Modelling electromagnetic problems in the presence of cased wells

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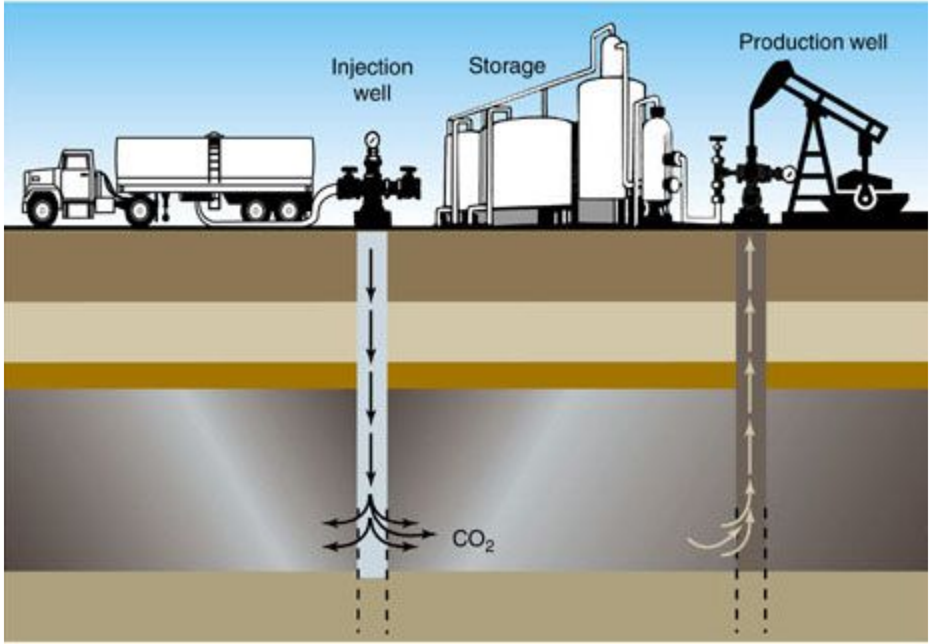
Why?

Electrical conductivity can be a diagnostic physical property

- e.g. Monitoring applications
  - CO_2 sequestration
  - Locating missed pay
  - Enhanced Oil Recovery
    - ie. water floods
  - Hydraulic fracturing



Source: http://www.oil-price.net/en/articles/novel-crude-oil-recovery.php

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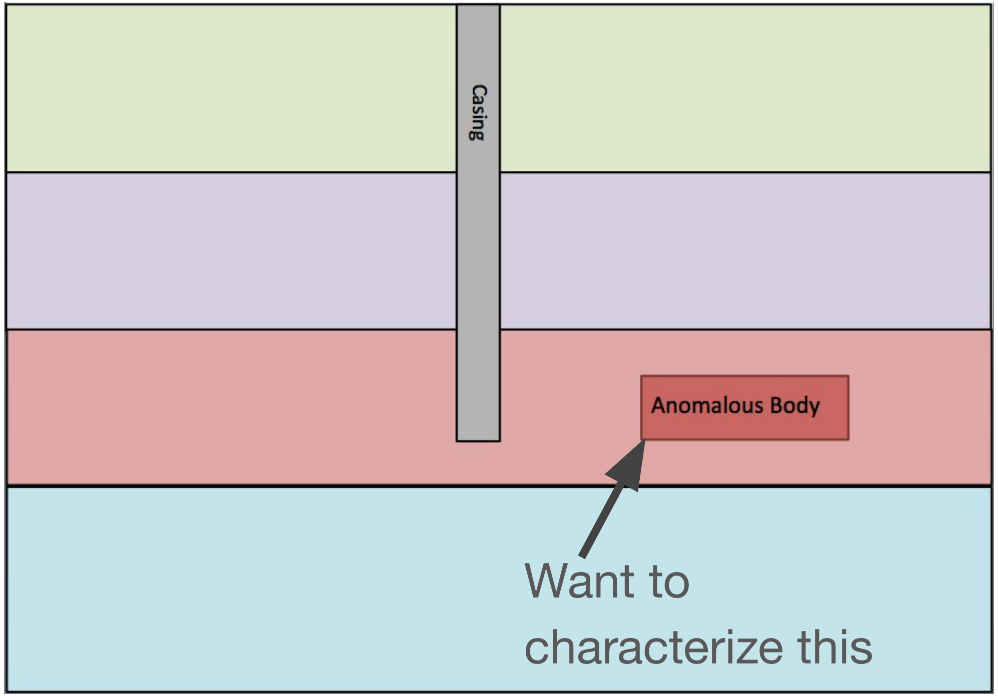
- EM sensitive to conductivity

- Inversion: characterize conductivity distribution



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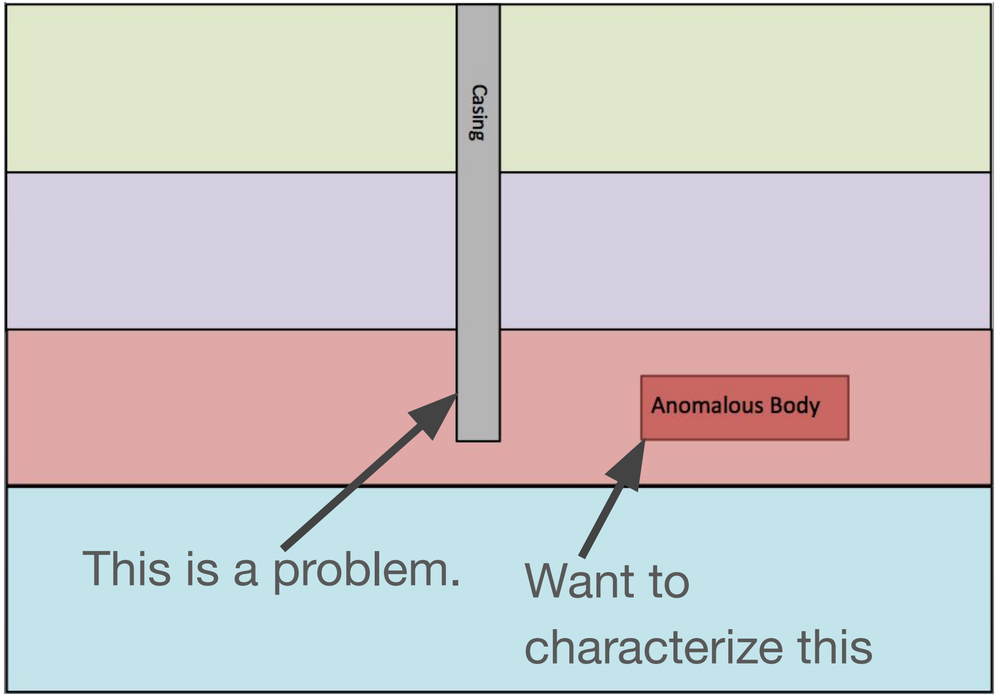


Steel casing in EM

Physical Properties

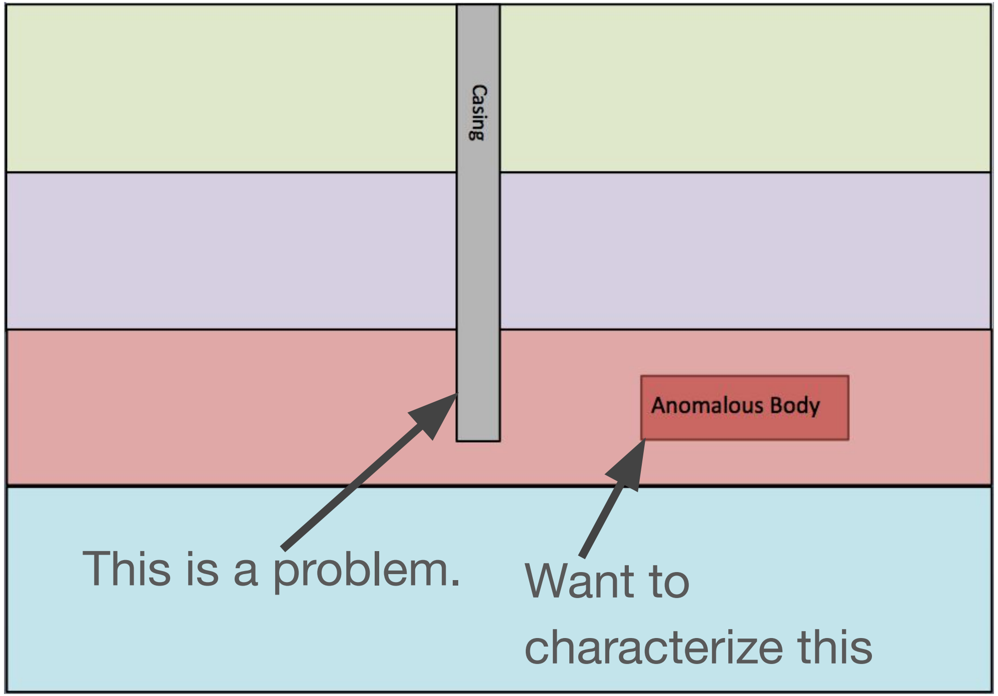
- highly conductive
- significant (variable) magnetic permeability

➡ ***Significant impact on signals***

Geometry

- cylindrical
- thin compared to length

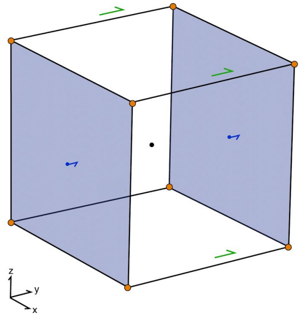
➡ ***Numerically challenging***



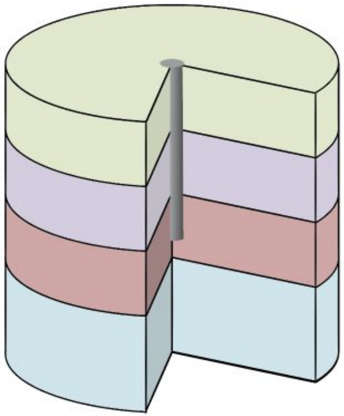
Overview

Motivation: How do we characterize 3D conductivity distributions in settings with steel cased wells?

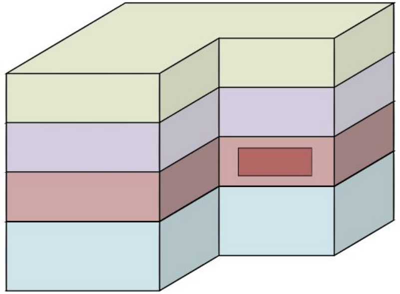
$$\nabla \times \mathbf{E} + i\omega \mathbf{B} = 0$$
$$\nabla \times \mathbf{H} - \mathbf{J} = \mathbf{q}$$



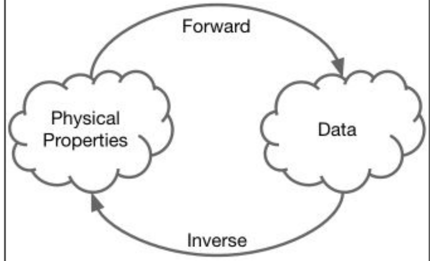
Modelling Maxwell's equations



Modelling the Casing



Modelling 3D geology



Approaching the inverse problem

Electromagnetics: Maxwell's Equations

Maxwell's Equations
(frequency domain, quasi-static)

$$\nabla \times \mathbf{E} + i\omega \mathbf{B} = 0$$
$$\nabla \times \mathbf{H} - \mathbf{J} = \mathbf{q}$$

Constitutive Relations

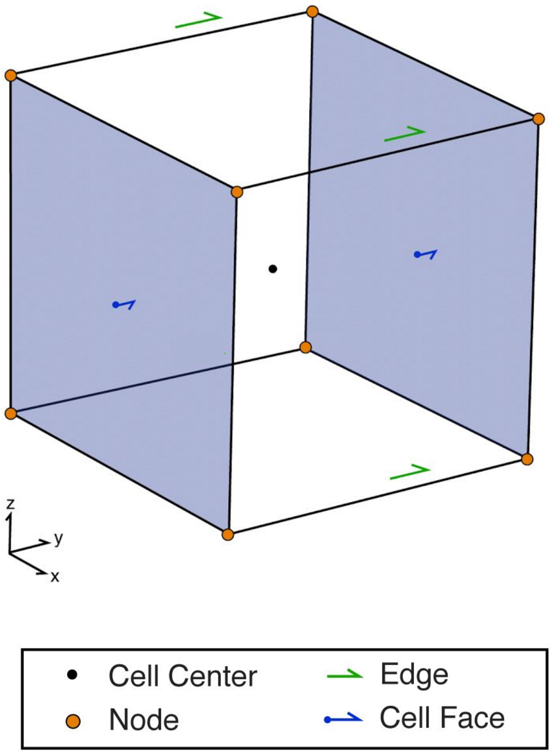
$$\mathbf{J} = \sigma \mathbf{E}$$
$$\mathbf{B} = \mu \mathbf{H}$$

- Fields
  - $\mathbf{E}$ electric field
  - $\mathbf{H}$ magnetic field

- Fluxes
  - $\mathbf{J}$ current density
  - $\mathbf{B}$ magnetic flux density

- Physical Properties
  - σ electrical conductivity
  - μ magnetic permeability

Finite Volume Forward Modelling



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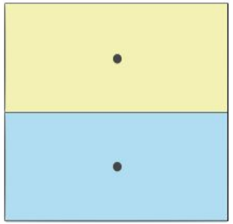
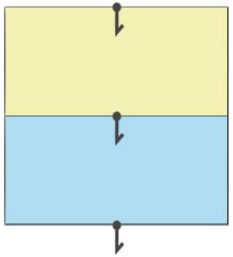


- Fluxes
  - $\mathbf{J}$ current density
  - $\mathbf{B}$ magnetic flux density



- Fields
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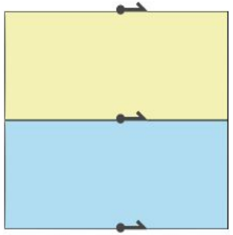
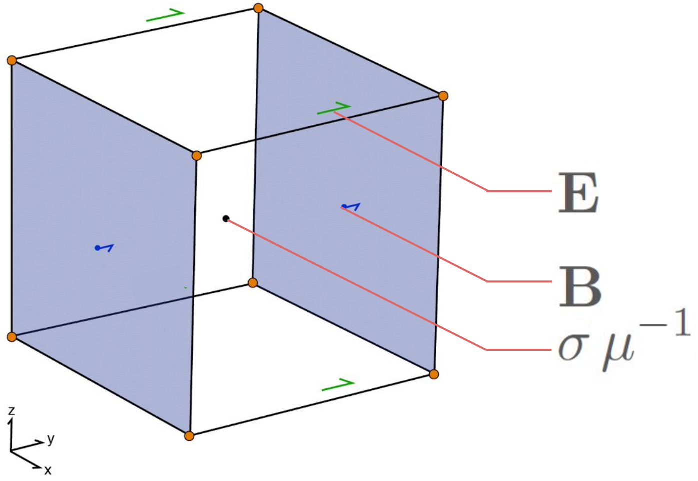


Two Formulations of Maxwell

E-B Formulation:

$$\nabla \times \mathbf{E} + i\omega \mathbf{B} = 0$$

$$\nabla \times \mu^{-1} \mathbf{B} - \sigma \mathbf{E} = \mathbf{q}$$



H-J Formulation:

$$\nabla \times \rho \mathbf{J} + i\omega \mu \mathbf{H} = 0$$

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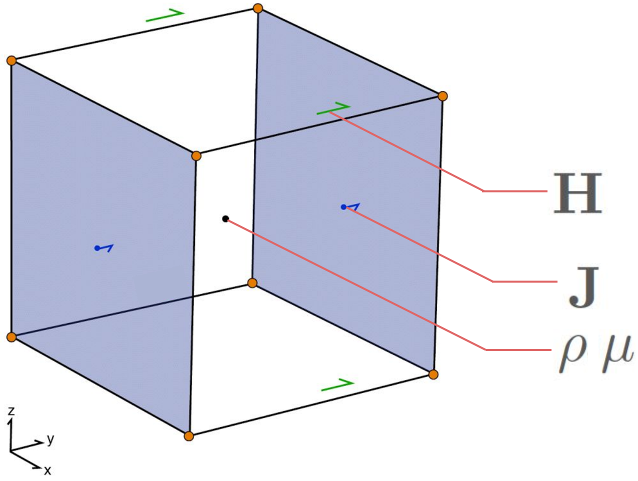
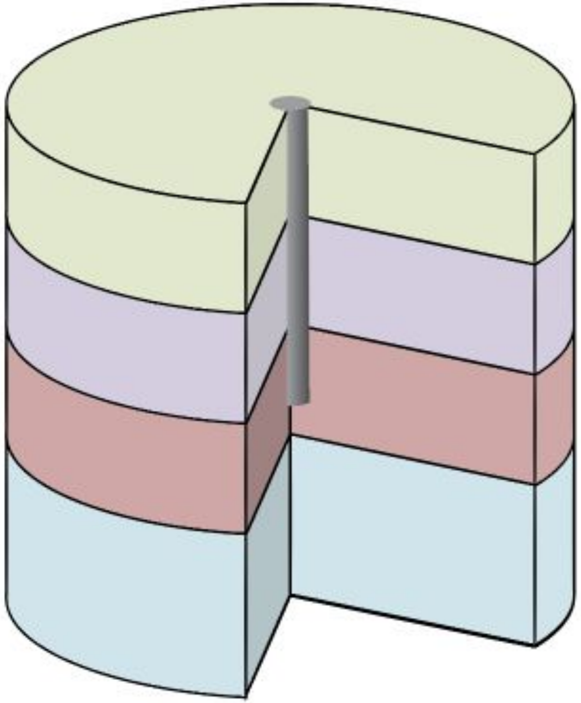
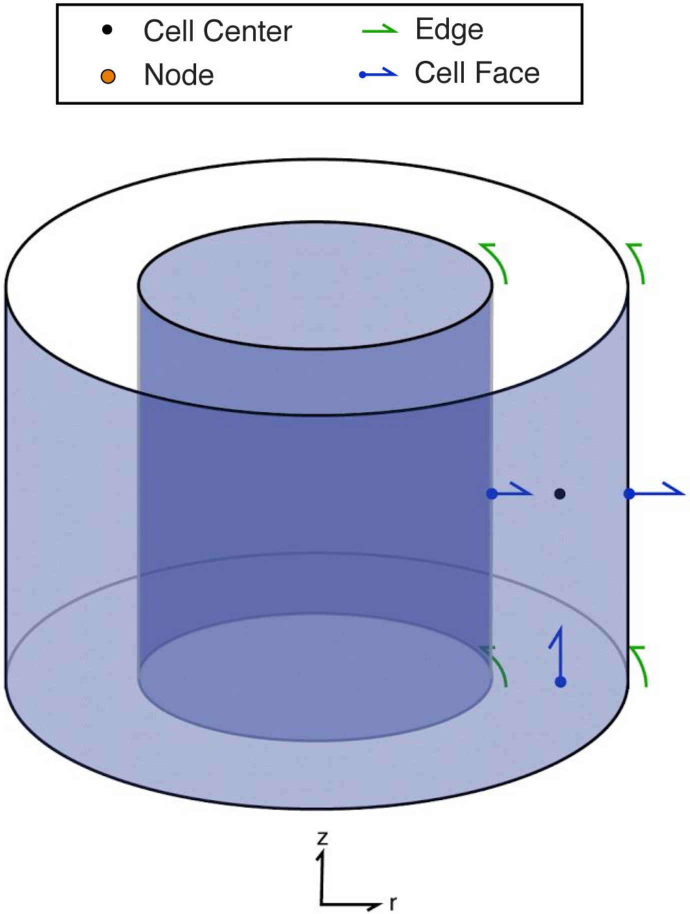
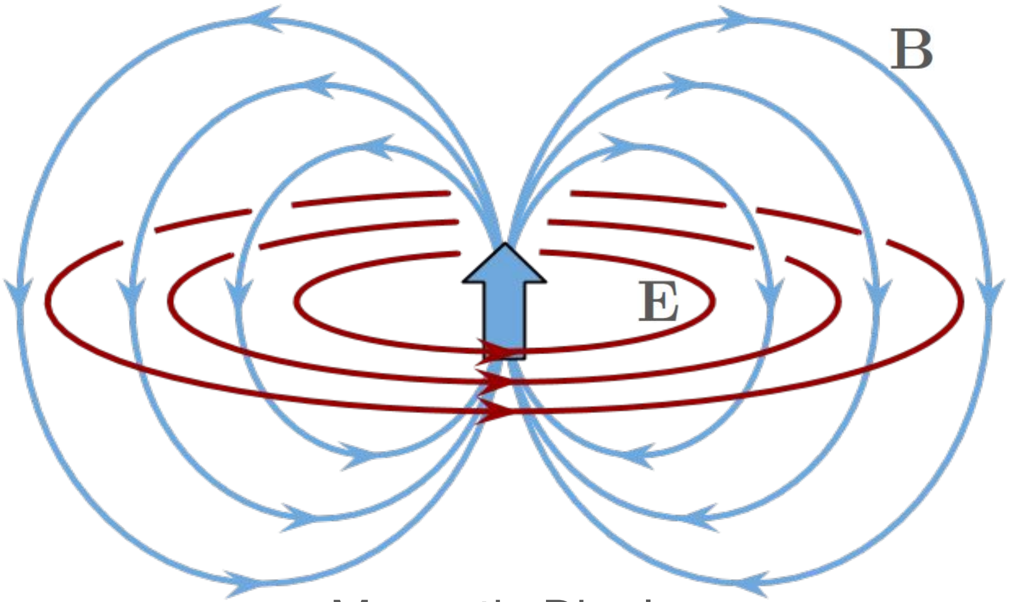


Cylindrical mesh



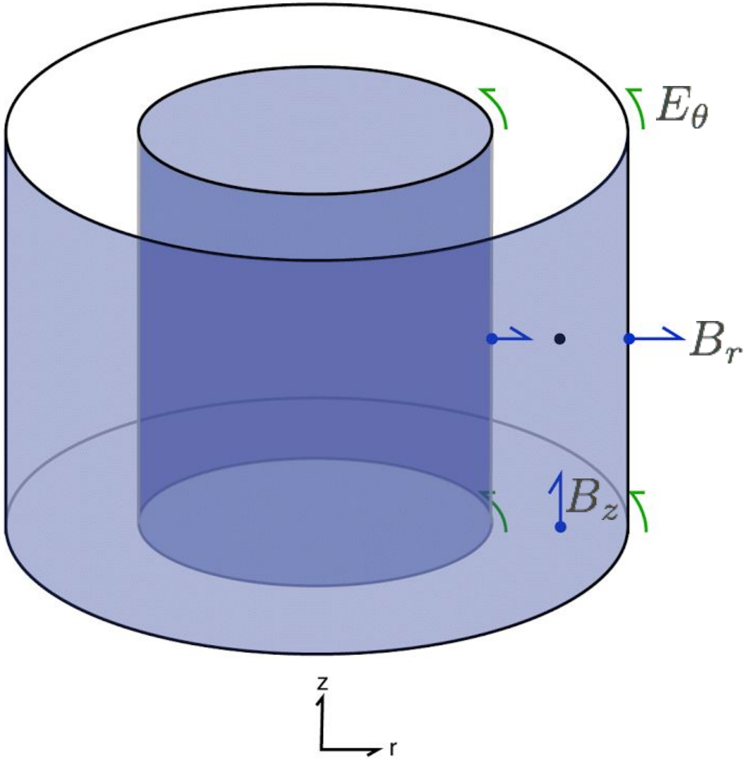


Primary: Cylindrical Symmetry - Dipole



Magnetic Dipole

$$\nabla \times \mathbf{E} + i\omega \mathbf{B} = 0$$



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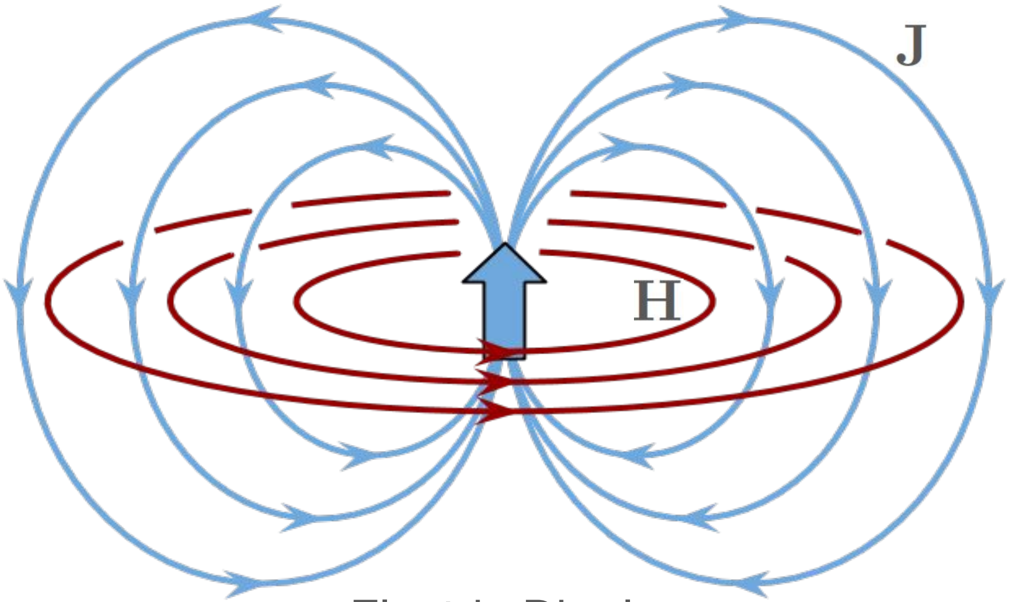
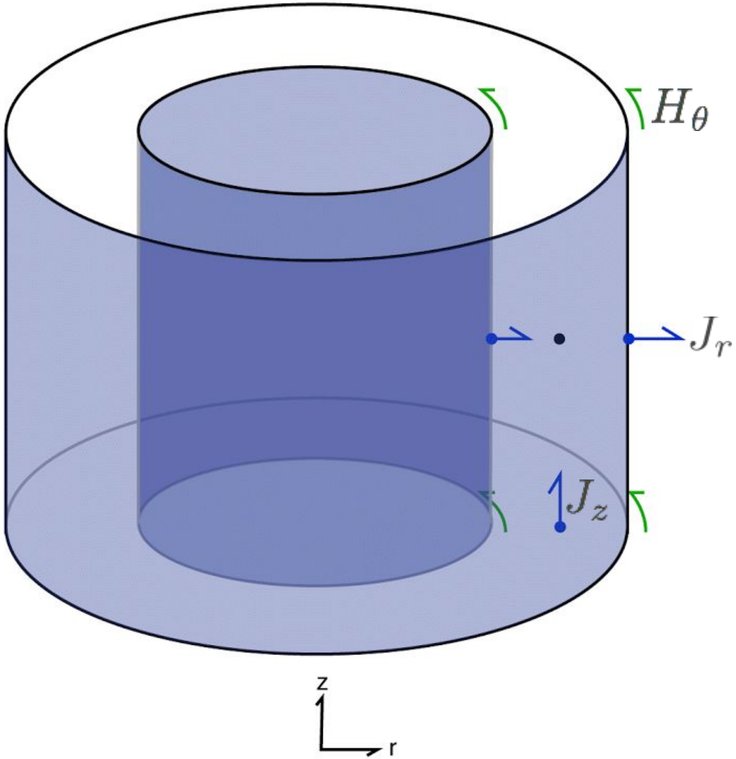


Electric Dipole

$$\nabla \times \mathbf{H} - \mathbf{J} = \mathbf{q}$$



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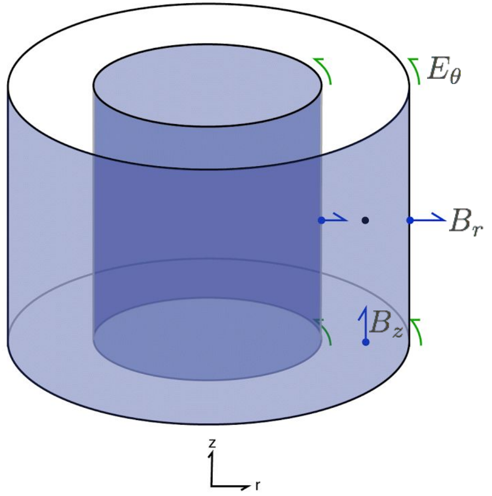

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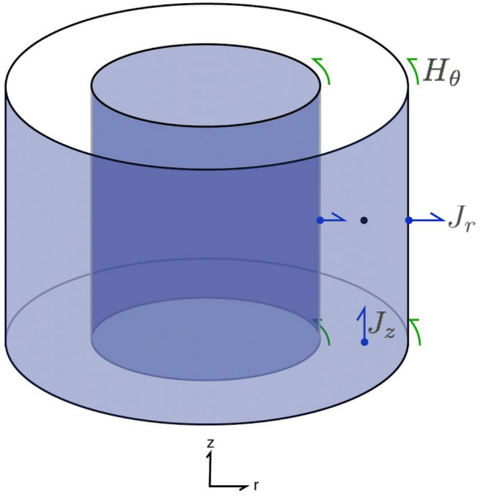
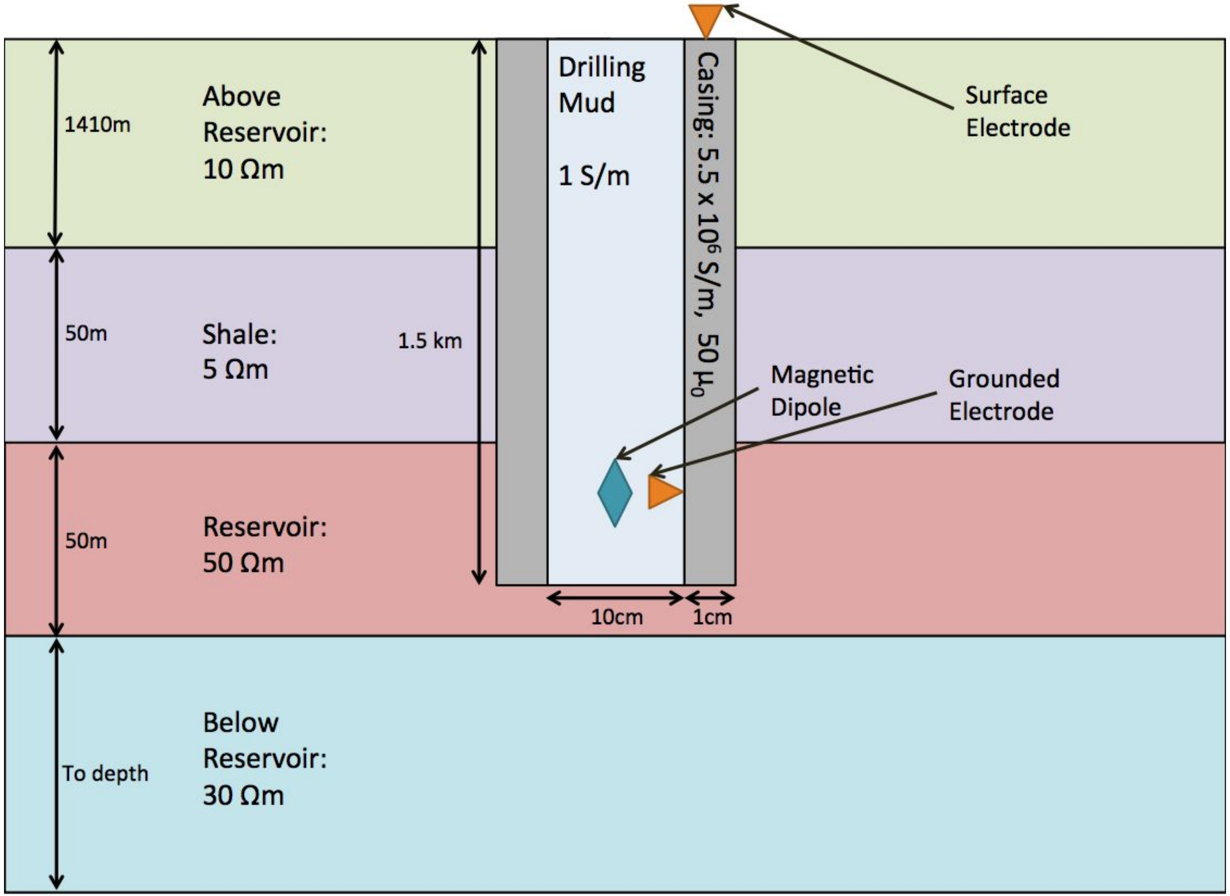
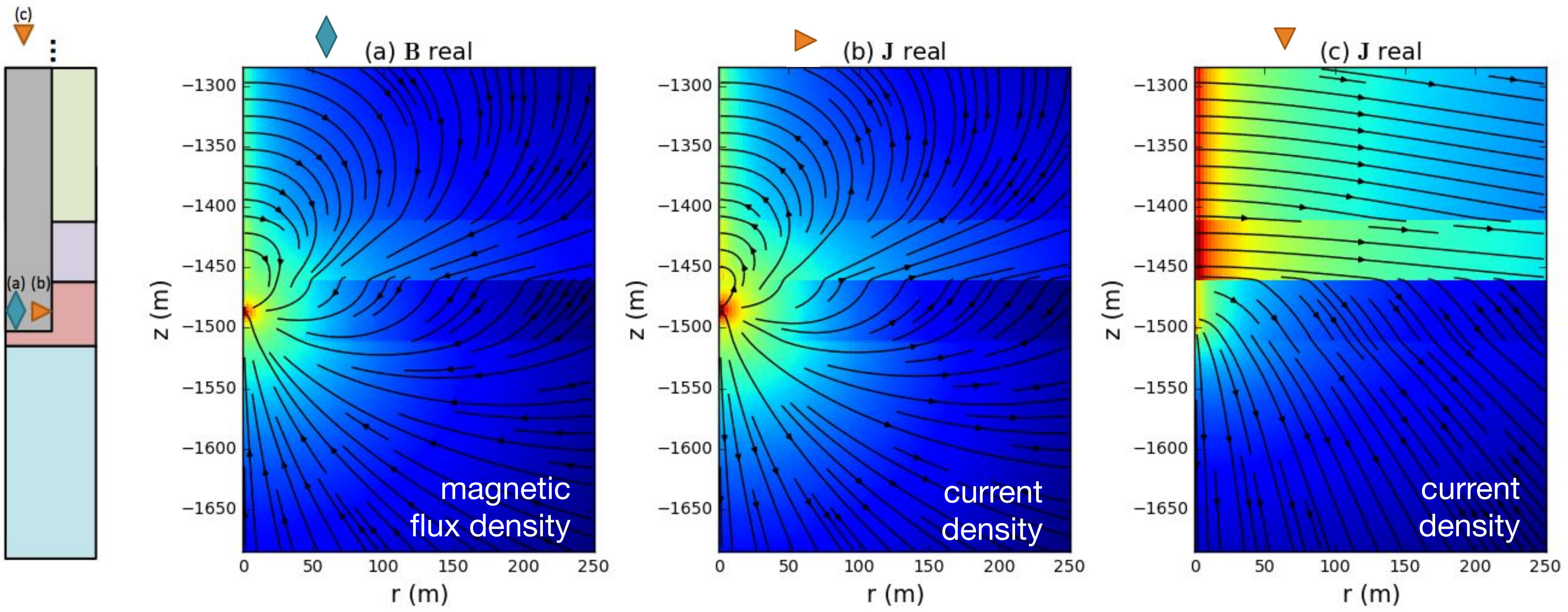


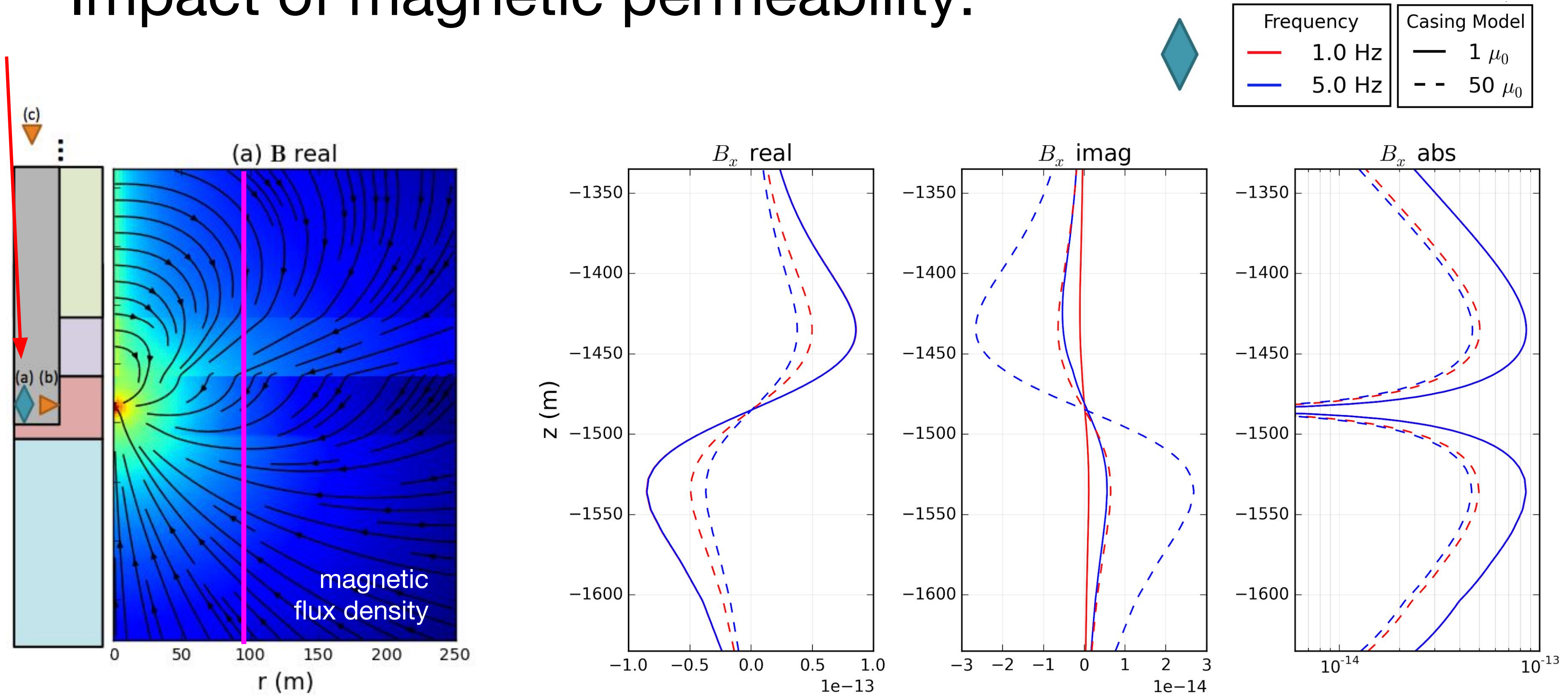
Modelling the casing



Modelling the casing: Source types



Impact of magnetic permeability:



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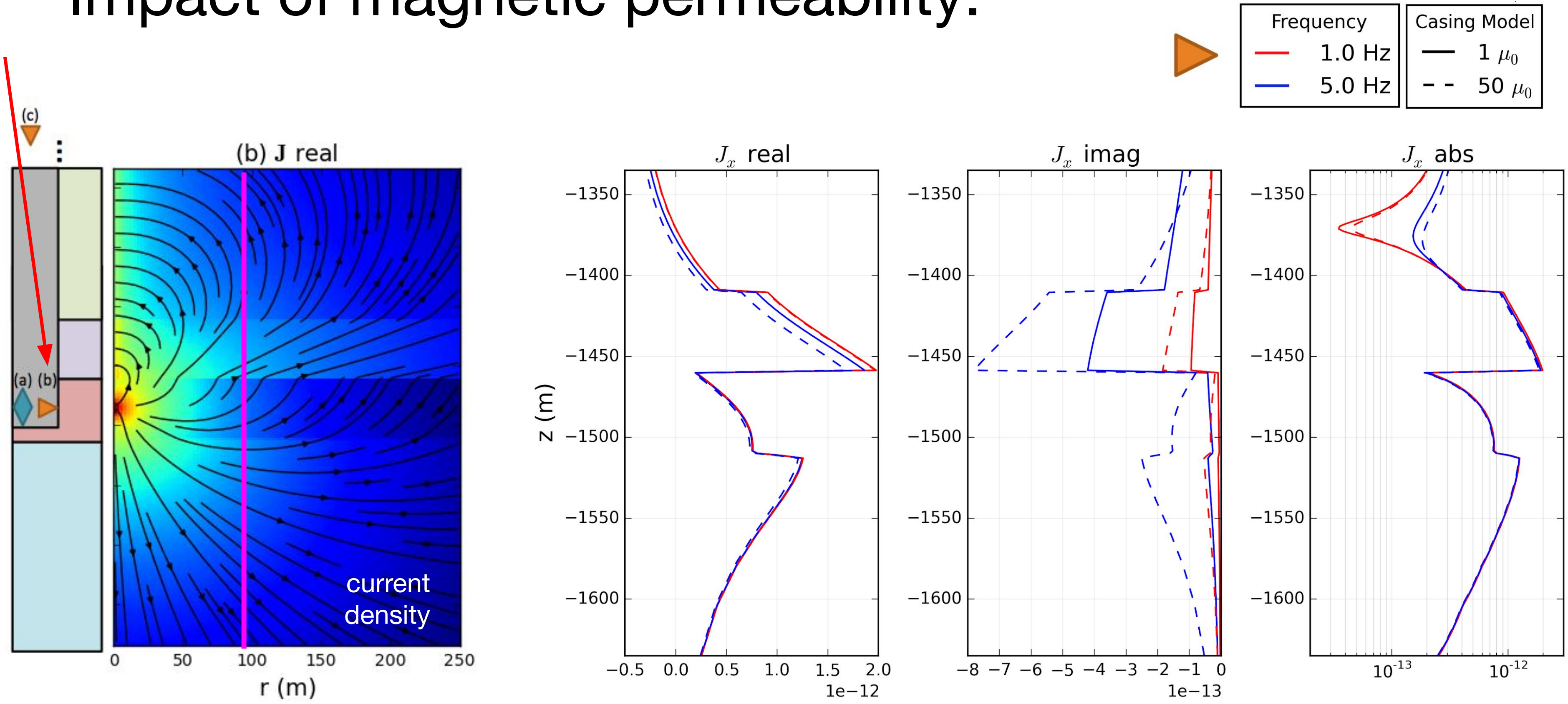

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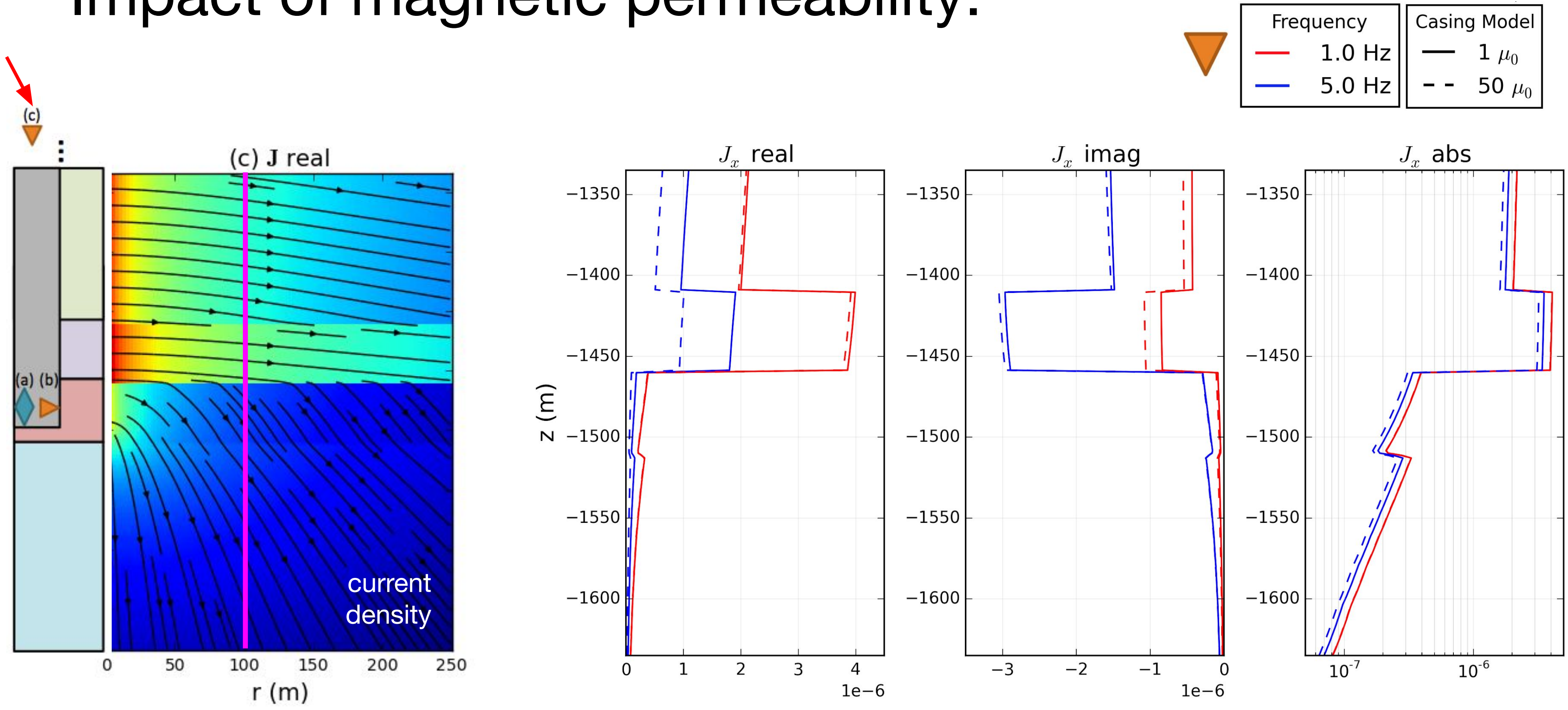
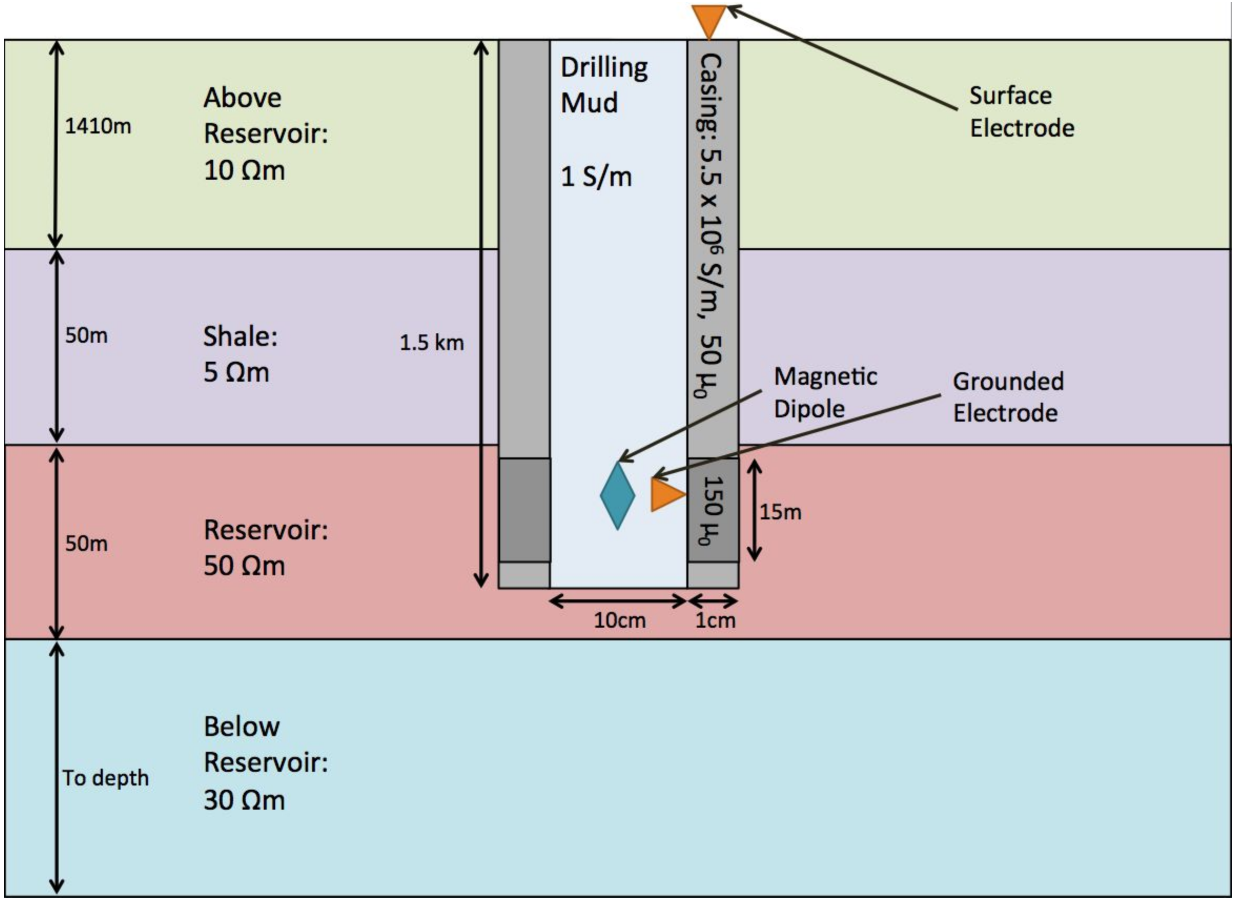
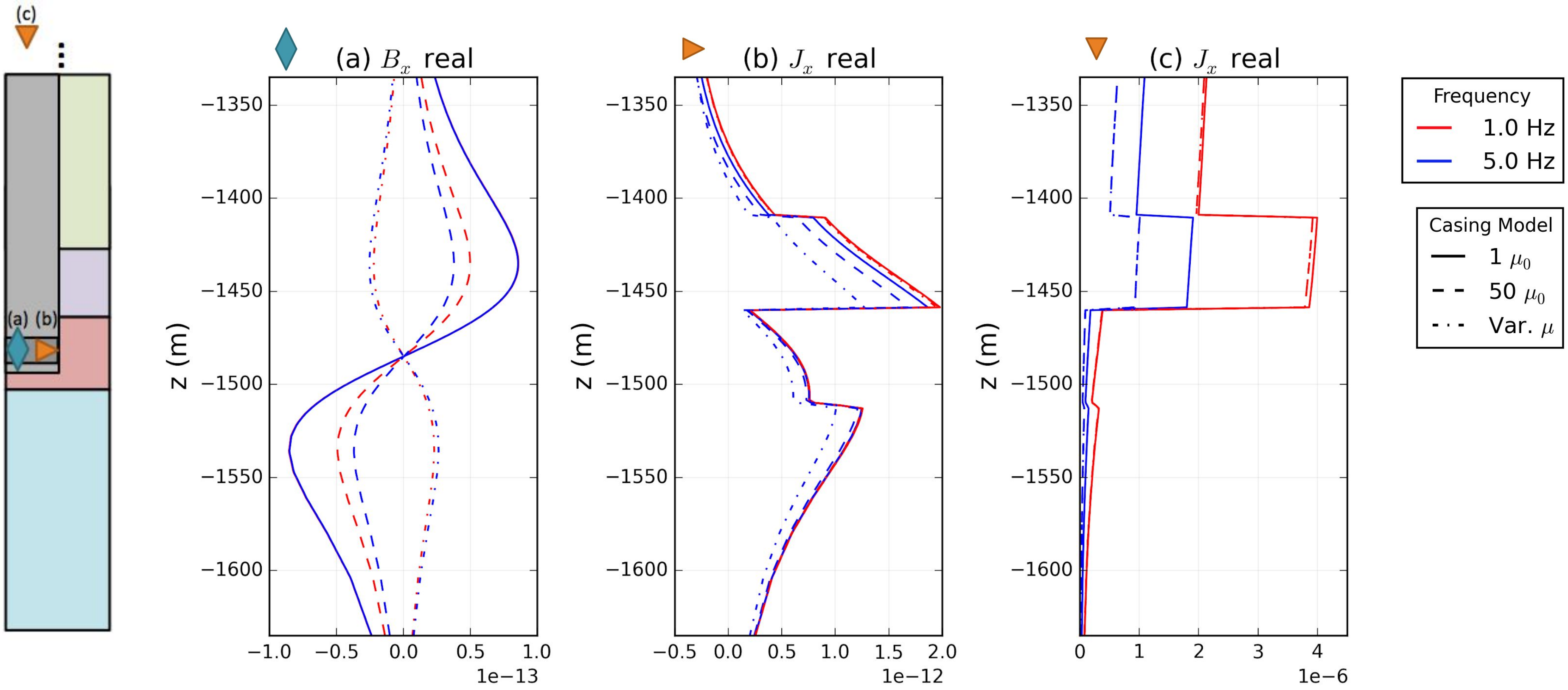


Impact of Variable Magnetic Permeability



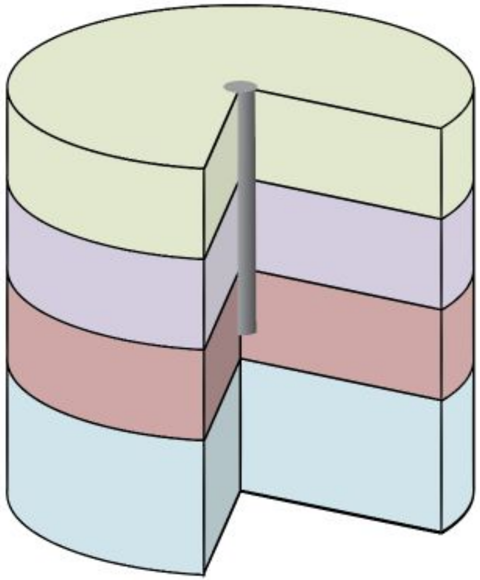
Variable Magnetic Permeability



Modelling with 3D geology

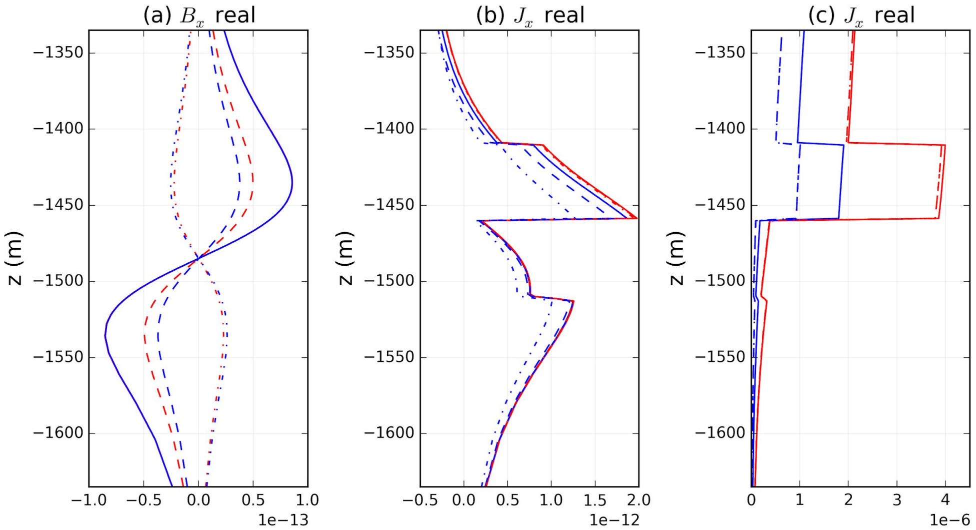
What we have done

- cylindrically symmetric
- variable σ μ



Casing & Source, Layered Earth ✓

- Steel casing has a significant impact on the signal
  - conductivity and magnetic permeability



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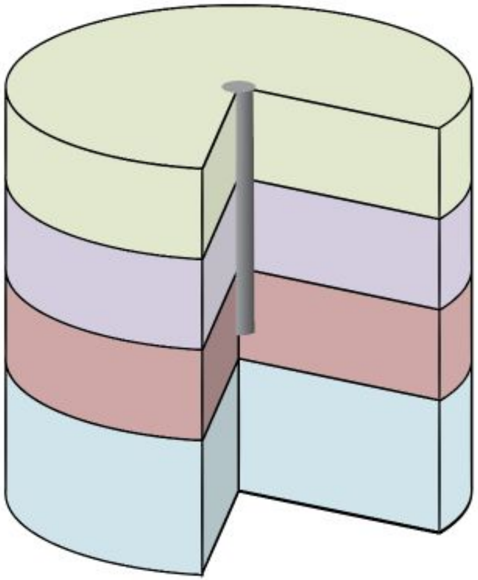

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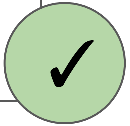
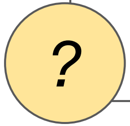
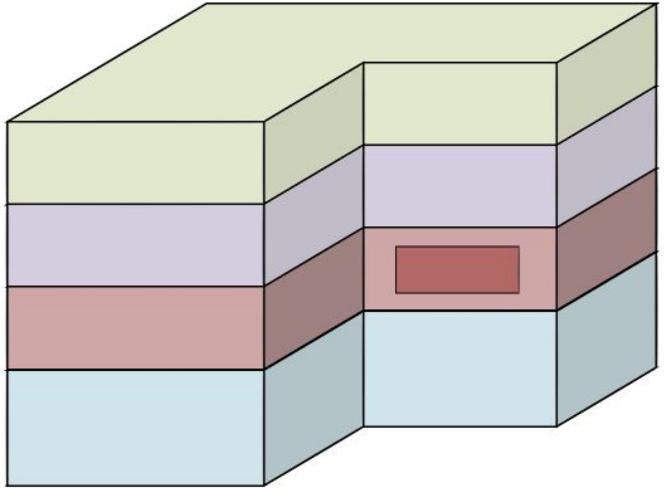




Want to model geologic structures

- 3 dimensional
- variable σ



Fields from casing, 3D Earth

Modelling with 3D geology: Primary Secondary

Primary:

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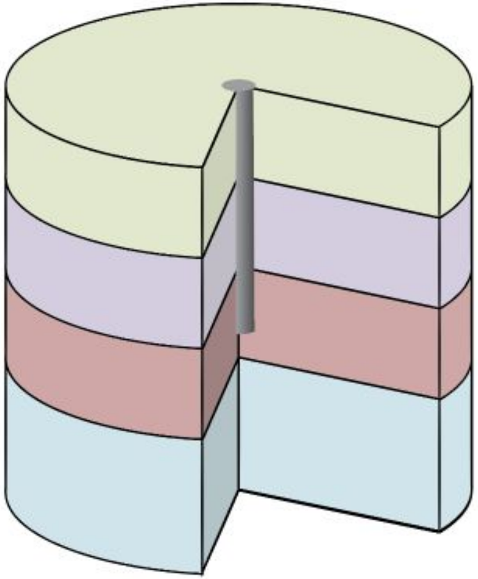

Casing & Source, Layered Earth

✓

Interpolate →

Secondary:

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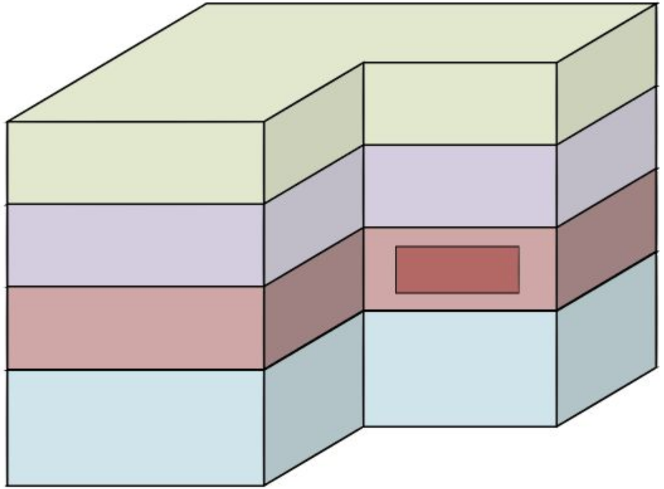
$$\tilde{\mathbf{q}} = -\left(\nabla \times (\mu^{-1} - \mu_p^{-1})\mathbf{B_p} - (\sigma - \sigma_p)\mathbf{E_p}\right)$$

$(\mu^{-1} - \mu_p^{-1}) \rightarrow 0$



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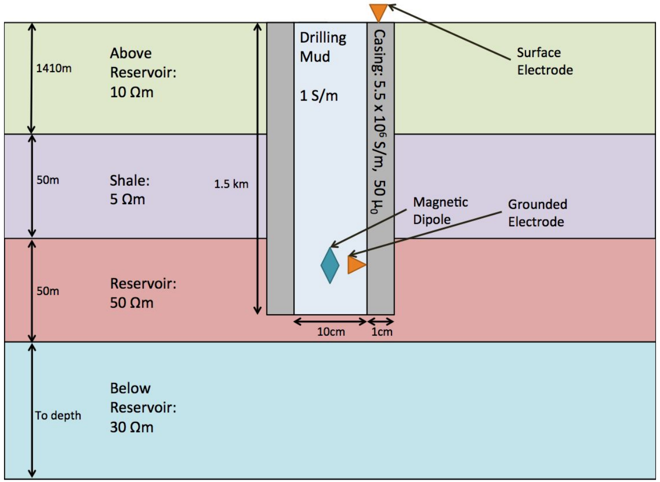

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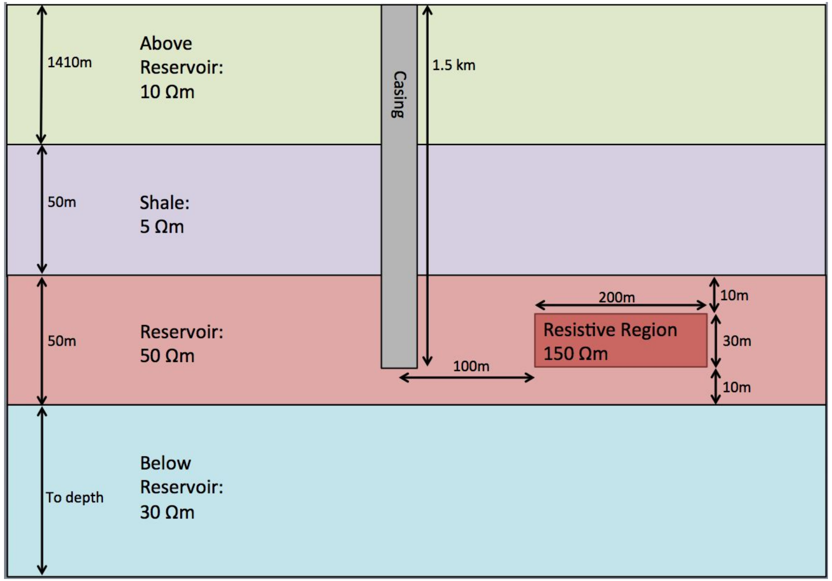

Primary-Secondary: 3D geology (magnetic dipole)

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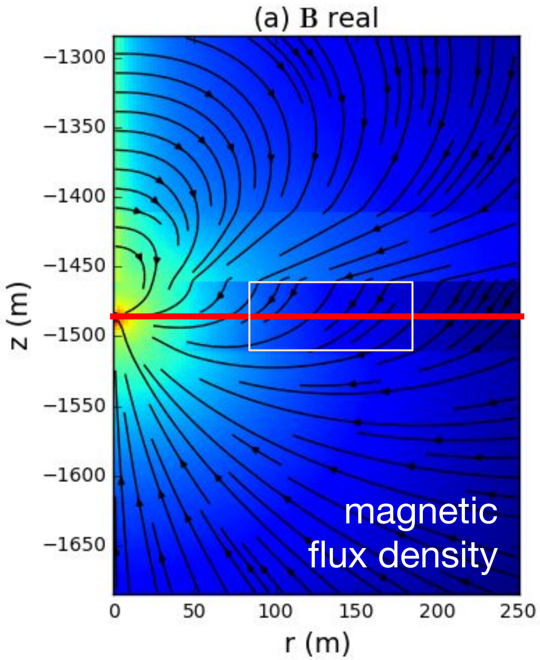

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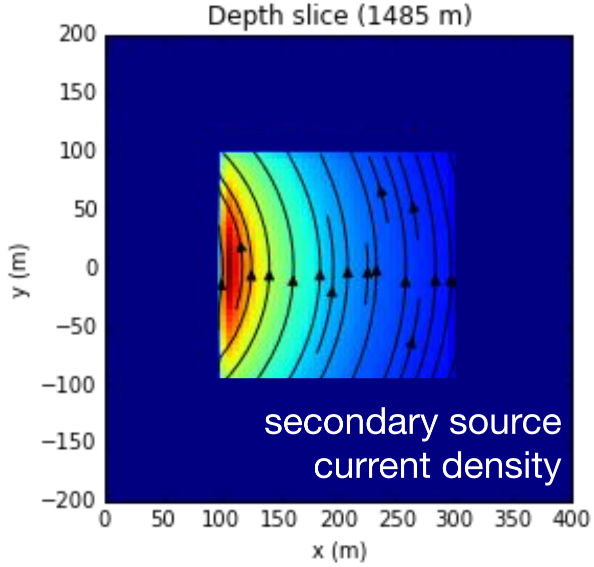

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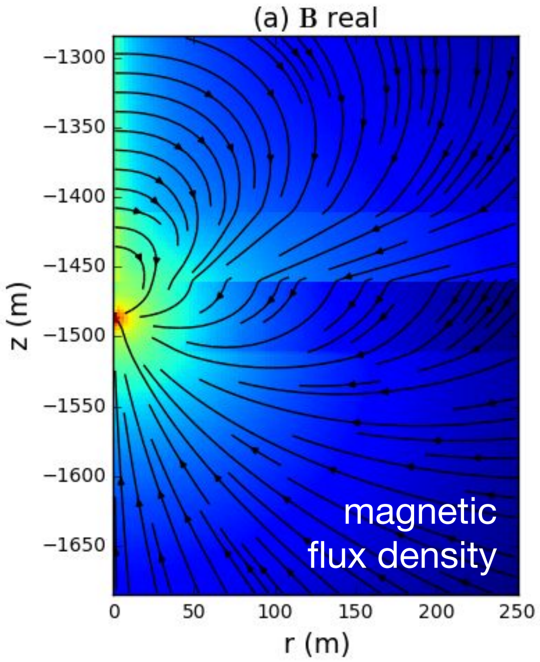

Interpolate

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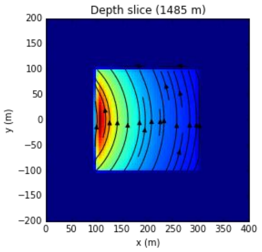
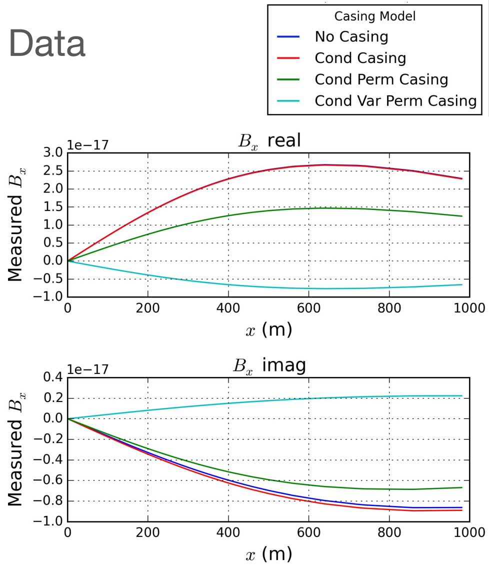
Source in 3D

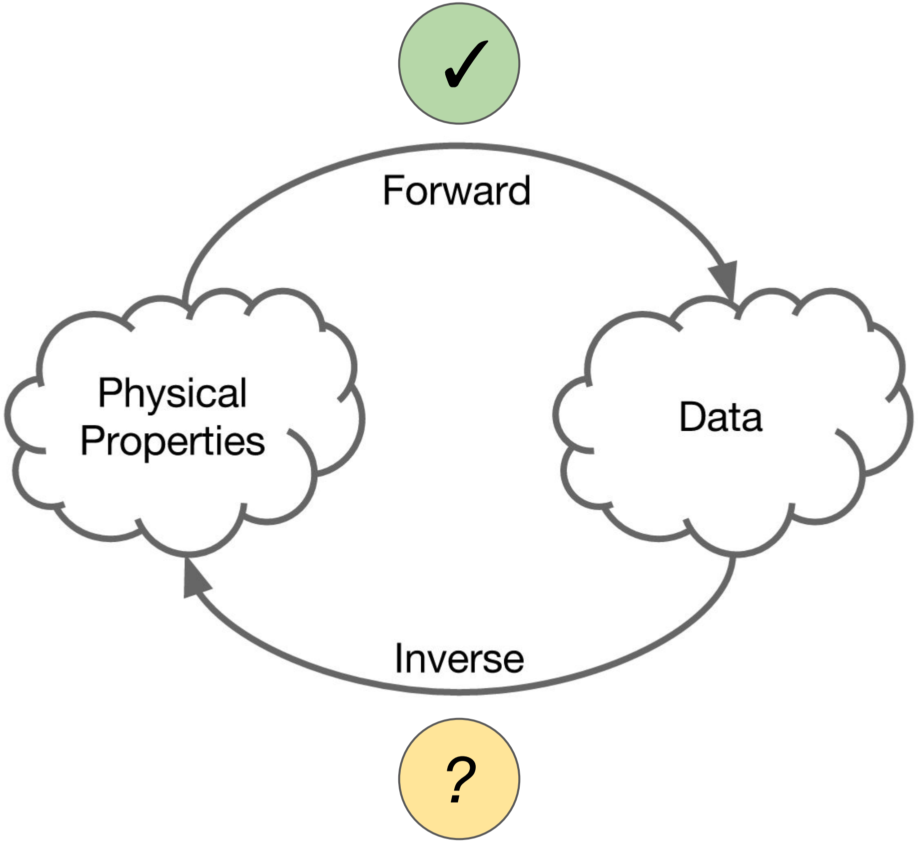


Solve

Data



Approaching the Inverse Problem



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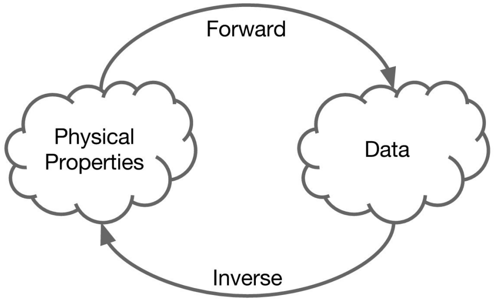
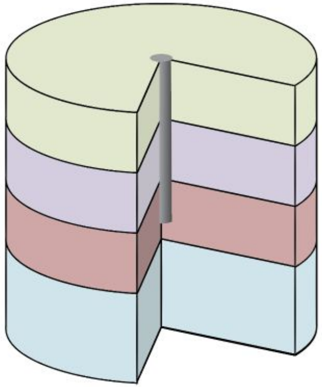


Estimate: $\sigma_p \; \mu_p$



$$\nabla \times \mathbf{E_p} + i\omega \mathbf{B_p} = 0$$

$$\nabla \times \mu_p^{-1} \mathbf{B_p} - \sigma_p \mathbf{E_p} = \mathbf{q}$$

Solve for: $\mathbf{E_p} \; \mathbf{B_p}$

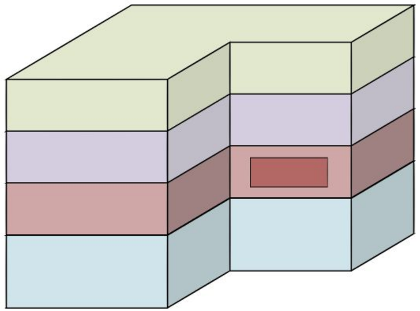
Interpolate to compute source

Invert for 3D conductivity : σ

$$\nabla \times \mathbf{E_s} + i\omega \mathbf{B_s} = 0$$

$$\nabla \times \mu^{-1} \mathbf{B_s} - \sigma \mathbf{E_s} = \tilde{\mathbf{q}}$$

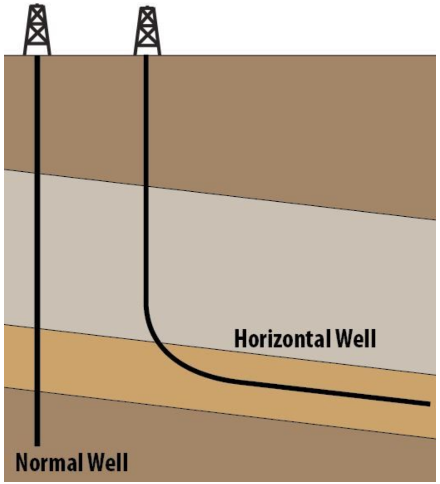
$$\tilde{\mathbf{q}} = (\sigma - \sigma_p) \mathbf{E_p}$$

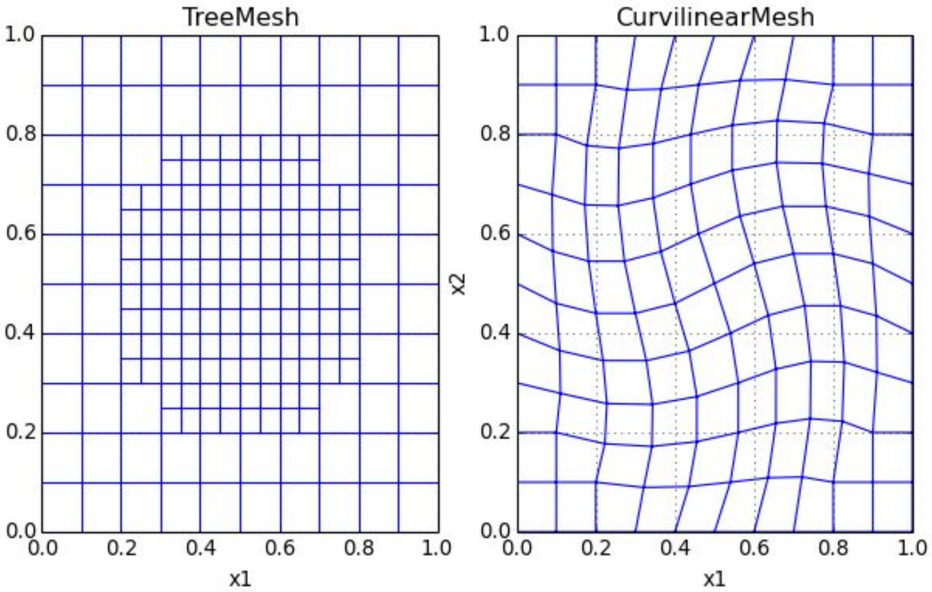


Model dependence on RHS
→ need to include in sensitivities

Generalizing

- Time domain EM
  - similar approach can be applied
- Non-symmetric settings:
  - deviated or horizontal wells
  - source outside of casing





Source: http://docs.simpeg.xyz/en/latest/api_Mesh.html

Source: http://www.drillingformulas.com/introduction-to-well-control-for-horizontal-wells/

Summary

Motivation: How do we characterize 3D conductivity distributions in settings with steel cased wells?

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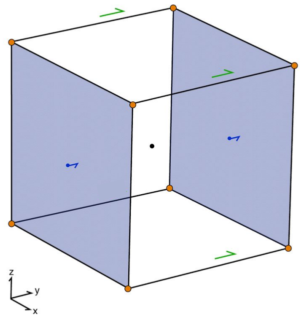
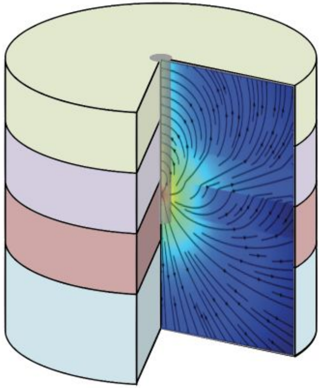
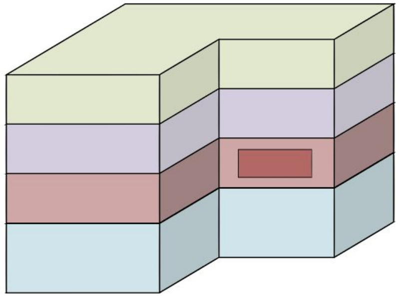


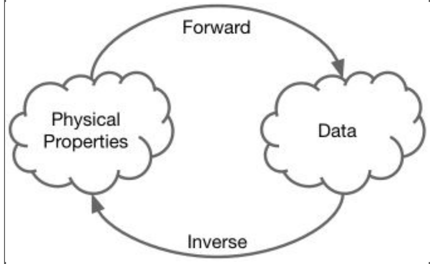
Modelling Maxwell's equations



Modelling the Casing



Modelling 3D geology



Approaching the inverse problem

Thank you!

Thanks to:

- developers of SimPEG and simpegEM
- UBC GIF

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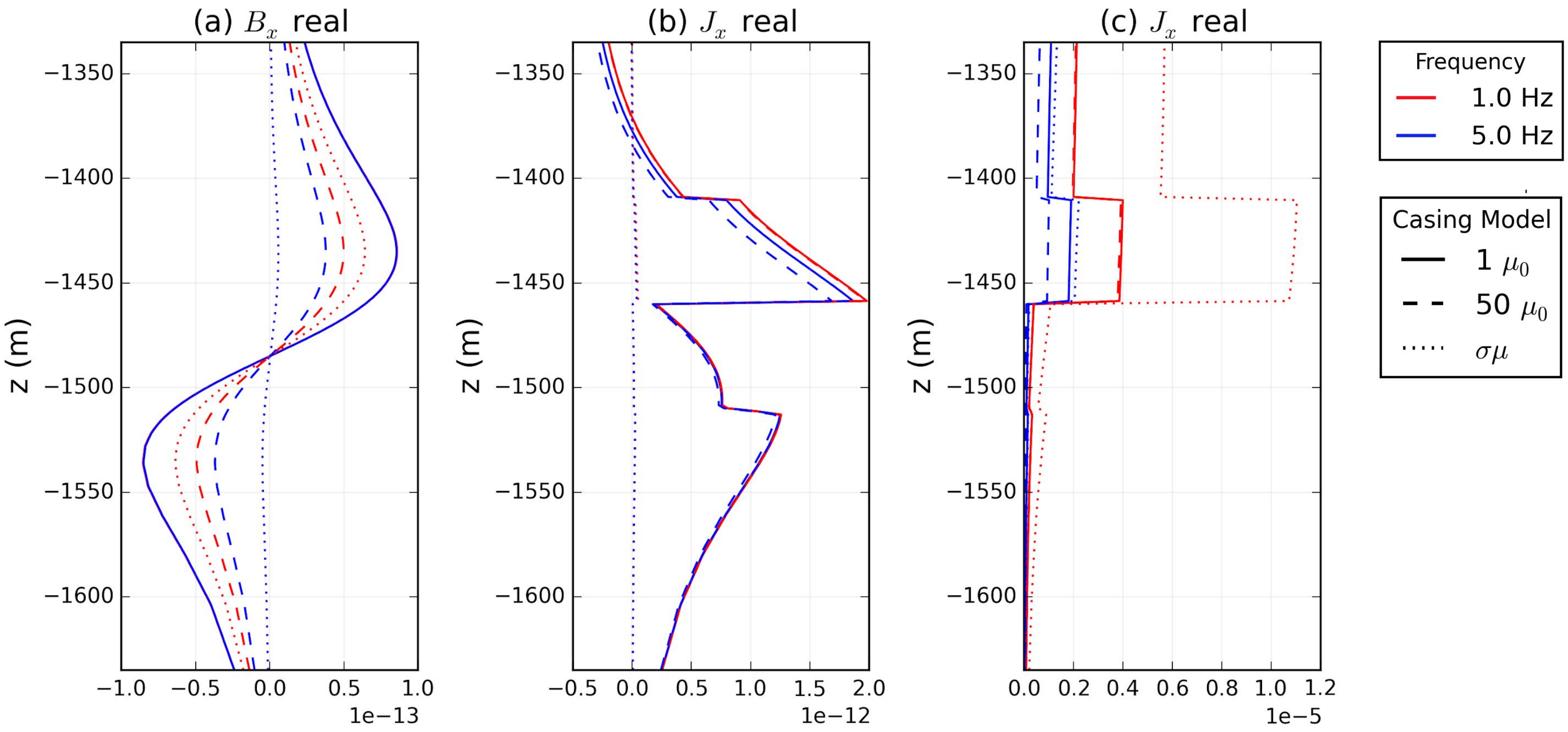
Using Conductivity Permeability product



SCRAPS

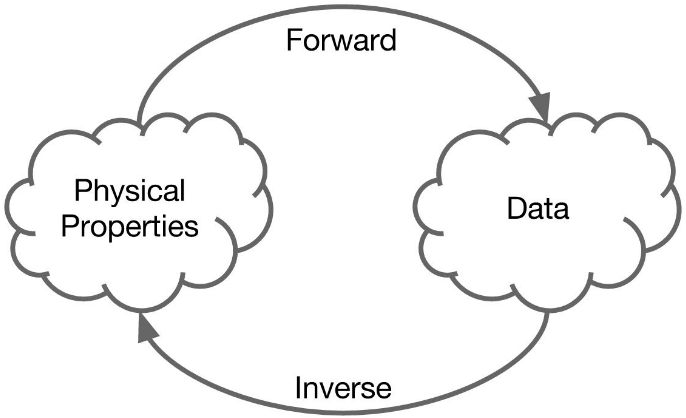
Approaching the Inverse Problem

- Inversion model is conductivity

Model dependence on RHS
→ need to include in sensitivities

$$\nabla \times \mathbf{E_s} + i\omega \mathbf{B_s} = 0$$
$$\nabla \times \mu^{-1} \mathbf{B_s} - \sigma \mathbf{E_s} = \tilde{\mathbf{q}}$$
$$\tilde{\mathbf{q}} = (\sigma - \sigma_p)\mathbf{E_p}$$

- Steps:
  - estimate background σ_p
  - solve for primary fields $\mathbf{E_p}$ $\mathbf{B_p}$
  - compute source term
  - do inv

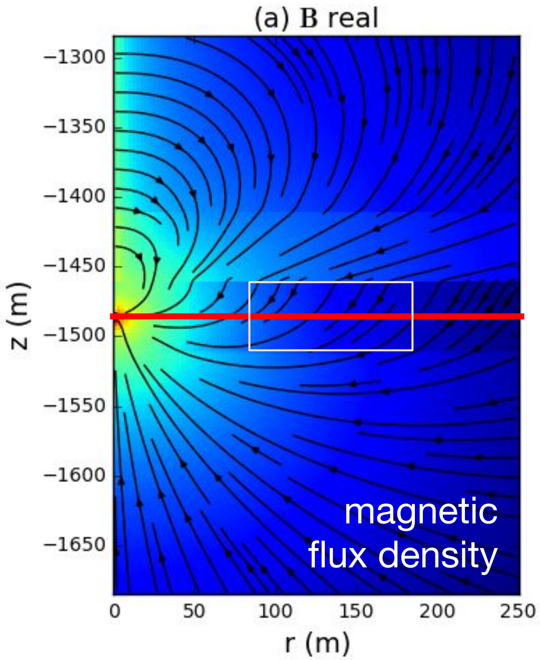


Primary-Secondary: 3D geology (magnetic dipole)

Primary:

$$\nabla \times \mathbf{E_p} + i\omega \mathbf{B_p} = 0$$

$$\nabla \times \mu_p^{-1} \mathbf{B_p} - \sigma_p \mathbf{E_p} = \mathbf{q}$$



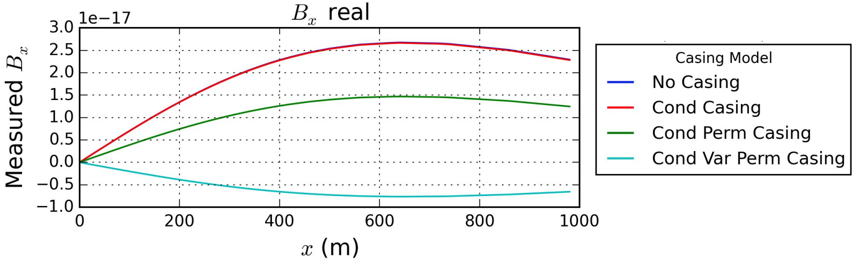
Interpolate

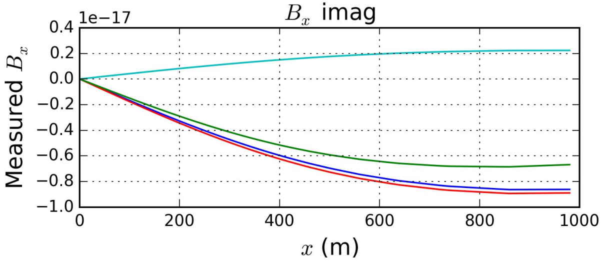
Secondary:

$$\nabla \times \mathbf{E_s} + i\omega \mathbf{B_s} = 0$$

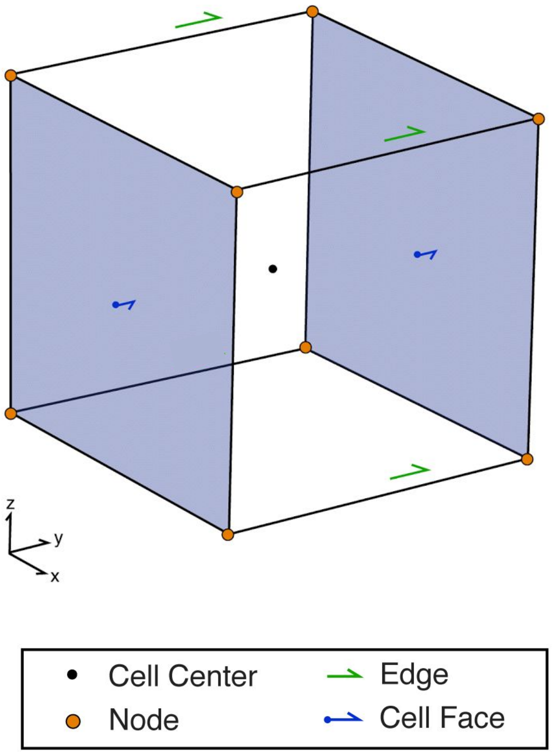
$$\nabla \times \mu^{-1} \mathbf{B_s} - \sigma \mathbf{E_s} = \tilde{\mathbf{q}}$$

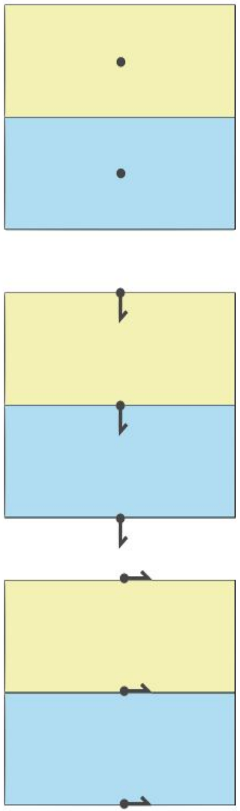
$$\tilde{\mathbf{q}} = -\left(\nabla \times (\mu^{-1} - \mu_p^{-1})\mathbf{B_p} - (\sigma - \sigma_p)\mathbf{E_p}\right)$$





Mimetic Finite Volume Forward Modelling





- Physical Properties (Cell Center)
  - σ electrical conductivity
  - μ magnetic permeability

- Fluxes (Cell Face)
  - $\mathbf{J}$ current density
  - $\mathbf{B}$ magnetic flux density

- Fields (Edge)
  - $\mathbf{E}$ electric field
  - $\mathbf{H}$ magnetic field

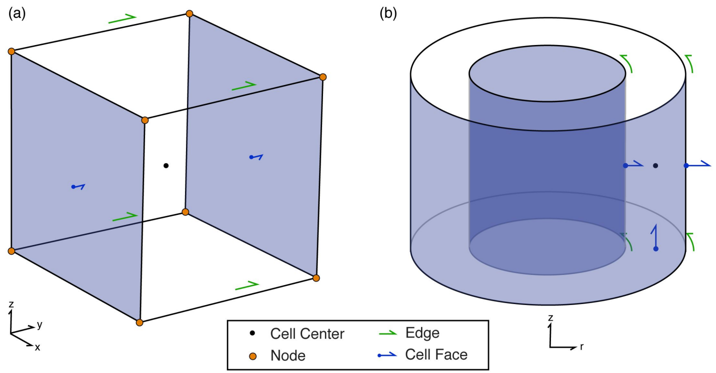
Primary: Modelling the Casing

- Finite volume forward simulation
  - staggered grid

Cell Centers:	Physical Properties
Faces:	Fluxes
Edges:	Fields

- exploit symmetry: cylindrically symmetric
  - when sources on or in well

- ˥



E-B: magnetic source	H-J: electric source
$\nabla \times \vec{E} + i\omega\vec{B} = 0$ $\nabla \times \mu^{-1}\vec{B} - \sigma\vec{E} = \vec{s}$	$\nabla \times \rho\vec{J} + i\omega\mu\vec{H} = 0$ $\nabla \times \vec{H} - \vec{J} = \vec{s}$

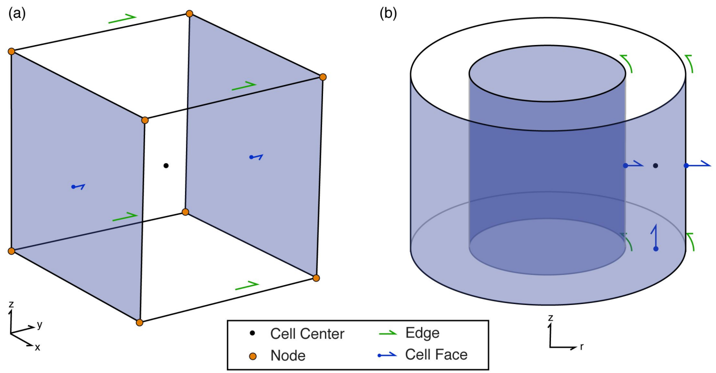
Primary: Modelling the Casing

- Finite volume forward simulation
  - staggered grid

Formulation	cell centers	edges	faces
E-B	μ^{-1}, σ	$\vec{E}$	$\vec{B}$
H-J	μ, ρ	$\vec{H}$	$\vec{J}$

- exploit symmetry: cylindrically symmetric
  - when sources on or in well

- 1



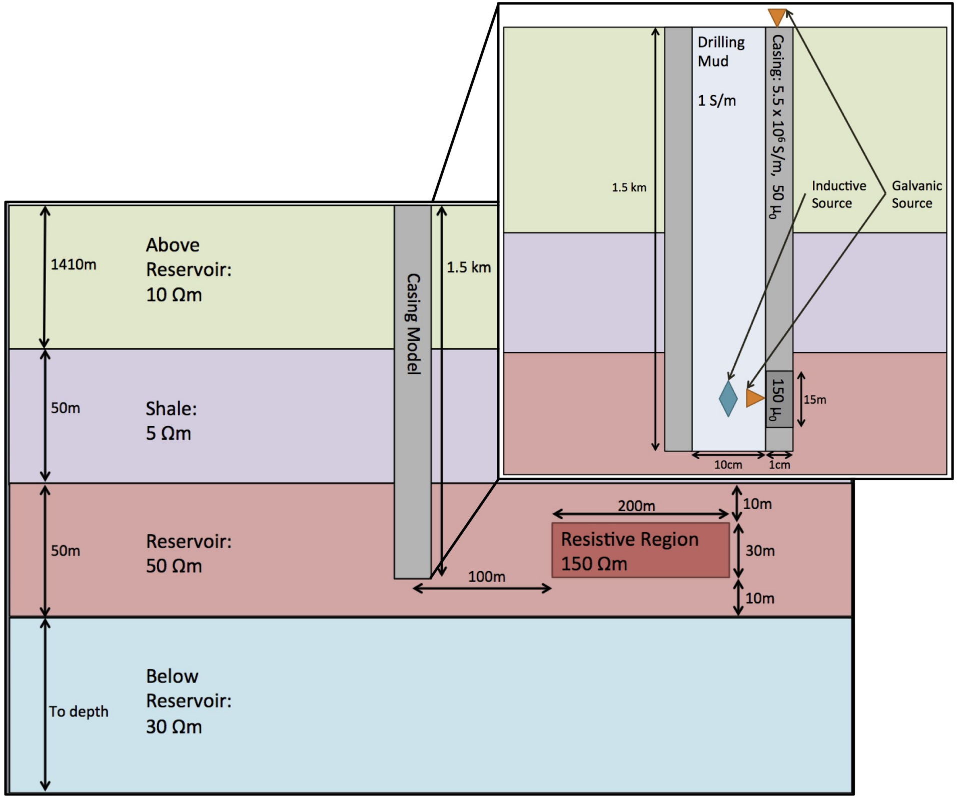
E-B: magnetic source	H-J: electric source
$\nabla \times \vec{E} + i\omega\vec{B} = 0$ $\nabla \times \mu^{-1}\vec{B} - \sigma\vec{E} = \vec{s}$	$\nabla \times \rho\vec{J} + i\omega\mu\vec{H} = 0$ $\nabla \times \vec{H} - \vec{J} = \vec{s}$

Electromagnetics in settings with cased wells

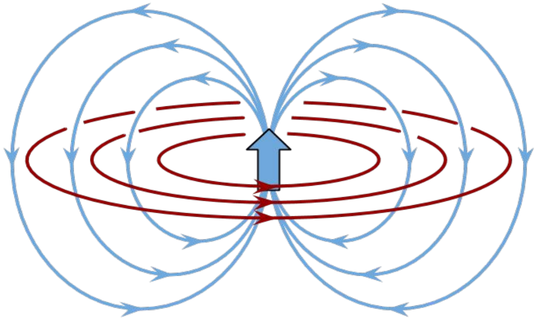
- ***Why EM?***
  - Electrical conductivity can be diagnostic
- ***Cased Wells***
  - significant contributor to signal
  - challenging features to model
    - geometry
    - conductivity contrast

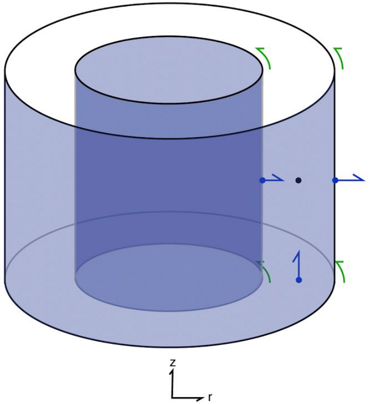
How do we model in settings with cased wells?

Inverse Problem?



Primary: Cylindrical Symmetry - Summary



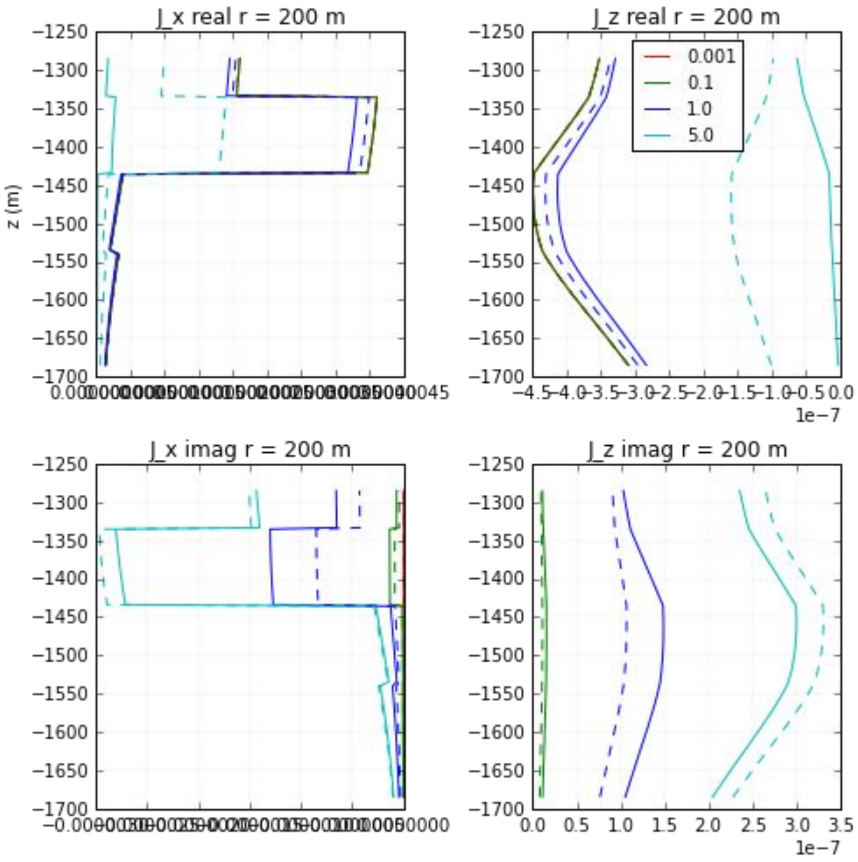


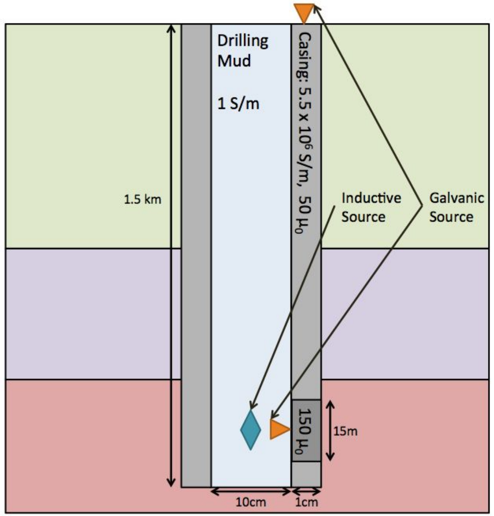
Two Formulations of Maxwell:

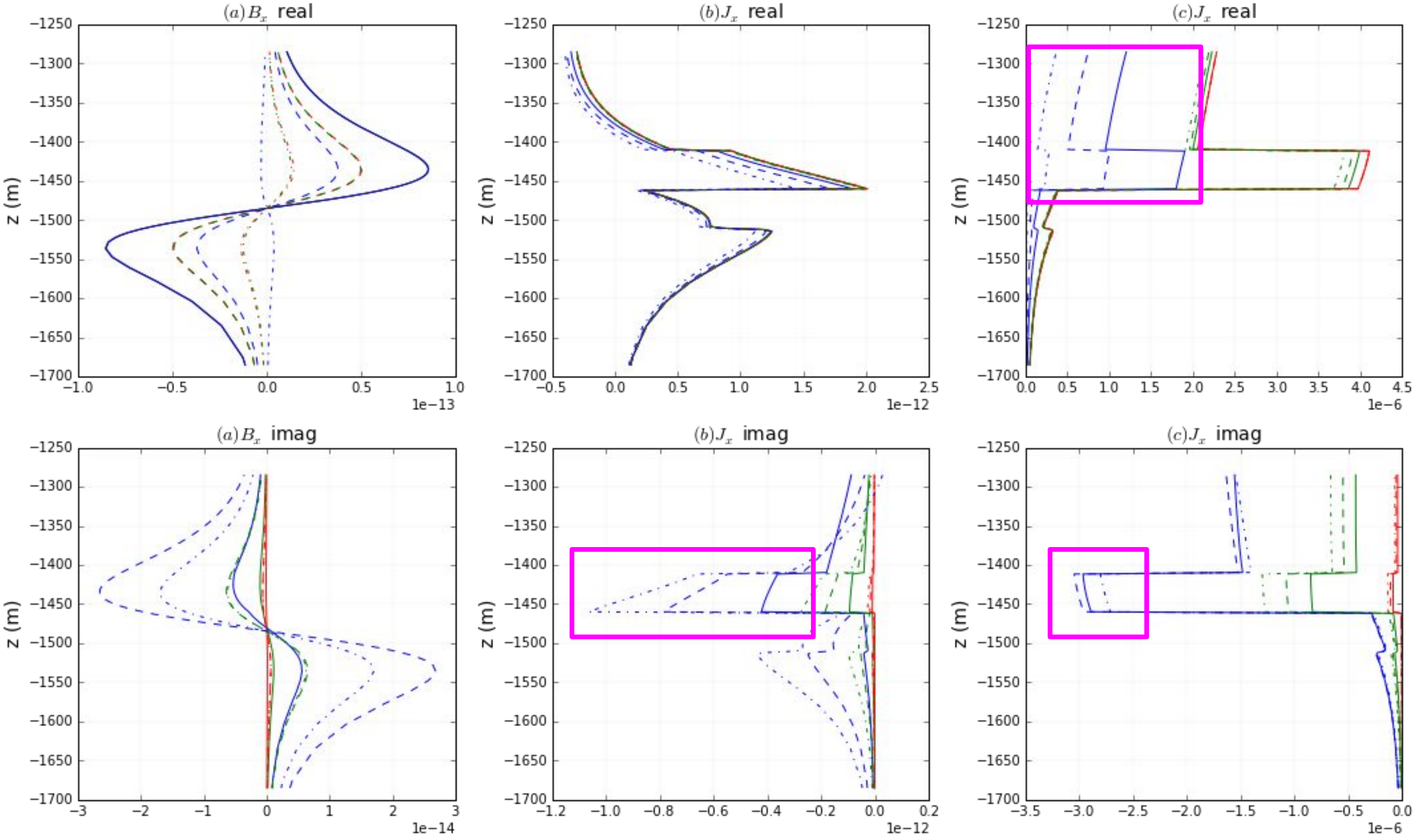
E-B: magnetic source	H-J: electric source
$\nabla \times \vec{E} + i\omega\vec{B} = 0$ $\nabla \times \mu^{-1}\vec{B} - \sigma\vec{E} = \vec{s}$	$\nabla \times \rho\vec{J} + i\omega\mu\vec{H} = 0$ $\nabla \times \vec{H} - \vec{J} = \vec{s}$

Formulation	cell centers	edges	faces
E-B	μ^{-1}, σ	$\vec{E}$	$\vec{B}$
H-J	μ, ρ	$\vec{H}$	$\vec{J}$

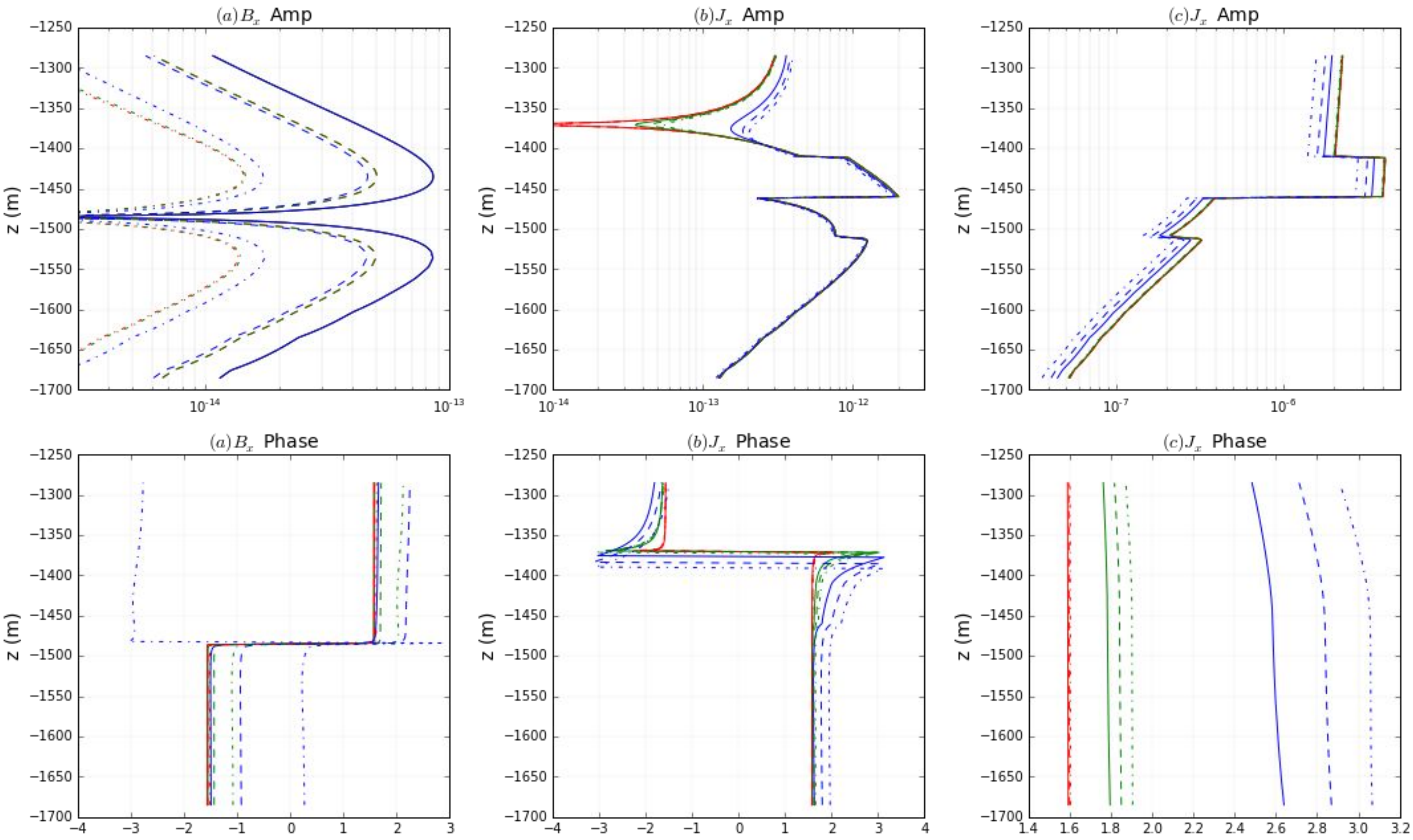
Examples: Surface Electric Src





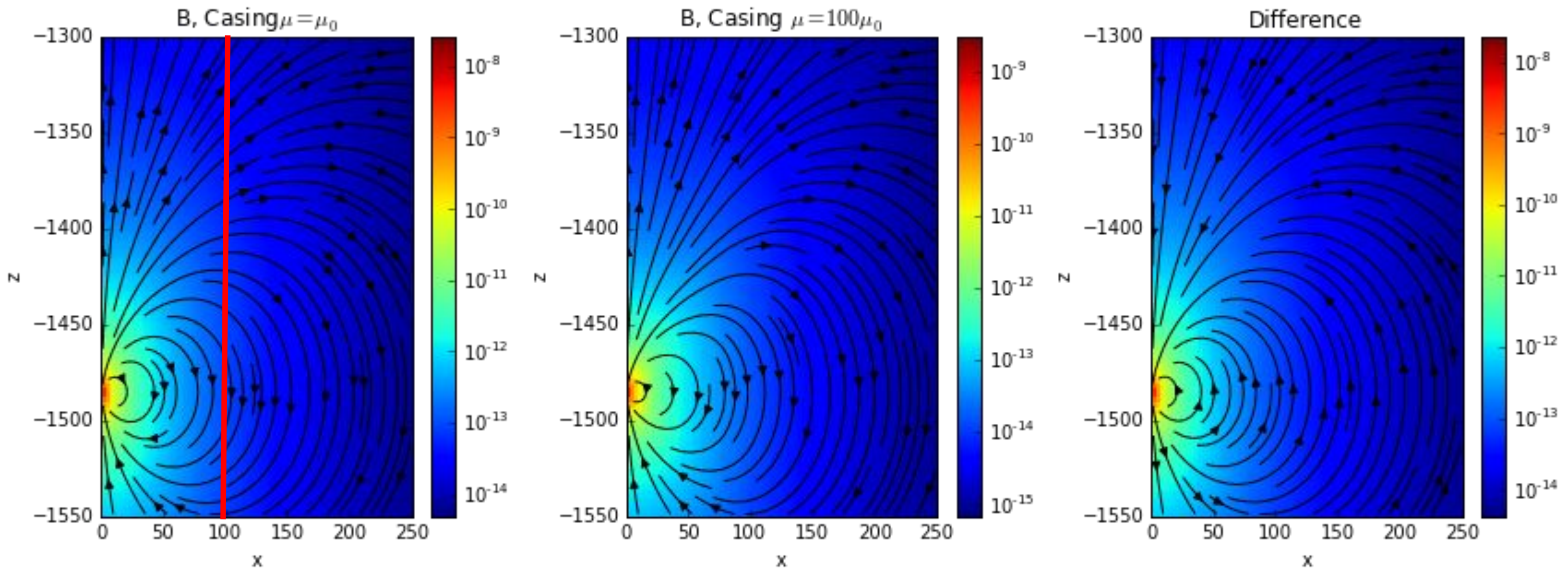


$(a)B_x$ real
$(b)J_x$ real
$(c)J_x$ real
$(a)B_x$ imag
$(b)J_x$ imag
$(c)J_x$ imag
z (m)
1e-13
1e-12
1e-6
1e-14
1e-12
1e-6

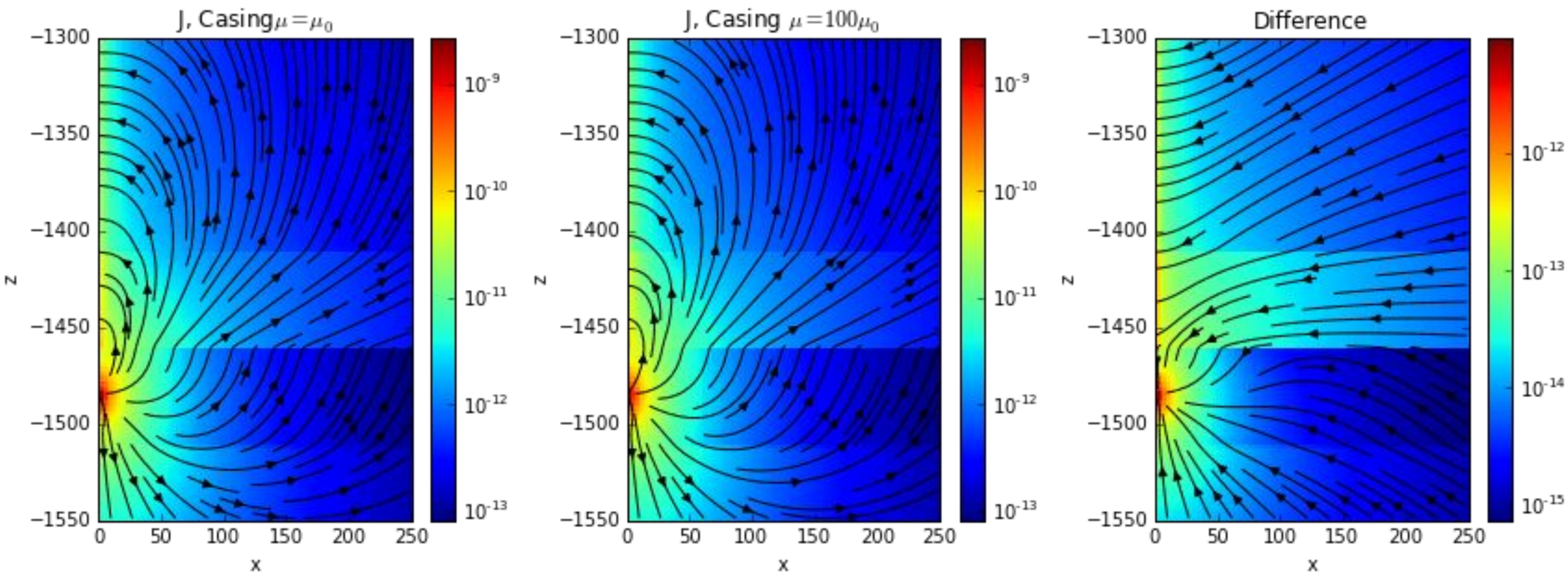


$(a) B_x$ Amp
$(b) J_x$ Amp
$(c) J_x$ Amp
$(a) B_x$ Phase
$(b) J_x$ Phase
$(c) J_x$ Phase
z (m)

Examples: Downhole Magnetic Dipole

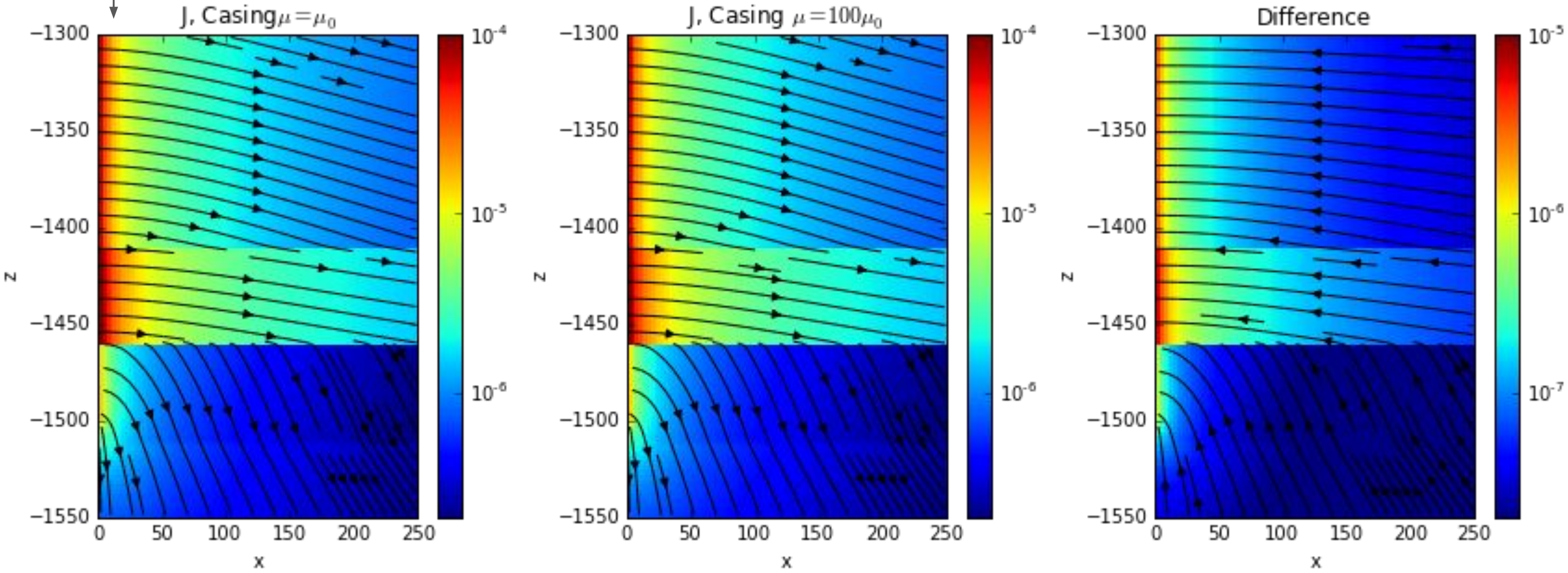


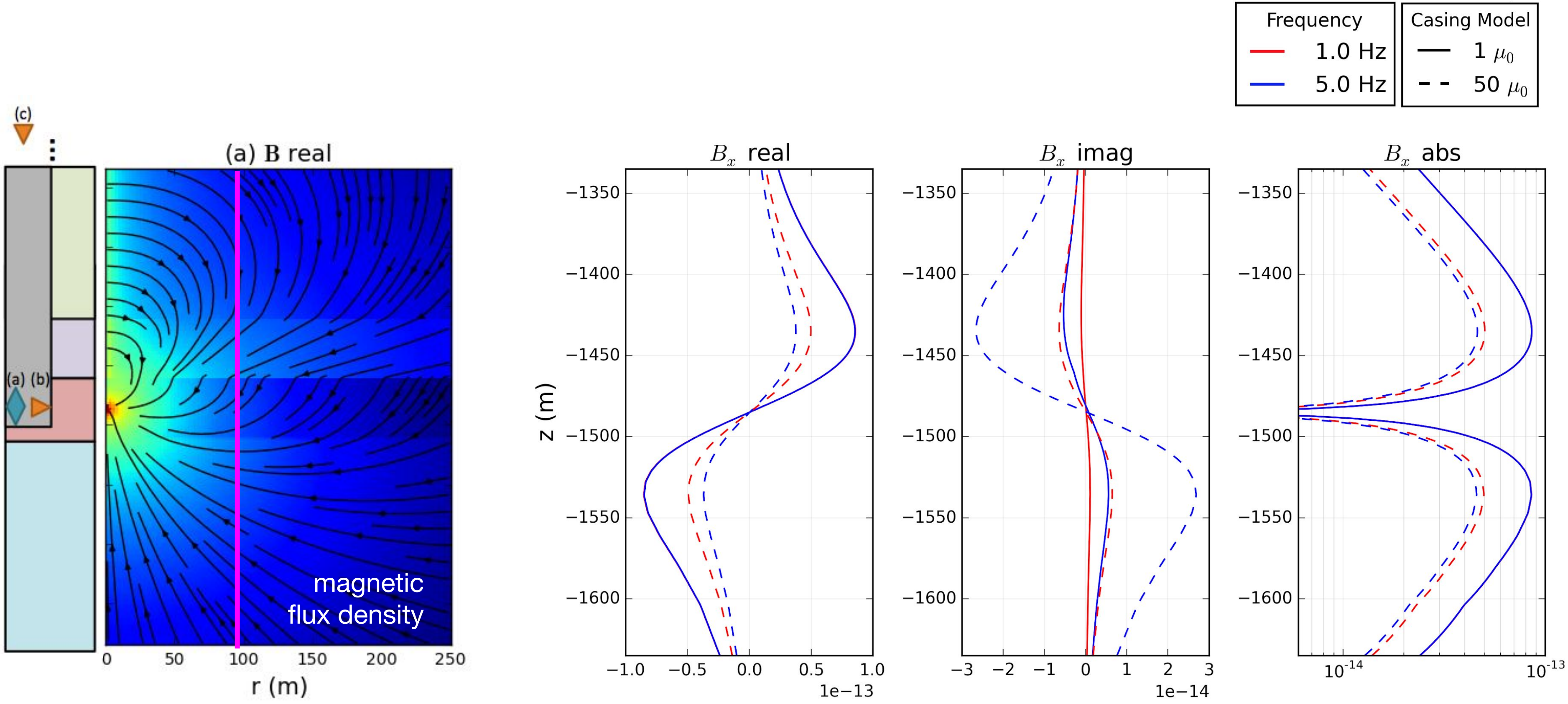
Down hole E src Couple to casing



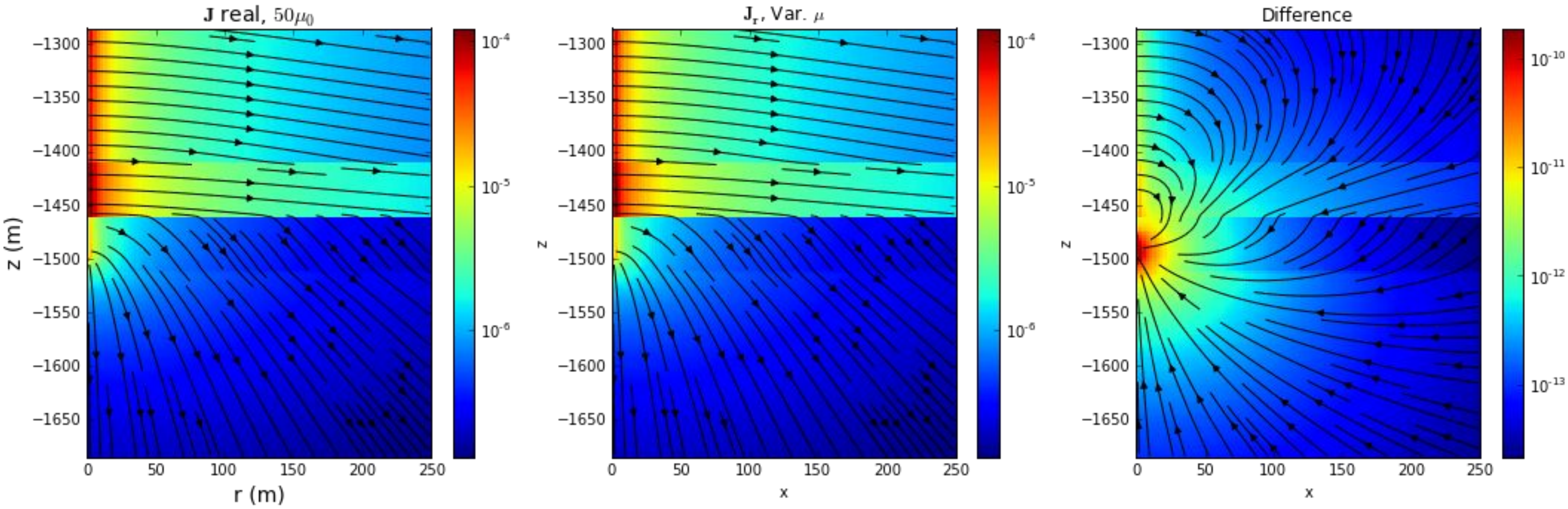
Examples: Surface Electric Sc

Current!

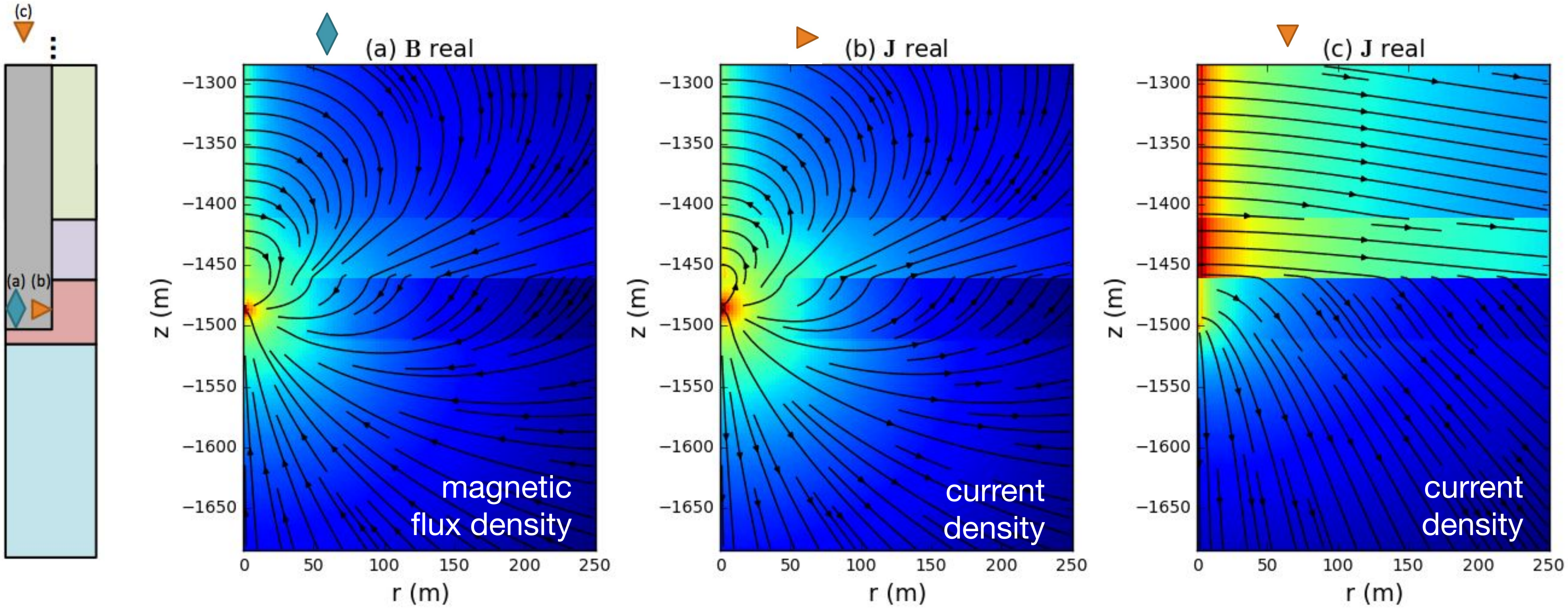



(c)
(a) (b)
(a) B real
magnetic
flux density
r (m)
0
50
100
150
200
250
Frequency
1.0 Hz
5.0 Hz
Casing Model
1 μ_0
50 μ_0
B_x real
B_x imag
B_x abs
z (m)
−1350
−1400
−1450
−1500
−1550
−1600
−1.0
−0.5
0.0
0.5
1.0
1e−13
−3
−2
−1
0
1
2
3
1e−14
10^{-14}
10^{-13}

Variable Magnetic Permeability



Modelling the casing: Source types



Approach: Break up the Problem

1. Primary Problem:

How do we model the casing in a simple background?

2. Secondary Problem:

How do model setting with 3D geologic features?