Modelling electromagnetic problems in the presence of cased wells

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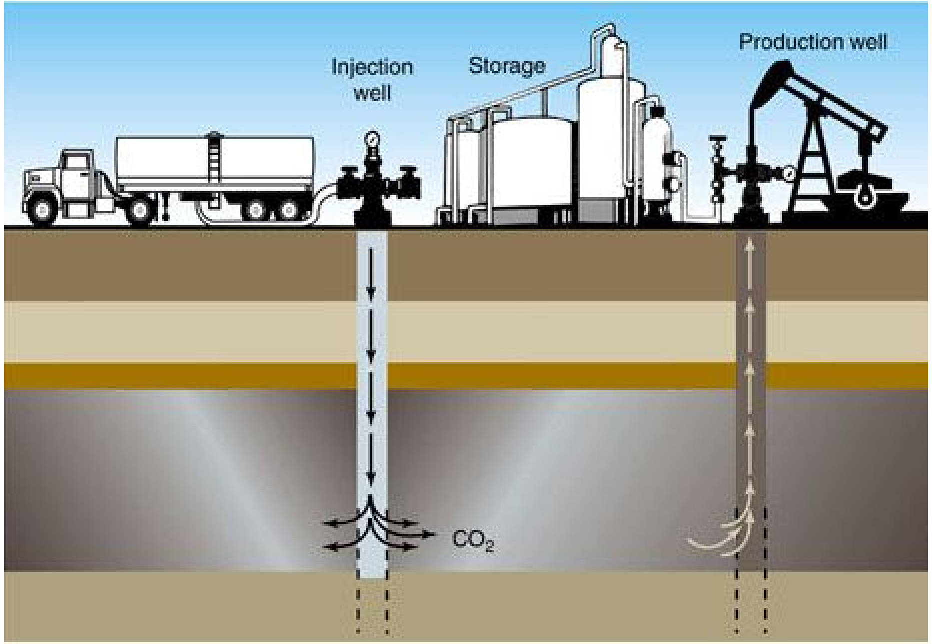
Why?

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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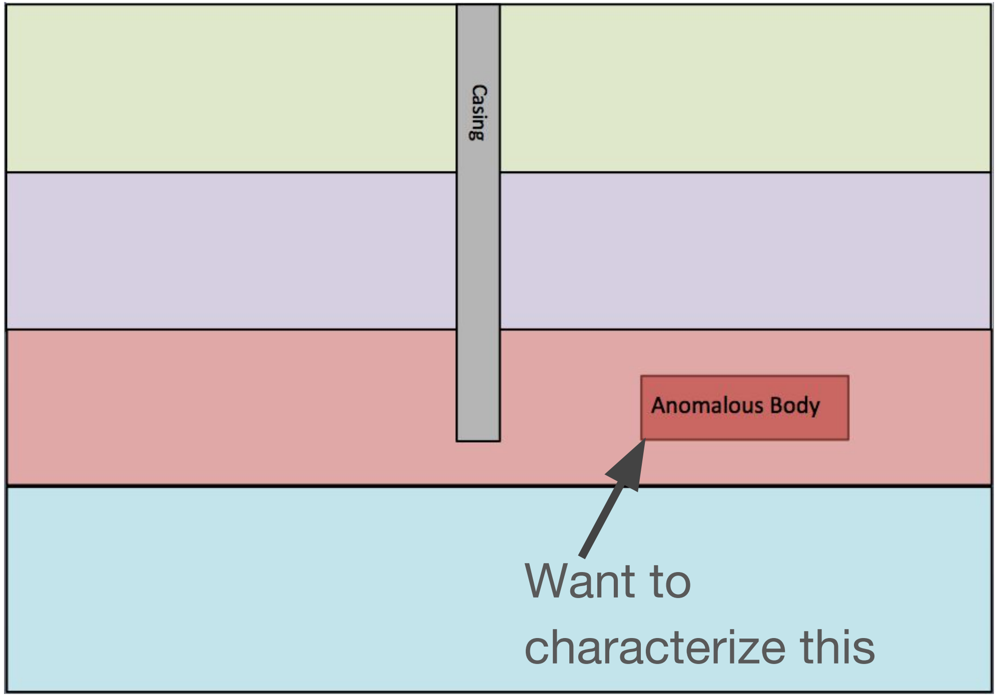
- Inversion: characterize conductivity distribution



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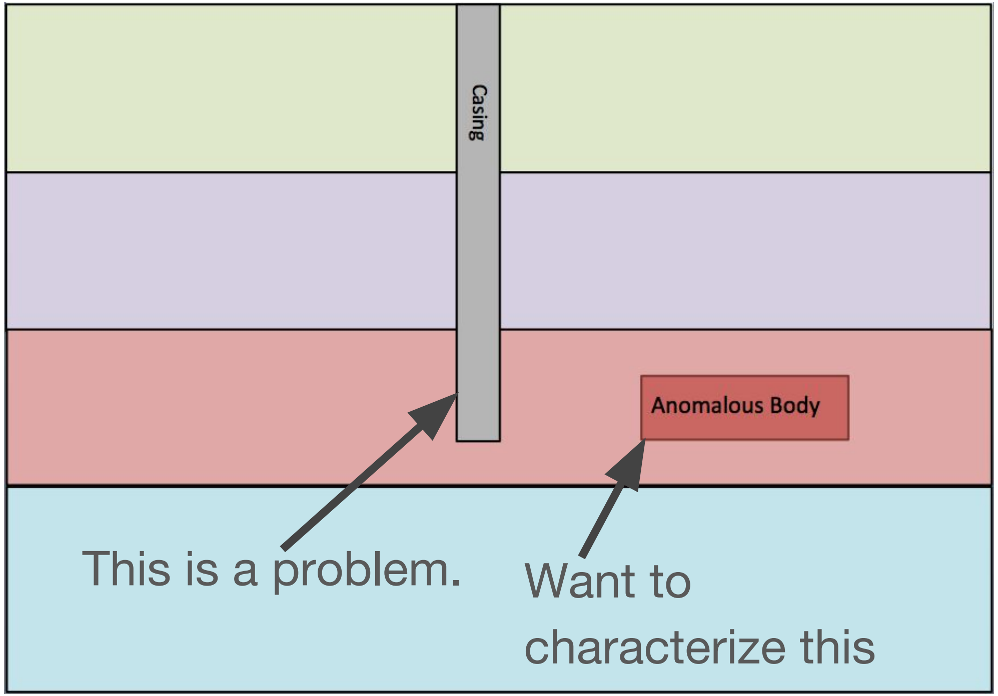


Steel casing in EM

Physical Properties

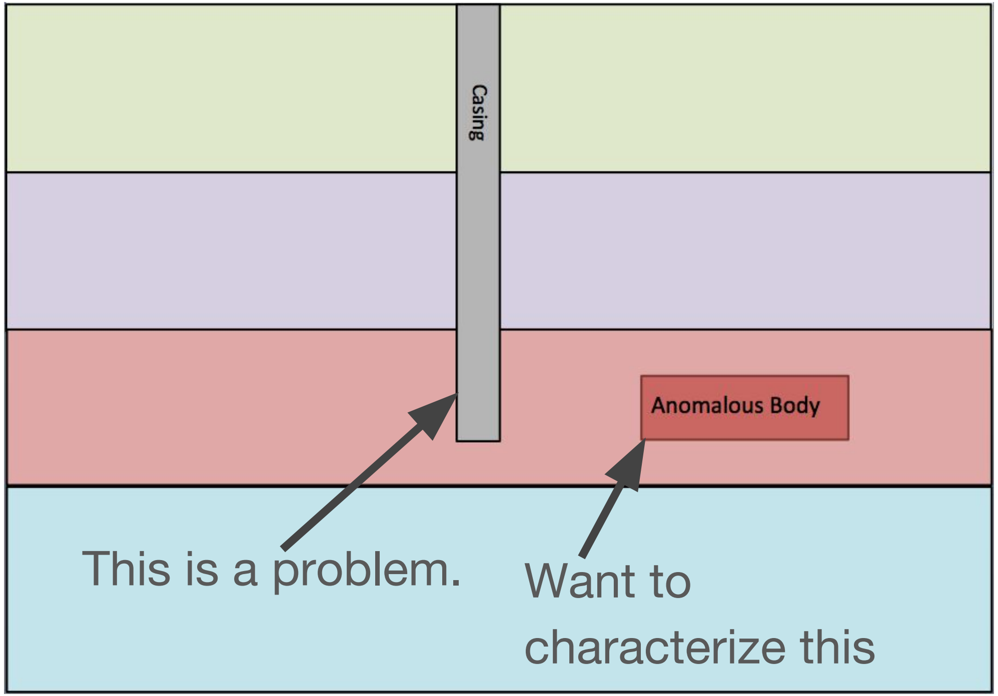
- highly conductive
- significant (variable) magnetic permeability

➡ ***Significant impact on signals***

Geometry

- cylindrical
- thin compared to length

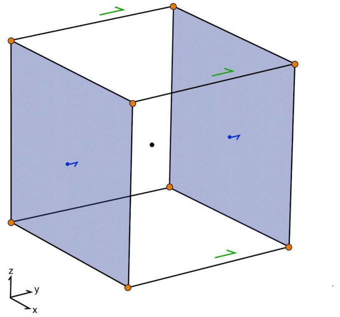
➡ ***Numerically challenging***



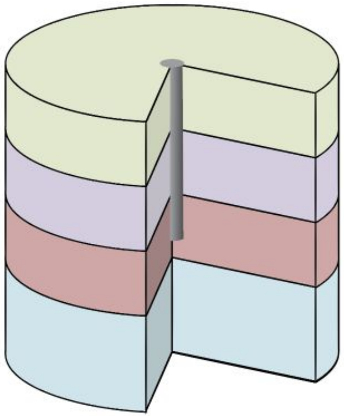
Overview

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

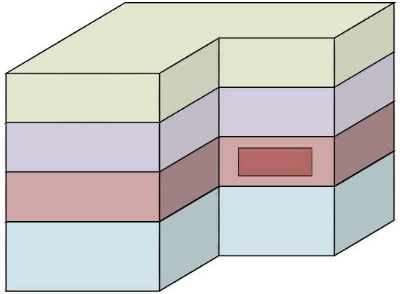
$$\nabla \times \mathbf{E} + i\omega \mathbf{B} = 0$$
$$\nabla \times \mathbf{H} - \mathbf{J} = \mathbf{q}$$



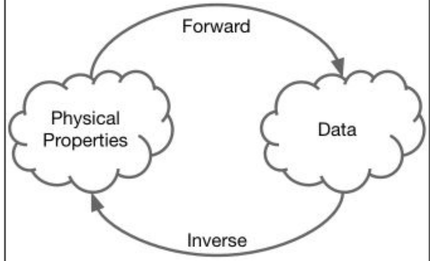
Modelling Maxwell's equations



Modelling the Casing



Modelling 3D geology



Approaching the inverse problem

Electromagnetics: Maxwell's Equations

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

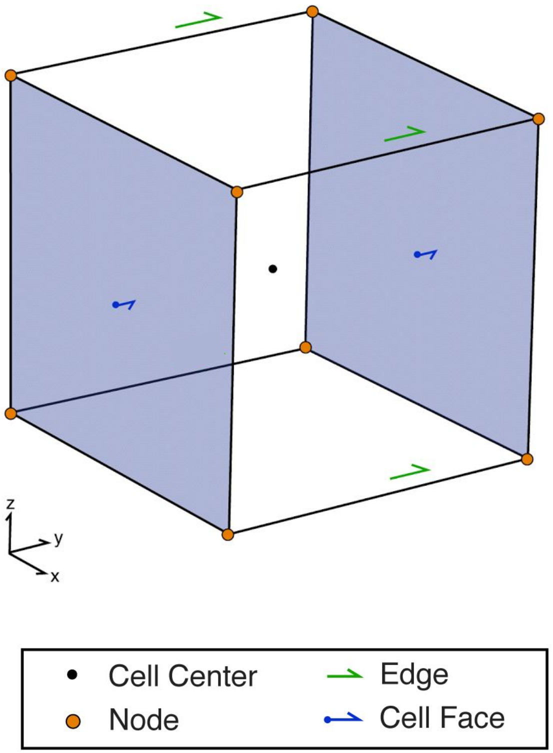
$$\nabla \times \mathbf{E} + i\omega \mathbf{B} = 0$$
$$\nabla \times \mathbf{H} - \mathbf{J} = \mathbf{q}$$

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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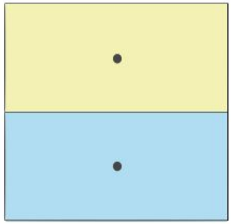
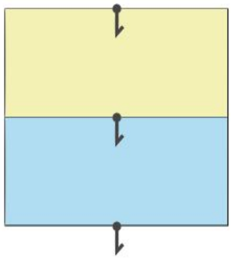
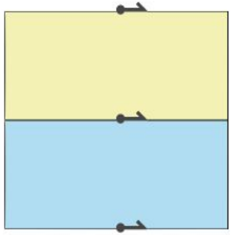


- Fluxes
  - $\mathbf{J}$ current density
  - $\mathbf{B}$ magnetic flux density



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

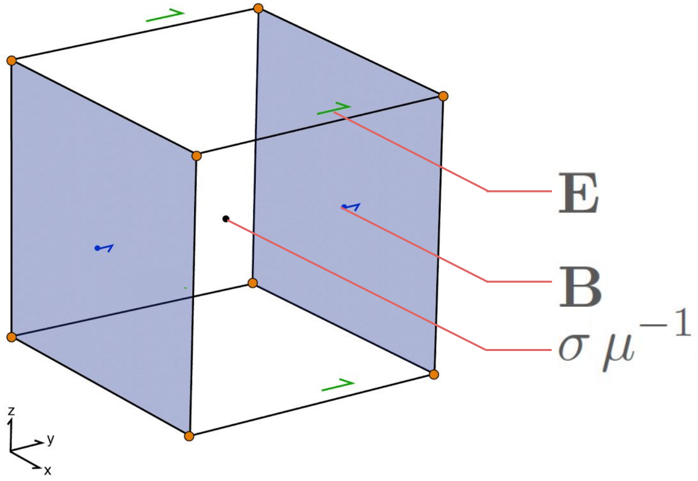


Two Formulations of Maxwell

E-B Formulation:

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

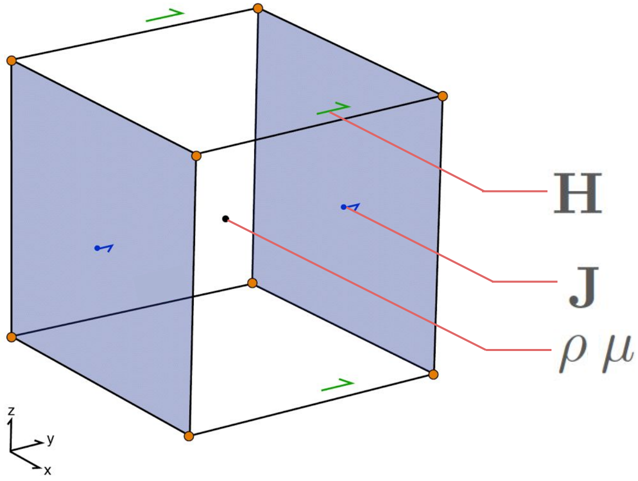
$$\nabla \times \mu^{-1}\mathbf{B} - \sigma \mathbf{E} = \mathbf{q}$$



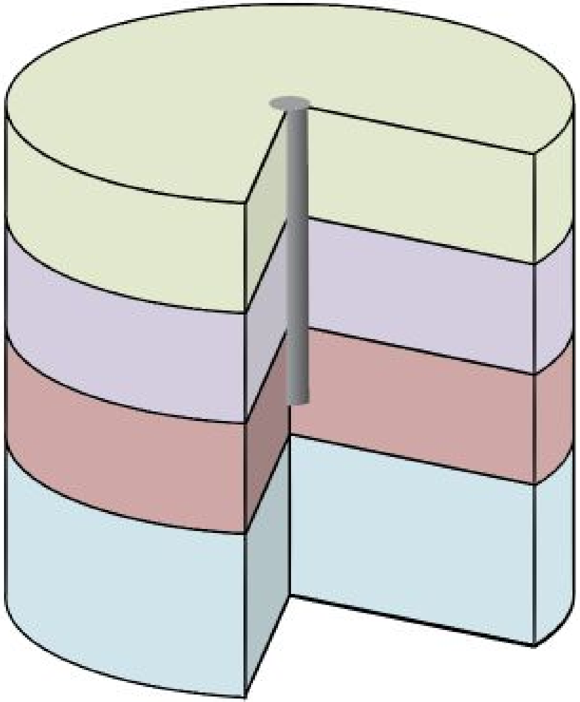
H-J Formulation:

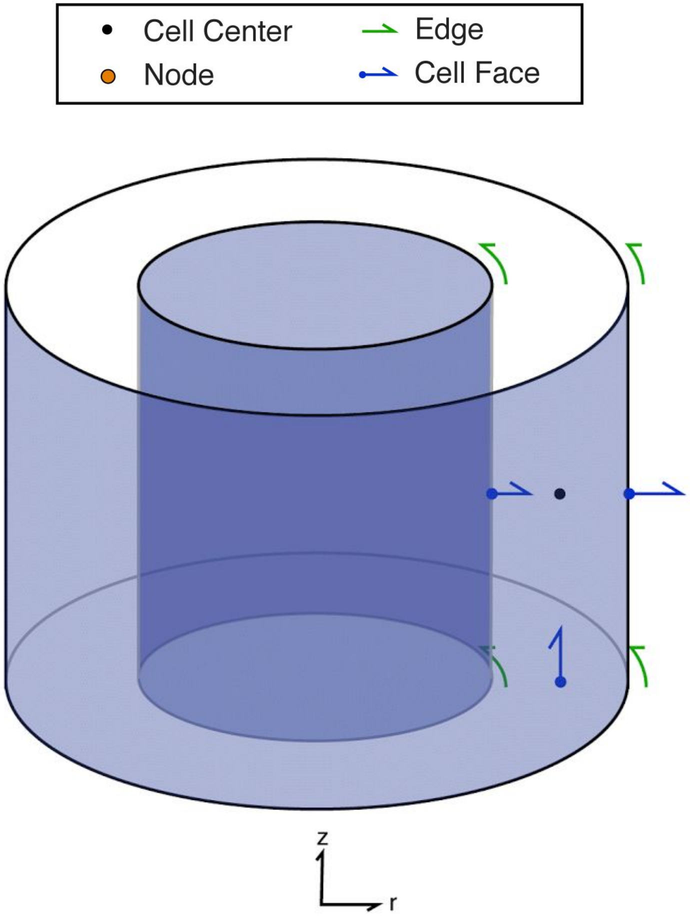
$$\nabla \times \rho \mathbf{J} + i\omega \mu \mathbf{H} = 0$$

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

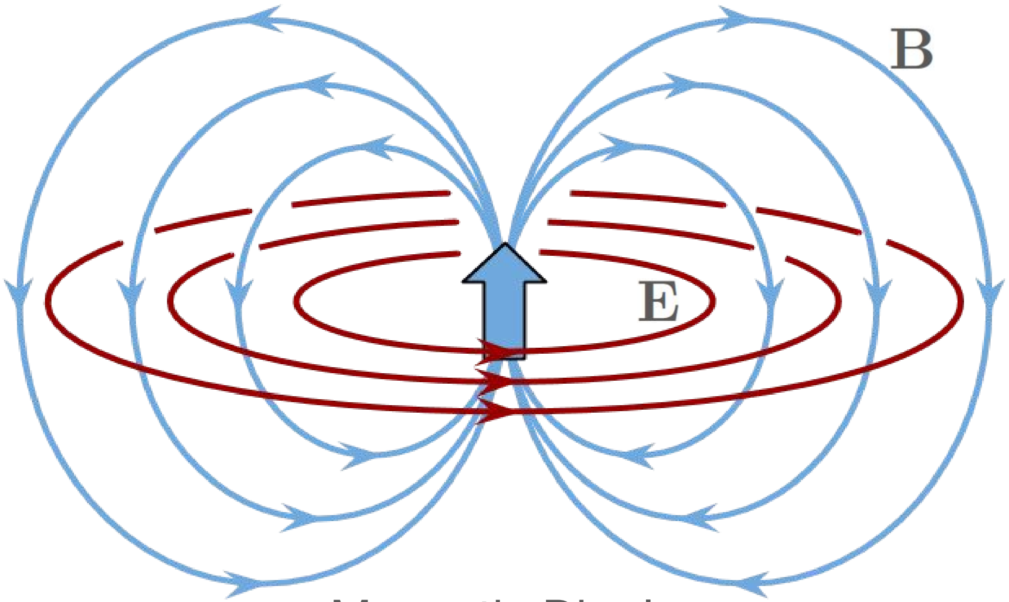


Cylindrical mesh



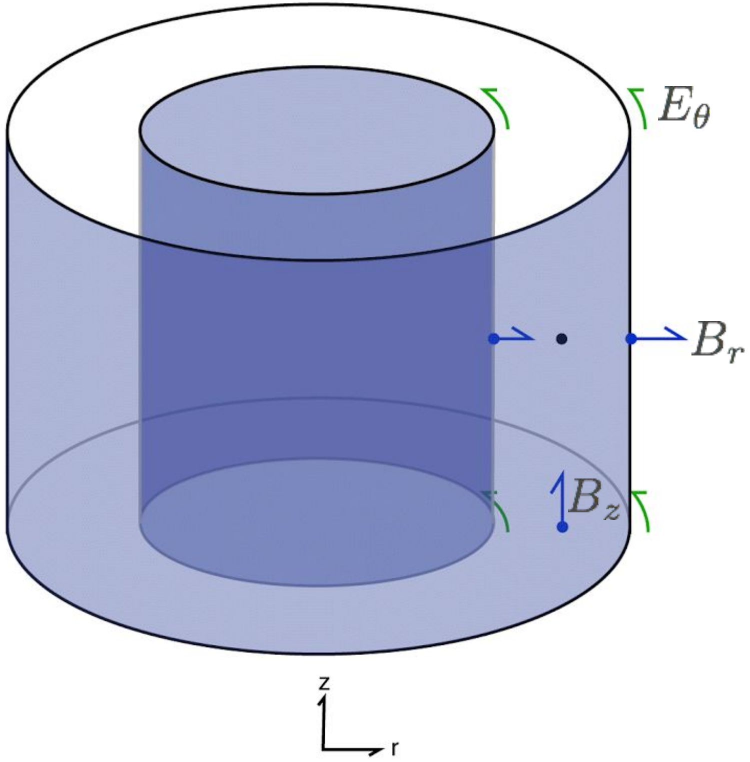


Primary: Cylindrical Symmetry - Dipole



Magnetic Dipole

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



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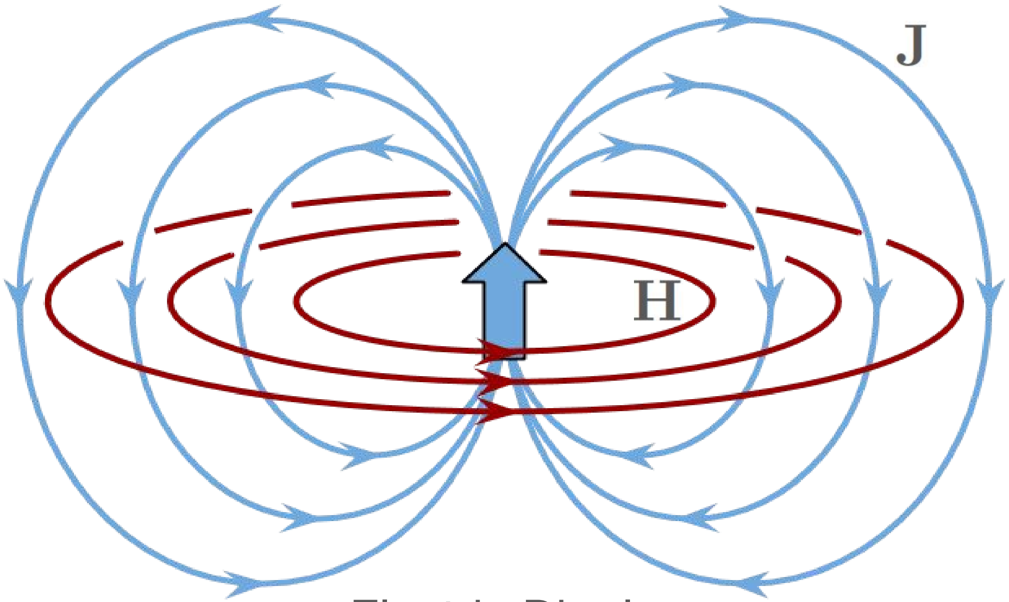
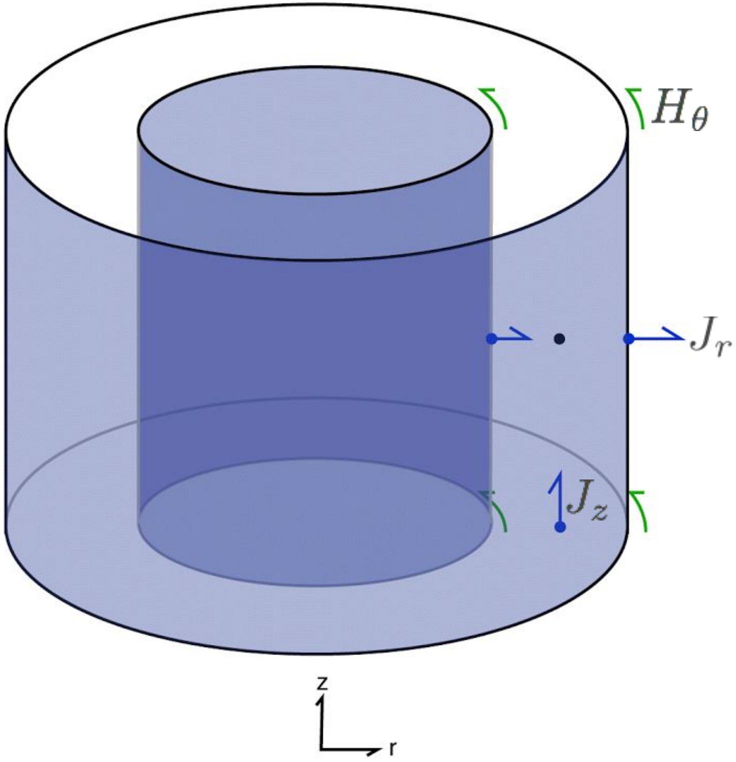


Electric Dipole

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



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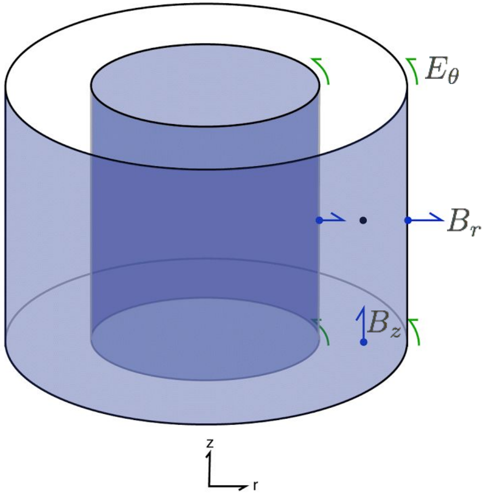

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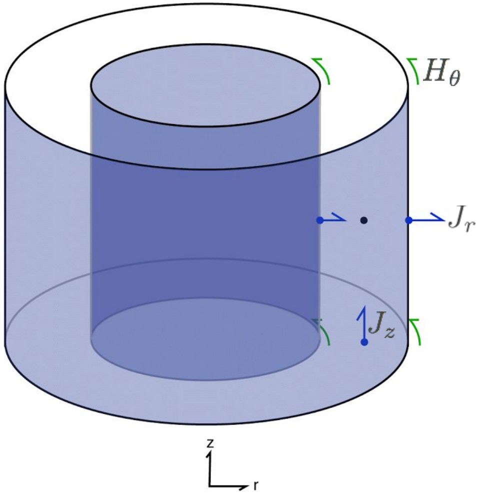
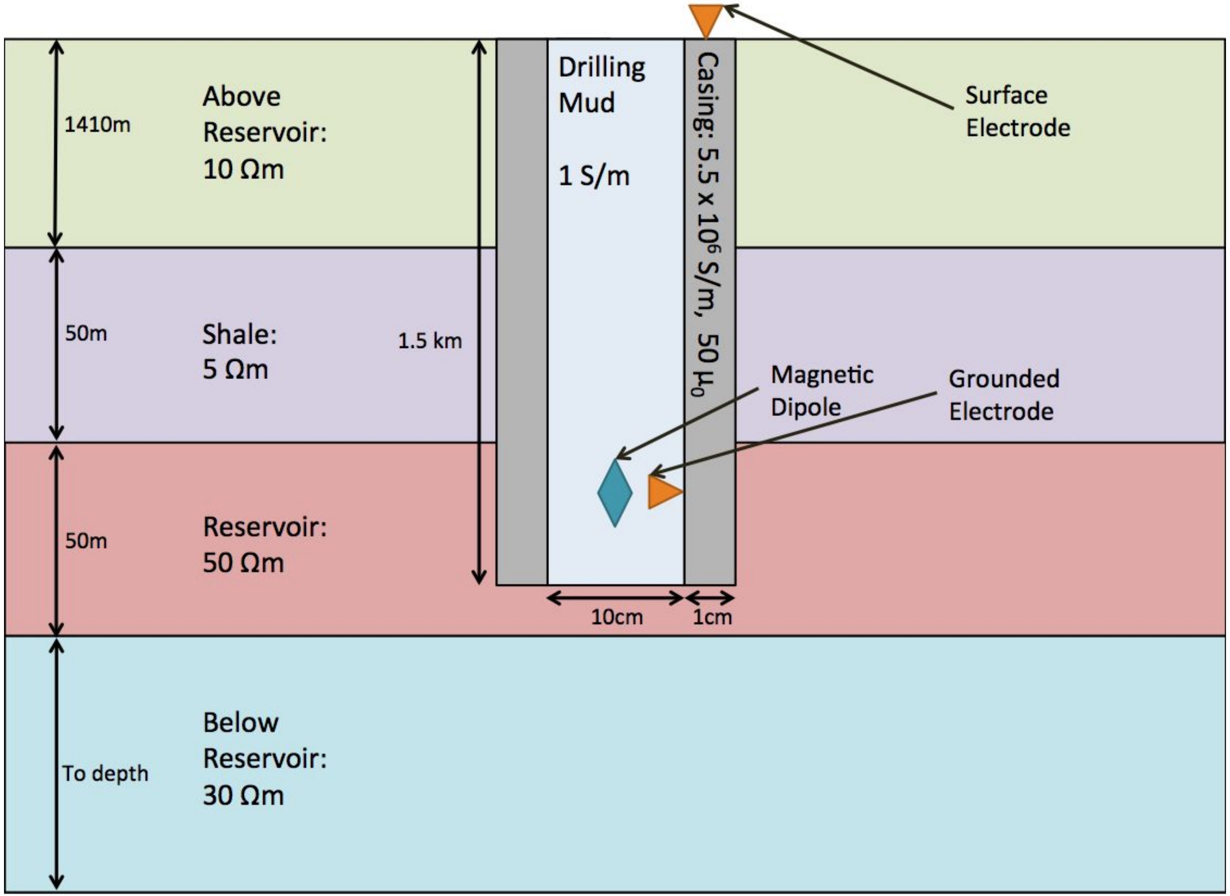
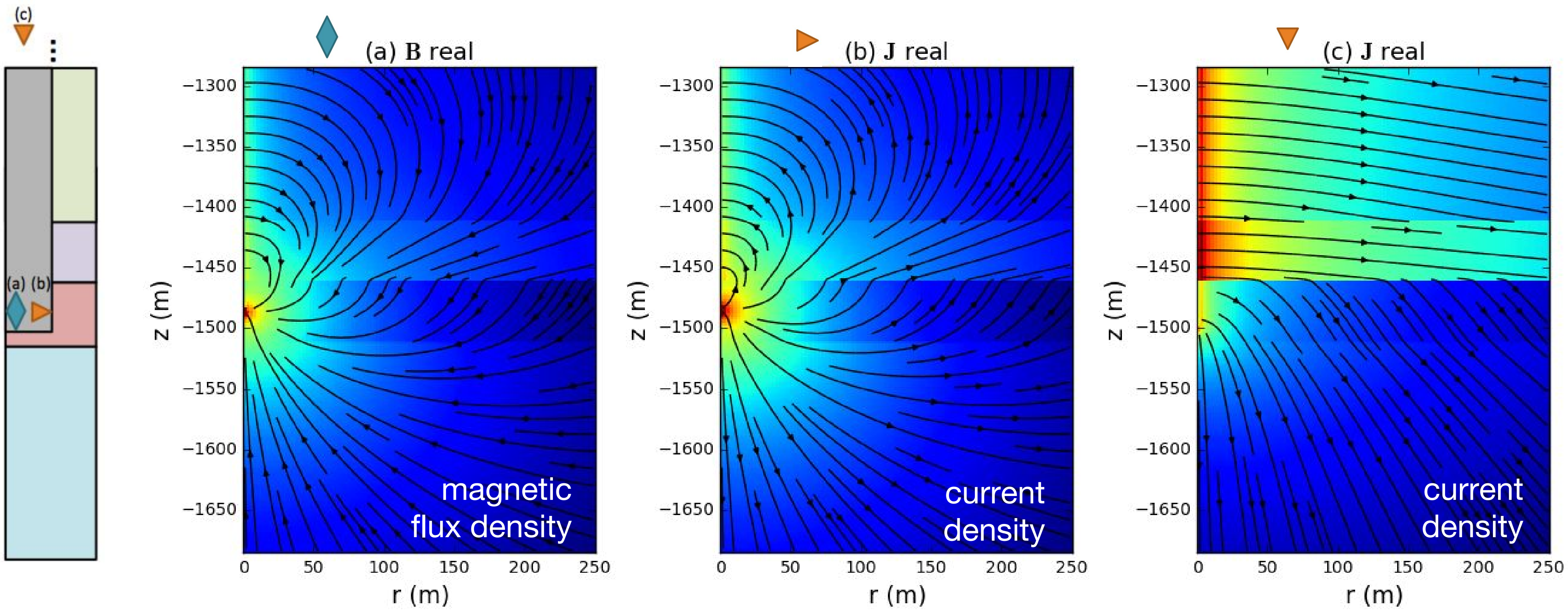


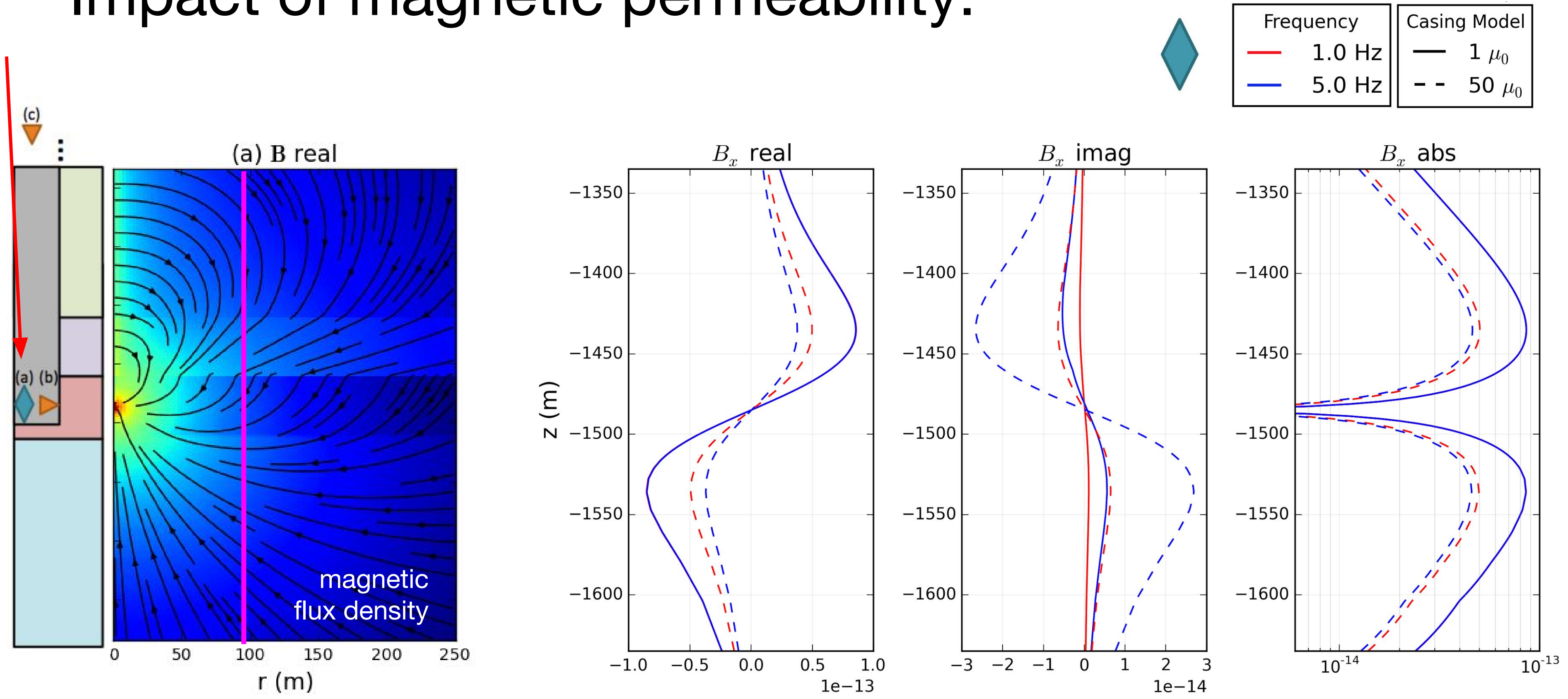
Modelling the casing



Modelling the casing: Source types



Impact of magnetic permeability:



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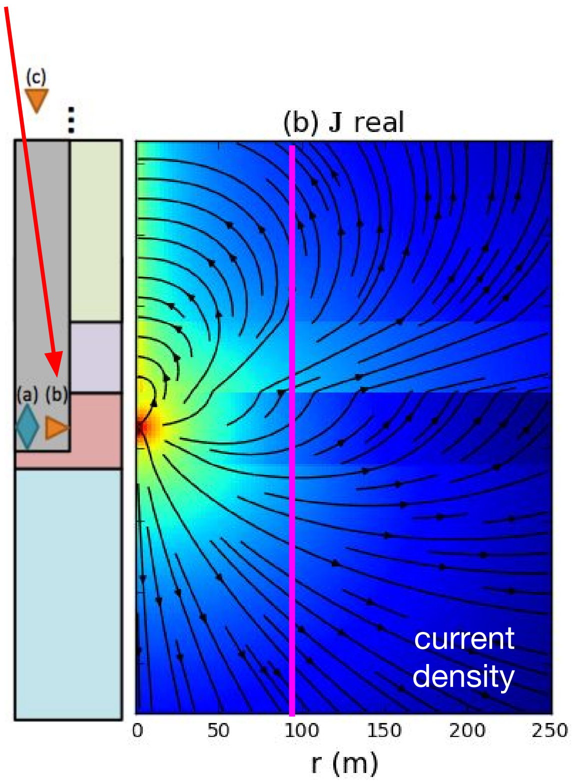

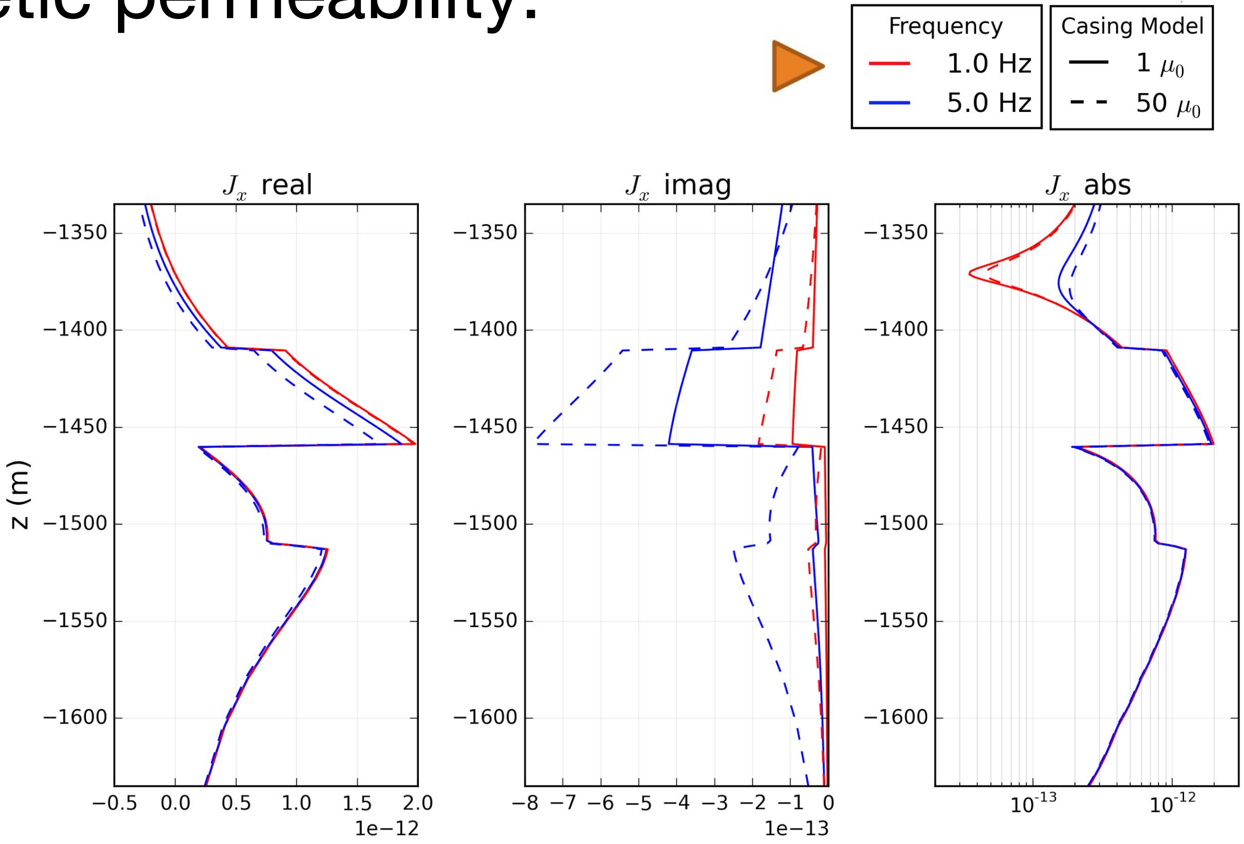

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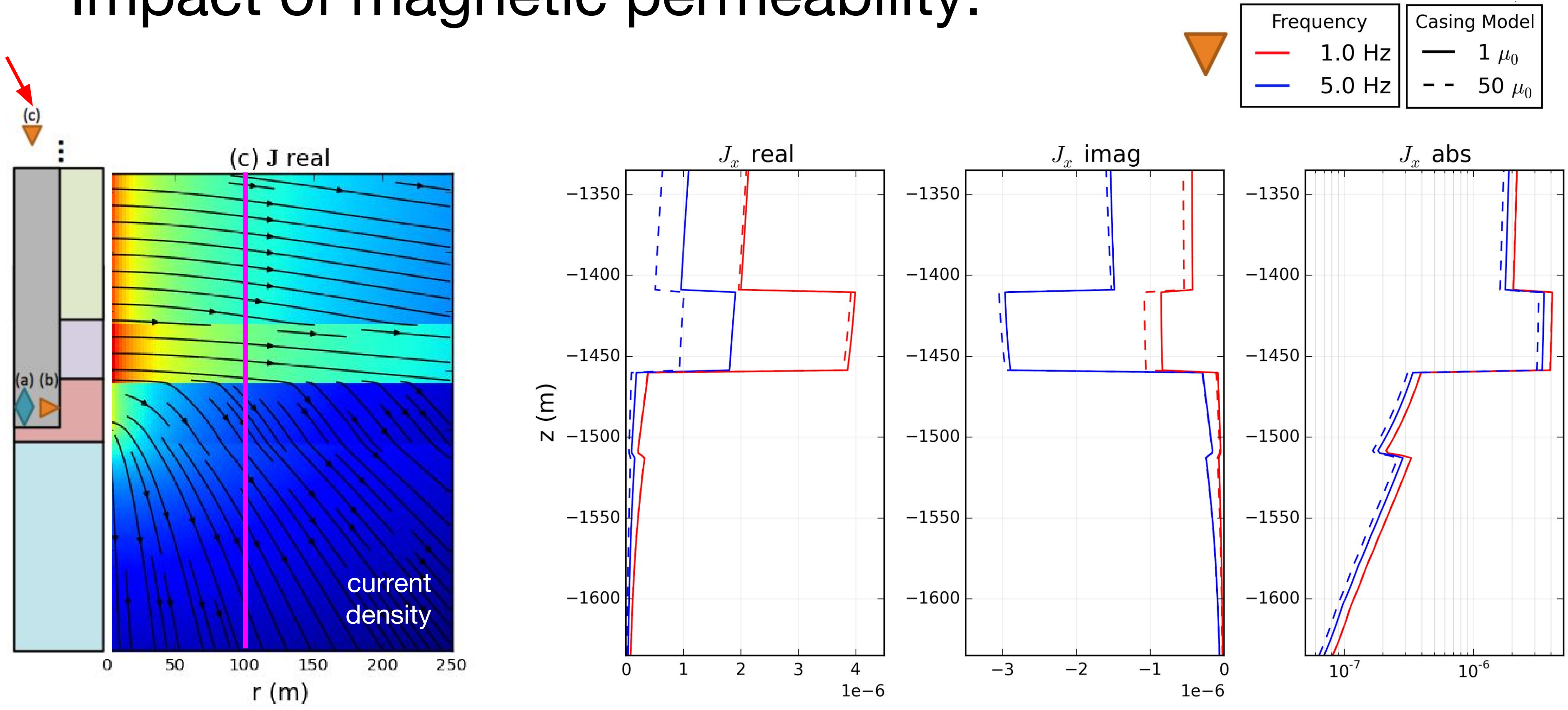
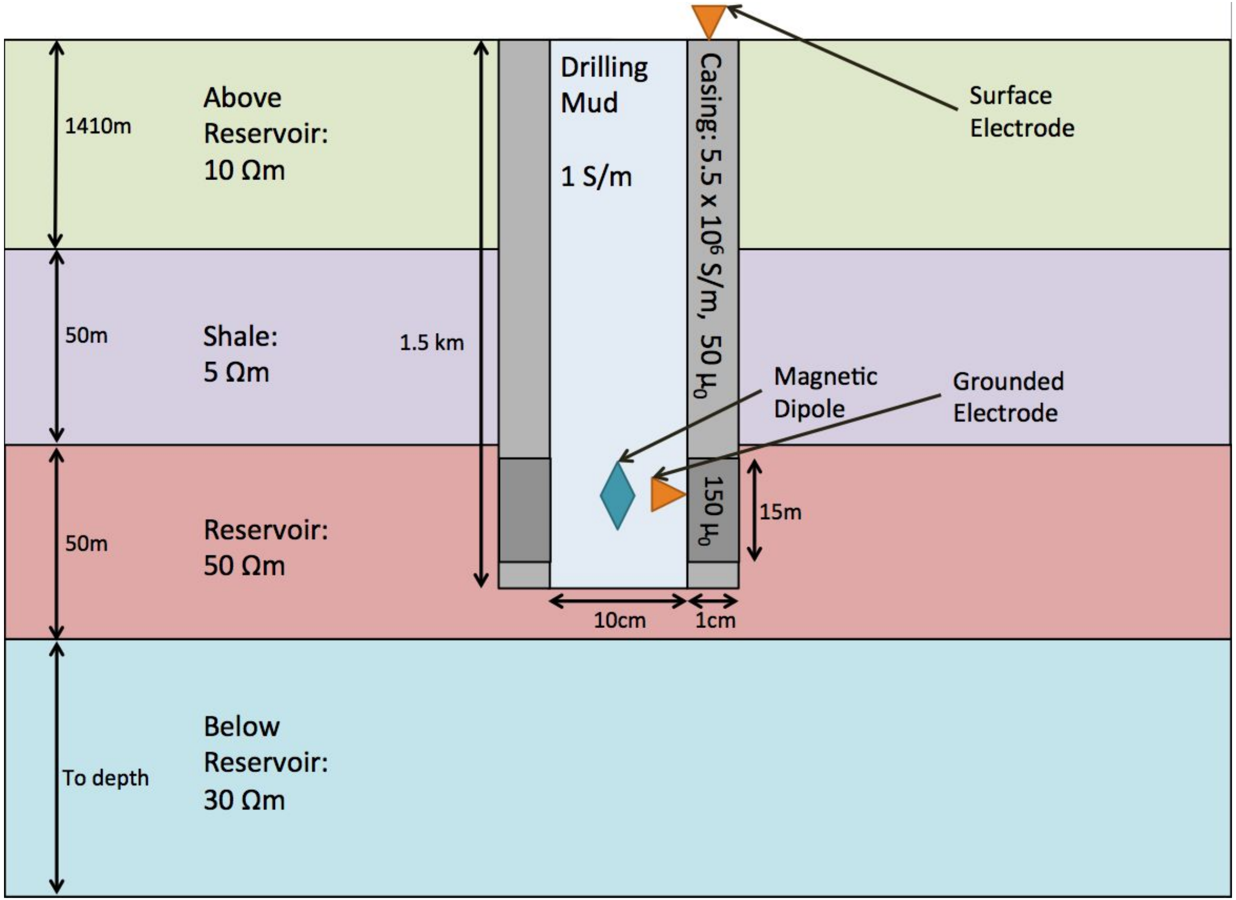


Impact of Variable Magnetic Permeability



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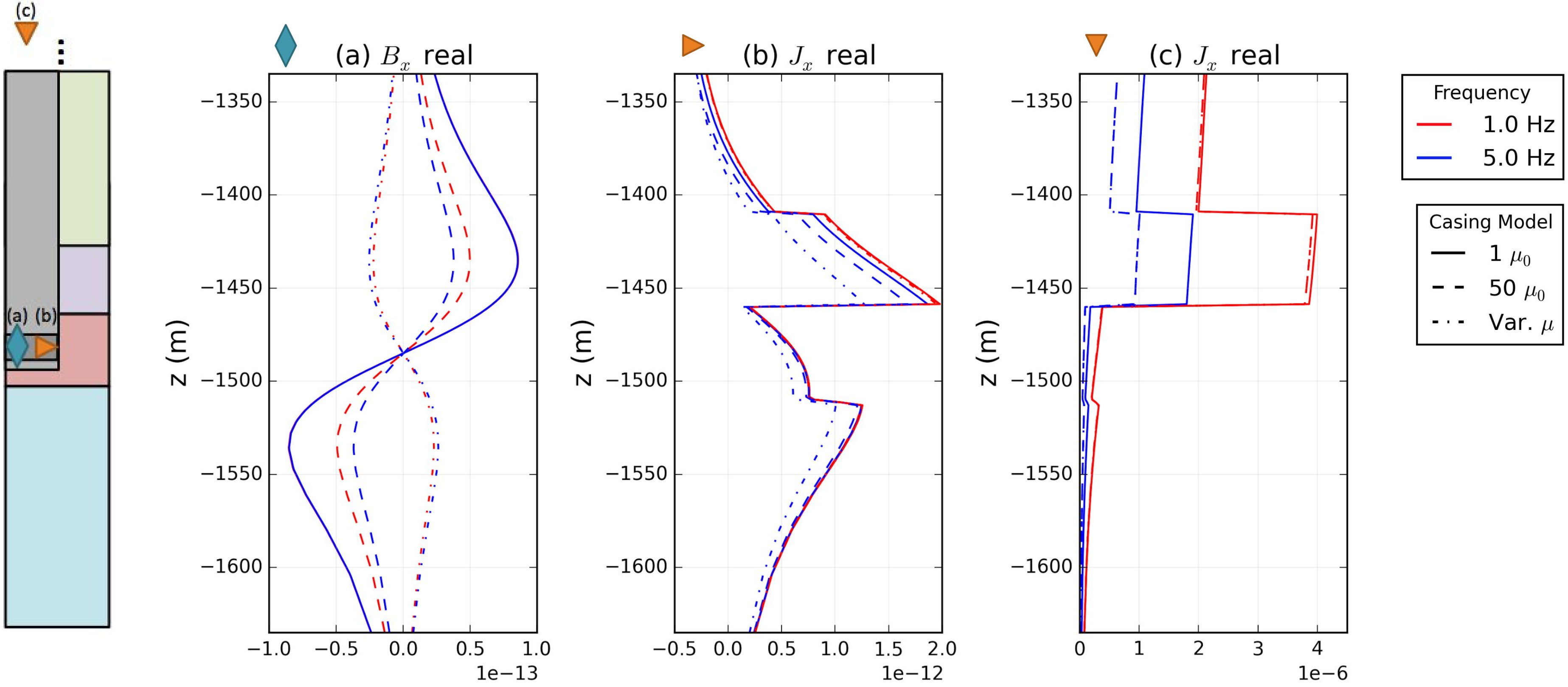
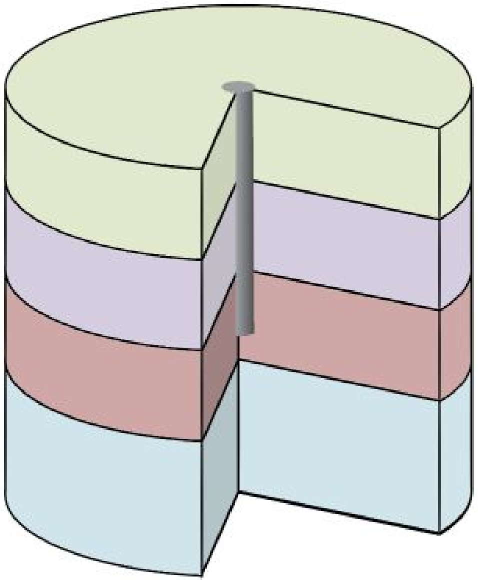


Modelling with 3D geology

What we have done

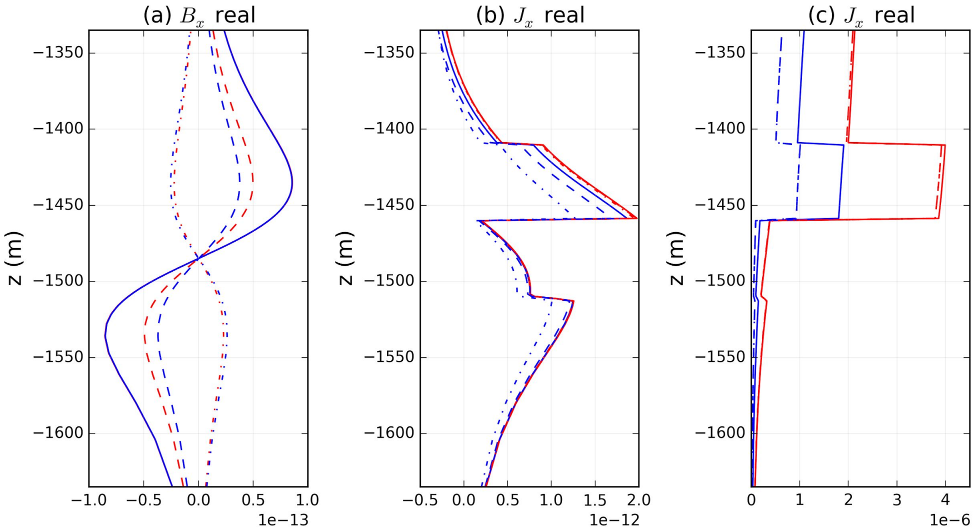
- cylindrically symmetric
- variable σ μ



Casing & Source, Layered Earth

✓

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



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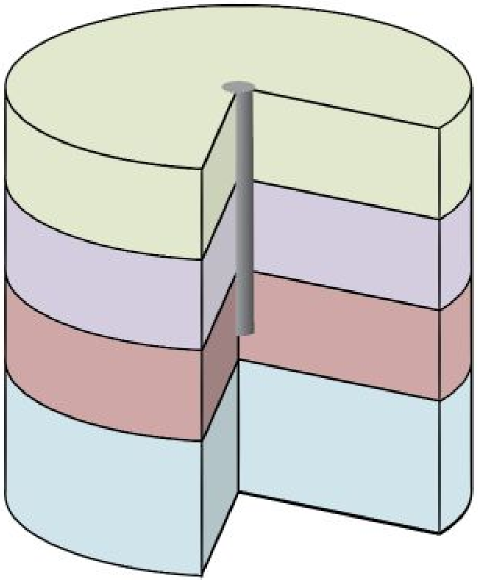


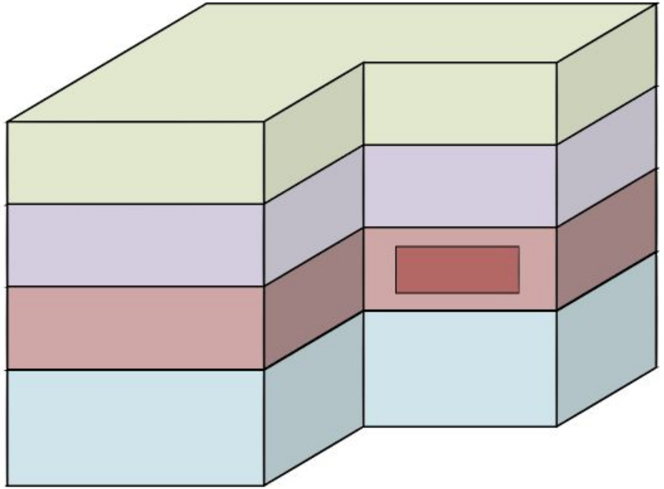
Casing & Source, Layered Earth

✓

?

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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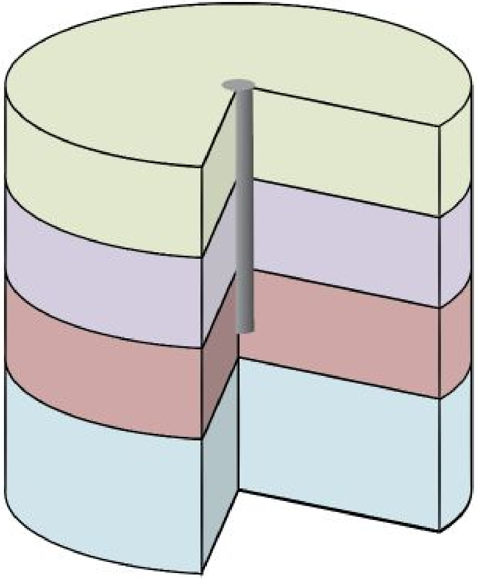

Casing & Source, Layered Earth

✓

Interpolate

Secondary:

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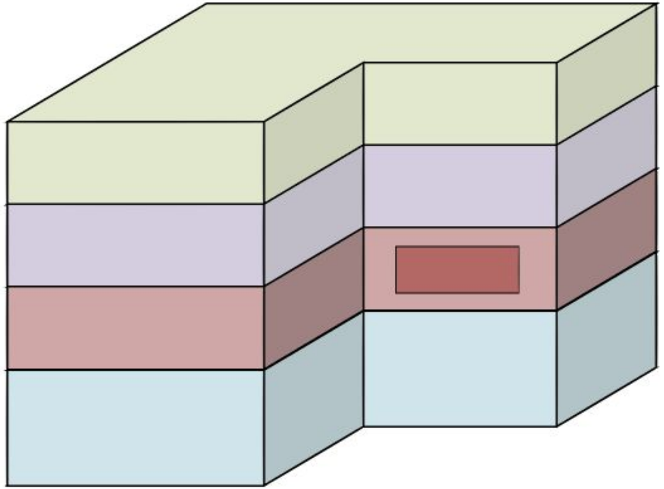

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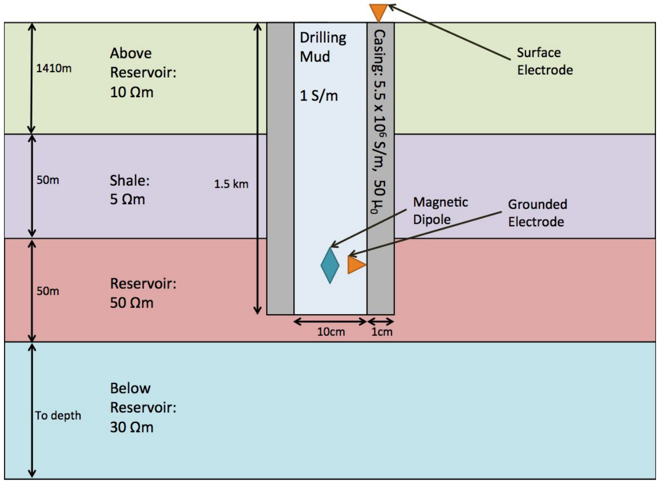

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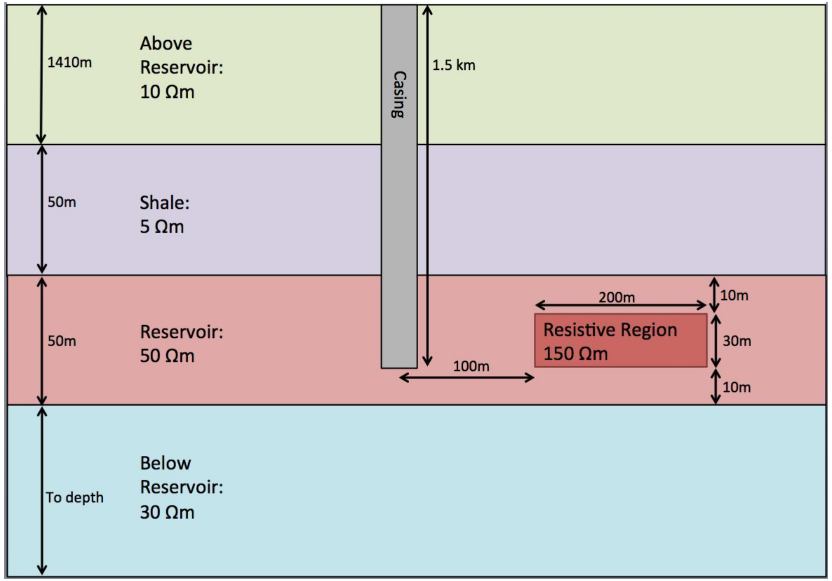

Primary-Secondary: 3D geology (magnetic dipole)

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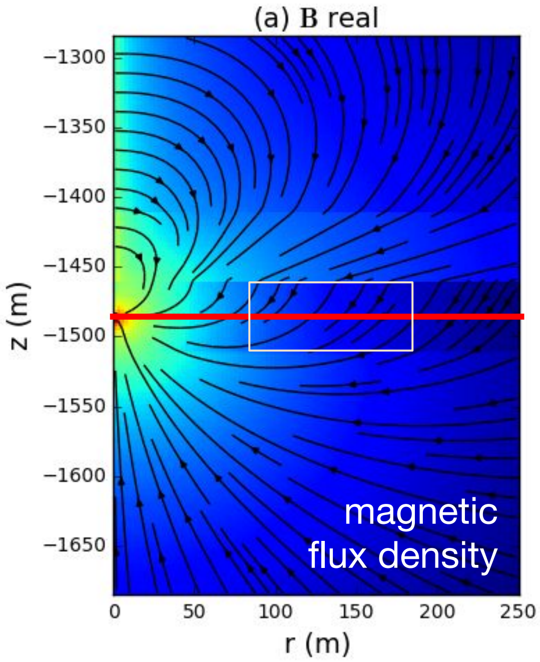

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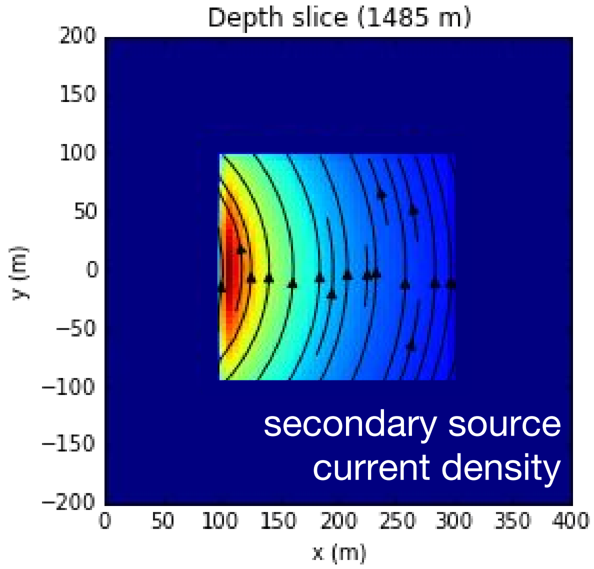

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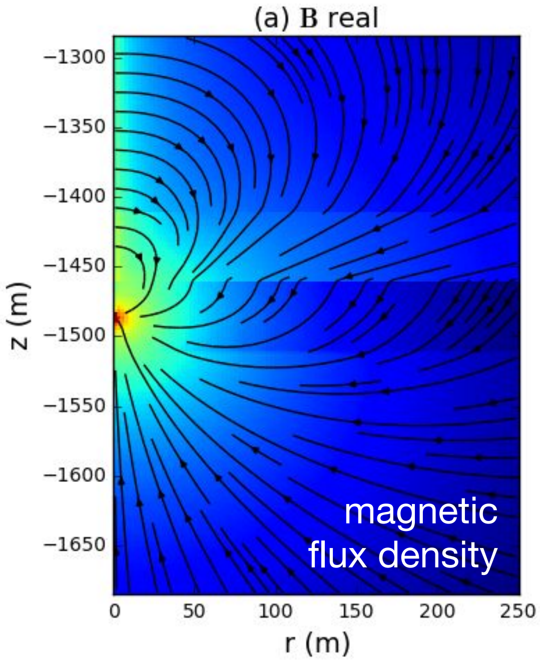

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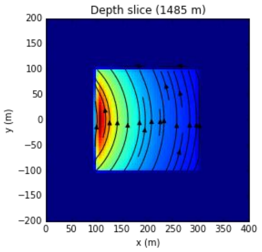
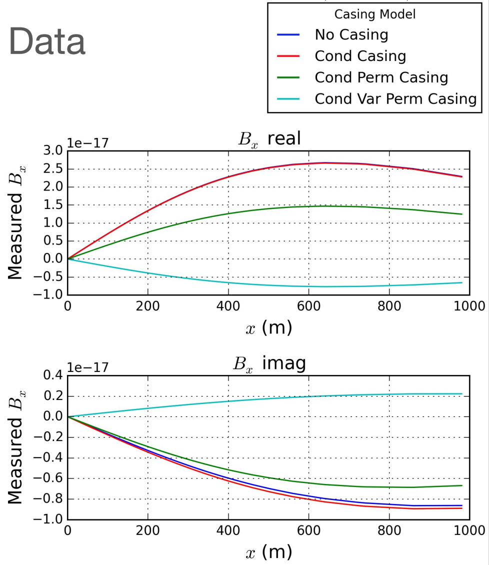
Source in 3D

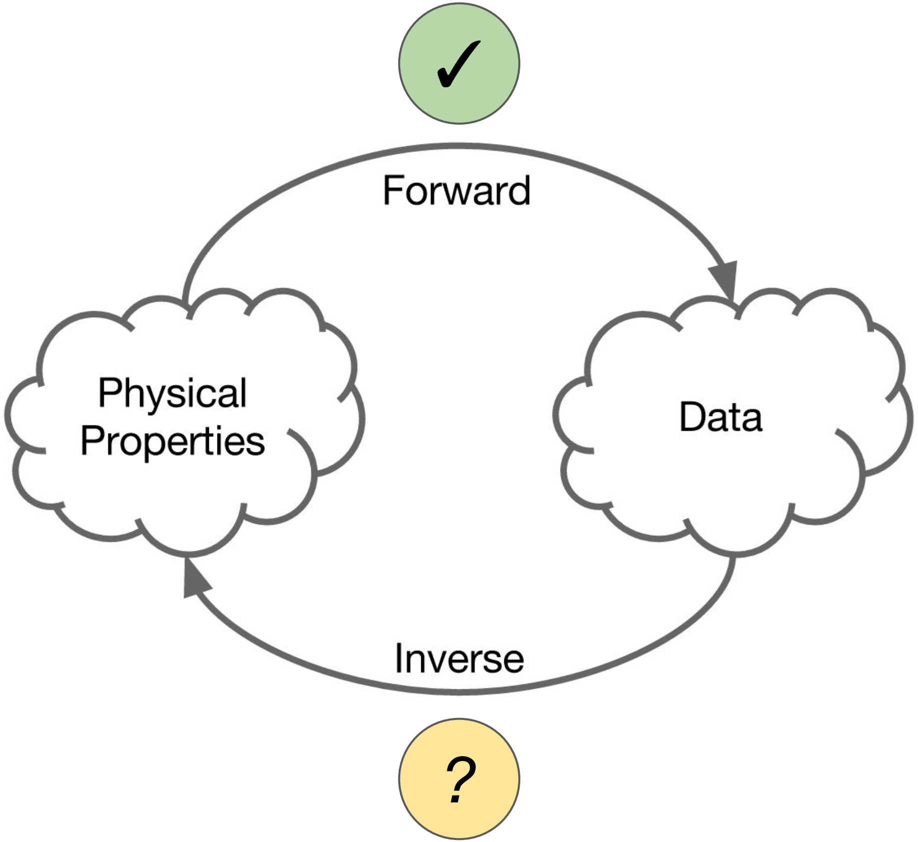


Solve

Data



Approaching the Inverse Problem



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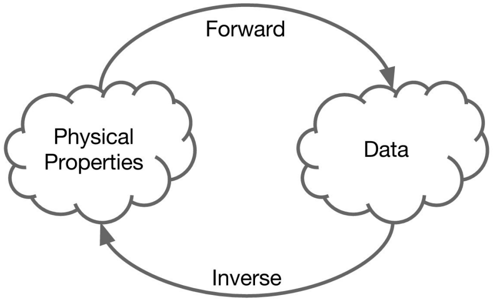
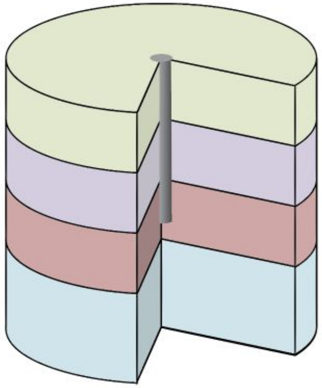


Estimate: $\sigma_p \; \mu_p$



$$\nabla \times \mathbf{E_p} + i\omega \mathbf{B_p} = 0$$
$$\nabla \times \mu_p^{-1} \mathbf{B_p} - \sigma_p \mathbf{E_p} = \mathbf{q}$$

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

Interpolate to compute source

Invert for 3D conductivity : σ

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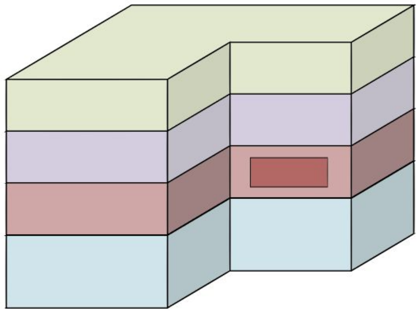
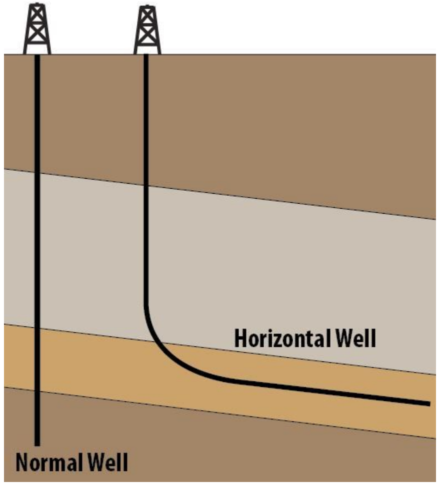
$$\nabla \times \mu^{-1} \mathbf{B_s} - \sigma \mathbf{E_s} = \tilde{\mathbf{q}}$$
$$\tilde{\mathbf{q}} = (\boxed{\sigma} - \sigma_p)\mathbf{E_p}$$



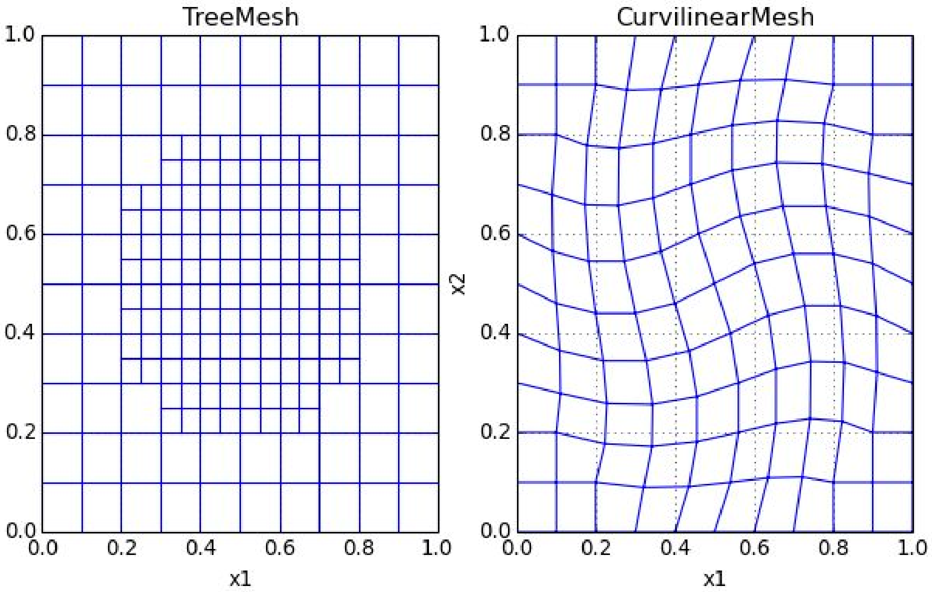
Model dependence on RHS
→ need to include in sensitivities

Generalizing

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



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



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

Summary

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

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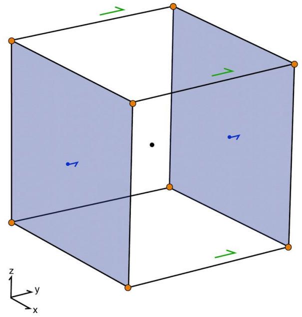
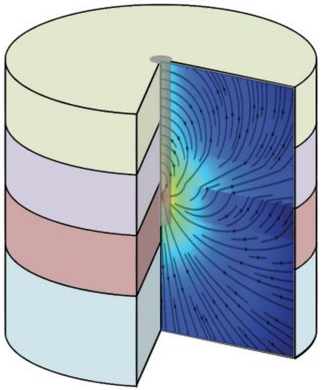
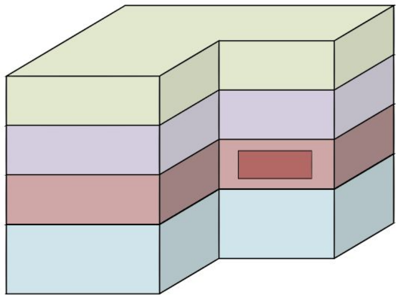


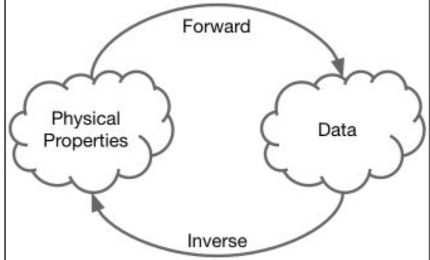
Modelling Maxwell's equations



Modelling the Casing



Modelling 3D geology



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Thank you!

Thanks to:

- developers of SimPEG and simpegEM
- UBC GIF

References:

Brill, T. M., J. L. Le Calvez, C. Demichel, E. Nichols, and F. Zapata Bermudez, 2012, Electromagnetic casing inspection tool for corrosion evaluation: Society of Petroleum Engineers - International Petroleum Technology Conference 2012, IPTC 2012, **3**, 2109–2122.

Cockett, R., S. Kang, A. Heagy L., Pidlisecky, and D. Oldenburg, 2015, SimPEG: An open-source framework for simulation and parameter estimation in geophysical applications (submitted): Computers and Geoscience.

Commer, M., G. M. Hoversten, and E. S. Um, 2015, Transient-electromagnetic finite-difference time-domain earth modeling over steel infrastructure: GEOPHYSICS, **80**, E147–E162.

Cuevas, N., 2012, Casing Effect in Borehole-surface (Surface-borehole) EM Fields: 74th EAGE Conference and Exhibition Expanded Abstracts, 4–7.

———, 2014a, Energizing a Bipole Casing Electromagnetic Source - Sensitivity Analysis: , 16–19.

Cuevas, N. H., 2014b, Analytical solutions of EM fields due to a dipolar source inside an infinite casing: GEOPHYSICS, **79**, E231–E241.

Gao, G., D. Alumbaugh, P. Zhang, H. Zhang, C. Levesque, R. Rosthal, J. Liu, A. Abubakar, and T. Habashy, 2008, Practical implications of nonlinear inversion for cross-well electromagnetic data collected in cased-wells: 2008 SEG Annual Meeting, 9-14 November, Las Vegas, Nevada, 299–303.

Haber, E., 2015, Computational Methods in Geophysical Electromagnetics: Mathematics in Industry.

Hoversten, G., M. Commer, E. Haber, and C. Schwarzbach, 2014, Hydro-frac Monitoring Using Ground Time-domain EM: 76th EAGE Conference and Exhibition, 76–78.

Kang, S., R. Cockett, and L. J. Heagy, 2015, simpegEM online documentation available at http://simpegem.rtfd.org.

Liu, H., Z. Wang, and Z. He, 2008, Electromagnetic Modeling by the Volume Integral Equation Method: 70th EAGE Conference and Exhibition: Expanded Abstracts, 9–12.

Marsala, A. F., M. Al-buali, Z. Ali, M. S. Ma, Z. He, T. Biyan, G. Zhao, and T. He, 2011, First Borehole to Surface Electromagnetic Survey in KSA: Reservoir Mapping and Monitoring at a New Scale: SPE Ann. Tech. Conf. and Exhib., SPE 146348.

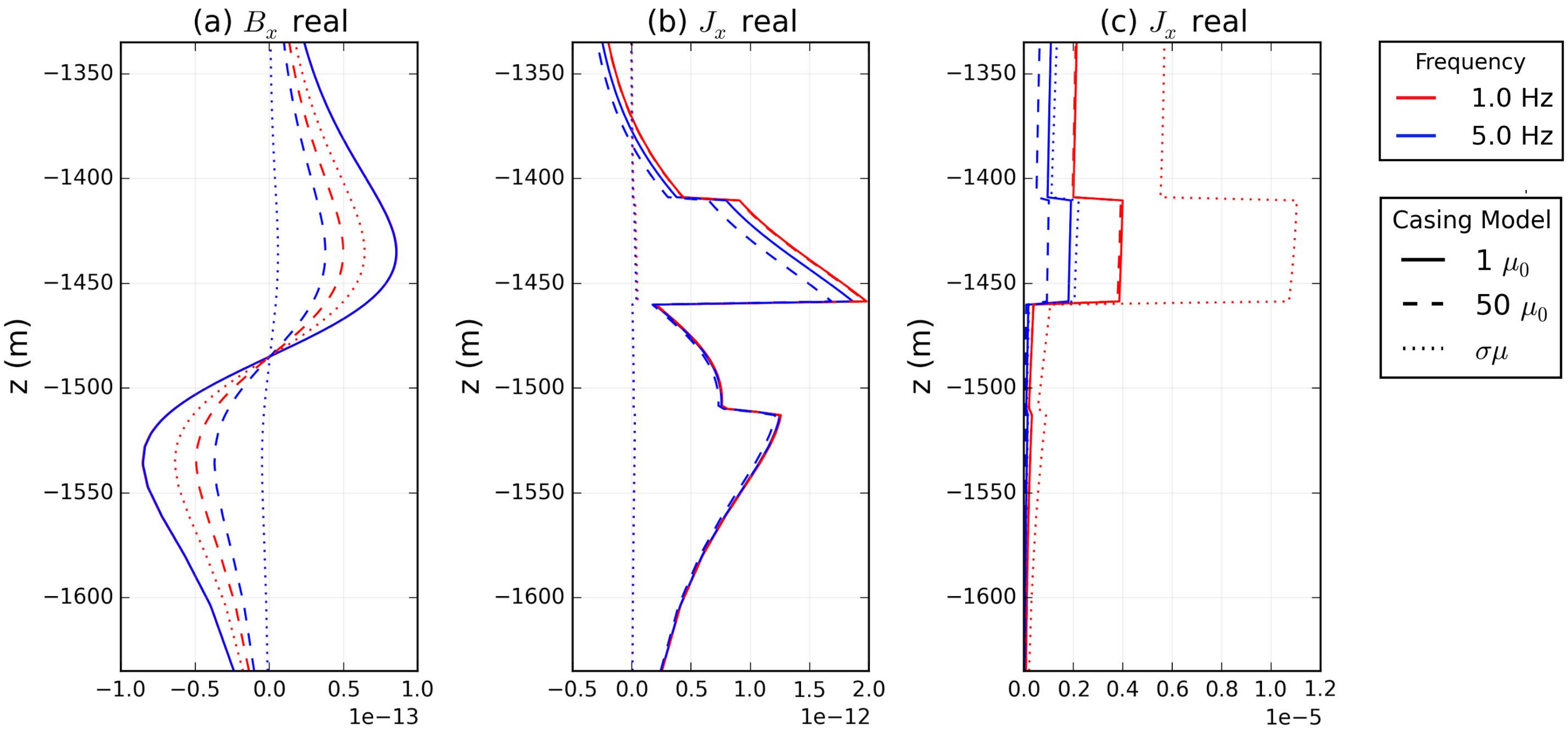
Marsala, A. F., A. D. Hibbs, and H. F. Morrison, 2014, Evaluation of Borehole Casing Sources for Electromagnetic Imaging of Deep Formations: Presented at the International Petroleum Technology Conference.

Marsala, A. F., S. Ruwaili, S. M. Ma, Z. Ali, M. Buali, S. Aramco, J. M. Donadille, S. Crary, and M. W. Schlumberger, 2008, Crosswell Electromagnetic Tomography : from Resistivity Mapping to Interwell Fluid Distribution: Distribution, 1–6.

Wilt, M. J., D. L. Alumbaugh, H. F. Morrison, a. Becker, K. H. Lee, and M. DeszczPan, 1995, Crosswell electromagnetic tomography: System design considerations and field results: Geophysics, **60**, 871–885.

Wu, X., and T. M. Habashy, 1994, Influence of steel casings on electromagnetic signals: Geophysics, **59**, 378.

Using Conductivity Permeability product



SCRAPS

Approaching the Inverse Problem

- Inversion model is $\boxed{\text{conductivity}}$

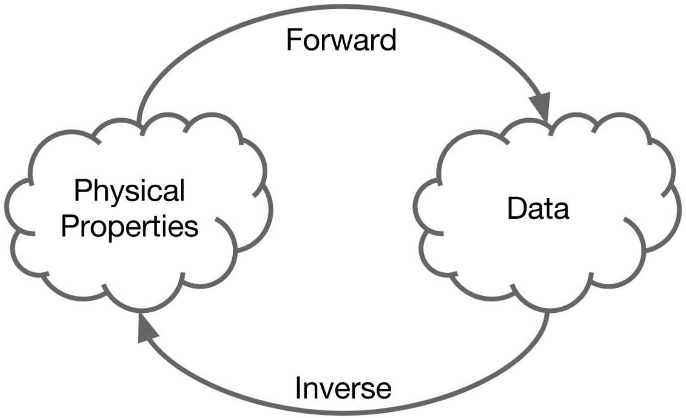
Model dependence on RHS
→ need to include in sensitivities

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

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

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

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

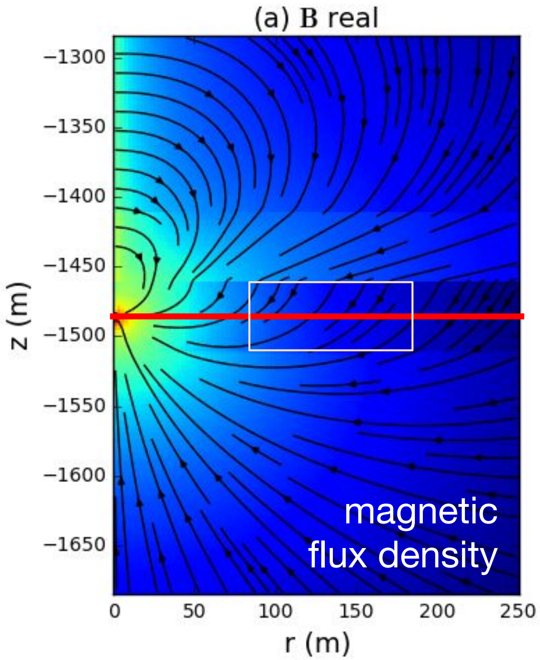


Primary-Secondary: 3D geology (magnetic dipole)

Primary:

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

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



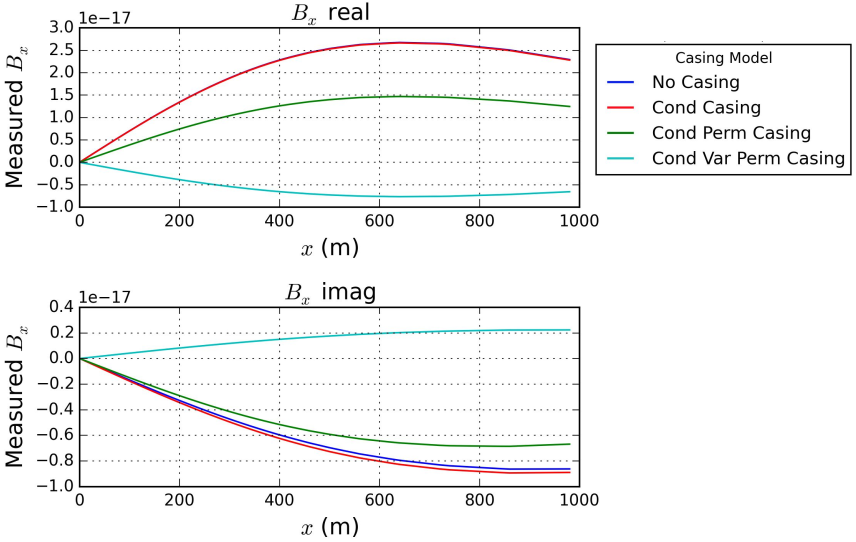
Interpolate

Secondary:

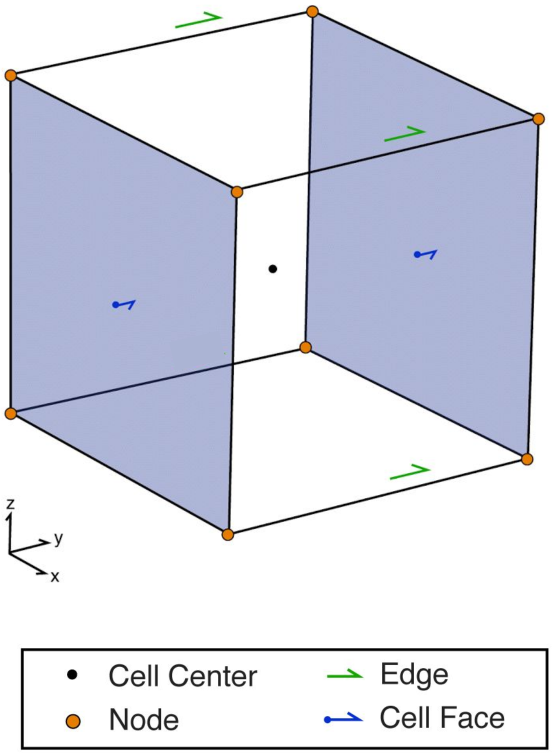
$$\nabla \times \mathbf{E_s} + i\omega \mathbf{B_s} = 0$$

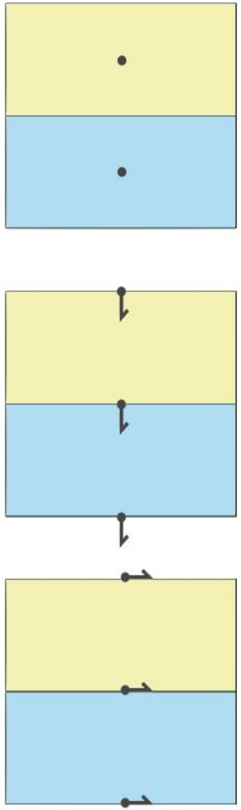
$$\nabla \times \mu^{-1} \mathbf{B_s} - \sigma \mathbf{E_s} = \tilde{\mathbf{q}}$$

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



Mimetic Finite Volume Forward Modelling





- Physical Properties
  - σ electrical conductivity
  - μ magnetic permeability

Cell Center

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

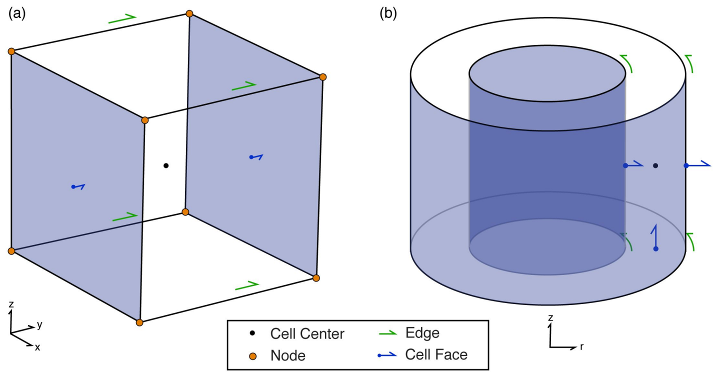
Cell Face

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

Edge

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

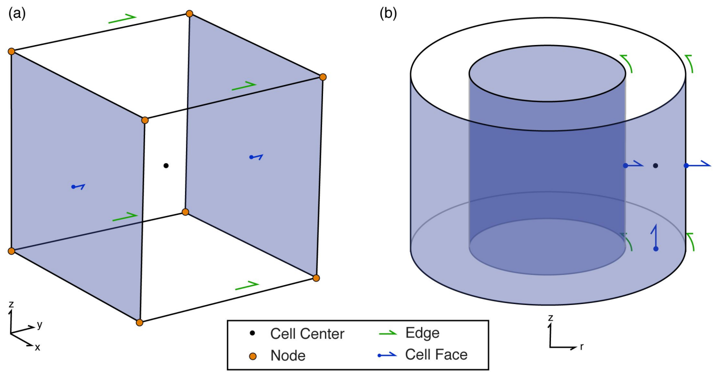
Primary: Modelling the Casing

- 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

- T



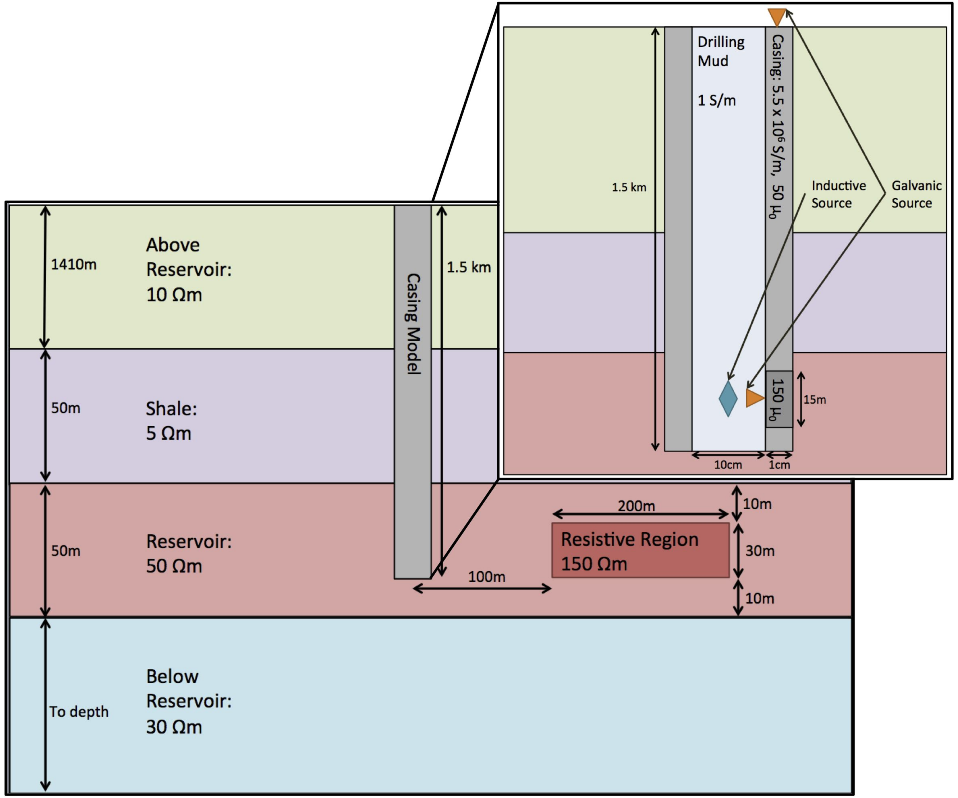
E-B: magnetic source	H-J: electric source
$\nabla \times \vec{E} + i\omega\vec{B} = 0$ $\nabla \times \mu^{-1}\vec{B} - \sigma\vec{E} = \vec{s}$	$\nabla \times \rho\vec{J} + i\omega\mu\vec{H} = 0$ $\nabla \times \vec{H} - \vec{J} = \vec{s}$

Electromagnetics in settings with cased wells

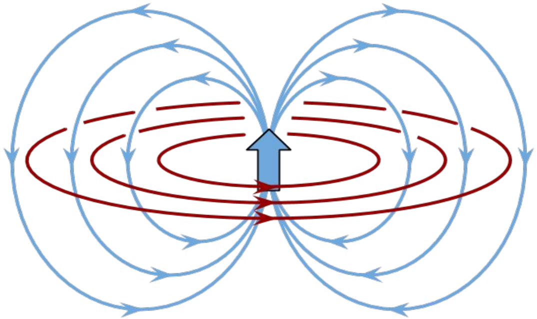
- ***Why EM?***
  - Electrical conductivity can be diagnostic
- ***Cased Wells***
  - significant contributor to signal
  - challenging features to model
    - geometry
    - conductivity contrast

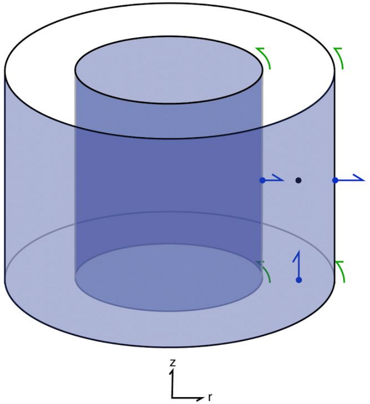
How do we model in settings with cased wells?

Inverse Problem?



Primary: Cylindrical Symmetry - Summary



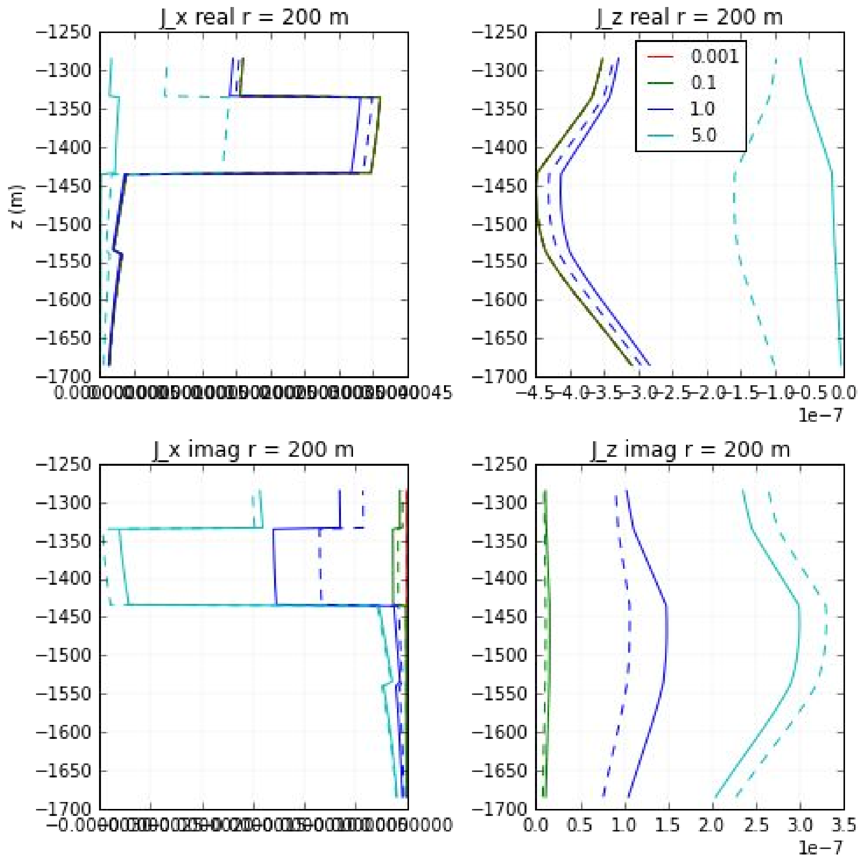


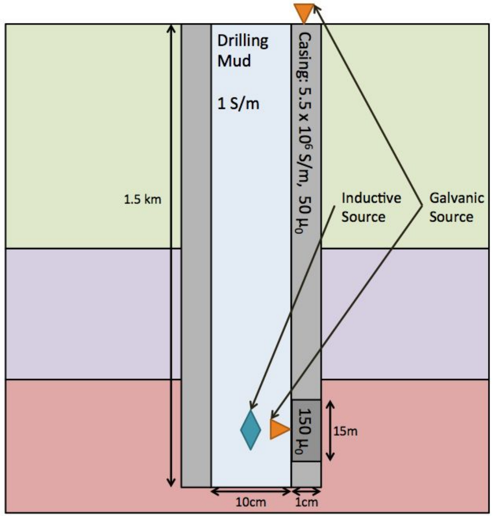
Two Formulations of Maxwell:

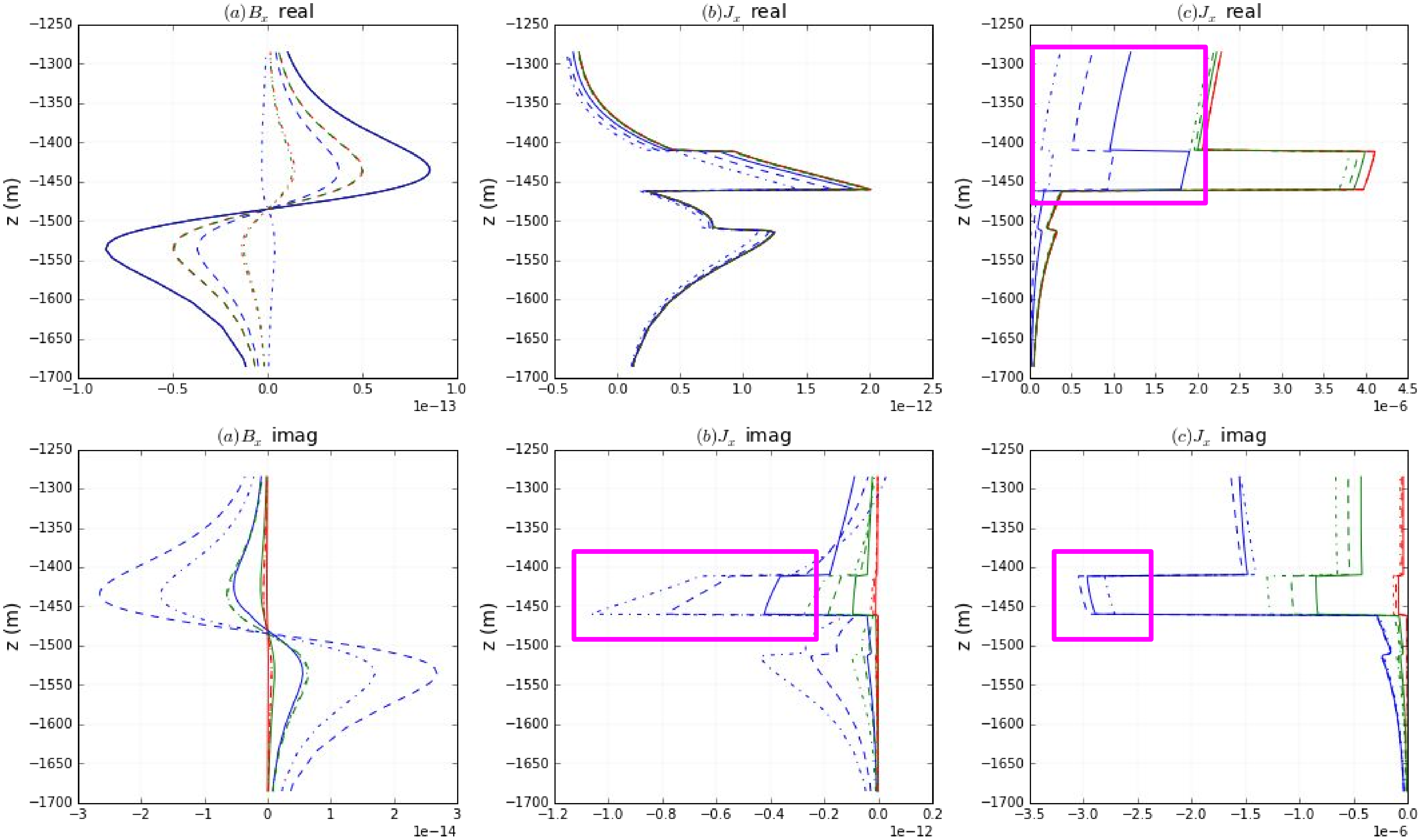
E-B: magnetic source	H-J: electric source
$\nabla \times \vec{E} + i\omega\vec{B} = 0$ $\nabla \times \mu^{-1}\vec{B} - \sigma\vec{E} = \vec{s}$	$\nabla \times \rho\vec{J} + i\omega\mu\vec{H} = 0$ $\nabla \times \vec{H} - \vec{J} = \vec{s}$

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

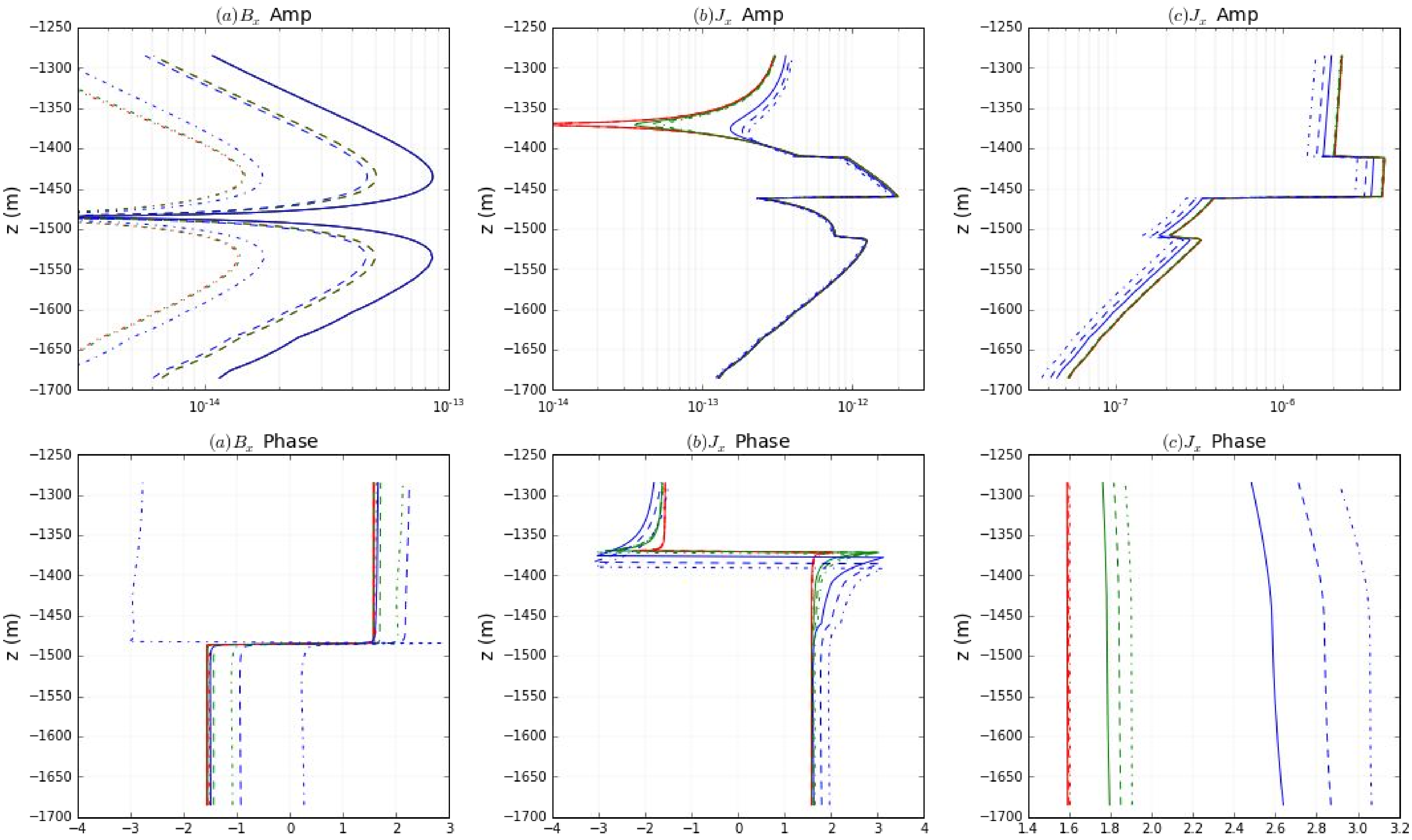
Examples: Surface Electric Src





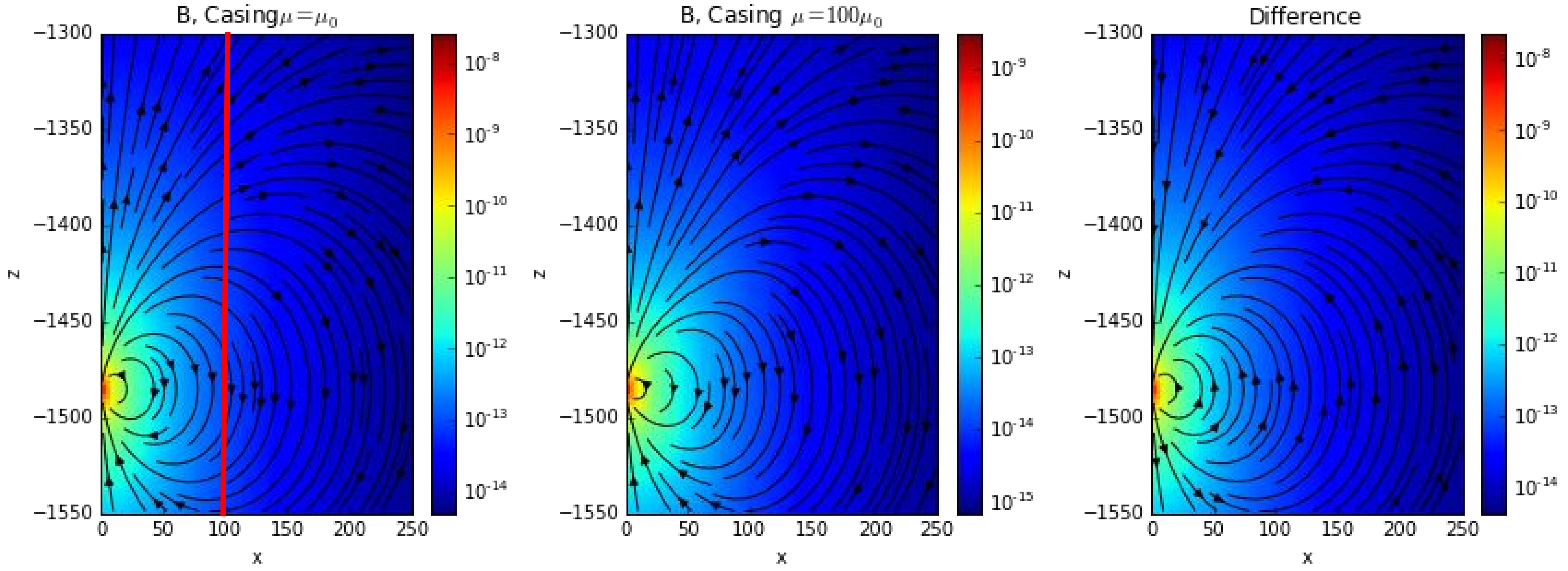


$(a) B_x$ real
$(b) J_x$ real
$(c) J_x$ real
$(a) B_x$ imag
$(b) J_x$ imag
$(c) J_x$ imag
z (m)
1e-13
1e-12
1e-6
1e-14
1e-12
1e-6

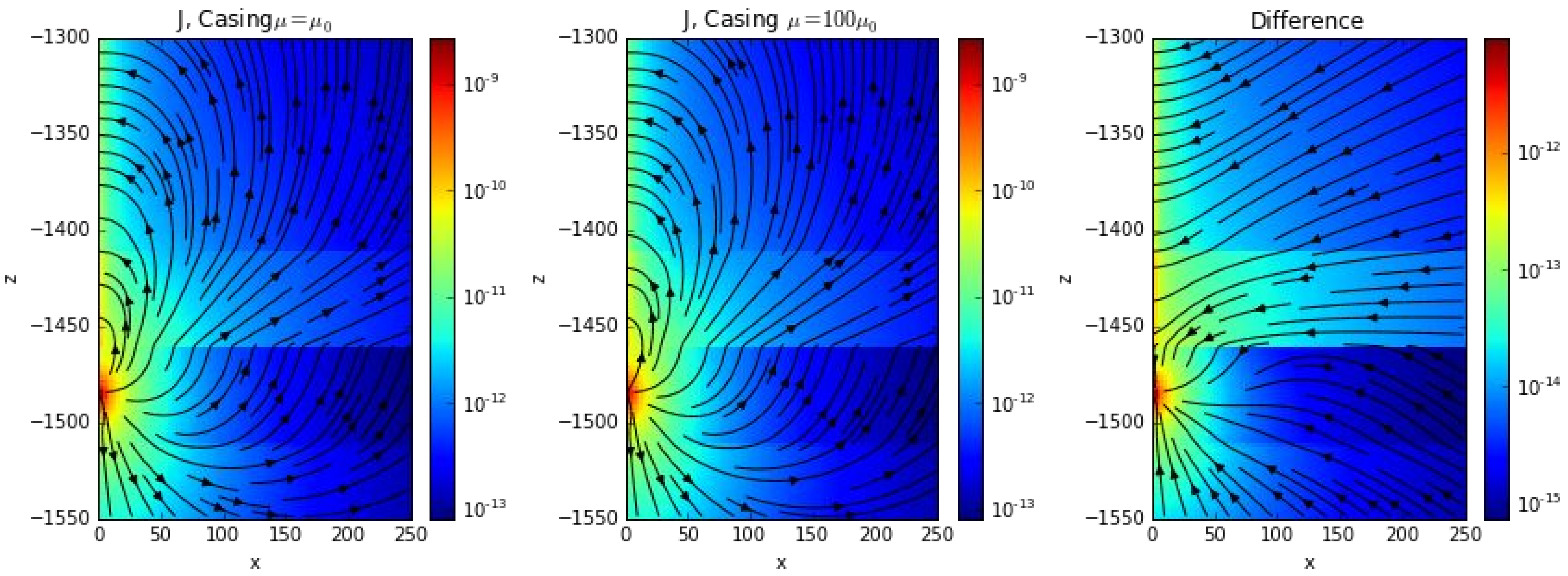


$(a) B_x$ Amp
$(b) J_x$ Amp
$(c) J_x$ Amp
$(a) B_x$ Phase
$(b) J_x$ Phase
$(c) J_x$ Phase
z (m)

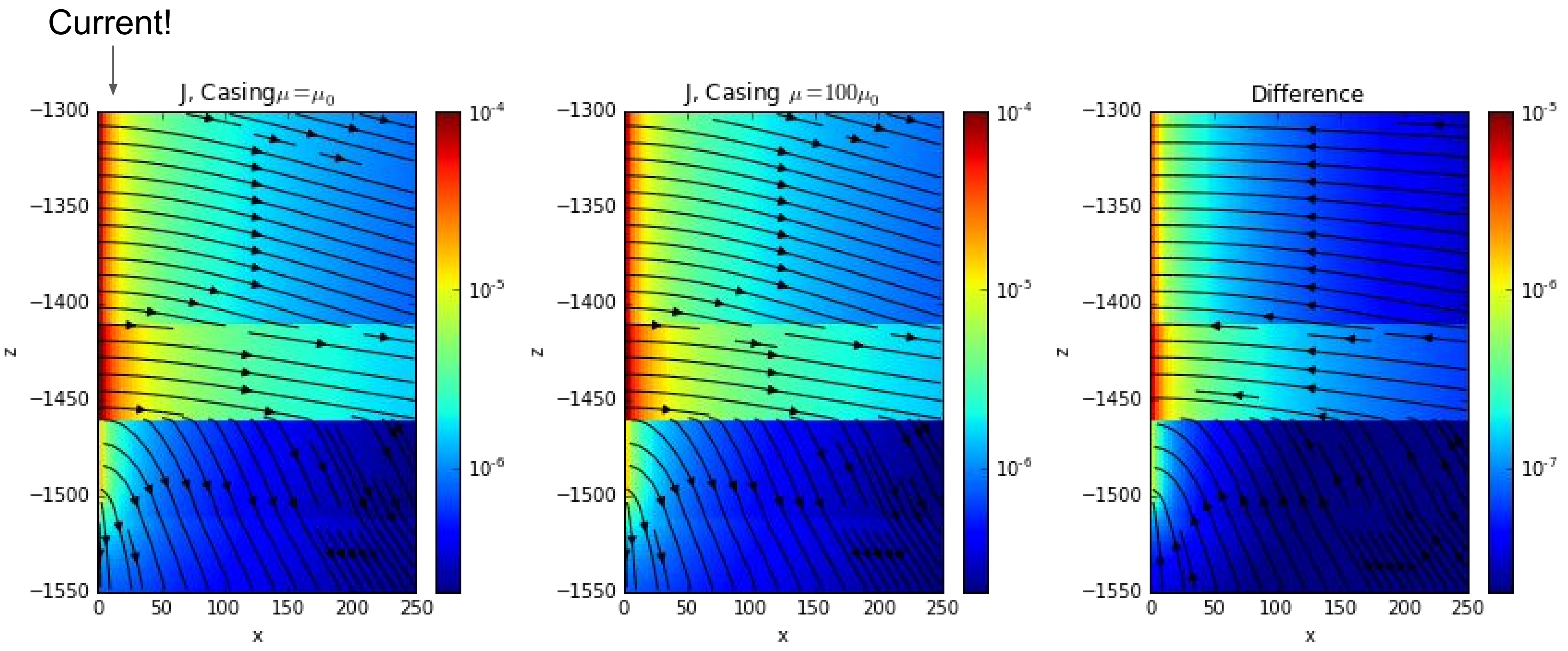
Examples: Downhole Magnetic Dipole



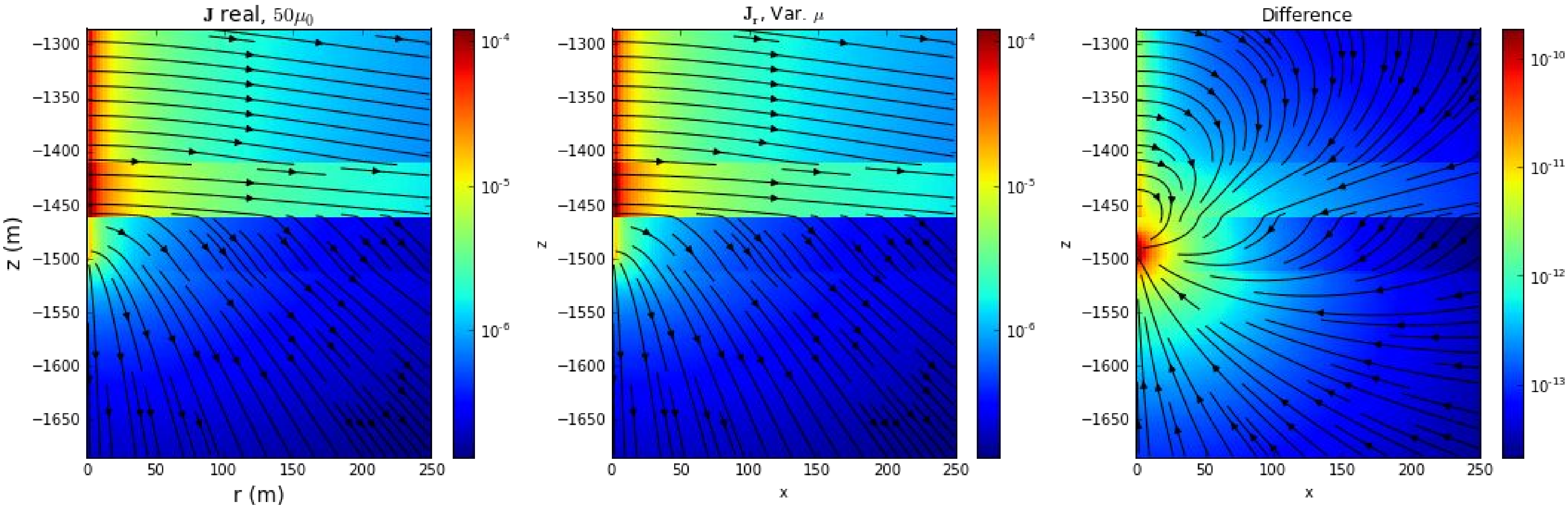
Down hole E src Couple to casing



Examples: Surface Electric Sc



Variable Magnetic Permeability



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?