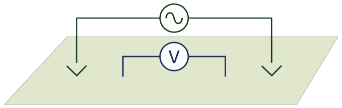
EM: Grounded Sources

DISC
2017
Electromagnetics
Fundamentals and Applications

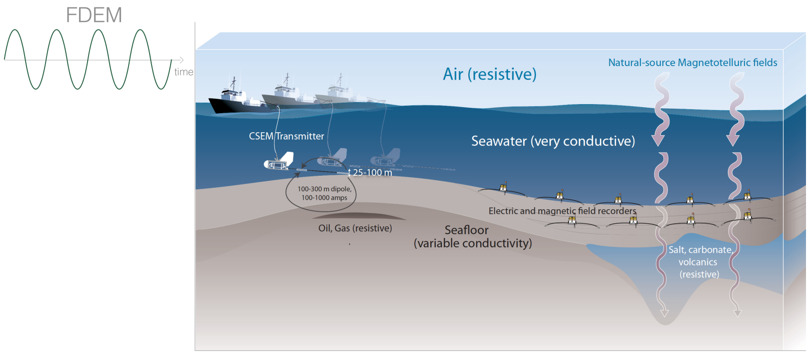


Outline

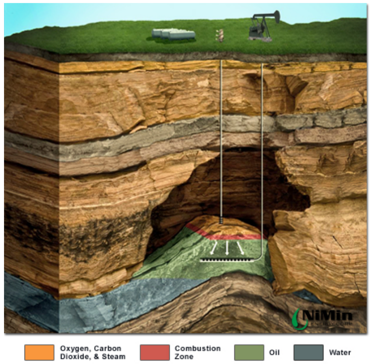
- Basic experiment
- FDEM: Electric dipole in a whole space
- TDEM: Electric dipole in a whole space
- Currents in grounded systems
- Conductive Targets: currents and data
- Resistive Targets: currents and data
- Case History: Barents Sea
- Synthetic Example: Gradient Array

Motivational examples

Marine EM for hydrocarbon



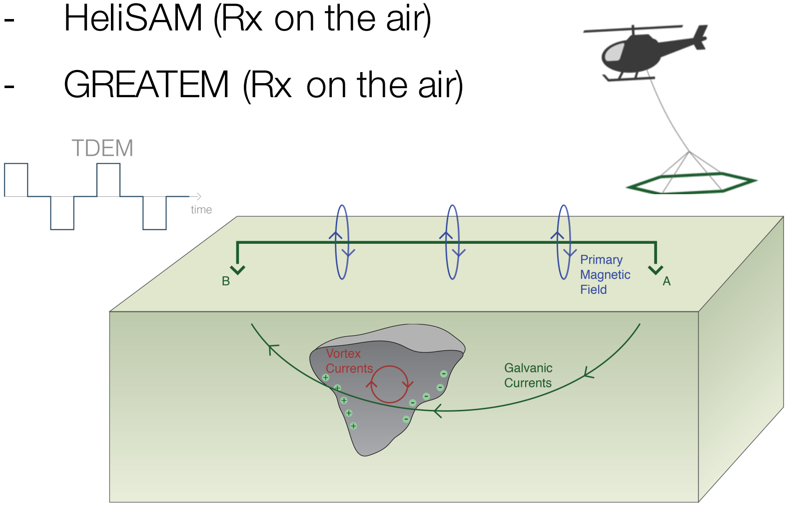
Oil and Gas (EOR)



Gas hydrates

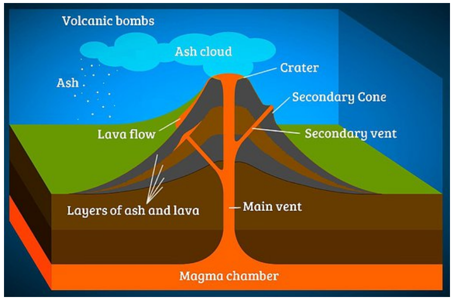
Galvanic source TEM

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

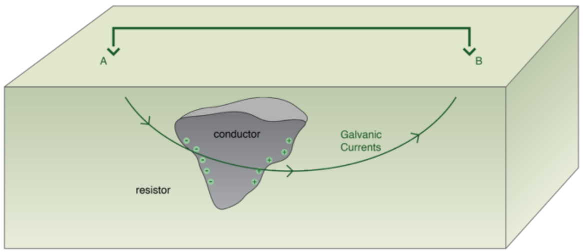


Minerals

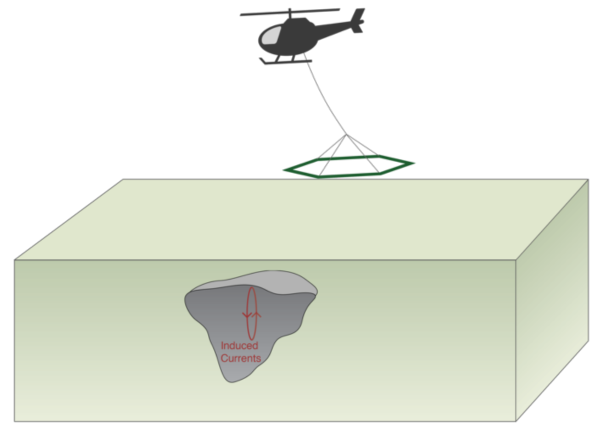
Volcanoes



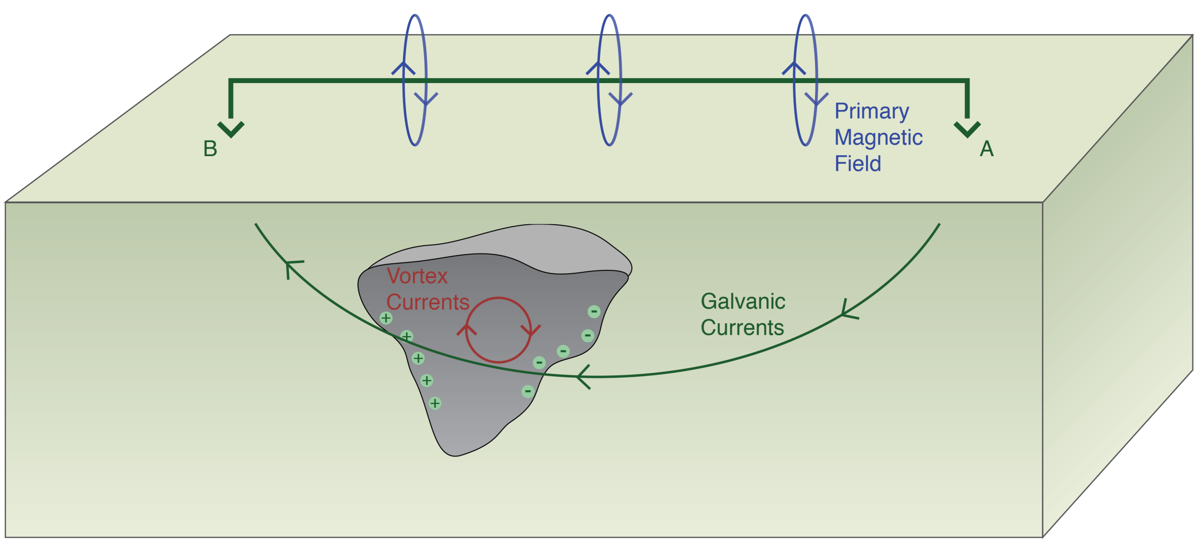
Basic experiment



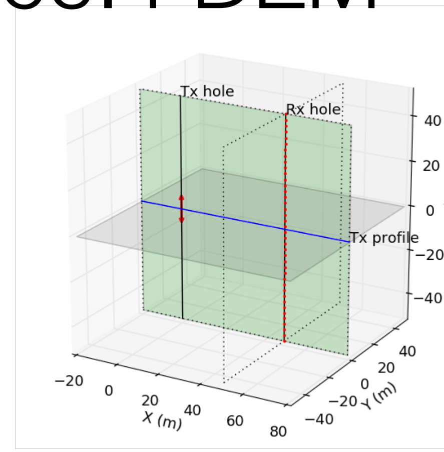
DC resistivity



Inductive source

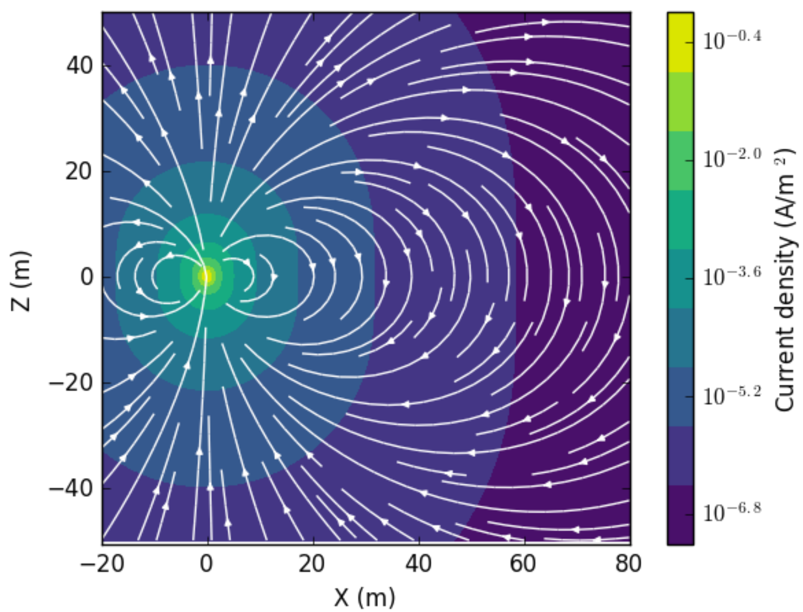


Electric Dipole in a whole space: FDEM



- Electric dipole in a whole space
  - 0 Hz (DC), 0.01 S/m

DC current density



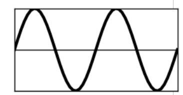
$$\mathbf{E}_{DC}(\mathbf{r}) = \frac{1}{4\pi\sigma|\mathbf{r}|^3}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m}\right)$$

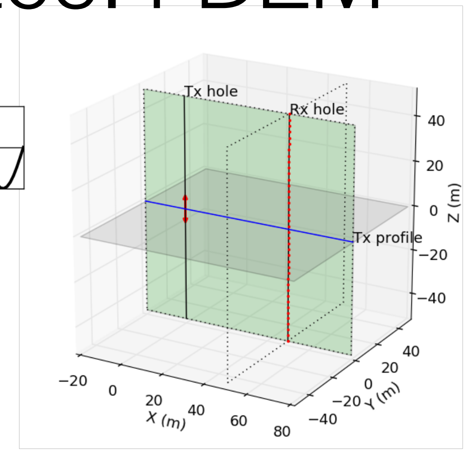
$$\mathbf{J}_{DC}(\mathbf{r}) = \frac{1}{4\pi|\mathbf{r}|^3}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{|\mathbf{r}|^2} - \mathbf{m}\right)$$

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

Electric Dipole in a whole space: FDEM

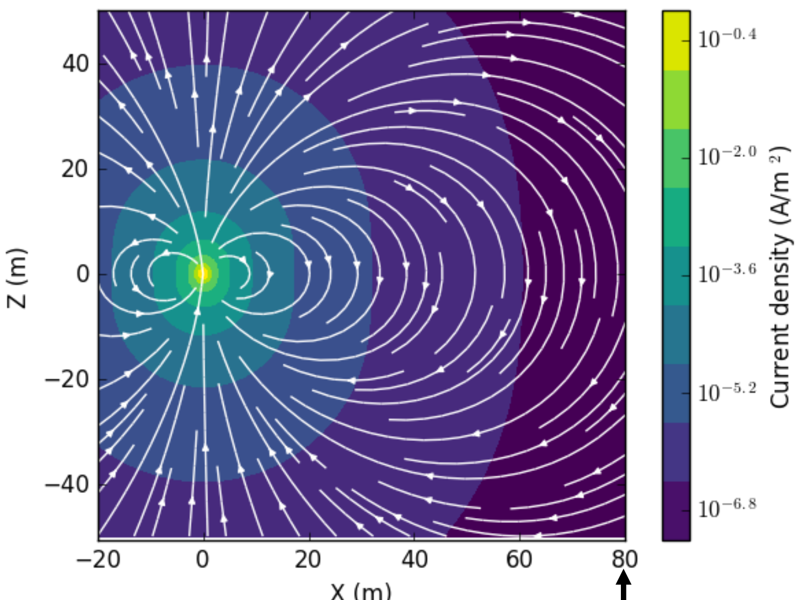
Skin depth: $\delta = \sqrt{\dfrac{2}{\omega\mu\sigma}}.$





- Electric dipole in a whole space
  - 1000 Hz, 0.01 S/m, δ= 160 m

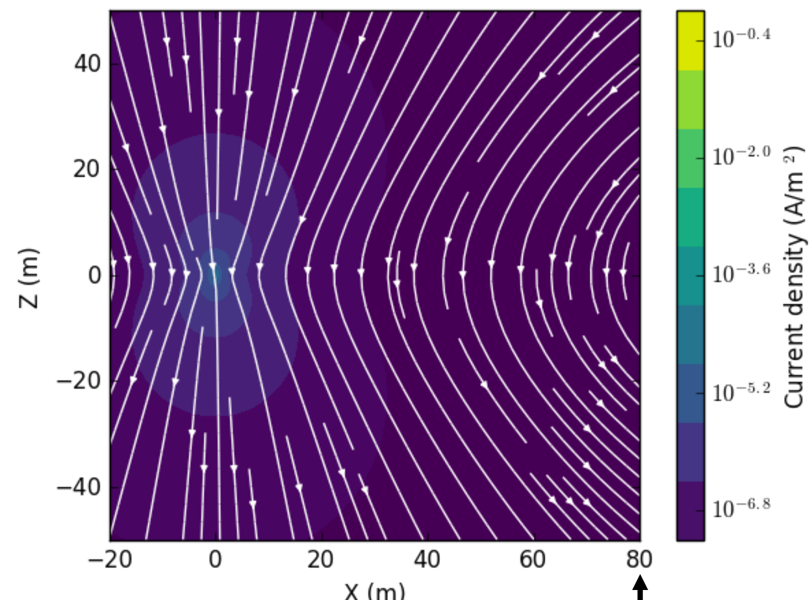
Current density (Real part)



½ δ

DC + EM induction

Current density (Imaginary part)

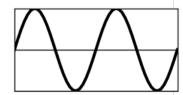


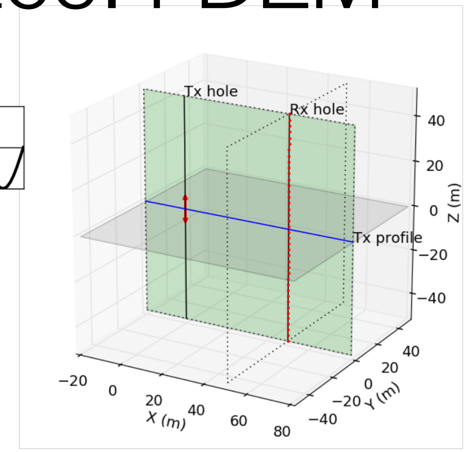
½ δ

EM induction

Electric Dipole in a whole space: FDEM

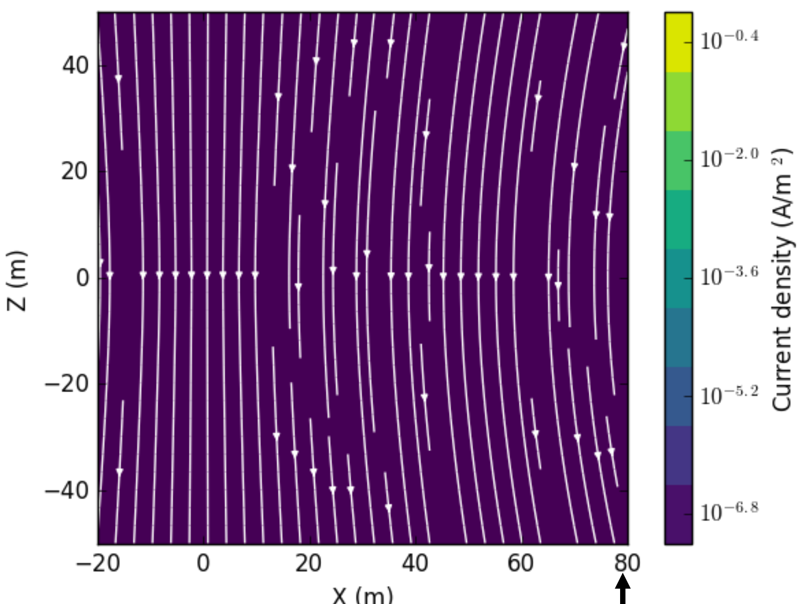
Skin depth: $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$.





- Electric dipole in a whole space
  - 1 kHz, 0.01 S/m, δ= 160 m

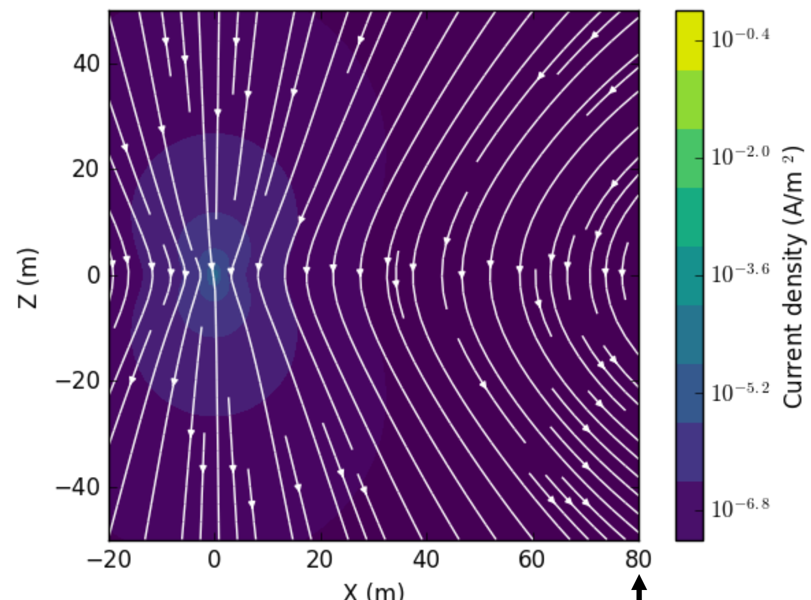
Remove DC part
Re (J) –J^{DC}



½ δ

EM induction

Im (J)

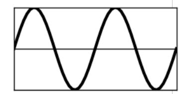


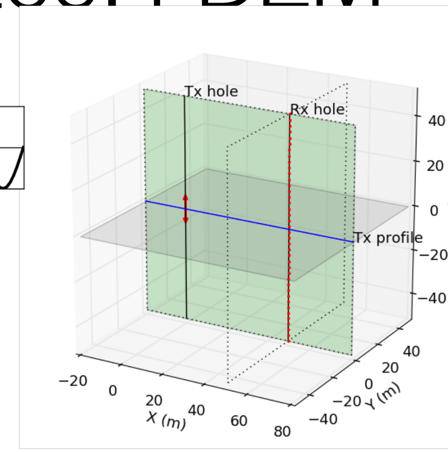
½ δ

EM induction

Electric Dipole in a whole space: FDEM

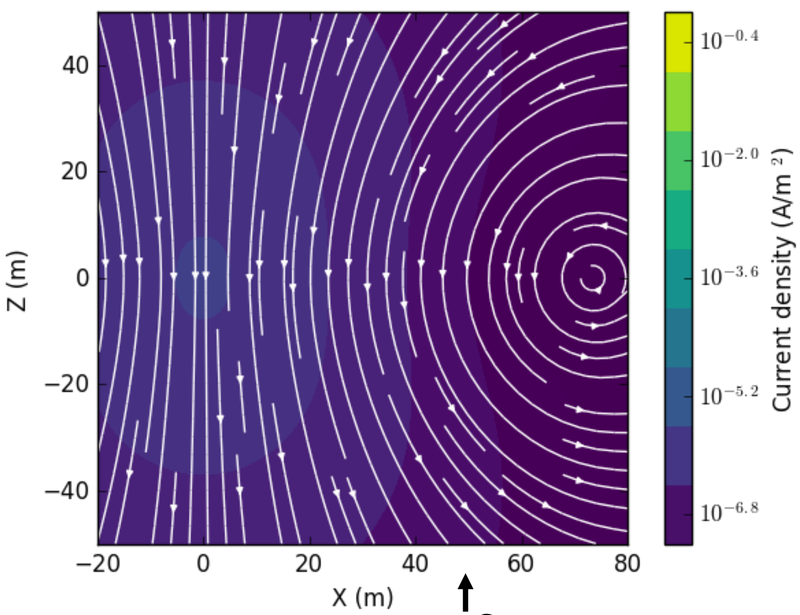
Skin depth: $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}.$





- Electric dipole in a whole space
  - 10 kHz, 0.01 S/m, δ= 50 m

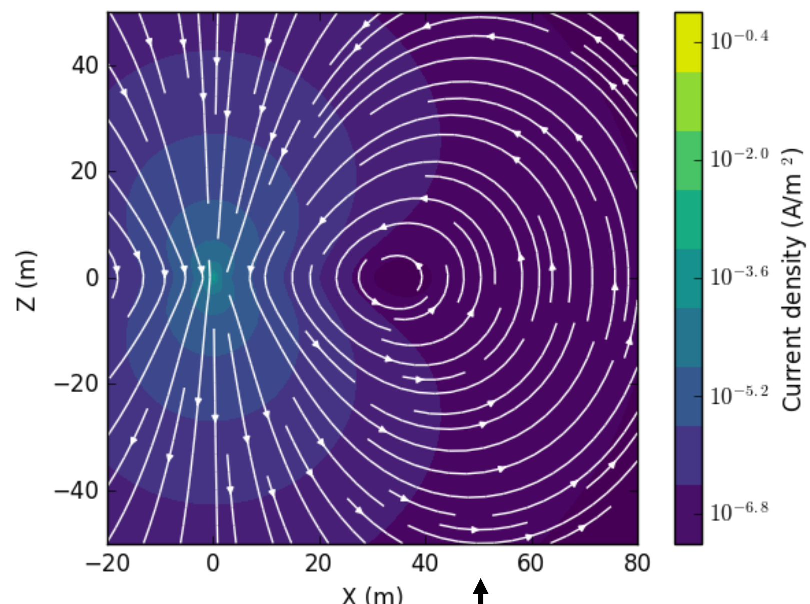
Re (J) $-J^{DC}$



1 δ

EM induction

Im (J)

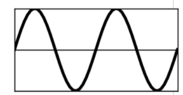


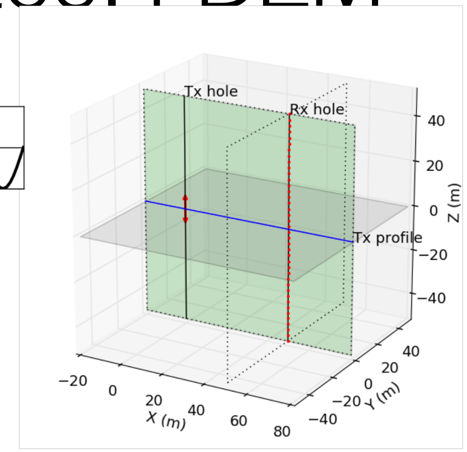
1 δ

EM induction

Electric Dipole in a whole space: FDEM

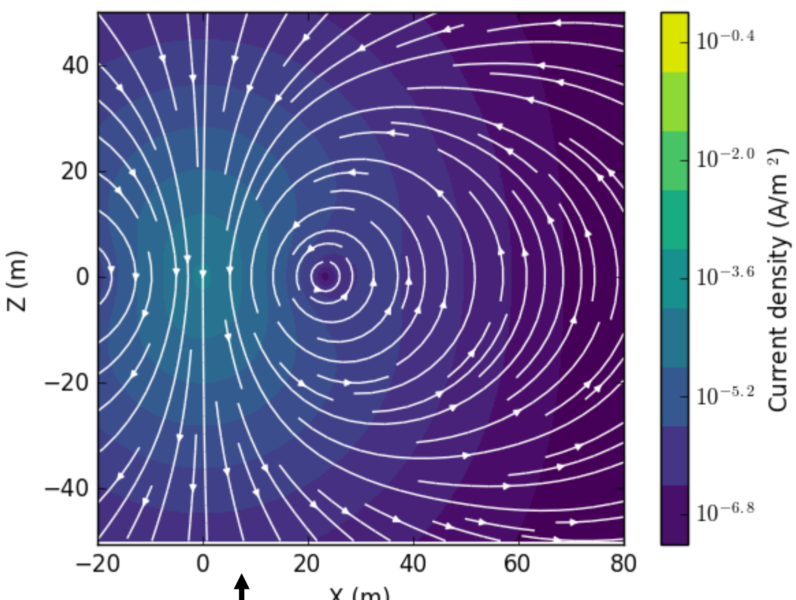
Skin depth: $\delta = \sqrt{\frac{2}{\omega\mu\sigma}}.$





- Electric dipole in a whole space
  - 100 kHz, 0.01 S/m, δ= 16 m

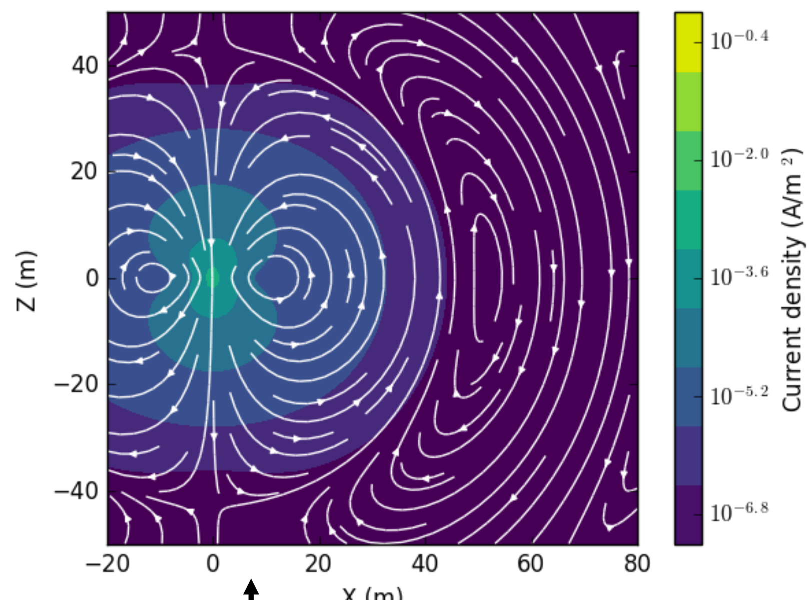
Re (J) –J^{DC}



1 δ

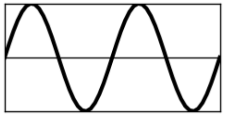
EM induction

Im (J)



1 δ

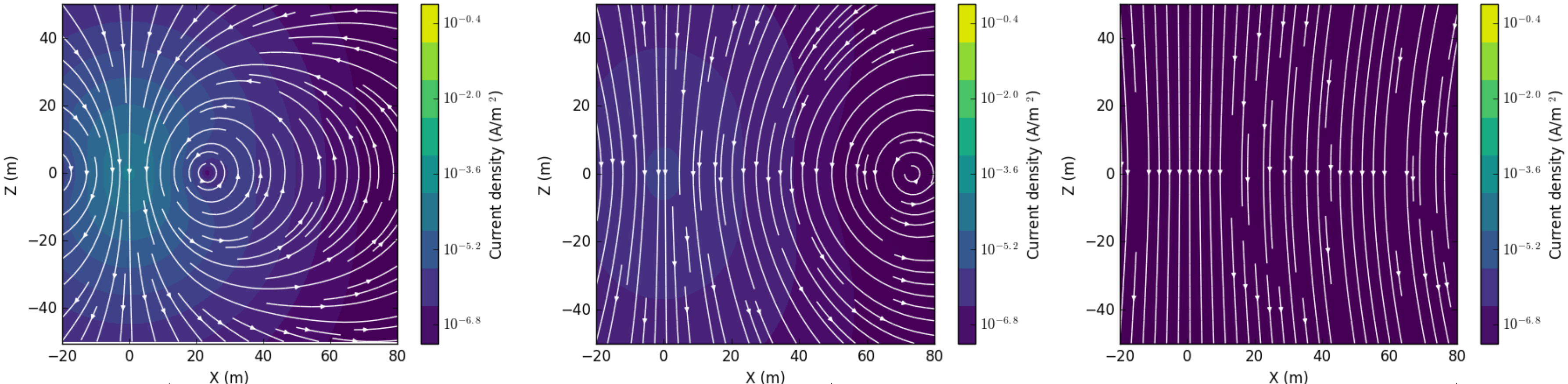
EM induction



Summary:
FDEM Electric Dipole in a whole space

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

Re (**J**) −**J**^{DC}



1 δ

1 δ

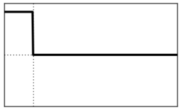
½ δ

100 kHz

10 kHz

1 kHz

In time…



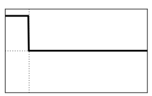
Electric Dipole in a whole space: TDEM

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

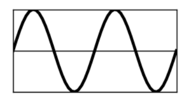
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

f=10^{4} kHz, δ = 2 m

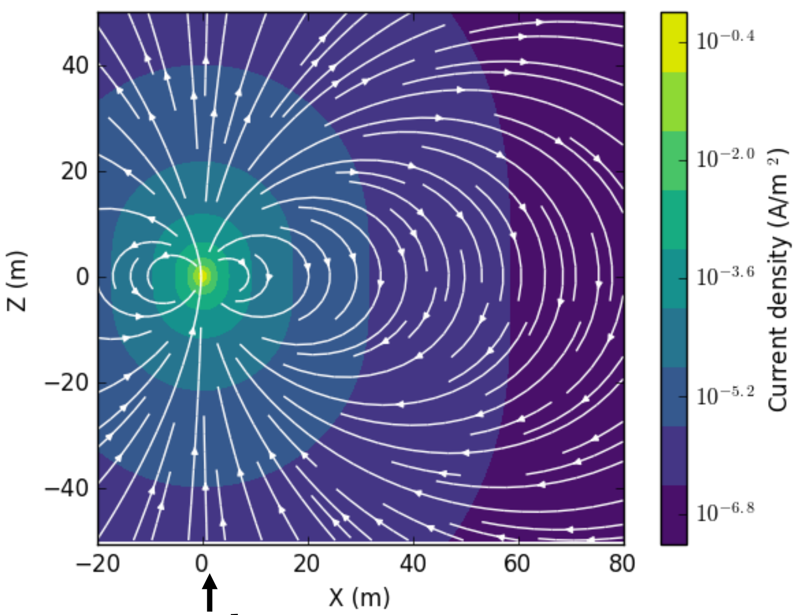
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



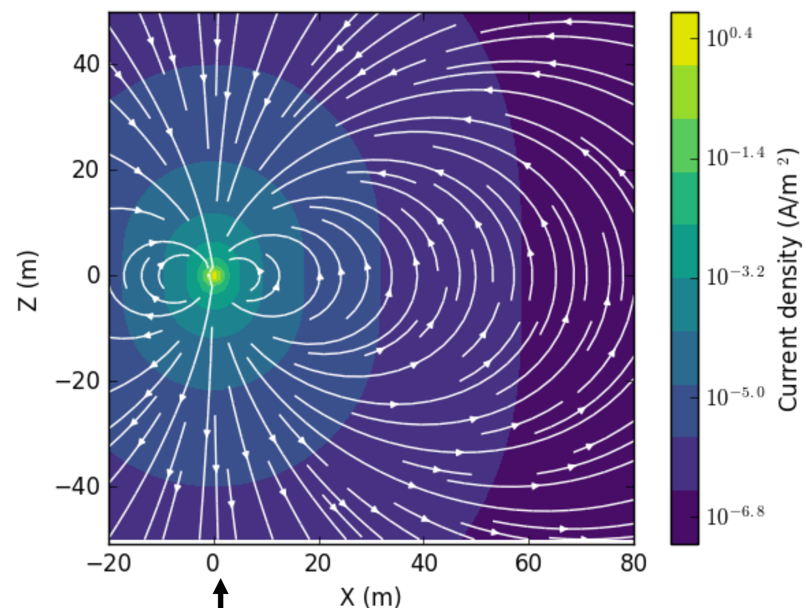
j



Re (J) – Re(J^{DC})



1 d

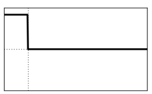


1 δ

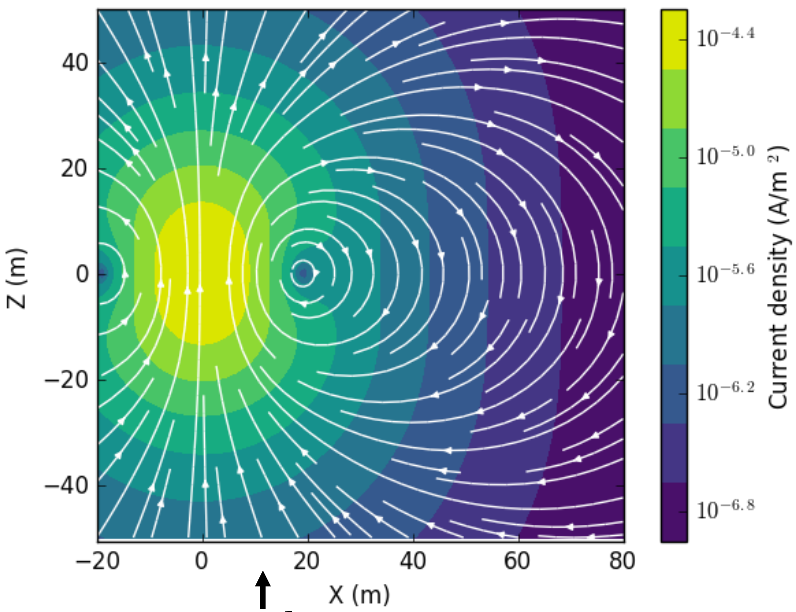
Electric Dipole in a whole space: TDEM

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

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



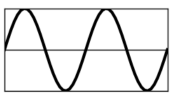
j



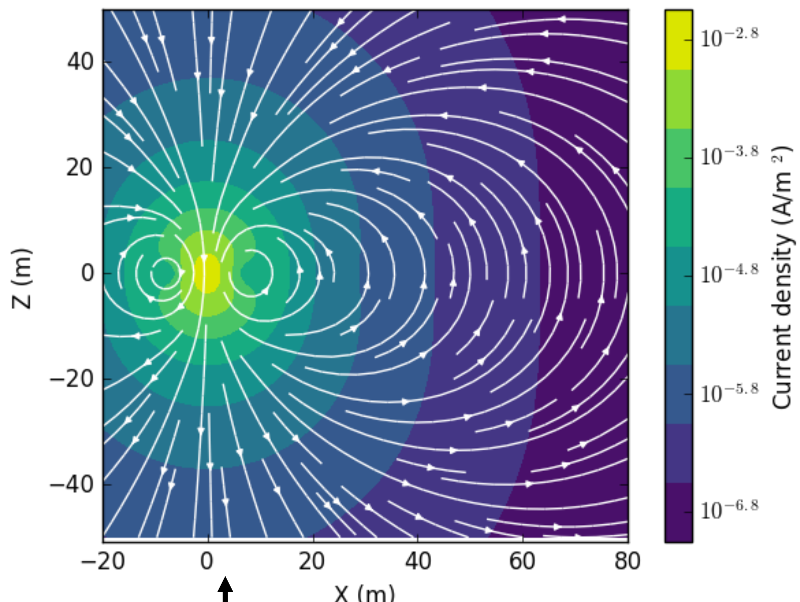
1 d

f=10^3 kHz, δ = 5 m

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



Re (J) – Re(J^{DC})



1 δ

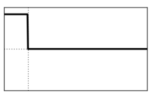
Electric Dipole in a whole space: TDEM

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

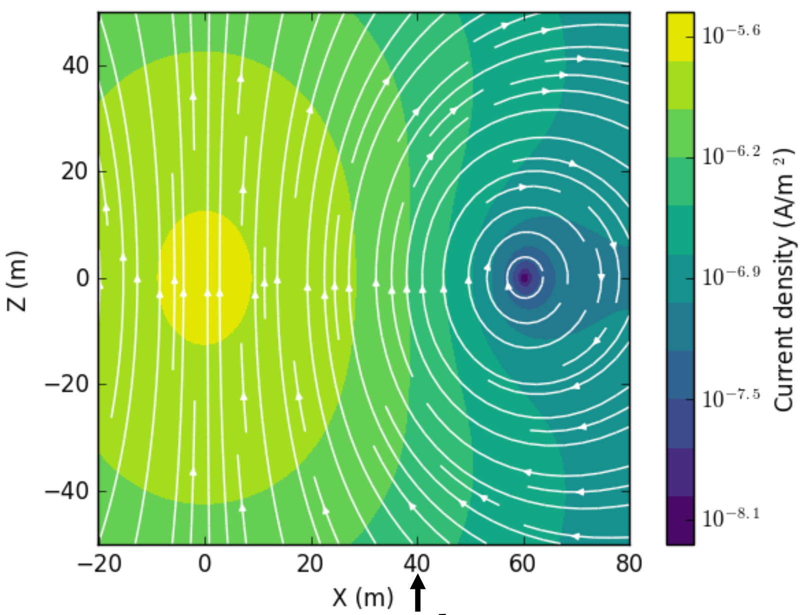
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

f=10^2 kHz, δ = 16 m

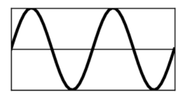
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$



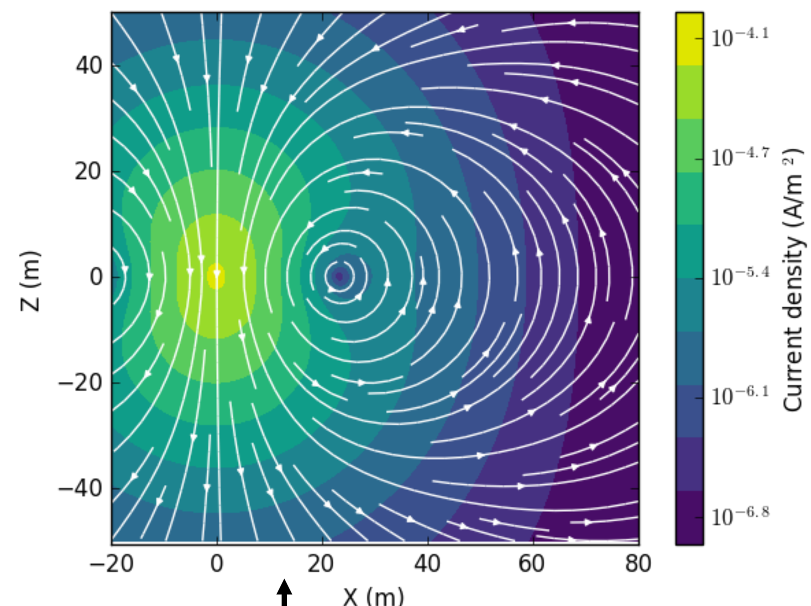
j



1 d



Re (J) – Re(J^{DC})

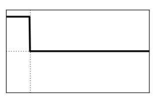


1 δ

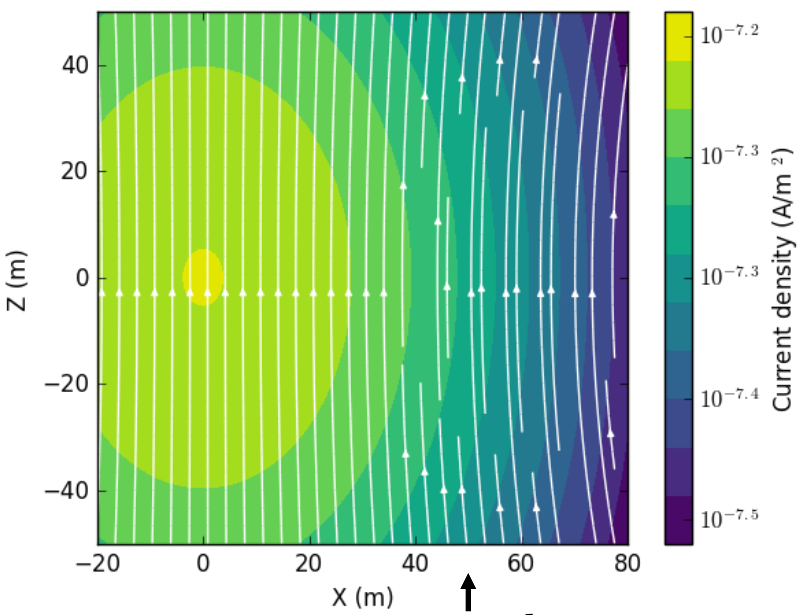
Electric Dipole in a whole space: TDEM

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

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



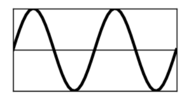
j



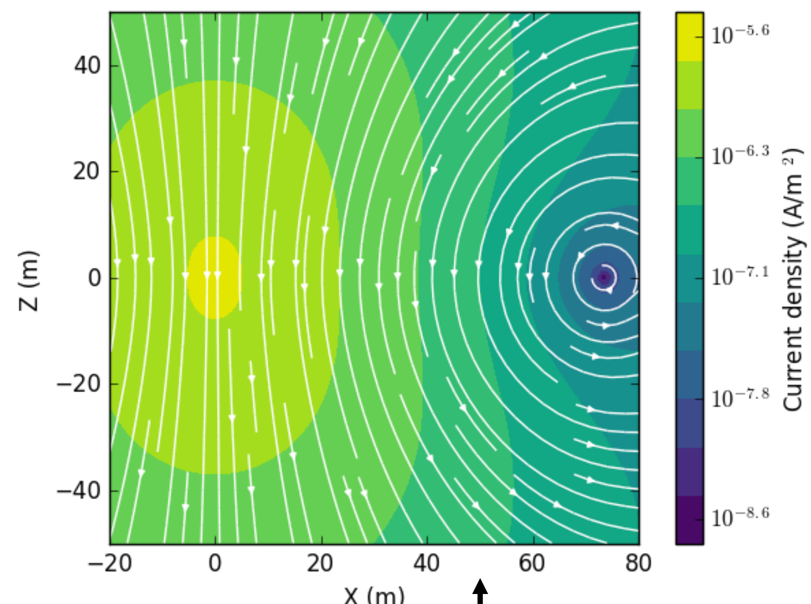
2/5 d

f=10^{1} kHz, δ = 50 m

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



Re (J) – Re(J^{DC})



1 δ

Electric Dipole in a whole space: TDEM

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

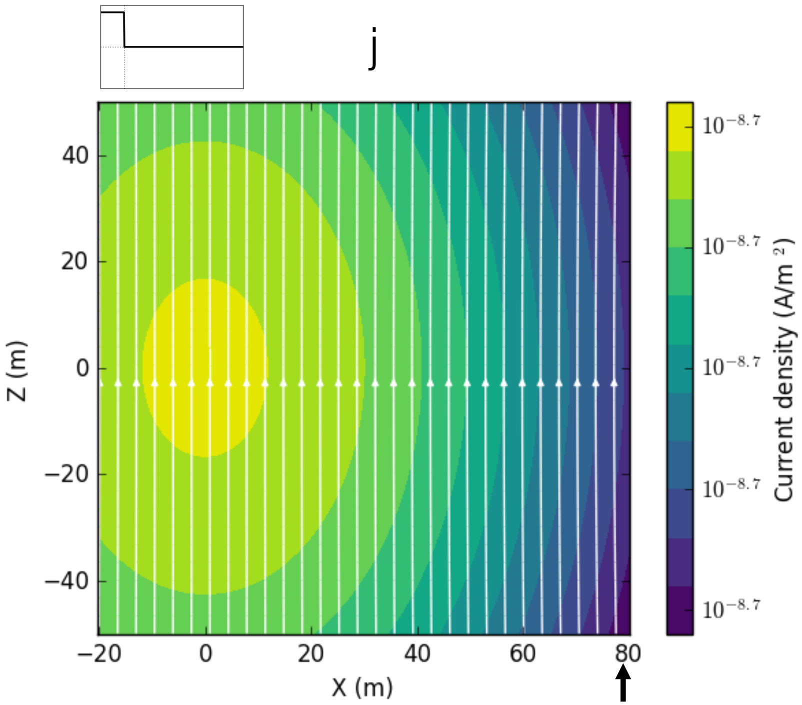
$$d = \sqrt{\frac{2t}{\mu\sigma}}$$

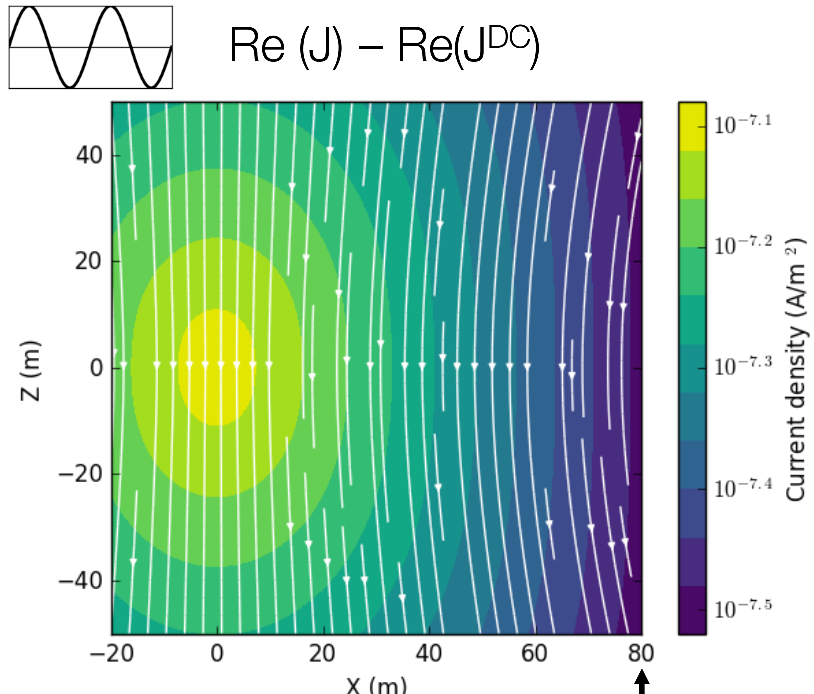
f=1 kHz, δ = 160 m

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

j

Re (J) – Re(J^{DC})



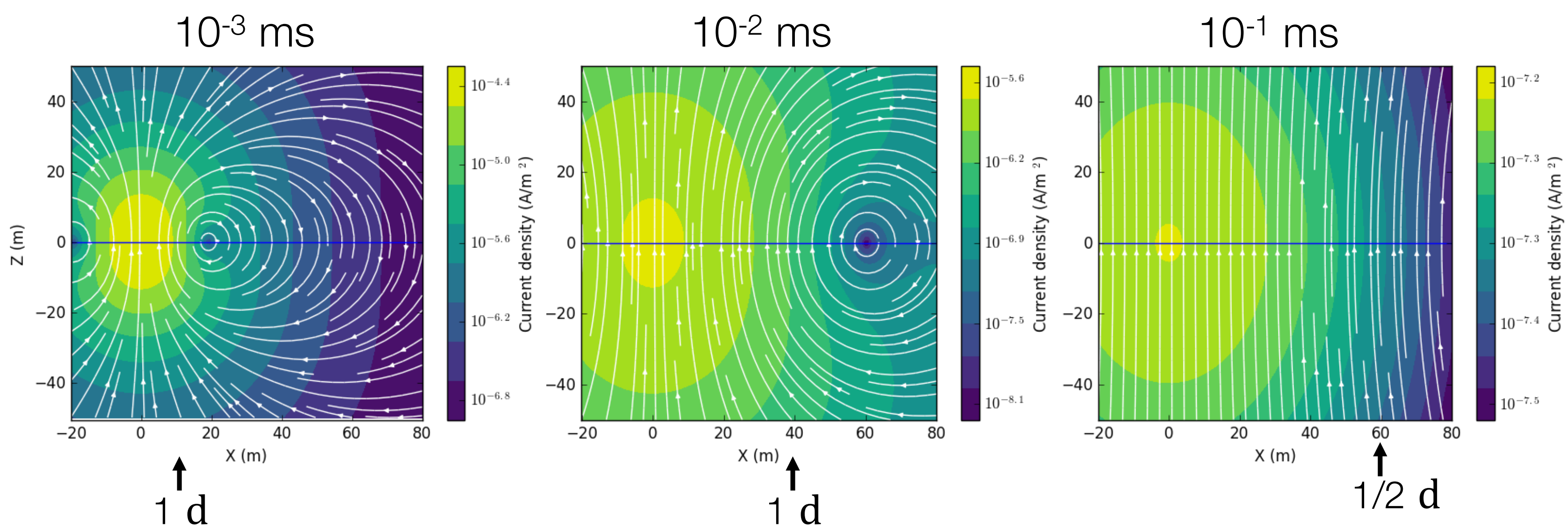


1/5 $\mathbf{d}$

½ δ

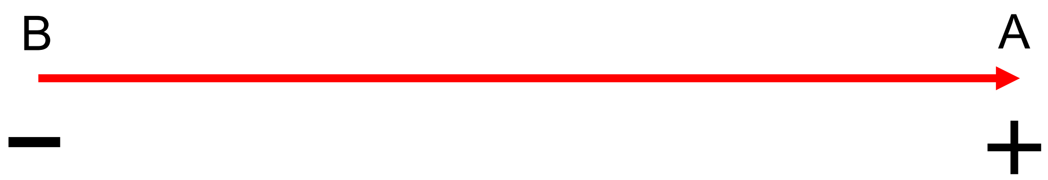
Diffusing currents

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



Bipole Sources

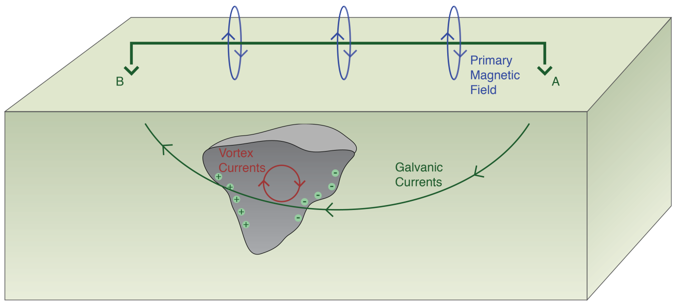
- Extended line sources
  - Grounded term (**galvanic**) + wire path (**inductive**)
  - Straight line



  - Crooked line (horse shoe)

Grounded Sources: On the surface

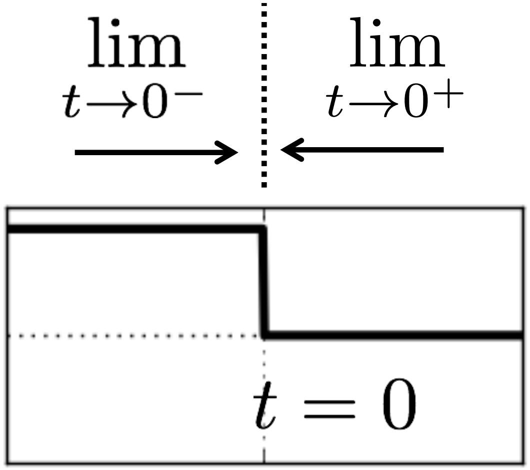
- Ability to detect target depends on
  - Geometry, conductivity of target & host
  - Geometry of TX
  - Frequency or time
  - Fields and components measured
    - e, b, db/dt
  - Location of Tx and Rx with respect to the target

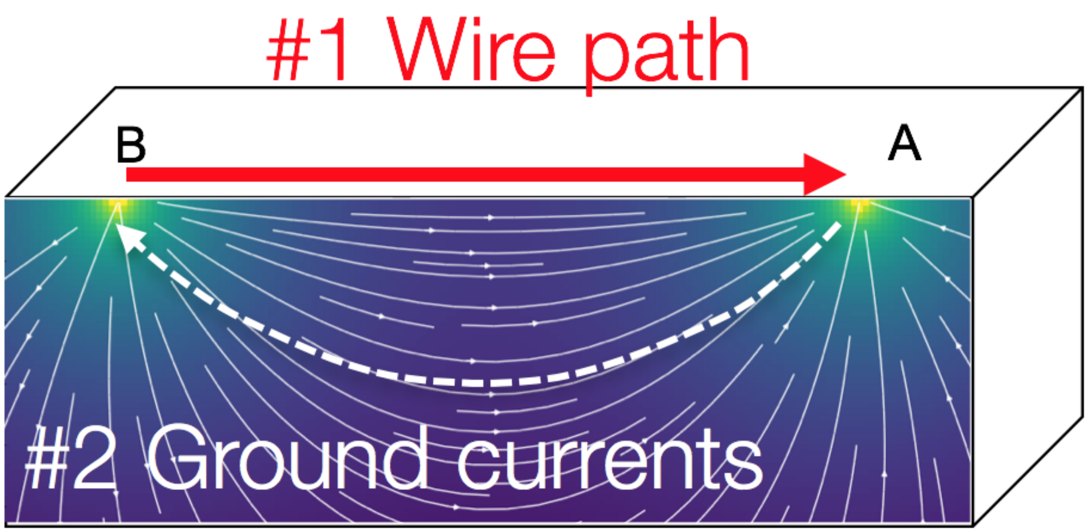


- Lots of variables…
  - Use an example to highlight important concepts

Currents: Grounded System

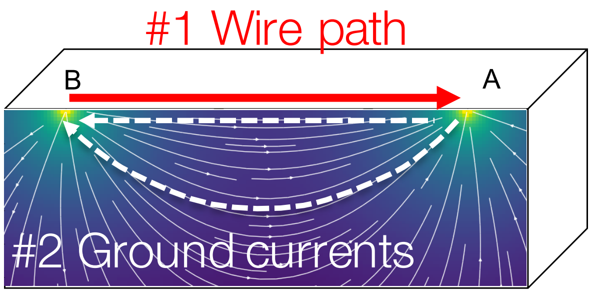
- t = 0⁻ Steady state
- t = 0 Shut off current
- t = 0⁺ Off-time

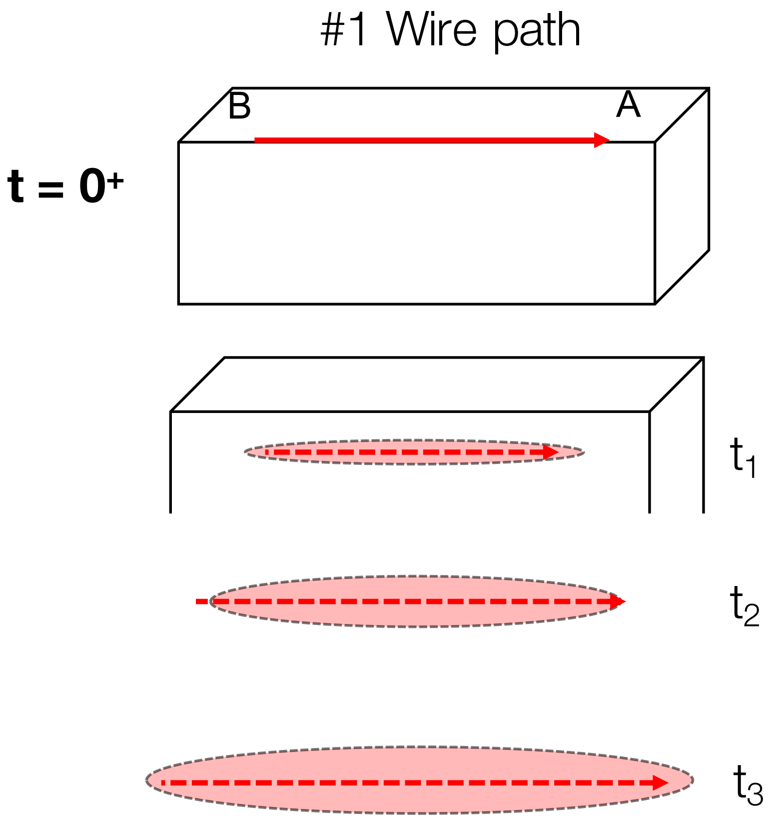




What happens when we shut the system off?

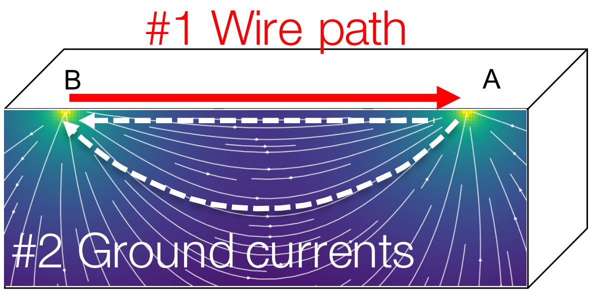
Currents: Grounded System



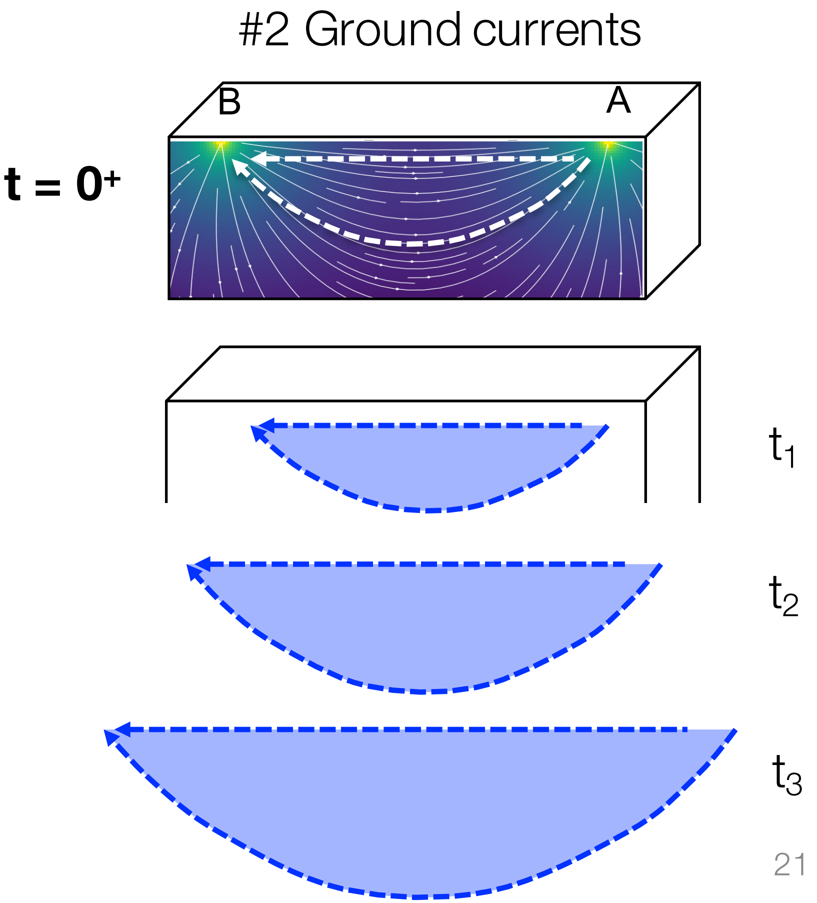


- Immediately after shut off: image current at the surface
- Successive time: currents diffuse downwards and outwards

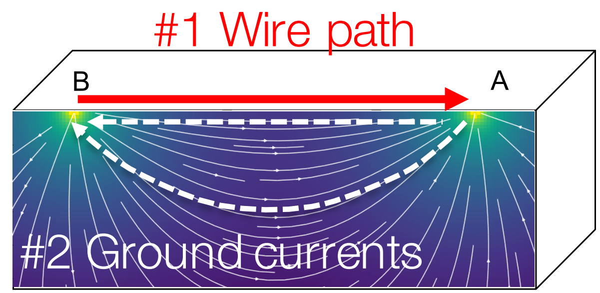
Currents: Grounded System

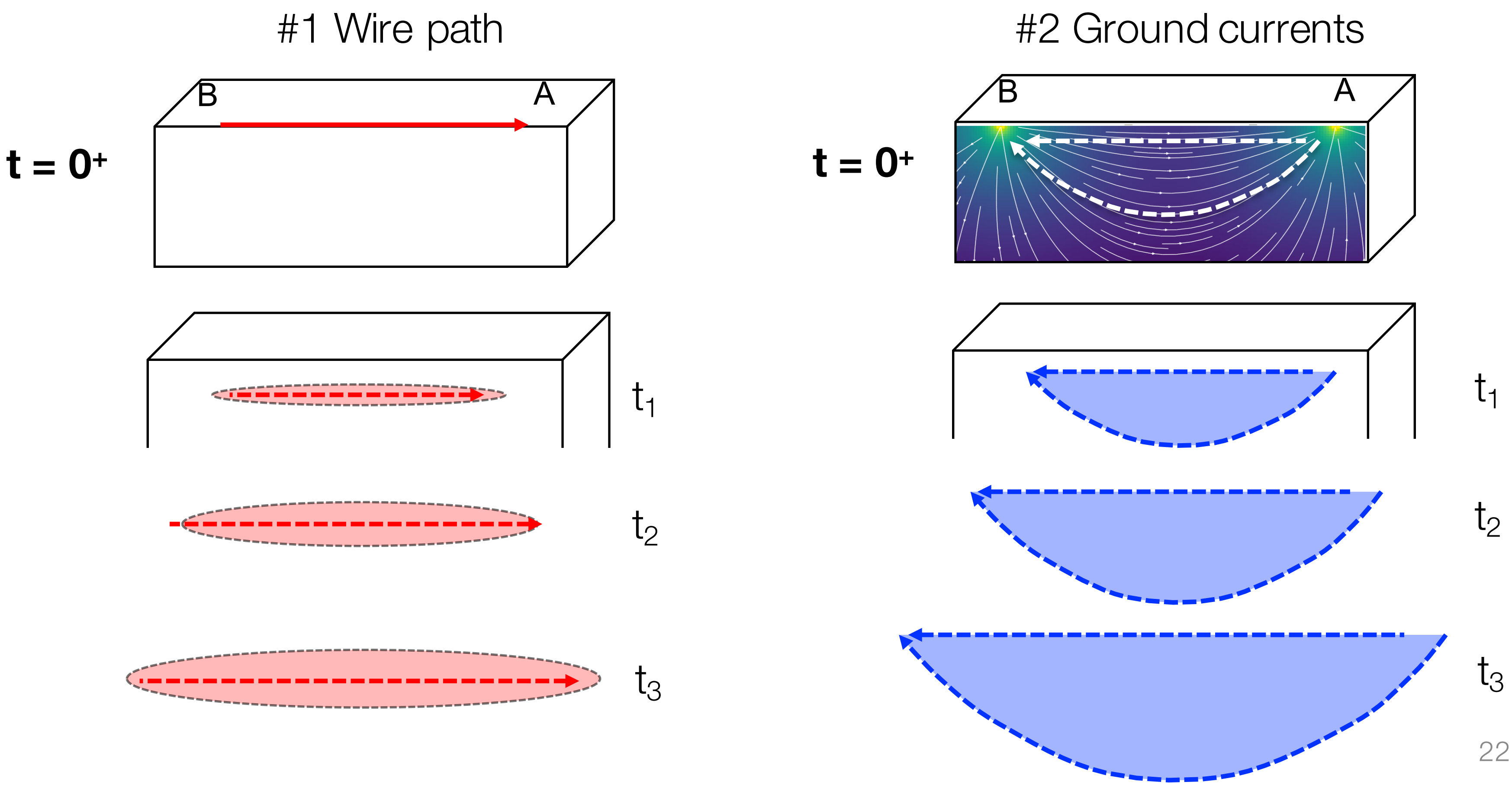


- Immediately after shut off: ground currents are still there
- Successive time: currents diffuse downwards and outwards

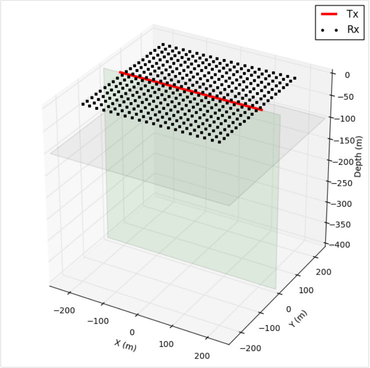


Currents: Grounded System



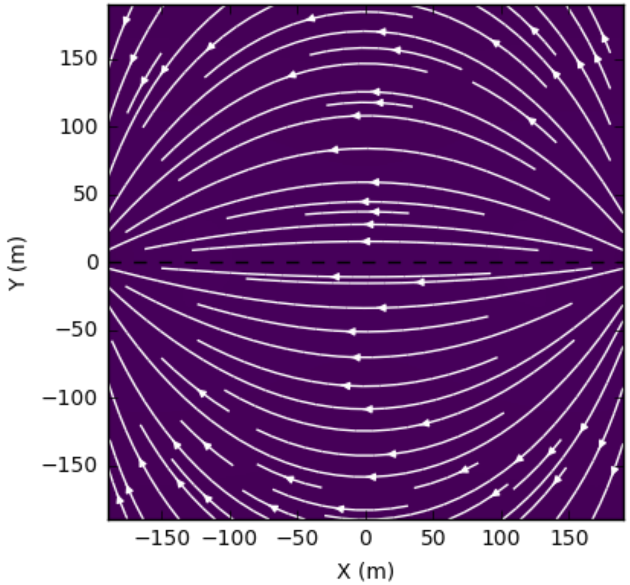


Grounded Source: Halfspace Currents

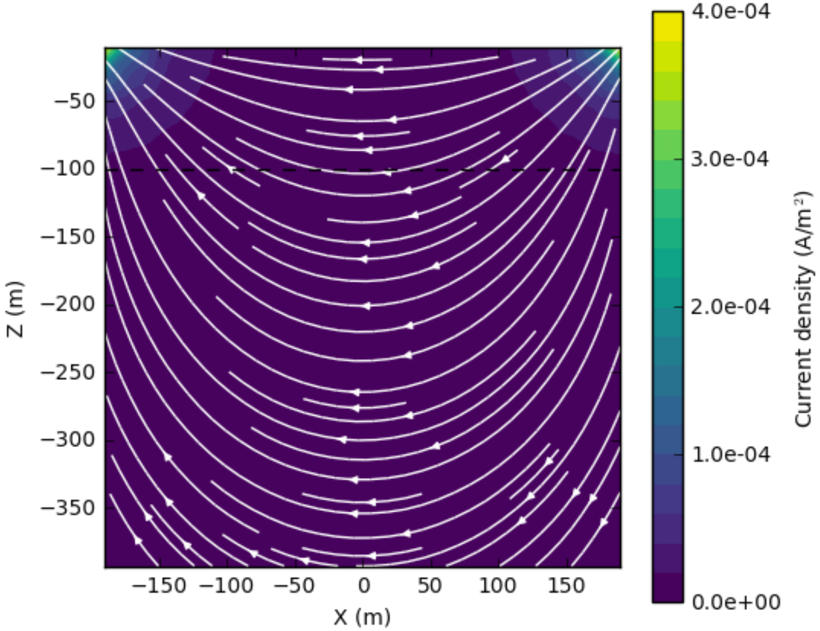


- Parameters:
  - halfspace (0.01 S/m)
  - **t=0$^-$**, steady state

XY plane at Z=-100 m

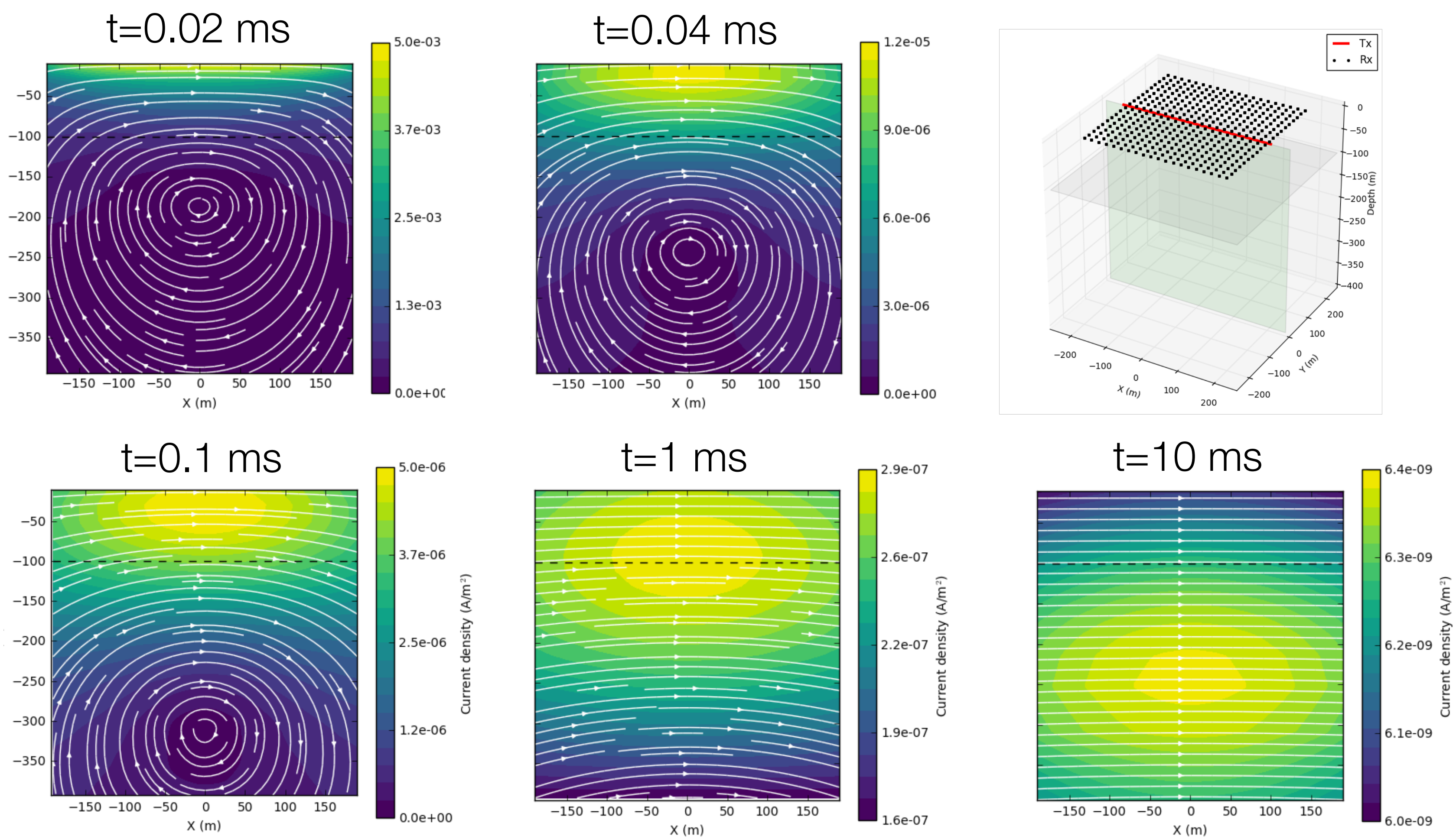


XZ plane at Y=0 m



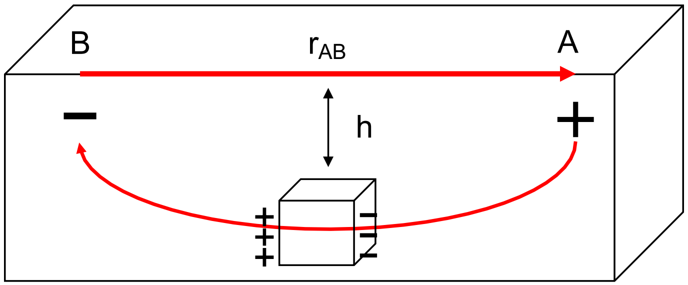
Grounded Source: Halfspace currents

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

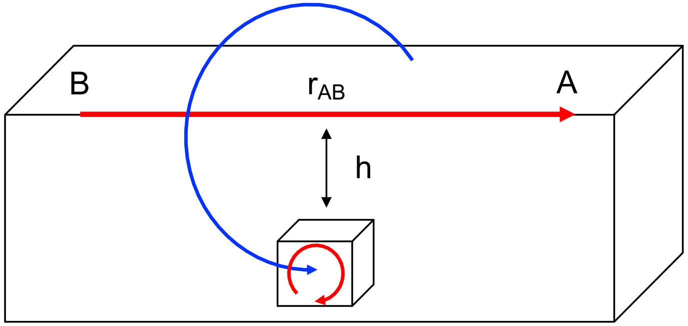


Grounded sources: with a target

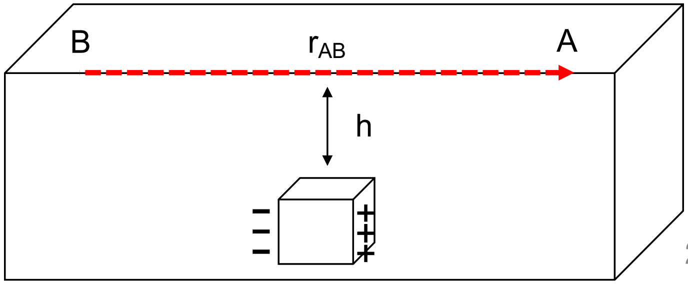
- Block in a halfspace
  - DC
    - Good coupling if h < r_{AB}



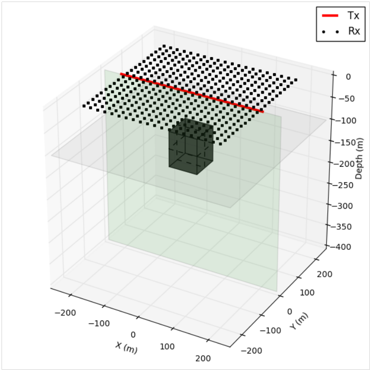
  - Vortex currents
    - Good coupling (magnetic fields)
    - Good signal for conductor
    - Resistor more difficult



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

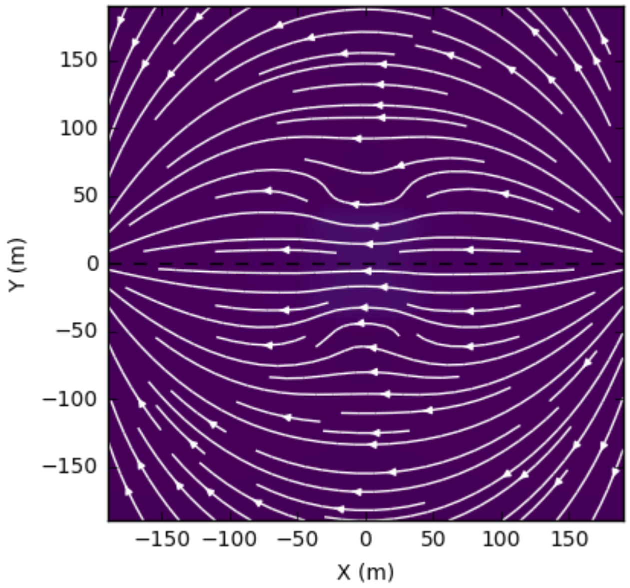


Conductor: currents

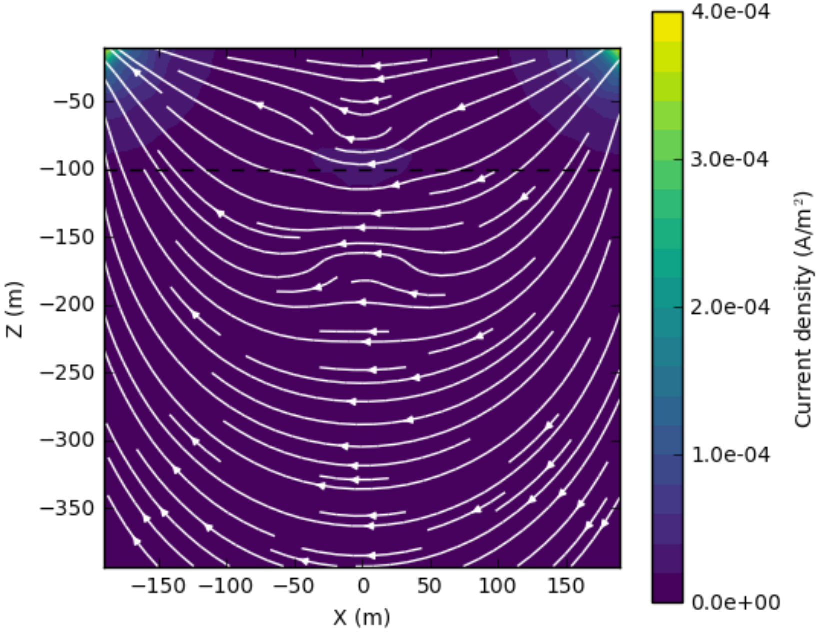


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **t=0⁻**, steady state

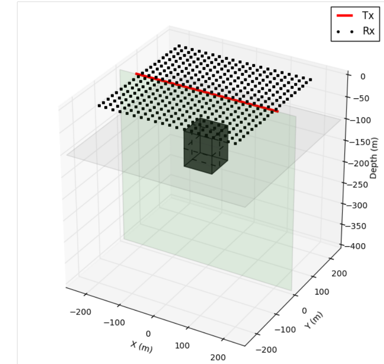
XY plane at Z=-100 m



XZ plane at Y=0 m

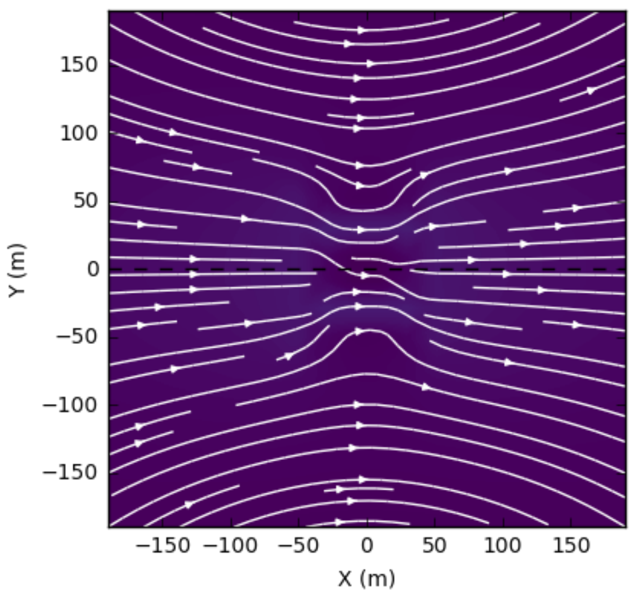


Conductor: currents

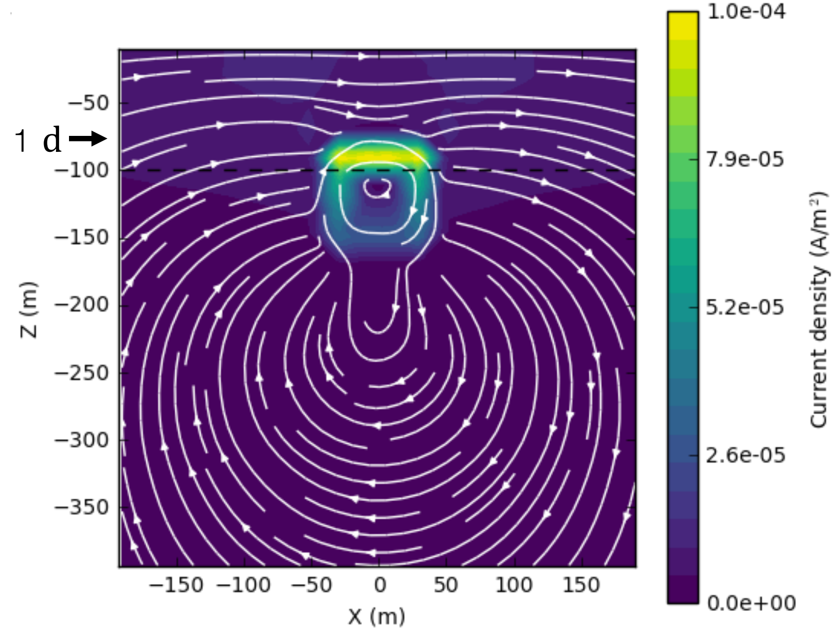


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **0.04** ms, d = 80 m

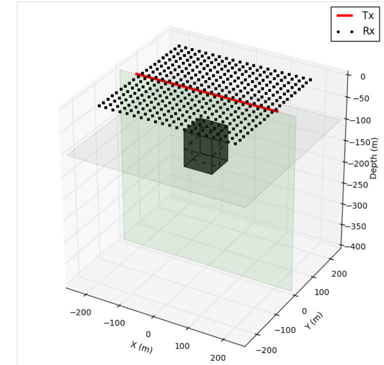
XY plane at Z=-100 m



XZ plane at Y=0 m

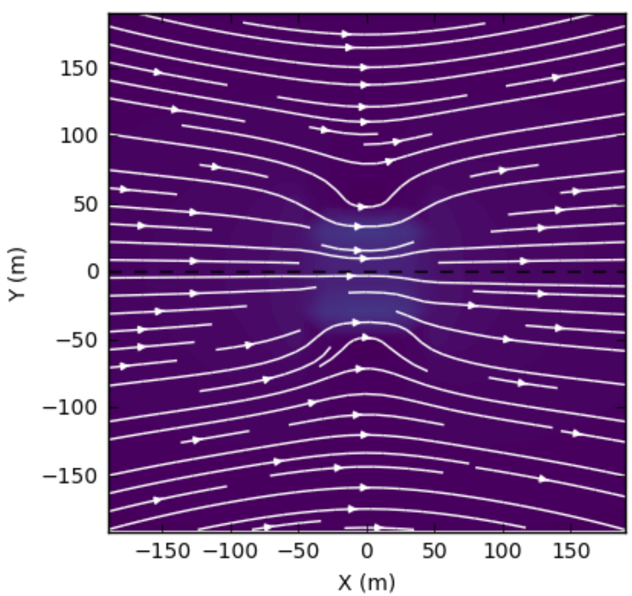


Conductor: currents

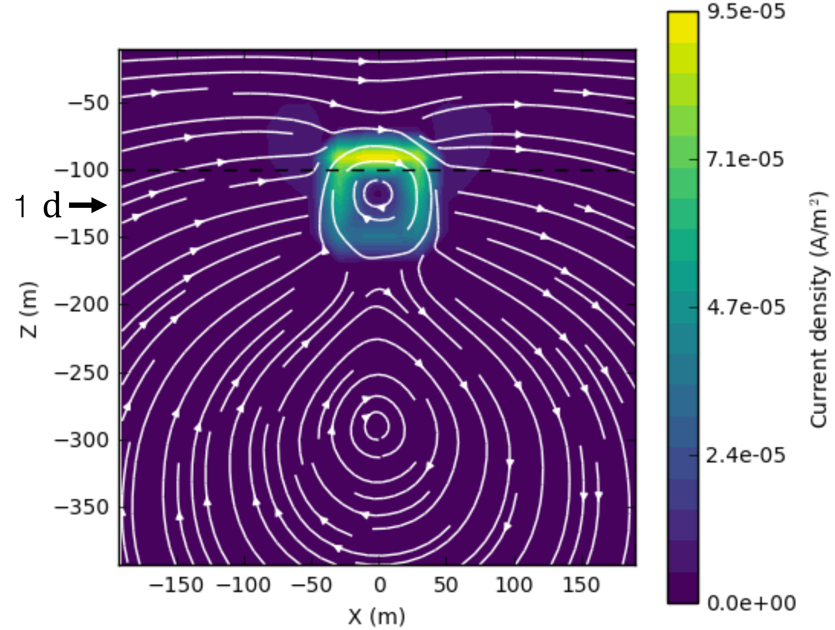


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **0.1** ms, d = 126 m

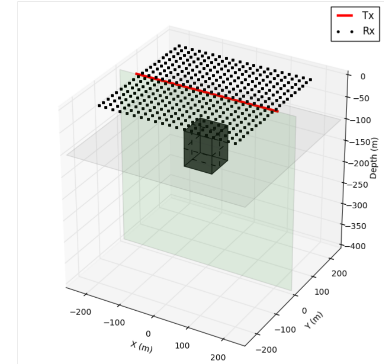
XY plane at Z=-100 m



XZ plane at Y=0 m

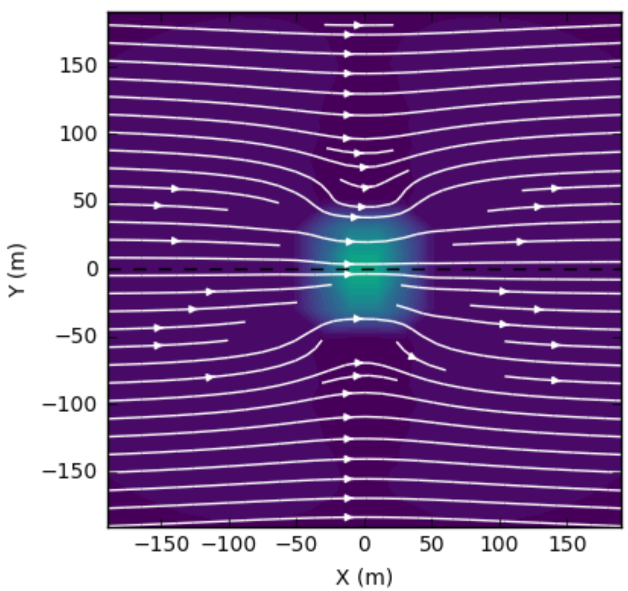


Conductor: currents

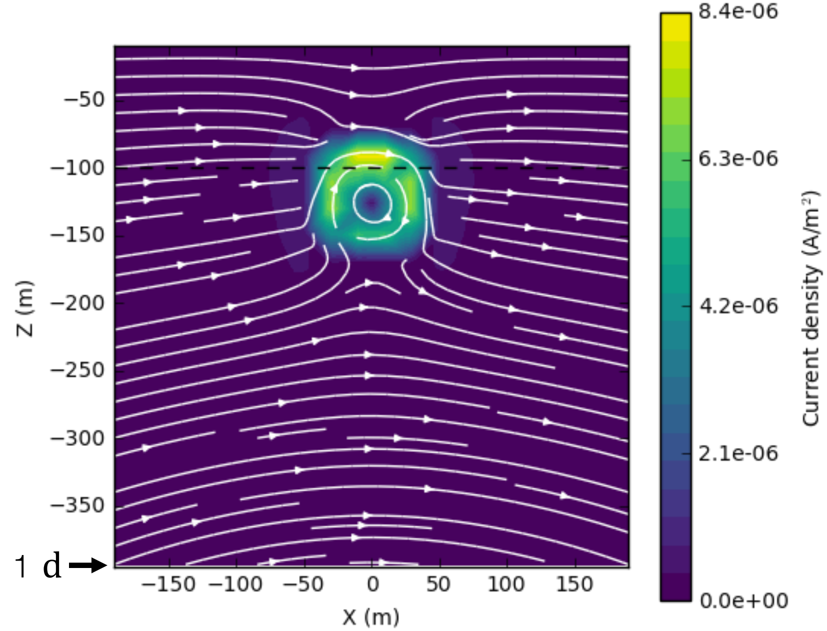


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - 1 ms, d = 400 m

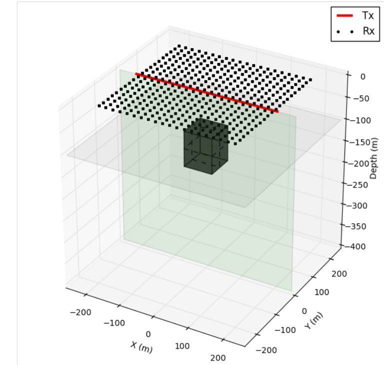
XY plane at Z=-100 m



XZ plane at Y=0 m

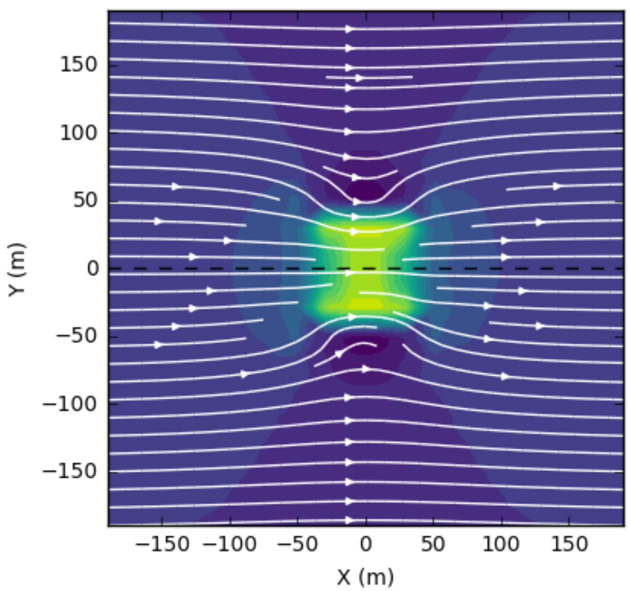


Conductor: currents

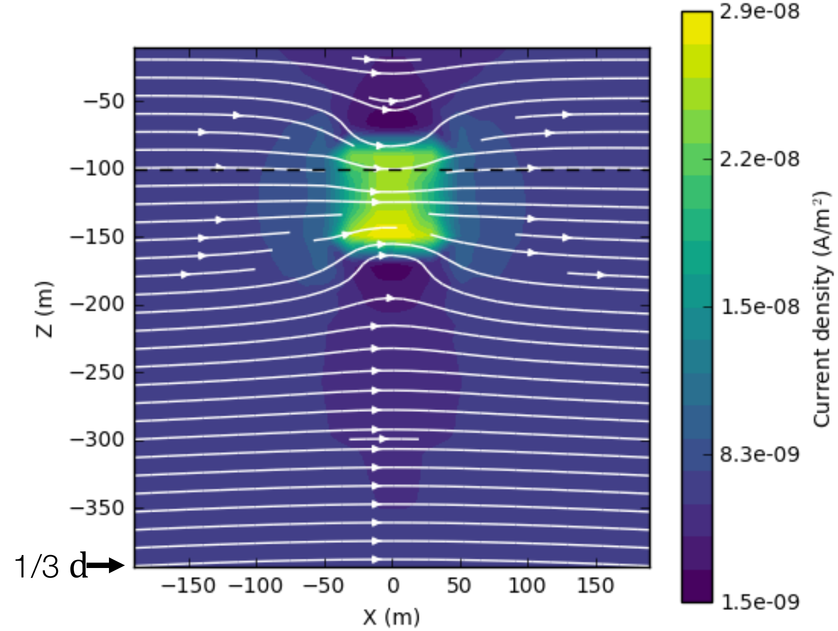


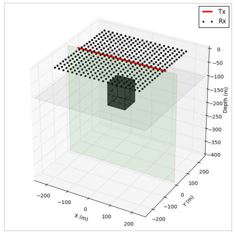
- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **10** ms, d = 1270 m

XY plane at Z=-100 m



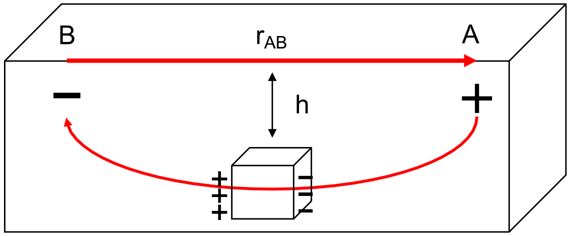
XZ plane at Y=0 m





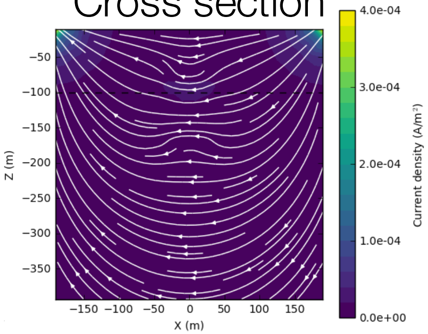
Conductor: currents

Steady State (galvanic current)

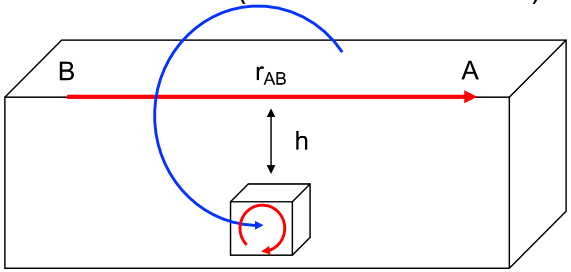


Galvanic current
$t = 0^-$

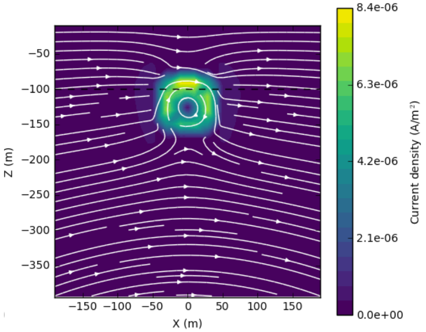
Cross section



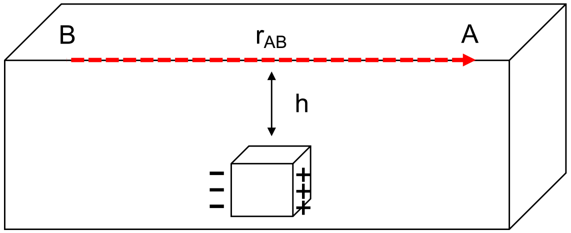
EM induction (vortex current)



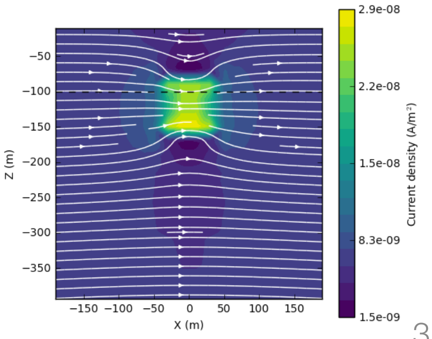
Vortex current
t = 1 ms



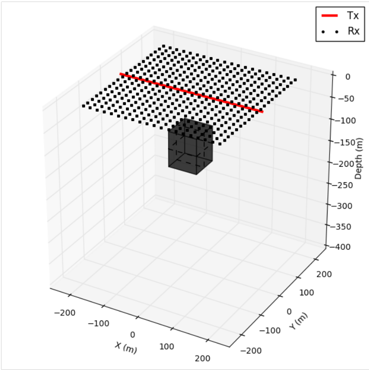
EM induction (galvanic current)

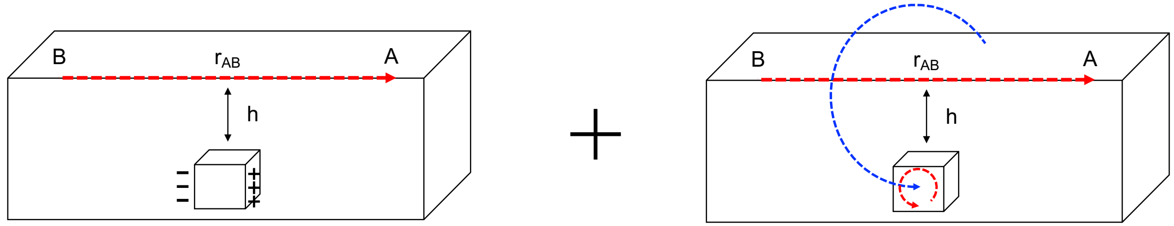


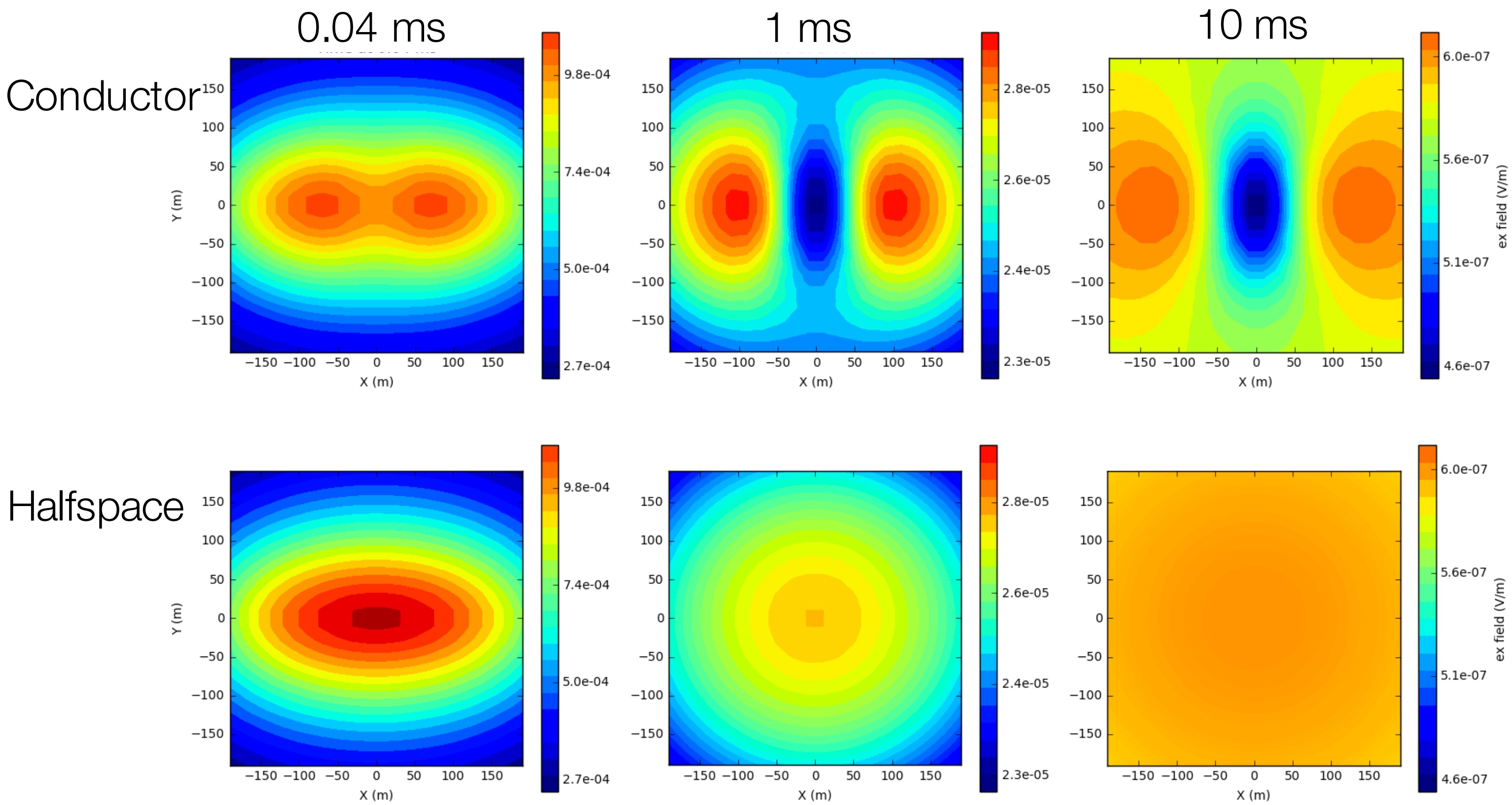
Galvanic current
t = 10 ms



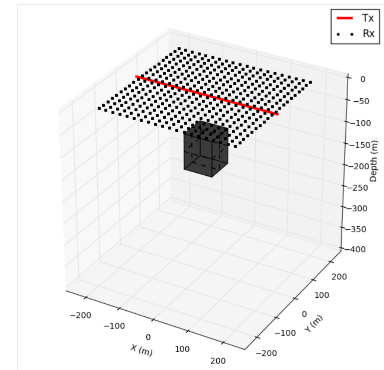
Data: e_x field

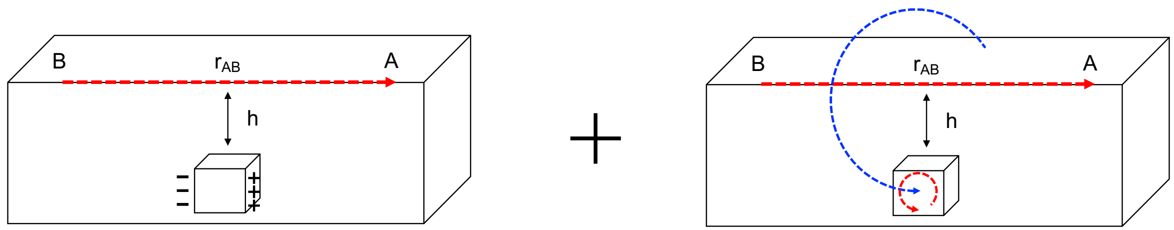


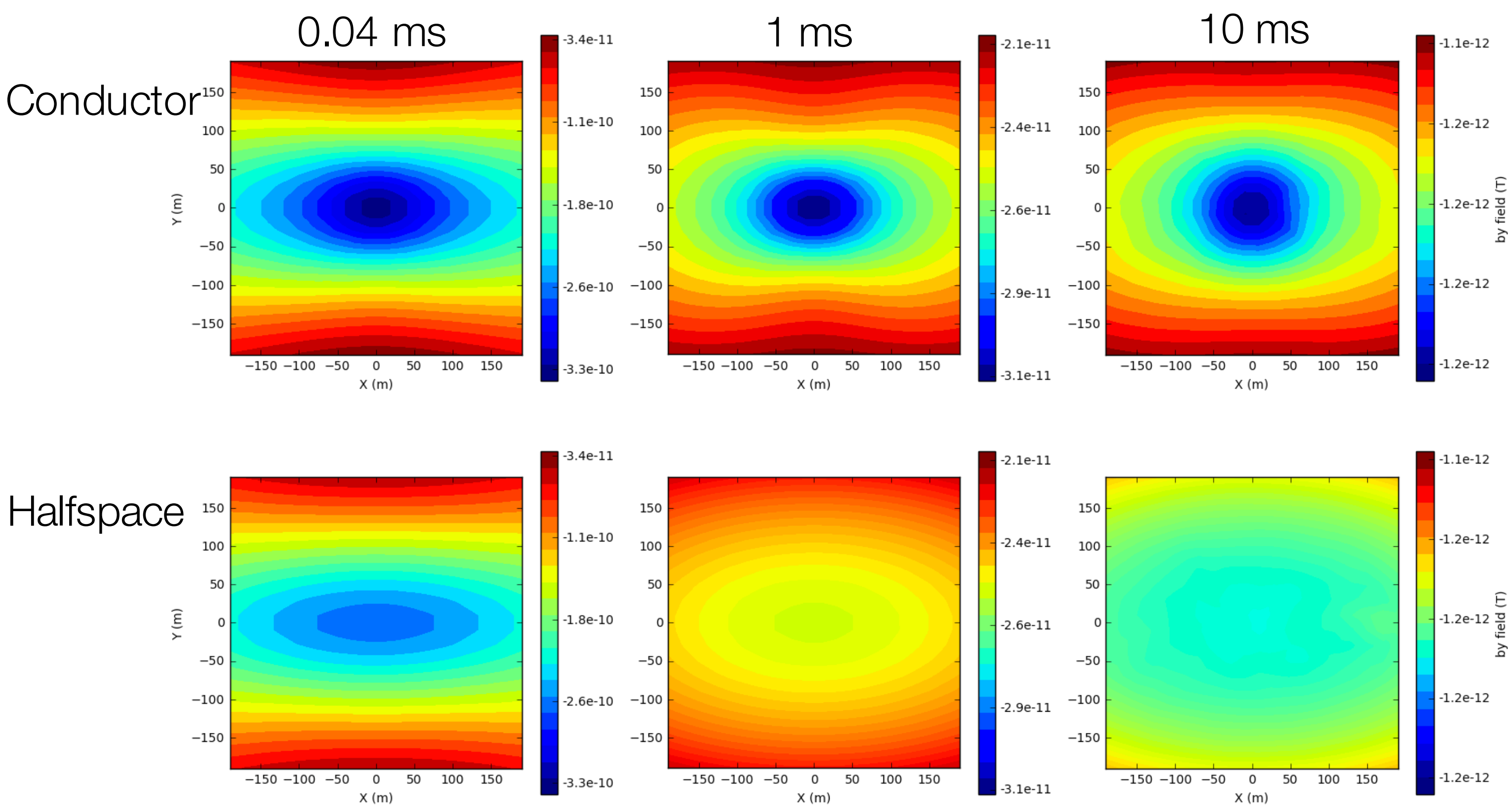




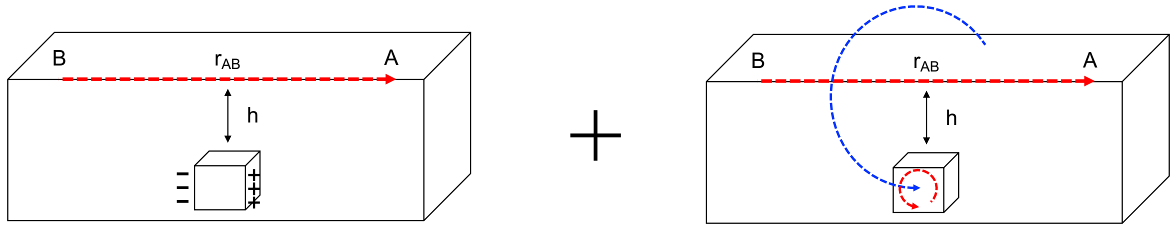
Data: b_y field

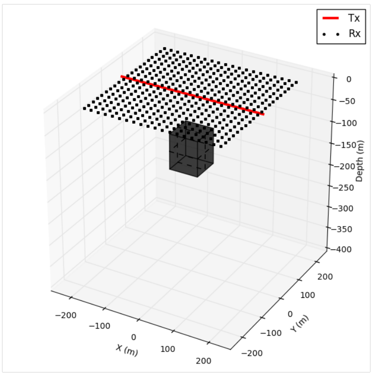


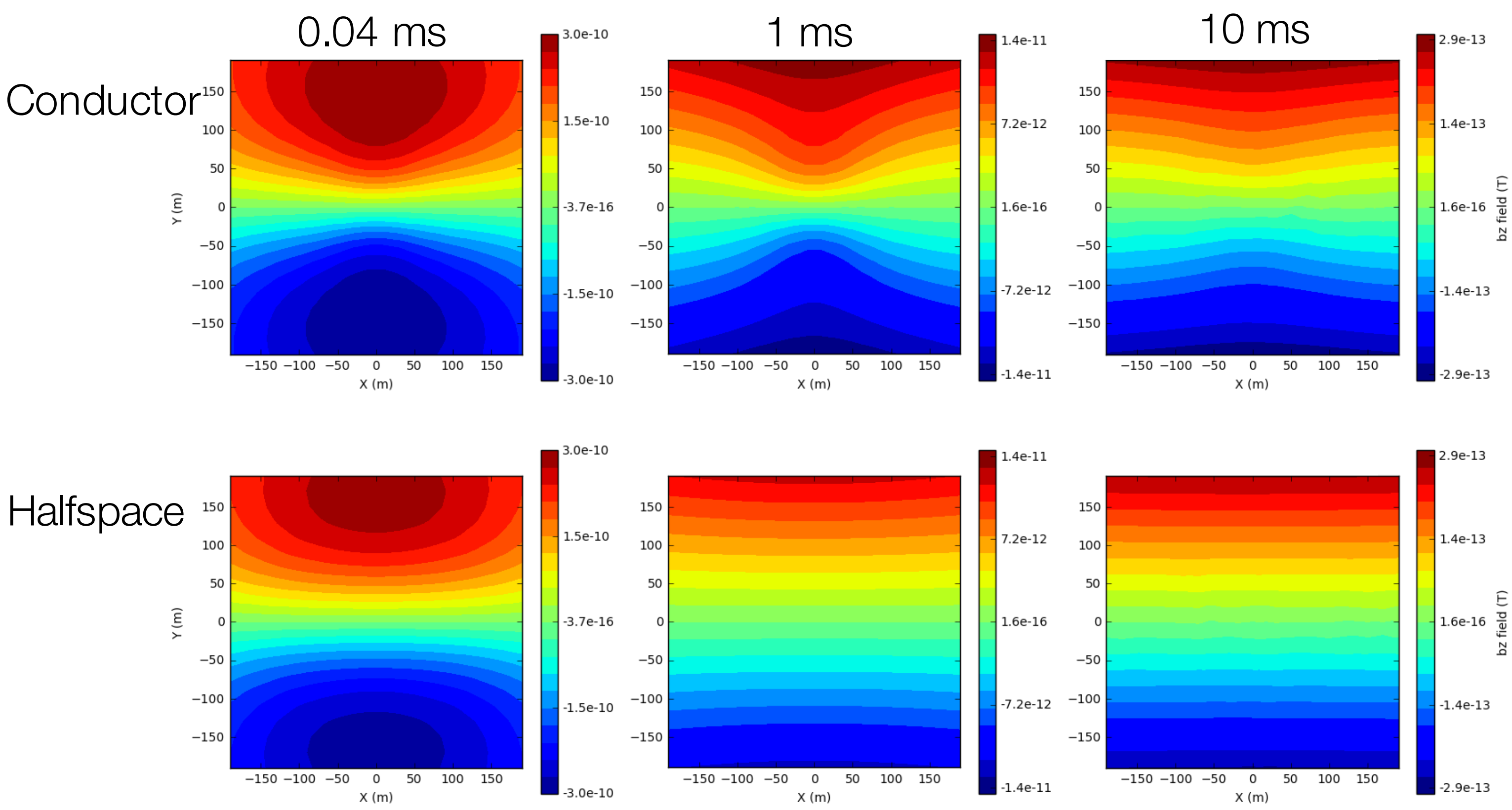




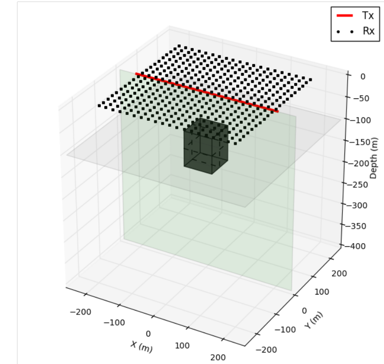
Data: b_z field





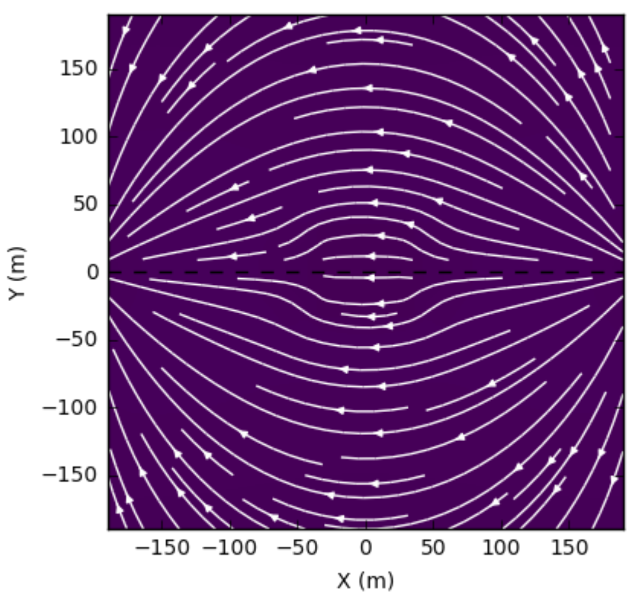


Resistor: currents

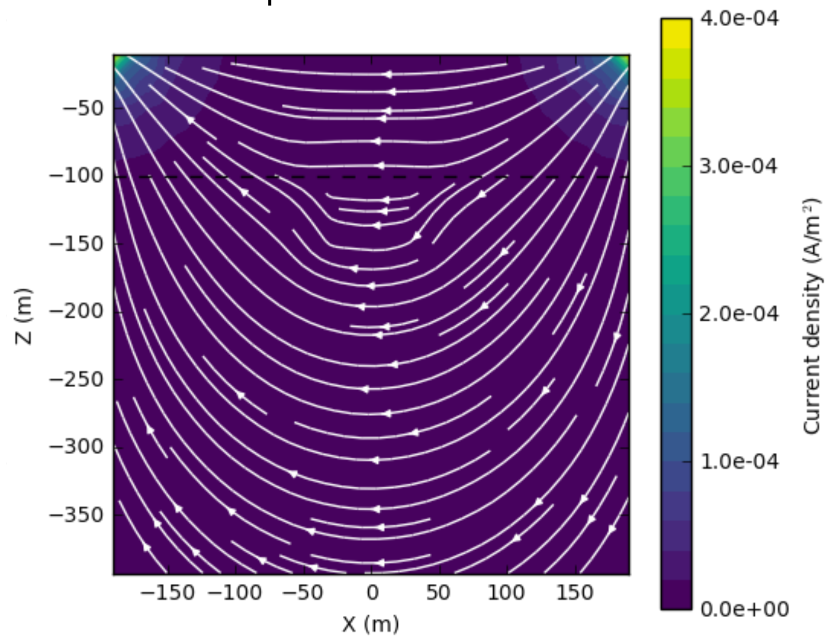


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **t=0⁻**, steady state

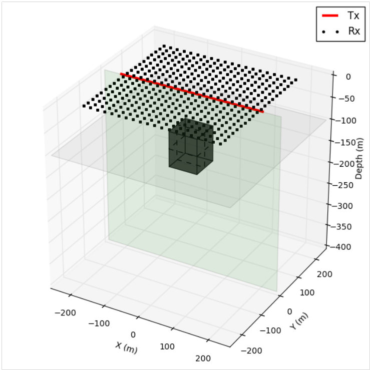
XY plane at Z=-100 m



XZ plane at Y=0 m

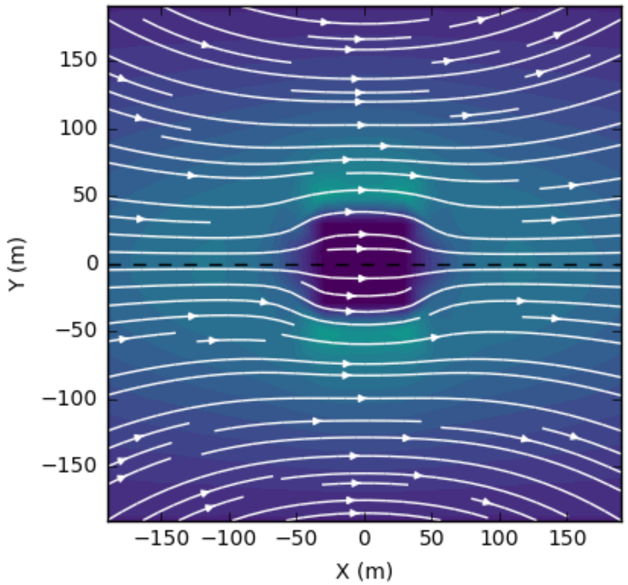


Resistor: currents

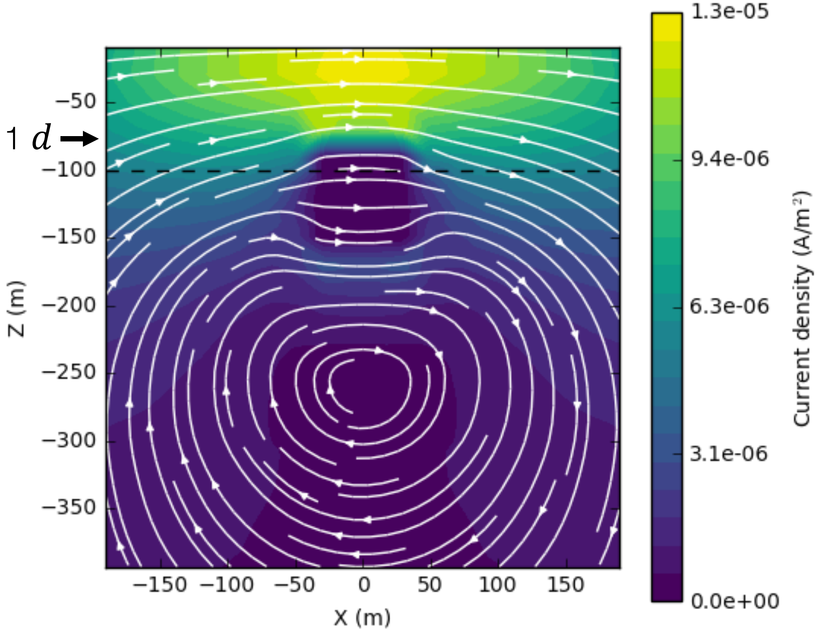


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **0.04** ms, d = 80 m

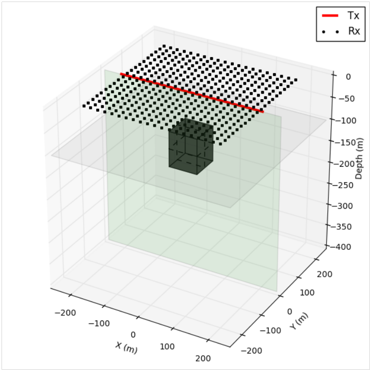
XY plane at Z=-100 m



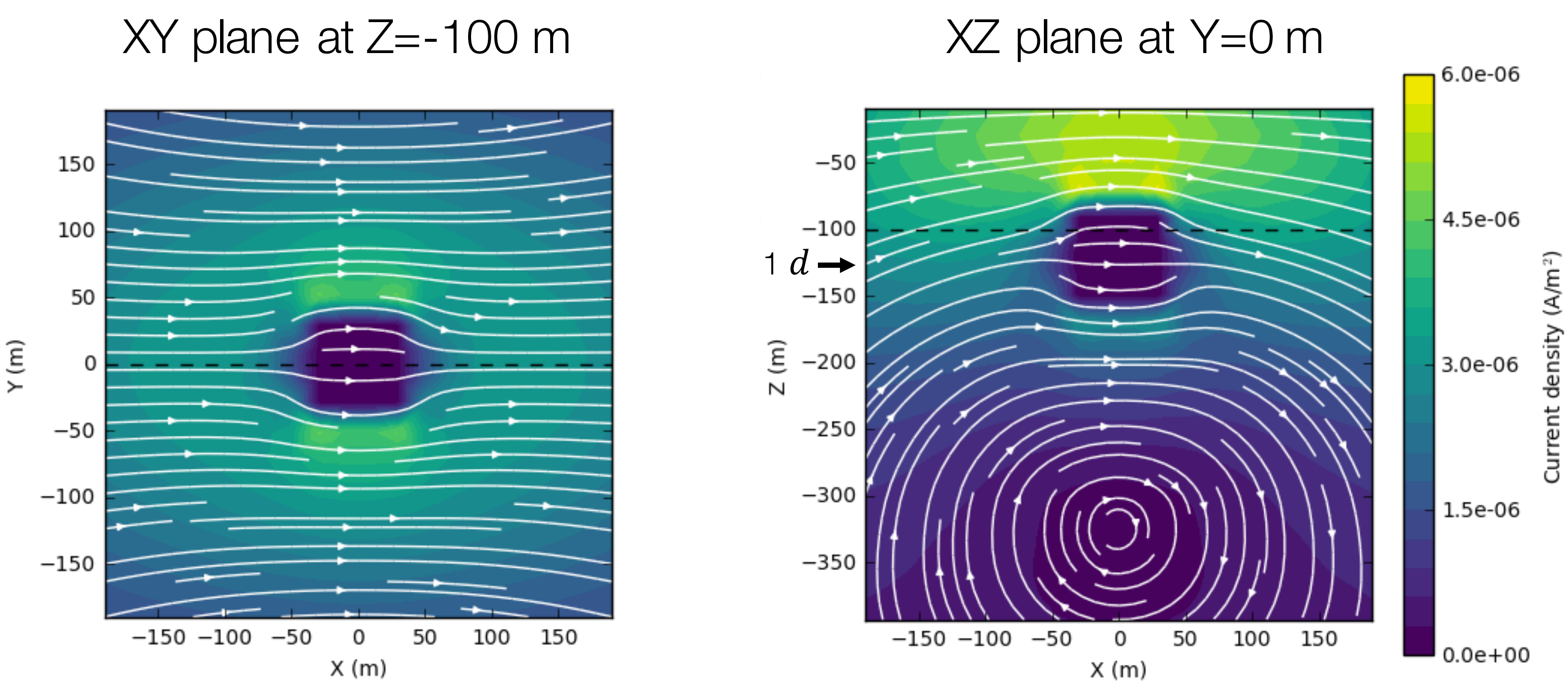
XZ plane at Y=0 m



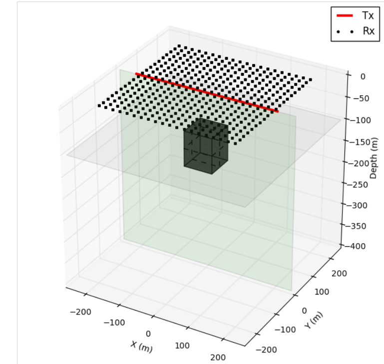
Resistor: currents



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

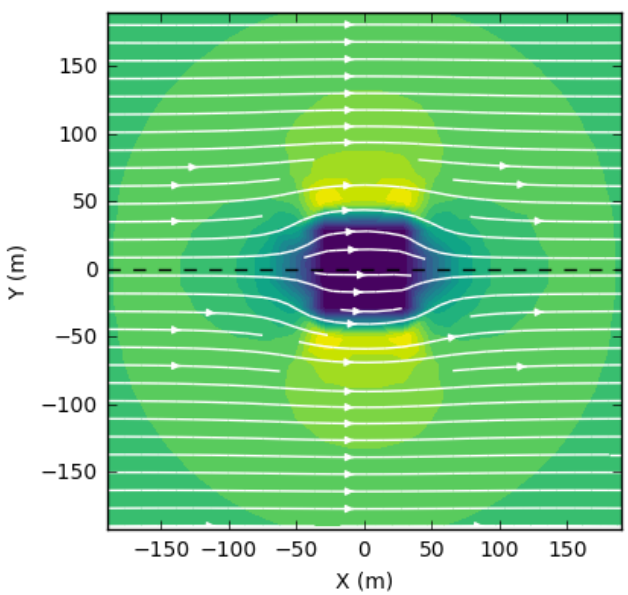


Resistor: currents

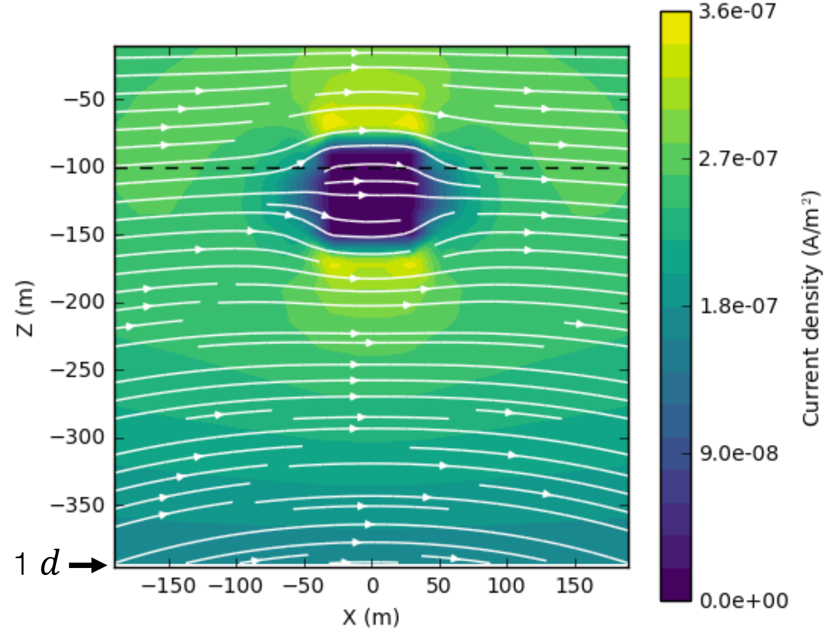


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **1** ms, d = 400 m

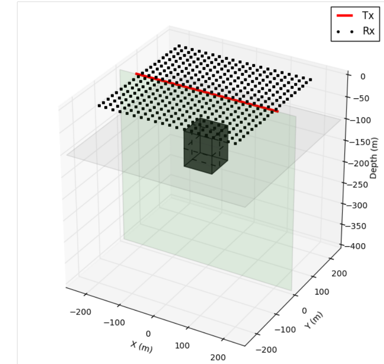
XY plane at Z=-100 m



XZ plane at Y=0 m

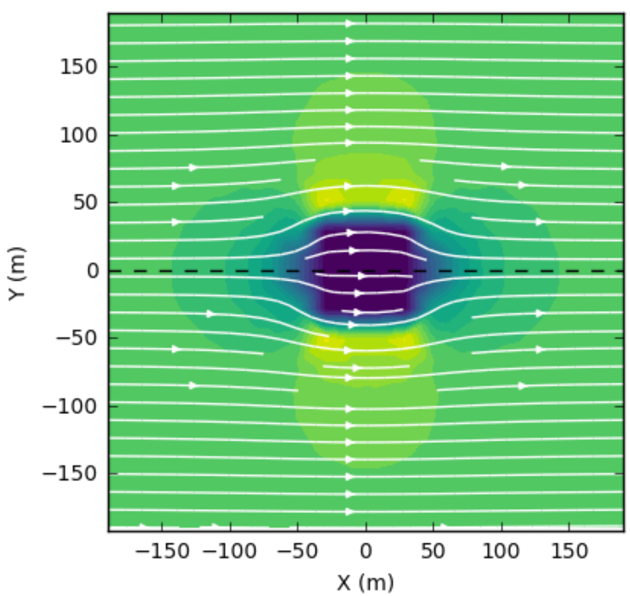


Resistor: currents

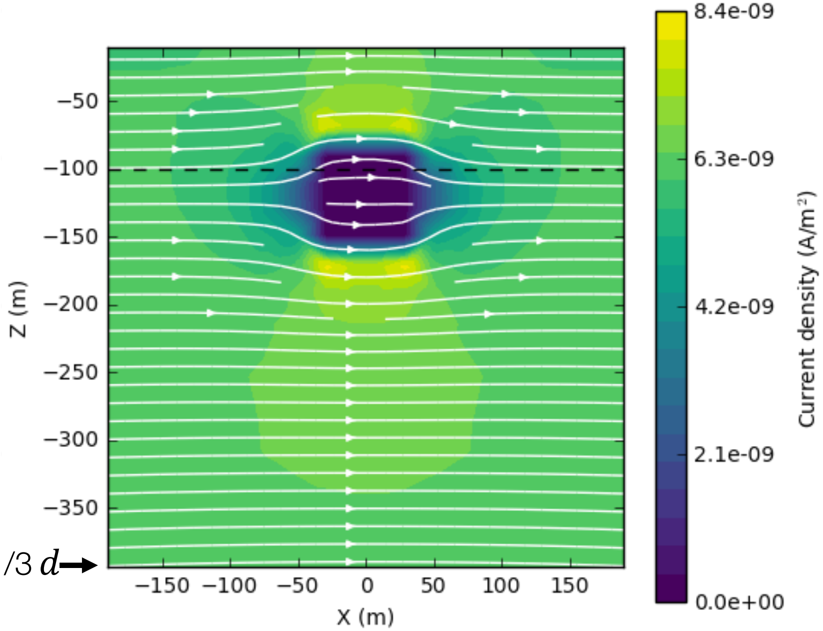


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **10** ms, d = 1270 m

XY plane at Z=-100 m

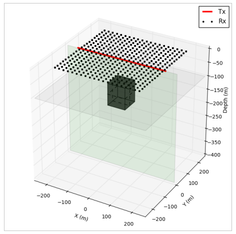


XZ plane at Y=0 m

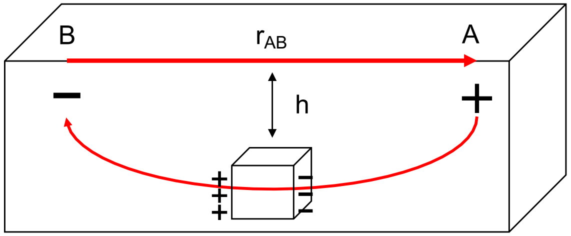


1/3 *d*→

Resistor: currents

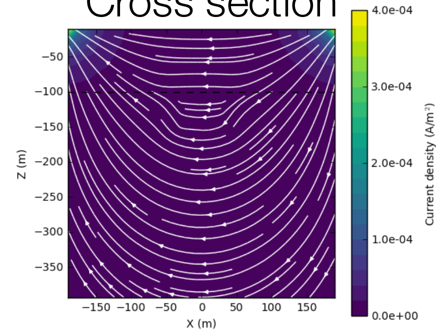


DC (galvanic current)

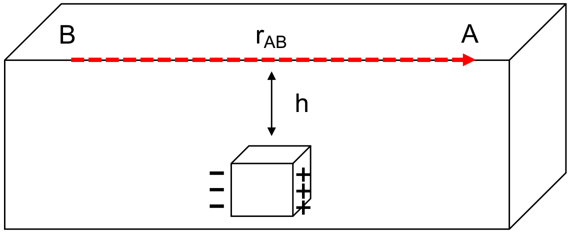


Galvanic current
$t = 0^-$

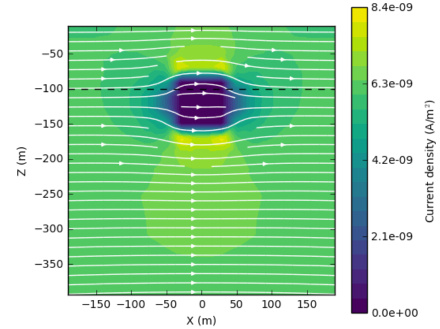
Cross section



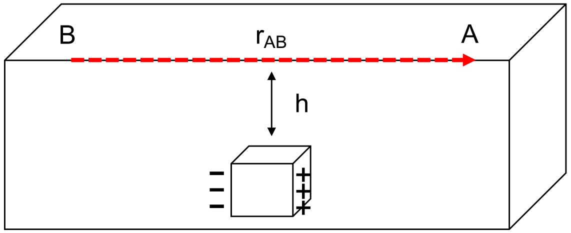
EM induction (galvanic current)



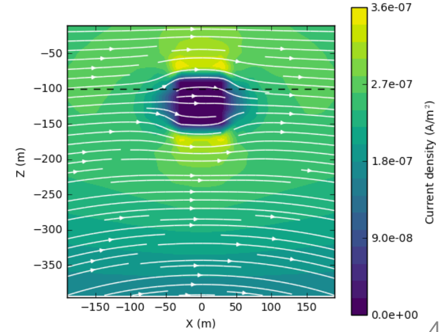
Galvanic current
$t = 1$ ms



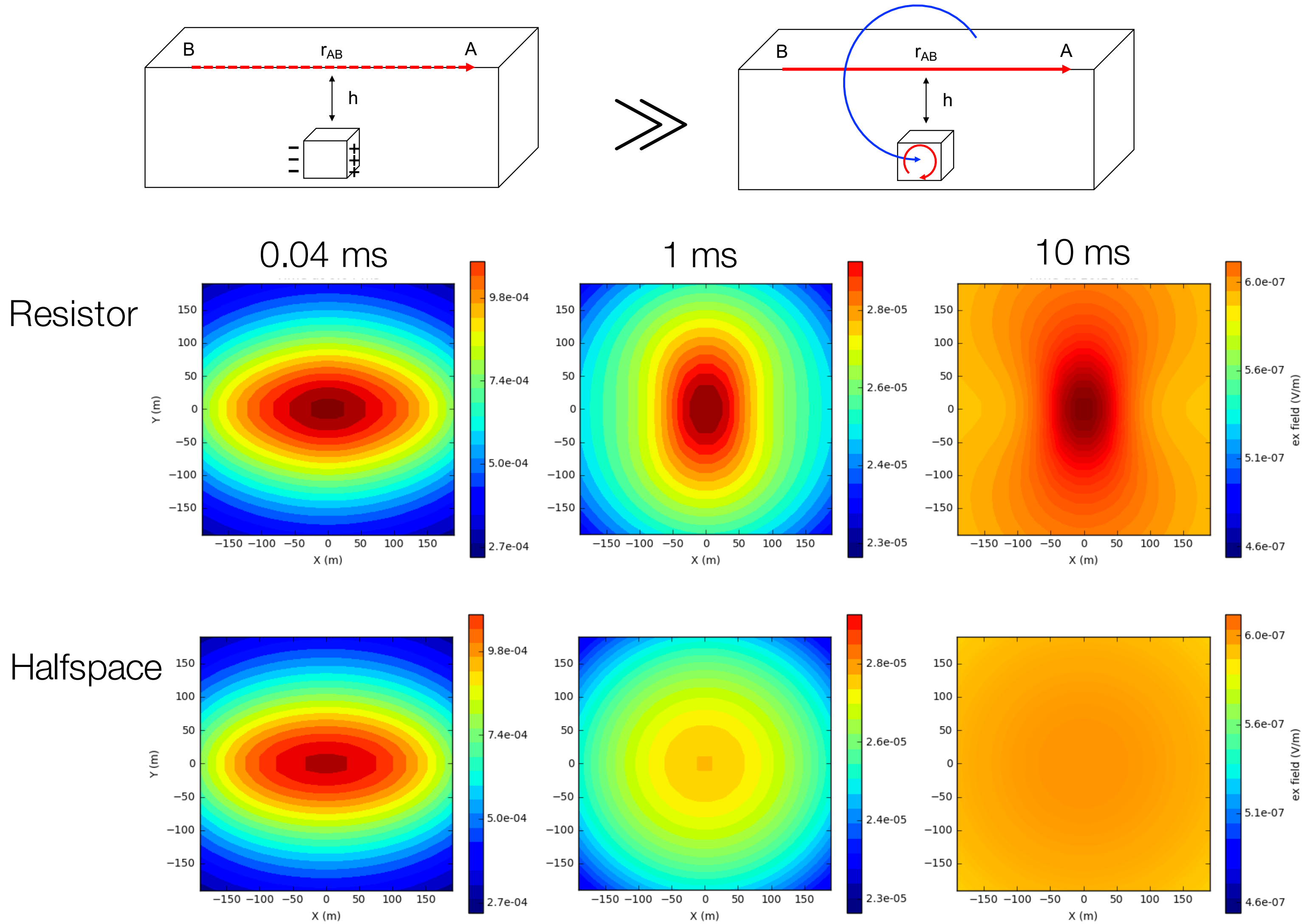
EM induction (galvanic current)



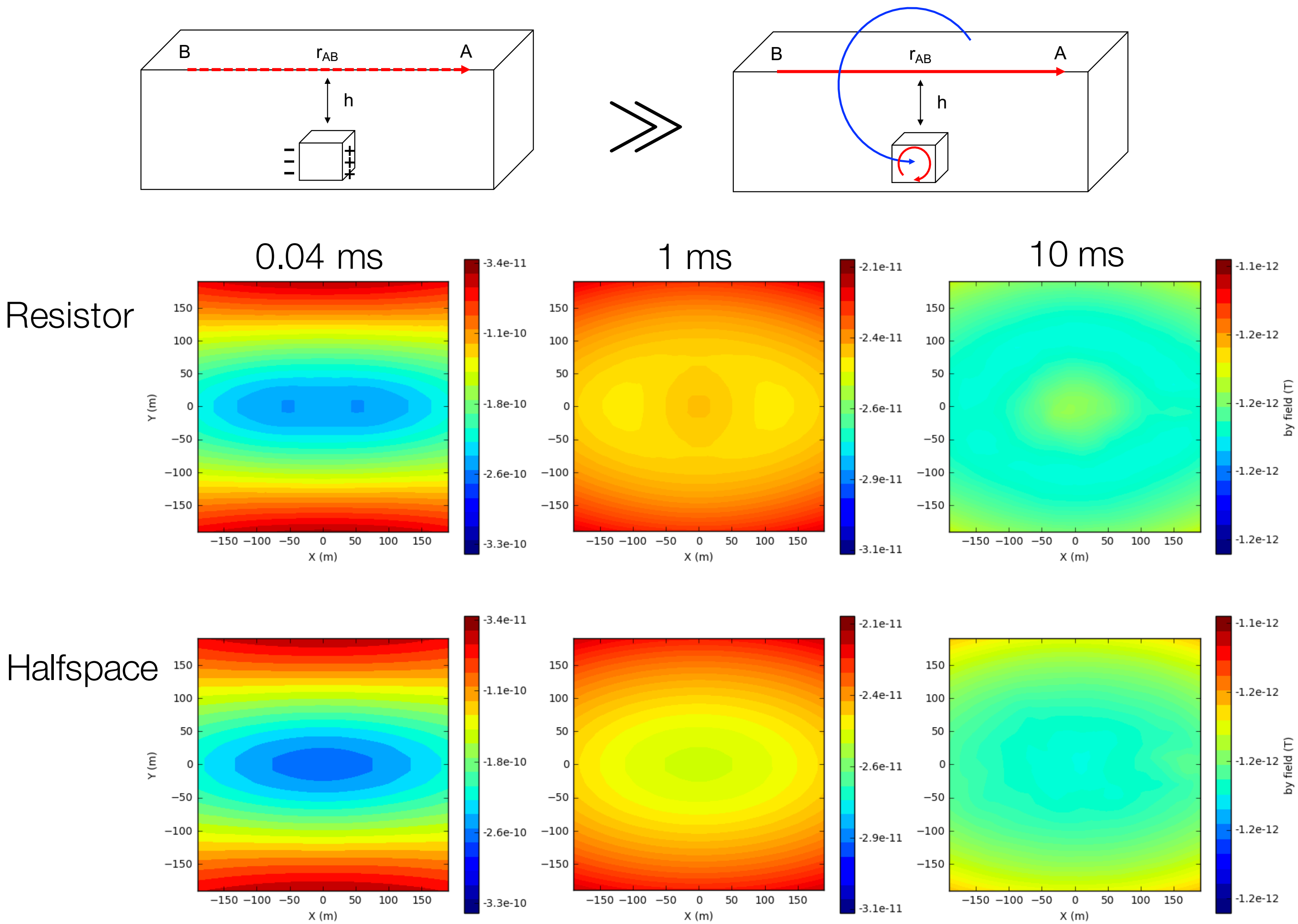
Galvanic current
$t = 10$ ms



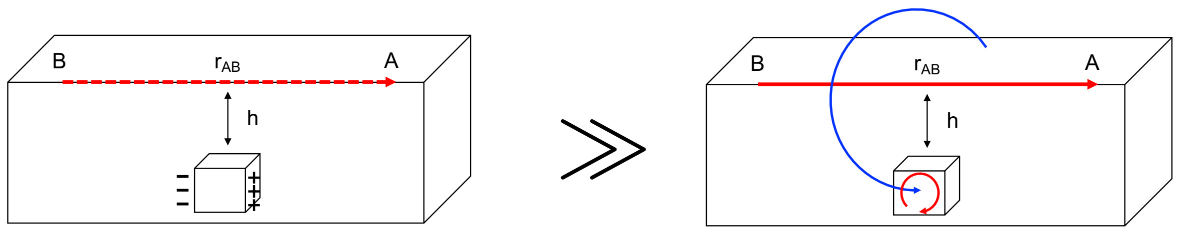
Data: e_x field

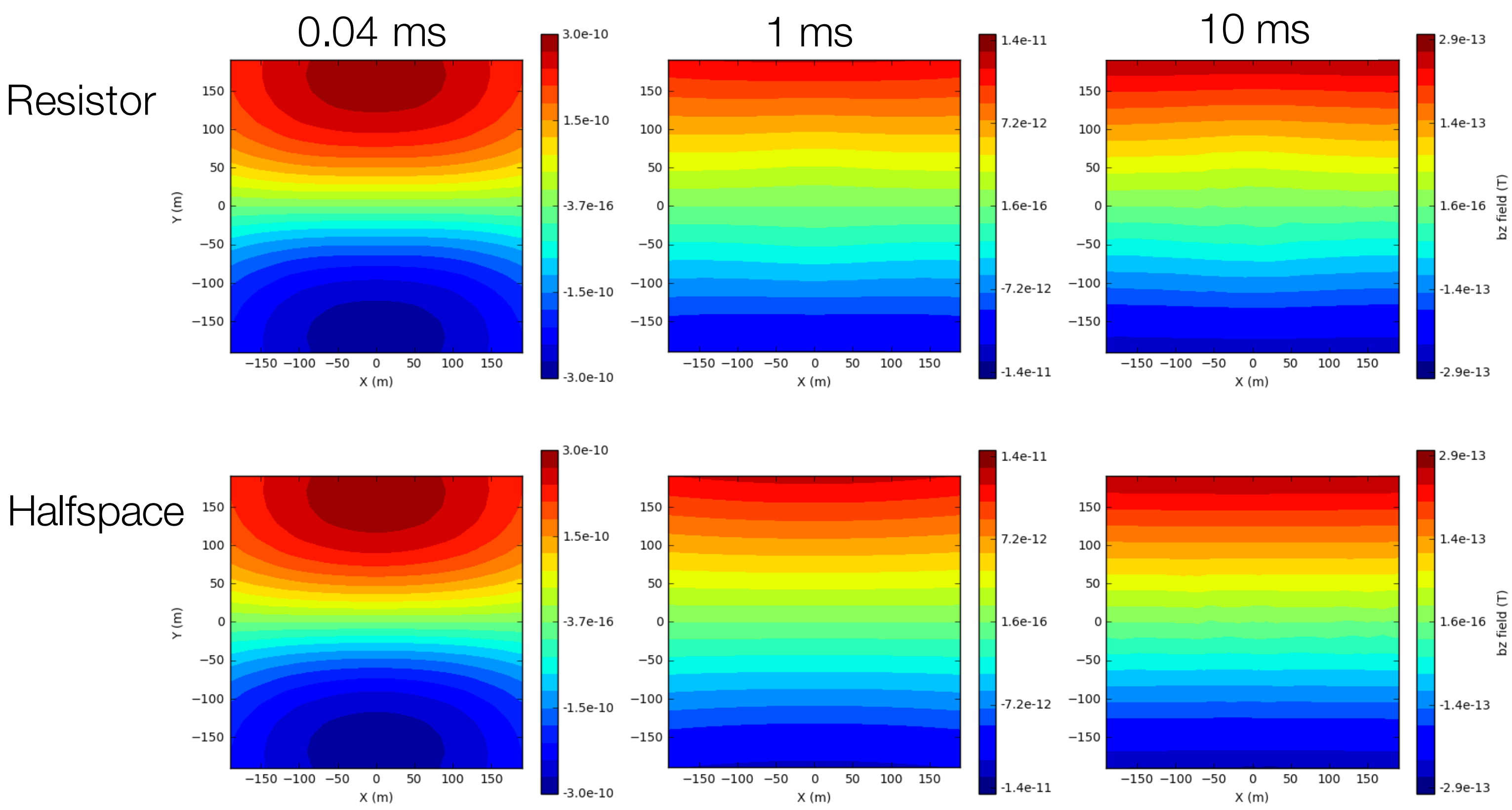


Data: b_y field



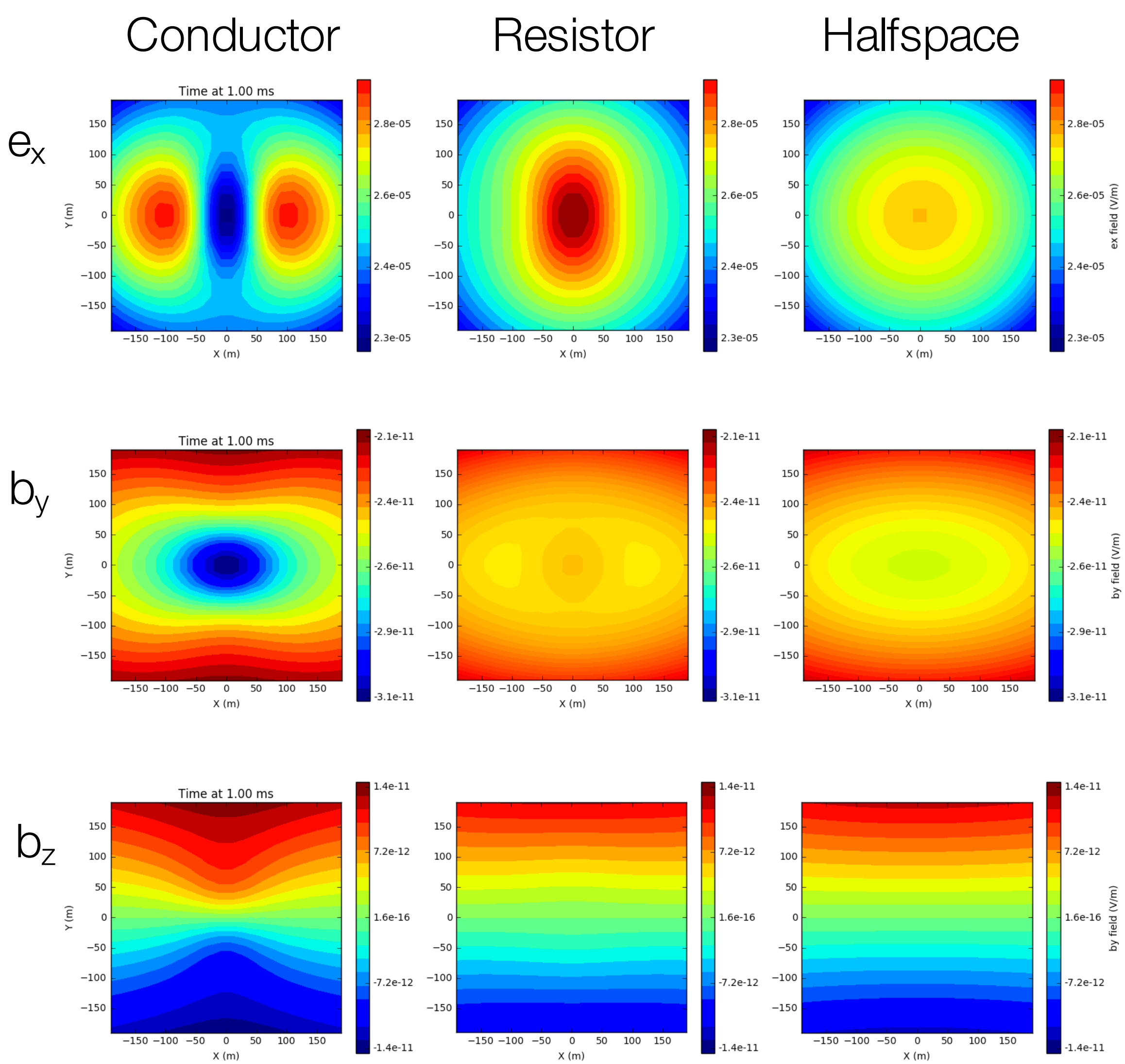
Data: b_z field





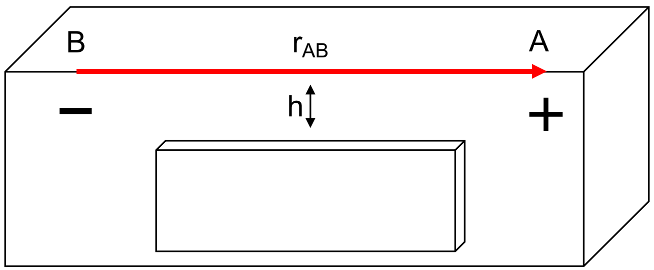
Data summary

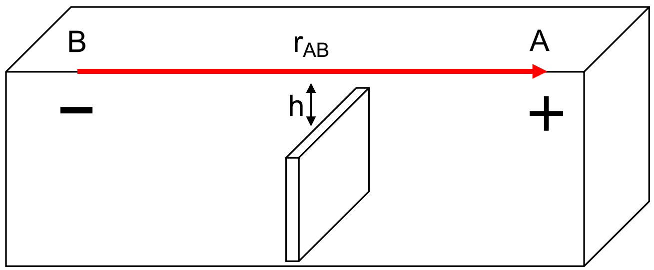
t = 1ms



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

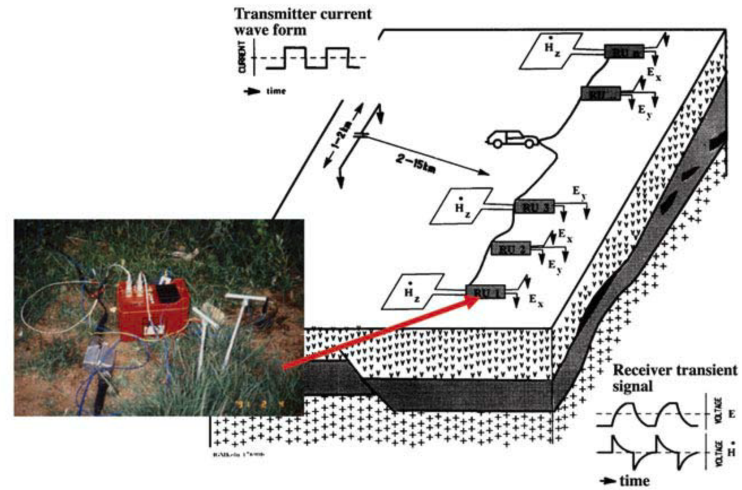
Grounded Sources: Summary

- Basic experiment
- 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

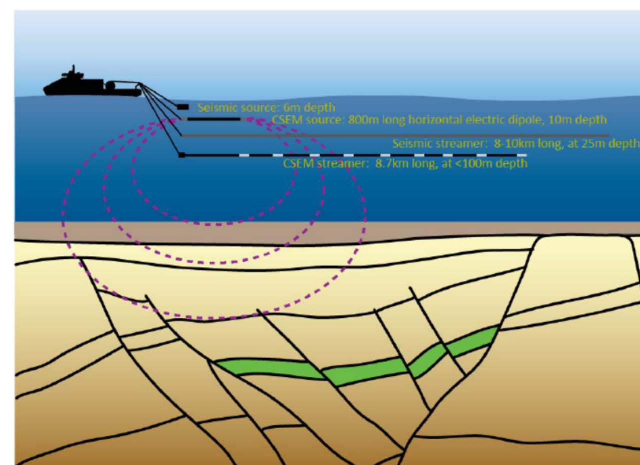
- Questions
- Case History: Barents Sea
- DC/EM Inversion

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

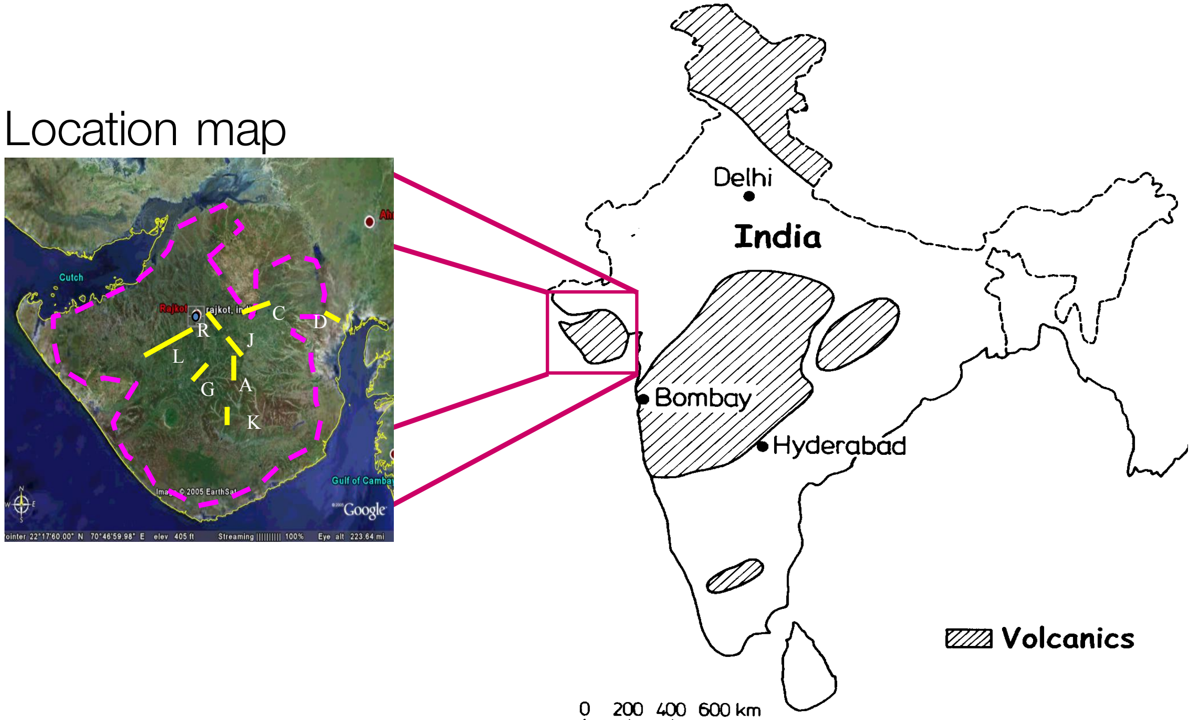


Case History: Mesozoic sediments beneath Deccan traps, India

Strack and Pandey, 2007

Setup

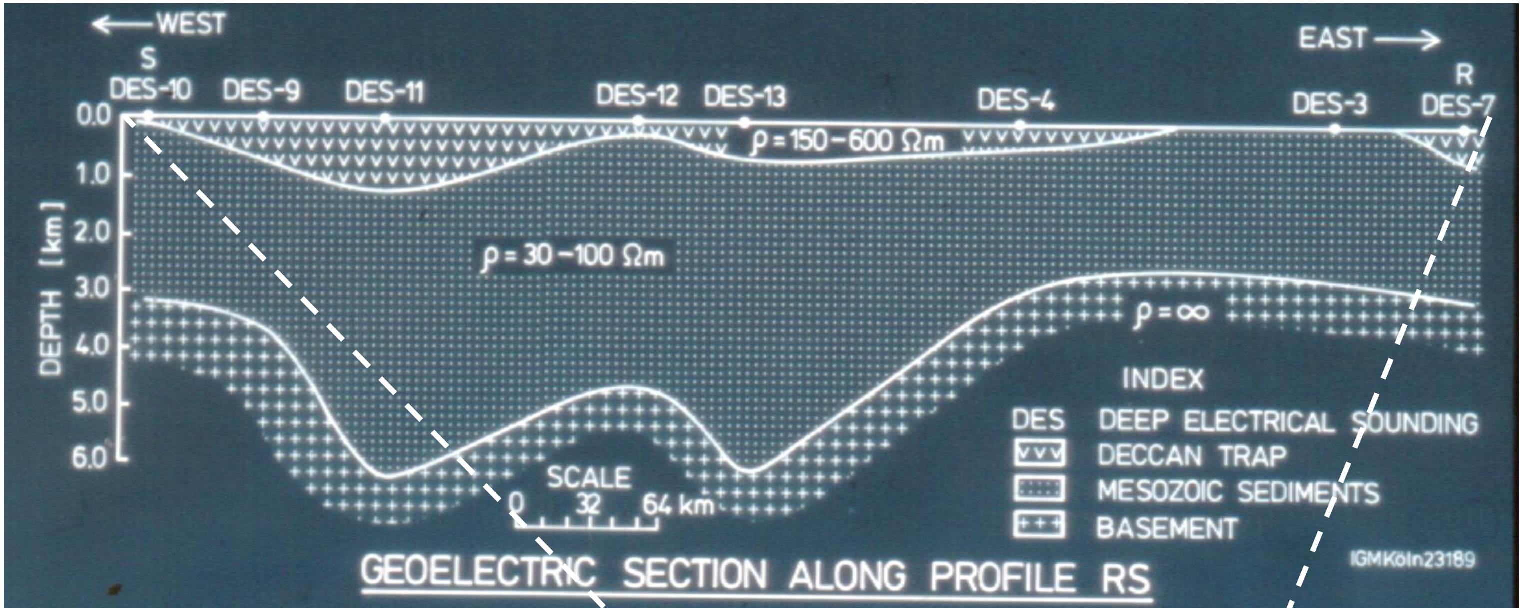
Location map



- 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)

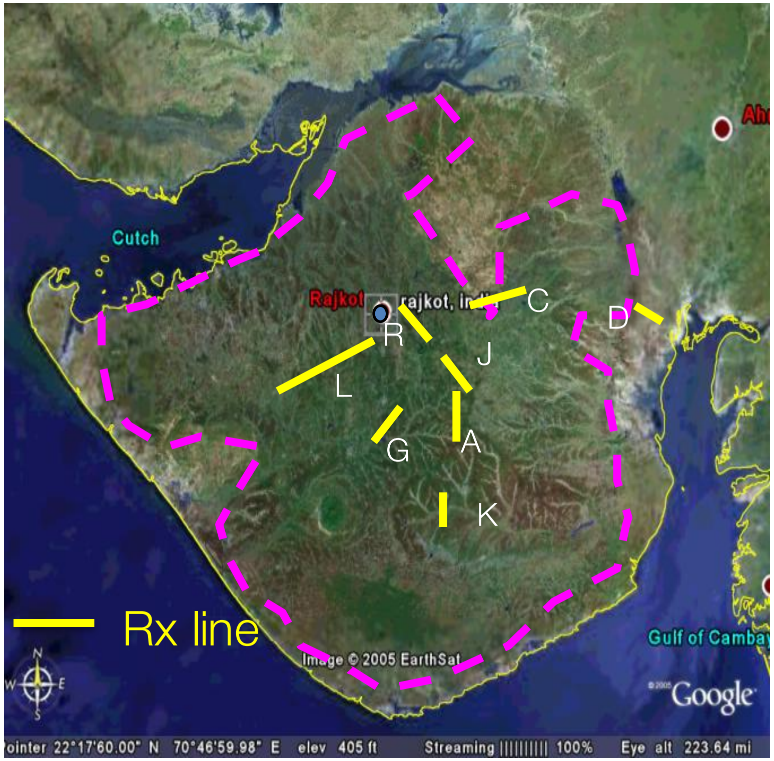
Resistivity section



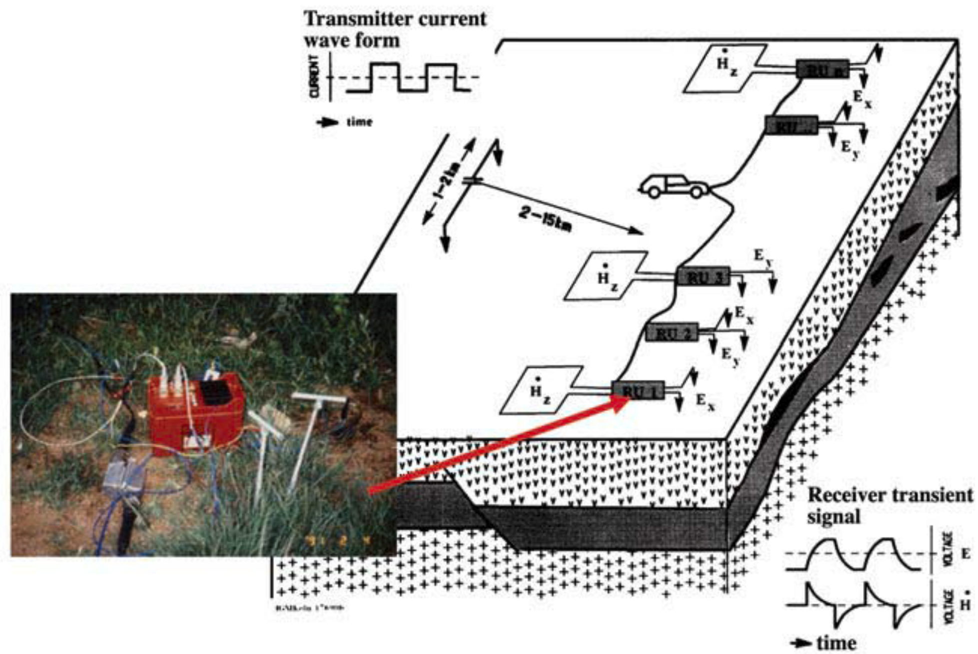
- Sediments exist but unclear where and how thick. Interpretation weak

Survey

Map

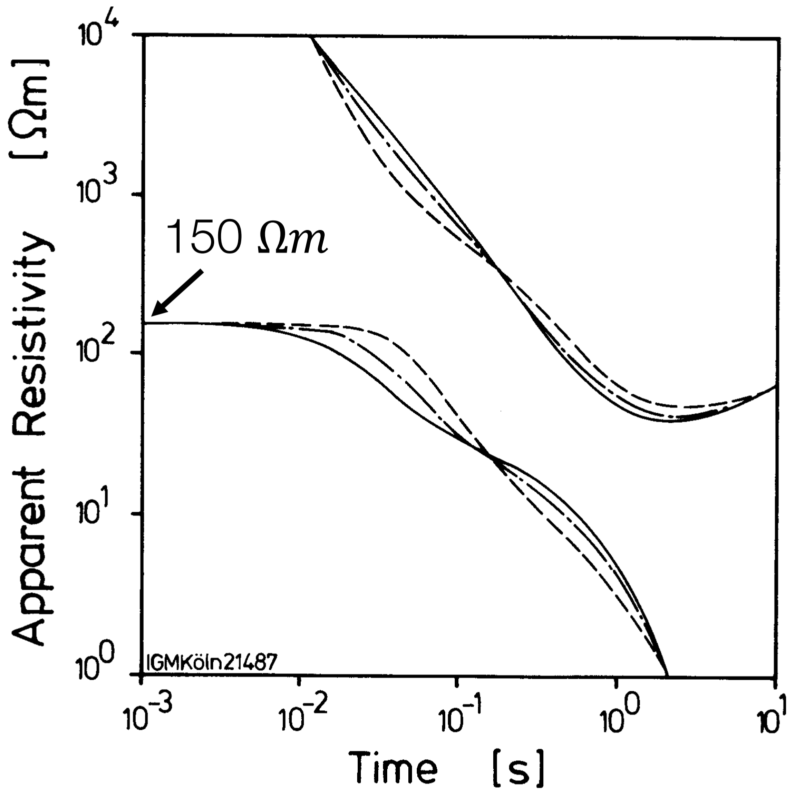


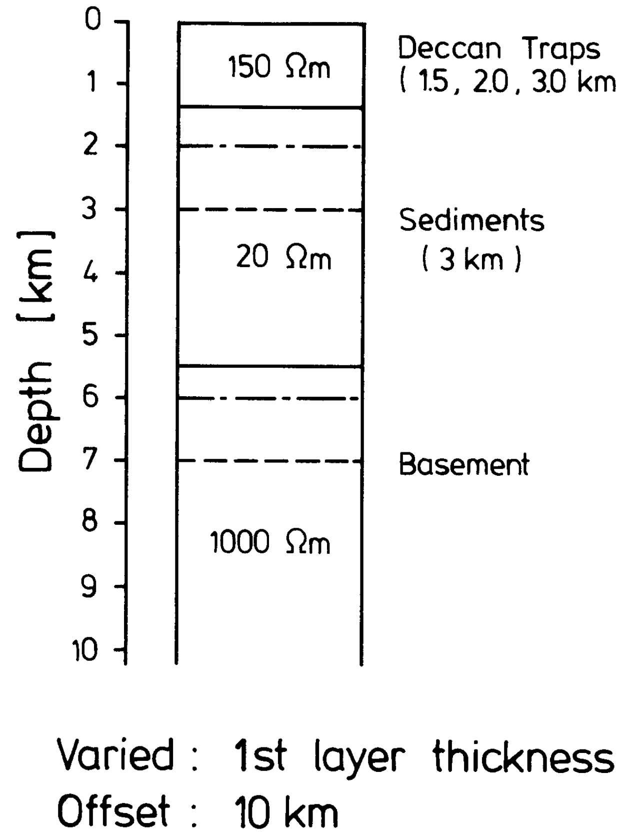
Long offset time domain EM (LOTEM)



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

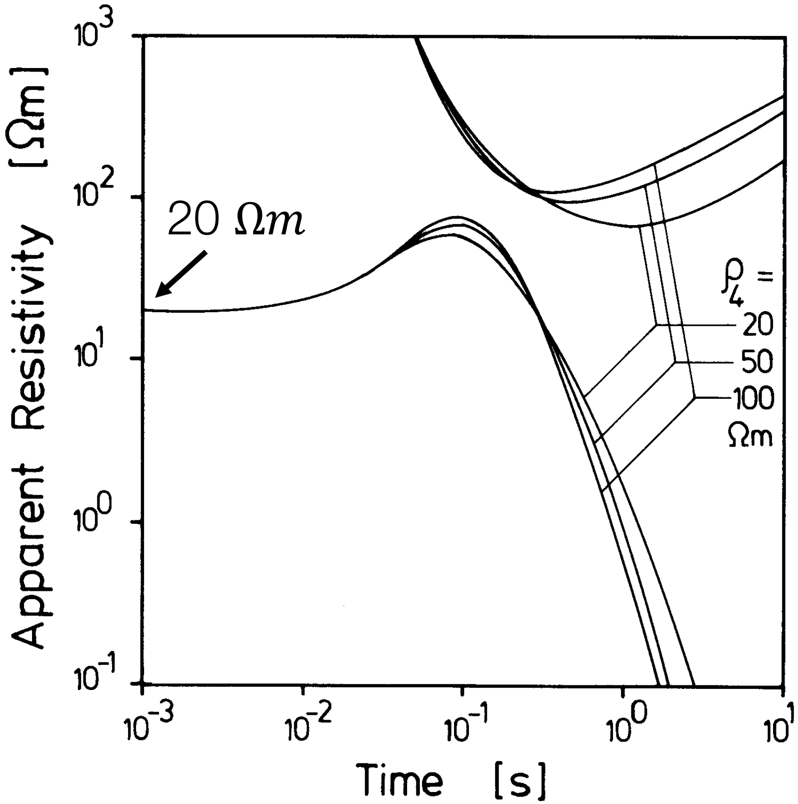
Survey design: basalt thickness

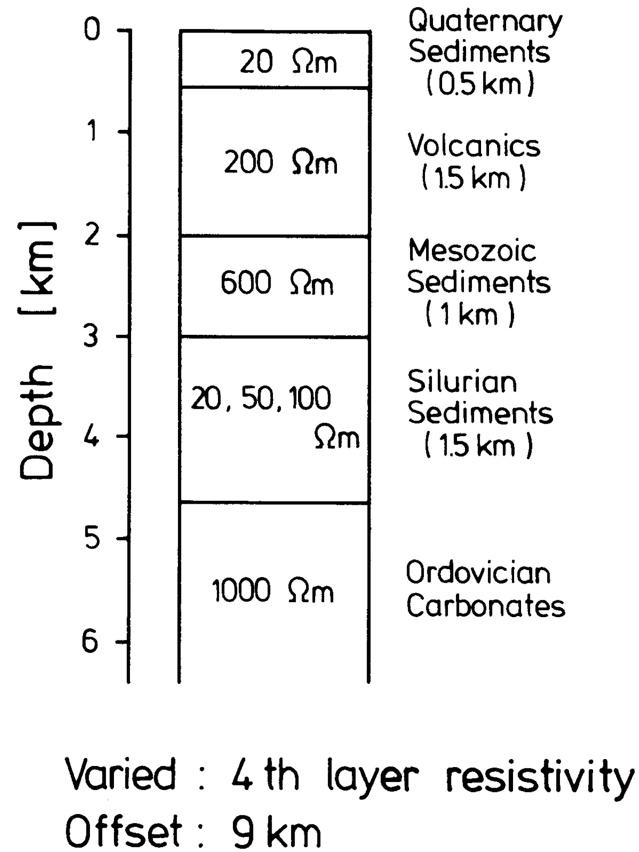




- Apparent resistivity changes with varying thickness of Deccan Traps: 1.5, 2 and 3 km

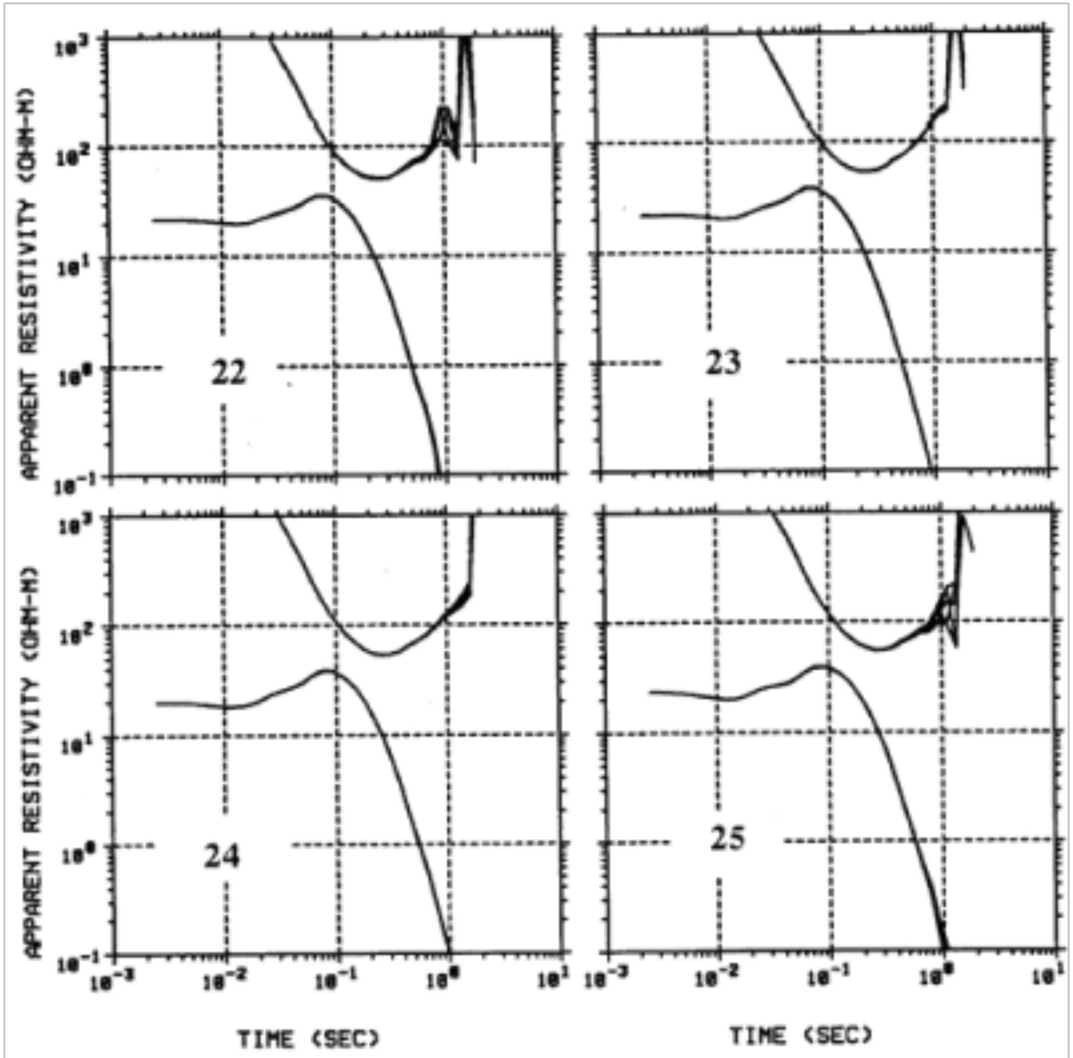
Survey design: sediment resistivity





- Apparent resistivity changes with varying resistivity of Silurian Sediments

Data



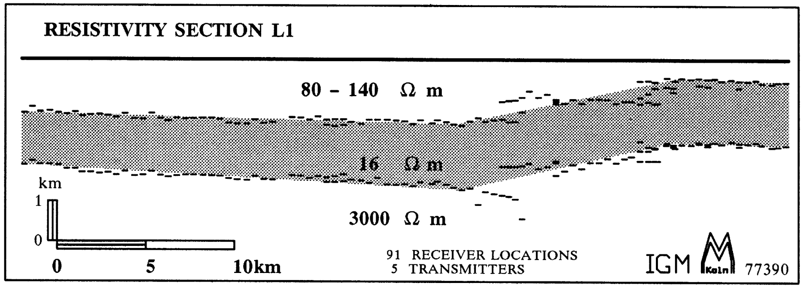
- Stacked data
- Time range: 1ms-10s
- High S/N ratio until 1s
- Similar to synthetic data

Processing

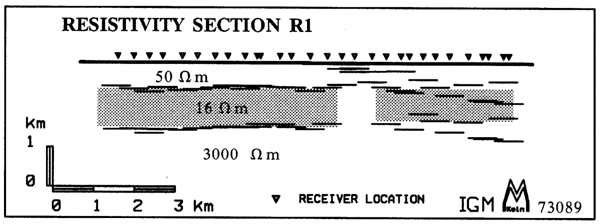
1D inversions (stitched)

Thickness decreases

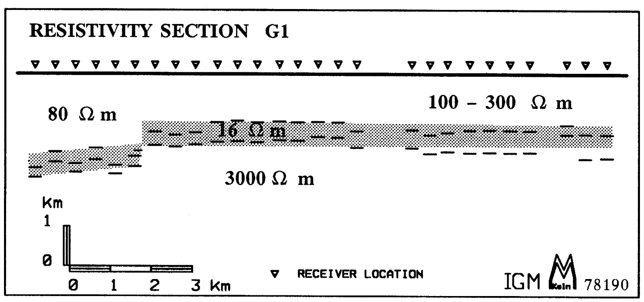
L



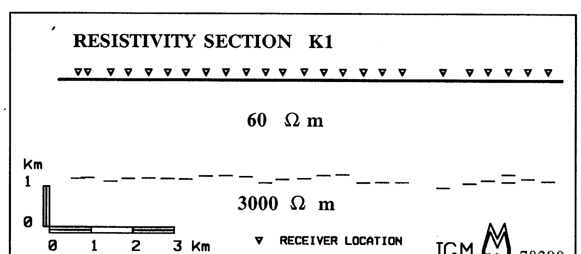
R



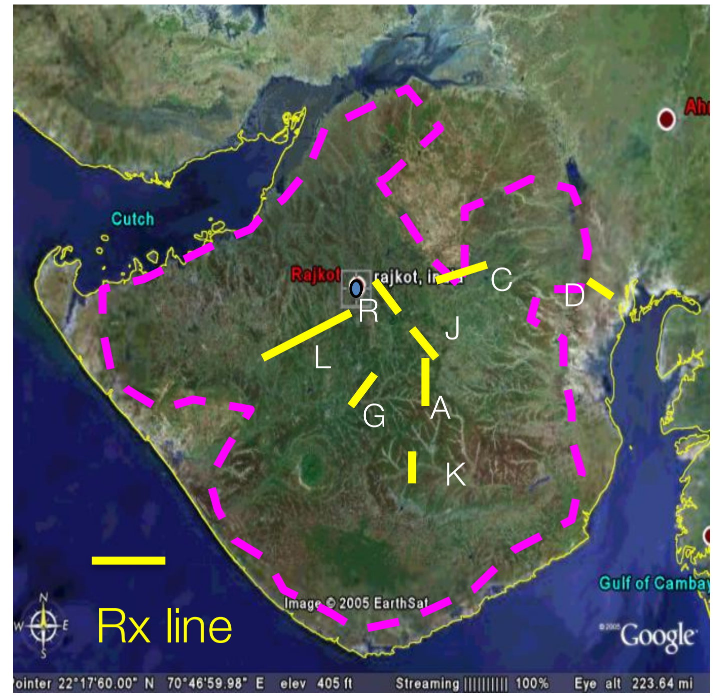
G



K



Location map

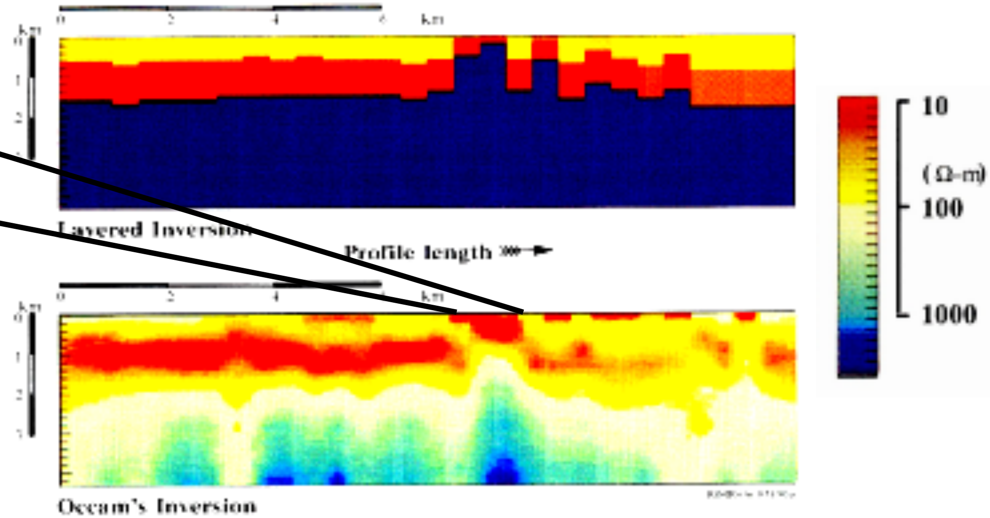


The sediment thickness:

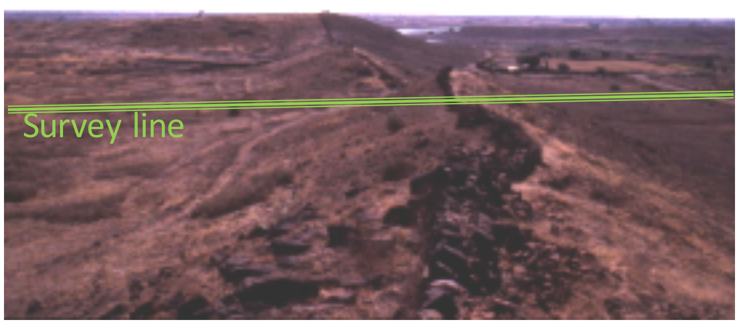
- Largest at **L**
- Smallest at **K**

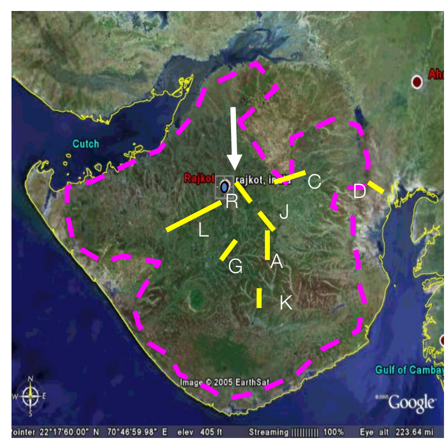
Interpretation: dyke. Profile **R**

Surface outcrop



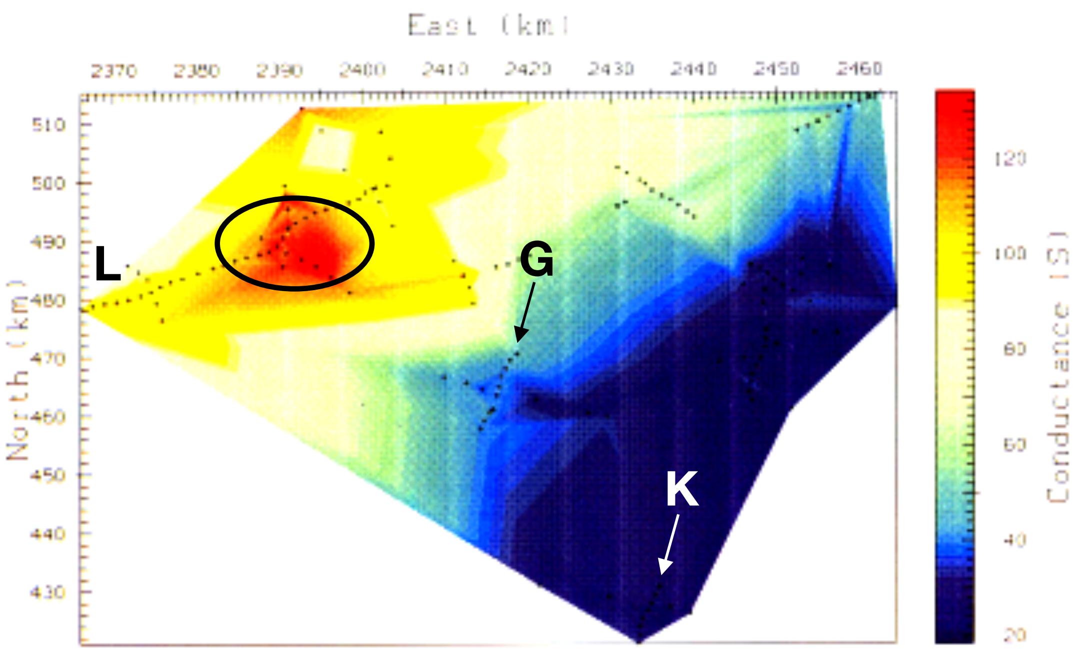
Extended view



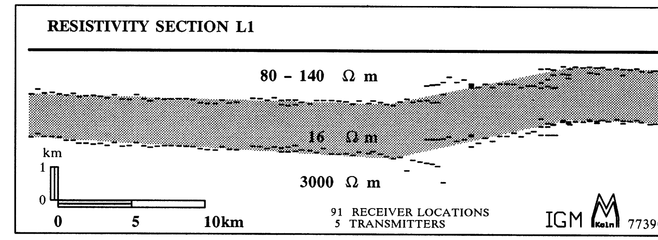


Dyke is a resistor

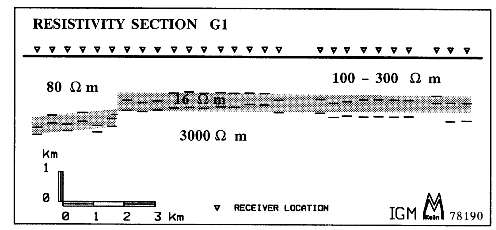
Interpretation:
sediment conductance and drill target



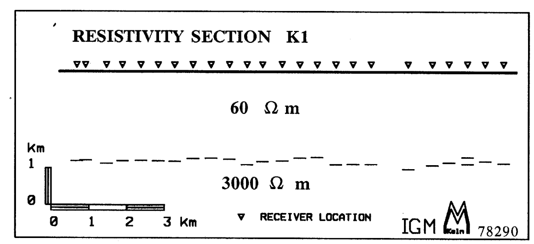
L



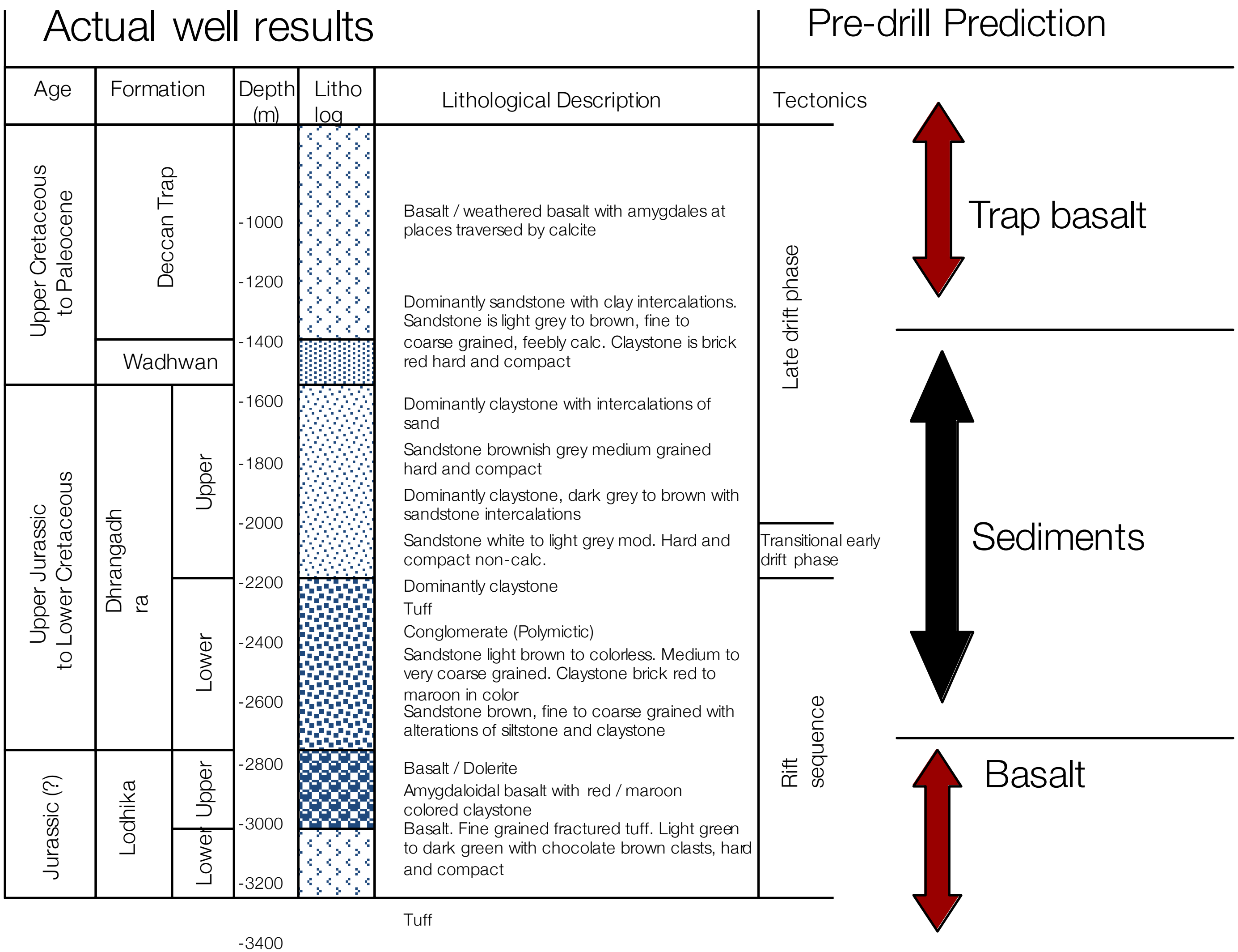
G



K



Synthesis

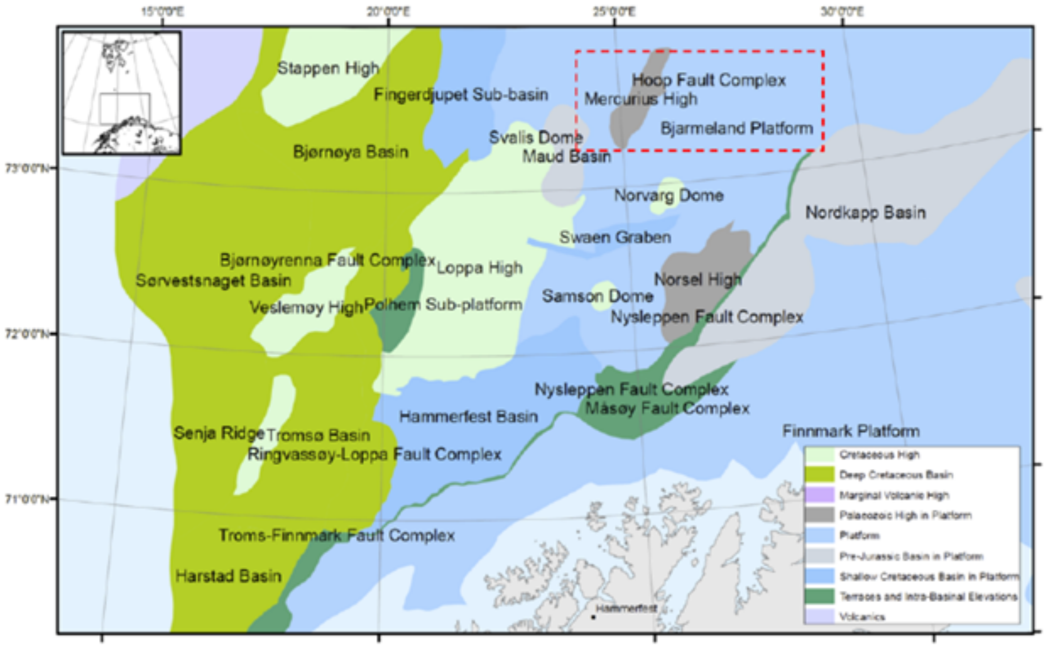

Actual well results
Pre-drill Prediction
Age
Formation
Depth (m)
Litho log
Lithological Description
Tectonics
Upper Cretaceous to Paleocene
Deccan Trap
Wadhwan
Upper Jurassic to Lower Cretaceous
Dhrangadhra
Upper
Lower
Jurassic (?)
Lodhika
Upper
Lower
-1000
-1200
-1400
-1600
-1800
-2000
-2200
-2400
-2600
-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

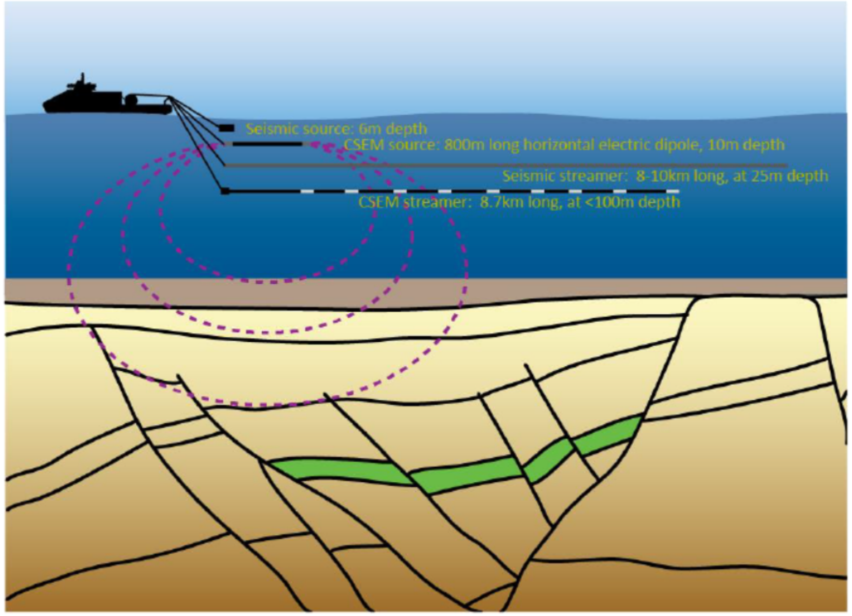
Alvarez et al., 2016. Rock Solid Images

Setup

Hoop Fault Complex, Barents Sea

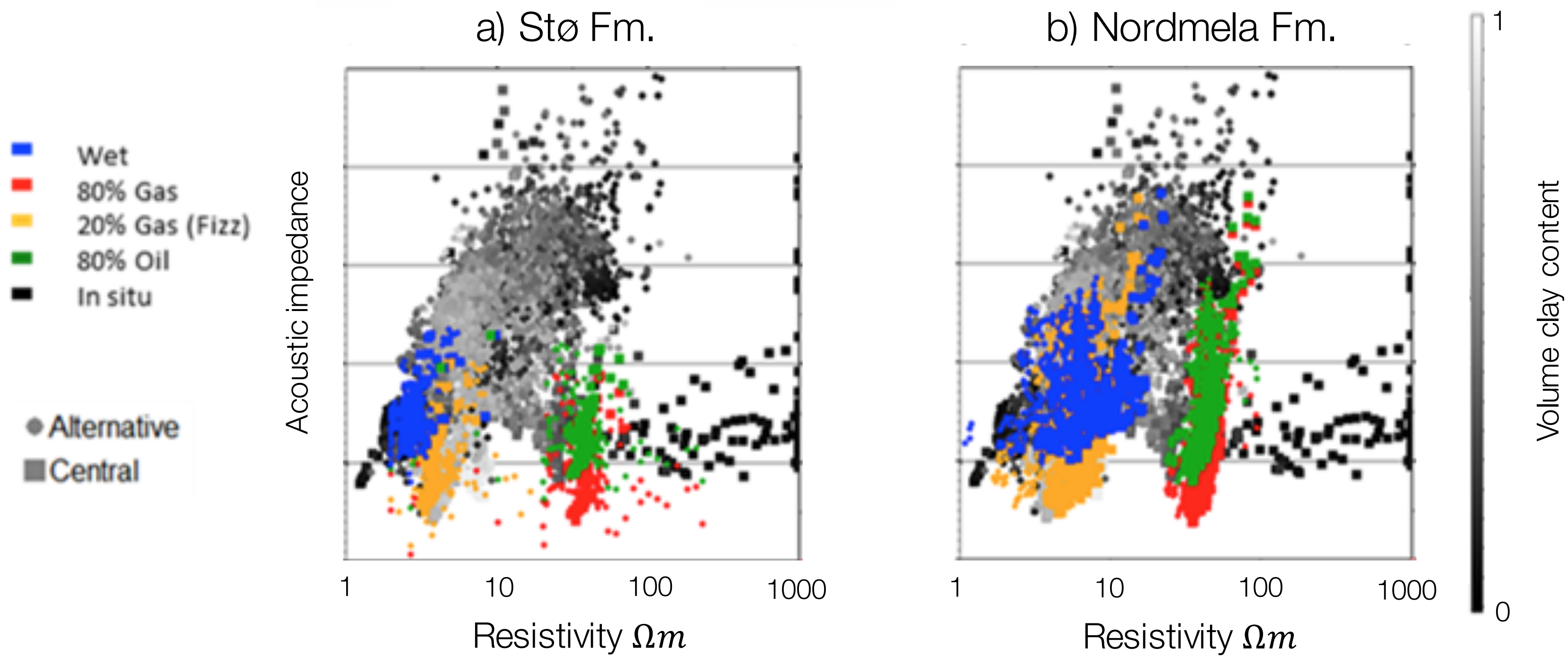


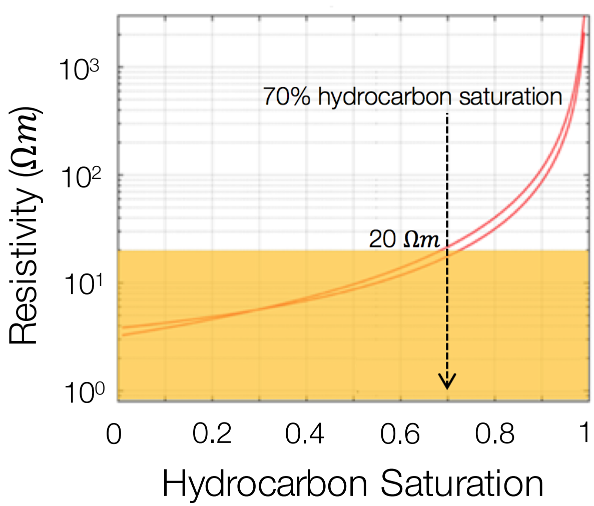
Marine CSEM



- 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

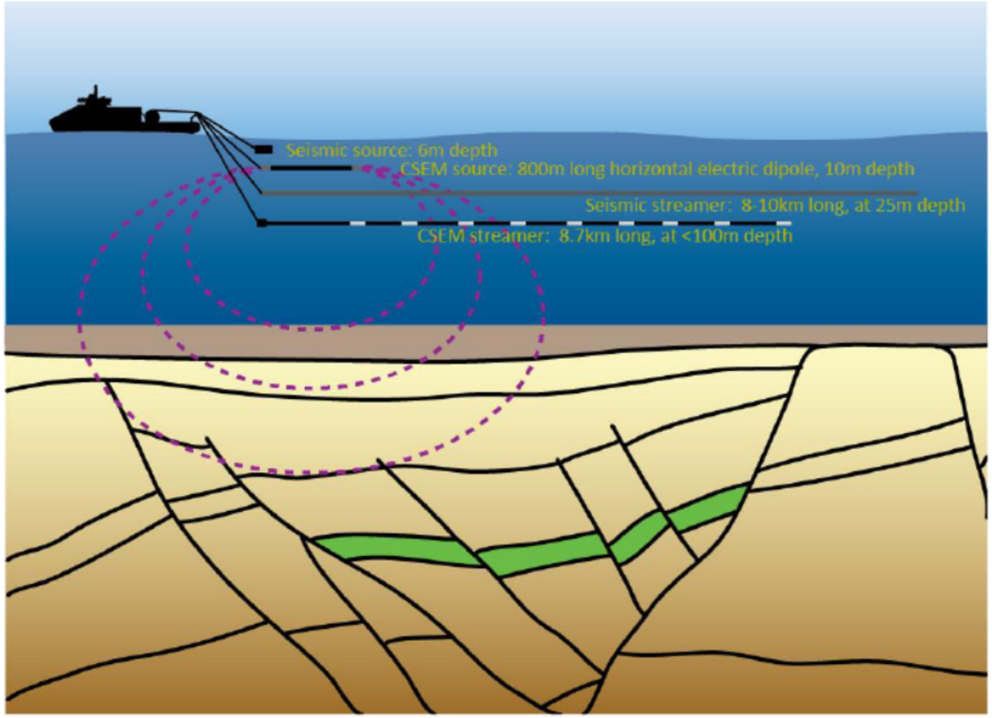




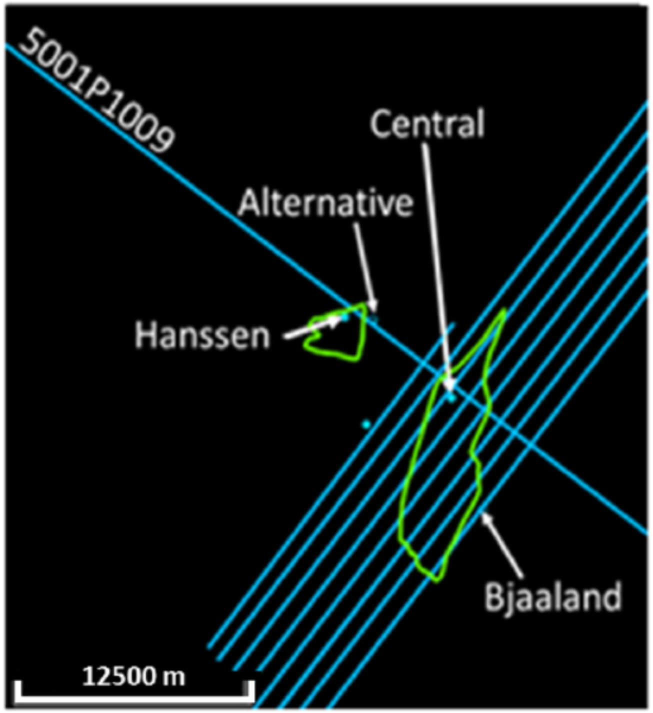
- Highly hydrocarbon-saturated reservoir (< 30% water-wet) significant resistivity
- CSEM can differentiate high from low quality reservoirs

Survey

Towed CSEM and 2D seismic



Survey lines

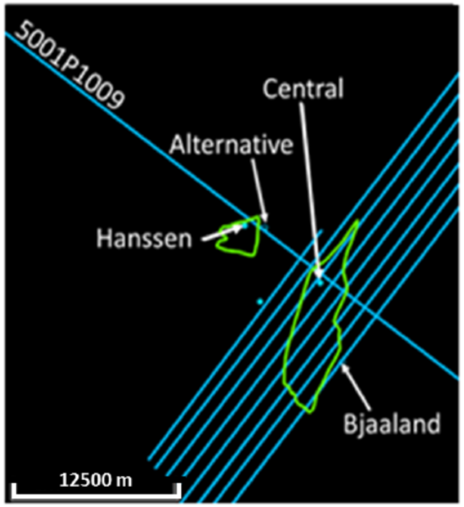


- 6 lines of 2D seismic and towed streamer CSEM data.
- 72 receivers collected CSEM data
  - offsets from 31m to 7.8 km
- CSEM frequencies: 0.2 Hz to 3 Hz.

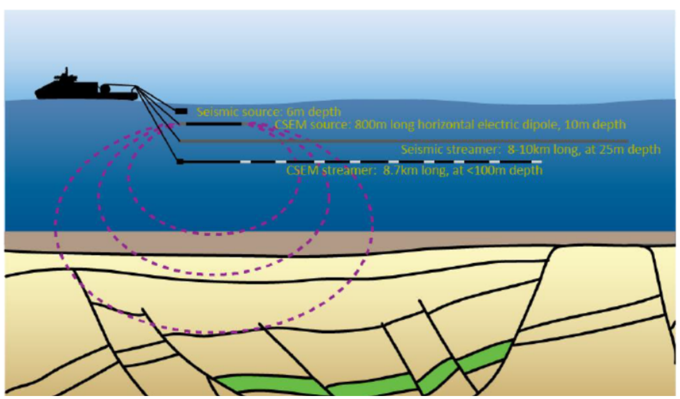
Alternative	Control well, dry
Central	Control well, productive
Hanssen	Validation well
Bjaaland	Validation well

CSEM Data

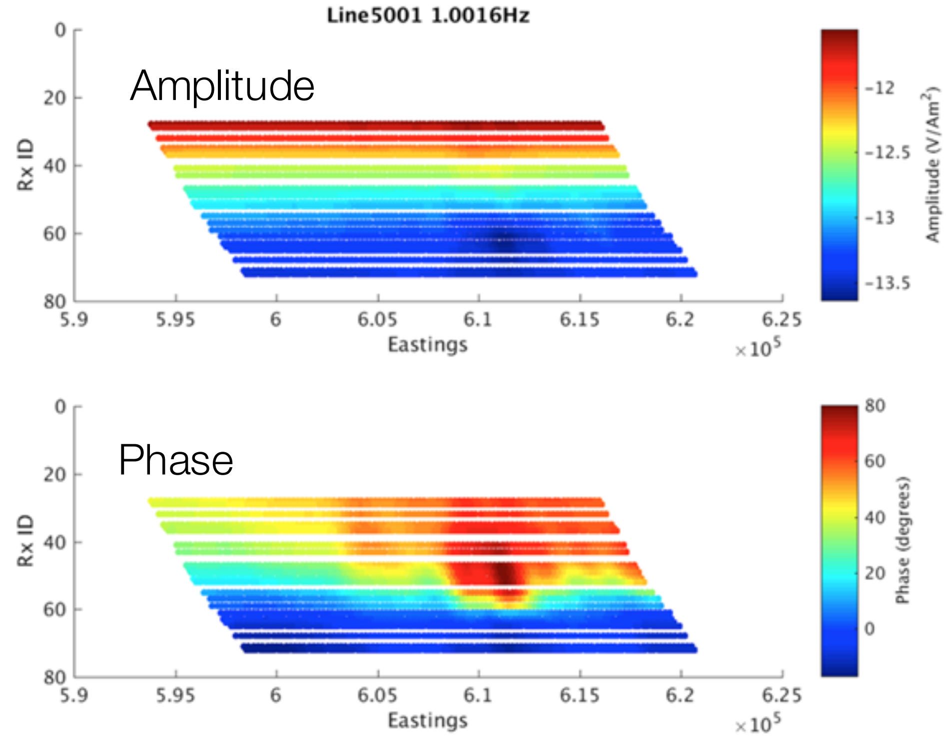
Survey lines



Towed-streamer EM



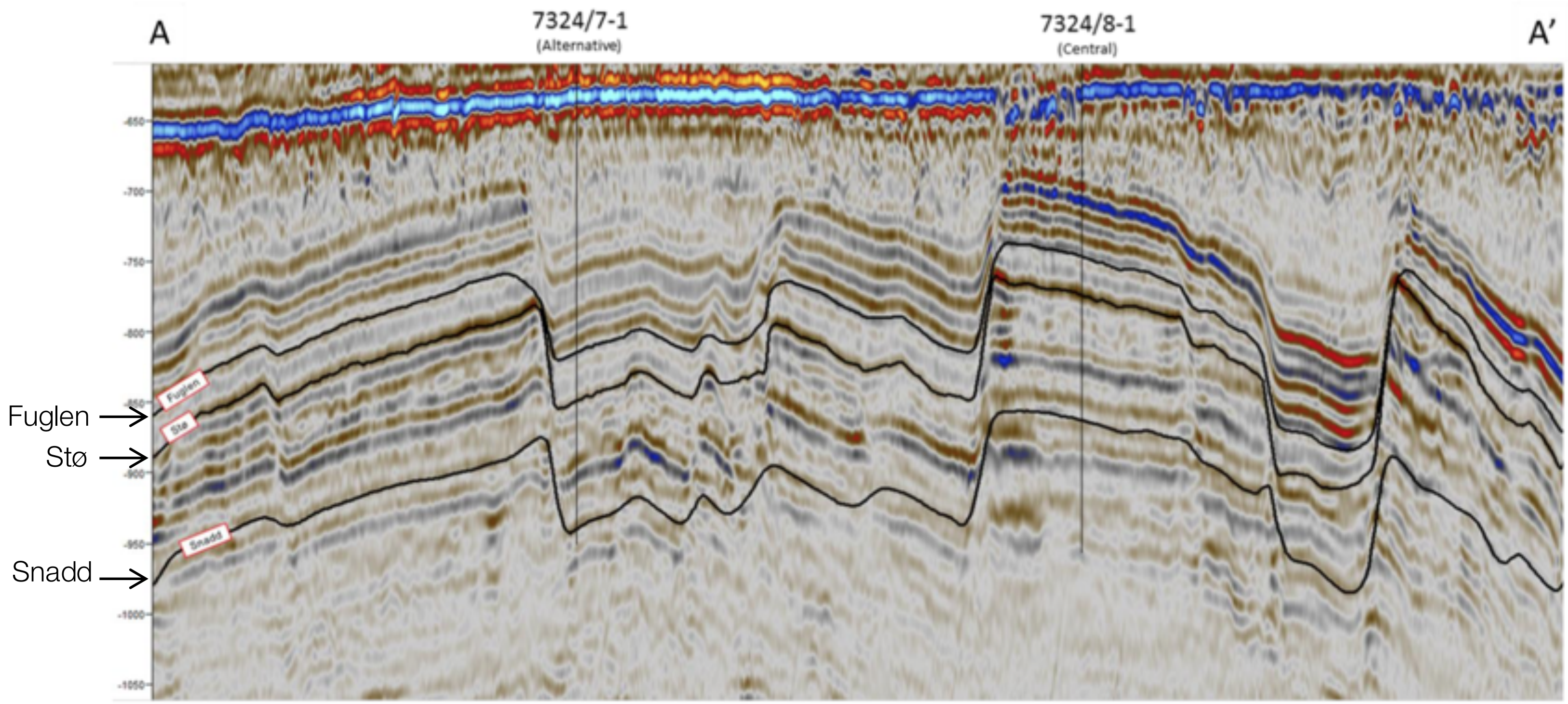
CSEM data over central reservoir (1 Hz)

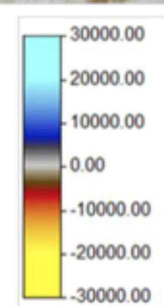


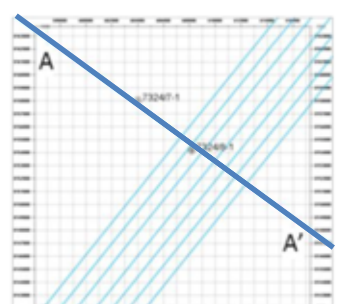
- Significant phase response over Central reservoir

Seismic data

Seismic section: Line 5001





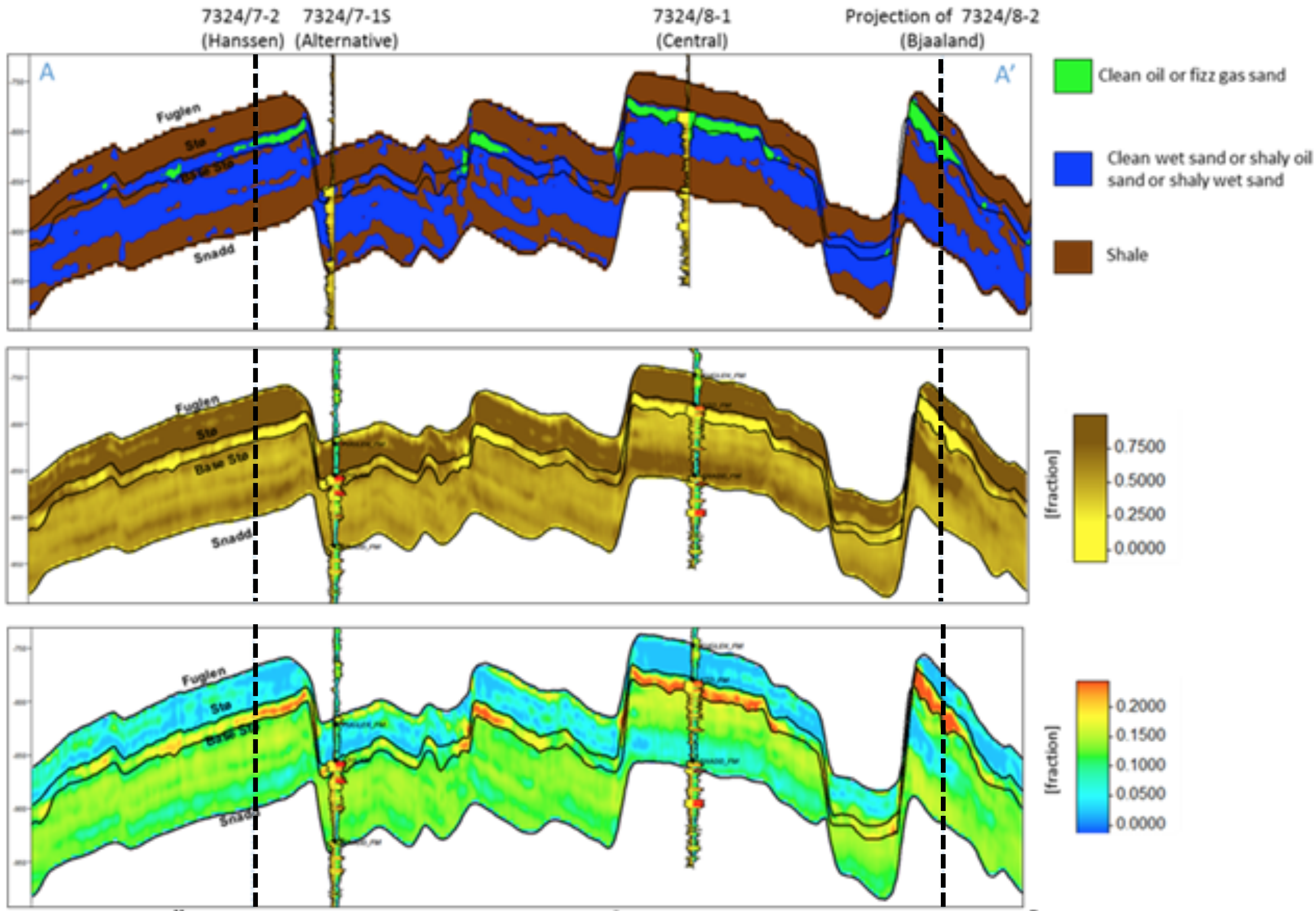


Well-Log and Seismic Inversion

Litho-fluid Facies

Clay Content

Total Porosity



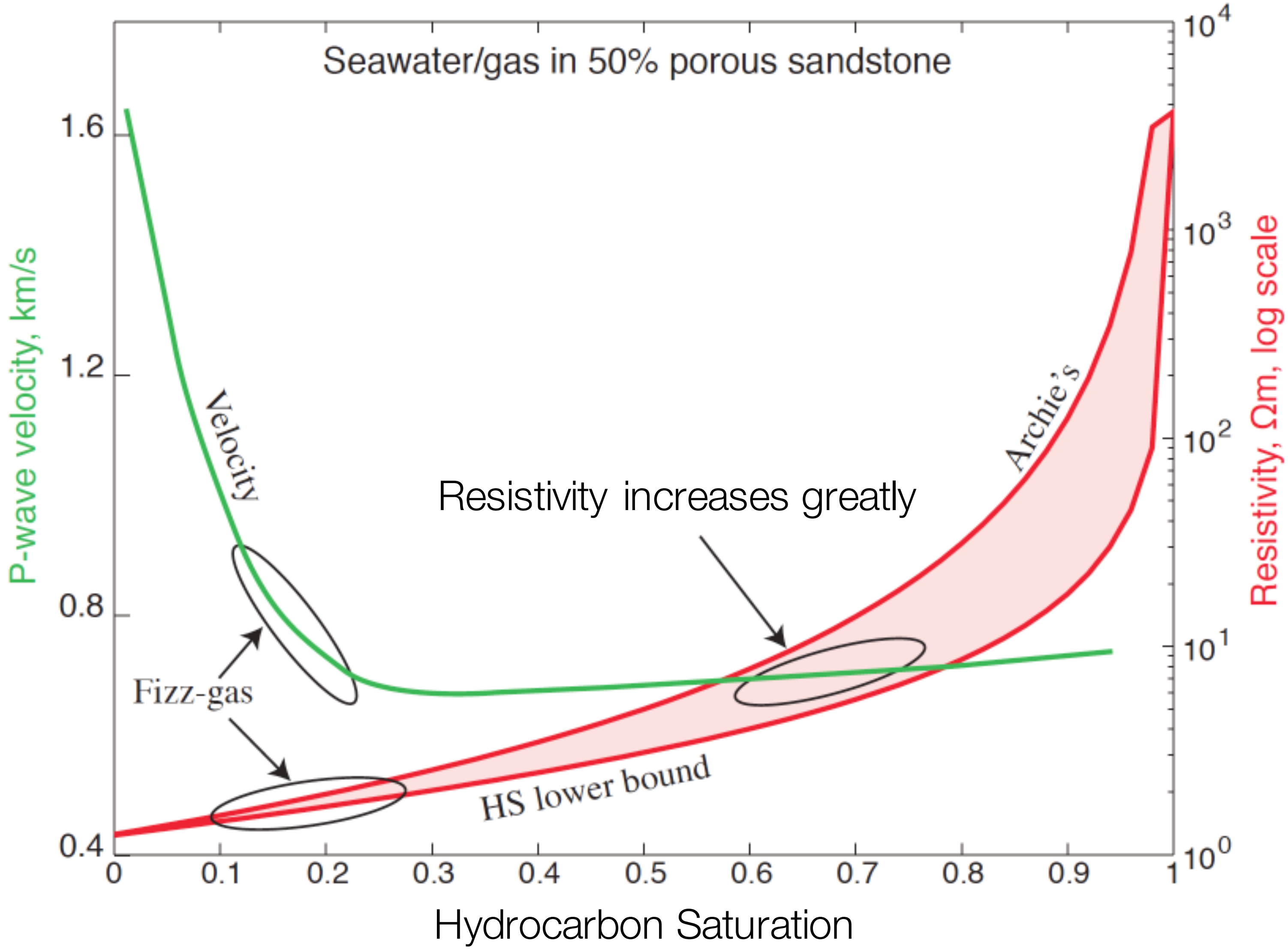
Hanssen
Validation well

Alternative
Control, dry

Central
Control, productive

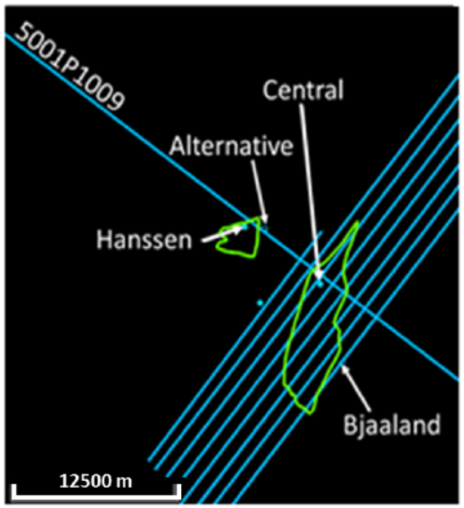
Bjaaland
Validation well

Revisiting physical properties

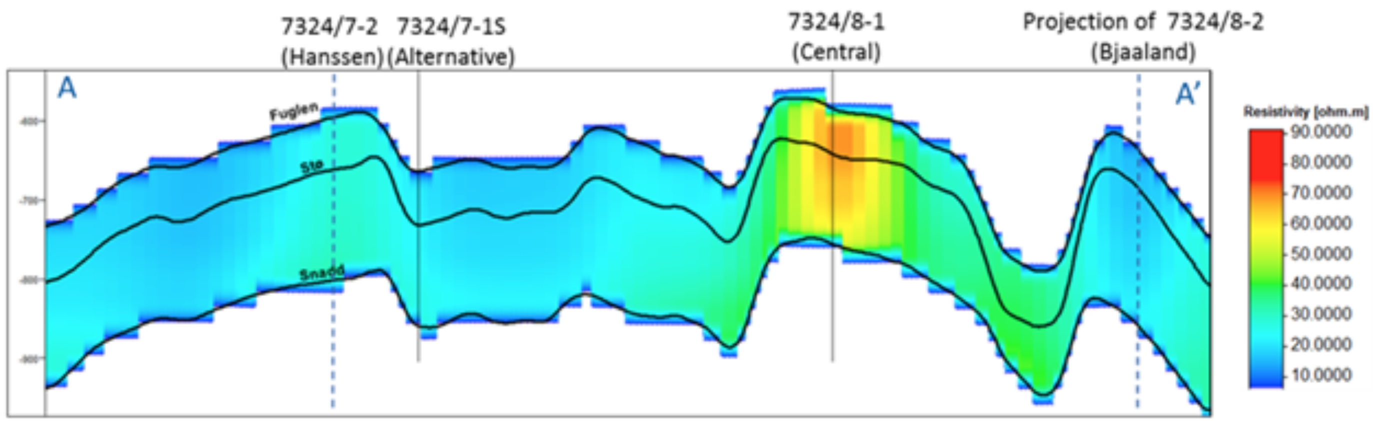


Processing: CSEM Inversion

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.

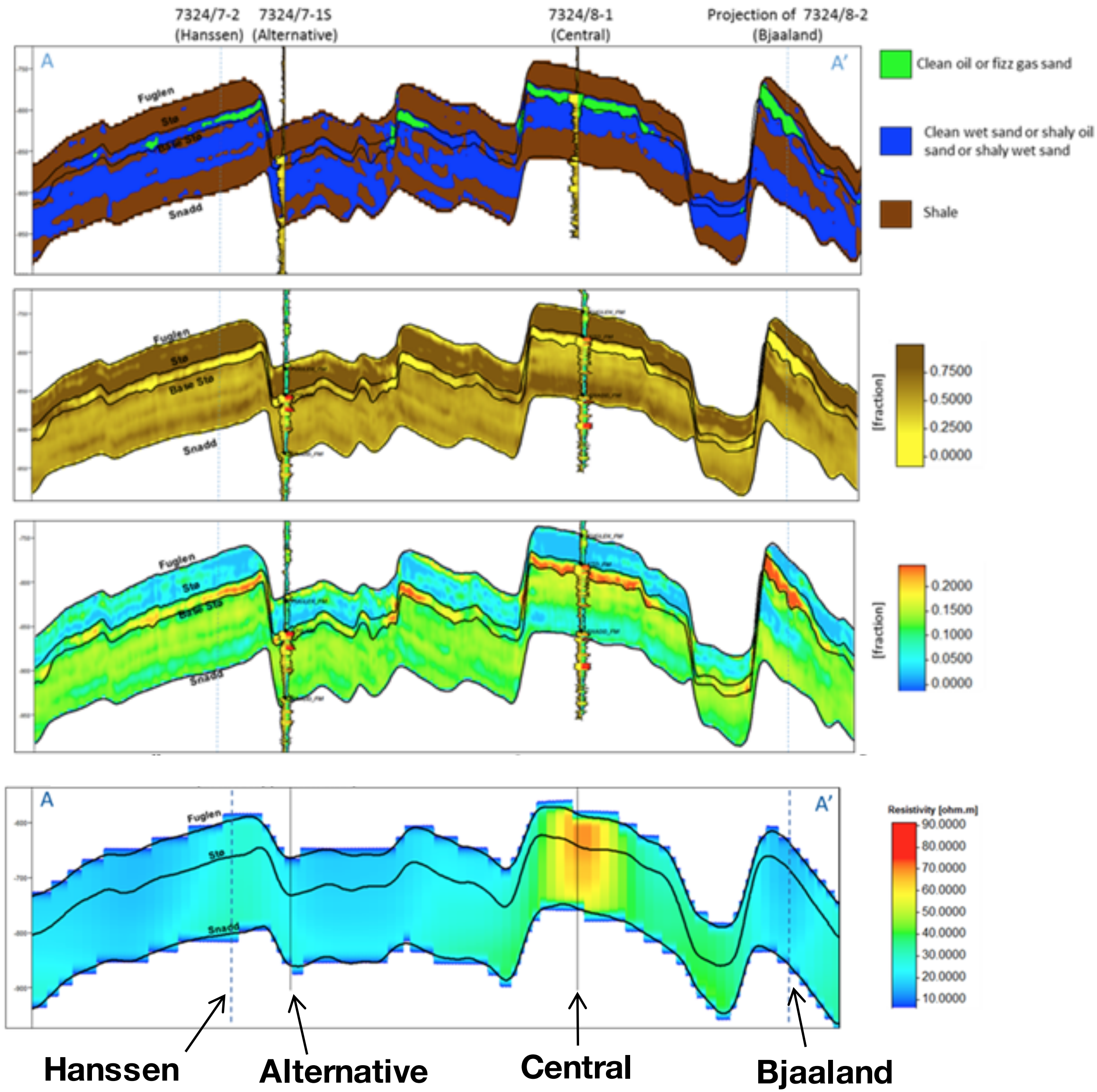
Processing: Multi-physics Approach

Litho-fluid Facies

Clay Content

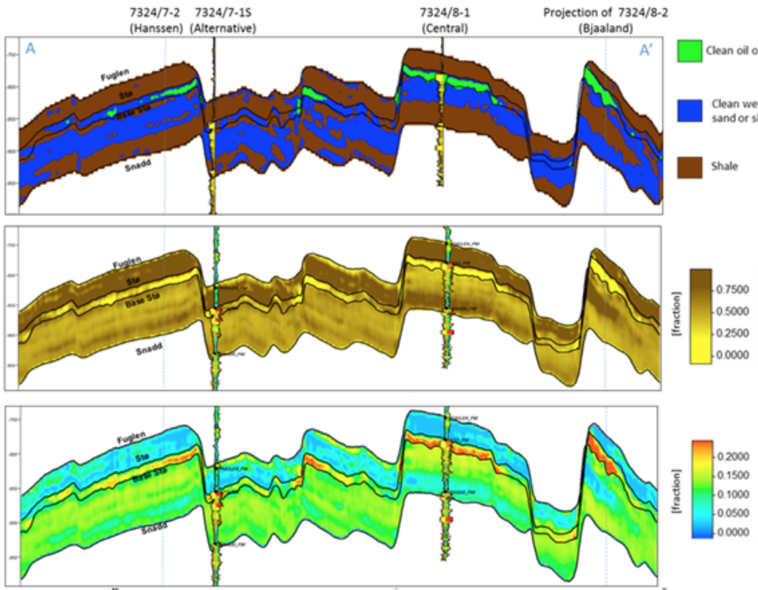
Total Porosity

Resistivity

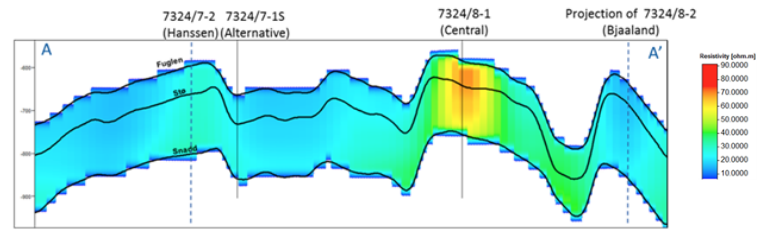


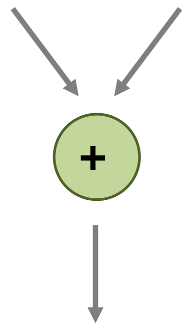
Interpretation & Synthesis

Seismic

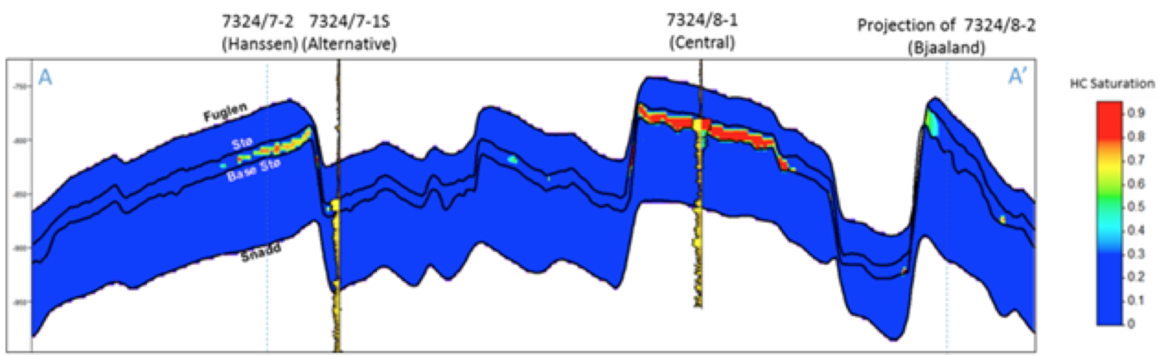


EM





Hydrocarbon saturation



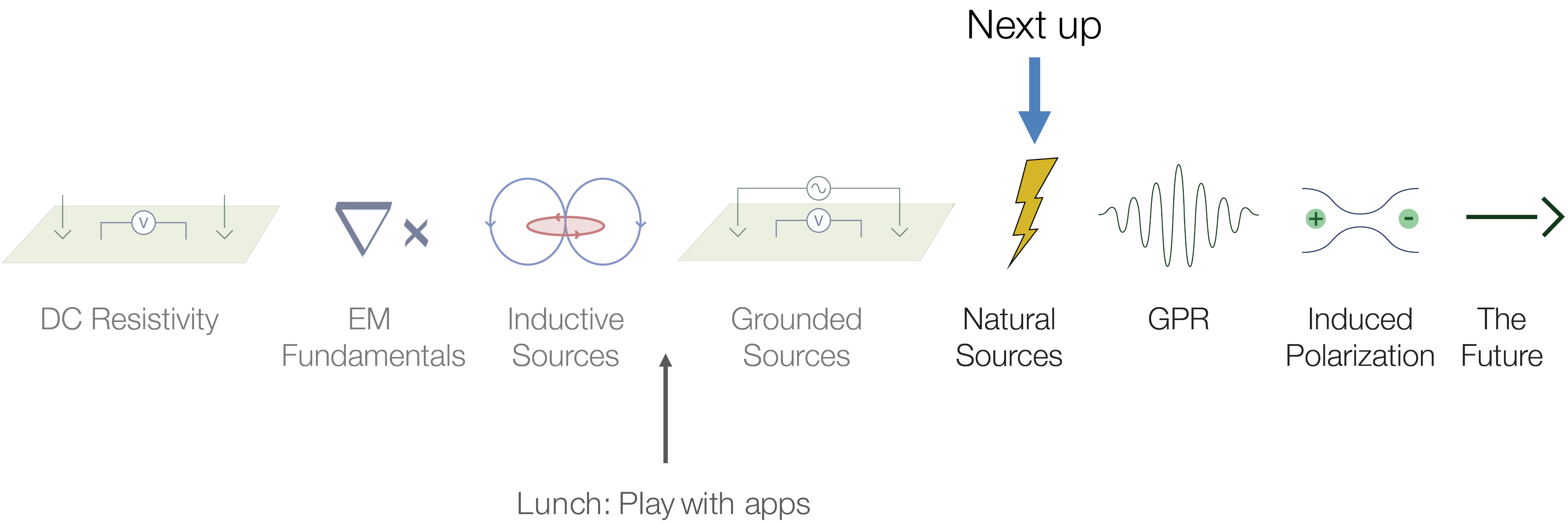
Hanssen
Validation well productive

Alternative
Control, dry

Central
Control, productive

Bjaaland
Validation well dry

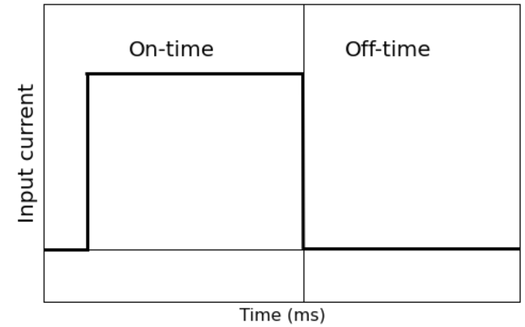
End of Grounded Sources

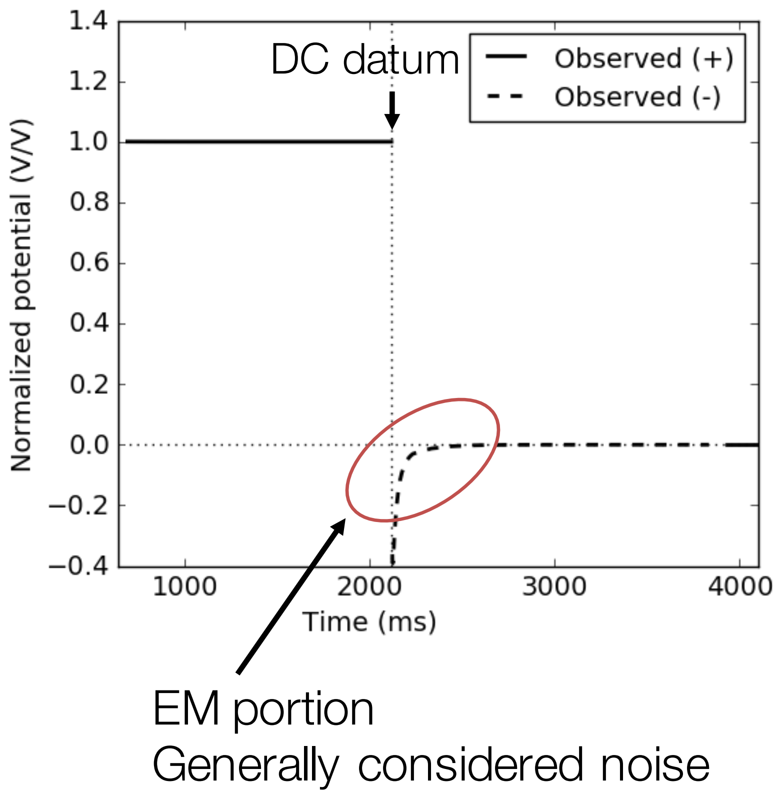


DC/EM Inversion

DC/EM: Goals

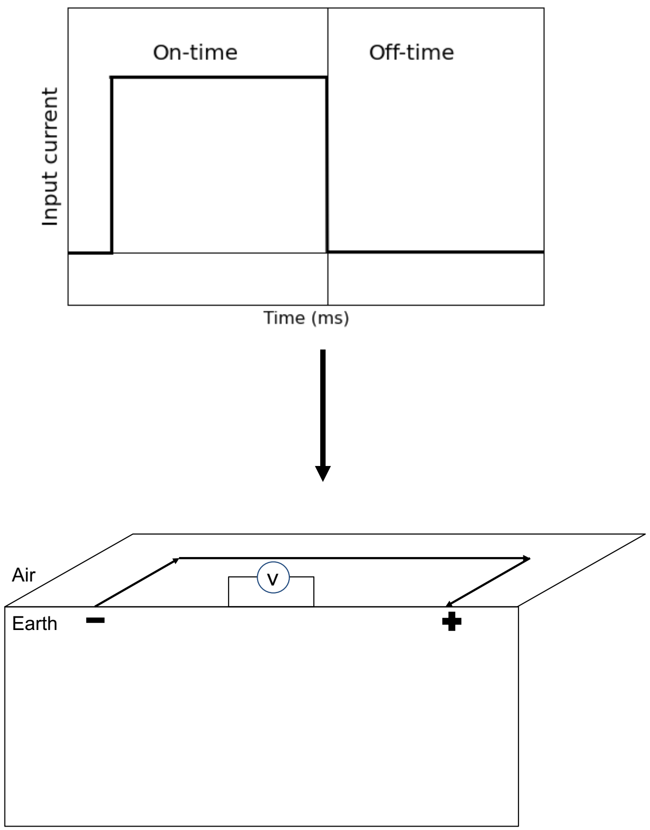
- Standard DCR time domain waveform
- Compare:
  - Inversions from DC data
  - Inversions from EM data
- Illustrate the value of data which is often discarded
- Numerical example from a gradient array



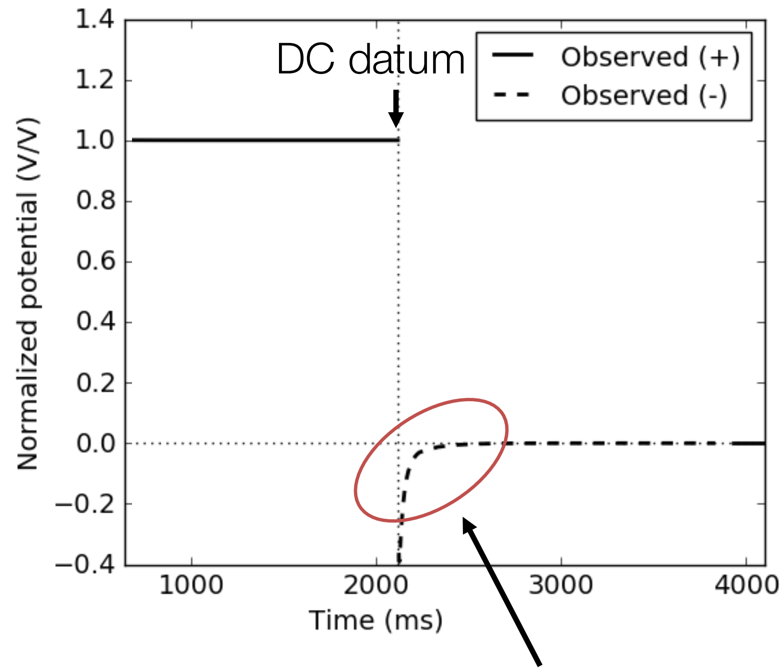


Survey and Data

Transmitter



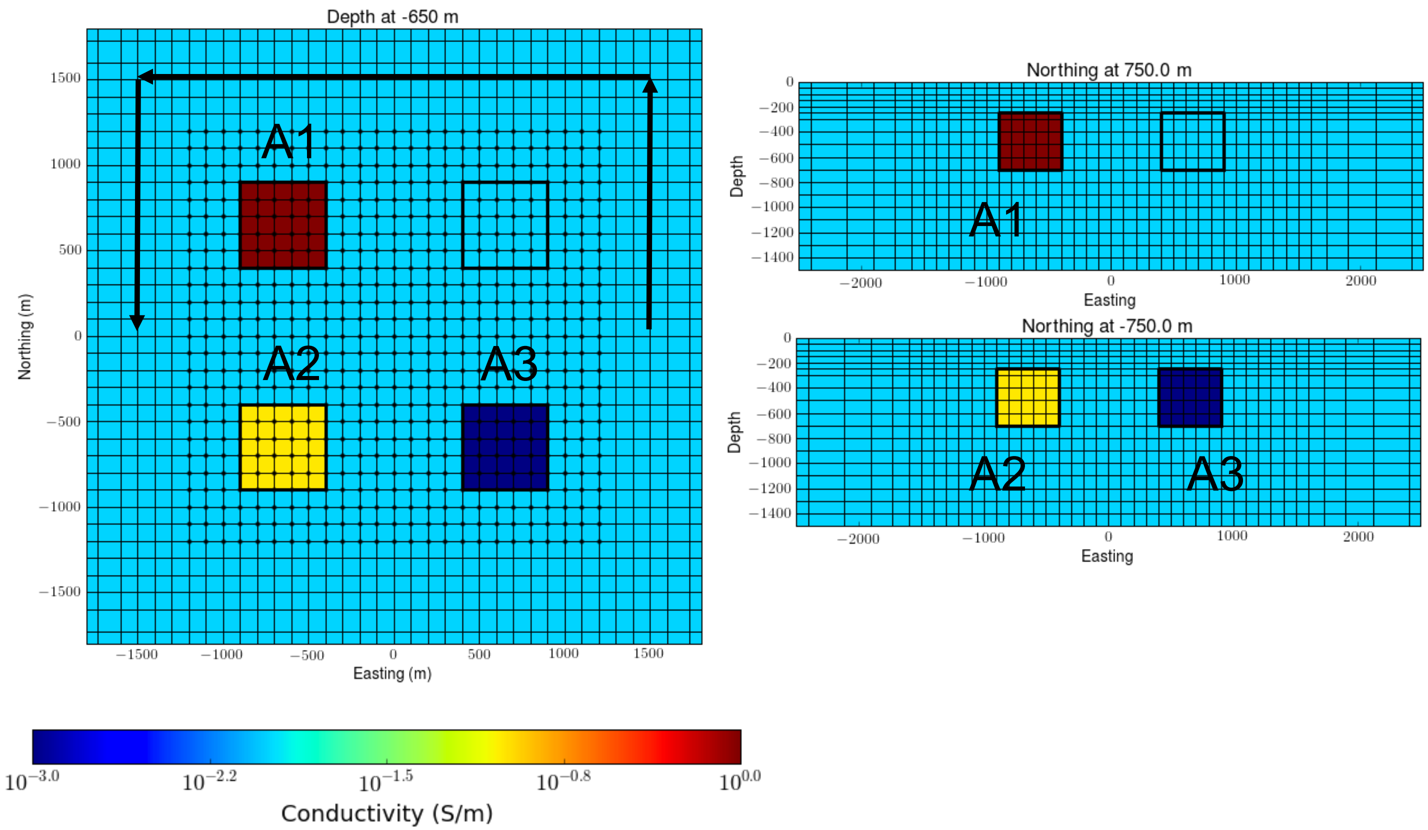
Measured Voltage



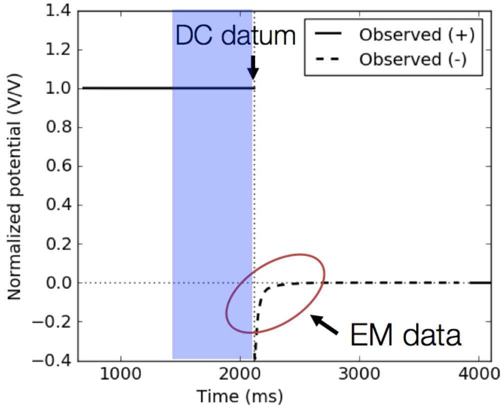
EM portion
Generally considered noise

Gradient array

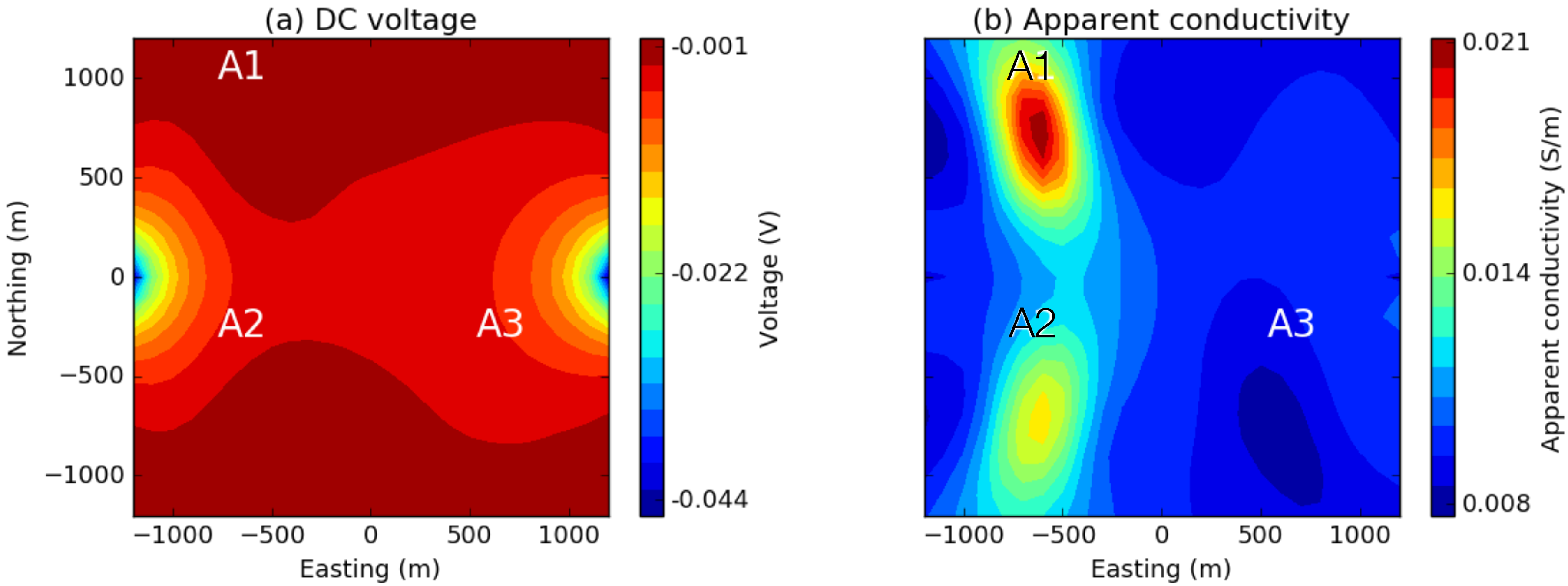
- Model
  - A1: high conductivity
  - A2: moderate conductivity
  - A3: resistive
- Survey
  - 200m bi-pole (625 data)
  - times: 1-600ms



DC data

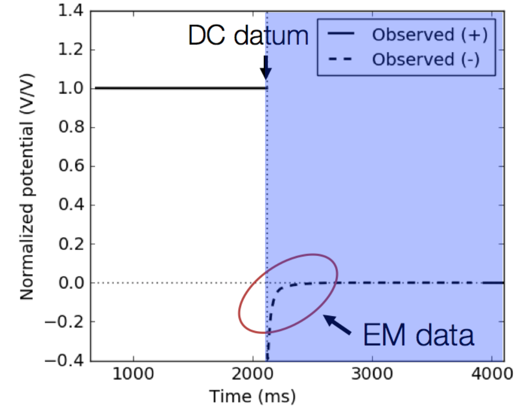


DC datum
Observed (+)
Observed (-)
EM data
Normalized potential (V/V)
Time (ms)

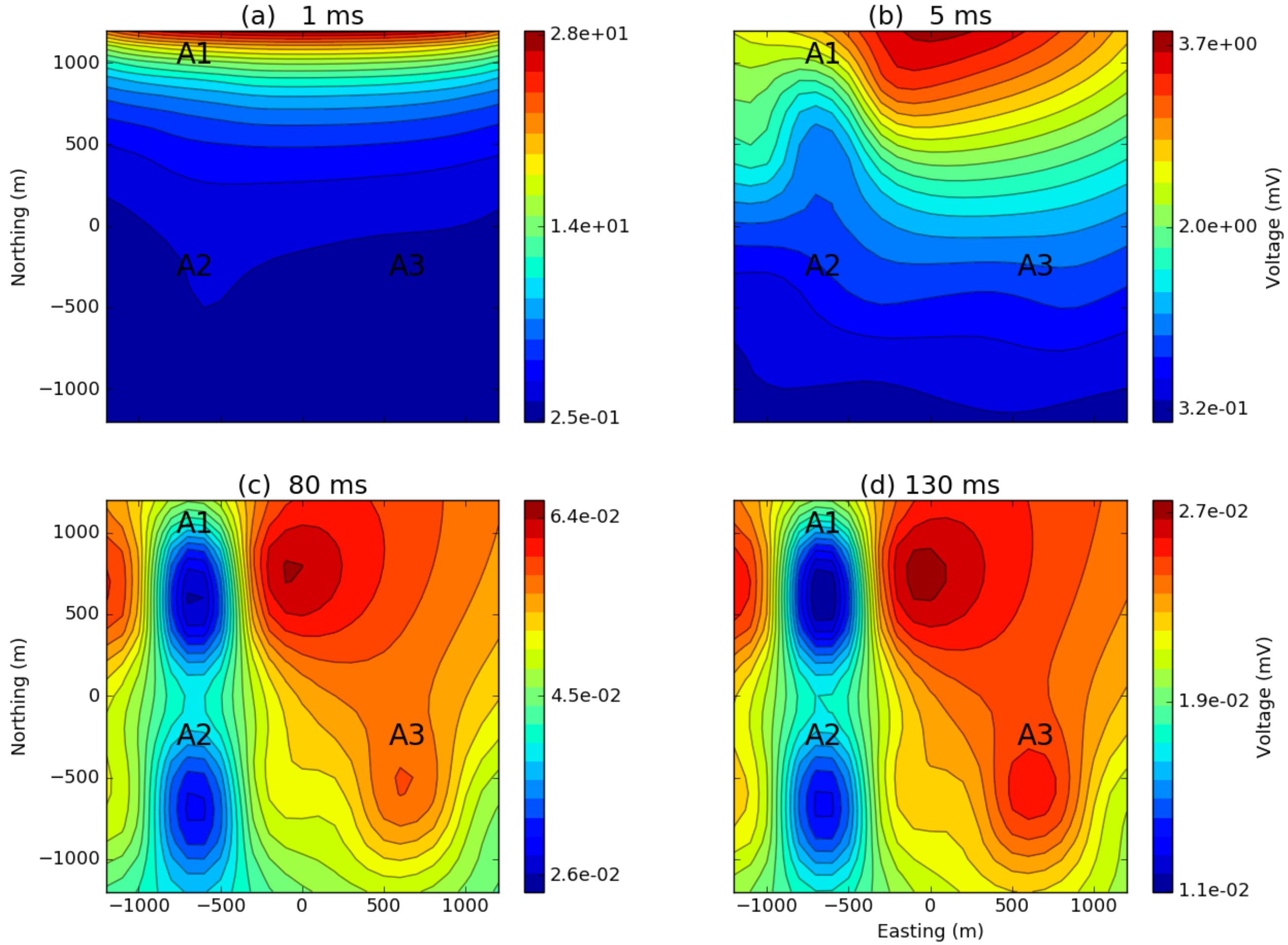


(a) DC voltage
A1
A2
A3
Northing (m)
Easting (m)
Voltage (V)
-0.001
-0.022
-0.044
(b) Apparent conductivity
A1
A2
A3
Easting (m)
Apparent conductivity (S/m)
0.021
0.014
0.008

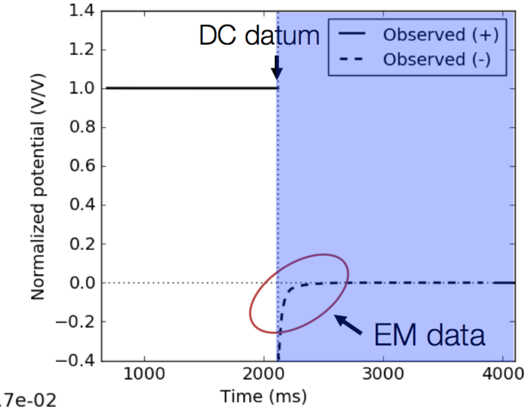
Off-time data



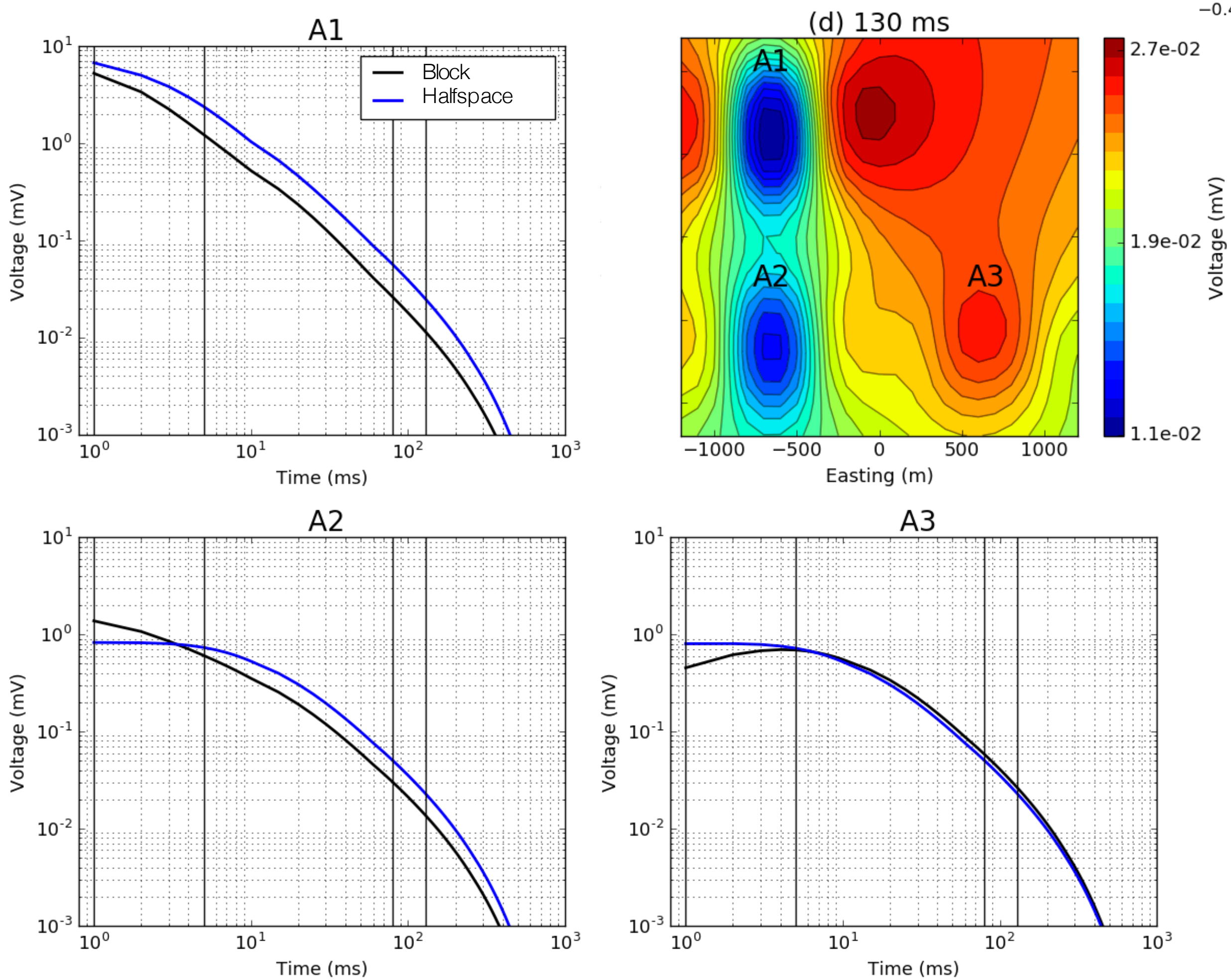
- TDEM data



Off-time data



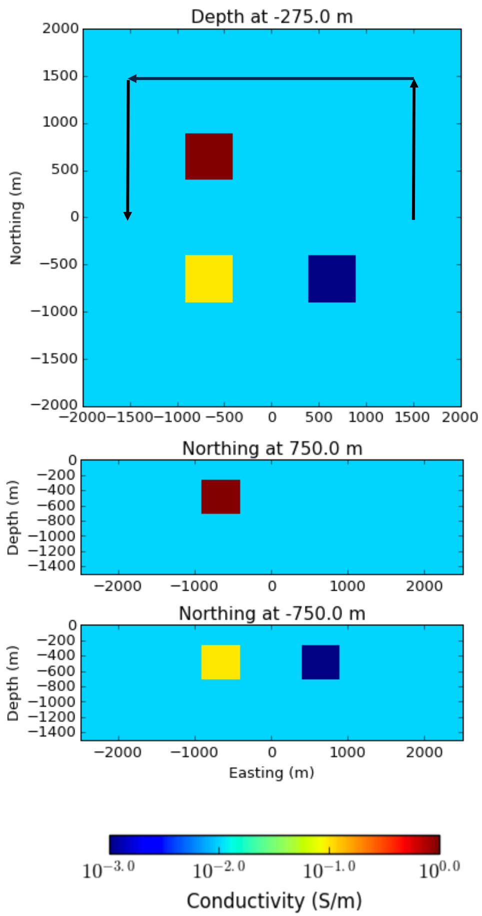
- E_x Decay curves at A1-A3



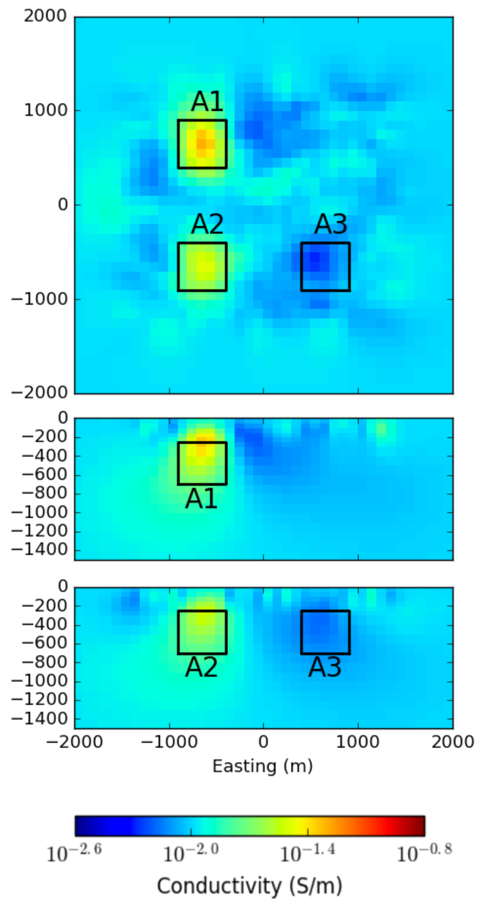
DC inversion

- Recovered 3D conductivity

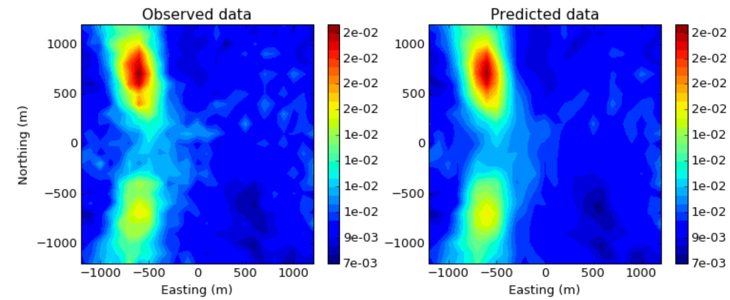
True



Recovered



Apparent conductivity



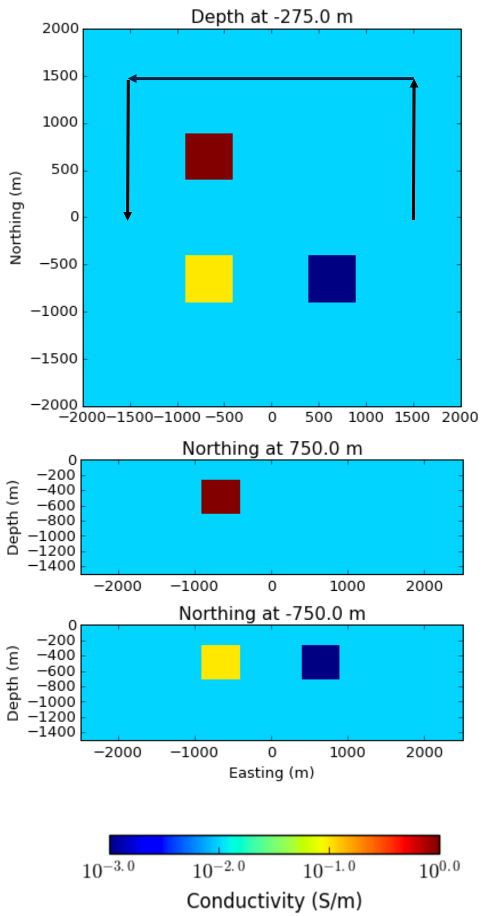
- Depth weighting
  - Compensate for high sensitivity near surface (similar to mag.)

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

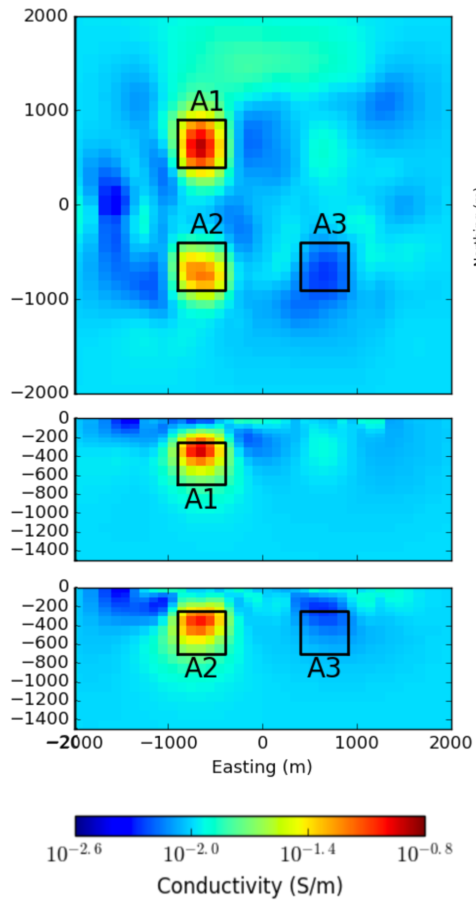
EM inversion

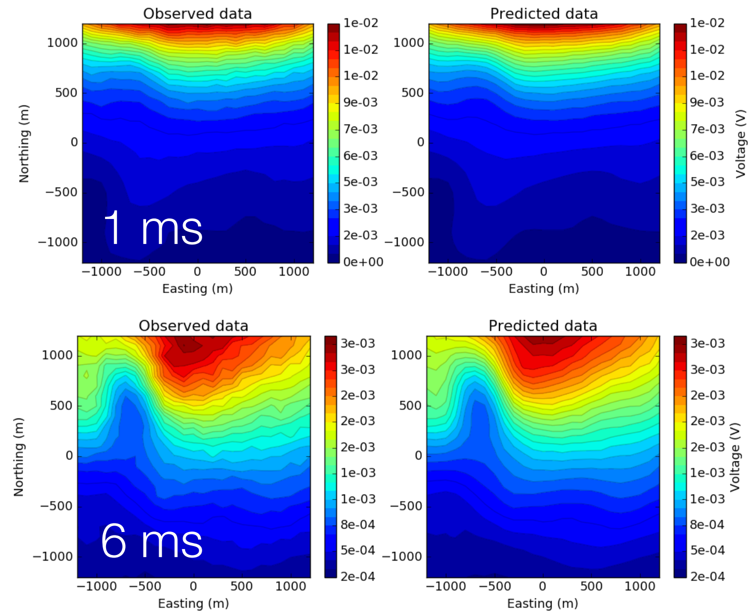
- Recovered 3D conductivity

True



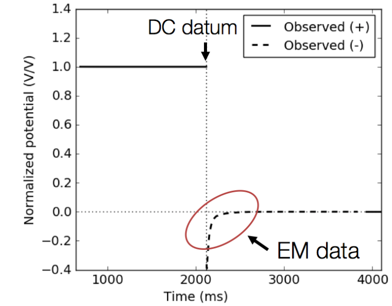
Recovered



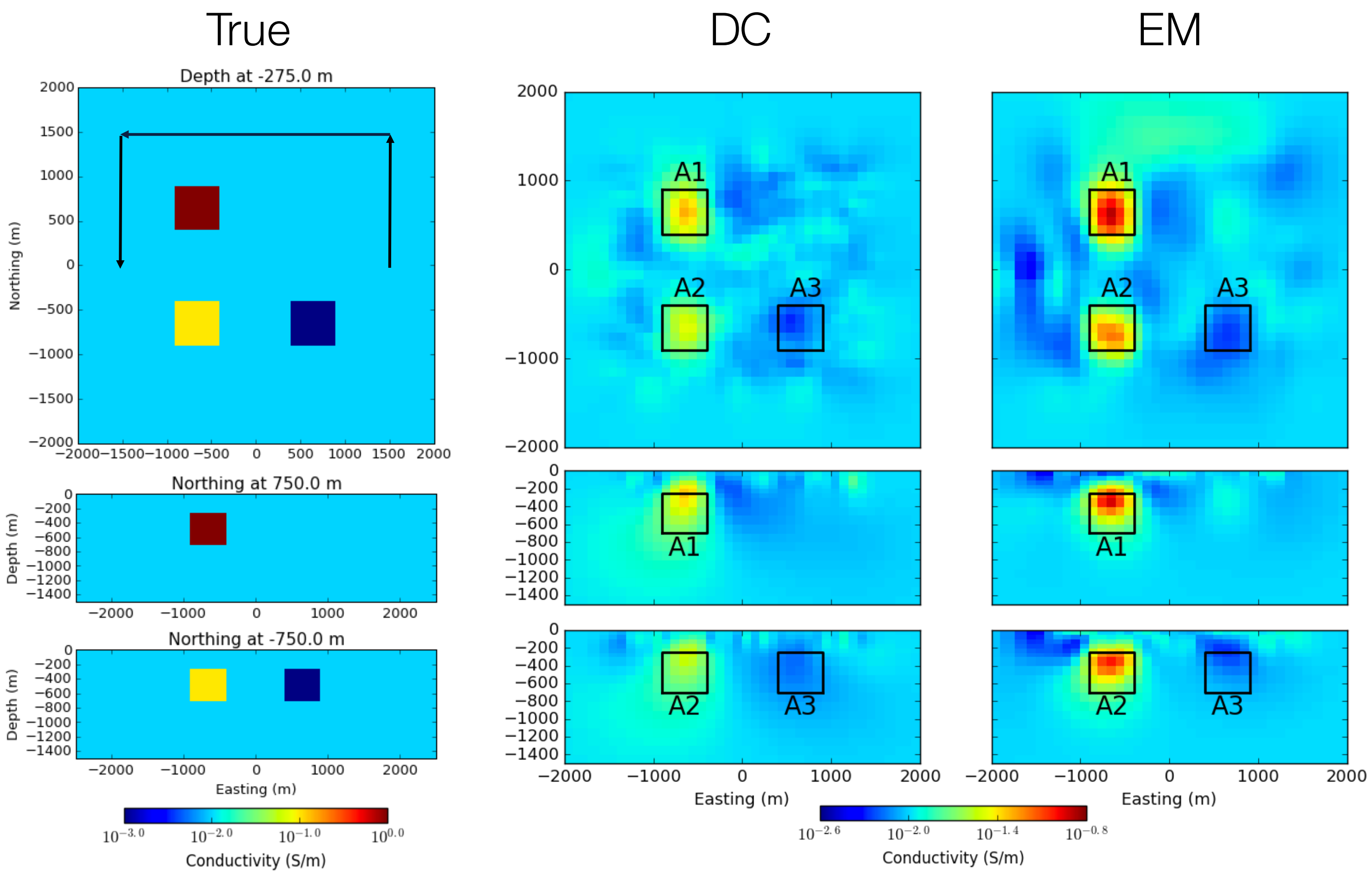


- No depth weighting

Conductivity models



- True, DC, and TEM conductivities



EM data contain signal

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: Barents Sea
- DC/EM Inversion