Impacts of magnetic permeability on electromagnetic data collected in settings with steel-cased wells

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University of British Columbia - Geophysical Inversion Facility

3DEM-7 Symposium

motivation

CO_2 sequestration

geothermal

hydrocarbons

wastewater injection

wellbore integrity

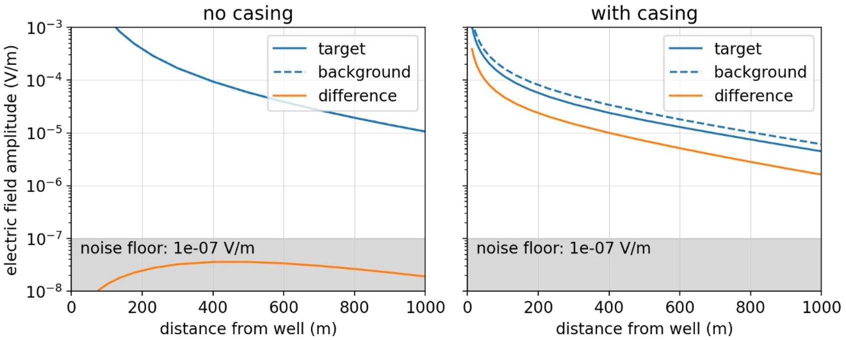
geophysics in urban settings

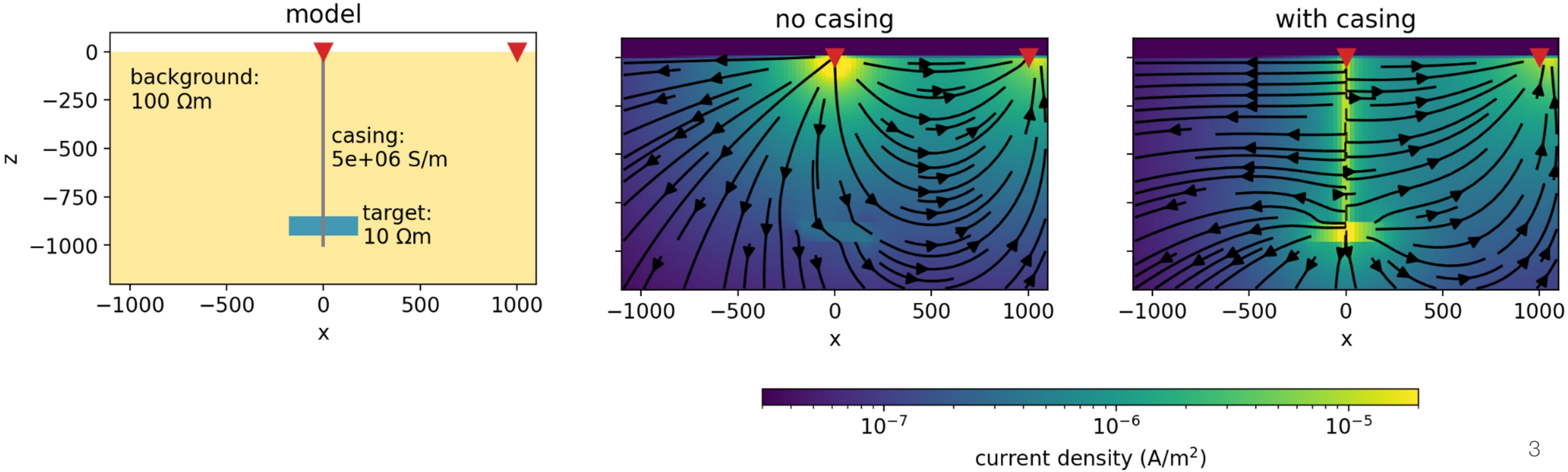
…

grounded source experiments

steel: highly conductive, magnetic

helps excite & detect targets at depth

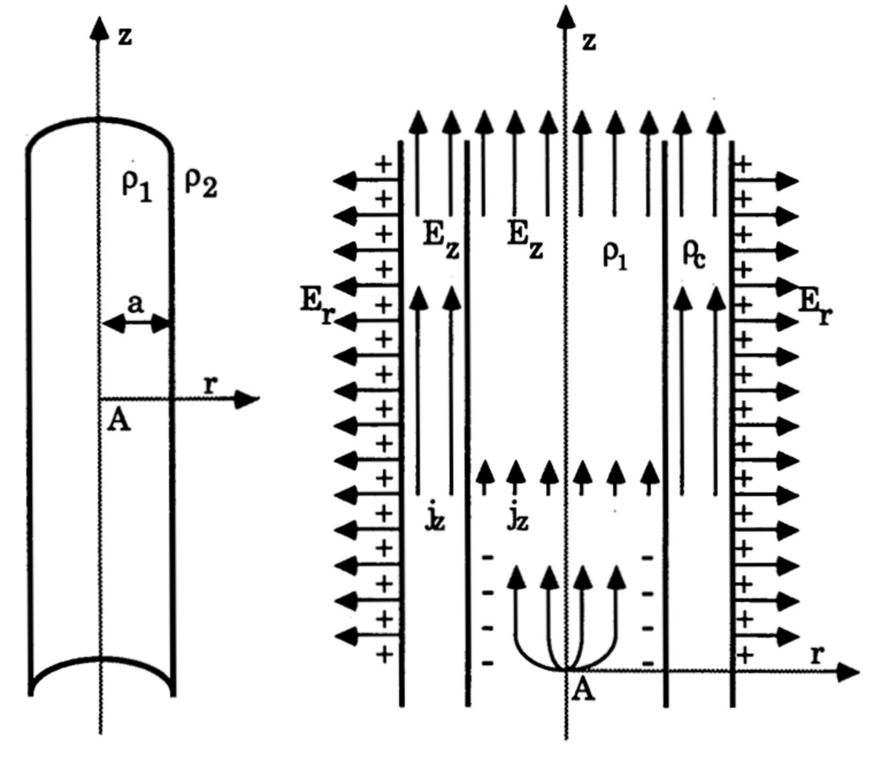




GEOPHYSICS, VOL. 55, NO. 1 (JANUARY 1990);

The electrical field in a borehole with a casing

Alexander A. Kaufman*



(a) (b)

GEOPHYSICS, VOL. 58, NO. 12 (DECEMBER 1993);

A transmission-line model for electrical logging through casing

Alexander A. Kaufman* and W. Edward Wightman‡

Case one, $\alpha L_c \ll 1$

Then, for the current I we have:

$$I(z) \approx I_o\left(1 - \frac{z}{L_c}\right), \tag{45}$$

showing that the current linearly decreases with the distance.

Case two, $\alpha L_c \gg 1$

where $z/L \ll 1$, and

$$\Delta\Delta U = \frac{I_o}{S}\,\alpha(MN)^2 e^{-\alpha z}, \tag{54}$$

that is, all functions decay exponentially with the distance from the electrode A.

GEOPHYSICS, VOL. 59, NO. 7 (JULY 1994);

Electrical resistivity measurement through metal casing

Clifford J. Schenkel* and H. Frank Morrison‡

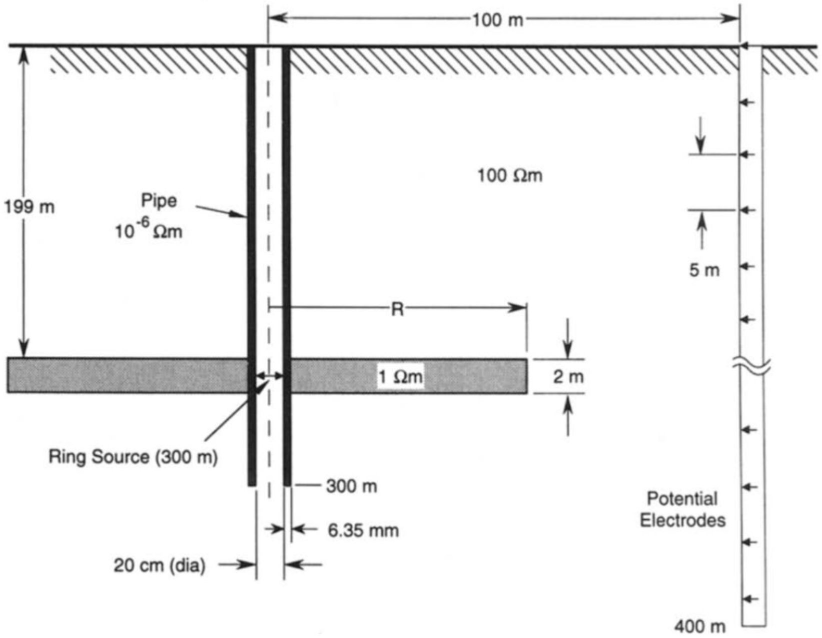


FIG. 13. Configuration for the crosshole resistivity monitoring simulation of an injection process.

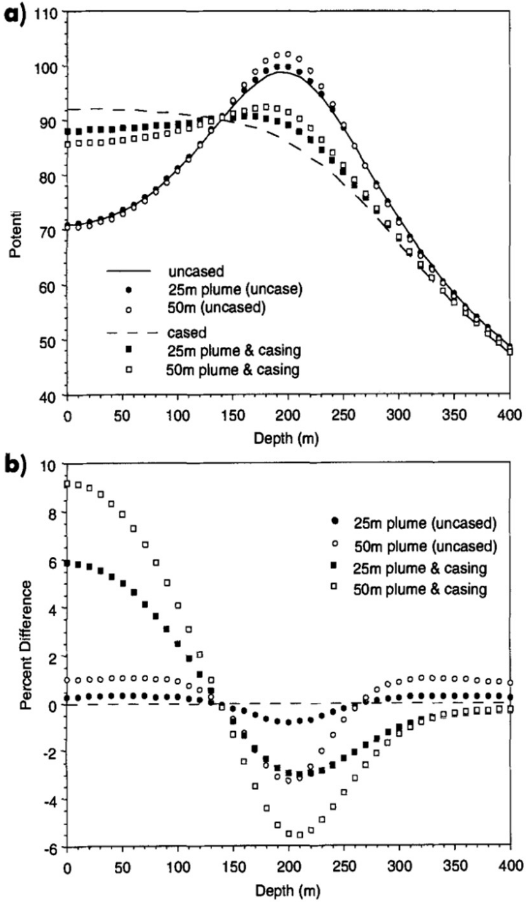


FIG. 14. Plots of the potentials (a) and percent difference between the background and injection potentials (b) for plume only (circles) and plume/casing (squares) for 25 m (black) and 50 m (white) plumes. The pre-injection potentials are the dashed lines (with casing) and solid lines (without casing).

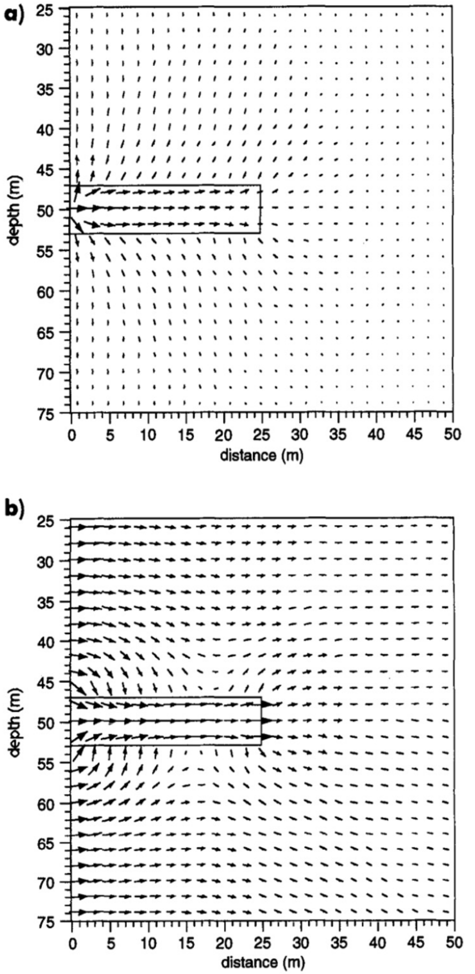
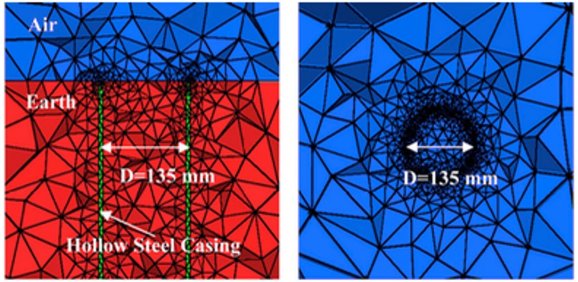


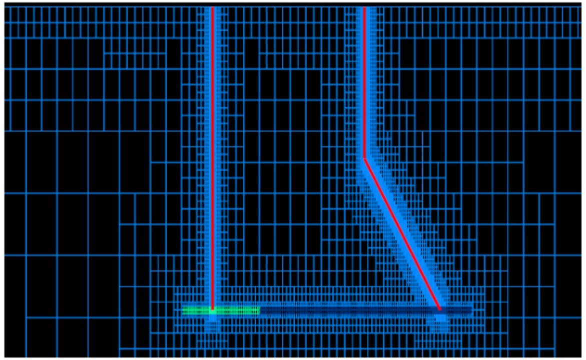
FIG. 15. Current patterns in the medium and conductive plume for the mise-à-la-masse, point source in an uncased hole, (a) and energized casing (b) configurations.

more recently… advances in modelling

highly refined meshes

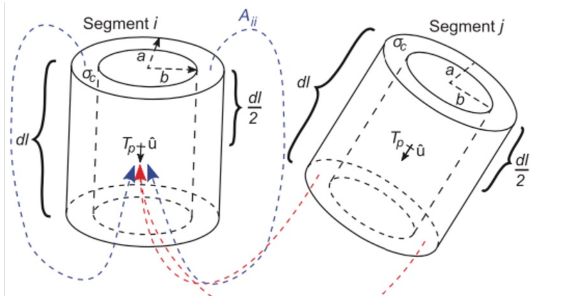


Um et al., (2015)



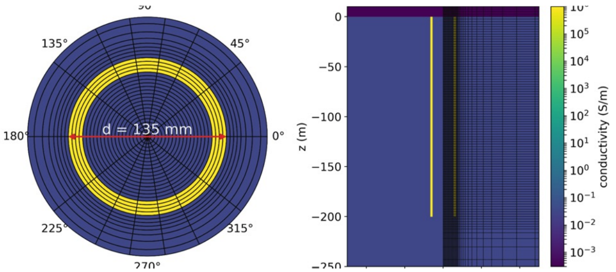
Haber et al., (2016)

method of moments



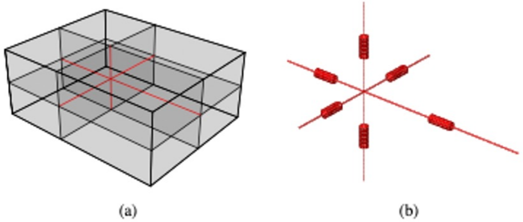
Tang et al., (2014), Kohnke et al., (2015)
Patzer et al., (2017)

cylindrical meshes

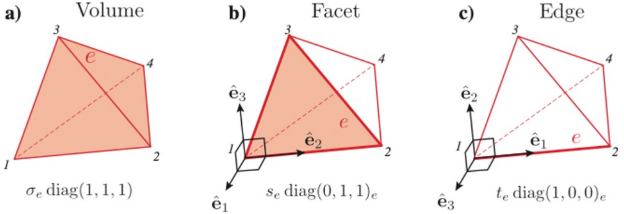


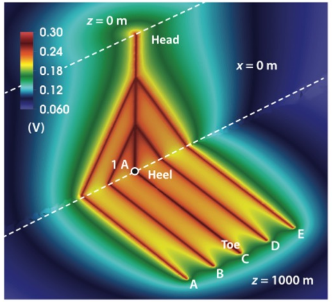
Heagy & Oldenburg (2019)

discretizing on edges, faces



Yang et al., (2016); Hu et al., (2022)

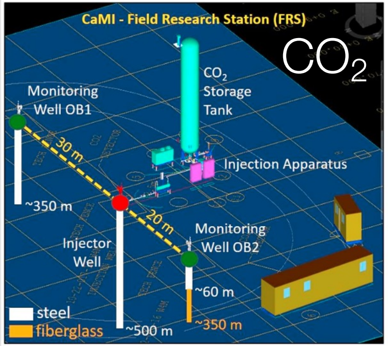


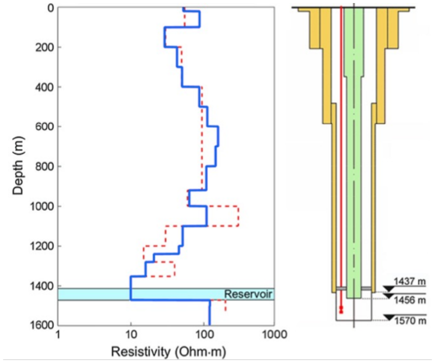


Weiss, (2017)

more recently… a number of applications

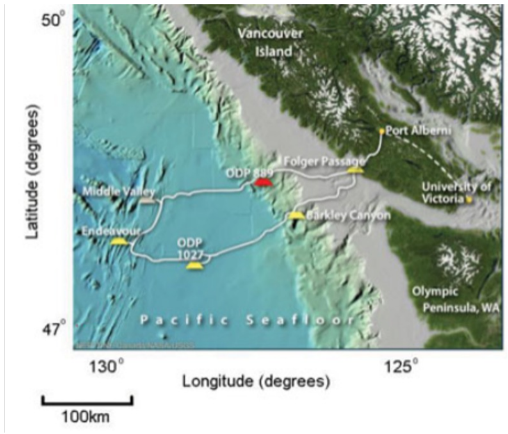
monitoring





Puzyrev et al., (2017); Um et al., (2020); Weiss et al., (2022) …

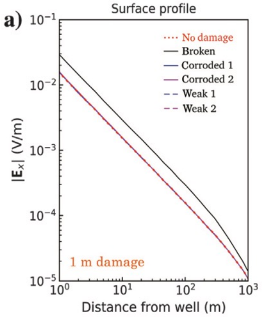
gas hydrates, hydrocarbons

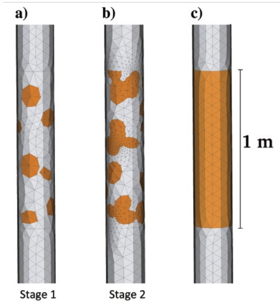


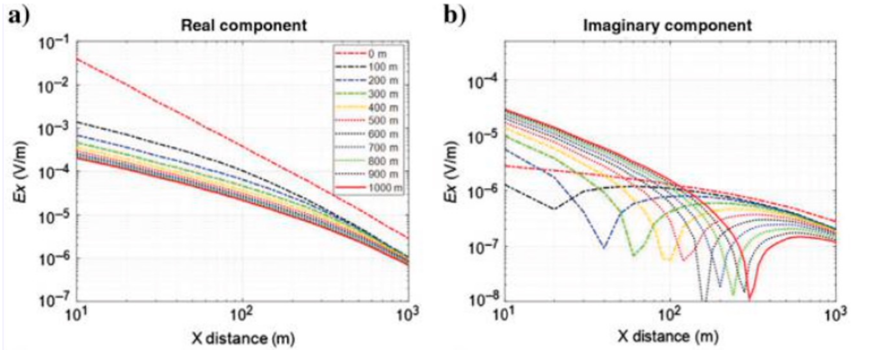
Pardo et al., (2018), Cuevas & Pezzoli (2022); Swidinsky et al., (2023)…

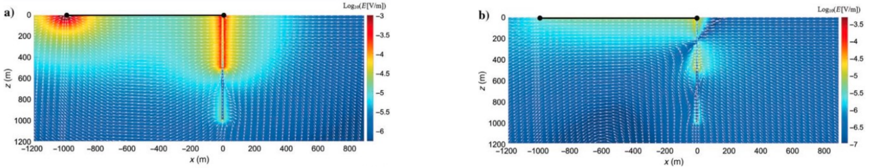
casing integrity

Beskardes, et al, (2021); Wilt, et al, (2020)









steel casings & electromagnetics

steel: highly conductive, magnetic

$$\sigma : 5.5 \times 10^6 \ \mathrm{S/m}$$
$$\mu : 50\mu_0 \text{ to } 150\mu_0$$

Wu & Habashy (1994)

high conductivity:

- helps channel currents to depth
- strategies for simulating

magnetic permeability

?

time domain

$$\nabla \times \vec{e} = -\frac{\partial \vec{b}}{\partial t}$$
$$\nabla \times \vec{h} = \vec{j} + \frac{\partial \vec{d}}{\partial t}$$

$$\vec{j} = \sigma \vec{e}$$
$$\vec{b} = \mu \vec{h}$$
$$\vec{d} = \varepsilon \vec{e}$$

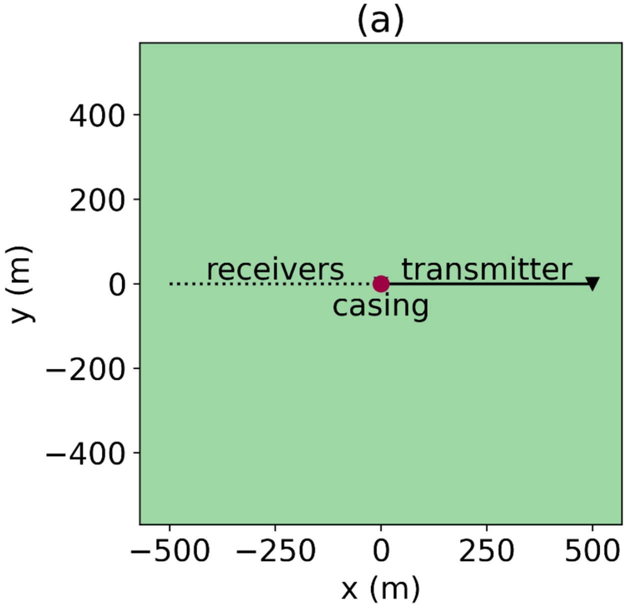
frequency domain

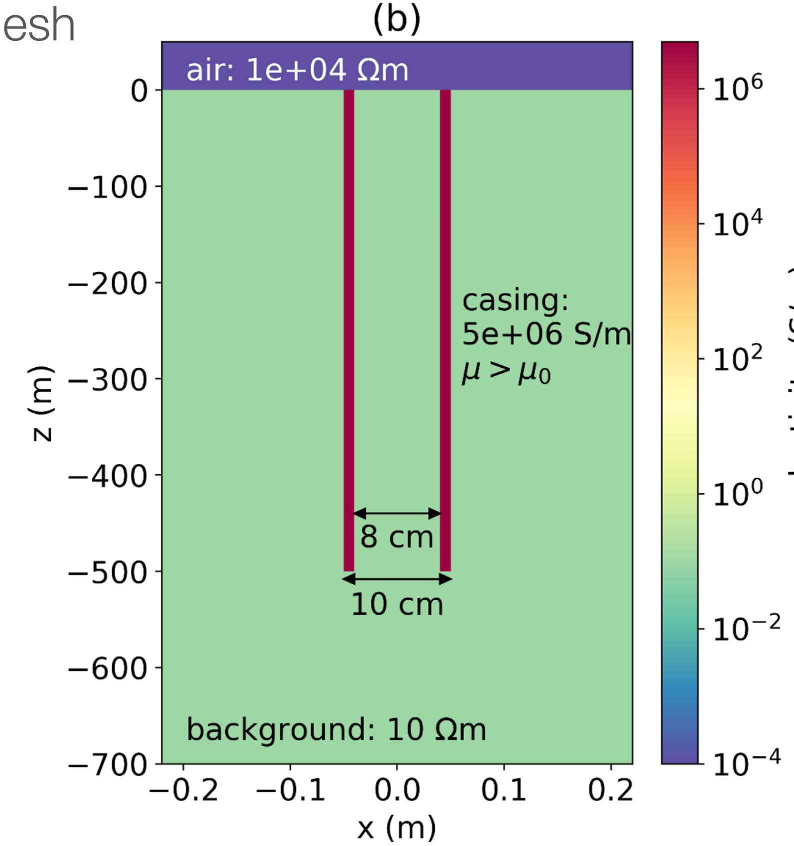
$$\nabla \times \vec{E} = -i\omega \vec{B}$$
$$\nabla \times \vec{H} = \vec{J} + i\omega \vec{D}$$

$$\vec{J} = \sigma \vec{E}$$
$$\vec{B} = \mu \vec{H}$$
$$\vec{D} = \varepsilon \vec{E}$$

setup: grounded source experiment

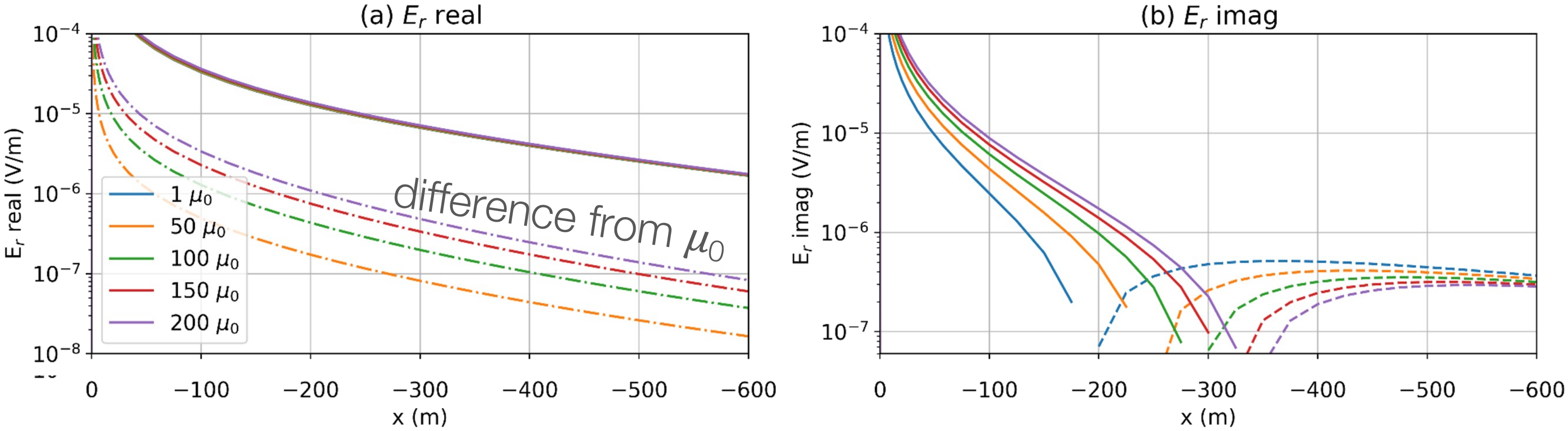
simulate with SimPEG 3D cylindrical mesh





impacts of permeability on EM data

FDEM: 5Hz



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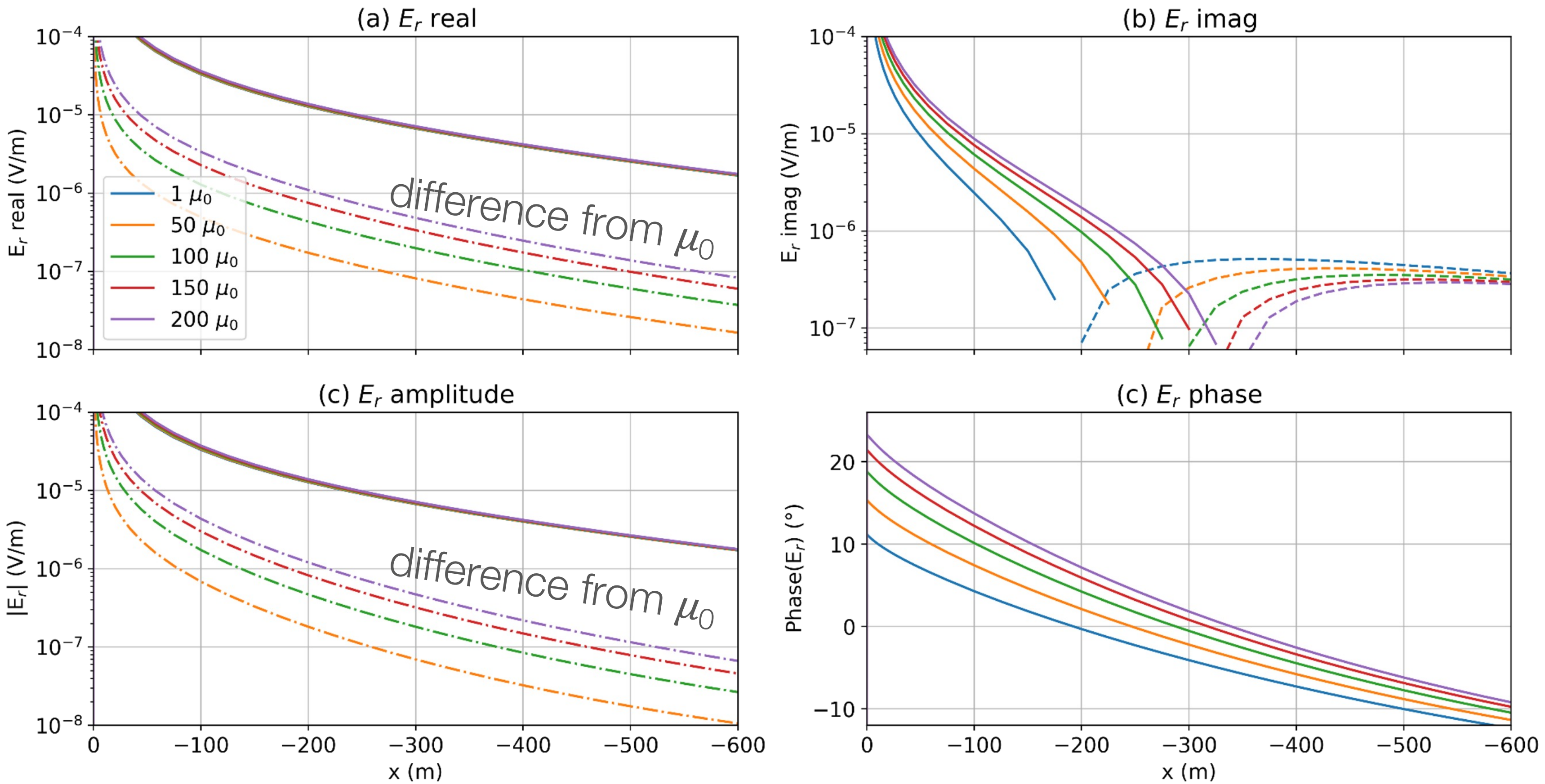

impacts of permeability on EM data

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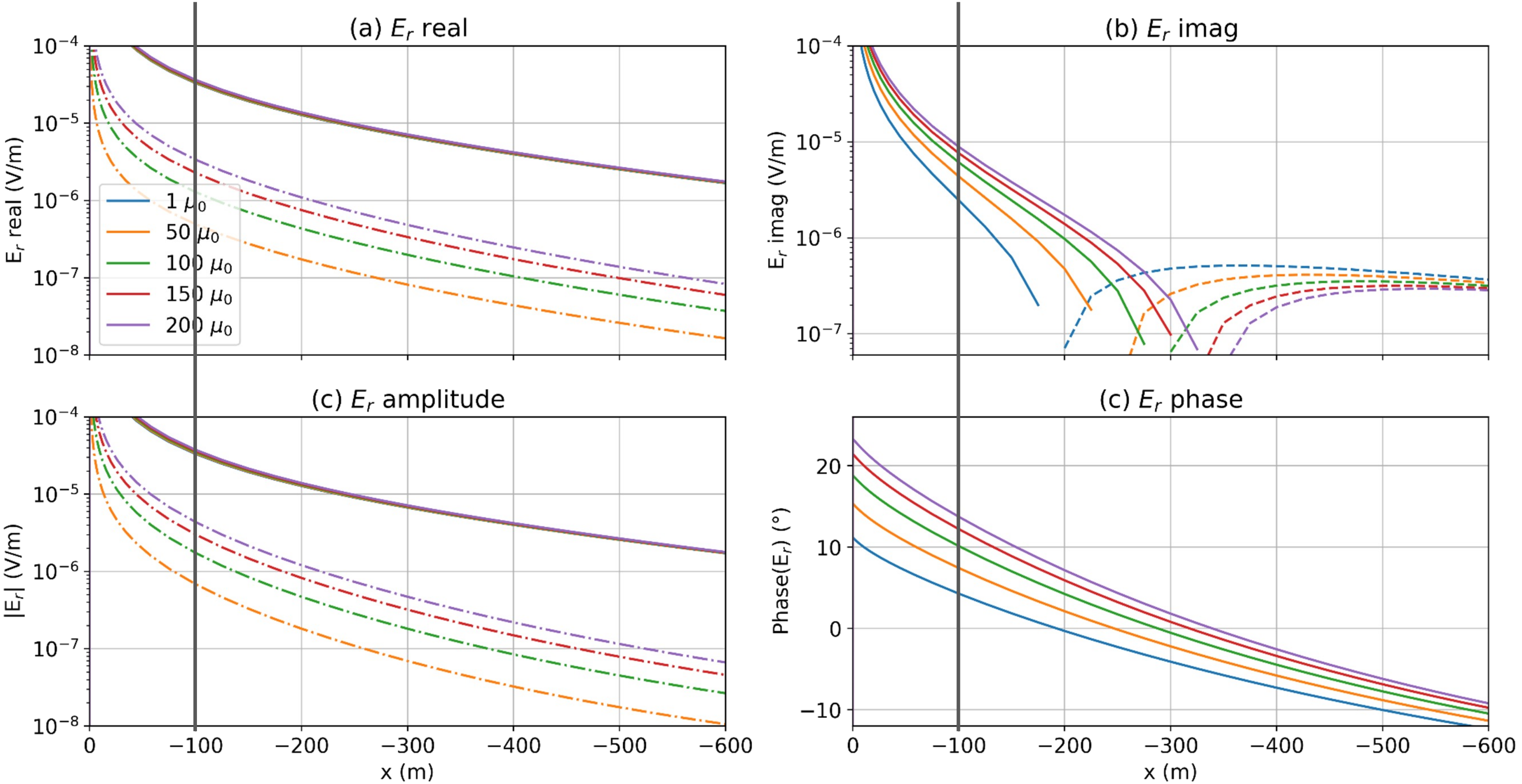
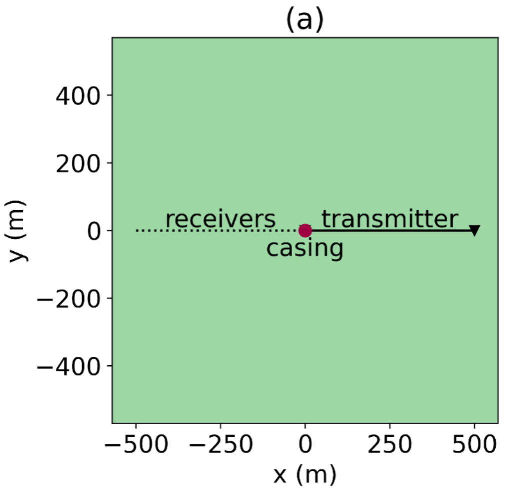
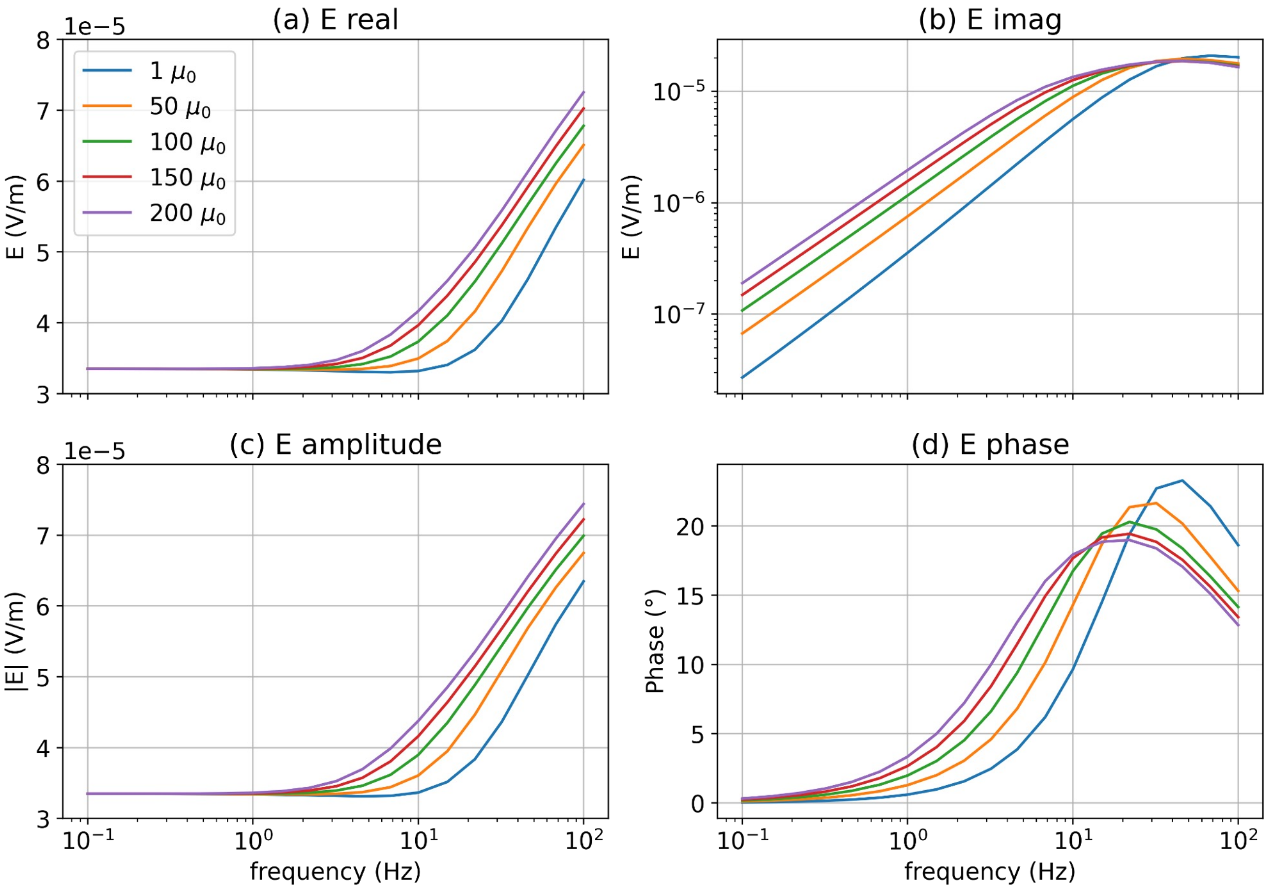


impacts of permeability on EM data

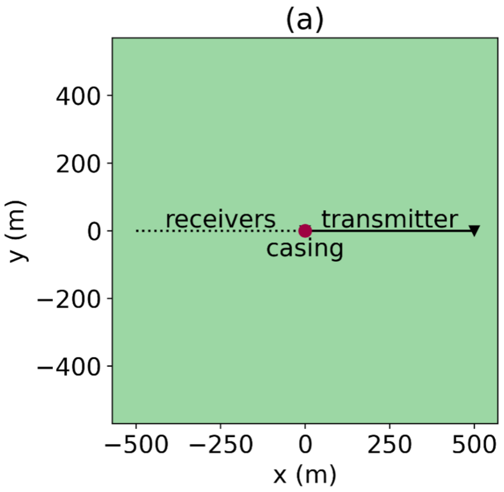
FDEM: 100m

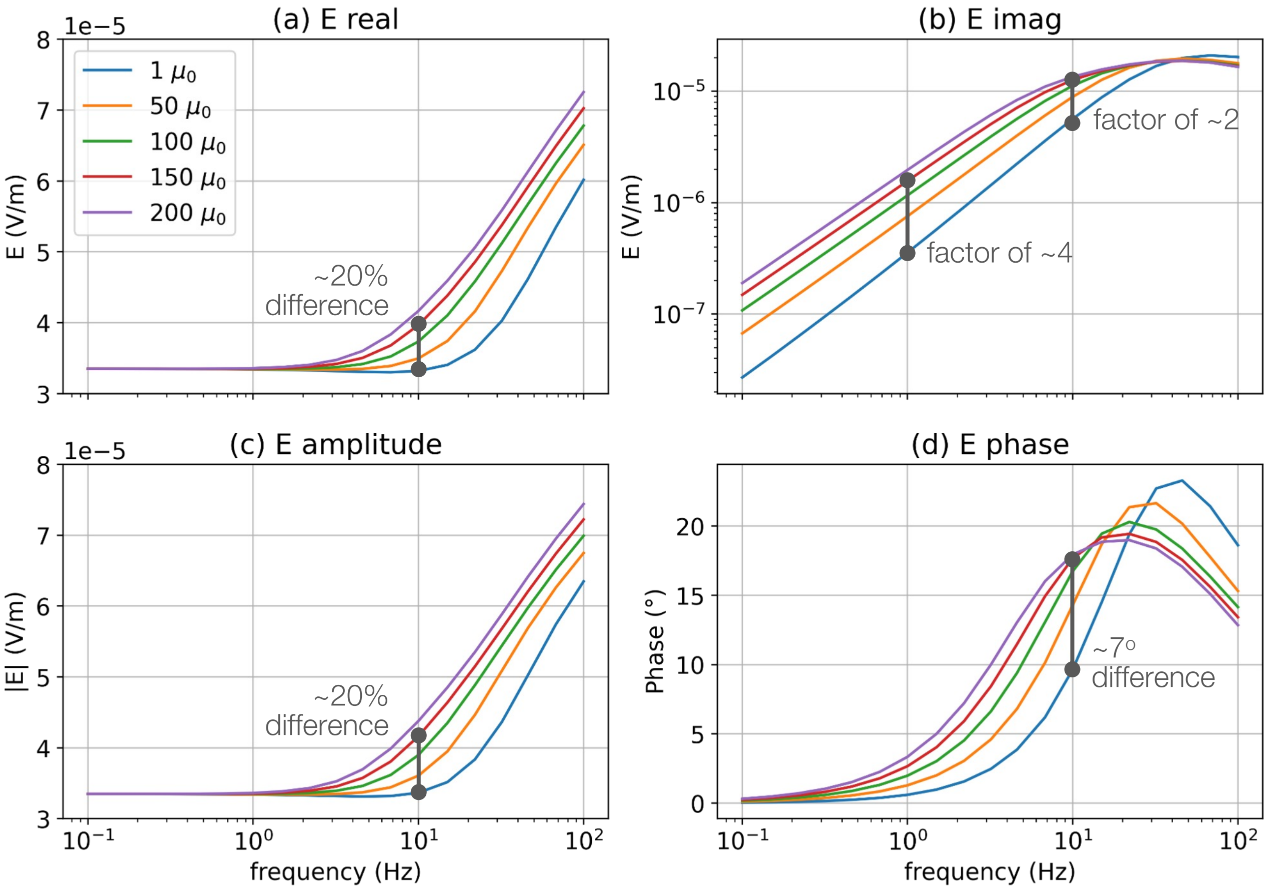




impacts of permeability on EM data

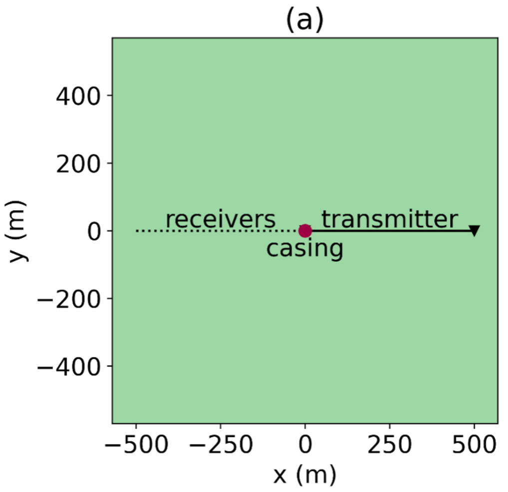
FDEM: 100m

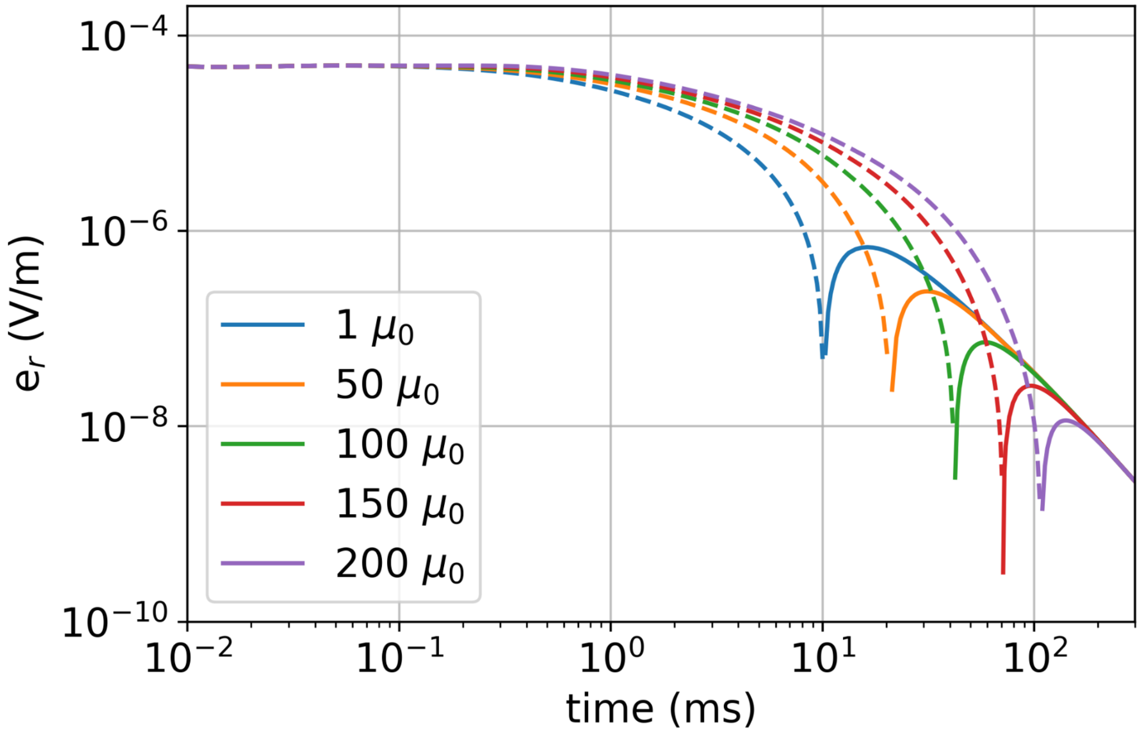




impacts of permeability on EM data

TDEM

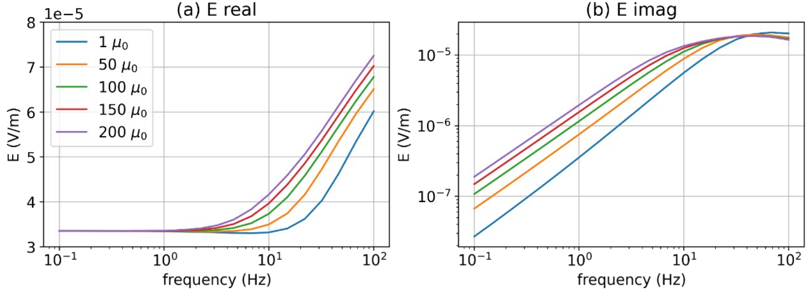




magnetic permeability in electromagnetic experiments

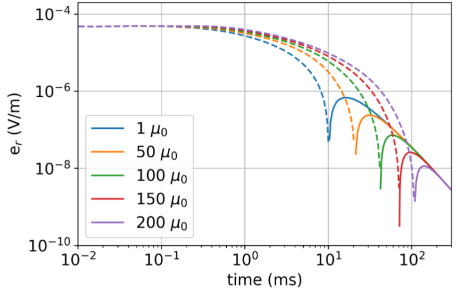
In frequency domain

- notable impact even at “low” frequencies



In time-domain

- delays the decay



impacts of μ have been studied in other applications…

Noh et al., (2016)

Frequency domain, inductive sources

Use integral formulation to describe role of permeability in terms of

- induction

$$\mathbf{H}_S^I(\mathbf{r}) = \int_V \left[\Delta\sigma(\mathbf{r}')\left\{\mathbf{E}_P(\mathbf{r}') + \mathbf{E}_S^{\mathrm{I}}(\mathbf{r}')\right\} \cdot \mathbf{G}_J^H(\mathbf{r}, \mathbf{r}')\right] \mathrm{d}V,$$

- magnetization

$$\mathbf{H}_S^M(\mathbf{r}) = \int_V \left[\frac{\Delta\mu(\mathbf{r}')}{\mu_0}\left\{\mathbf{H}_P(\mathbf{r}') + \mathbf{H}_S^{\mathrm{M}}(\mathbf{r}')\right\} \cdot \mathbf{G}_M^H(\mathbf{r}, \mathbf{r}')\right] \mathrm{d}V,$$

- and coupling effects

$$\mathbf{H}_S^C(\mathbf{r}) = \int_V \left[\Delta\sigma(\mathbf{r}')\left\{\mathbf{E}_S^{\mathrm{M}}(\mathbf{r}') + \mathbf{E}_S^{\mathrm{C}}(\mathbf{r}')\right\} \cdot \mathbf{G}_J^H(\mathbf{r}, \mathbf{r}') + \frac{\Delta\mu(\mathbf{r}')}{\mu_0}\left\{\mathbf{H}_S^{\mathrm{I}}(\mathbf{r}') + \mathbf{H}_S^{\mathrm{C}}(\mathbf{r}')\right\} \cdot \mathbf{G}_M^H(\mathbf{r}, \mathbf{r}')\right] \mathrm{d}V.$$

Geophysical Journal International

Geophys. J. Int. (2016) **204,** 1550–1564 doi: 10.1093/gji/ggv537
GJI Marine geosciences and applied geophysics

Analysis of anomalous electrical conductivity and magnetic permeability effects using a frequency domain controlled-source electromagnetic method

Kyubo Noh,[1] Seokmin Oh,[1] Soon Jee Seol,[1] Ki Ha Lee[2] and Joongmoo Byun[1]

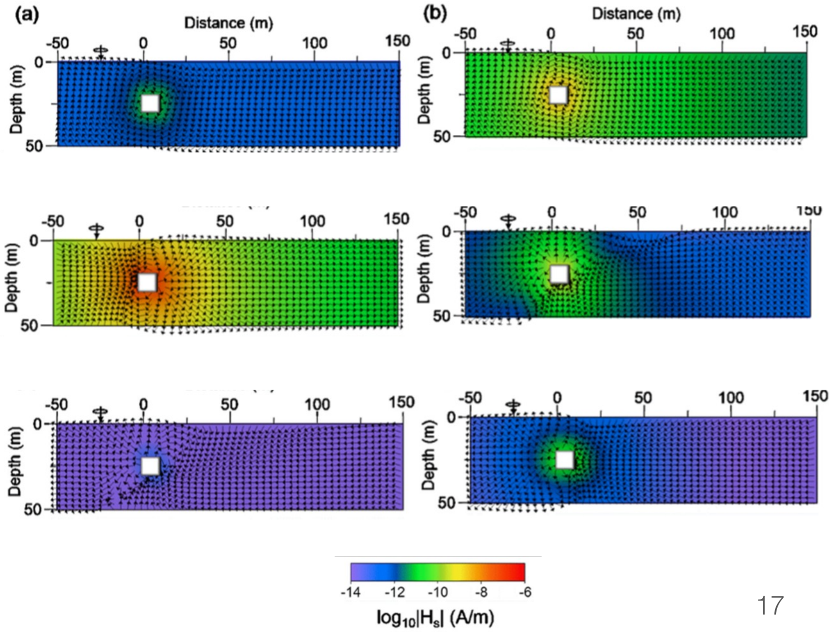
[1] *Department of Earth Resources and Environmental Engineering, Hanyang University, 222 Wangsimni-Ro, Seongdong-gu, 133–791, Seoul, Korea. E-mail: ssjdoolly@hanyang.ac.kr*
[2] *Exploration Geophysics & Mining Engineering Department, Korea Institute of Geoscience and Mineral Resources (KIGAM), 124 Gwahang-no, Yuseong-gu, 305–350, Daejeon, Korea*

anomalous real   anomalous imag

inductive

magnetization

coupling



Pavlov & Zhdanov (2001)

Time domain, inductive sources

Rewrite the Maxwell's equations

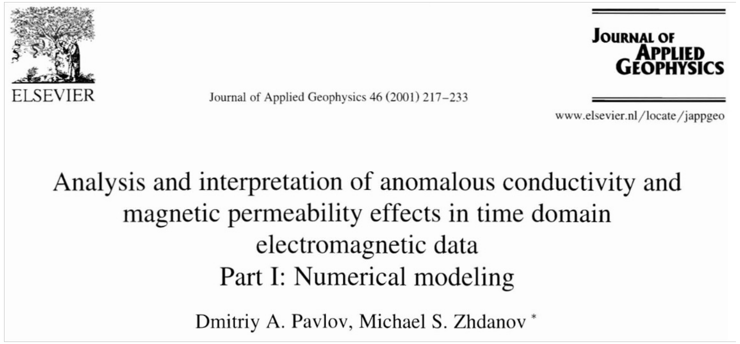
$$\nabla \times (\nabla \times E) - \underline{\nabla \ln \mu_r} \times (\nabla \times E) + \underline{\mu_0 \mu_r \sigma} \frac{\partial E}{\partial t} = - \mu_0 \mu_r \frac{\partial j^e}{\partial t} .$$

(1) contribution due to magnetization

(2) contribution to inductive component

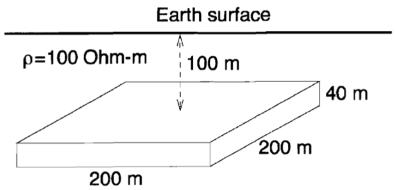
Two conclusions. Anomalous permeability…

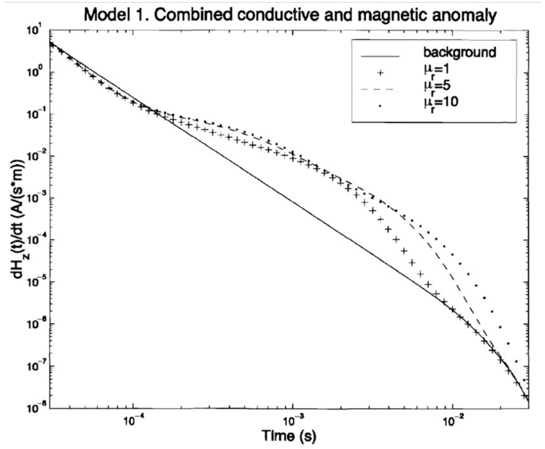
- prolongs anomalous TDEM response
- increases response as compared to only conductive target


ELSEVIER
Journal of Applied Geophysics 46 (2001) 217–233
JOURNAL OF APPLIED GEOPHYSICS
www.elsevier.nl/locate/jappgeo

Analysis and interpretation of anomalous conductivity and magnetic permeability effects in time domain electromagnetic data
Part I: Numerical modeling

Dmitriy A. Pavlov, Michael S. Zhdanov *





magnetic permeability in electromagnetic experiments

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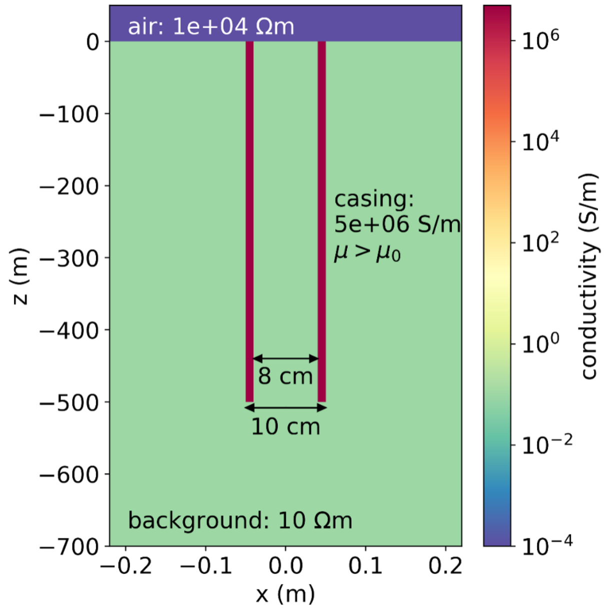
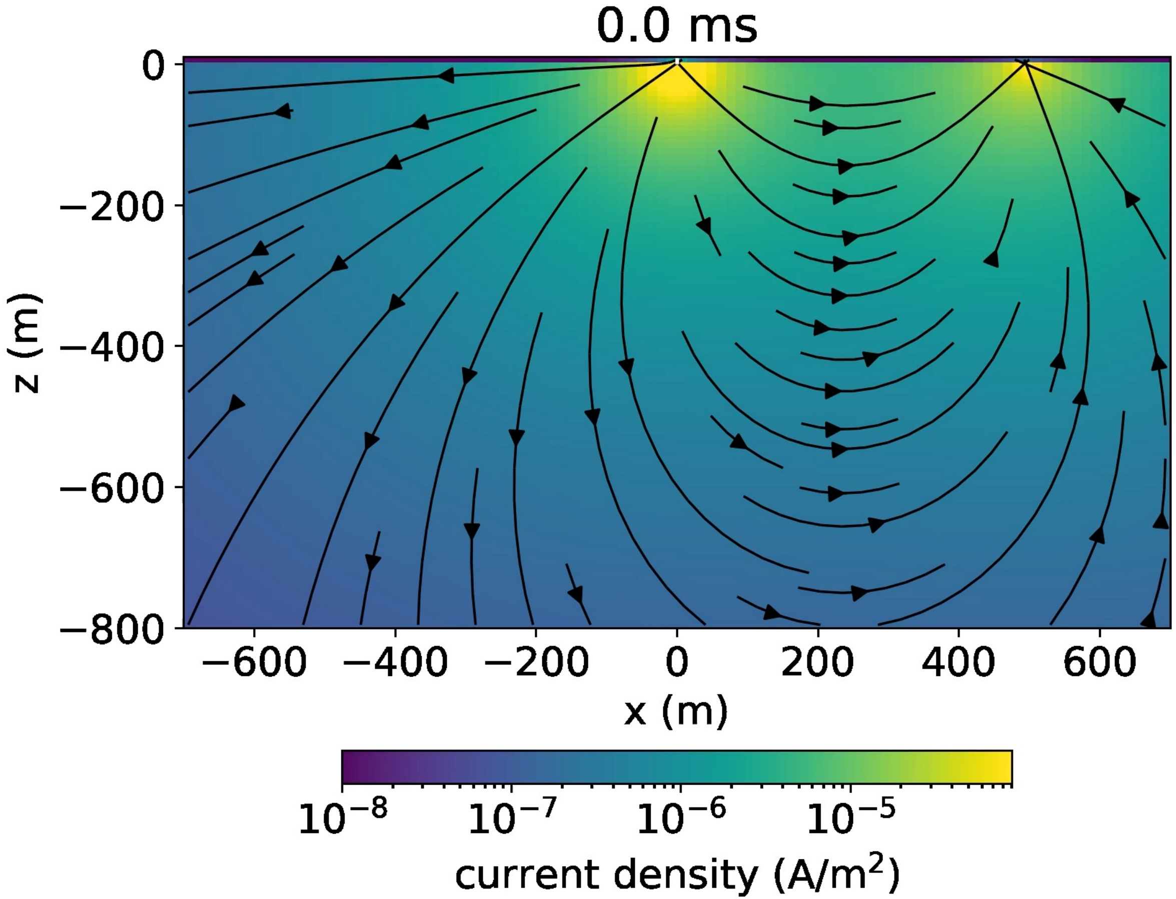
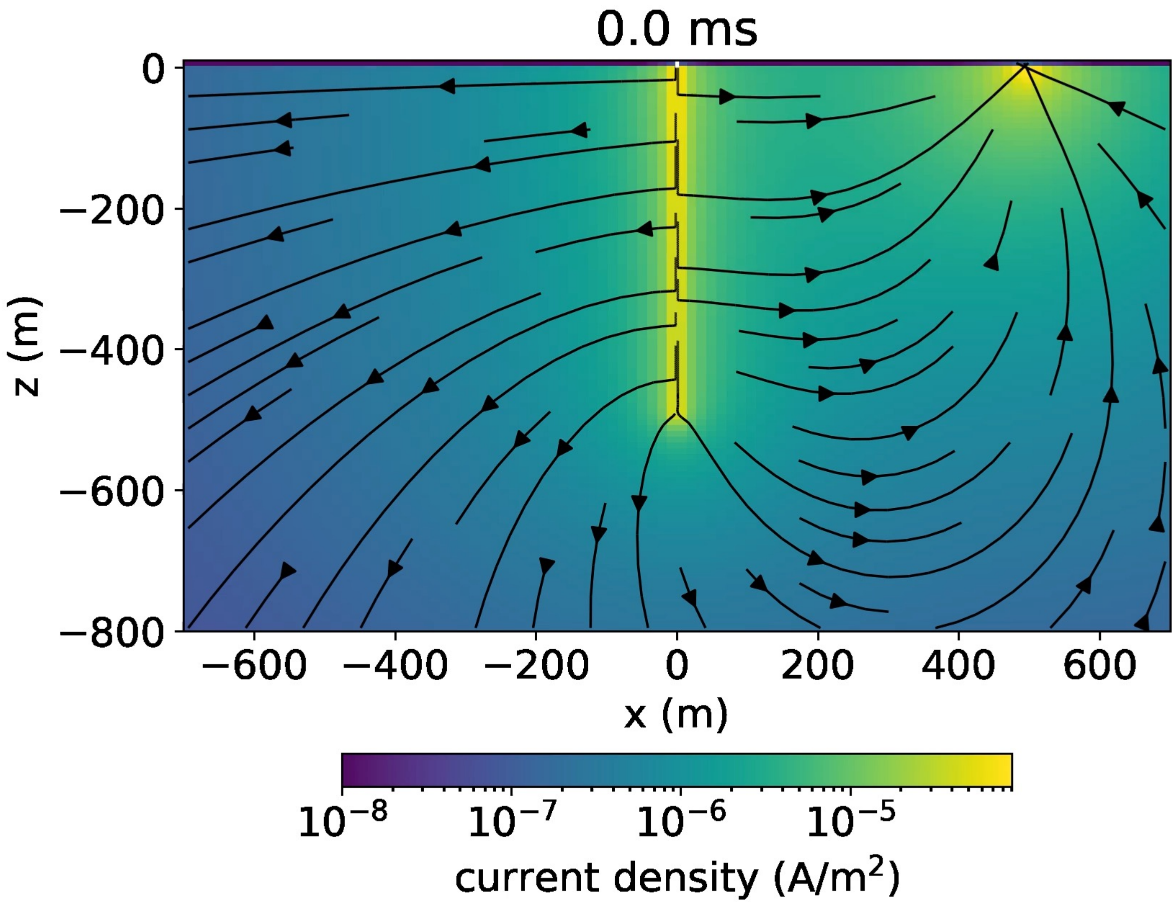


what about for grounded sources? interplay of high conductivity, permeability?

TDEM response: halfspace



TDEM response: conductive casing

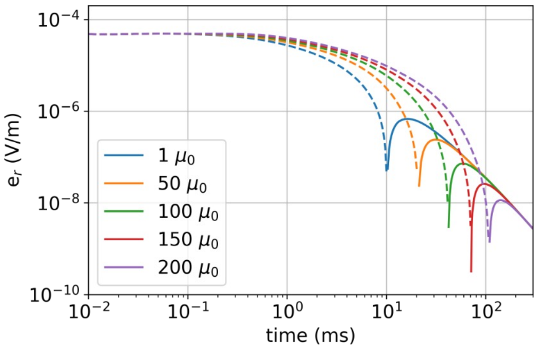


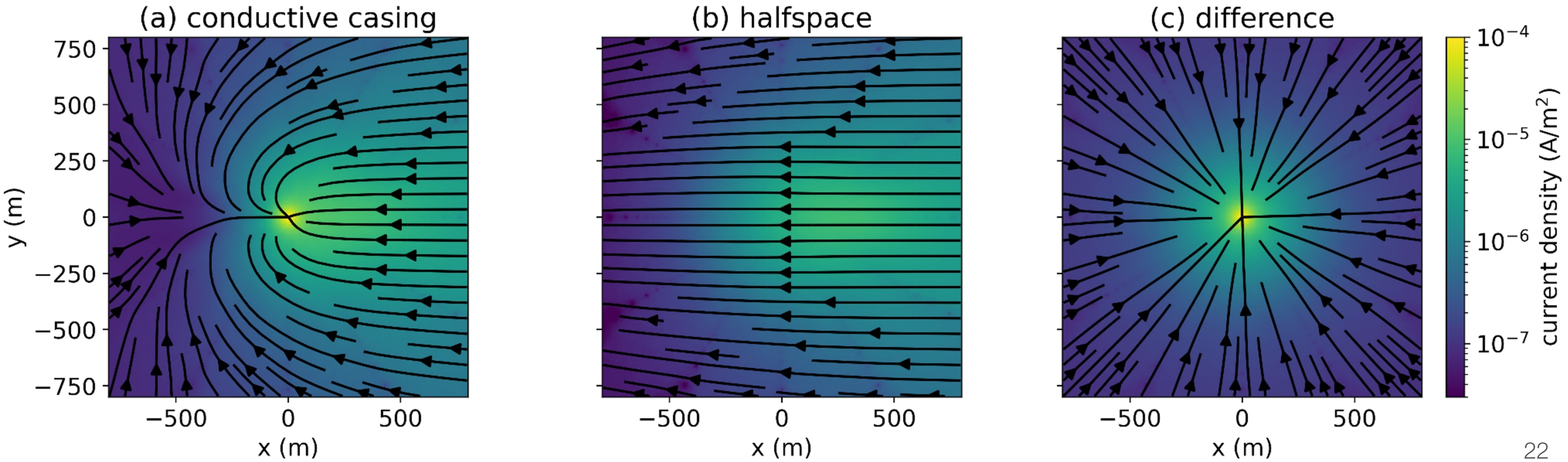
TDEM response: conductive casing

the zero-crossing in TDEM, FDEM responses…

due to geometry, currents channelling into casing

depth slices of currents

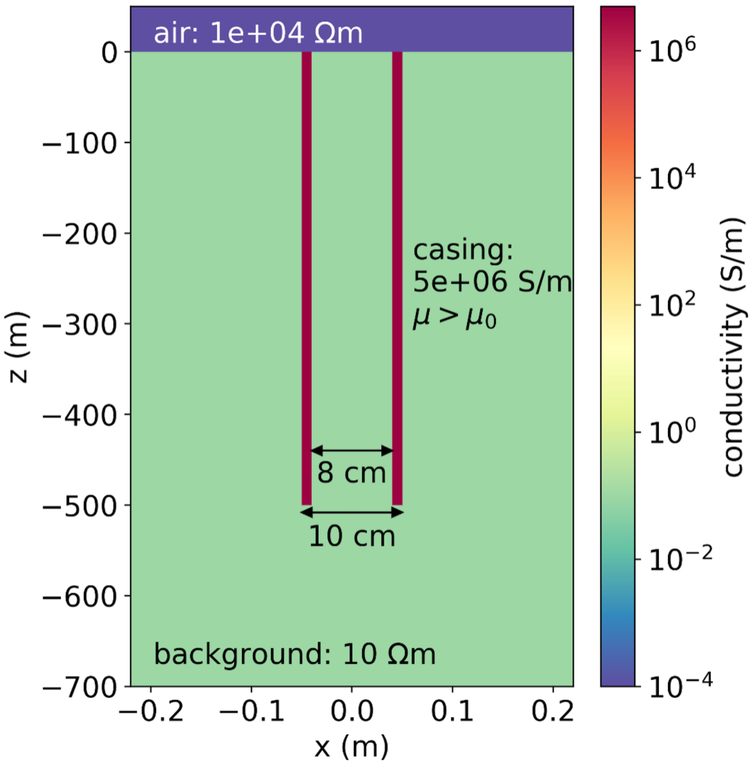


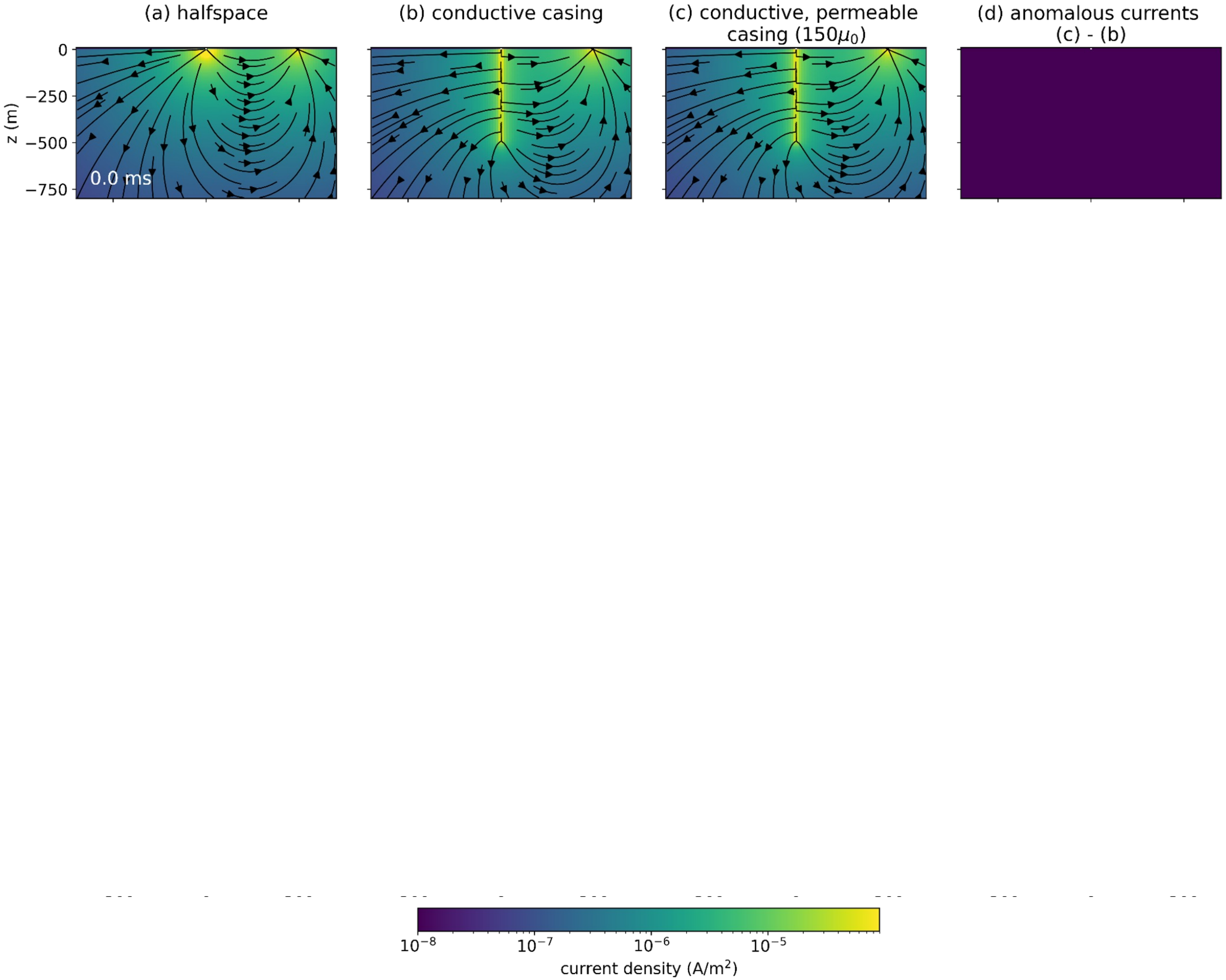


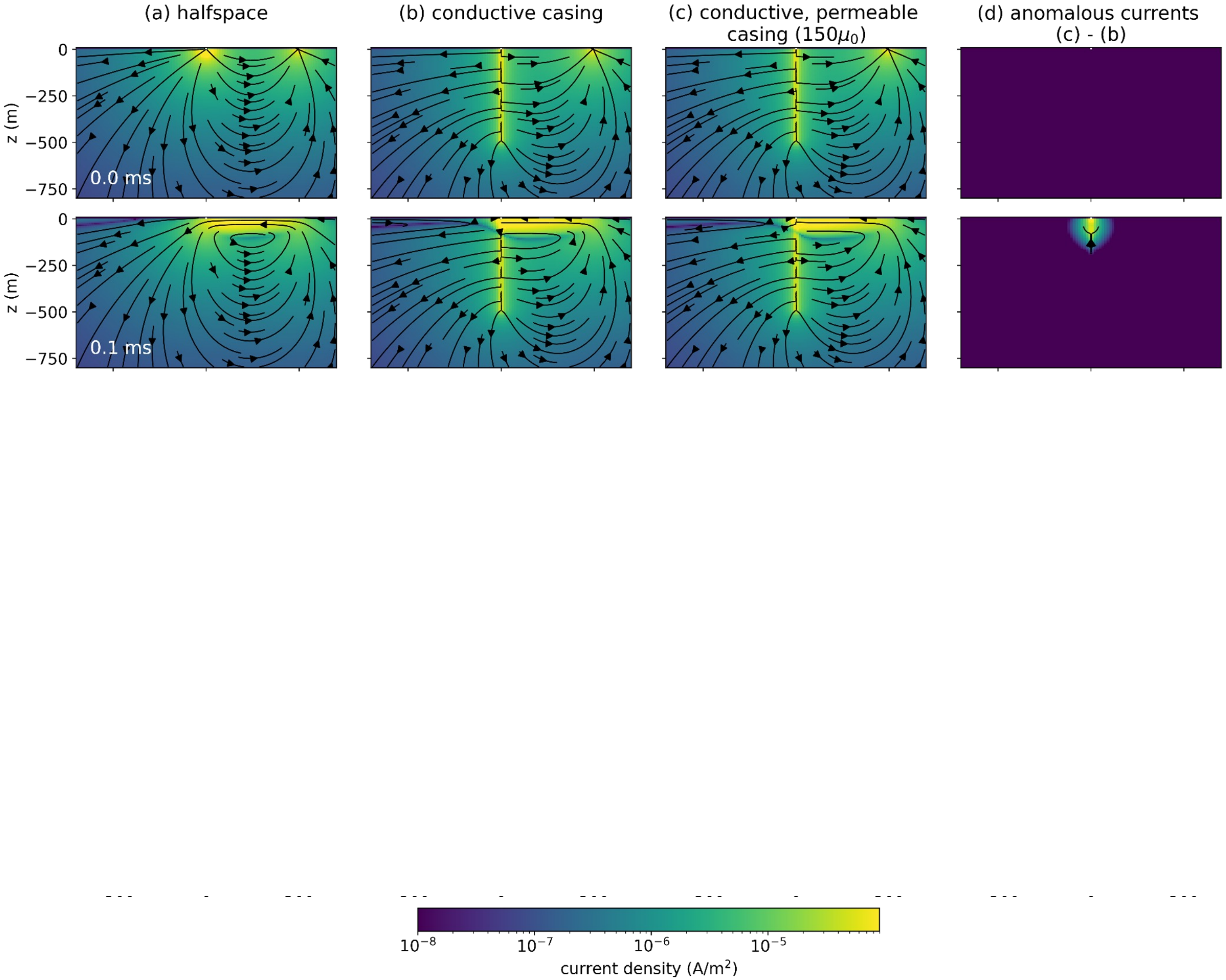
TDEM response: conductive, permeable casing

$\sigma = 5.5 \times 10^6$ S/m

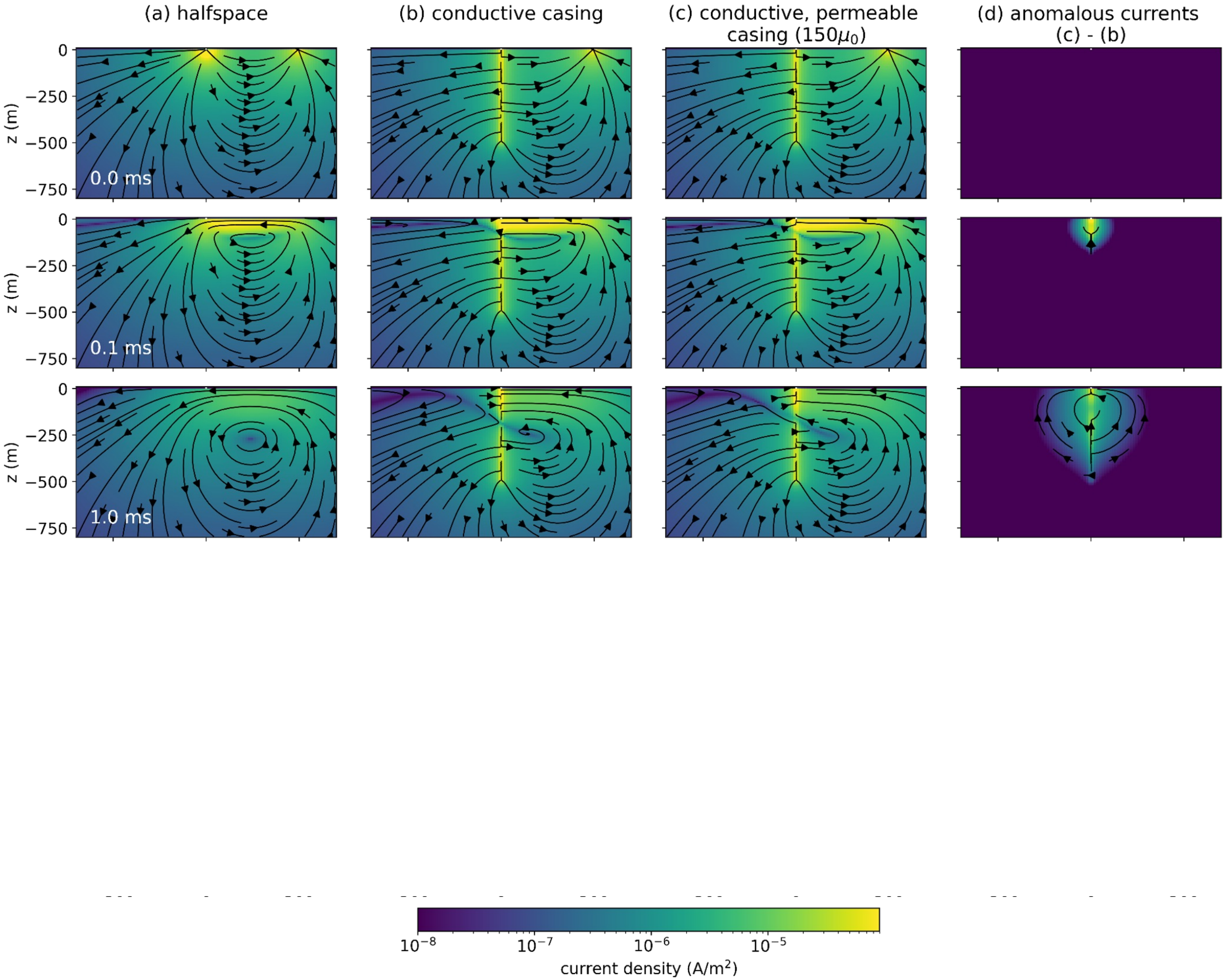
$\mu = 150\mu_0$




(a) halfspace
(b) conductive casing
(c) conductive, permeable casing (150μ_0)
(d) anomalous currents (c) - (b)
0
−250
−500
−750
z (m)
0.0 ms
10^{-8}
10^{-7}
10^{-6}
10^{-5}
current density (A/m^2)



(a) halfspace
(b) conductive casing
(c) conductive, permeable casing ($150\mu_0$)
(d) anomalous currents (c) - (b)
z (m)
0
−250
−500
−750
0.0 ms
0.1 ms
10^{-8}
10^{-7}
10^{-6}
10^{-5}
current density (A/m^2)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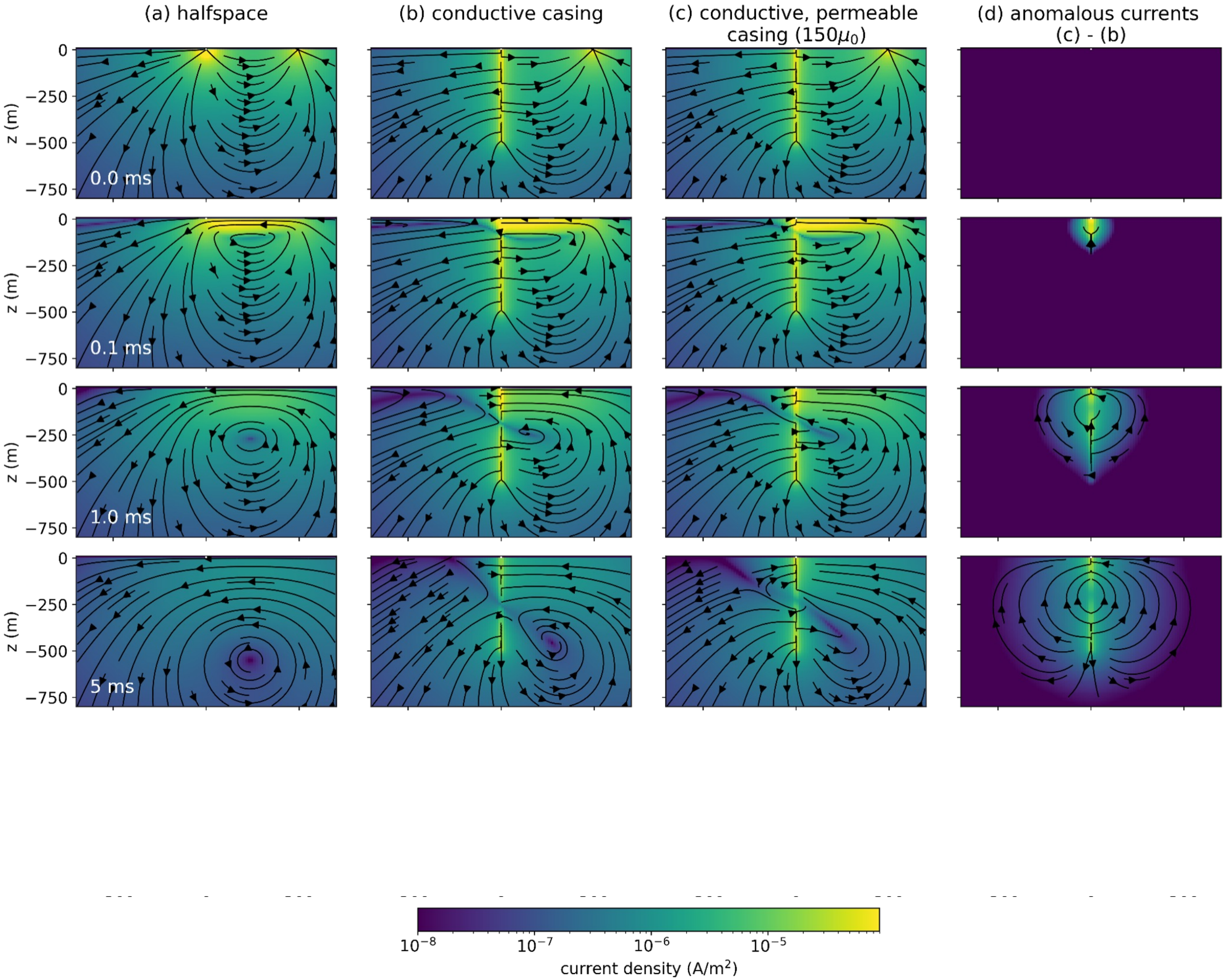

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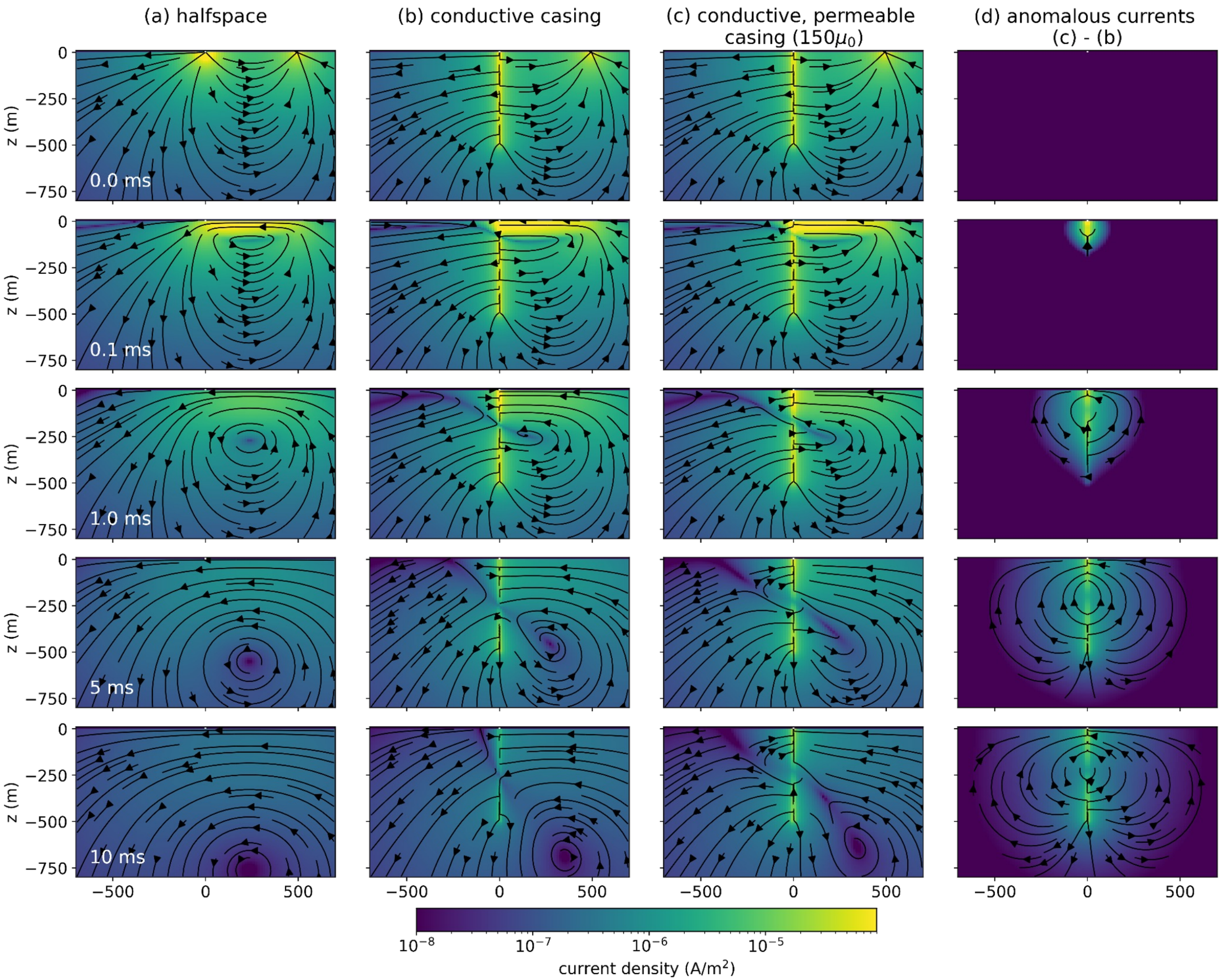
z (m)
0
−250
−500
−750
0.0 ms
0.1 ms
1.0 ms
5 ms
10^{-8}
10^{-7}
10^{-6}
10^{-5}
current density (A/m^2)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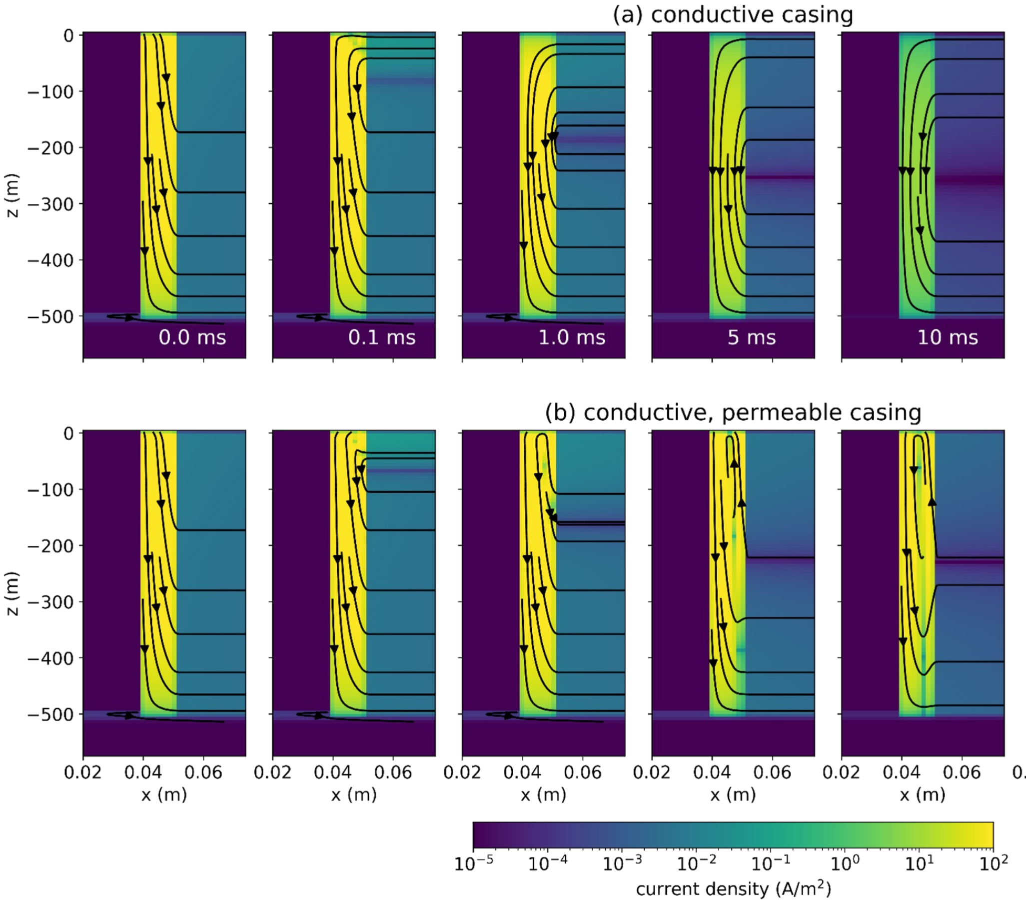
(d) anomalous currents (c) - (b)
0.0 ms
0.1 ms
1.0 ms
5 ms
10 ms
z (m)
0
−250
−500
−750
−500
500
10^{-8}
10^{-7}
10^{-6}
10^{-5}
current density (A/m^2)

TDEM response: conductive, permeable casing

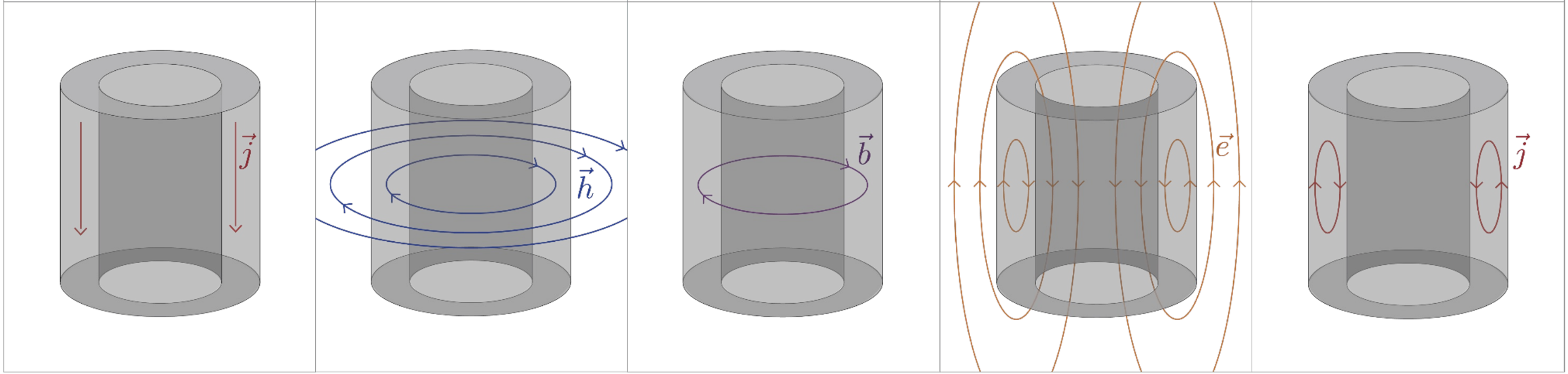
zooming in…



why do we have a poloidal current?

the cartoon explanation

(a)	(b)	(c)	(d)	(e)
	$\nabla \times \vec{h} = \vec{j}$	$\vec{b} = \mu \vec{h}$	$\nabla \times \vec{e} = -\dfrac{\partial \vec{b}}{\partial t}$	$\vec{j} = \sigma \vec{e}$



why do we have a poloidal current?

start from Ampere's law $\nabla \times \vec{h} - \sigma \vec{e} = \vec{j}_s$ use constitutive relation $\vec{b} = \mu \vec{h}$	$\nabla \times \frac{1}{\mu}\vec{b} - \sigma \vec{e} = \vec{j}_s$
vector identity $\nabla \times (\psi \vec{v}) = \psi \nabla \times \vec{v} + (\nabla \psi) \times \vec{v}$	$\frac{1}{\mu}\nabla \times \vec{b} + \left(\nabla \frac{1}{\mu}\right) \times \vec{b} - \sigma \vec{e} = \vec{j}_s$
multiply by μ	$\nabla \times \vec{b} + \left(\mu \nabla \frac{1}{\mu}\right) \times \vec{b} - \mu \sigma \vec{e} = \mu \vec{j}_s$
identity $\mu \nabla \left(\frac{1}{\mu}\right) = -\nabla \ln \mu_r$	$\nabla \times \vec{b} - \nabla \ln \mu_r \times \vec{b} - \mu \sigma \vec{e} = \mu \vec{j}_s$
away from the source	$\nabla \times \vec{b} = \nabla \ln \mu_r \times \vec{b} + \mu \sigma \vec{e}$

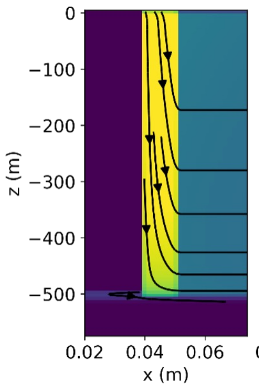
why do we have a poloidal current?

$$\nabla \times \vec{b} = \underbrace{\nabla \ln \mu_r \times \vec{b}}_{\substack{(1)\\ \text{magnetization} \\ \text{term}}} + \underbrace{\mu\sigma\vec{e}}_{\substack{(2)\\ \text{induction} \\ \text{term}}}$$

why do we have a poloidal current?

$$\nabla \times \vec{b} = \underbrace{\nabla \ln \mu_r \times \vec{b}}_{\substack{(1)\\ \text{magnetization}\\ \text{term}}} + \underbrace{\mu \sigma \vec{e}}_{\substack{(2)\\ \text{induction}\\ \text{term}}}$$

- role of μ acts in same manner as σ
- enhances inductive component of response

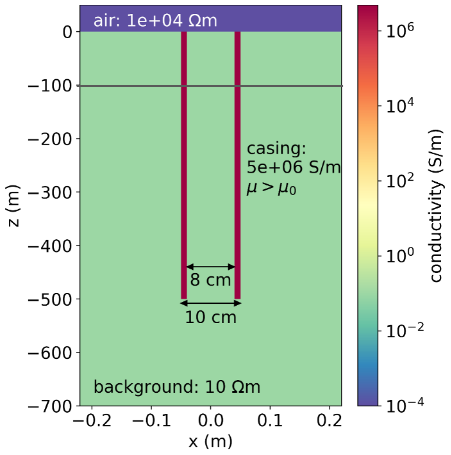


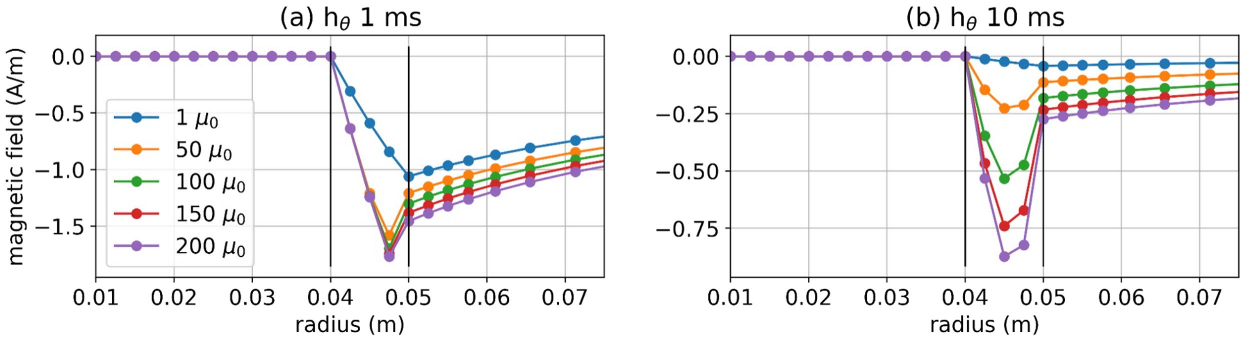
why do we have a poloidal current?

$$\nabla \times \vec{b} = \underbrace{\nabla \ln \mu_r \times \vec{b}}_{\substack{(1)\\ \text{magnetization}\\ \text{term}}} + \underbrace{\mu\sigma\vec{e}}_{\substack{(2)\\ \text{induction}\\ \text{term}}}$$

- non-zero only where μ changes (at the casing walls)
- role… ???

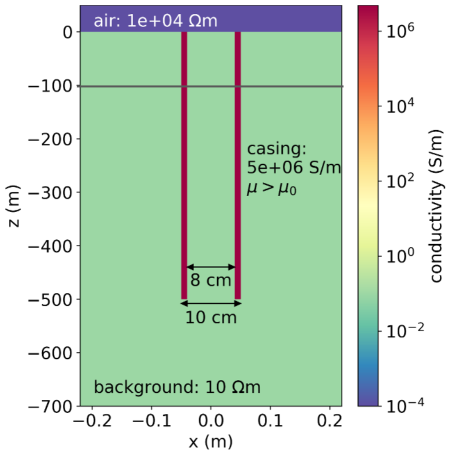
$$\nabla \ln \mu_r \times \vec{b}$$

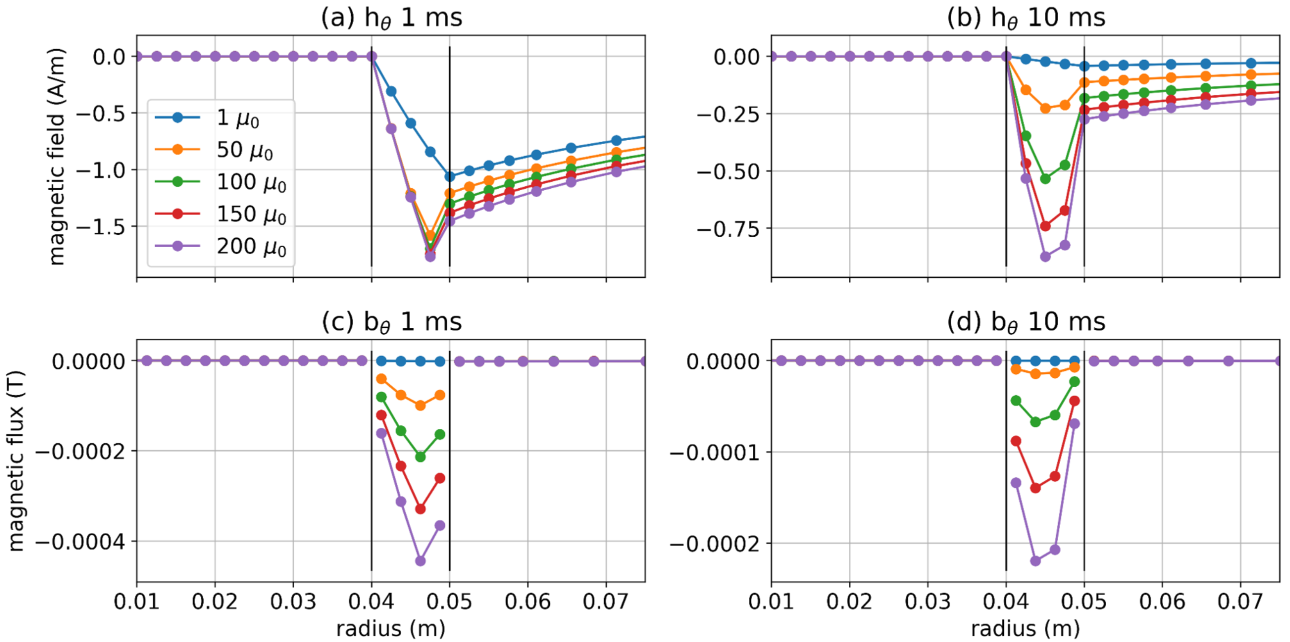




by symmetry, magnetic field mostly rotational

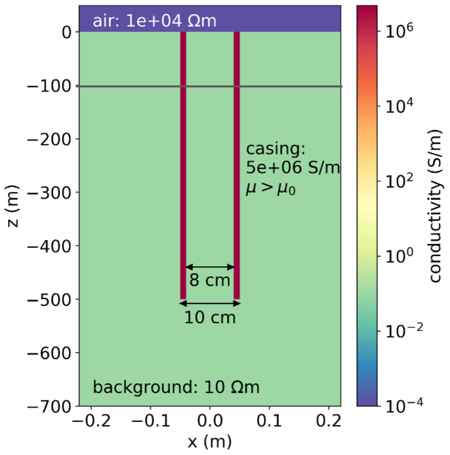
$$\nabla \ln \mu_r \times \vec{b}$$

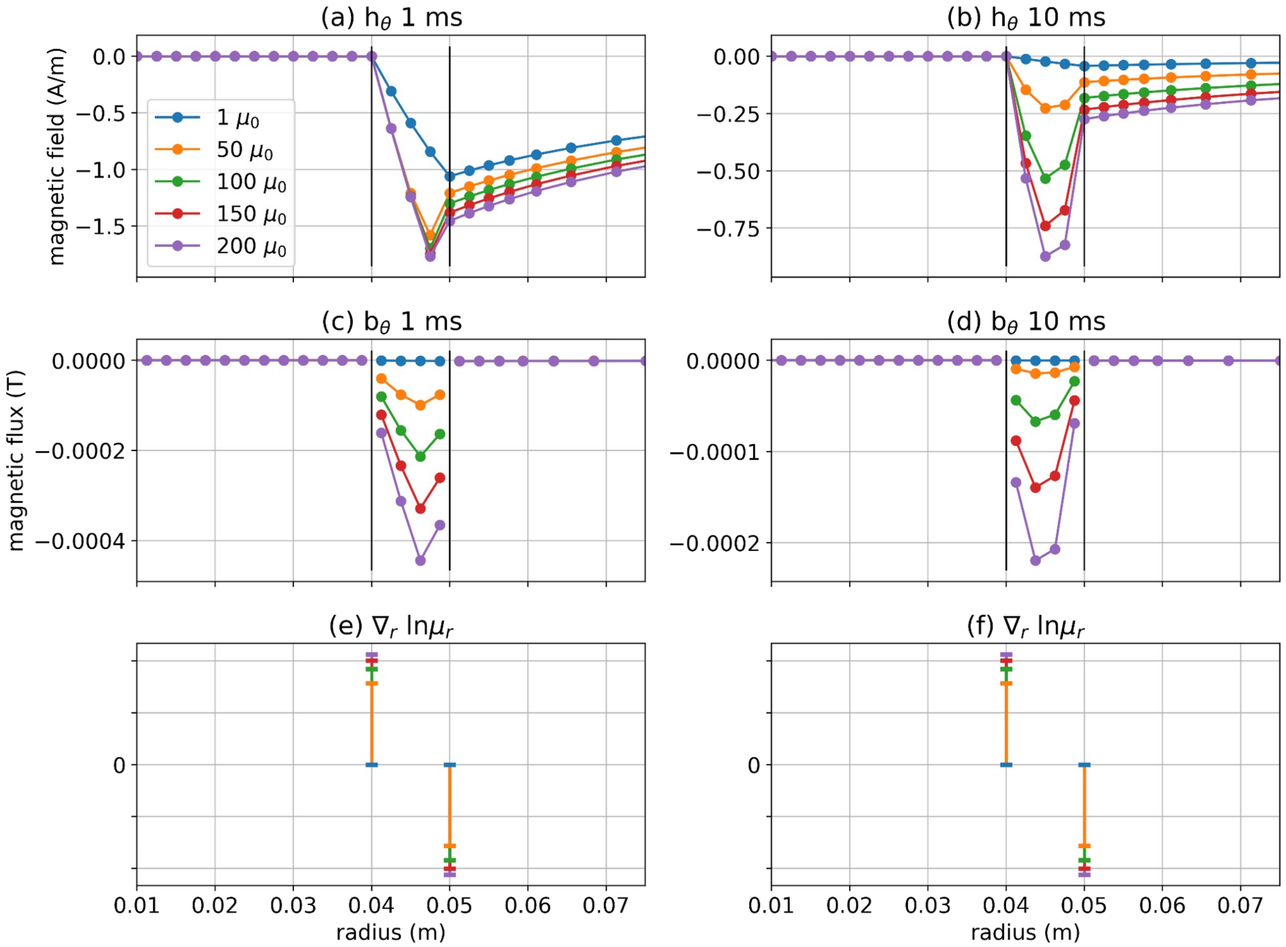




b-field discontinuous, negligible on inner casing wall

$$\nabla \ln \mu_r \times \vec{b}$$



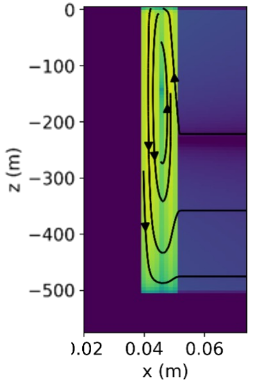


negative radial x negative azimuthal = positive vertical

why do we have a poloidal current?

$$\nabla \times \vec{b} = \underbrace{\nabla \ln \mu_r \times \vec{b}}_{\text{(1) magnetization term}} + \underbrace{\mu\sigma\vec{e}}_{\text{(2) induction term}}$$

- non-zero only where μ changes (at the casing walls)
- role: contributes an upwards oriented magnetization current



why do we care?

(it's interesting!)

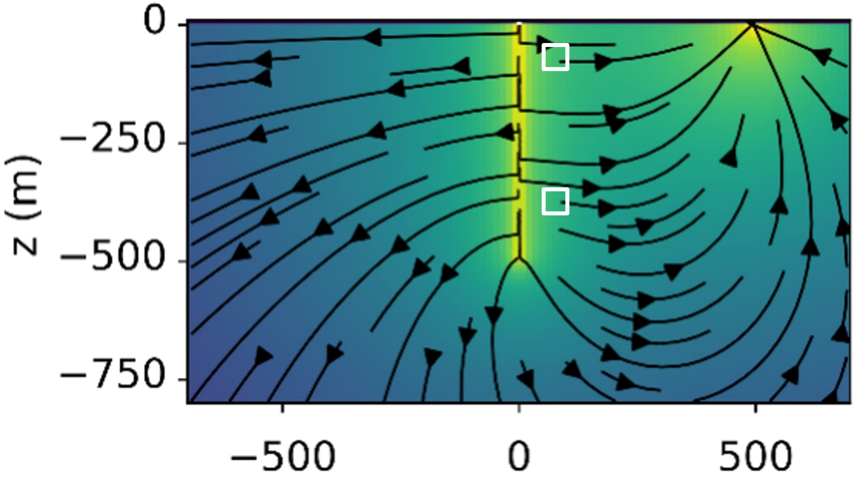
magnetic permeability…

- enhances inductive component of the response
- introduces a magnetization current

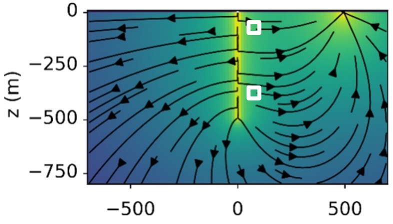
as a result…

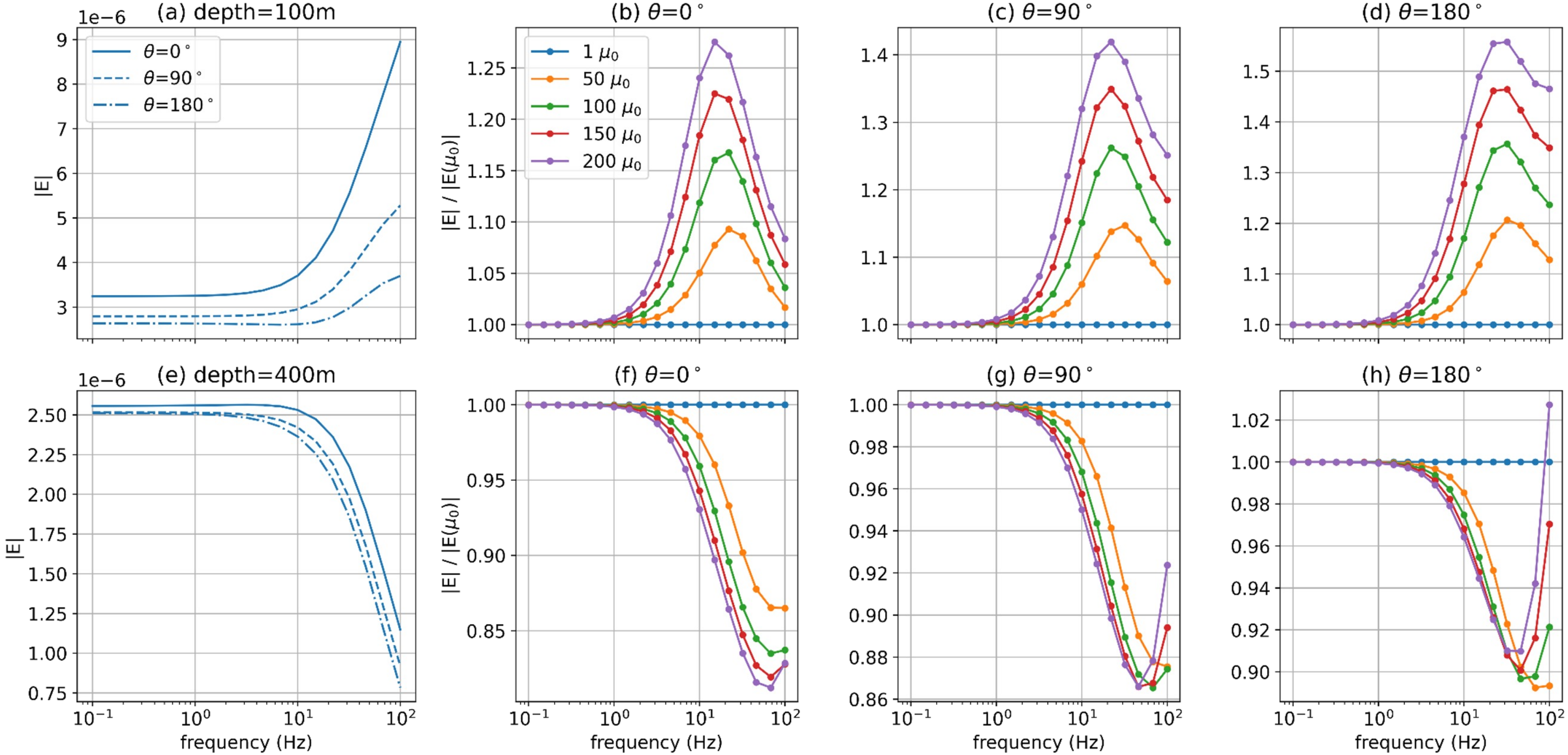
- alters EM excitation
- alters EM data

consider a test volume…



why do we care?





summary

magnetic permeability…

- enhances inductive component of the response
- introduces a magnetization current

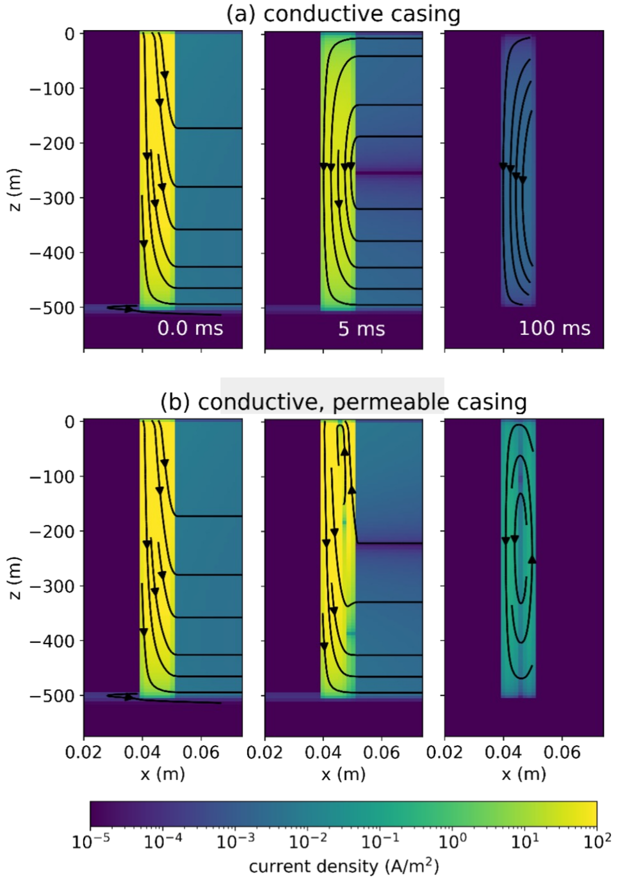
as a result…

- alters EM excitation & data

implications…

- not equal to a simple scaling of conductivity
- can't be modelled by "equivalent" magnetic dipoles
- questions for modelling in 3D
- additional complication: μ usually not known…

but … we understand the physics and can simulate responses

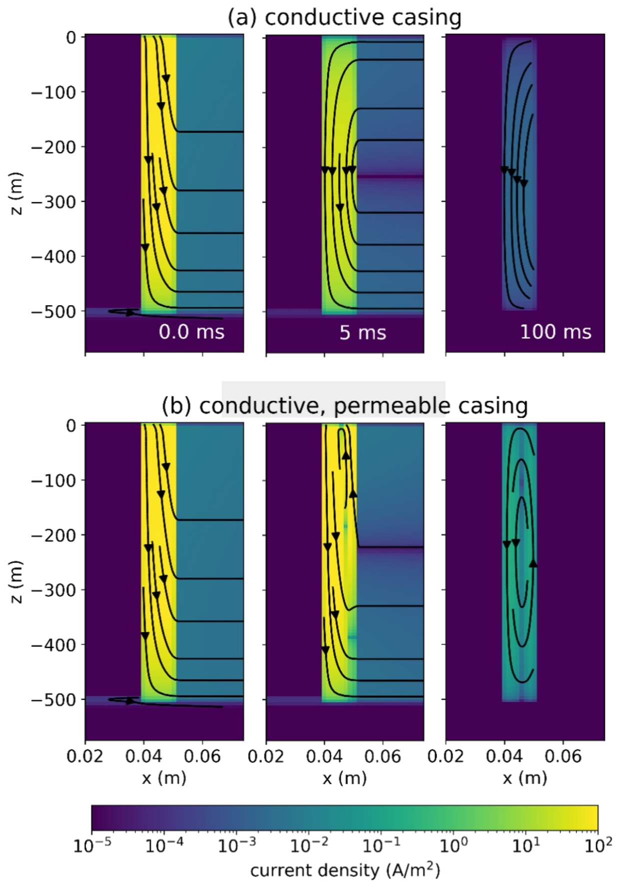


thank you! questions?

simpeg.xyz

lheagy@eoas.ubc.ca

bit.ly/heagy-2023-3dem



Heagy, L.J., Oldenburg, D.W., 2023. Impacts of magnetic permeability on electromagnetic data collected in settings with steel-cased wells. Geophysical Journal International 234, 1092–1110. https://doi.org/10.1093/gji/ggad122

$$\nabla \times \vec{b} = \nabla \ln \mu_r \times \vec{b} + \mu\sigma\vec{e}$$

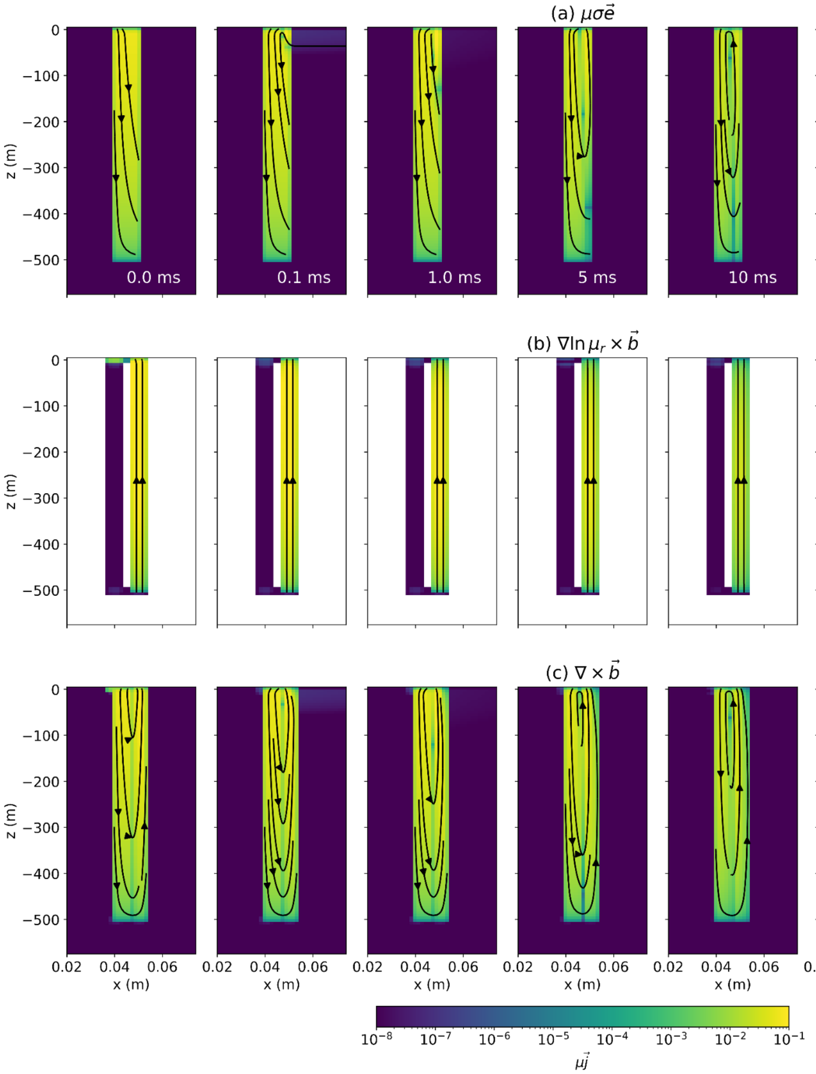
$$\mu\sigma\vec{e}$$

$$+$$

$$\nabla \ln \mu_r \times \vec{b}$$

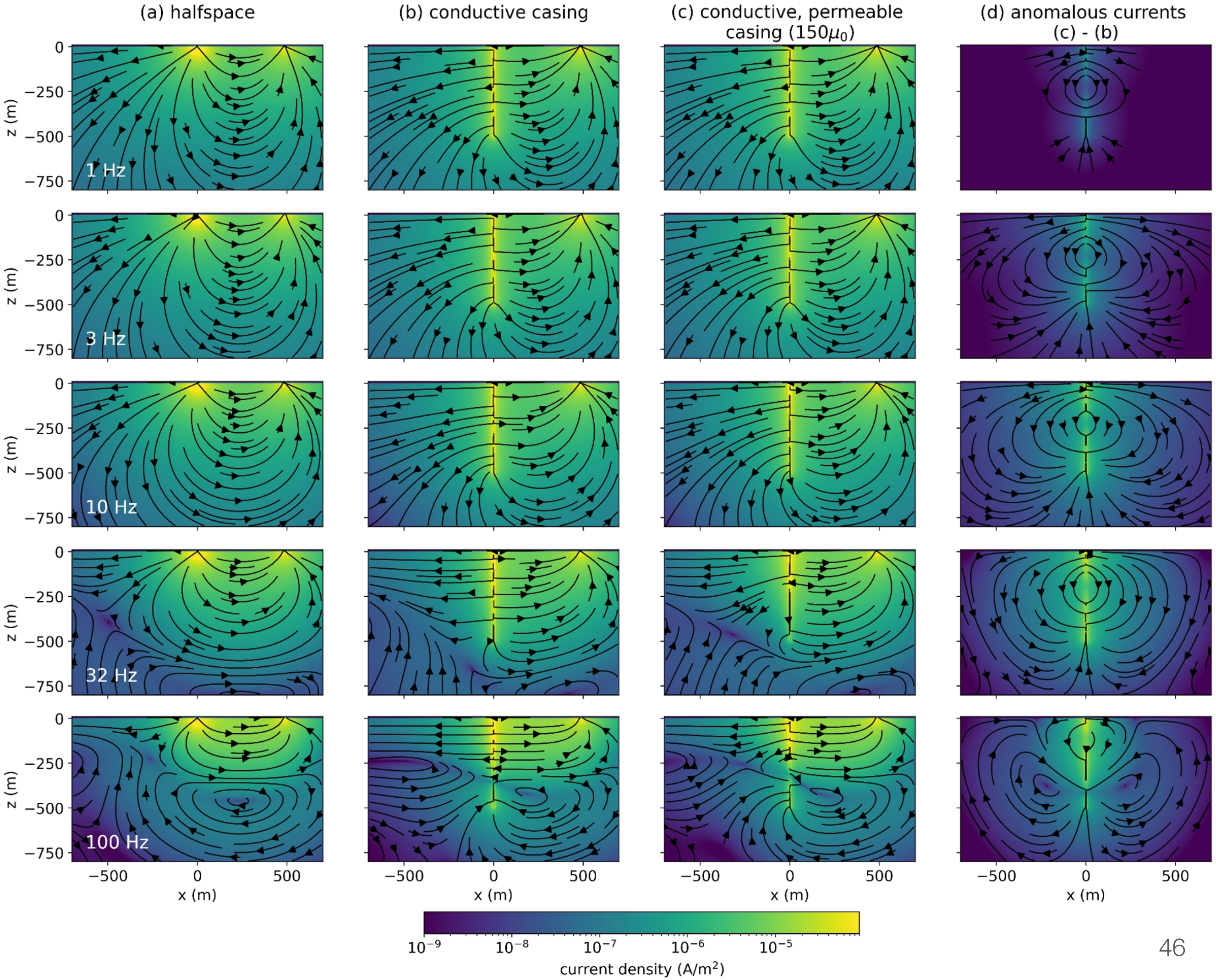
$$=$$

$$\nabla \times \vec{b}$$

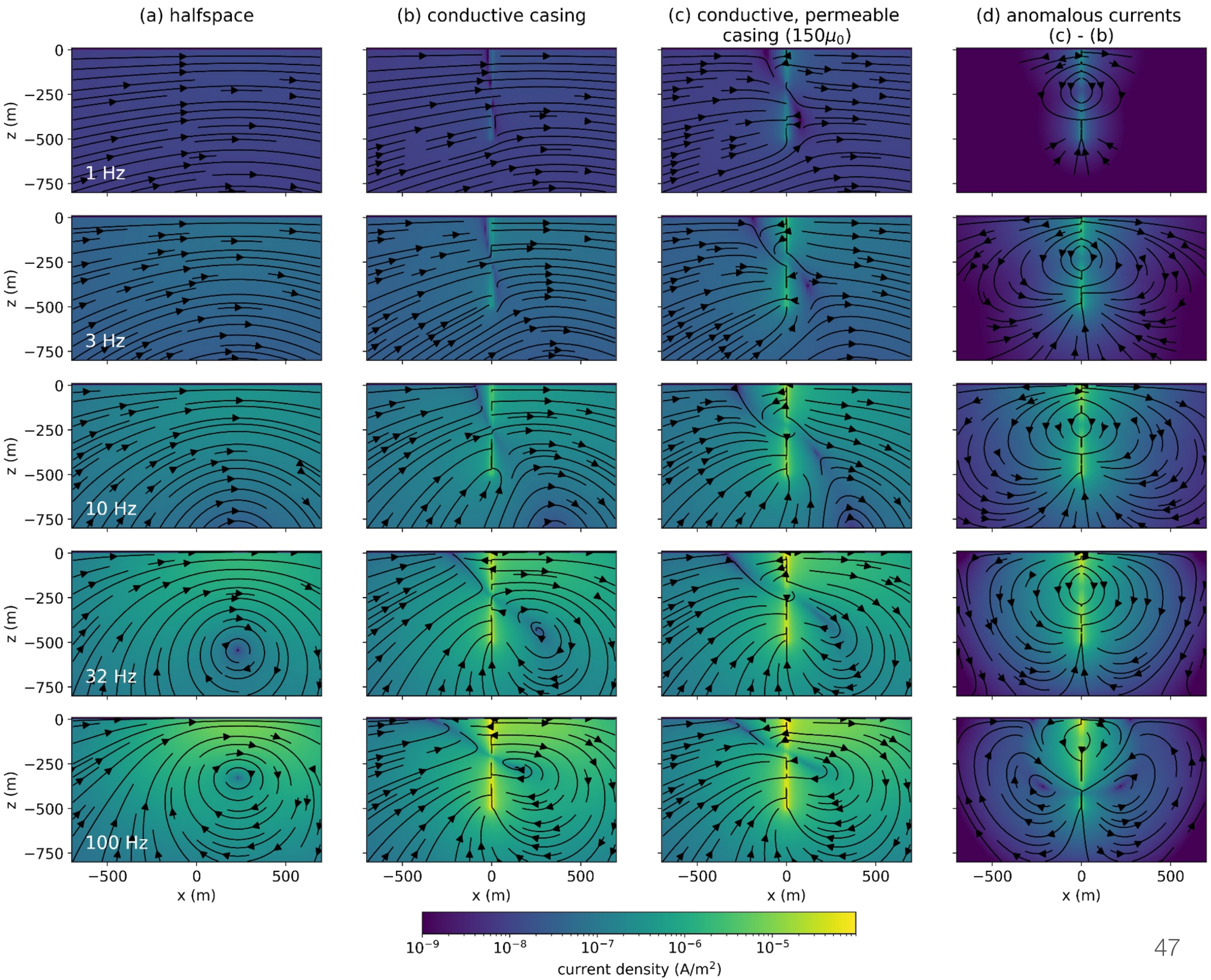


FDEM response

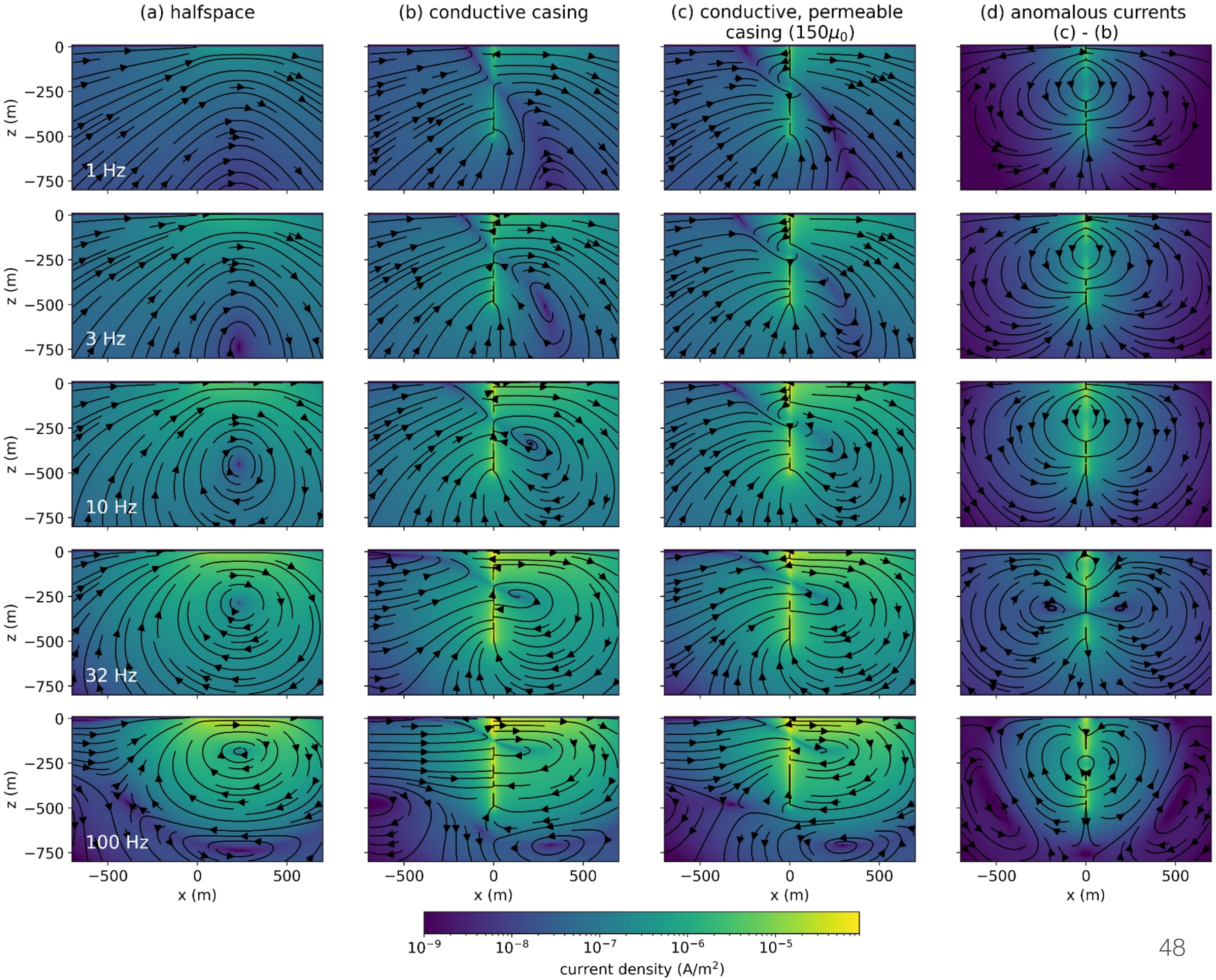
FDEM currents (real)



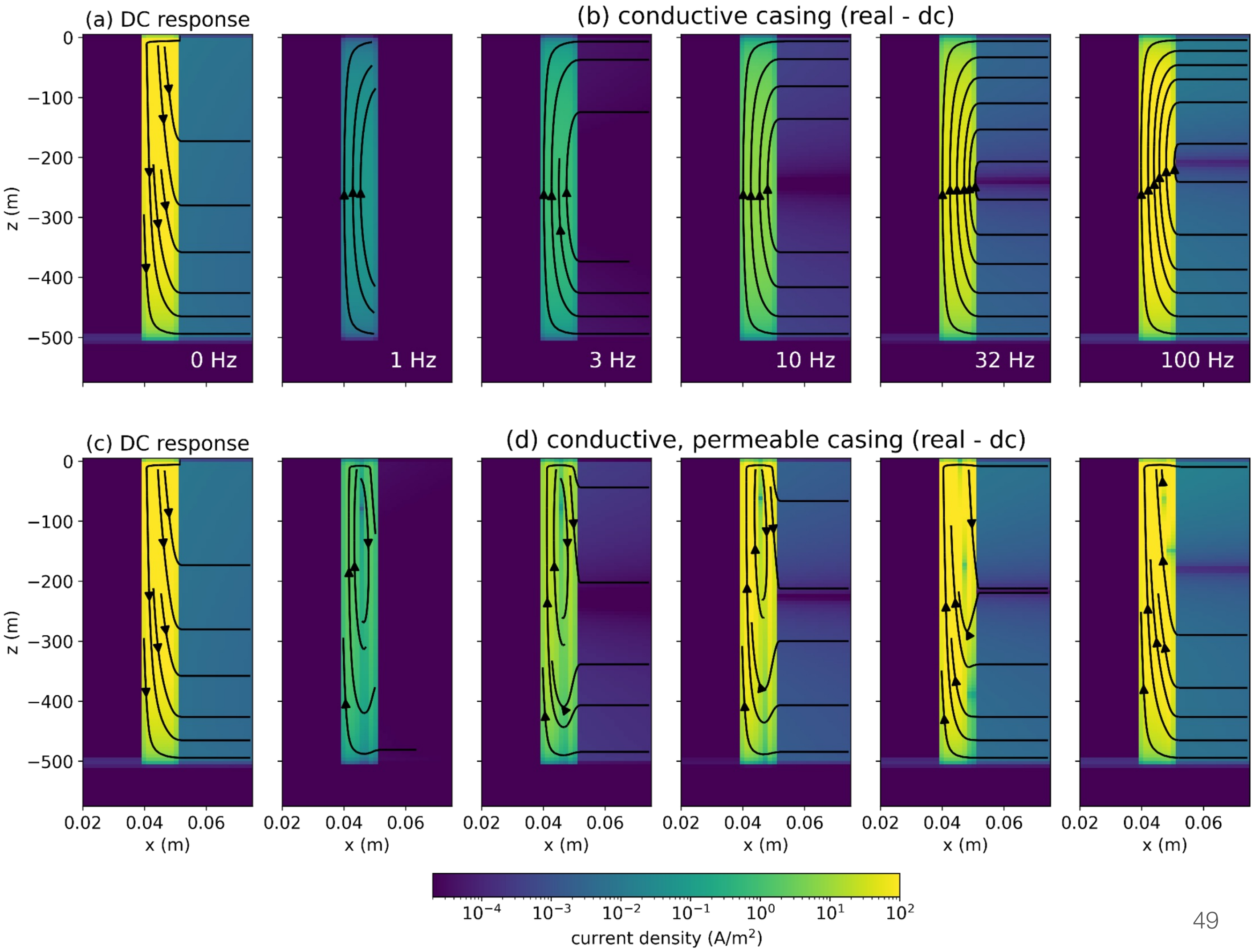
FDEM currents (real - dc)



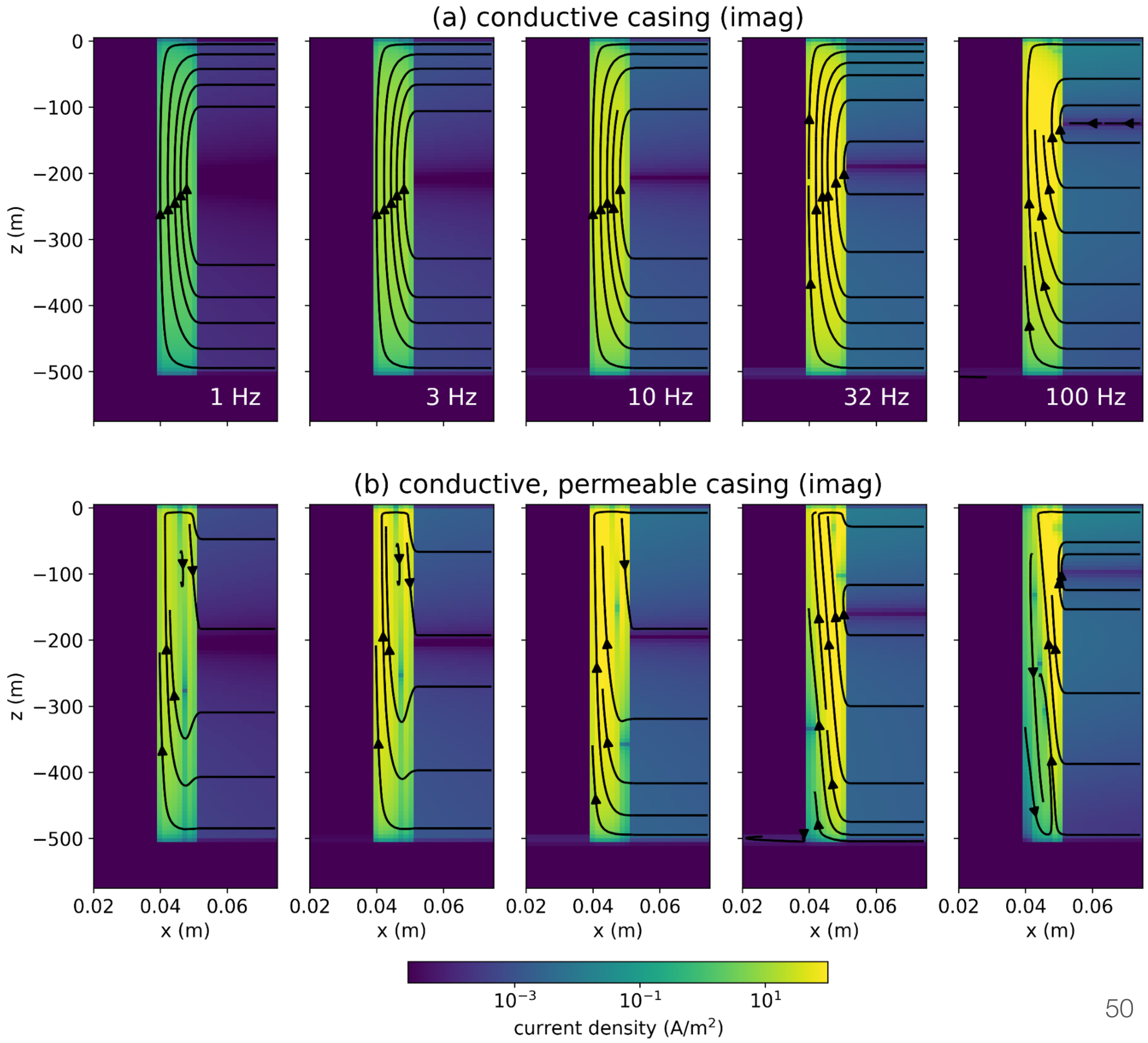
FDEM currents (imag)



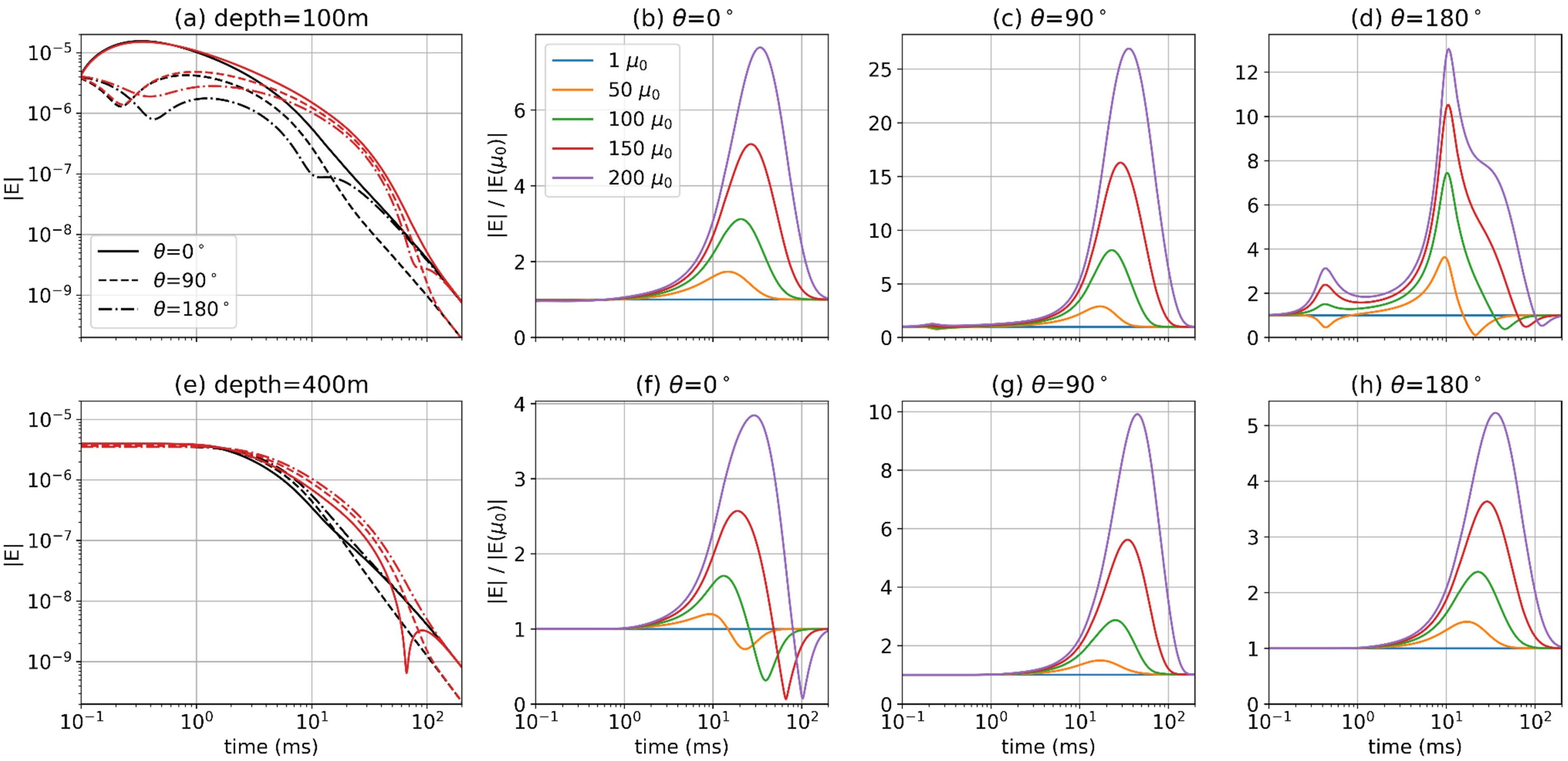
FDEM zoomed in (real)



FDEM zoomed in (real)



excitation in time

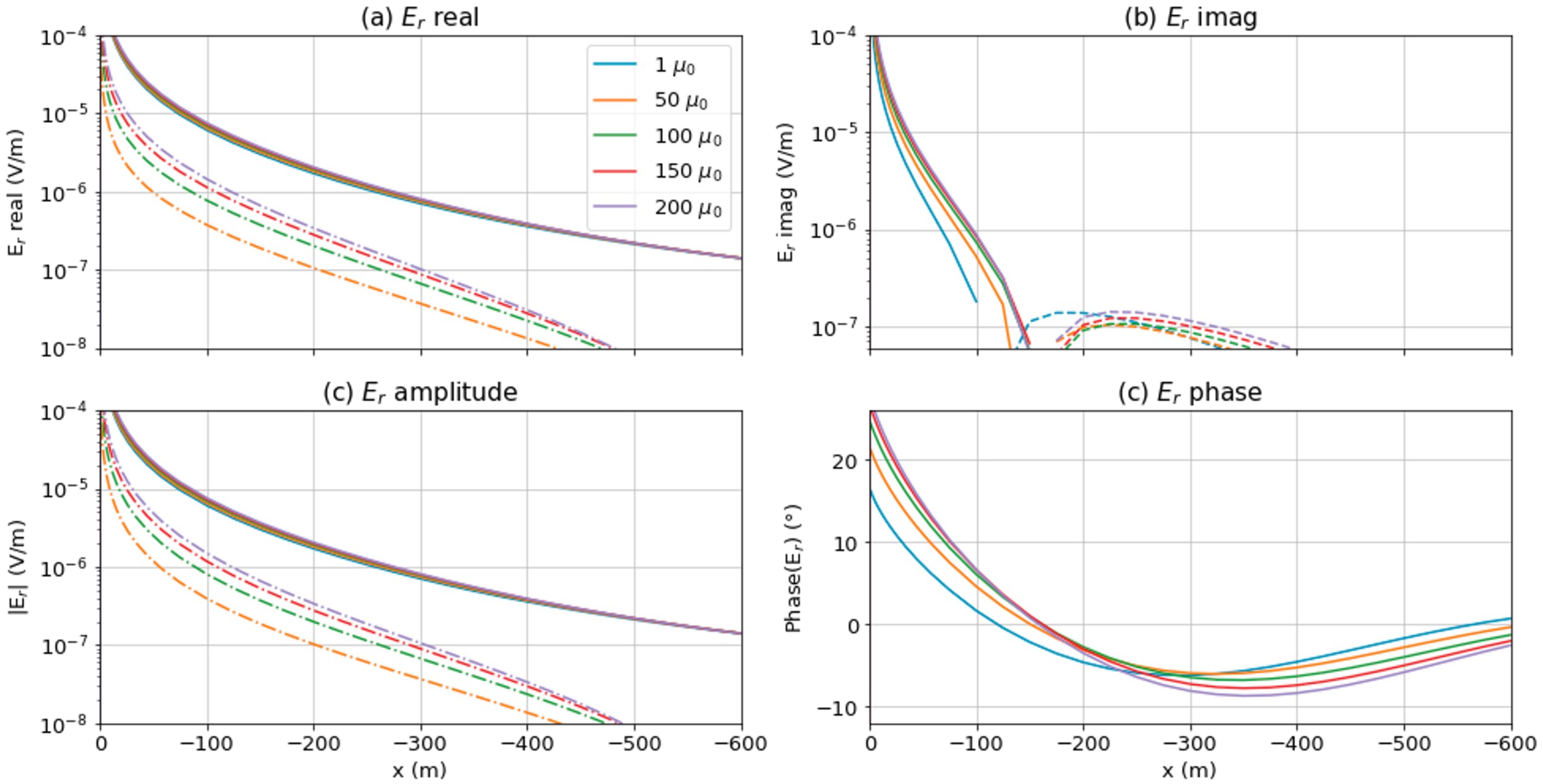


(a) depth=100m
(b) θ=0°
(c) θ=90°
(d) θ=180°
(e) depth=400m
(f) θ=0°
(g) θ=90°
(h) θ=180°
|E|
|E| / |E(μ0)|
time (ms)
θ=0°
θ=90°
θ=180°
1 μ0
50 μ0
100 μ0
150 μ0
200 μ0

a more conductive background 1 S/m

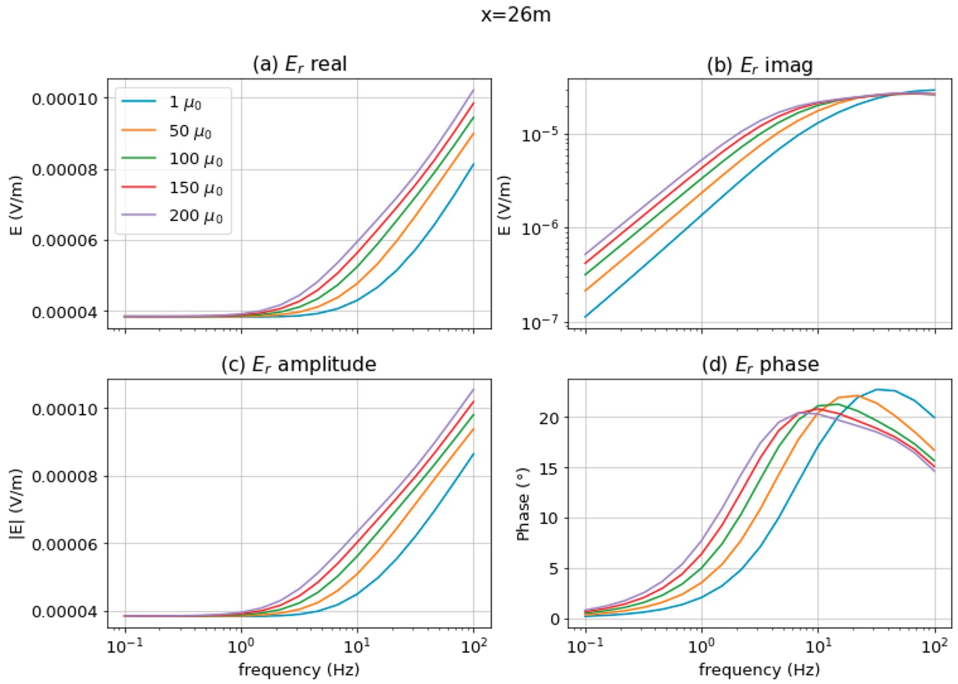
More conductive background (1 S/m)

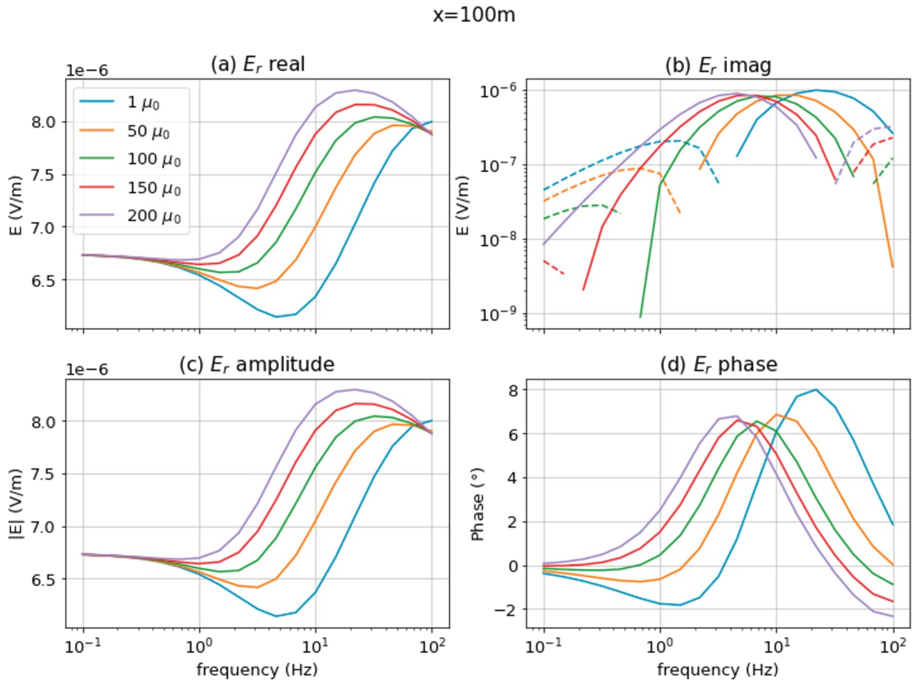
5 Hz



More conductive background (1 S/m)

x = 26, 100m





More conductive background (1 S/m)