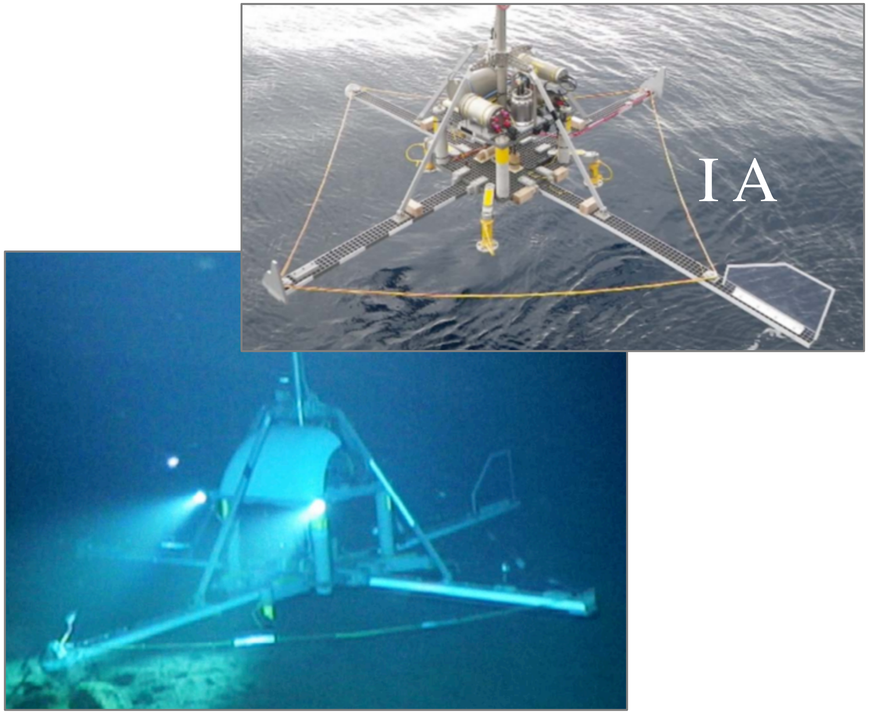
- Galvanic source
  - Towed E-field receivers
- Inductive source
  - Towed on ROV
  - db/dt sensors (coil)

Transmitters

Galvanic (Scripps: SUESI)



Inductive (Waseda Univ., GEOMAR)



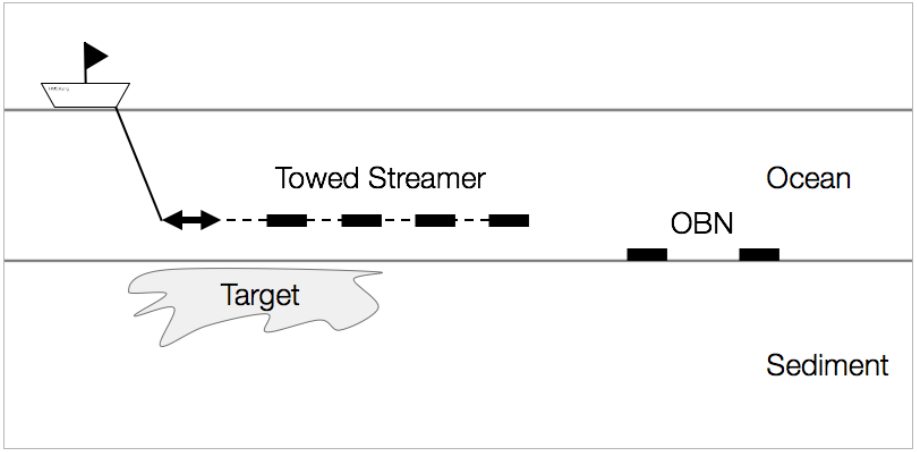
Geometric Decay $\frac{1}{r^3}$

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

Receivers

Data

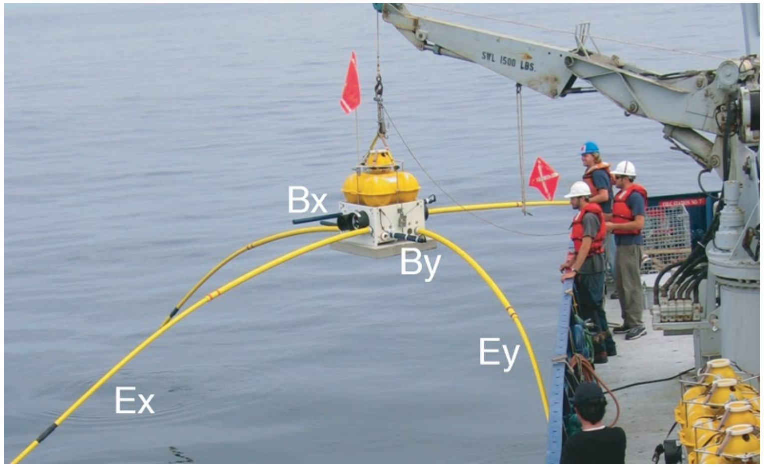
- Ex, Ey, (Recently: Ez)
- Bx, By, Bz



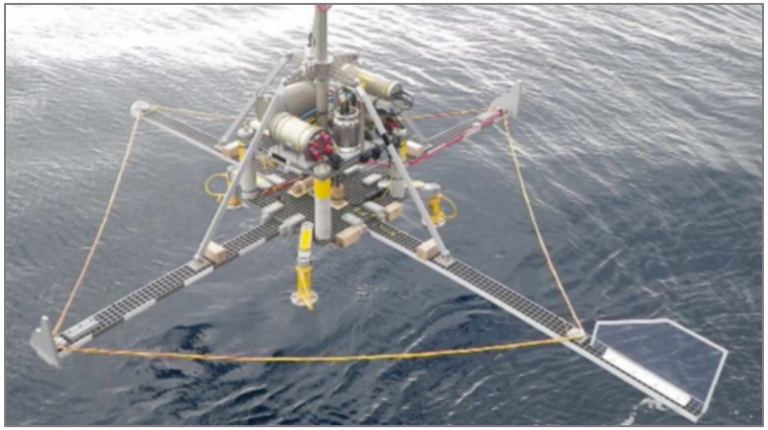
Common Systems

- Scripps: Vulcan and Porpoise
- PGS
- EMGS

Ocean Bottom Nodes (Scripps, EMGS)

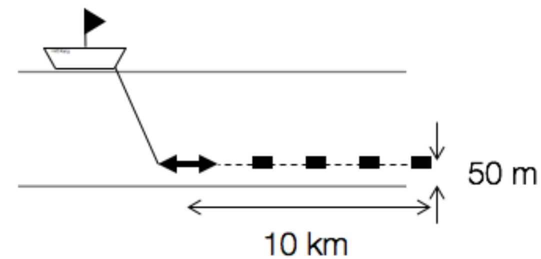


Inductive Loop (Waseda Univ)

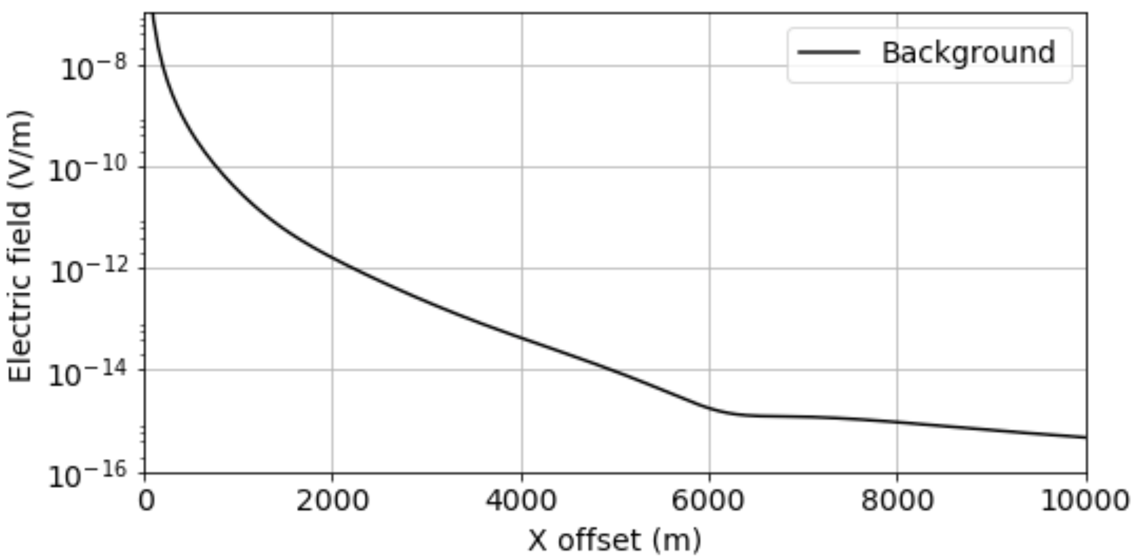


Marine CSEM: Hydrocarbons

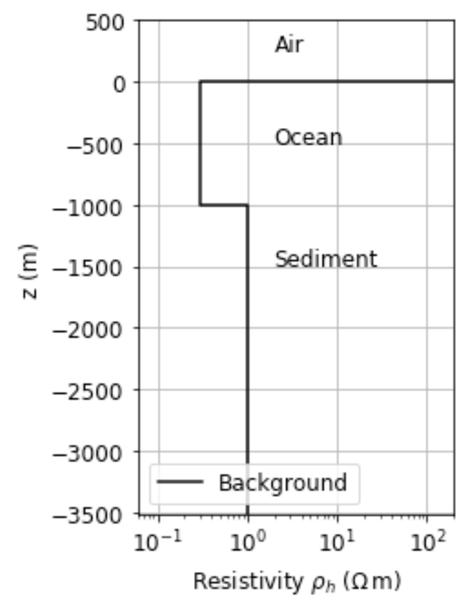
- Towed electric dipole streamer
  - Long offset range (500m-10 km)
  - Frequency: 0.5 Hz



|Ex|

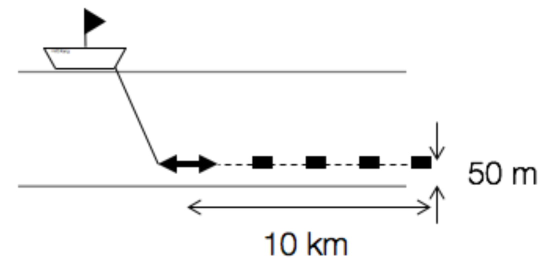


Canonical model

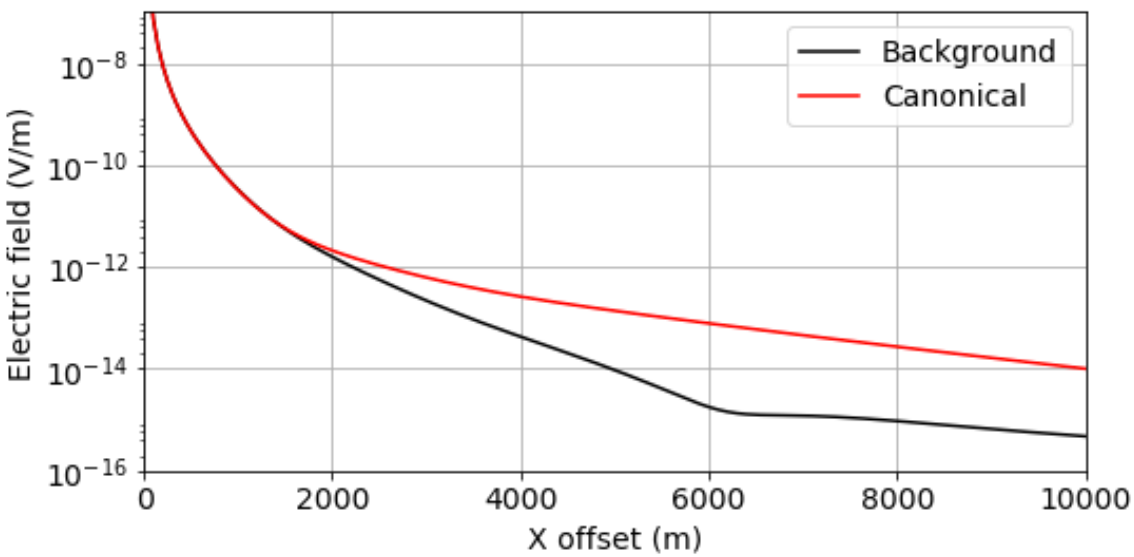


Marine CSEM: Hydrocarbons

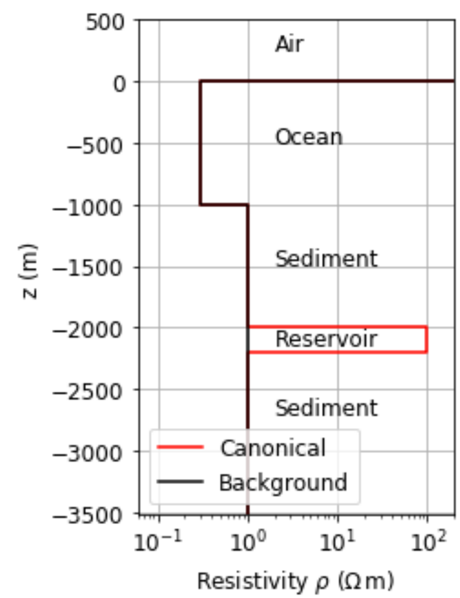
- Towed electric dipole streamer
  - Long offset range (500-10 km)
  - Frequency: 0.5 Hz



|Ex|



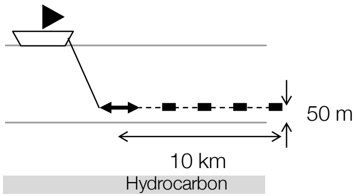
Canonical model



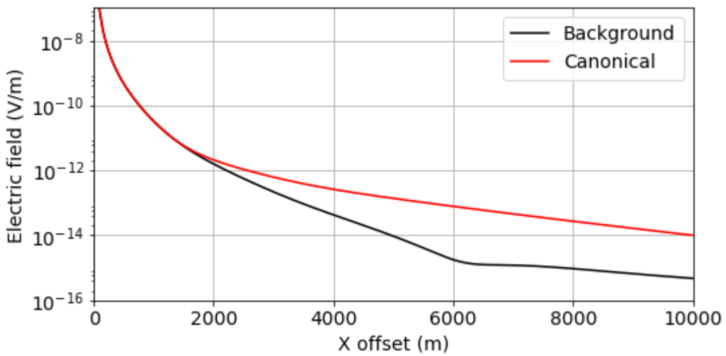
Hydrocarbon reservoir: significant signal

How do we understand the response?

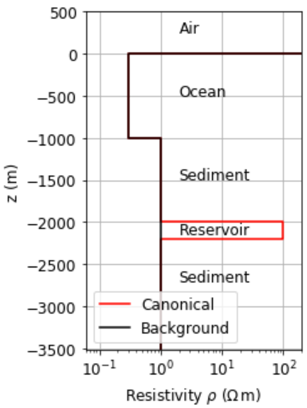
Setup



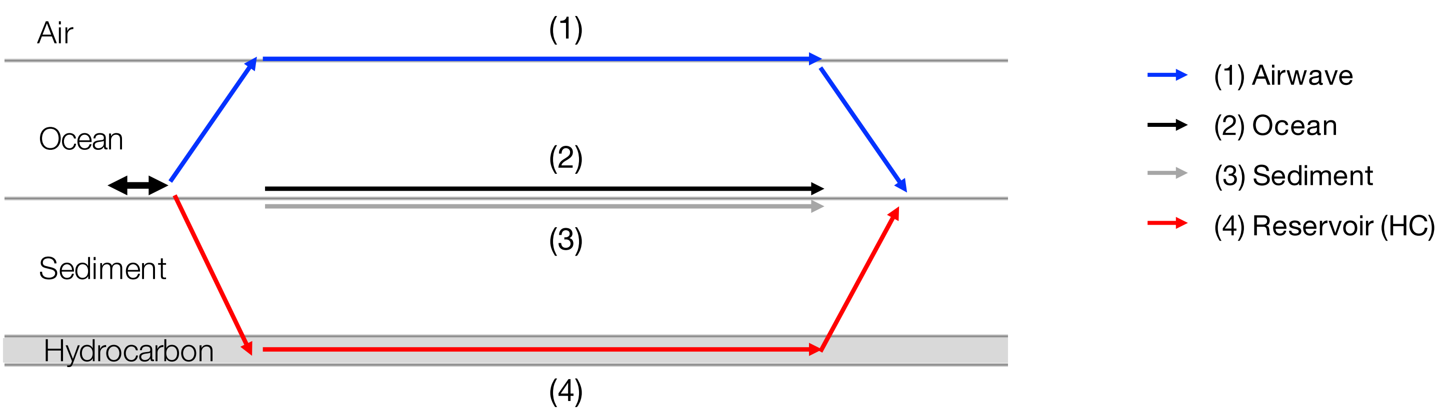
|Ex|



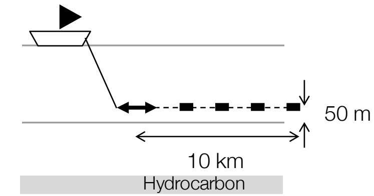
Resistivity



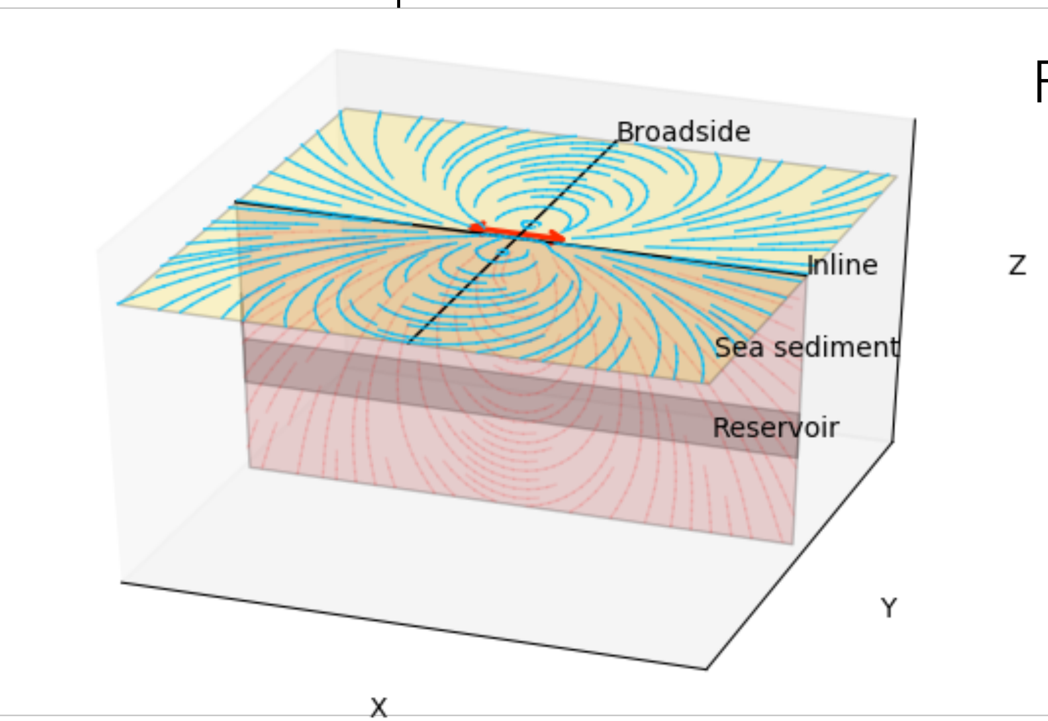
Ray paths



Which fields to examine?



Fields from a dipole

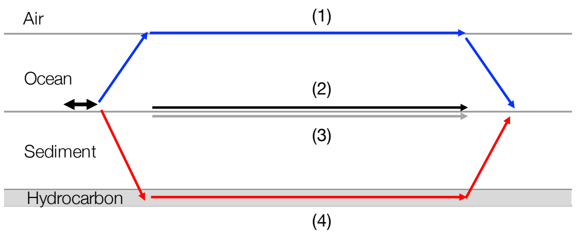


Focus on:

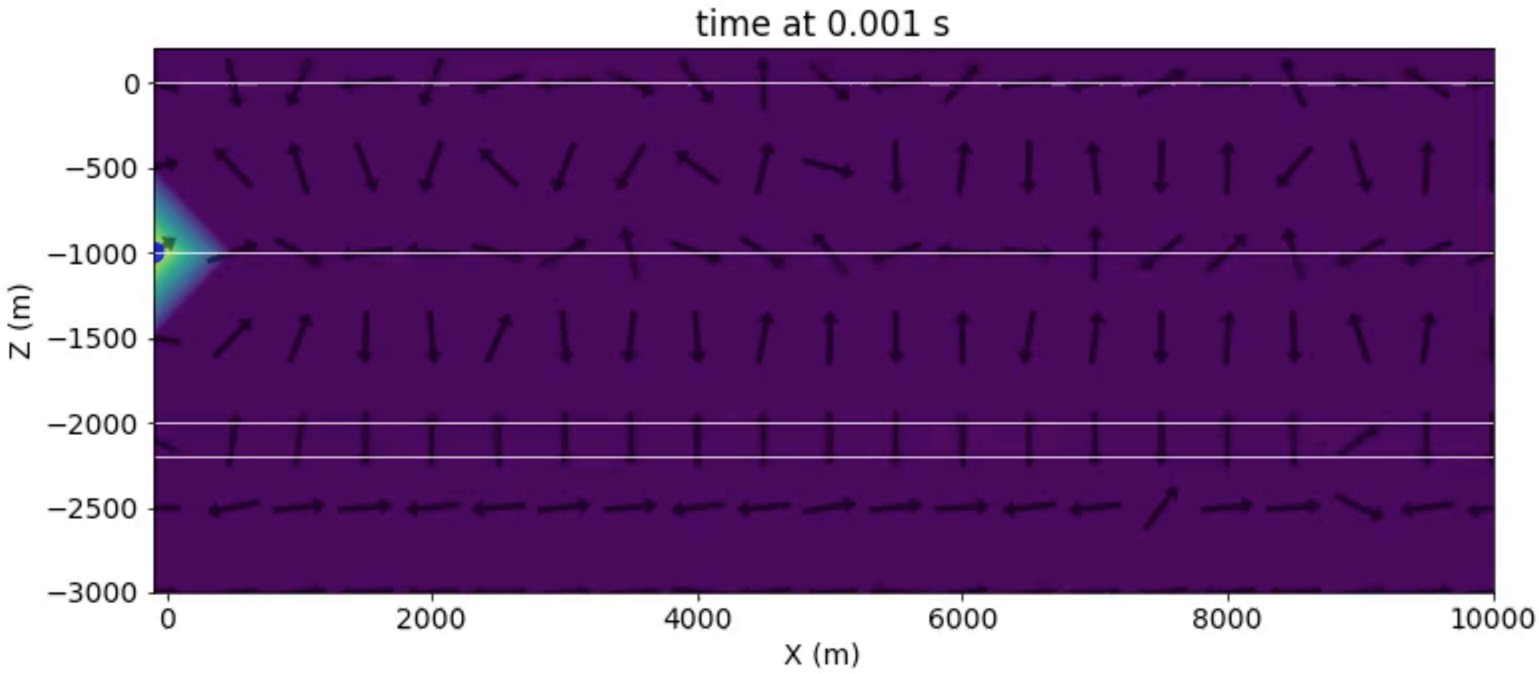
- Inline electric field
- Inline poynting vector (energy propagation)

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

Electric field

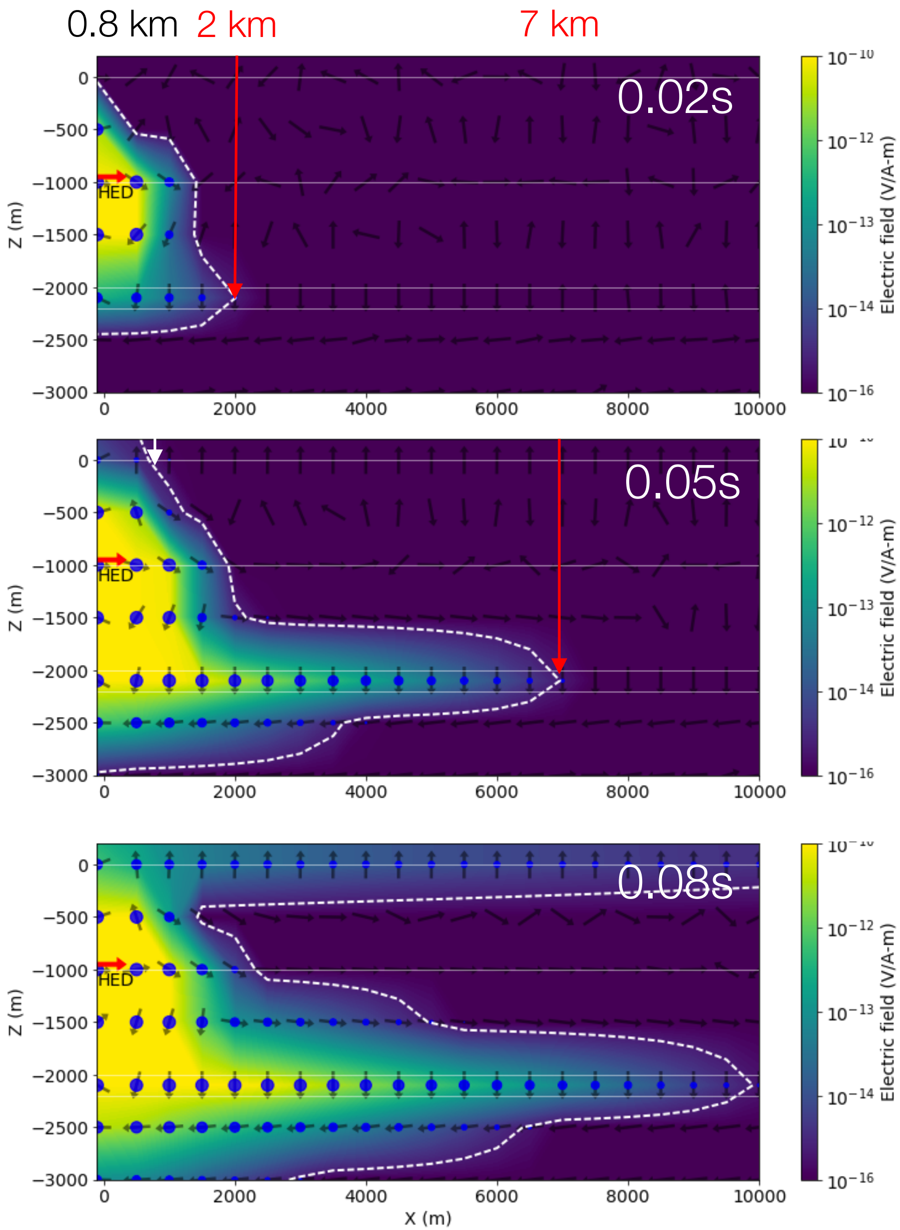


On XZ plane (HED source in x-direction)



Powered by: empymod. Werthmüller, D., 2017

Electric field at multiple times



- In reservoir:

  5 km / 0.03s = 166km/s

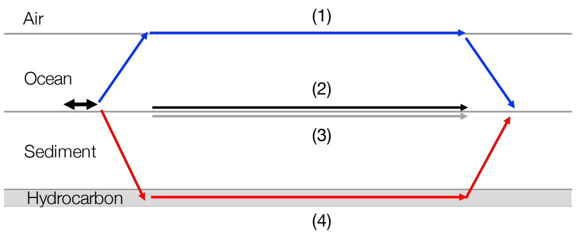
- In air:

  >10km / 0.03 = > 333 km/s

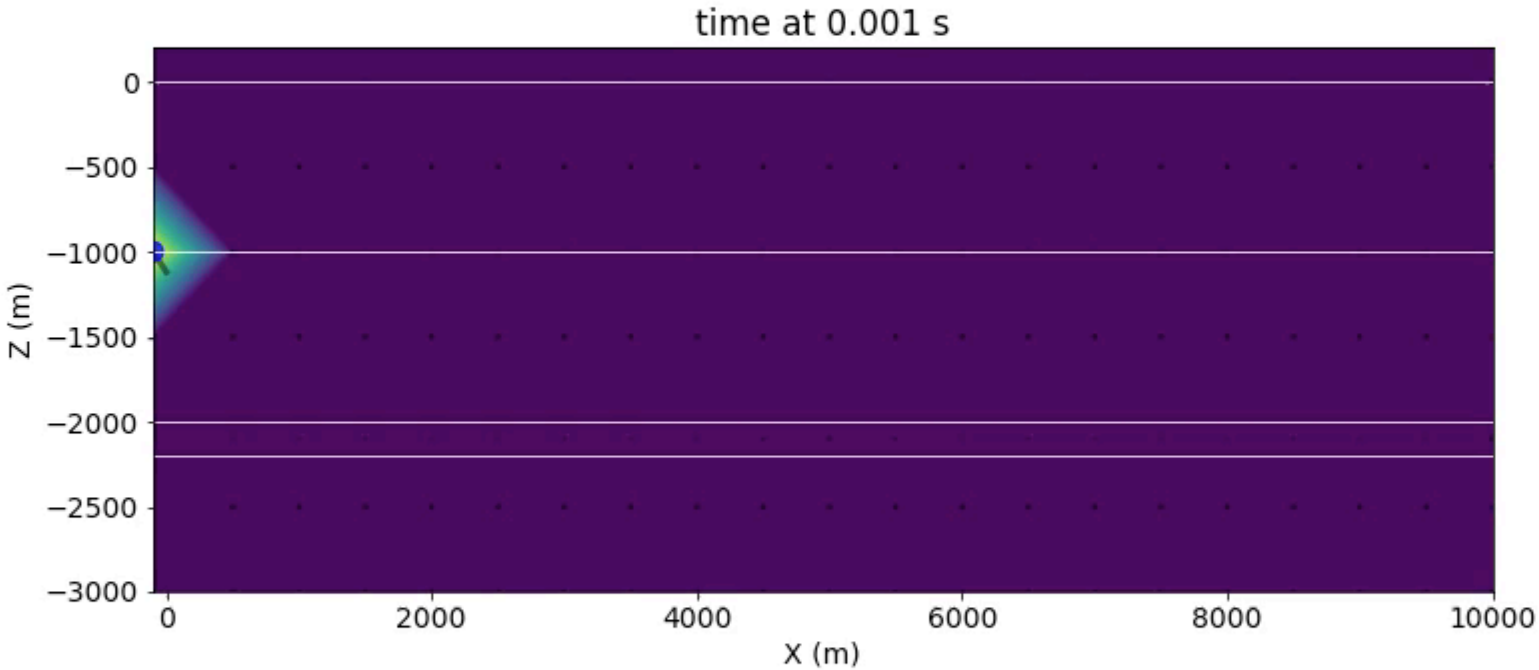
- Propagation much faster in air

- More attenuation in the reservoir

Poynting vector



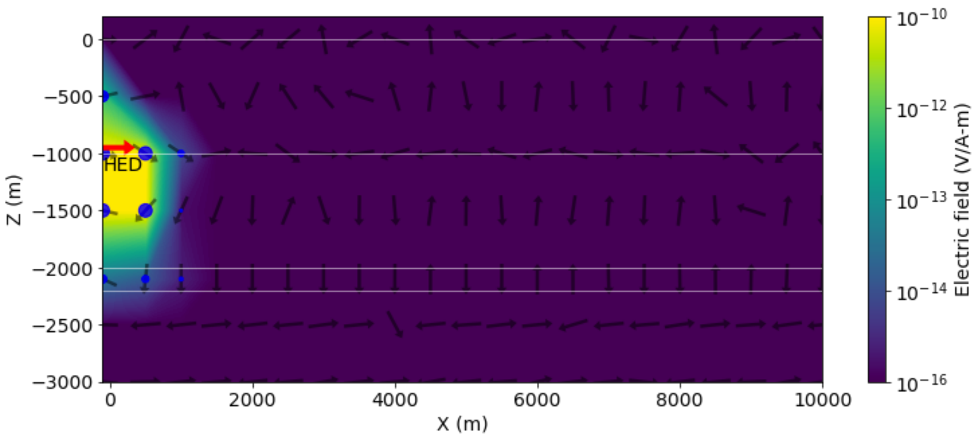
On XZ plane (HED source in x-direction)



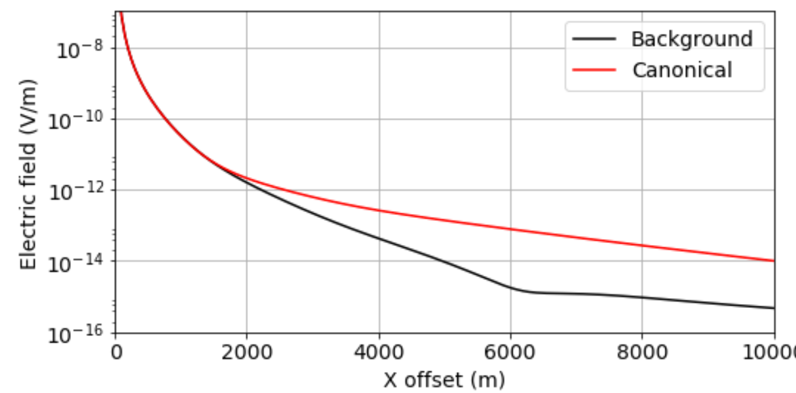
Poynting vector: $\bar{\mathbf{S}} = \frac{1}{\mu_0}\mathbf{E} \times \mathbf{B}$

Fields at time: 0.016s

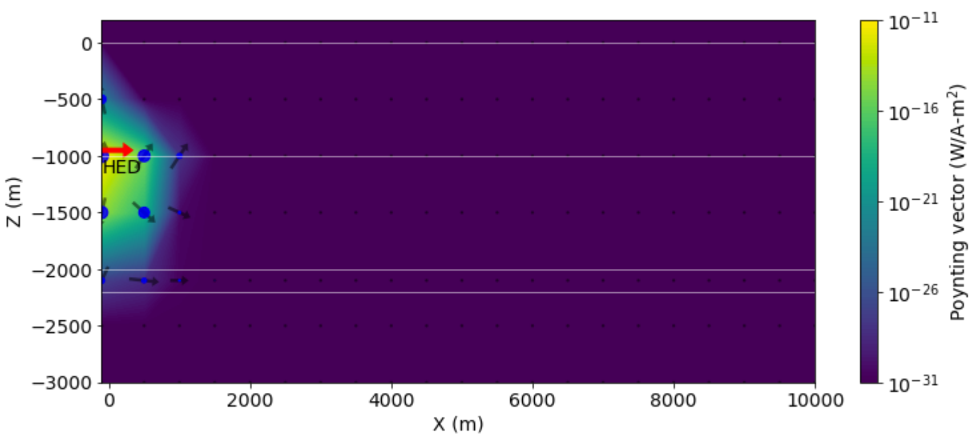
E-field



|Ex|



Poynting vector

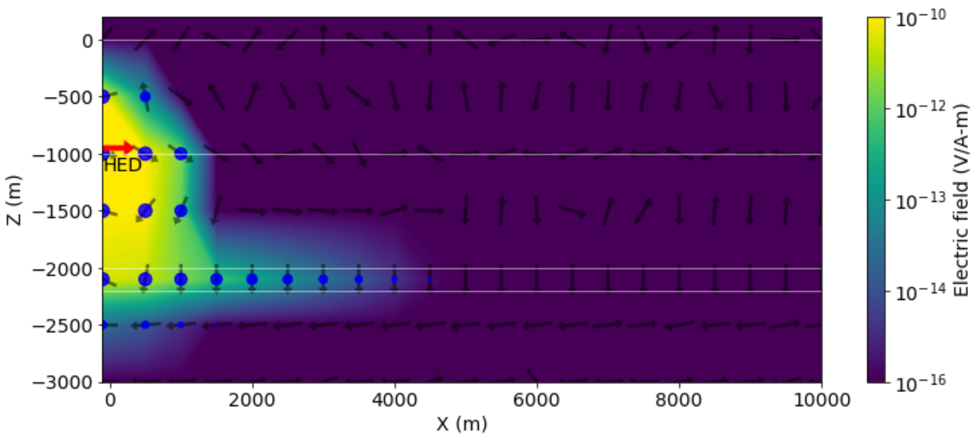


Peak velocity

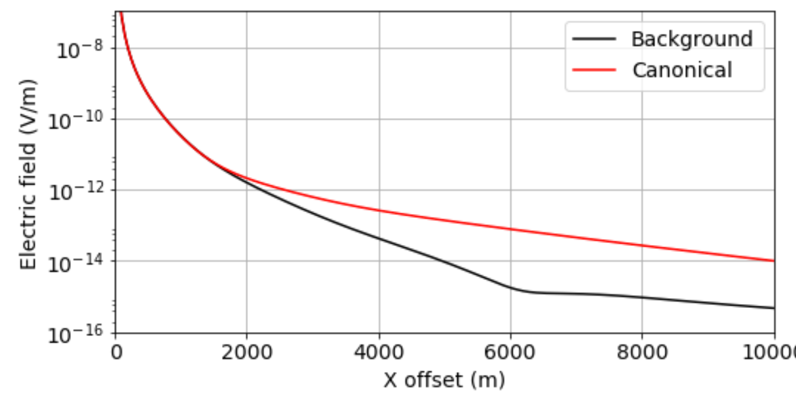
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

Fields at time: 0.03s

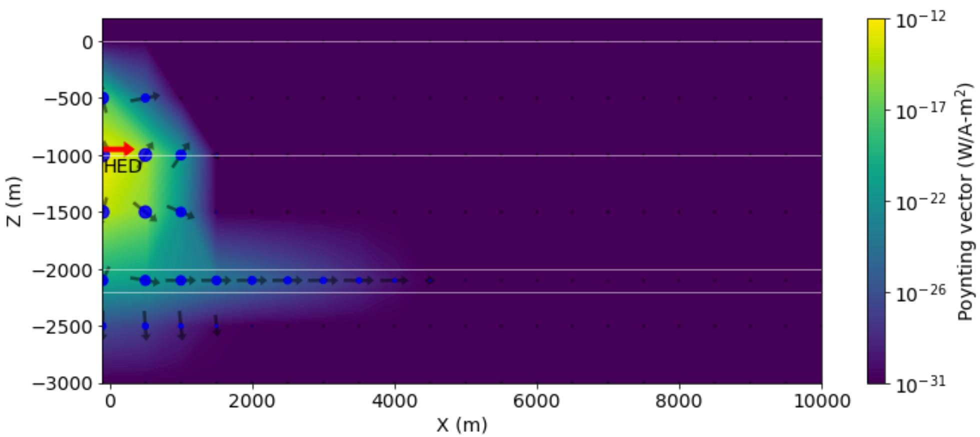
E-field



|Ex|



Poynting vector

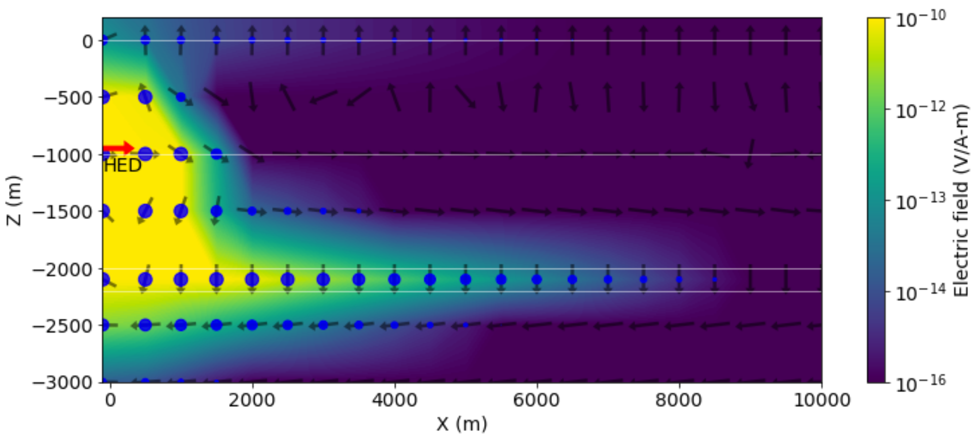


Peak velocity

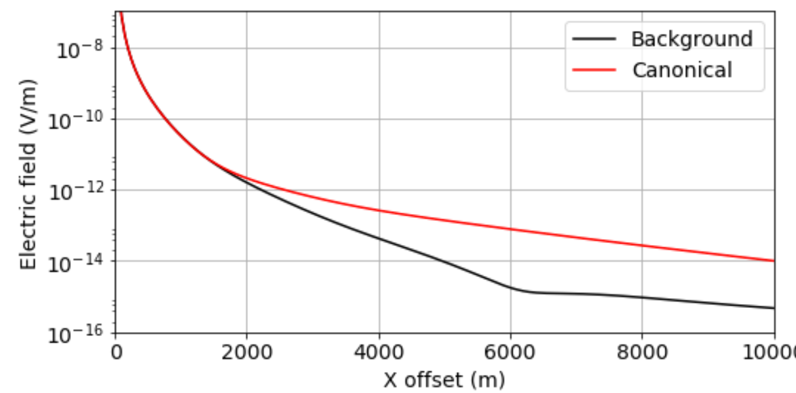
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

Fields at time: 0.08s

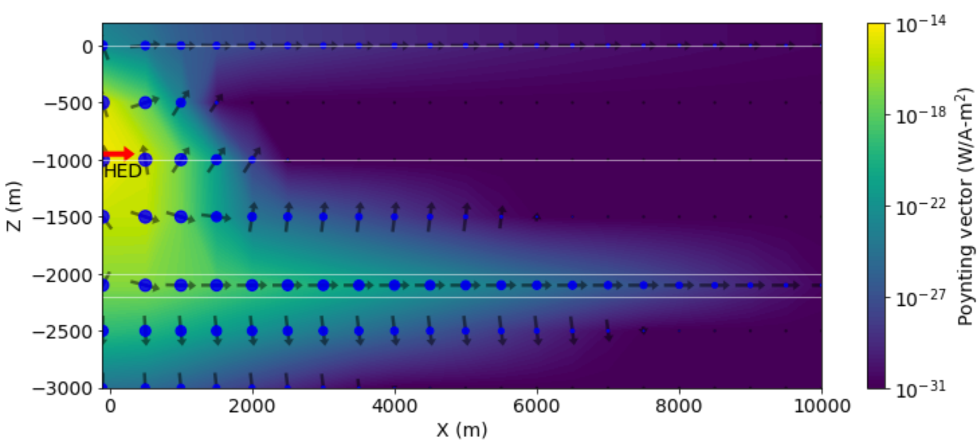
E-field



|Ex|



Poynting vector

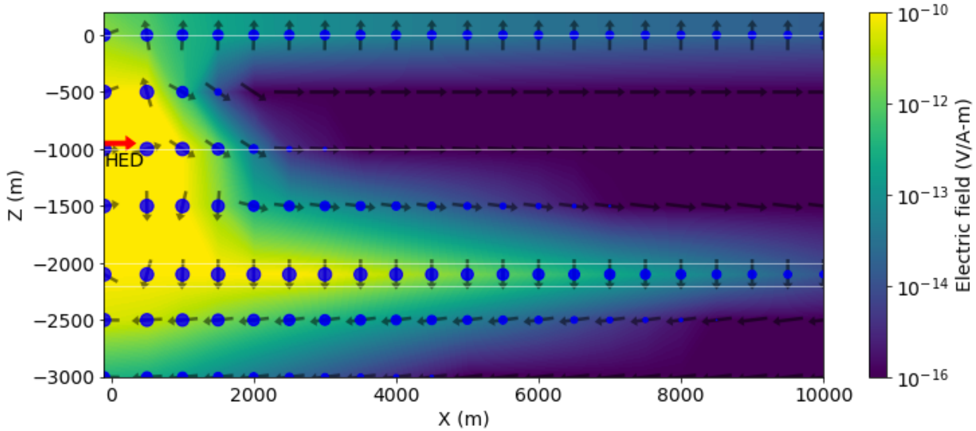


Peak velocity

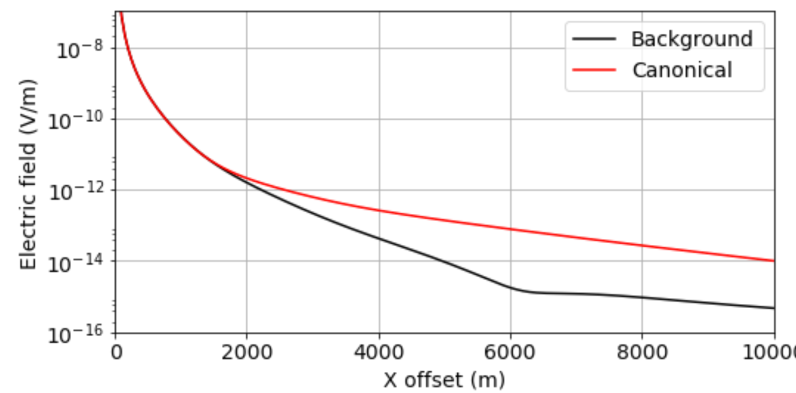
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

Fields at time: 0.10s

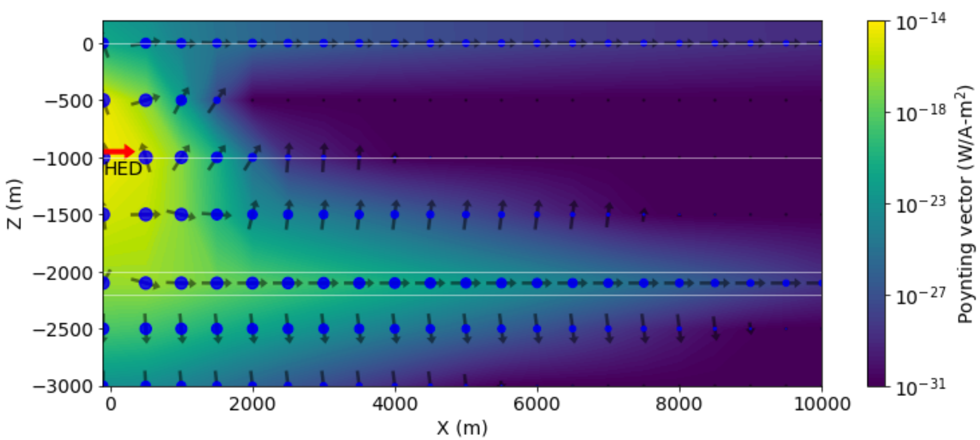
E-field



|Ex|



Poynting vector

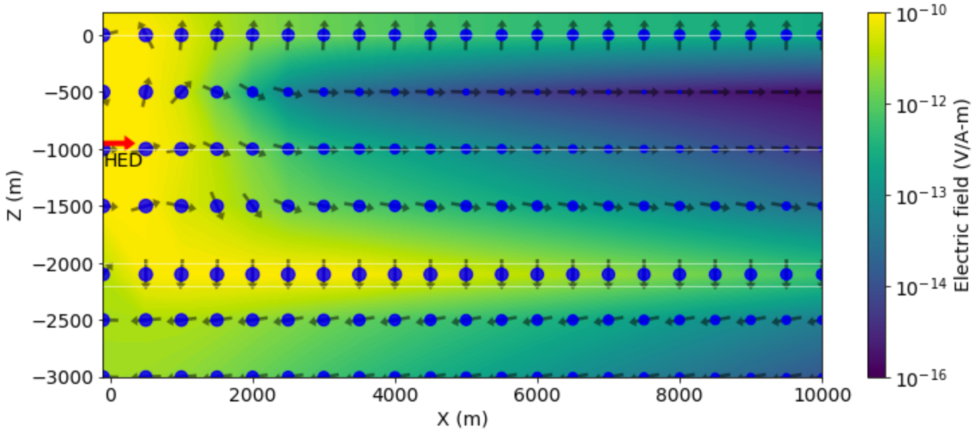


Peak velocity

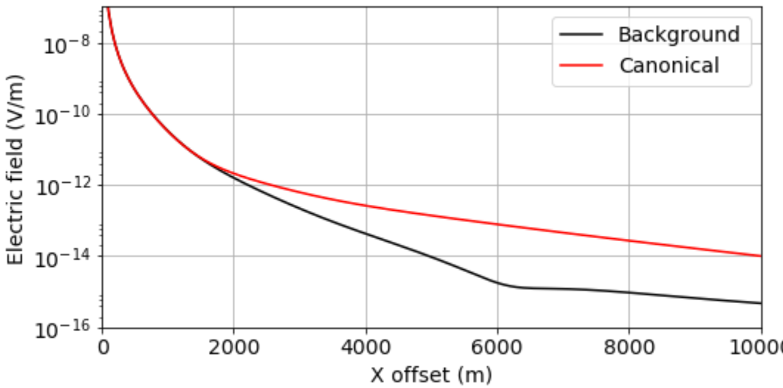
$$v = \sqrt{\frac{\rho}{2\mu t}}$$

Fields at time: 0.32s

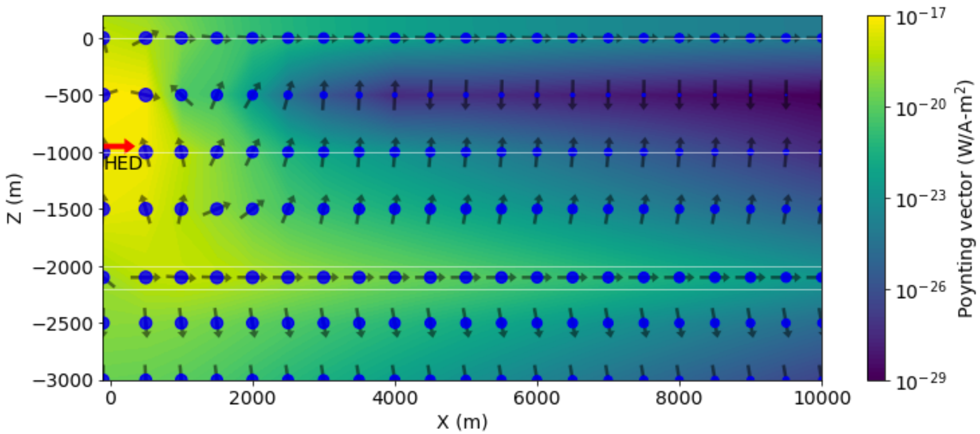
E-field



|Ex|



Poynting vector



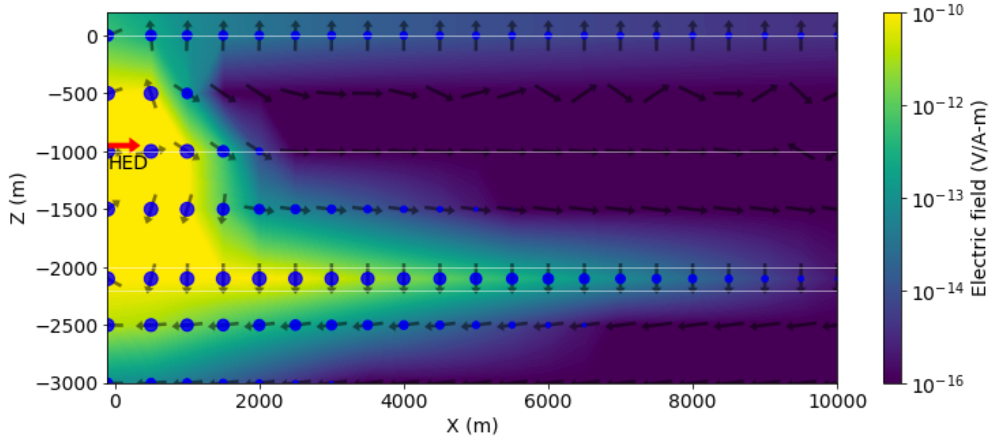
Peak velocity

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

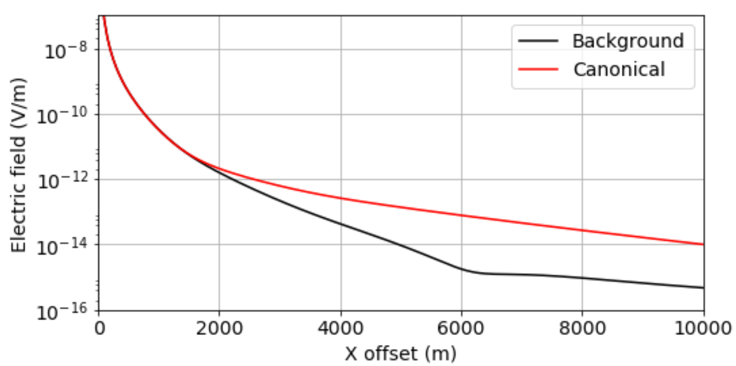
Amplitude vs offset

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

E-field at 0.08s

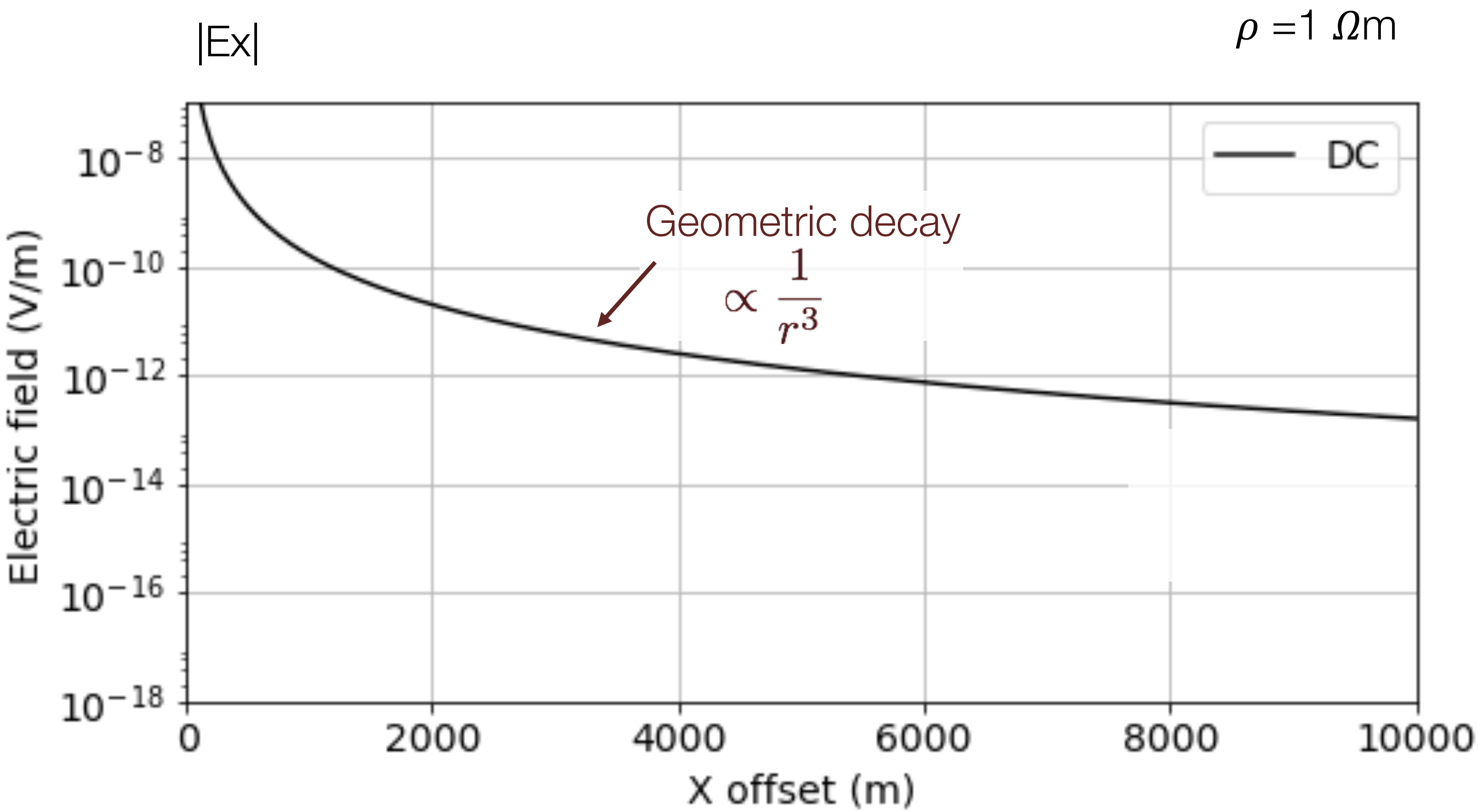


|Ex|

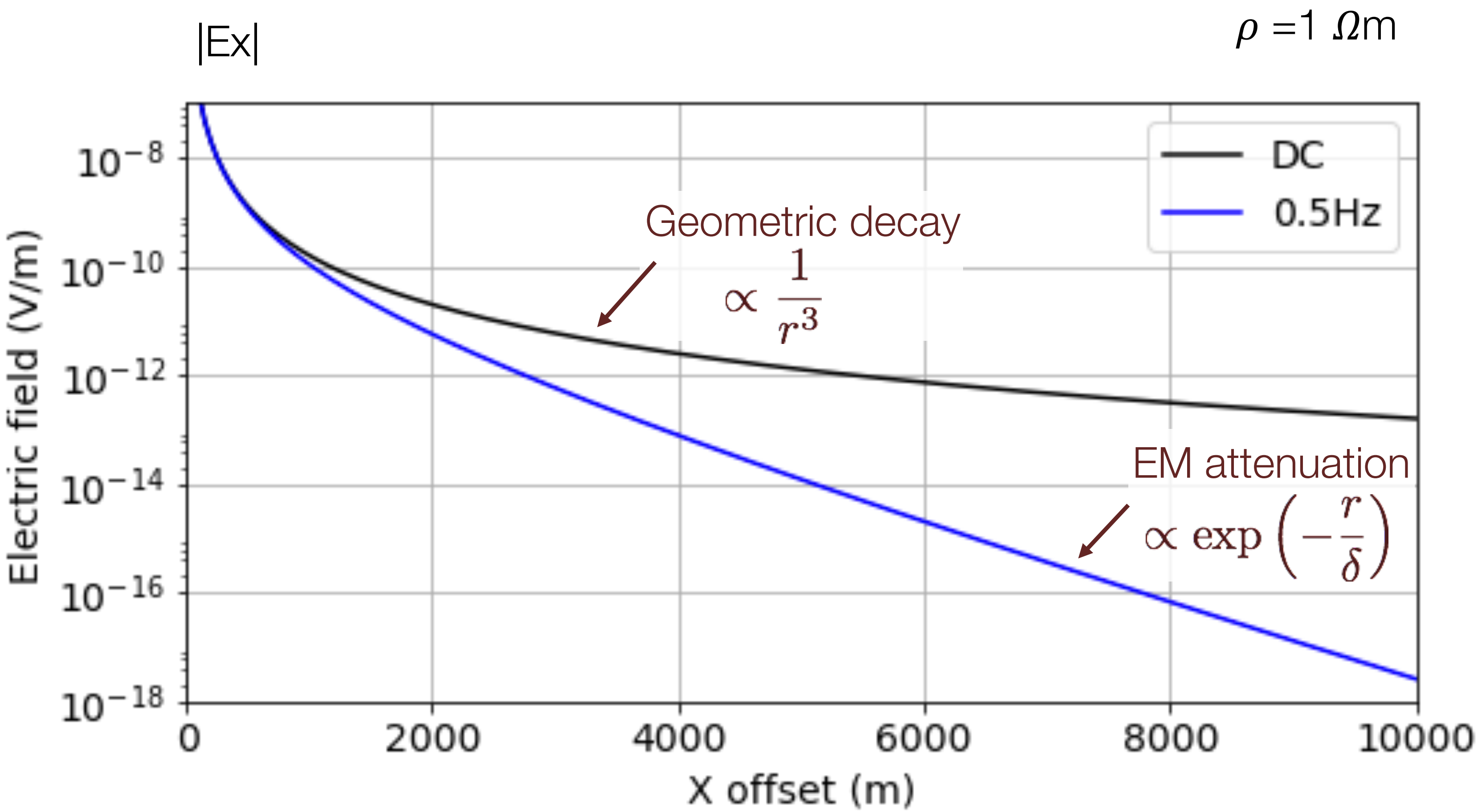


- What about amplitudes?
- Work in frequency domain

Amplitude: Electric dipole in a wholespace

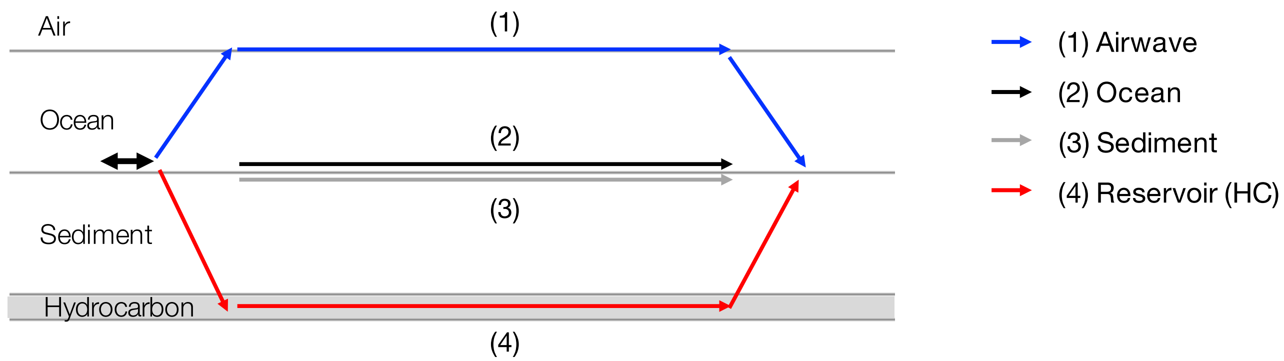


Amplitude: Electric dipole in a wholespace

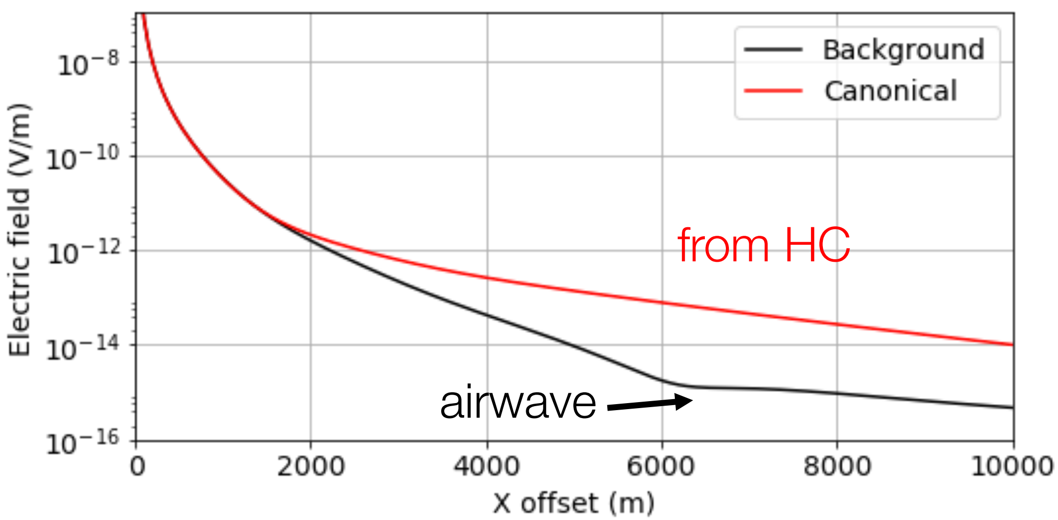


Amplitude vs Offset

Ray paths



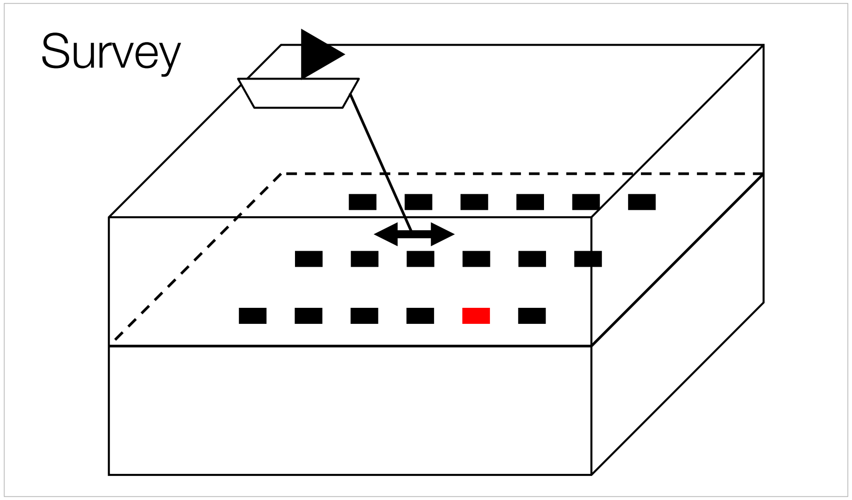
|Ex|

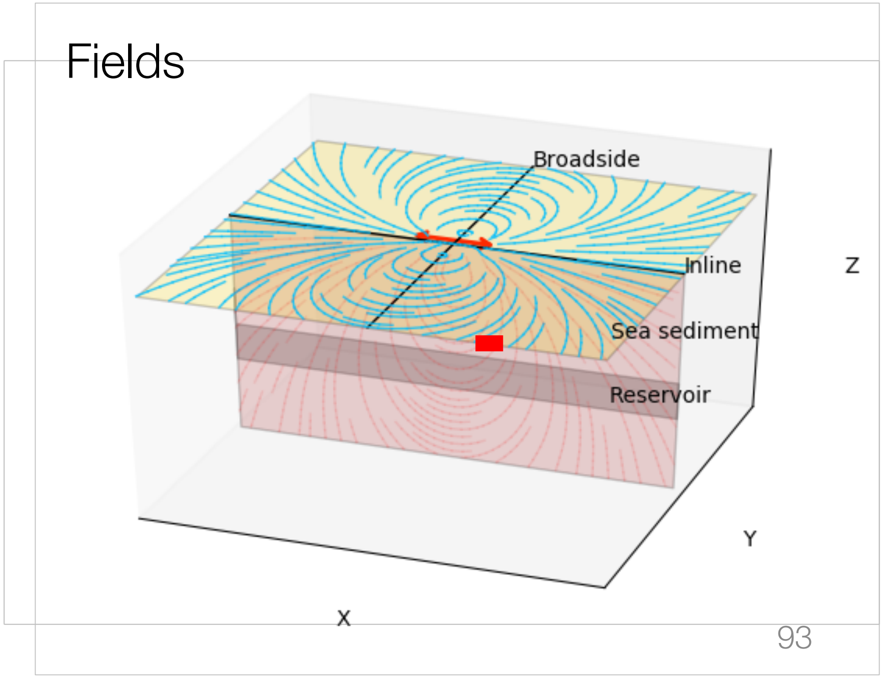


- Short offset (<2km):
  - geometric decay ($1/r^3$)
- Intermediate offset (2-6 km):
  - skin effects + HC
- Large offset (6-10 km):
  - airwave + HC

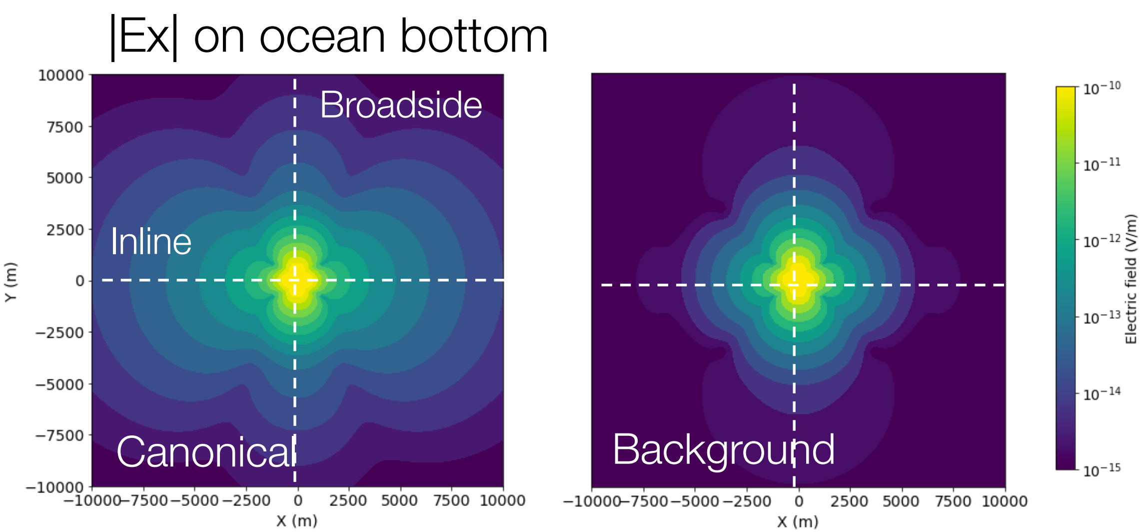
General CSEM

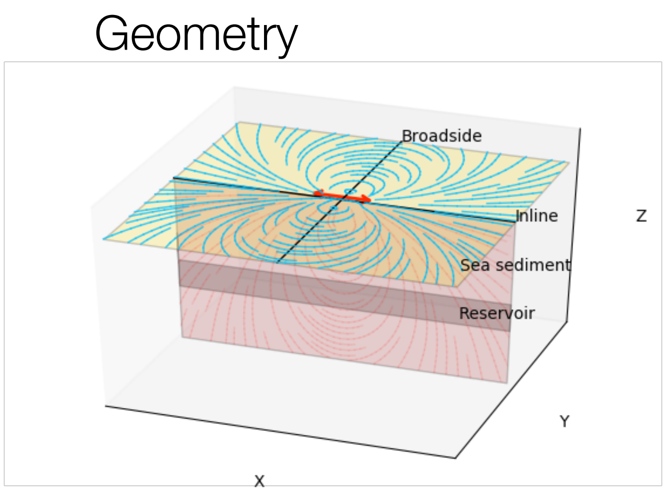
- Fields are 3D: All three components exists
  - Ex, Ey, Ez
  - Bx, By, Bz
- Inline (Ex, Ez, By)
  - Electric field crosses the HC layer boundary
  - Galvanic dominates
- Broadside (Ex, By, Bz)
  - No vertical electric field (no charge build up)
  - Inductive dominates

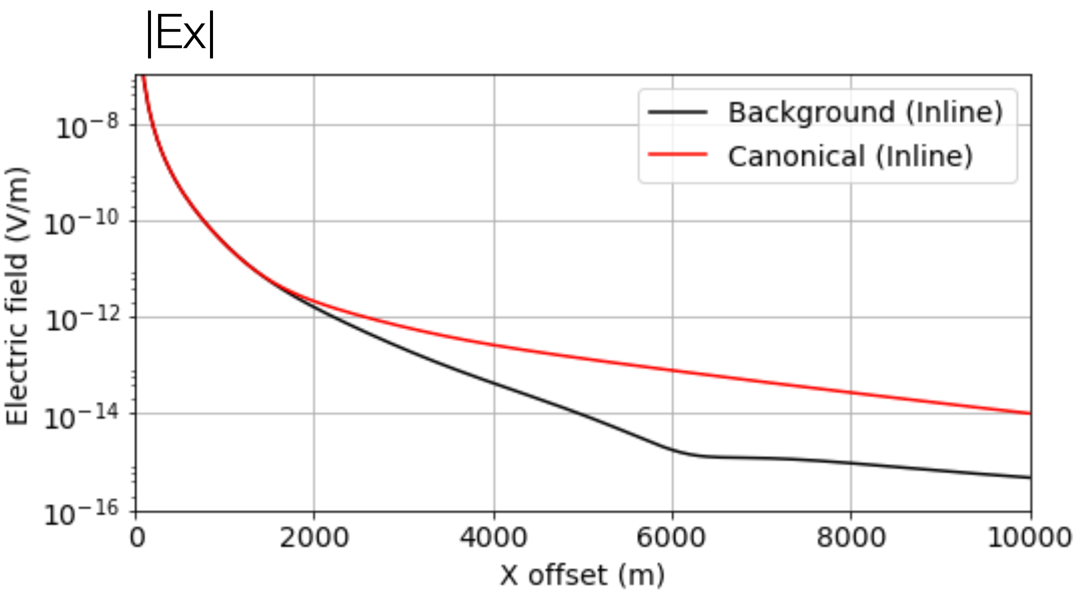




Measured data: inline and broadside



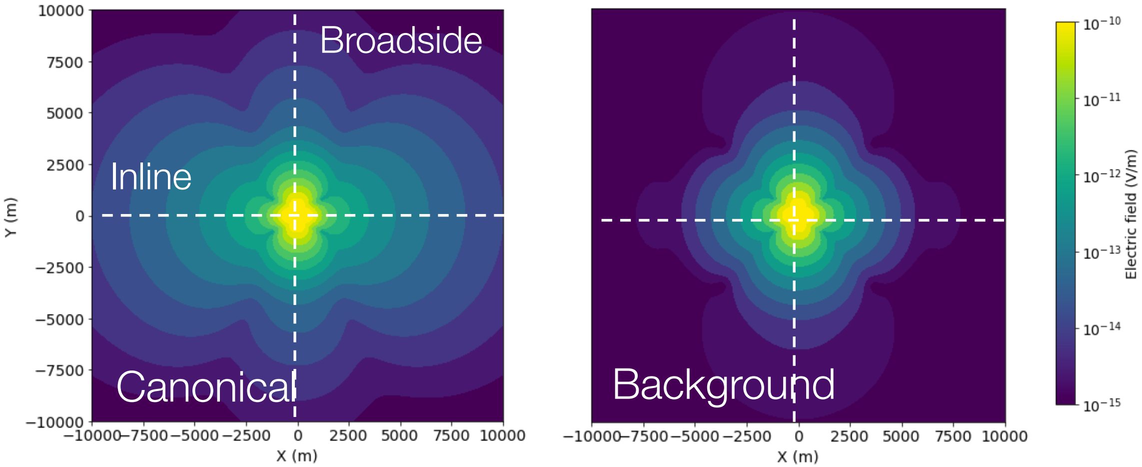




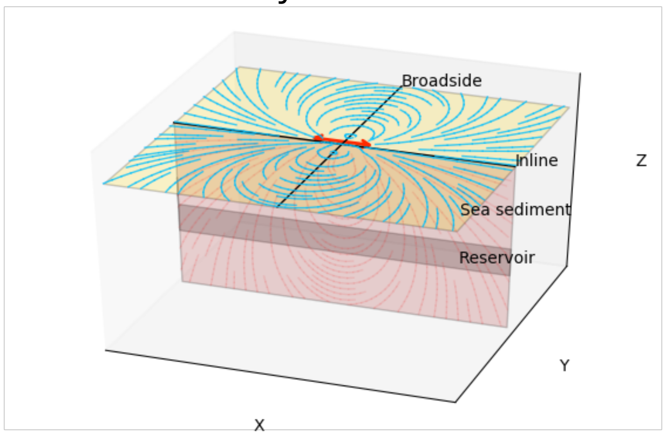
- Inline |Ex|
  - Significant signal from reservoir

Measured data: inline and broadside

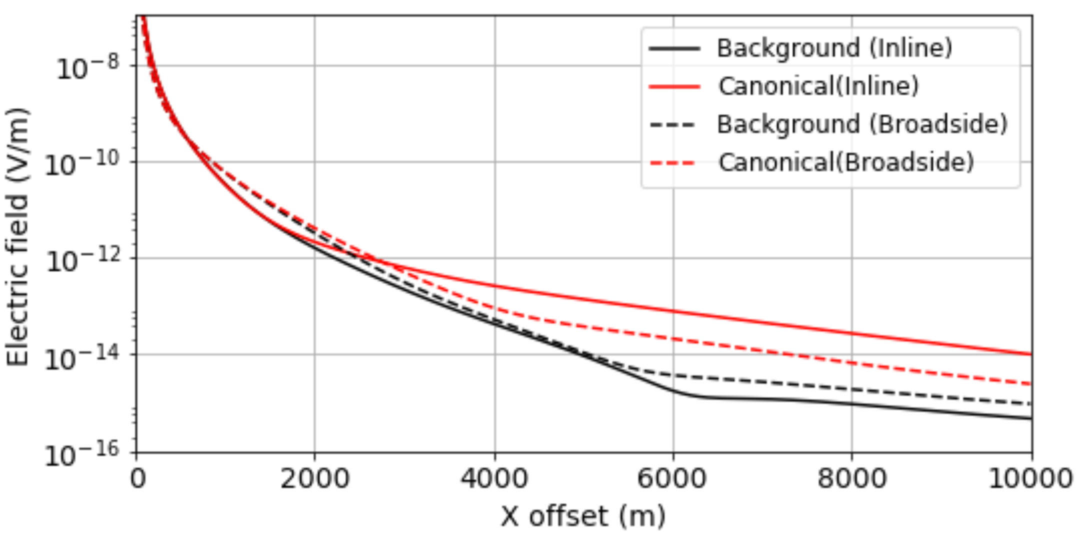
|Ex| on ocean bottom



Geometry



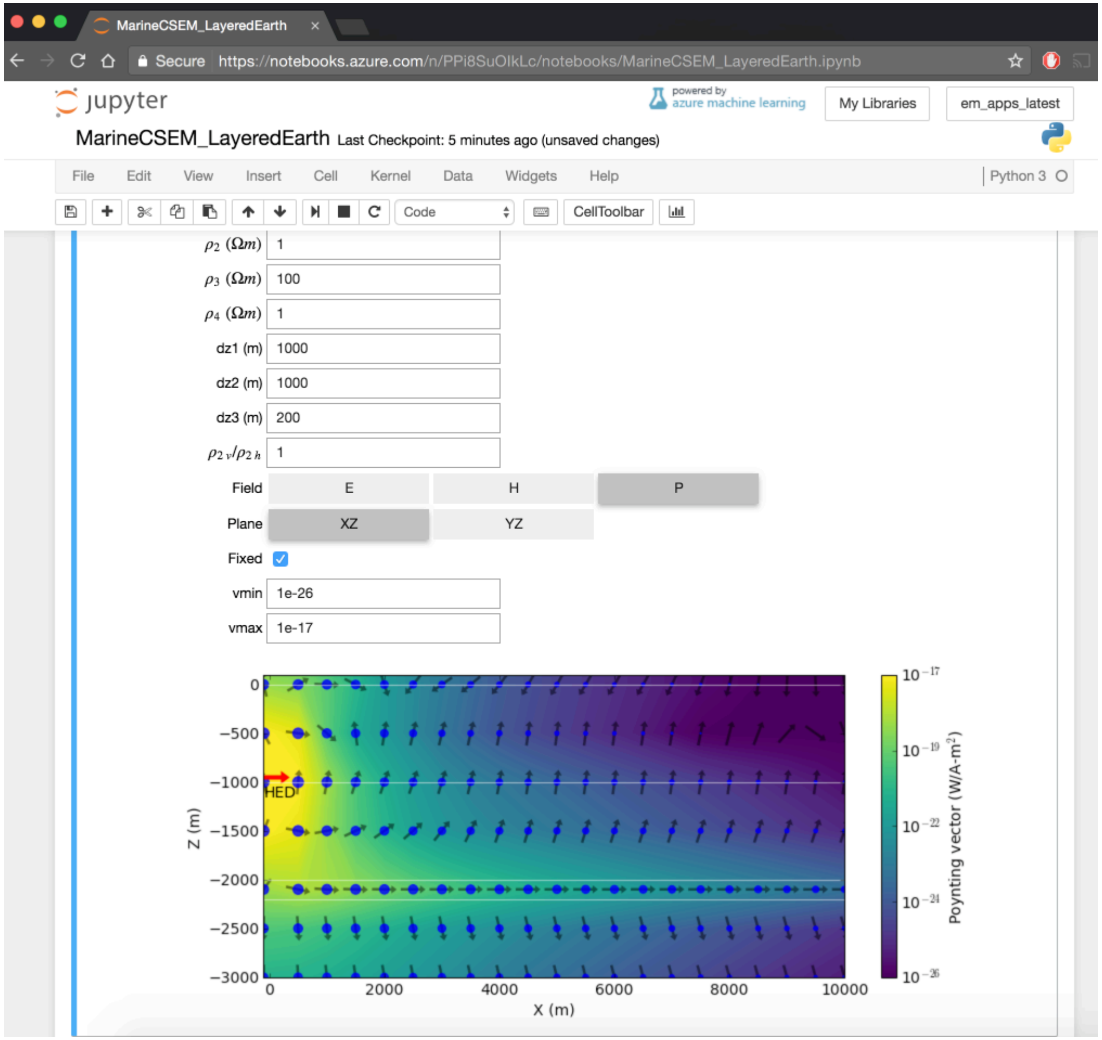
|Ex|



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

Marine CSEM App

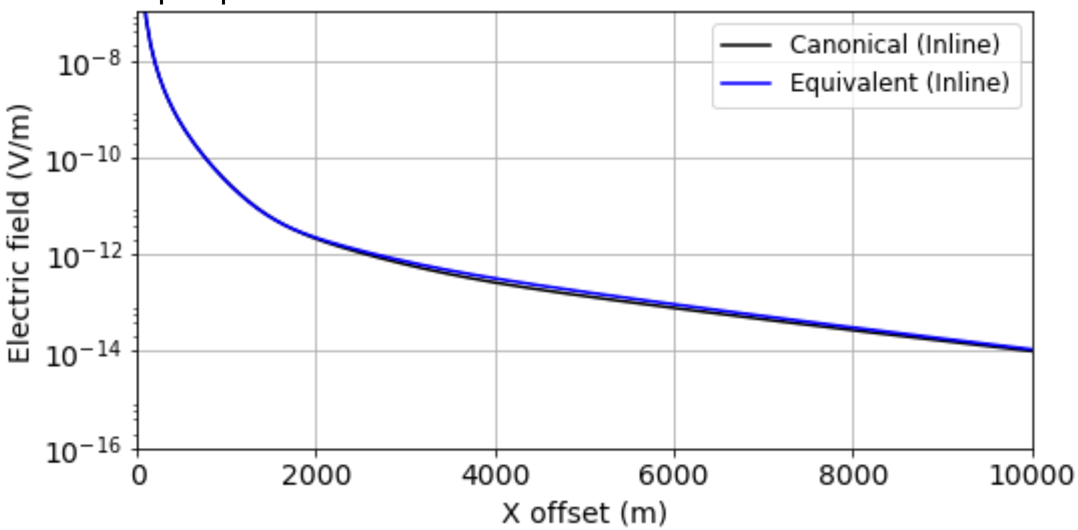
- Simulate Marine CSEM
  - 4 layers
  - E, H Fields
  - Poynting vector



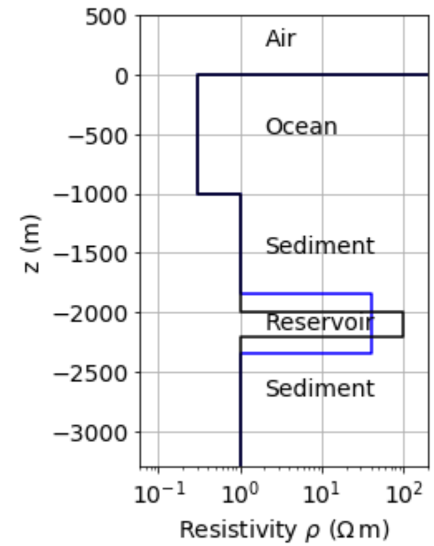
http://em.geosci.xyz/apps.html

Equivalence: resistivity-thickness product

|Ex|



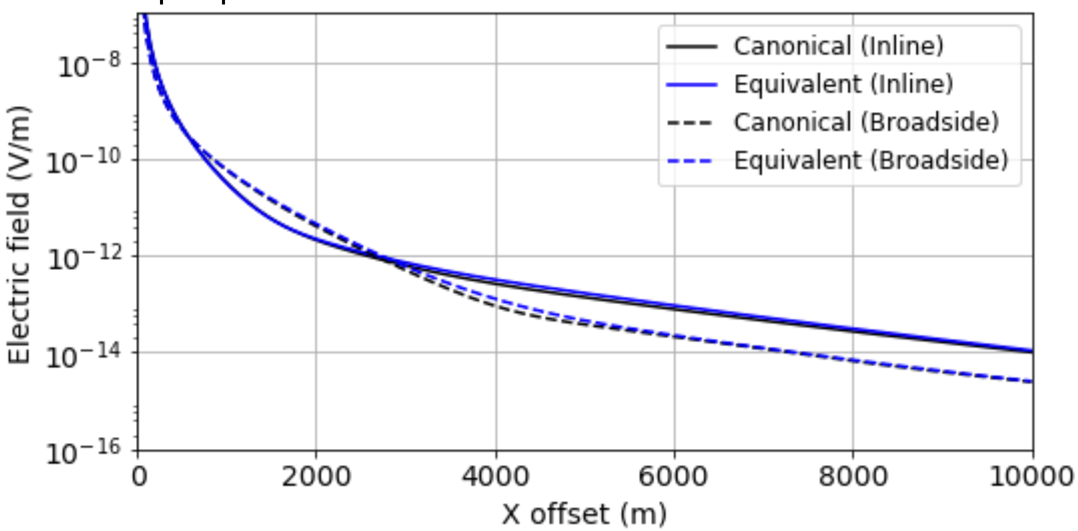
Resistivity models



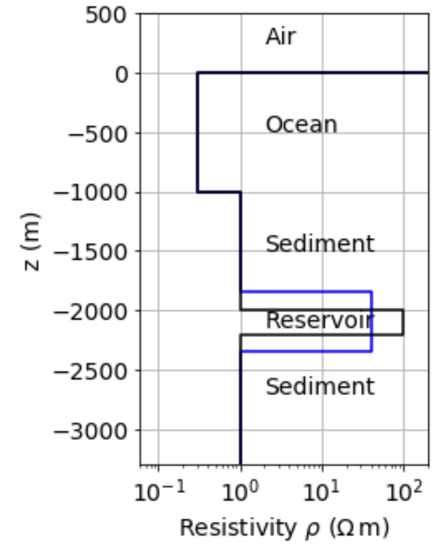
- Electric fields are sensitive to resistivity-thickness product
- Reduce non-uniqueness with better data coverage, more components, other information (e.g. seismic)

Equivalence: resistivity-thickness product

|Ex|

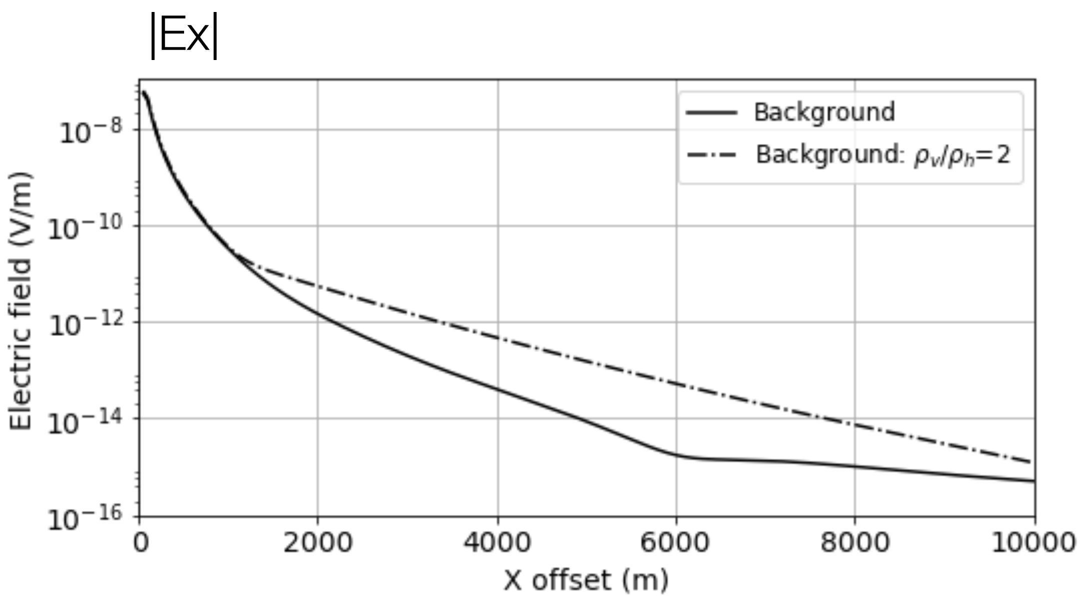


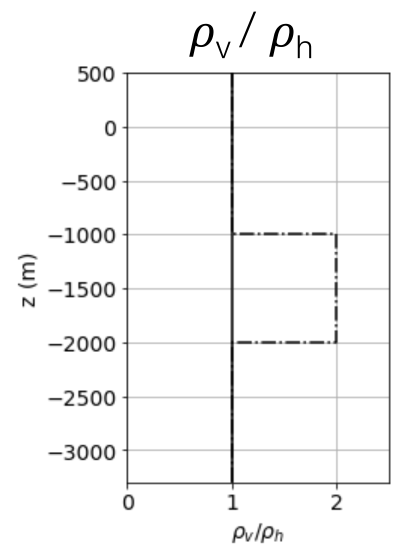
Resistivity models



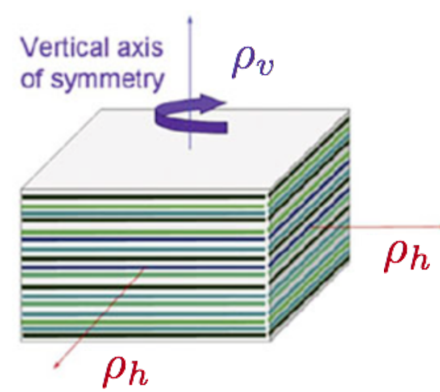
- Electric fields are sensitive to resistivity-thickness product
- Reduce non-uniqueness with better data coverage, more components, other information (e.g. seismic)

Anisotropy

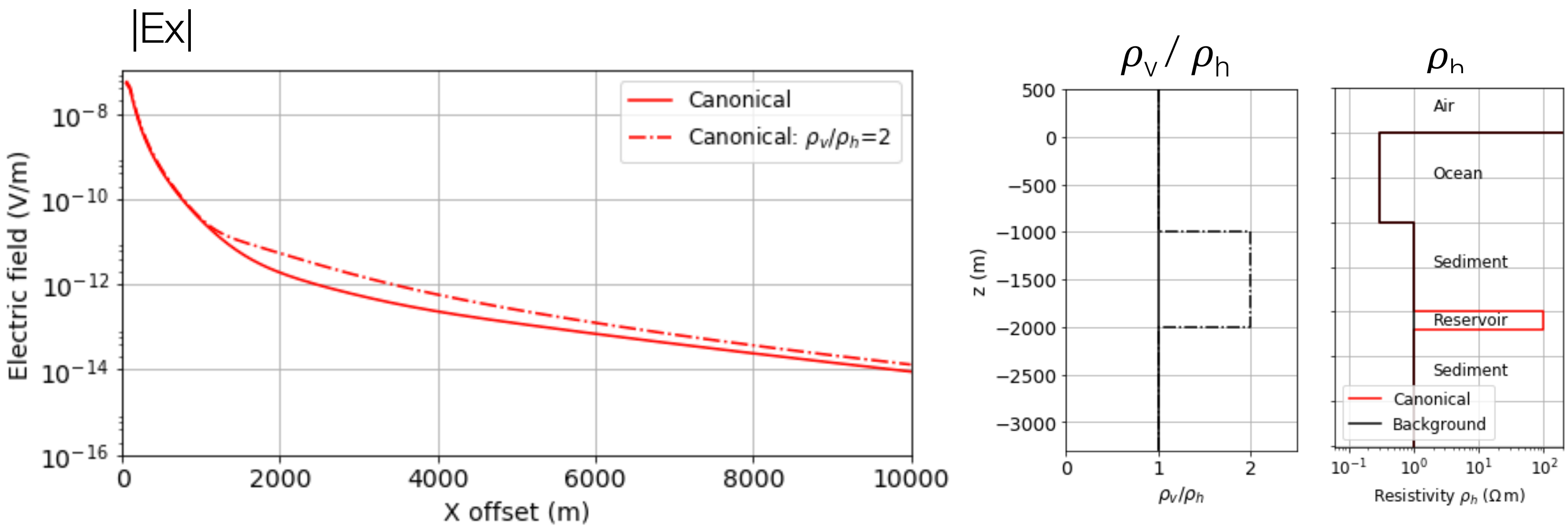




- Sediment could have vertical anisotropy
- $\rho_v > \rho_h$: |Ex| larger at far offsets

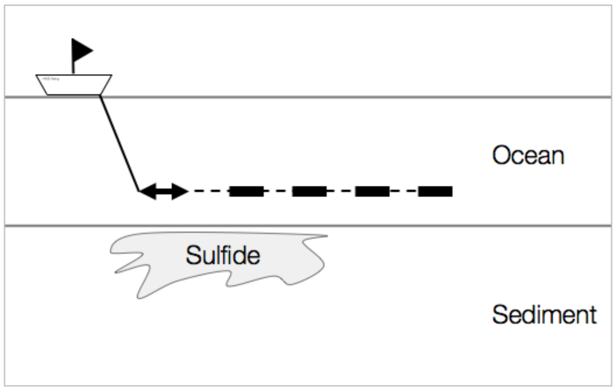


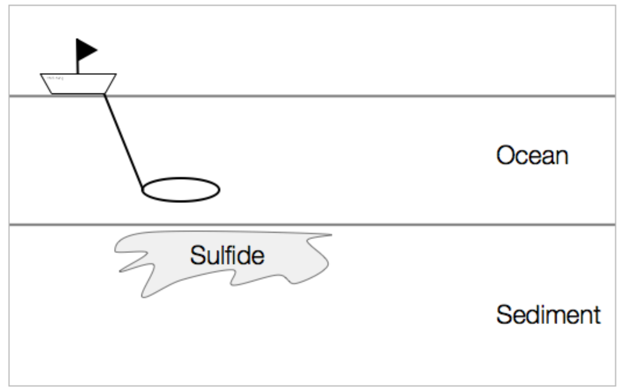
Anisotropy

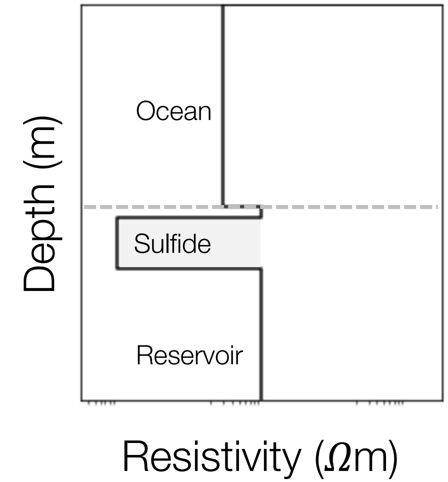


- Significant impact to signal from reservoir
  – need to account for this when interpreting marine CSEM data

Finding conductors



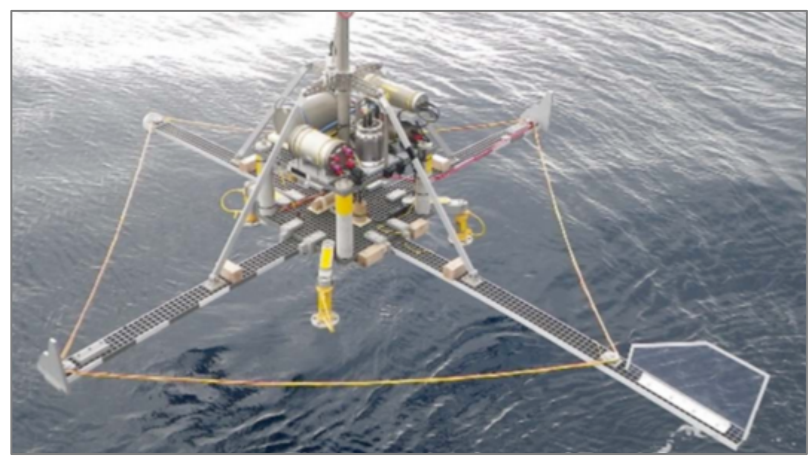




Source: towed

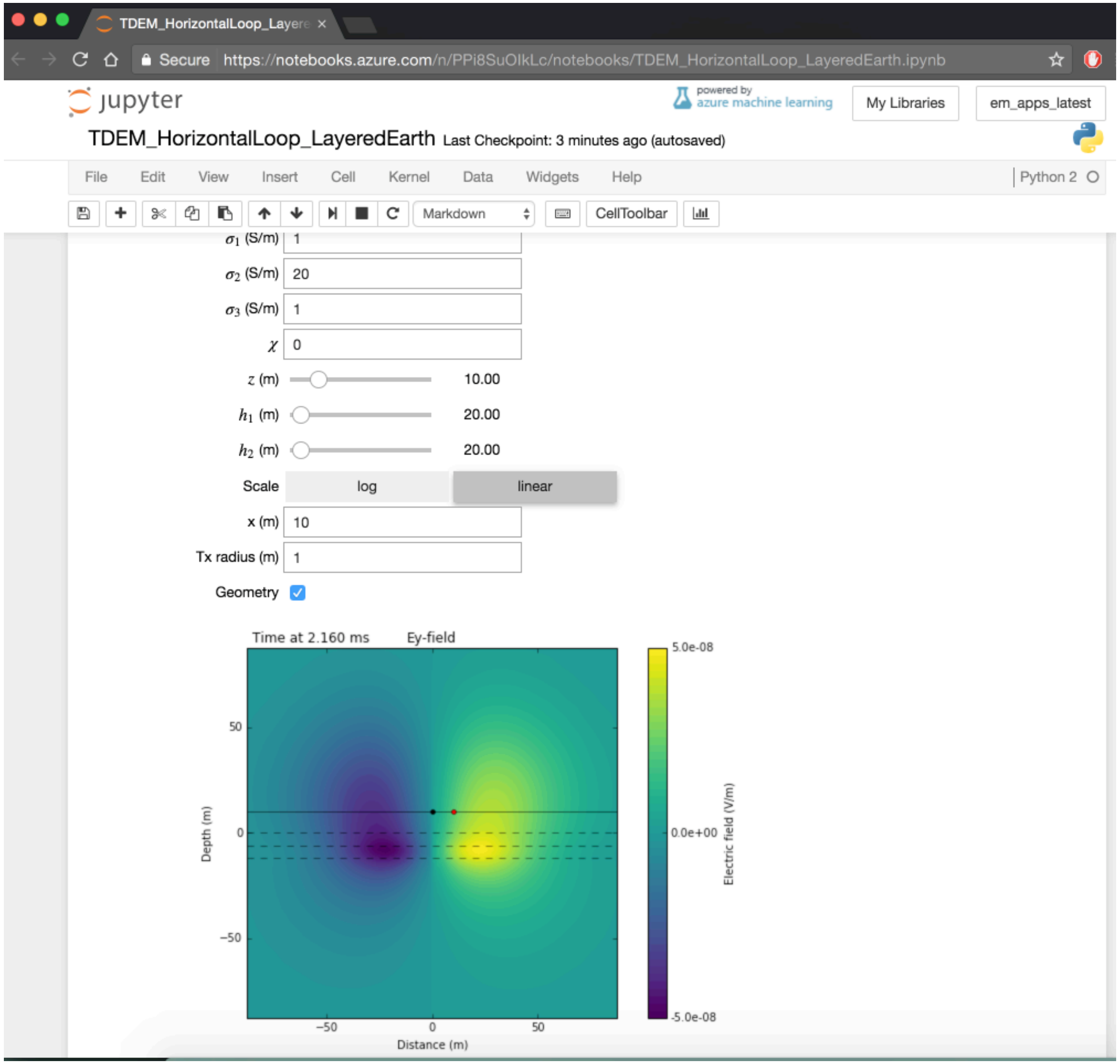
- Galvanic source
- Inductive source

- Receivers: (towed)
  - E-field
  - B-field



TDEM Horizontal Loop App

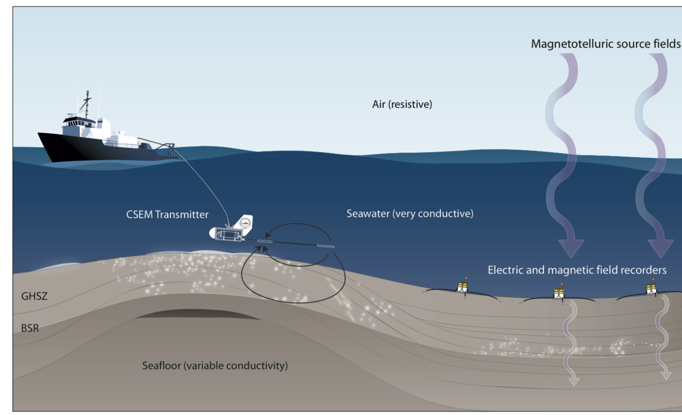
- TDEM
  - 4 layers
  - Fields, currents
  - Plot time decays



http://em.geosci.xyz/apps.html

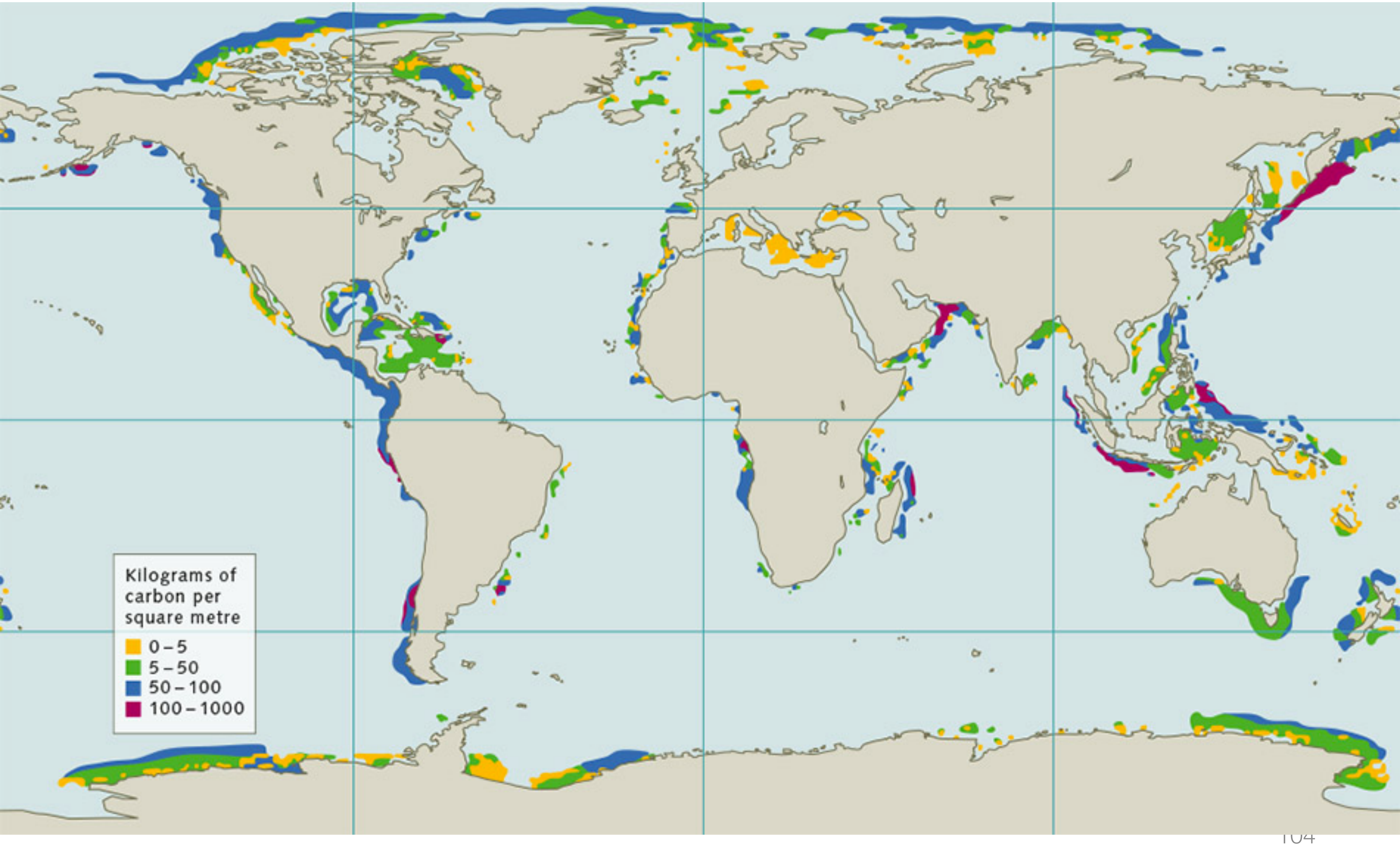
Summary

- 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

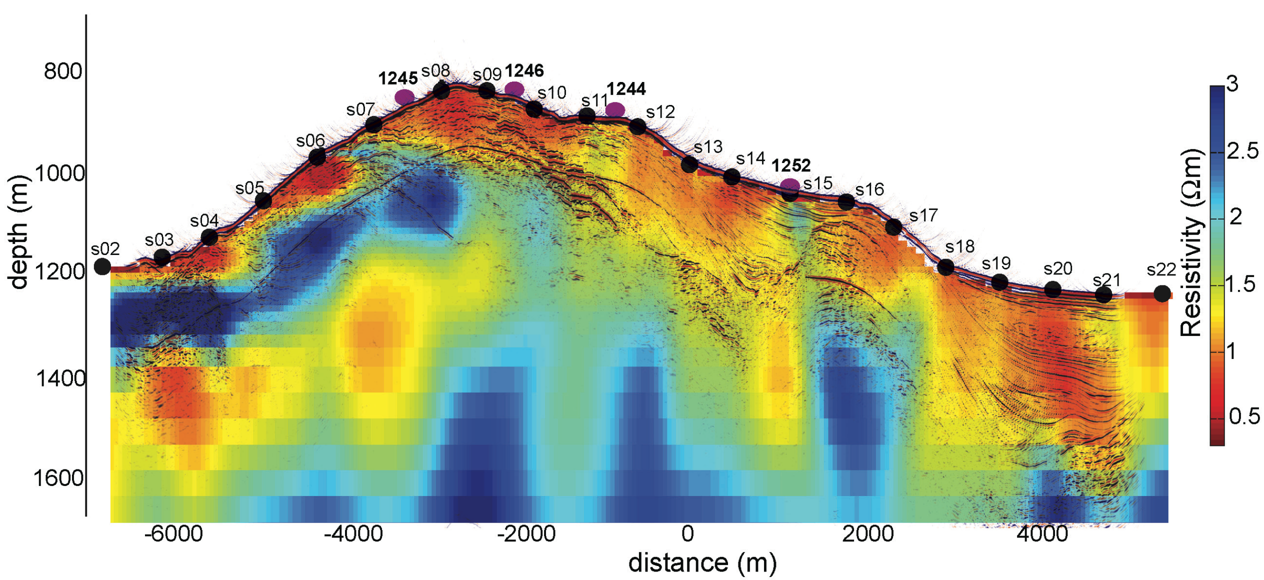
Methane Hydrates



Courtesy of Geomar

Case History: Hydrate Ridge offshore Oregon, USA

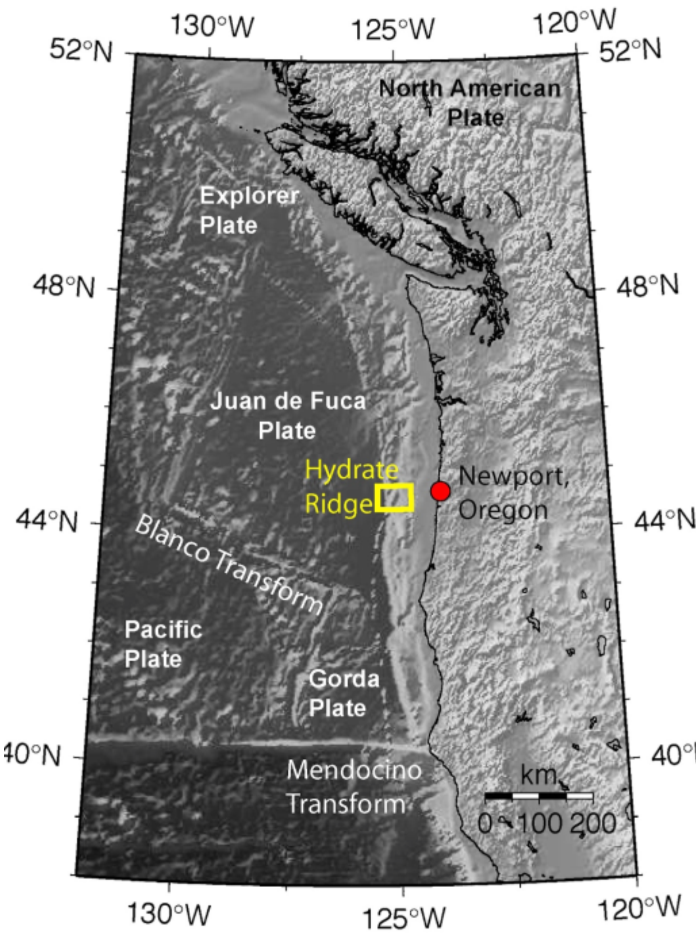
Weitemeyer et al. 2011

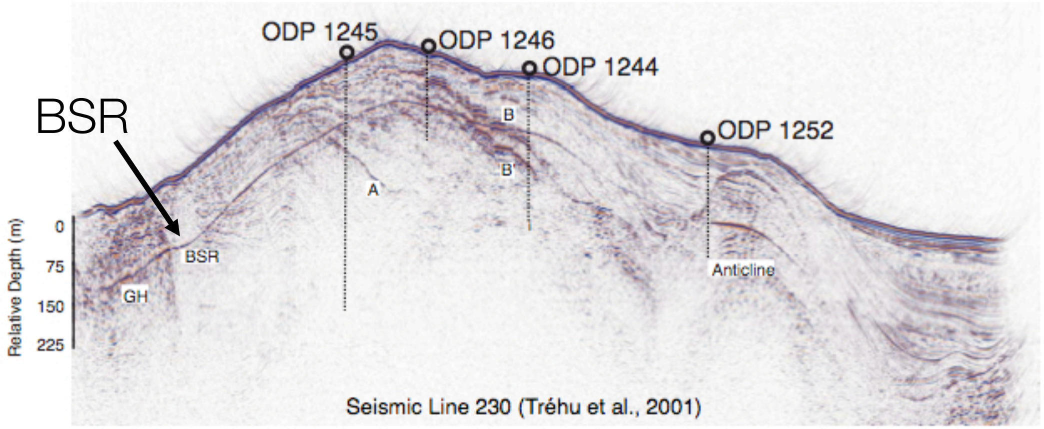


Setup

Methane hydrate

Hydrate Ridge, offshore Oregon

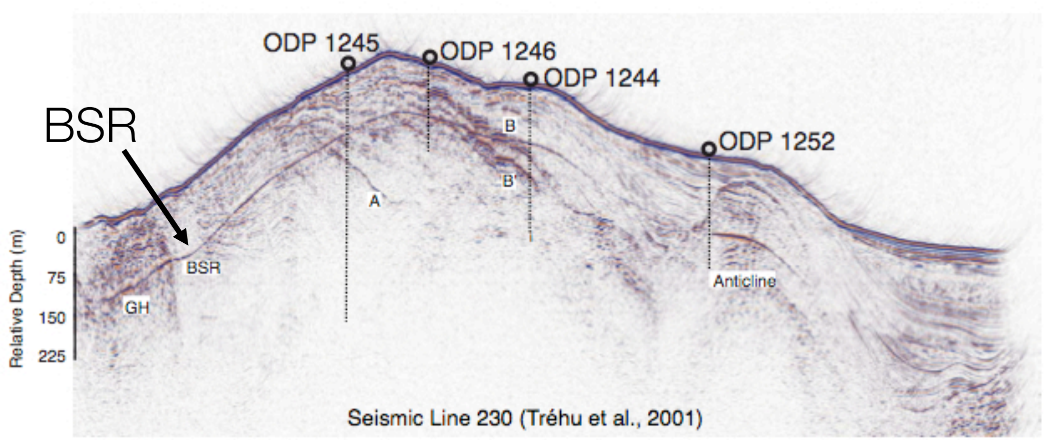




- On the accretionary complex of the Cascadia subduction zone
- Bottom simulating reflector (BSR)
  - Obtained from seismic reflection data
  - Acoustic impedance contrast between hydrate and free gas

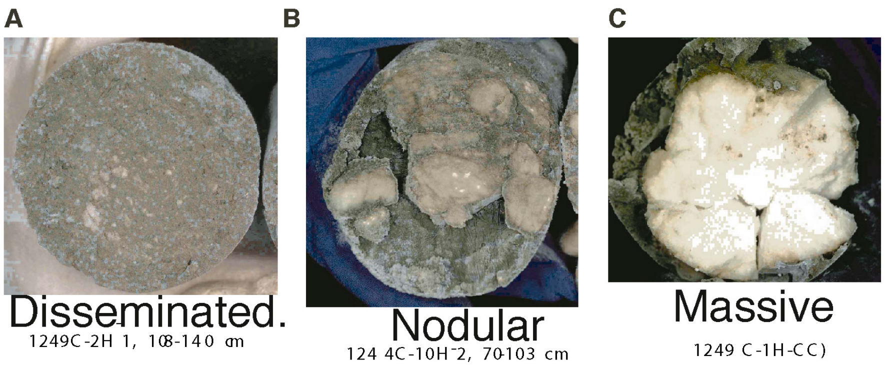
Questions

- 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



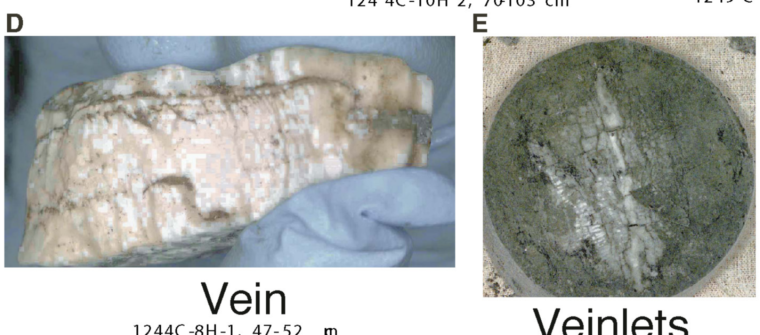
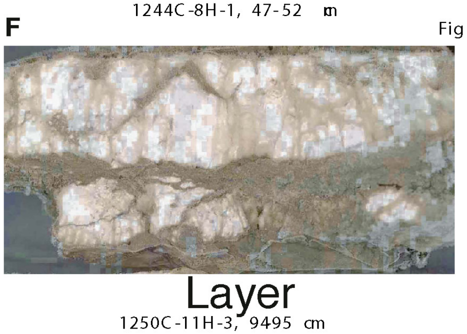


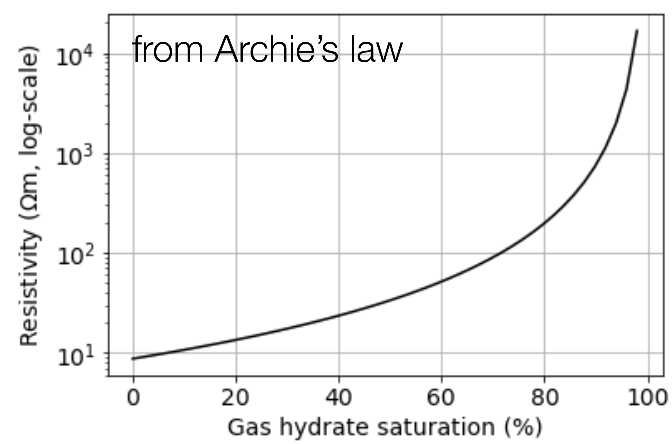
Fig 8C p. 43, in the "Site 1249" chapter)



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

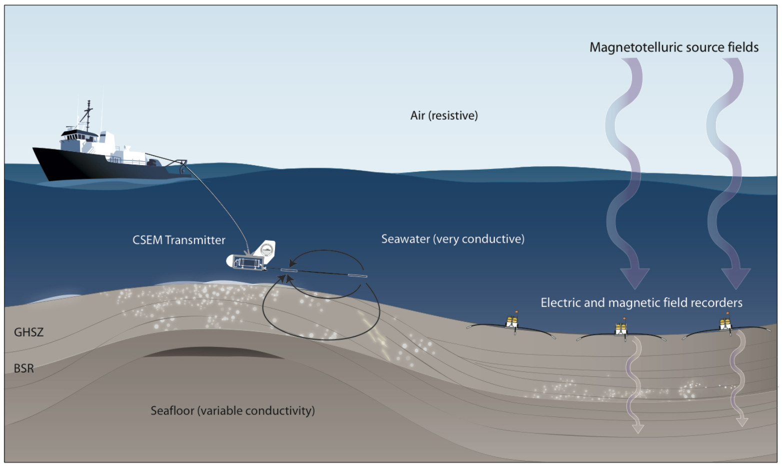
	Resistivity (Ωm)
Seawater	0.25-0.31 (15-3°C)
Freshwater	100-1000
Sediment	1-5
CH_4 hydrate	20,000 (at 0°C)
Basement	~10-20

Resistivity vs. Hydrate saturation



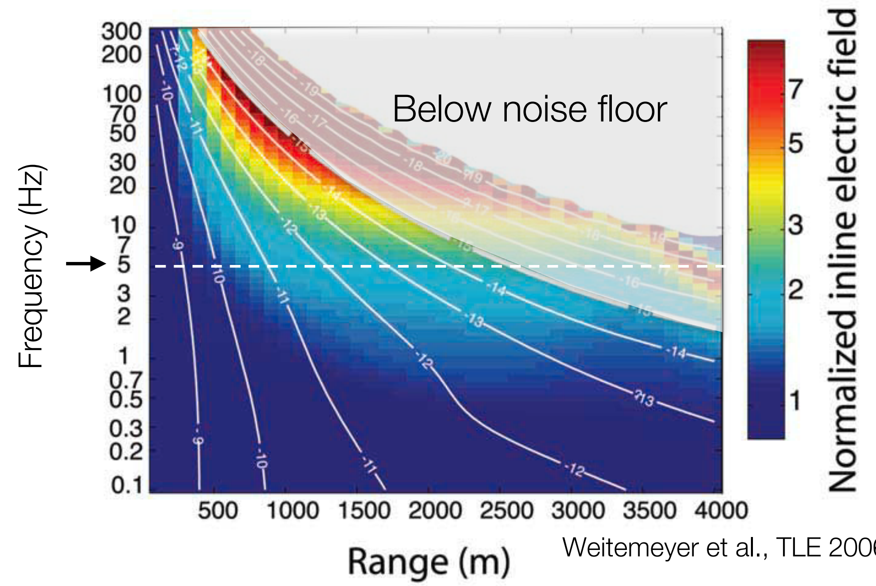
Survey design

Marine CSEM survey



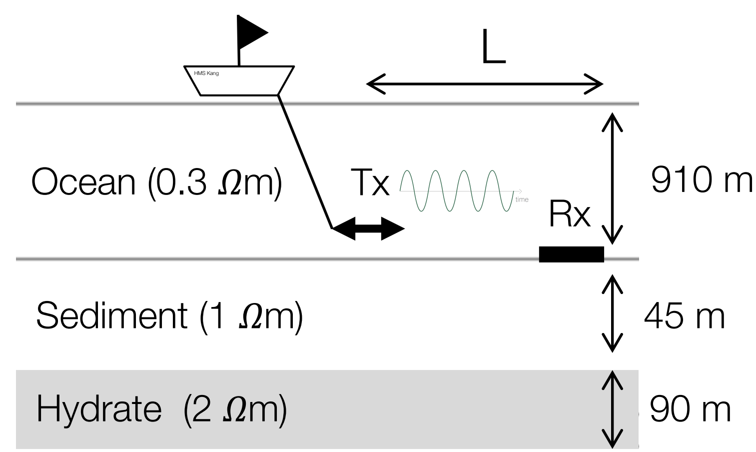
Weitemeyer et al., TLE 2006

E-field anomaly



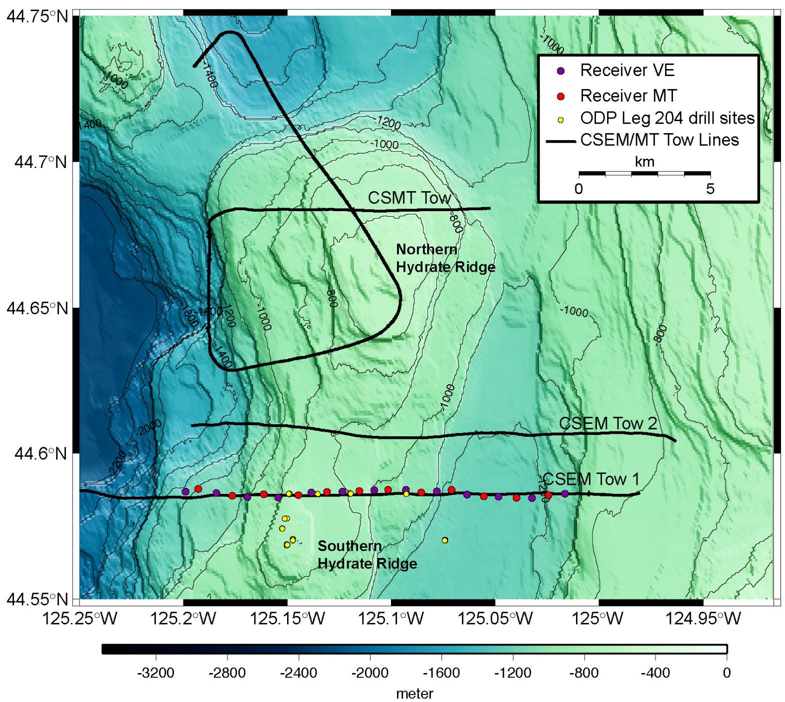
Weitemeyer et al., TLE 2006

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



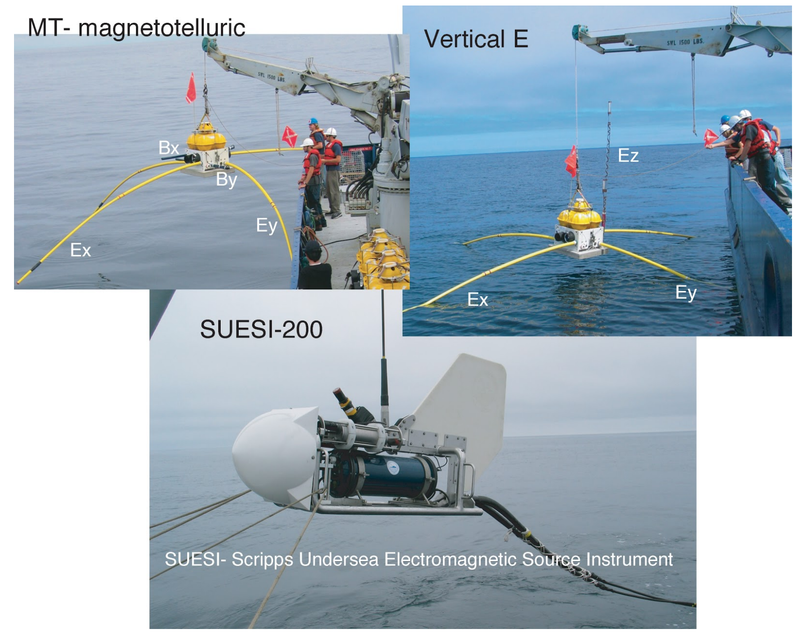
Survey

Geometry



Bathymetry data is ETOPO2V2C from the National Geophysical Data Center

Transmitter and receivers

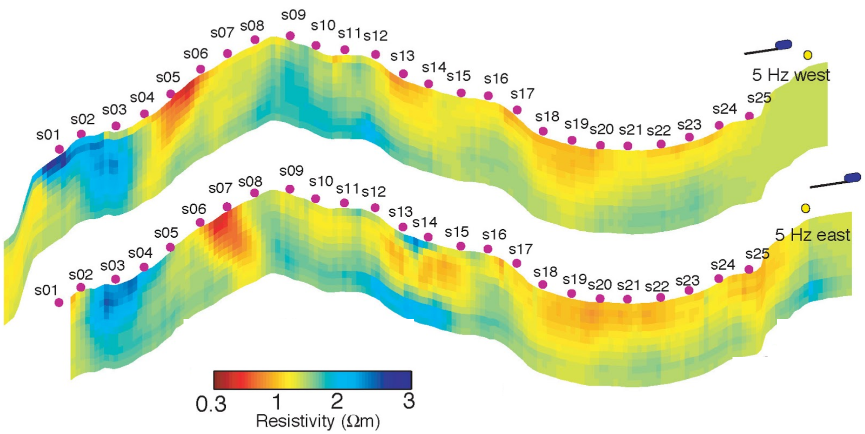


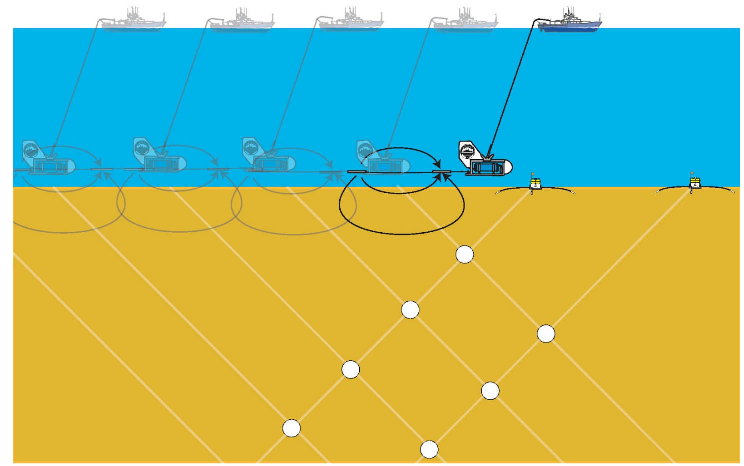
from Weitemeyer 2008 PhD Thesis

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

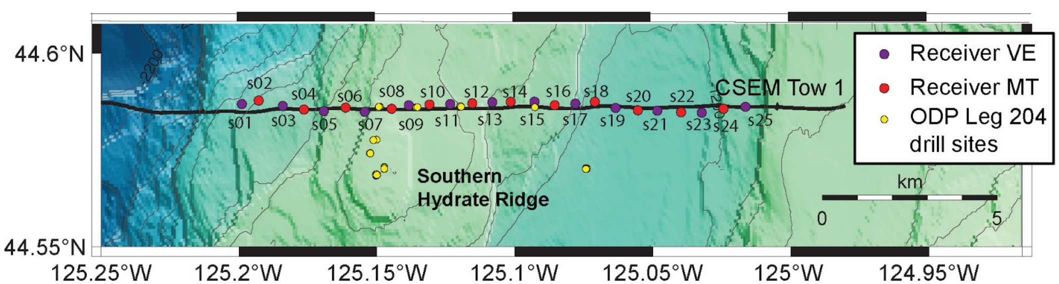
Processing: pseudo-section

Pseudo-section (apparent resistivity)





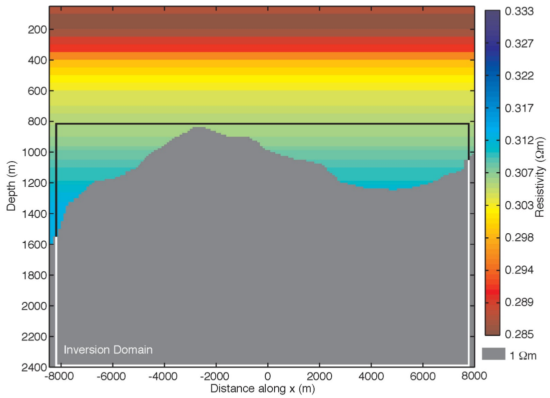
Survey geometry



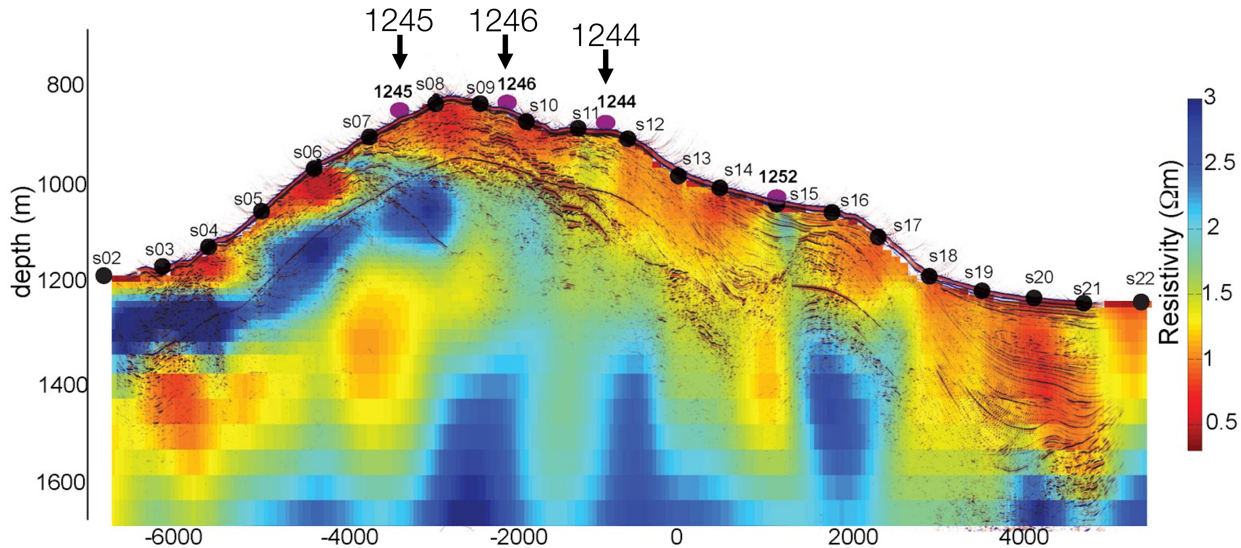
- pseudo-section:
  - fixed ocean resistivity
  - find effective subsea resistivity

Processing: 2.5D inversion

Initial model



Resistivity section



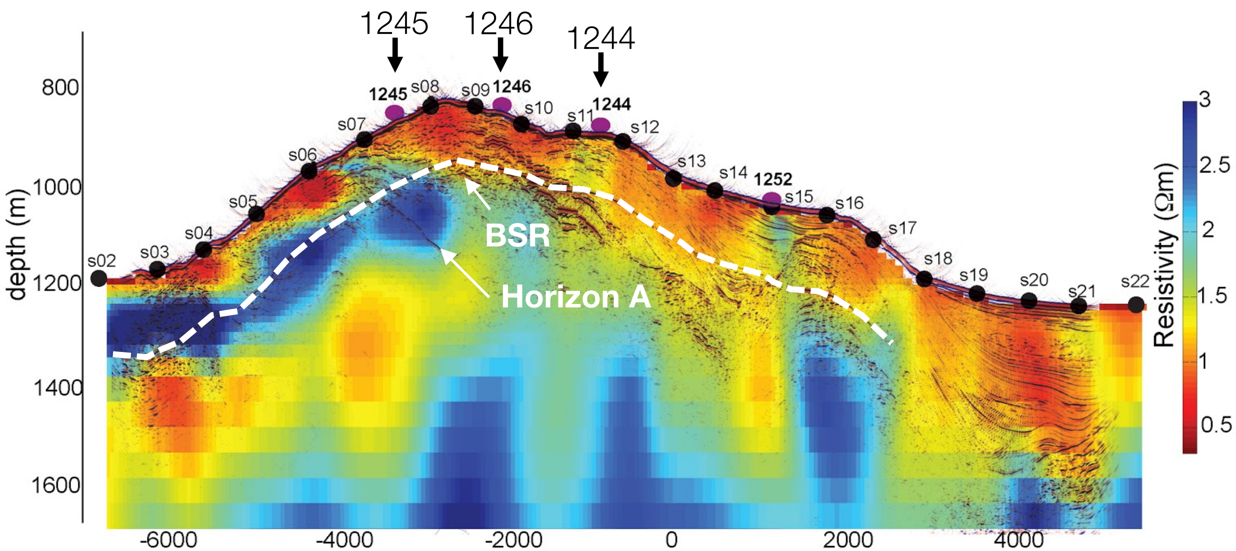
- Variable ocean σ
  - assign conductivity from CTD data (conductivity, temperature, depth)

- Significant near surface resistivity structure on the west

- Seismic image overlaid on the resistivity

Interpretation: 2.5D inversion

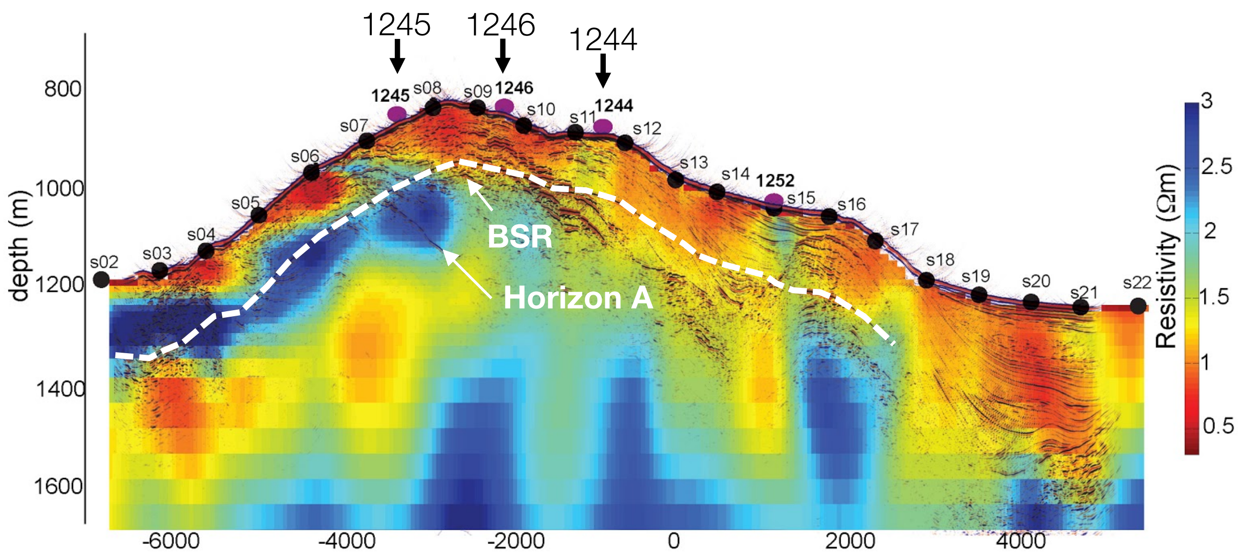
Resistivity section



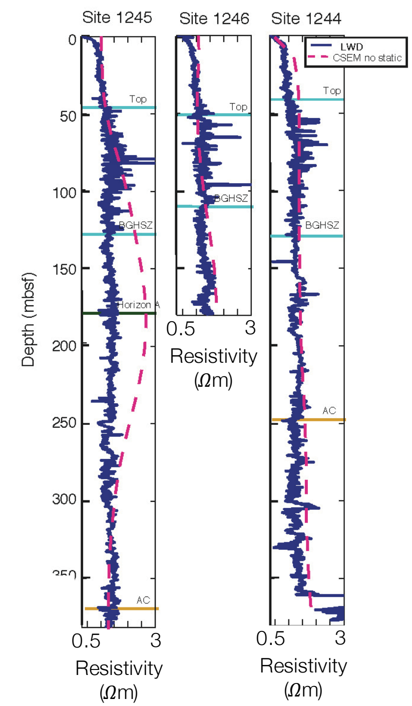
- Resistors are imaged near BSR
- Hydrate stability
  - Above BSR: hydrate
  - Below BSR: free gas

Interpretation / Synthesis

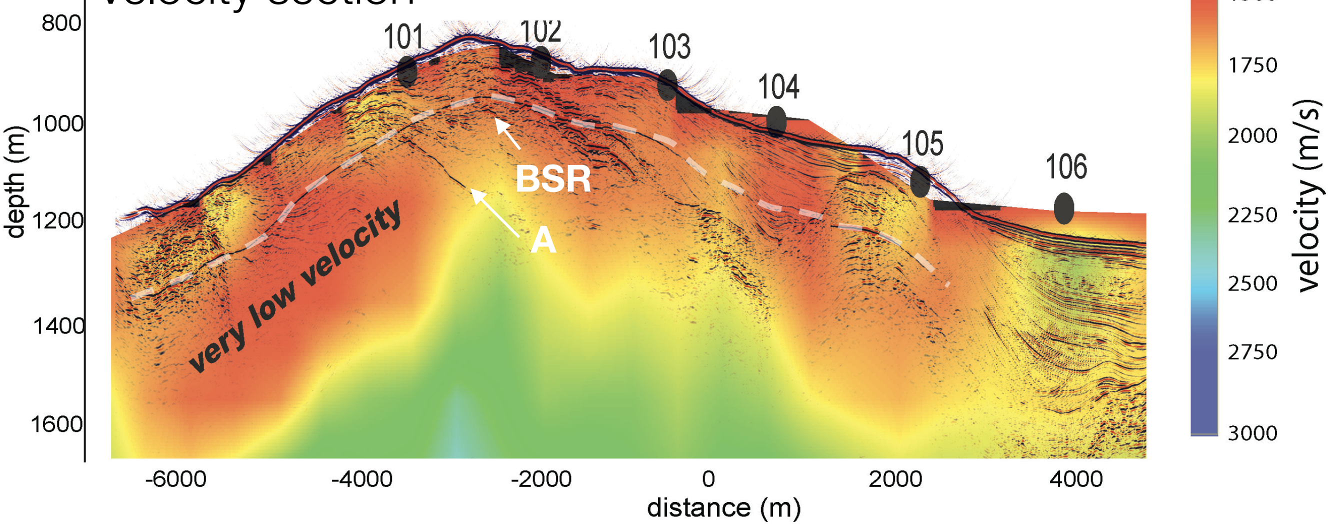
Resistivity section



Well-logs



Velocity section

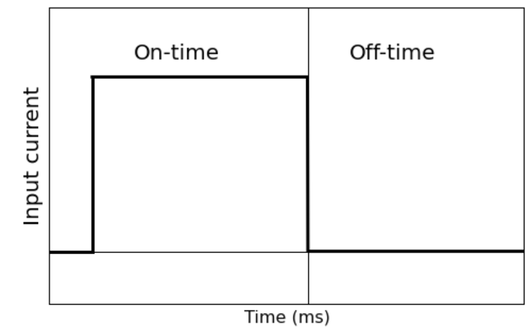


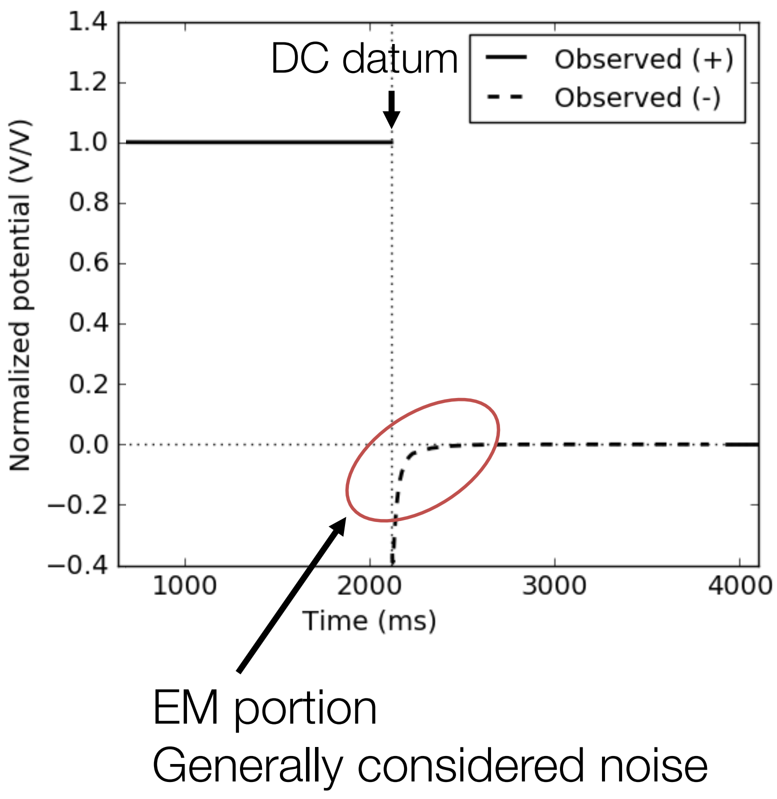
Hydrate	ρ	V_p
Free gas	High	Low
Solid	High	High

DC/EM Inversion

DC/EM: Goals

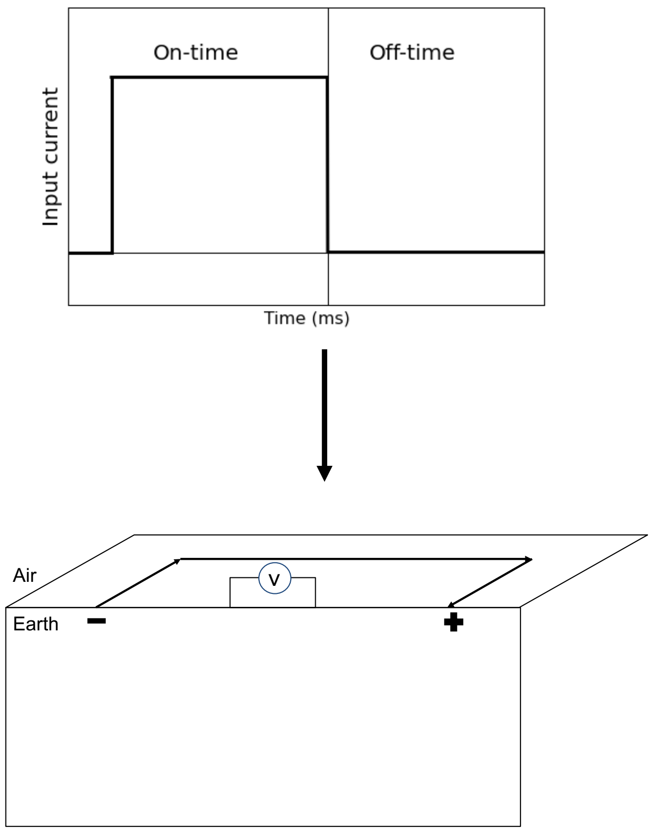
- Standard DCR time domain waveform
- Compare:
  - Inversions from DC data
  - Inversions from EM data
- Illustrate the value of data which is often discarded
- Numerical example from a gradient array



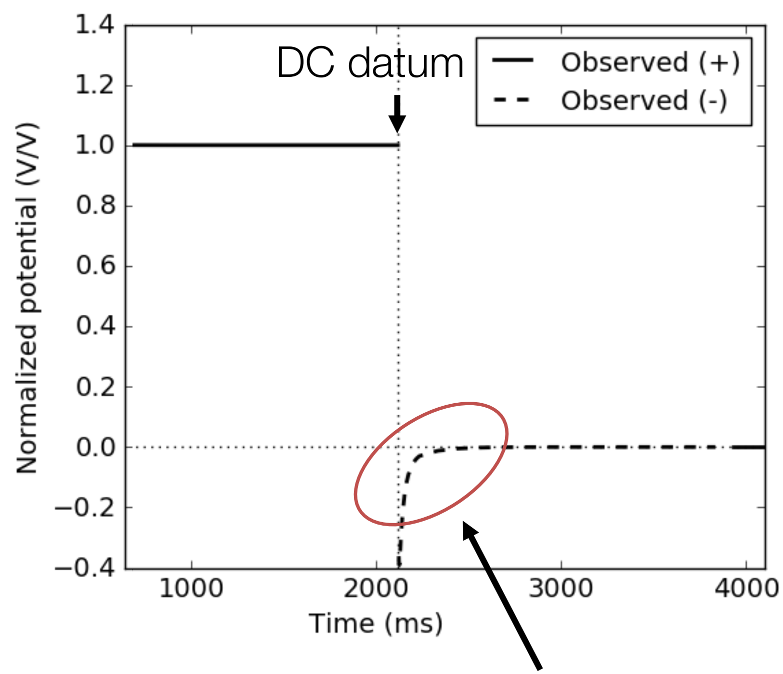


Survey and Data

Transmitter



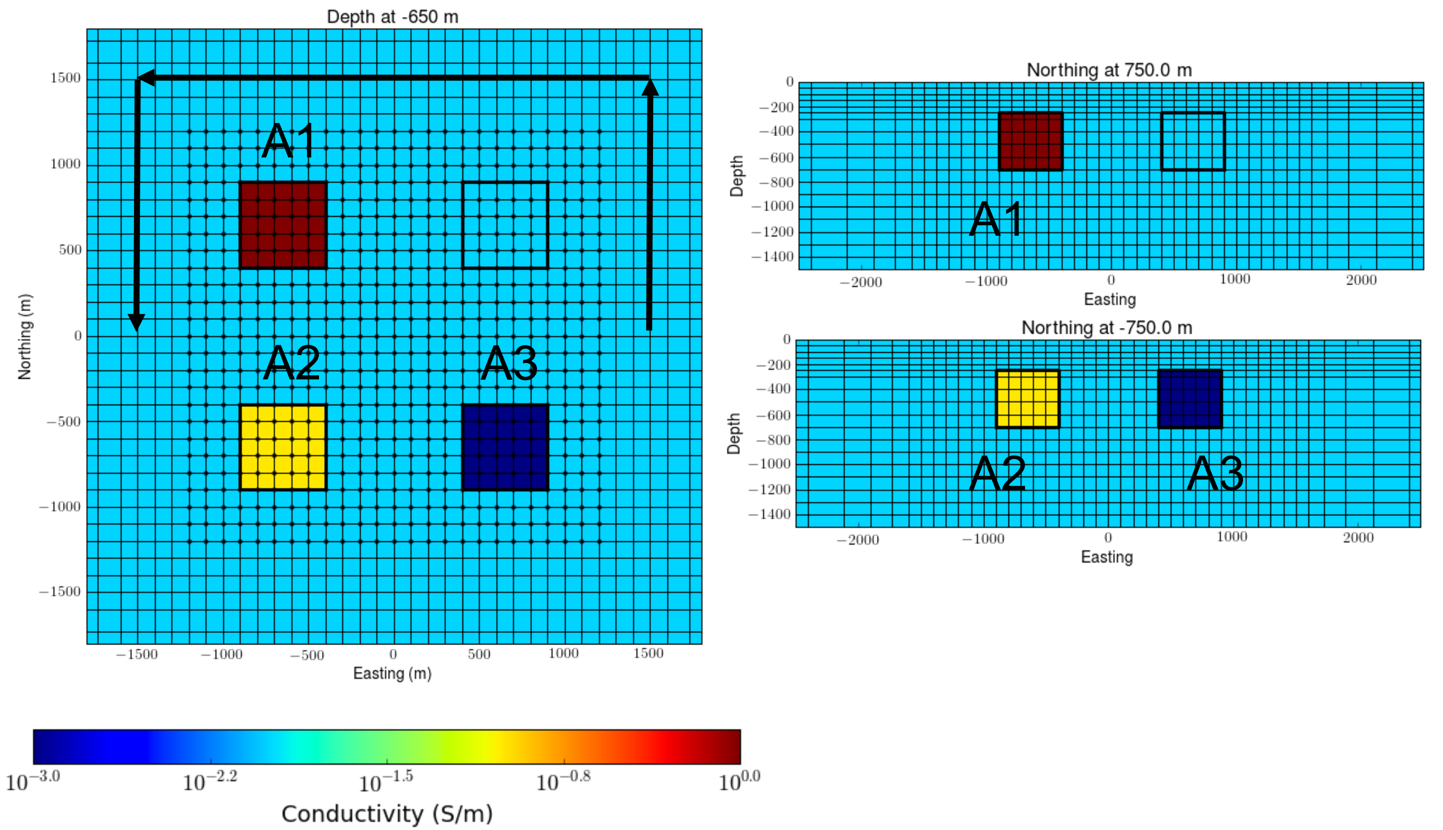
Measured Voltage



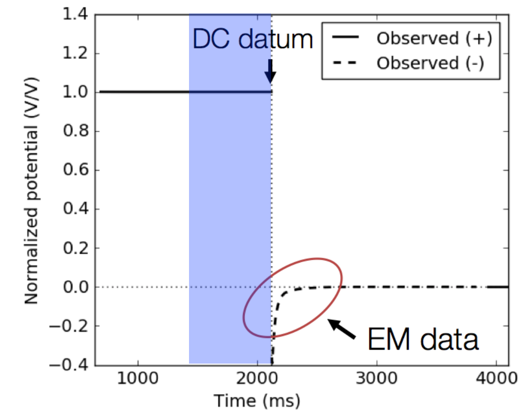
EM portion
Generally considered noise

Gradient array

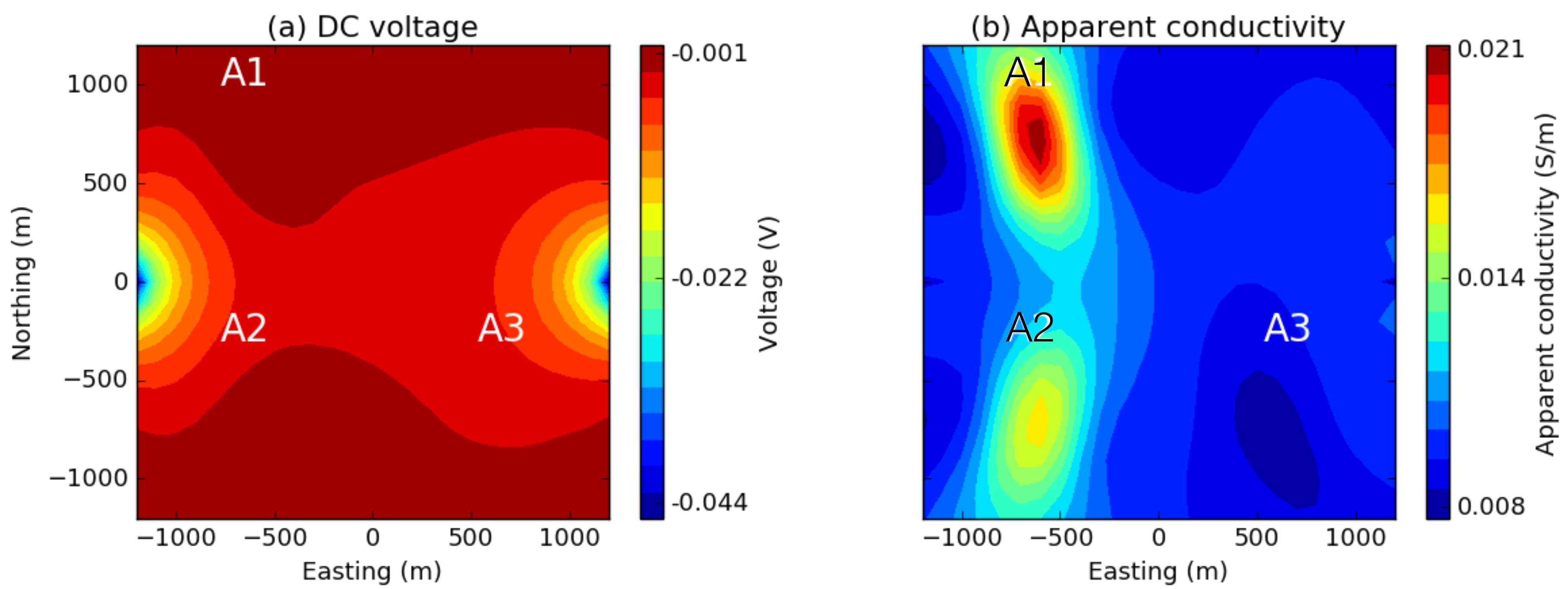
- Model
  - A1: high conductivity
  - A2: moderate conductivity
  - A3: resistive
- Survey
  - 200m bi-pole (625 data)
  - times: 1-600ms



DC data

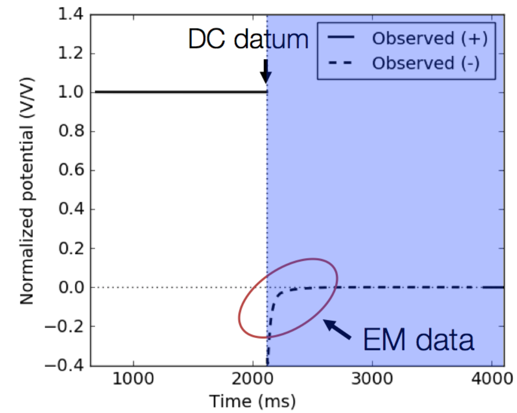


DC datum
Observed (+)
Observed (-)
EM data
Normalized potential (V/V)
Time (ms)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
1000
2000
3000
4000

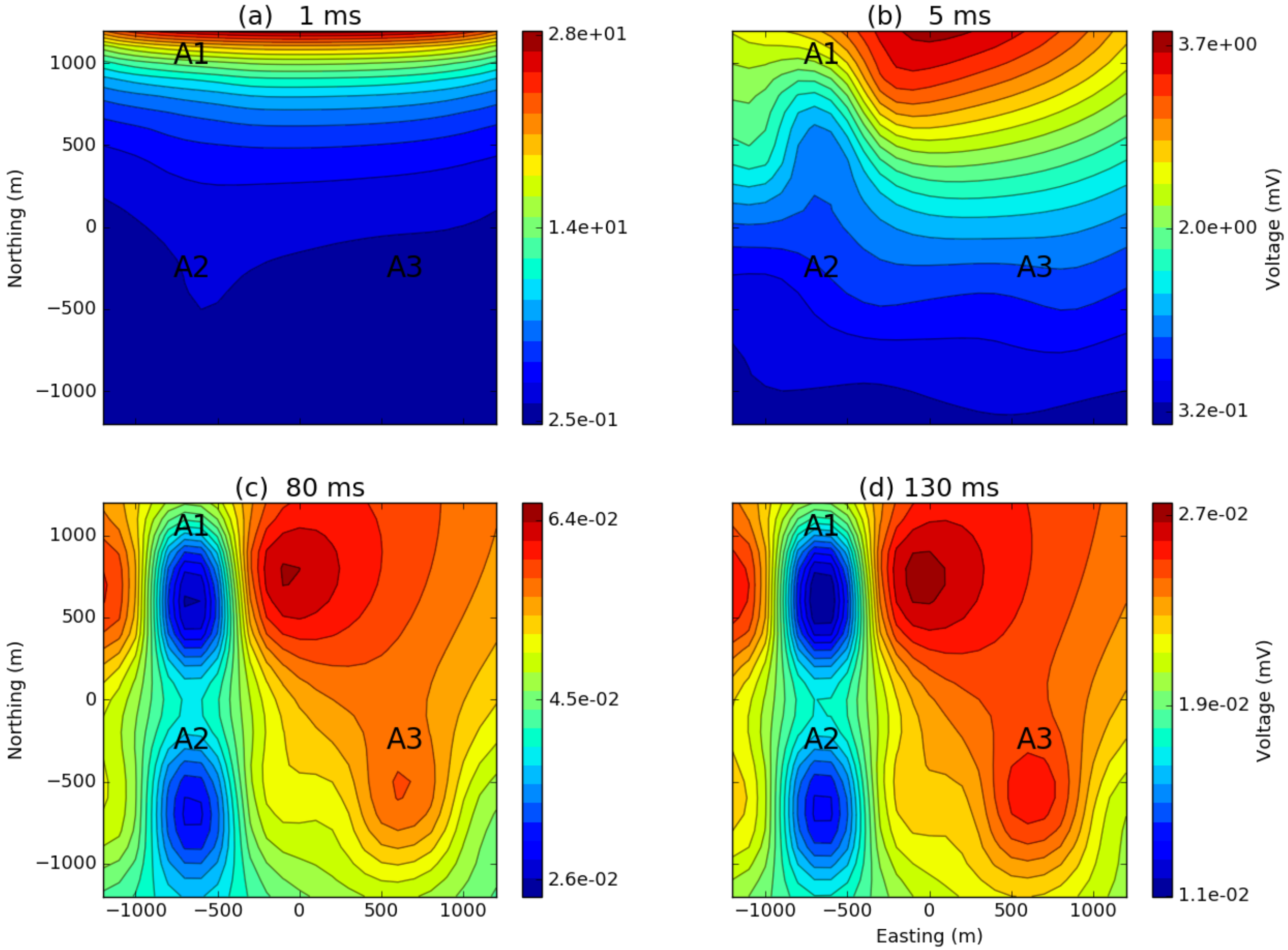


(a) DC voltage
A1
A2
A3
Northing (m)
Easting (m)
Voltage (V)
-0.001
-0.022
-0.044
1000
500
0
−500
−1000
(b) Apparent conductivity
A1
A2
A3
Easting (m)
Apparent conductivity (S/m)
0.021
0.014
0.008
−1000
−500
0
500
1000

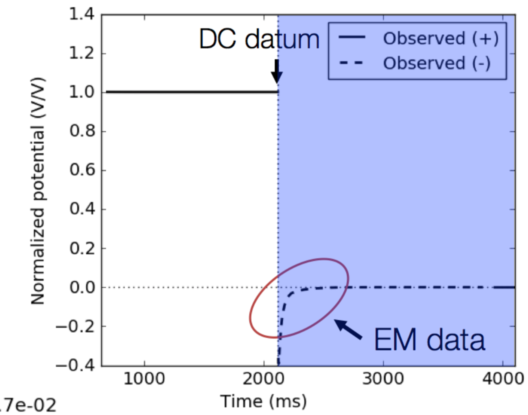
Off-time data



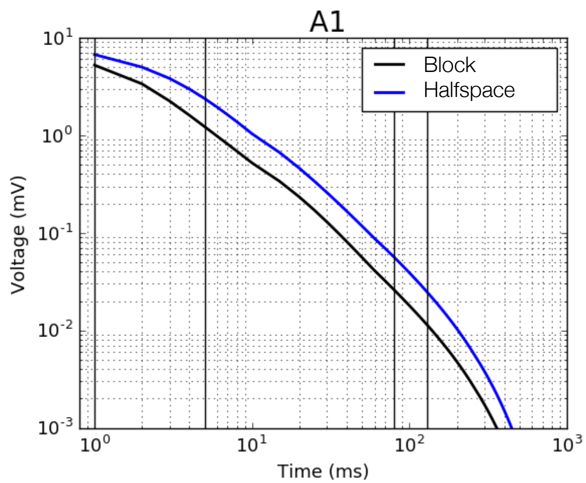
- TDEM data

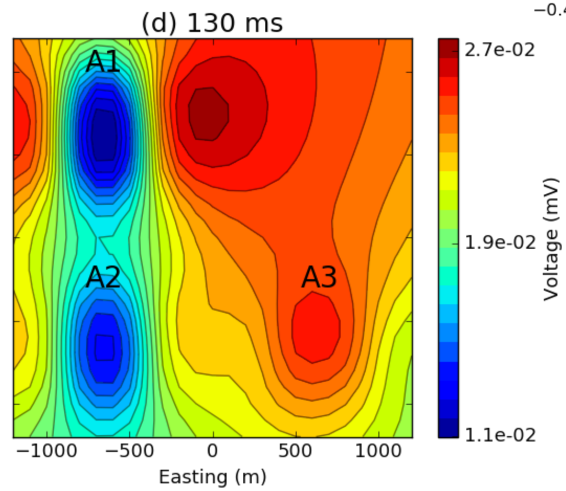


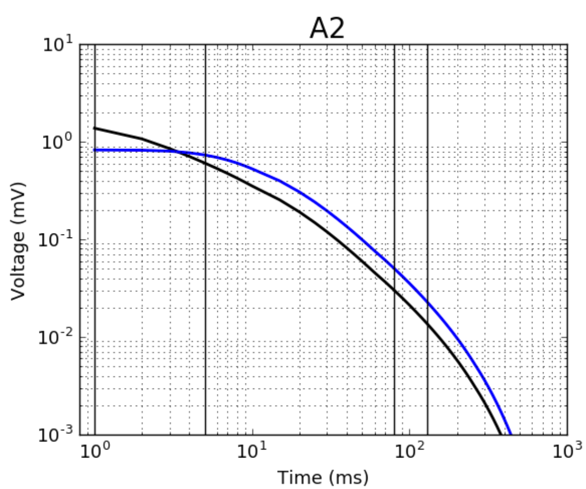
Off-time data

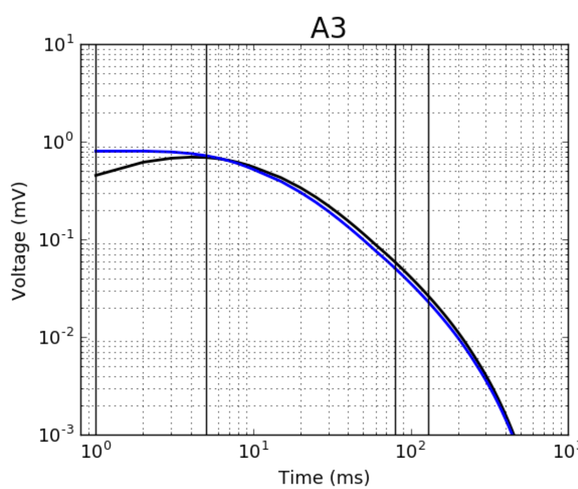


- E_x Decay curves at A1-A3



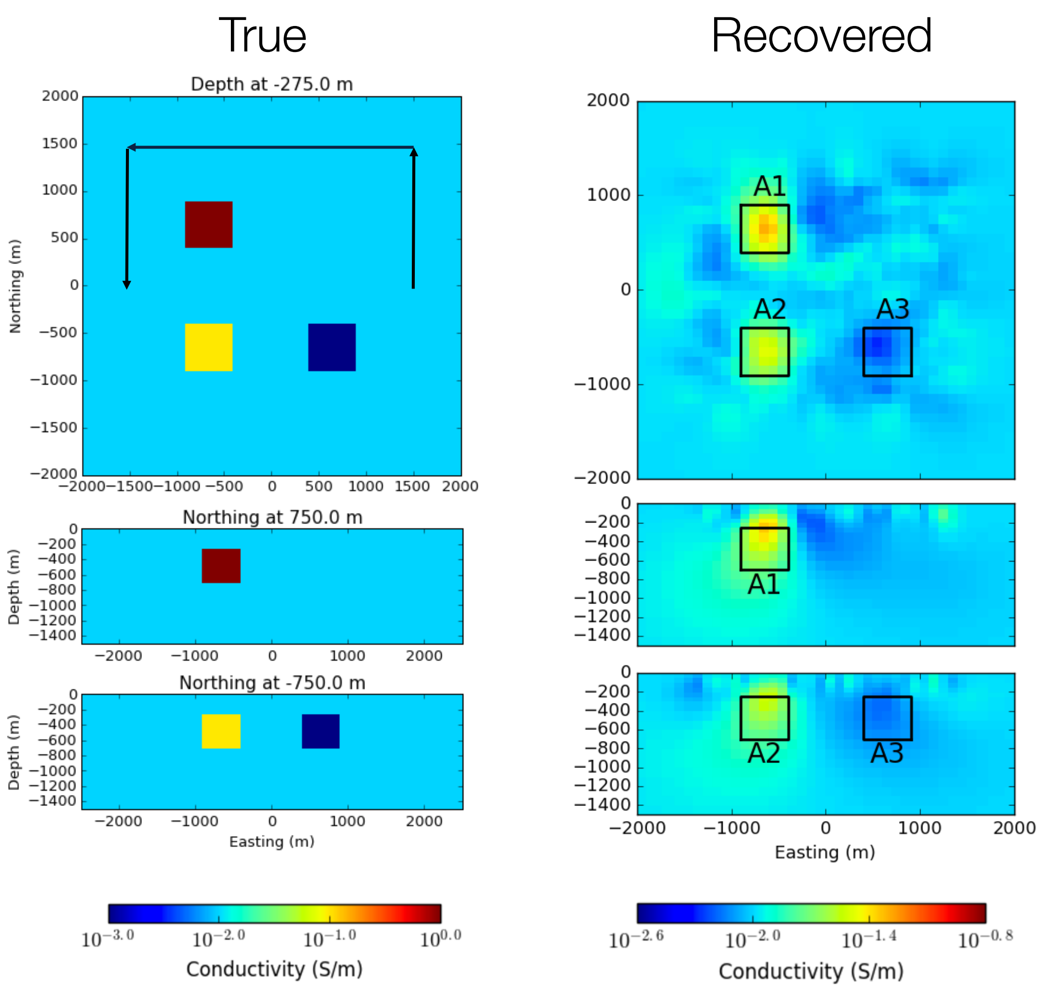




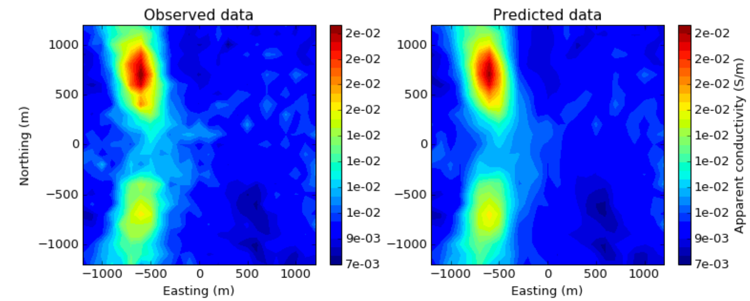


DC inversion

- Recovered 3D conductivity



Apparent conductivity

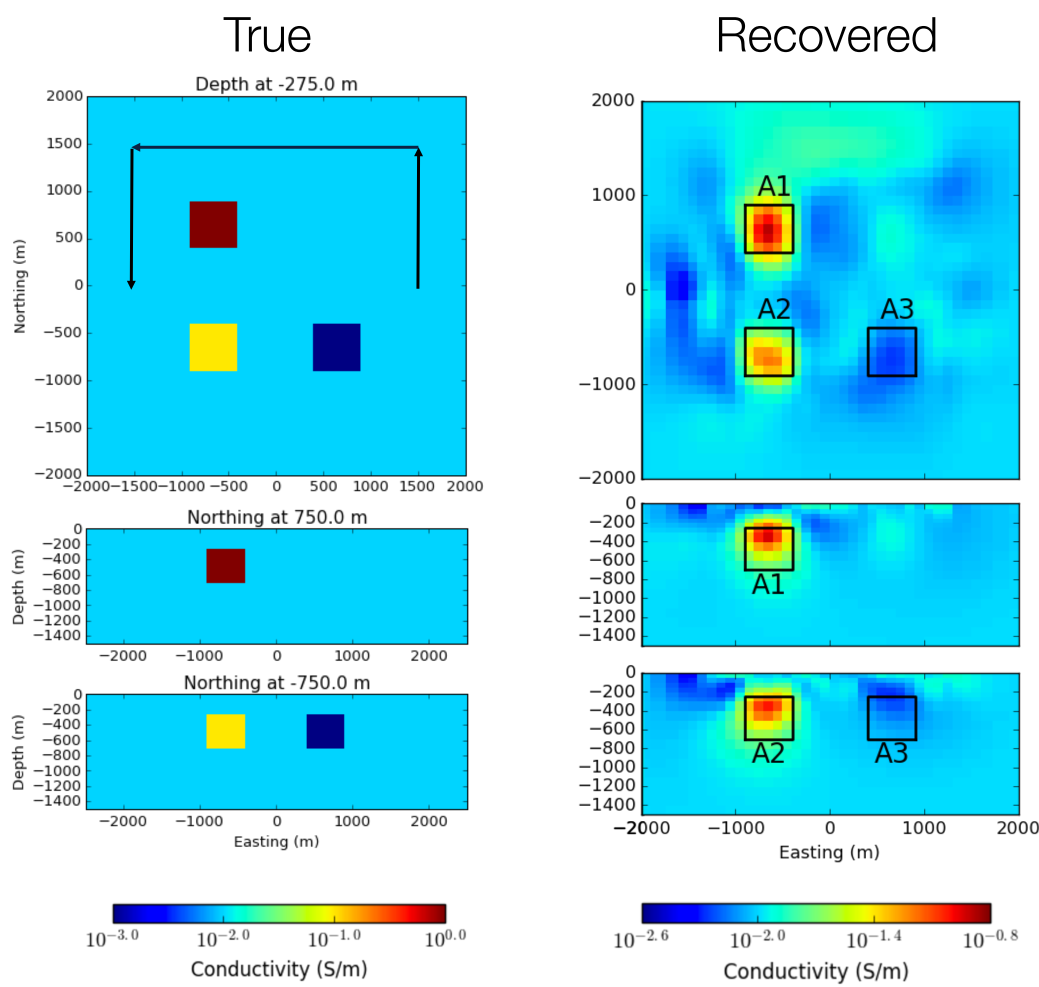


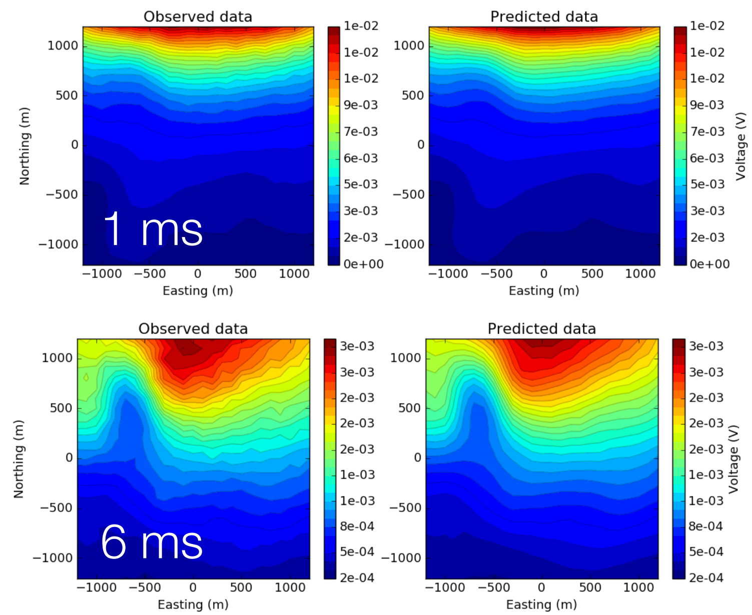
- Depth weighting
  - Compensate for high sensitivity near surface (similar to mag.)

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

EM inversion

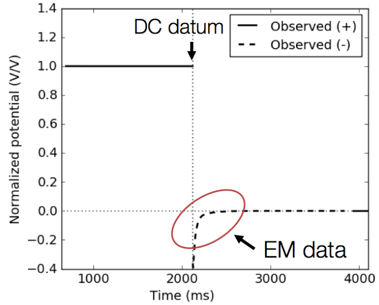
- Recovered 3D conductivity





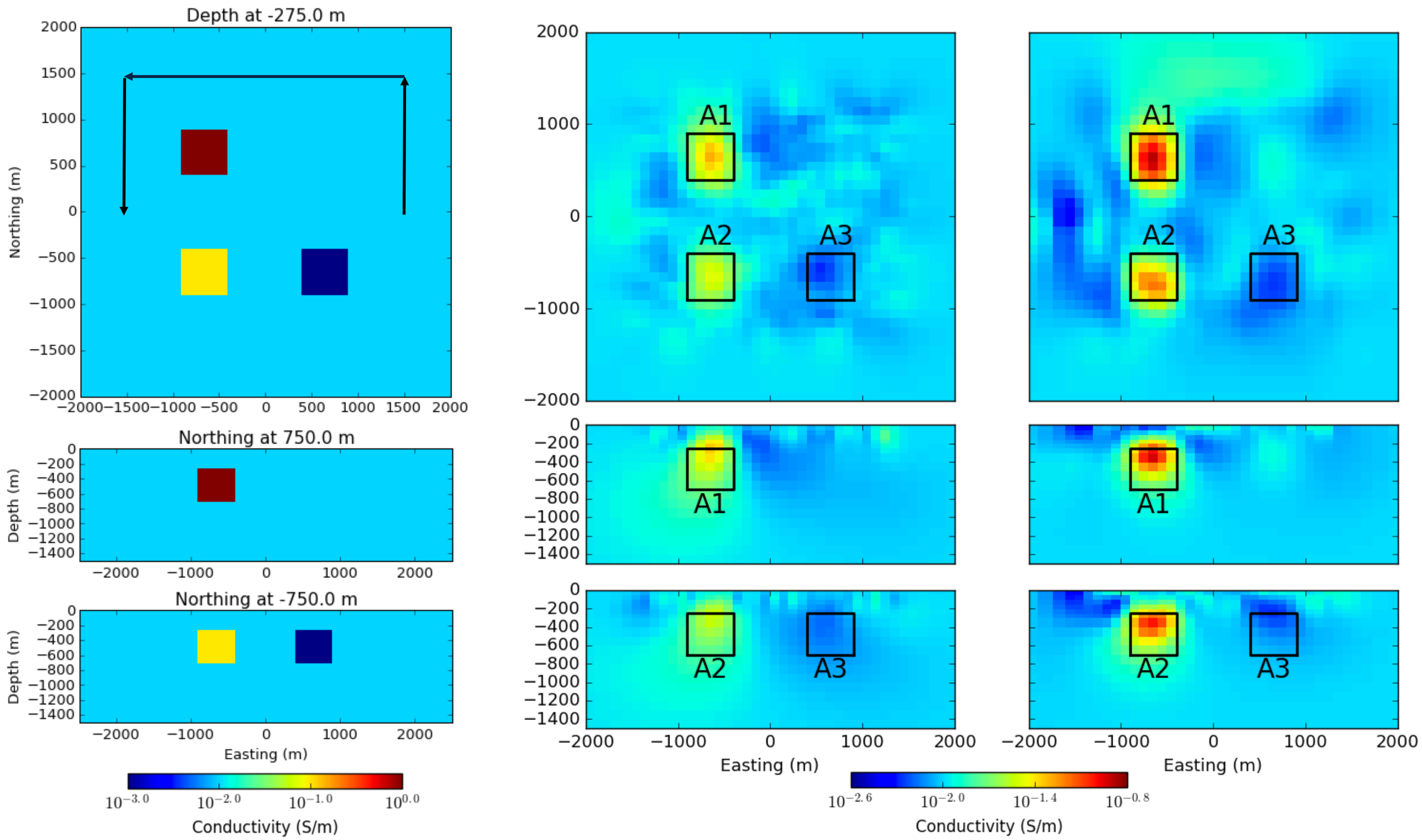
- No depth weighting

Conductivity models



- True, DC, and TEM conductivities

True DC EM



EM data contain signal

End of Grounded Sources