Lecture 4

DC Resistivity: Basic Principles

GEOL 4397: Electromagnetic Methods for Exploration
GEOL 6398: Special Problems

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August 30th, 2018

UNIVERSITY of HOUSTON
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EARTH AND ATMOSPHERIC SCIENCES

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Agenda

- Recap
- Two current electrodes
- Apparent resistivity
- Understanding charges

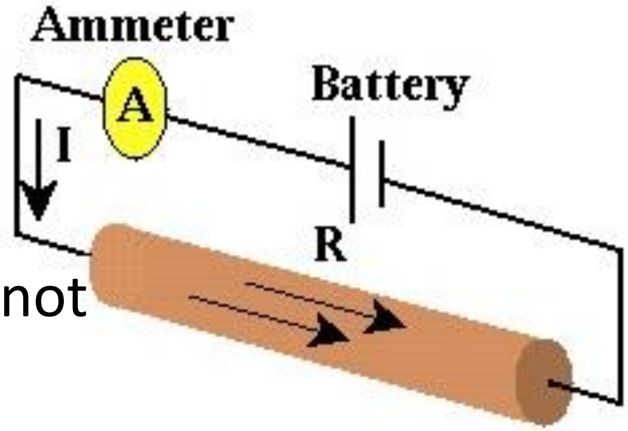
Ohm's law

https://en.wikipedia.org/wiki/Georg_Ohm

- In 1827, Georg Ohm discovered an empirical relationship between the current flowing through a wire and the voltage required to drive that current.

$$V = IR$$

$$R = \frac{V}{I}$$



- Note that here R represents resistance, not the resistivity. In fact, resistivity $\rho = \frac{RA}{L}$

https://pburnley.faculty.unlv.edu/GEOL442_642/RES/NOTES/ResistivityNotes04Ohm.html

What does Ohm's law tell us?

- Given current and voltage, we can estimate the resistance (which is related to resistivity).

Another version of Ohm's law

$$\boldsymbol{J} = \sigma \boldsymbol{E}$$

Question

- Is it possible to apply Ohm's law to determine the electrical resistivities of the Earth materials in the subsurface?

Simple answer

- Yes!
- That is exactly what DC resistivity does.

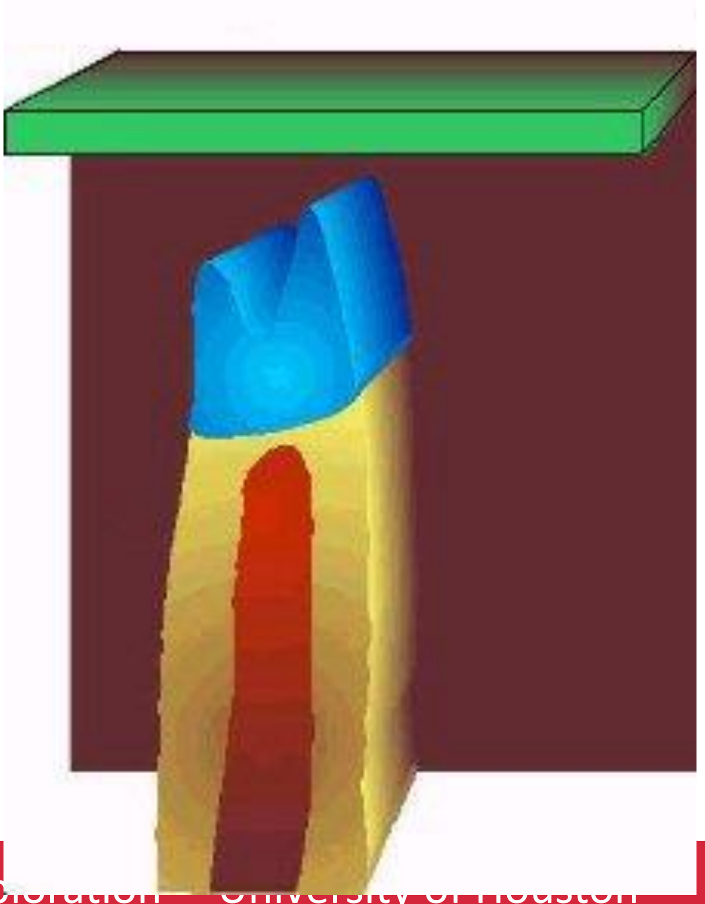
Basic Experiment

- **Target:**

  Ore body. Mineralized regions less resistive than host

Elura Orebody Electrical resistivities

Rock Type	*Ohm-m*
Overburden	12
Host rocks	200
Gossan	420
Mineralization (pyritic)	0.6
Mineralization (pyrrhotite)	0.6



Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

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  Tx: Current electrodes

  Rx: Potential electrodes

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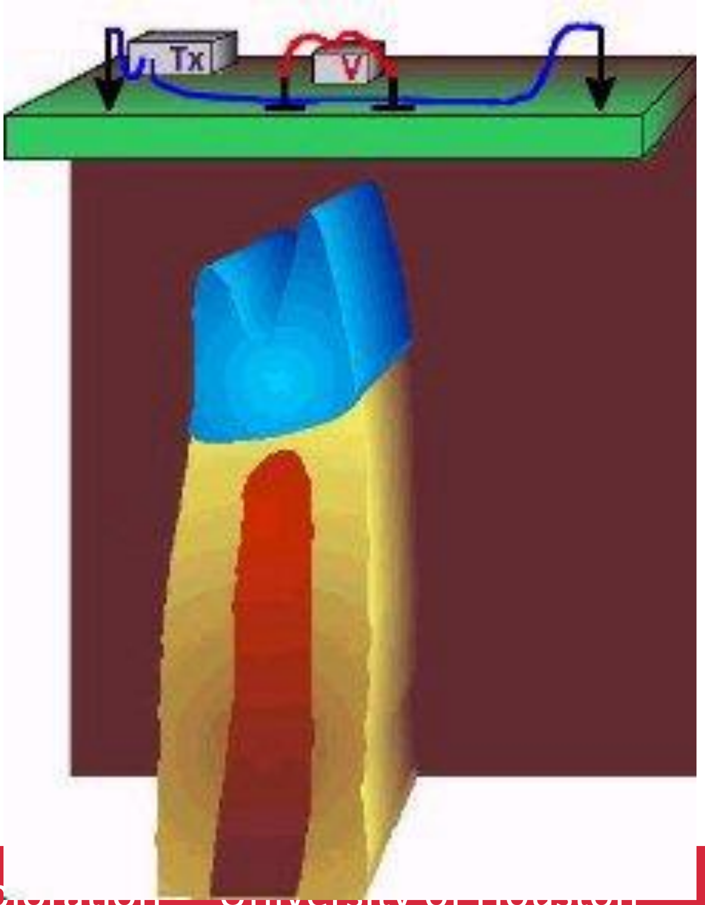

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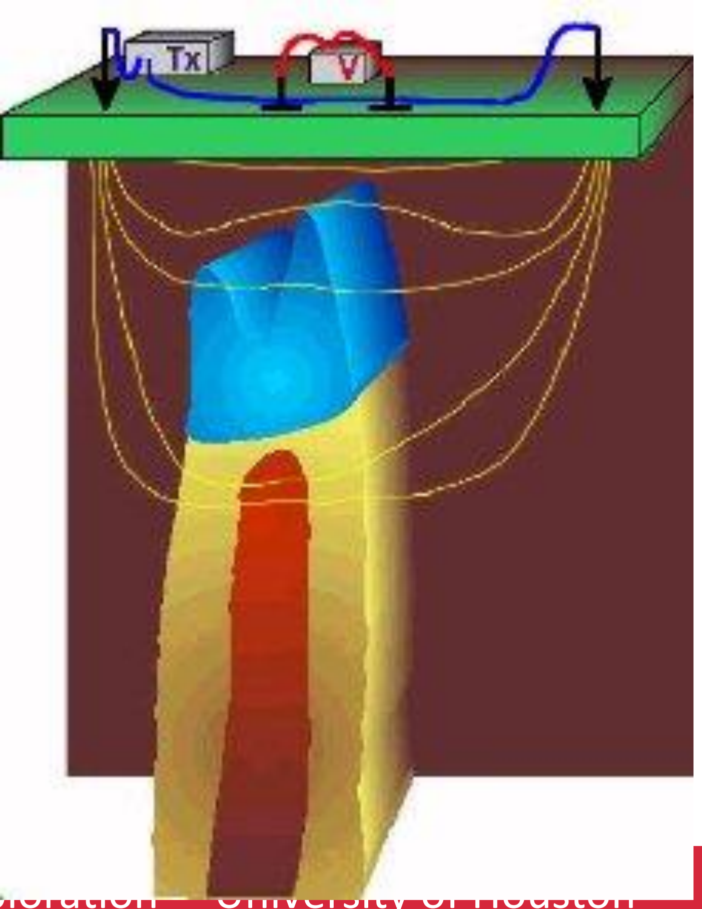
- **Currents:**

  Preferentially flow through conductors



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Basic Experiment

- **Target:**

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  Build up at interfaces

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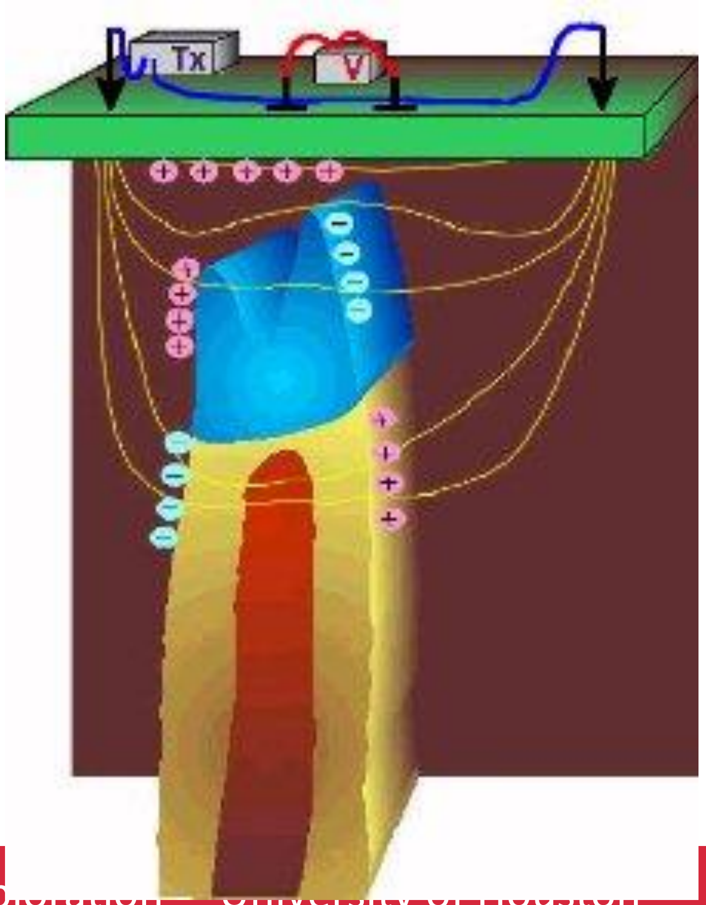

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Basic Experiment

- **Target:**

  Ore body. Mineralized regions less resistive than host

- **Setup:**

  Tx: Current electrodes

  Rx: Potential electrodes

- **Currents:**

  Preferentially flow through conductors

- **Charges:**

  Build up at interfaces

- **Potentials:**

  Associated with the charges are measured at the surface

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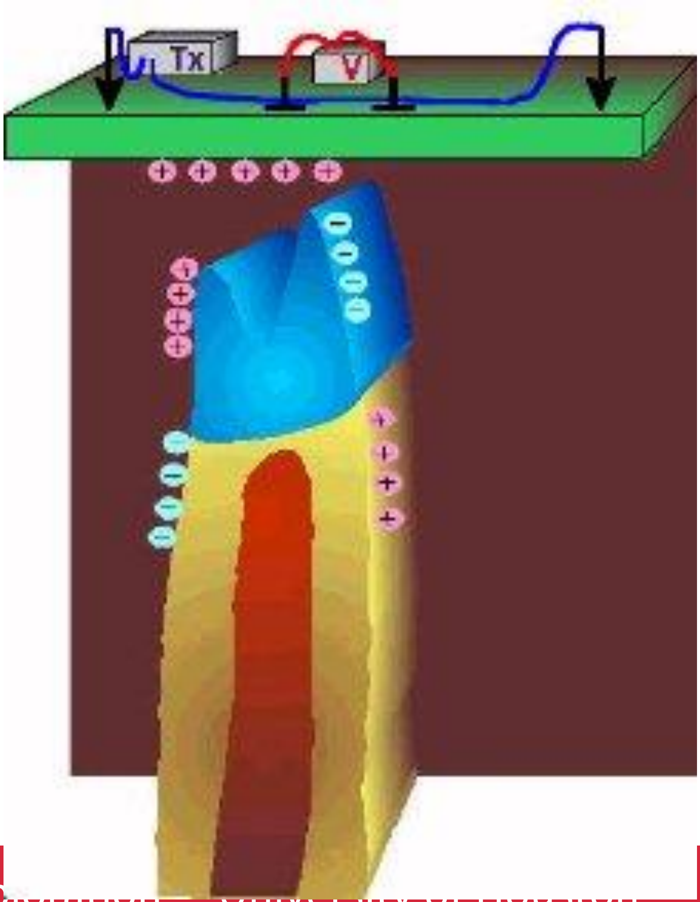

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How do we obtain resistivity?

Simple answer for uniform halfspace

$$\rho = \frac{2\pi r V}{I}$$

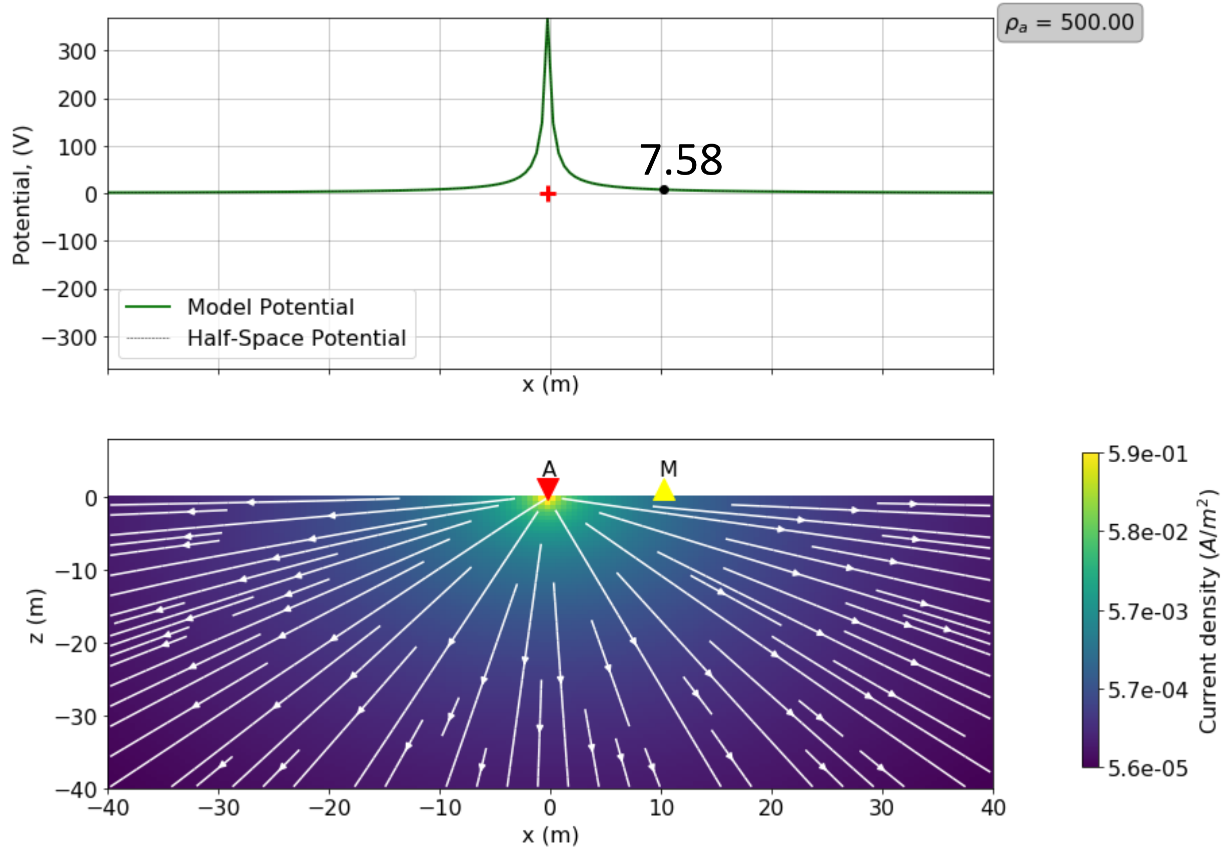

Image generated using DC_Plate2_5D. Pole-Pole. A -0.25 m, M 10.25 m. DC_Layer_Cylinder_2_5D would also do.

Special thanks to Thibaut Astic from UBC-GIF

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Think about Ohm's law

$$V = IR$$

Note that R is resistance

But we want to relate potential to resistivity

$$\rho = \frac{RA}{L}$$

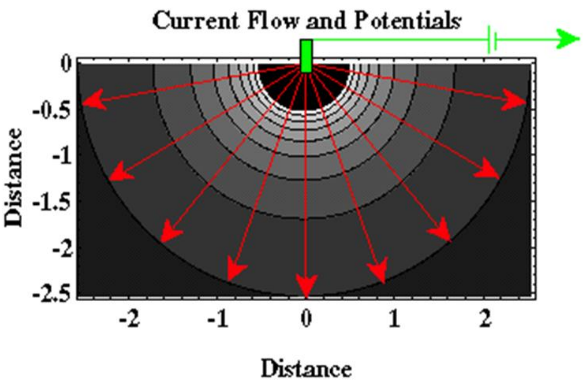
$$R = \frac{\rho L}{A}$$

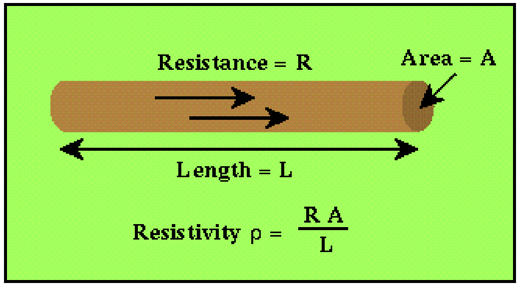
What is the L and A for our DC survey?

$$L = r$$
$$A = 2\pi r^2$$

Therefore, $R = \frac{\rho L}{A} = \frac{\rho}{2\pi r}$

Therefore, $V = IR = \frac{\rho I}{2\pi r}$





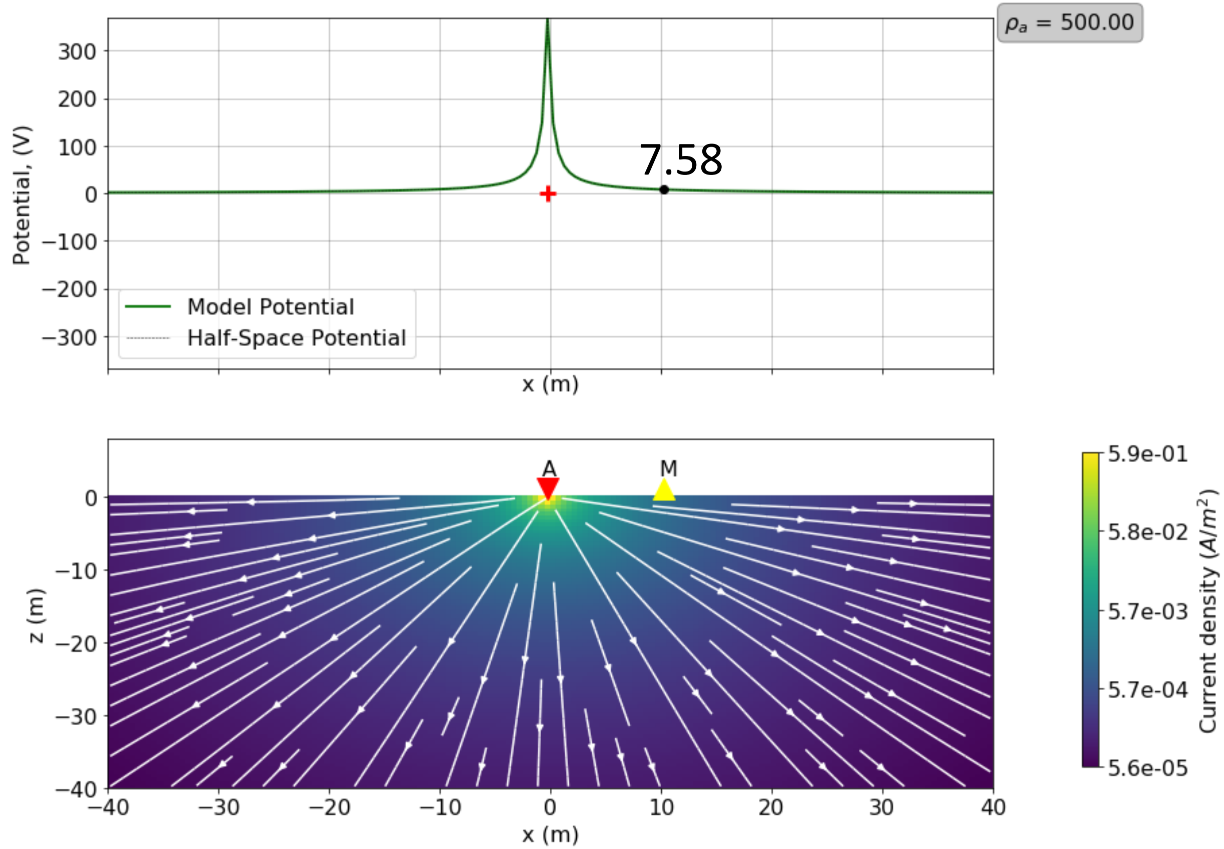
https://pburnley.faculty.unlv.edu/GEOL442_642/RES/NOTES/ResistivityNotes05Resistivity.html

A summary thus far

$$V = \frac{\rho I}{2\pi r}$$

$$\rho = \frac{2\pi r V}{I}$$

If we know current I
then, measure the potential value at any location
We can derive the resistivity of the Earth!!!



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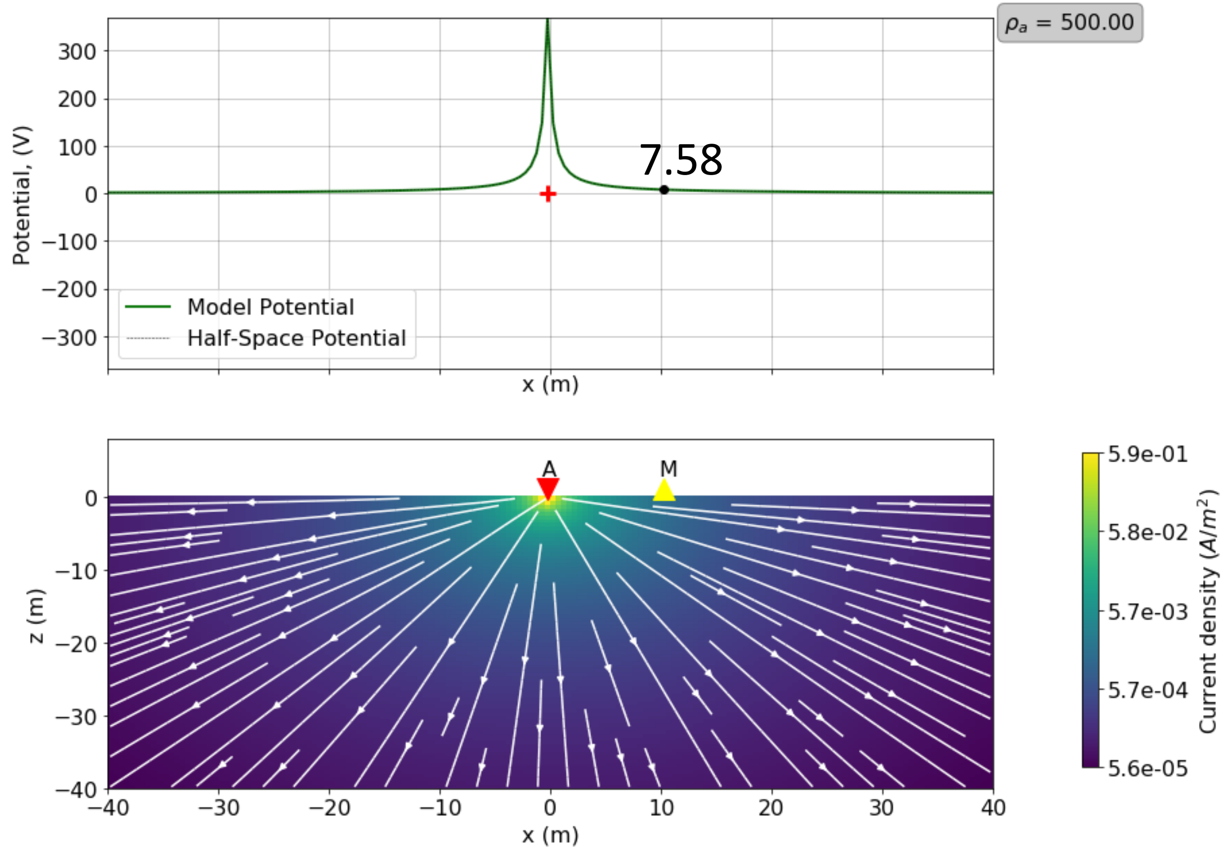
Exercise

- Calculate the potential at 10.5 m.

- Calculate the resistivity of the Earth, given a measured potential value.

Electric potential from single current electrode

$$V = \frac{\rho I}{2\pi r}$$



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Two electrode current sources

- Recall, for single current electrode,

$$V = IR = \frac{\rho I}{2\pi r}$$

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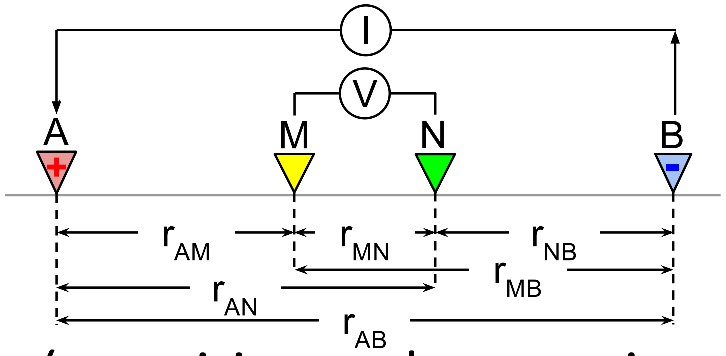
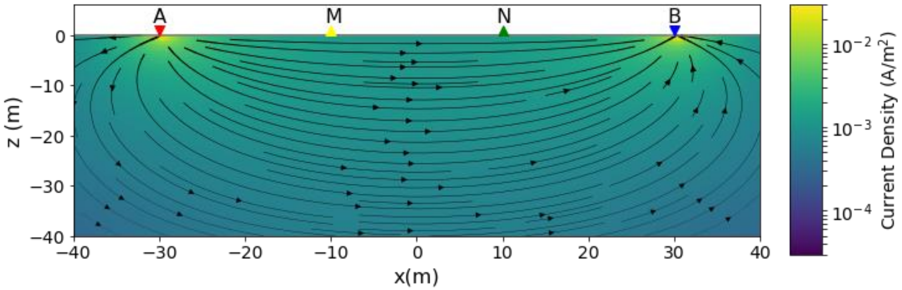


- What if we have two current electrodes (a positive and a negative electrode)?



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A: -30 m, B: 30 m, M: -10 m, N = 10 m. ρ = 500Ω·m

Observation:

- Current flows along the curved paths connecting the two electrodes

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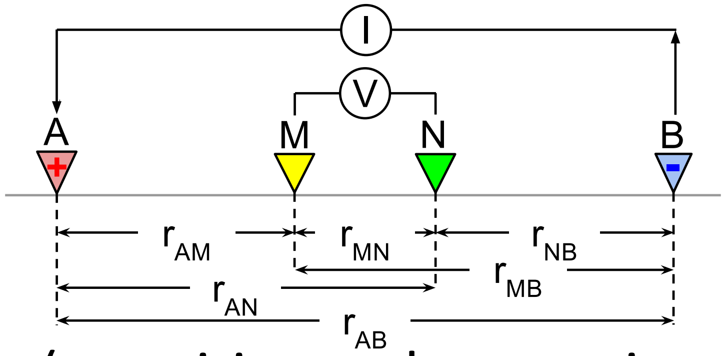

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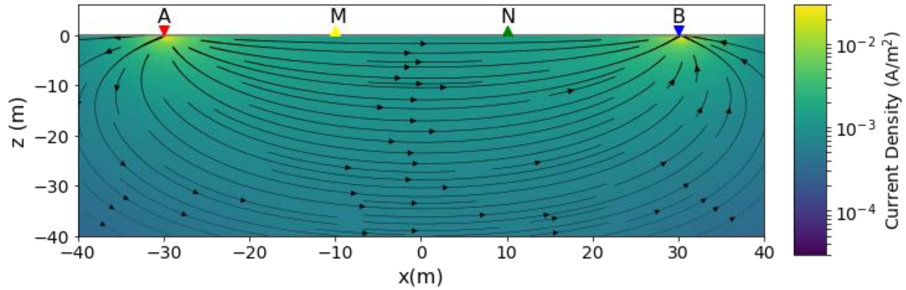

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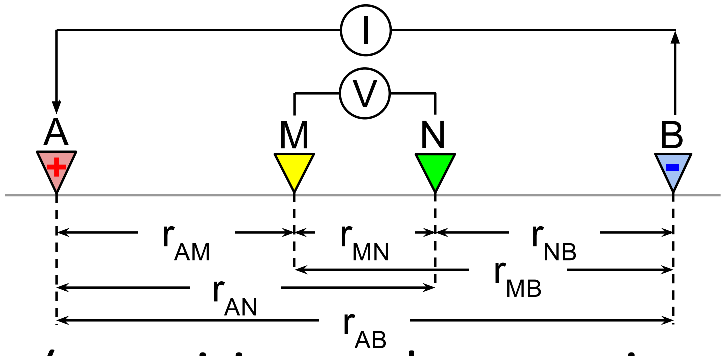

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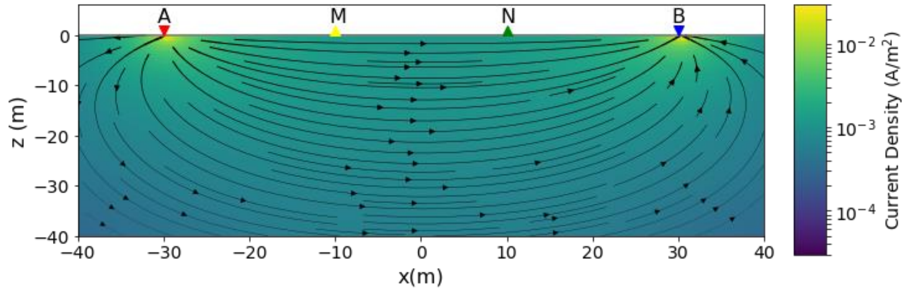

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$$V_M = \frac{\rho I}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}}\right)$$

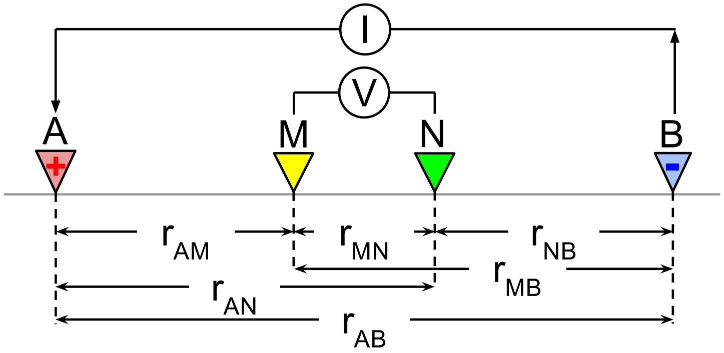
Observation:

- Current flows along the curved paths connecting the two electrodes

Voltage

- What we measure in practice is voltage (using voltmeter)
- That is, potential difference

What is the potential difference between potential electrodes M and N?



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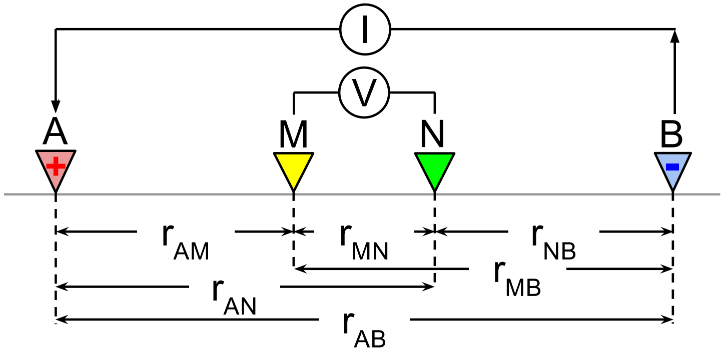

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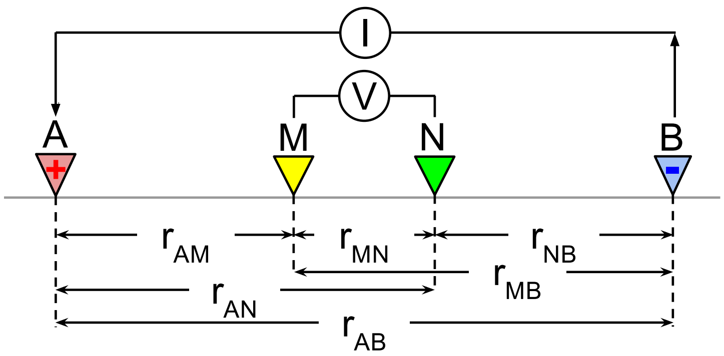

$$V_M = \frac{\rho I}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}}\right)$$

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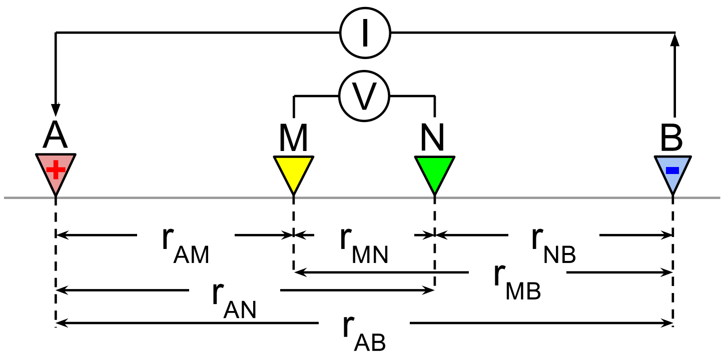

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$$V_M = \frac{\rho I}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}}\right)$$

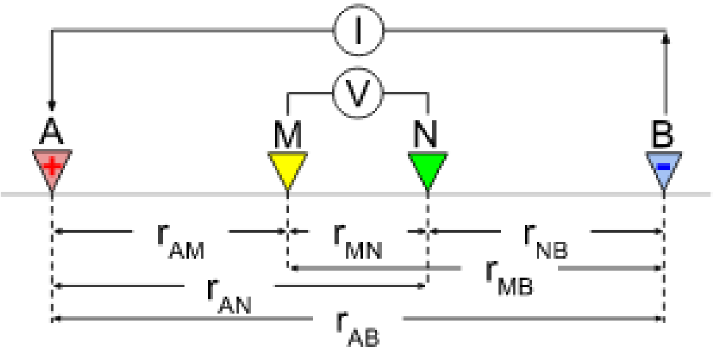
$$V_N = \frac{\rho I}{2\pi}\left(\frac{1}{r_{AN}} - \frac{1}{r_{BN}}\right)$$

$$\Delta V_{MN} = V_M - V_N = \rho I \frac{1}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right)$$

From voltage to resistivity

- Remember that, we want to estimate resistivity from the measured voltage

$$\Delta V_{MN} = V_M - V_N = \rho I \frac{1}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right)$$



From voltage to resistivity

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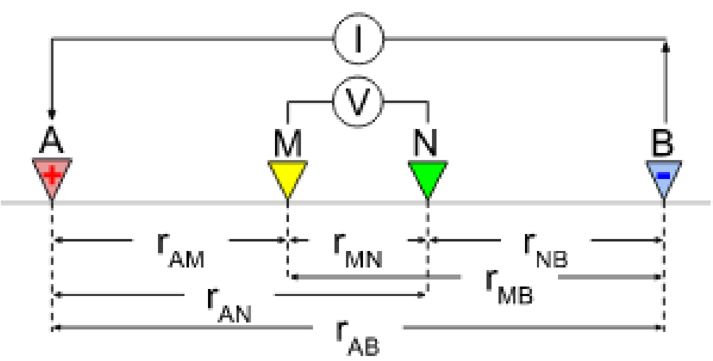
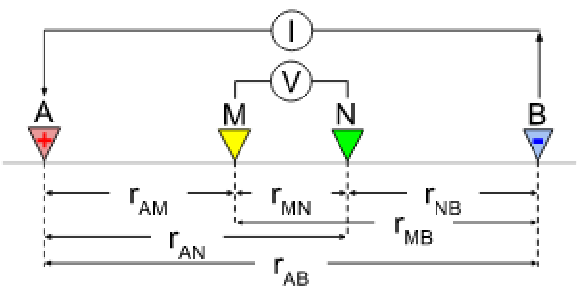
Geometric constant $G = \boxed{\frac{1}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right)}$



$$\rho = \frac{\Delta V_{MN}}{IG}$$

G is purely determined by survey geometry (i.e., locations of the electrodes)

Currents and potentials: 4-electrode array

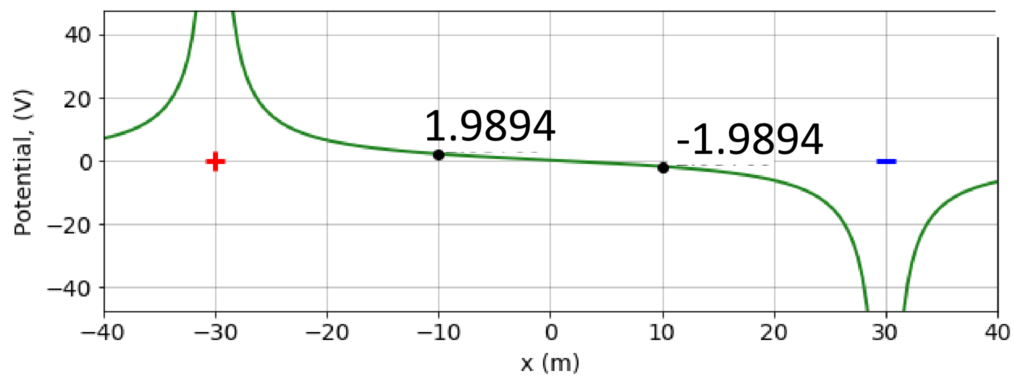


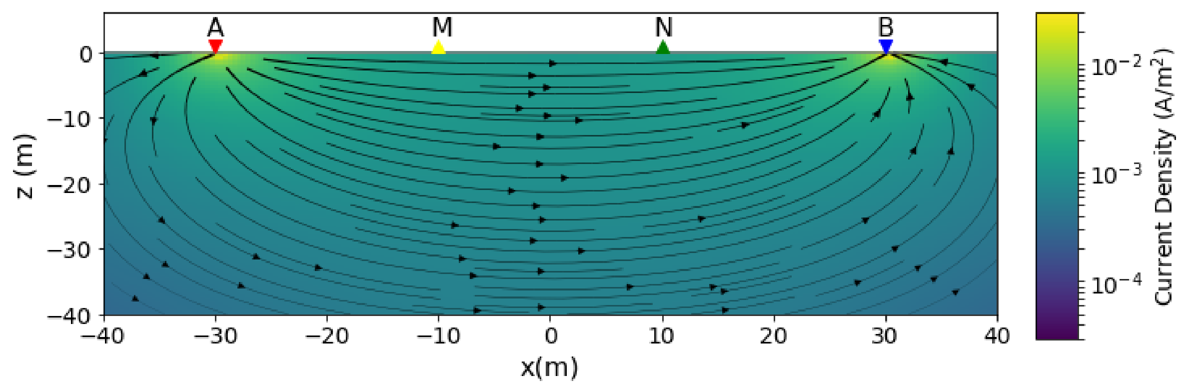
$$\Delta V_{MN} = \rho I \underbrace{\frac{1}{2\pi}\left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB}\right]}_{G}$$

Resistivity

$$\rho = \frac{\Delta V_{MN}}{IG}$$

Halfspace (500 Ωm)





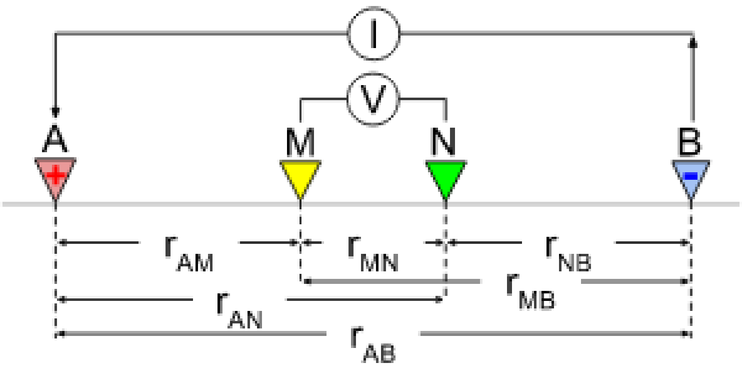
Images generated using DC_Layered Earth.ipynb.
A: -30 m, B: 30 m, M: -10 m, N = 10 m. ρ = 500Ω·m

Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Exercise

- Calculate the Earth's resistivity based on the following information:

$$V_M = 1.9894\ V$$
$$V_N = -1.9894\ V$$
$$I = 1\ A$$
$$A: -30\ m$$
$$B: 30\ m$$
$$M: -10\ m$$
$$N: 10\ m$$



$$\rho = \frac{\Delta V_{MN}}{IG}$$

$$G = \frac{1}{2\pi}\left(\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right)$$

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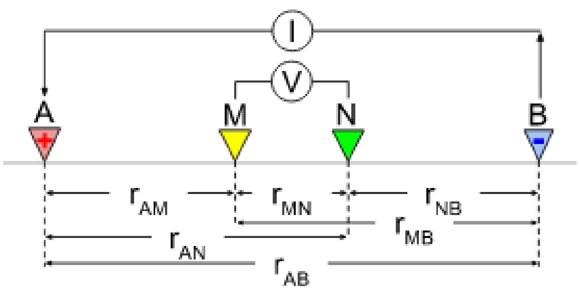

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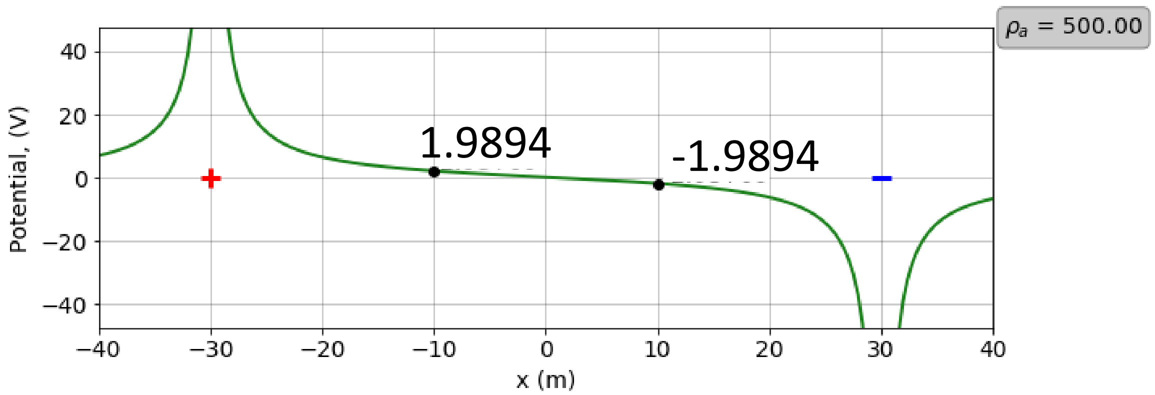

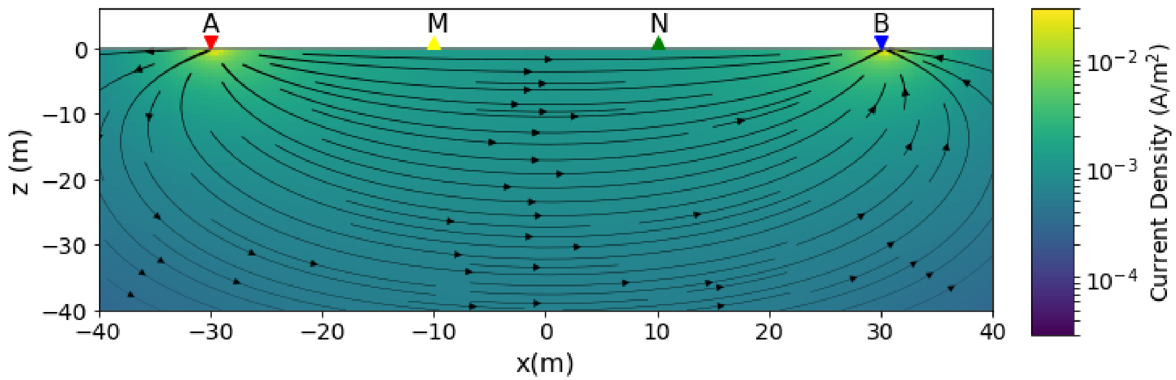

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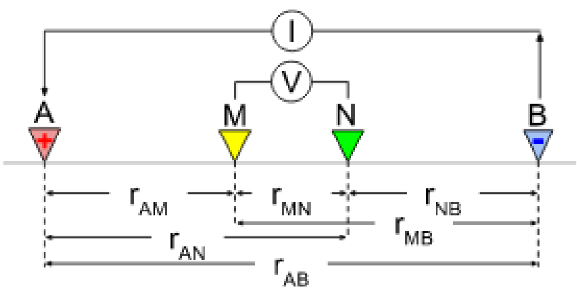
Inhomogeneous Earth

- So far so good!
- But remember that we have assumed a homogeneous Earth
- The real Earth is, unfortunately, not homogeneous!

Currents and Apparent Resistivity



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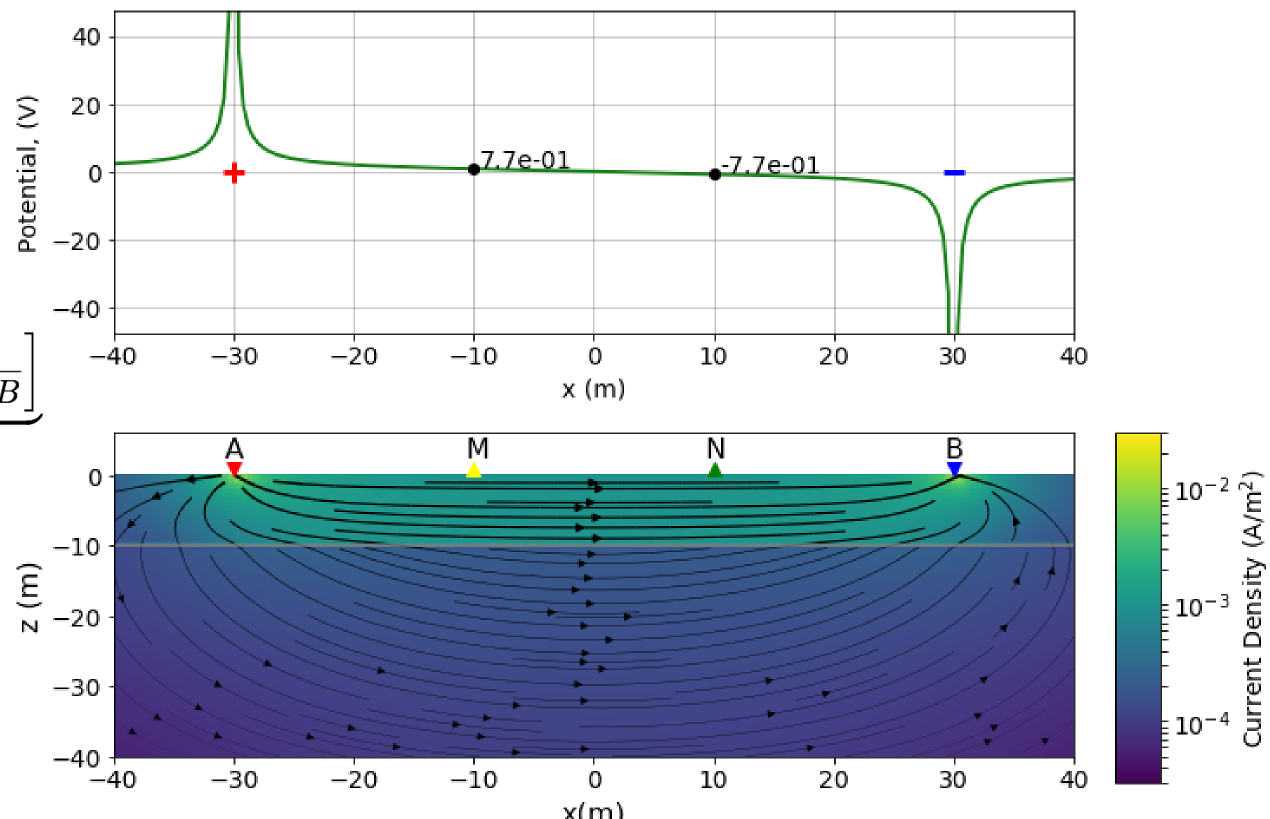
Apparent resistivity

$$\rho_a = \frac{\Delta V_{MN}}{IG}$$

Conductive overburden (100 Ωm)



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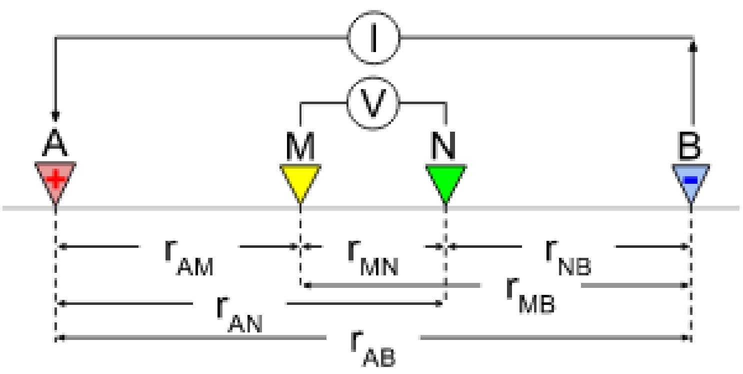
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Exercise

- Calculate the Earth's resistivity based on the following information:

$$V_M = 0.77\ V$$
$$V_N = -0.77\ V$$
$$I = 1\ A$$
$$A: -30\ m$$
$$B: 30\ m$$
$$M: -10\ m$$
$$N: 10\ m$$



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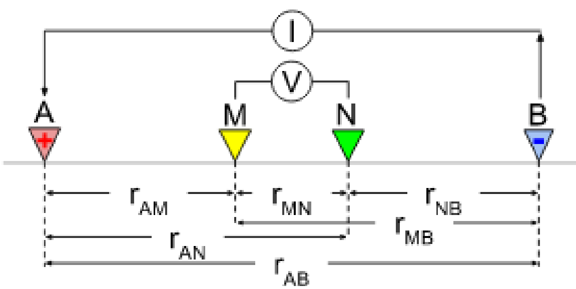
Currents and Apparent Resistivity



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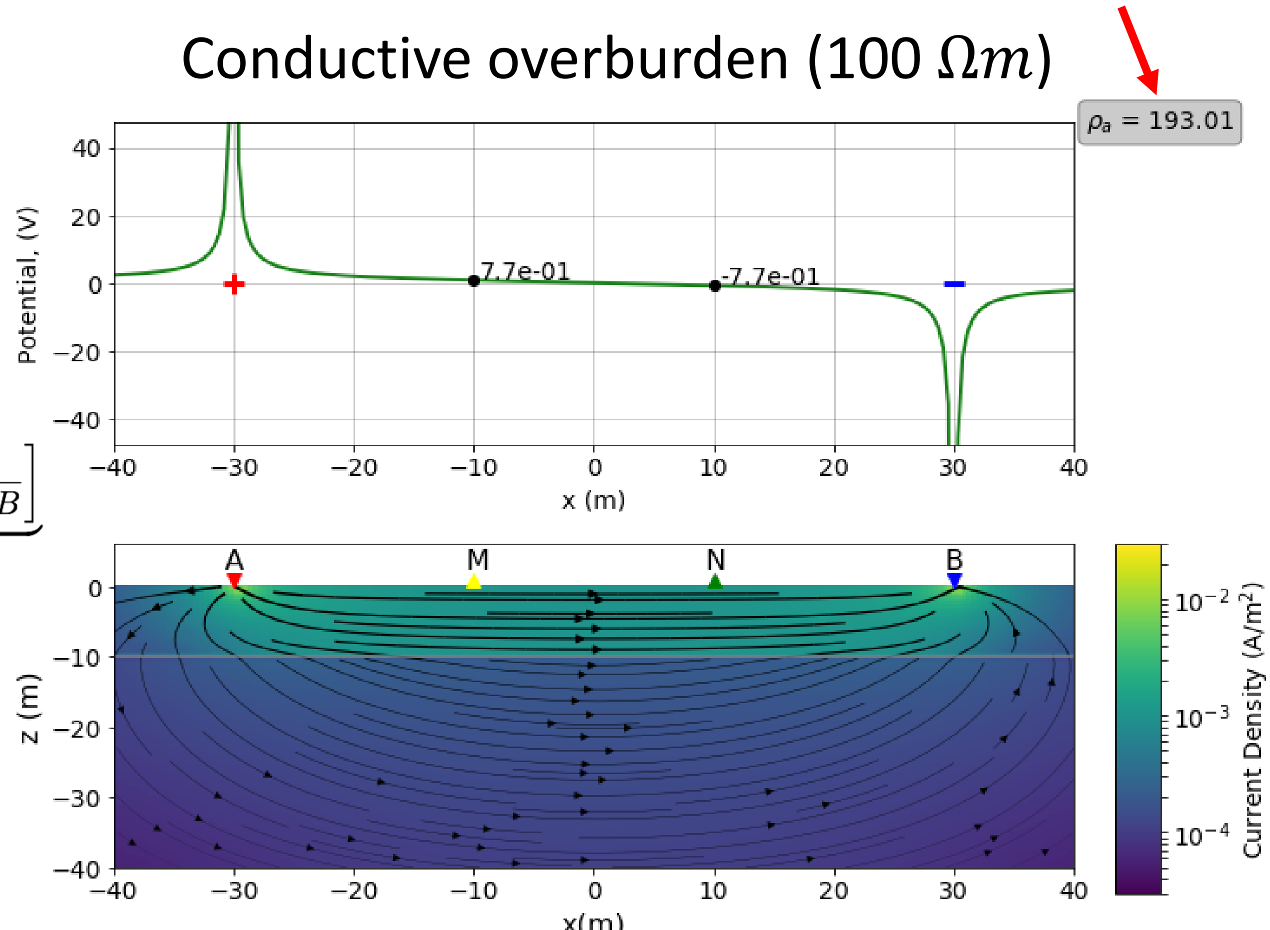

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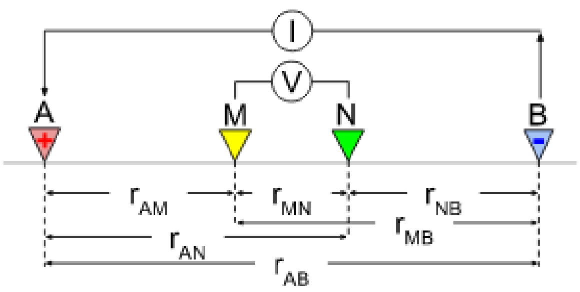
Currents and Apparent Resistivity



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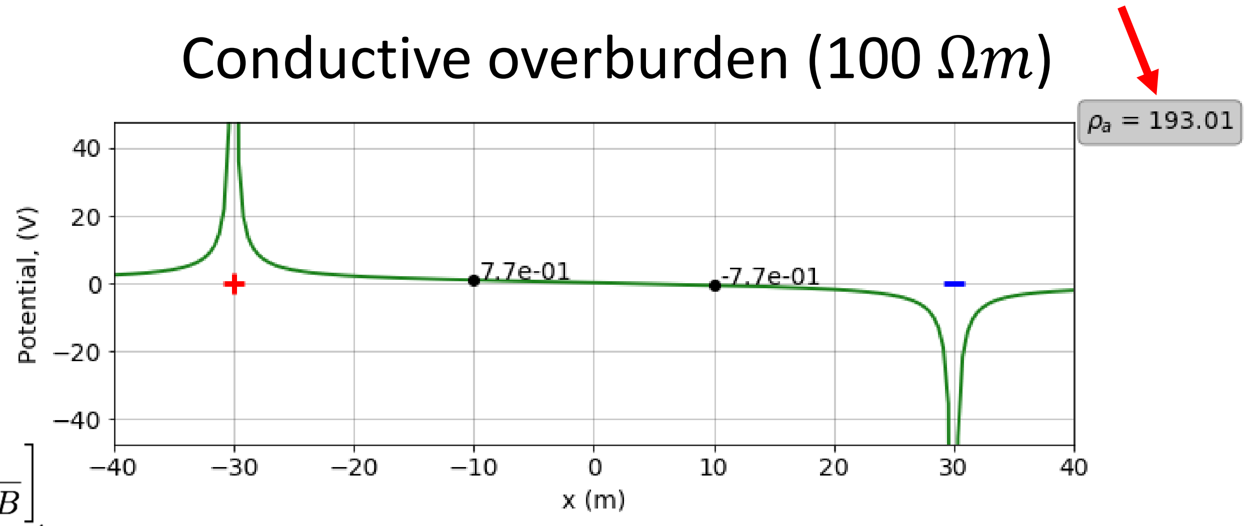

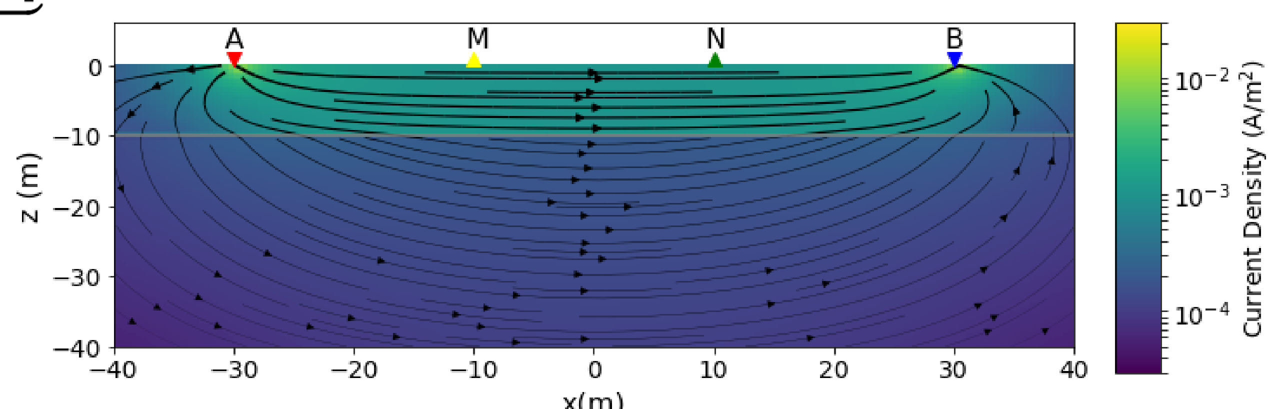

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Apparent resistivity

$$\rho_a = \frac{\Delta V_{MN}}{IG}$$

- Compare it with Ohm's law:

Apparent resistivity

$$\rho_a = \frac{\Delta V_{MN}}{IG} \qquad\qquad R = \frac{V}{I}$$

- Compare it with Ohm's law: apparent resistivity is equal to voltage divided by current (multiplied by G)

Apparent resistivity

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- If the Earth is homogeneous, the apparent resistivity is equal to the true resistivity of the Earth.

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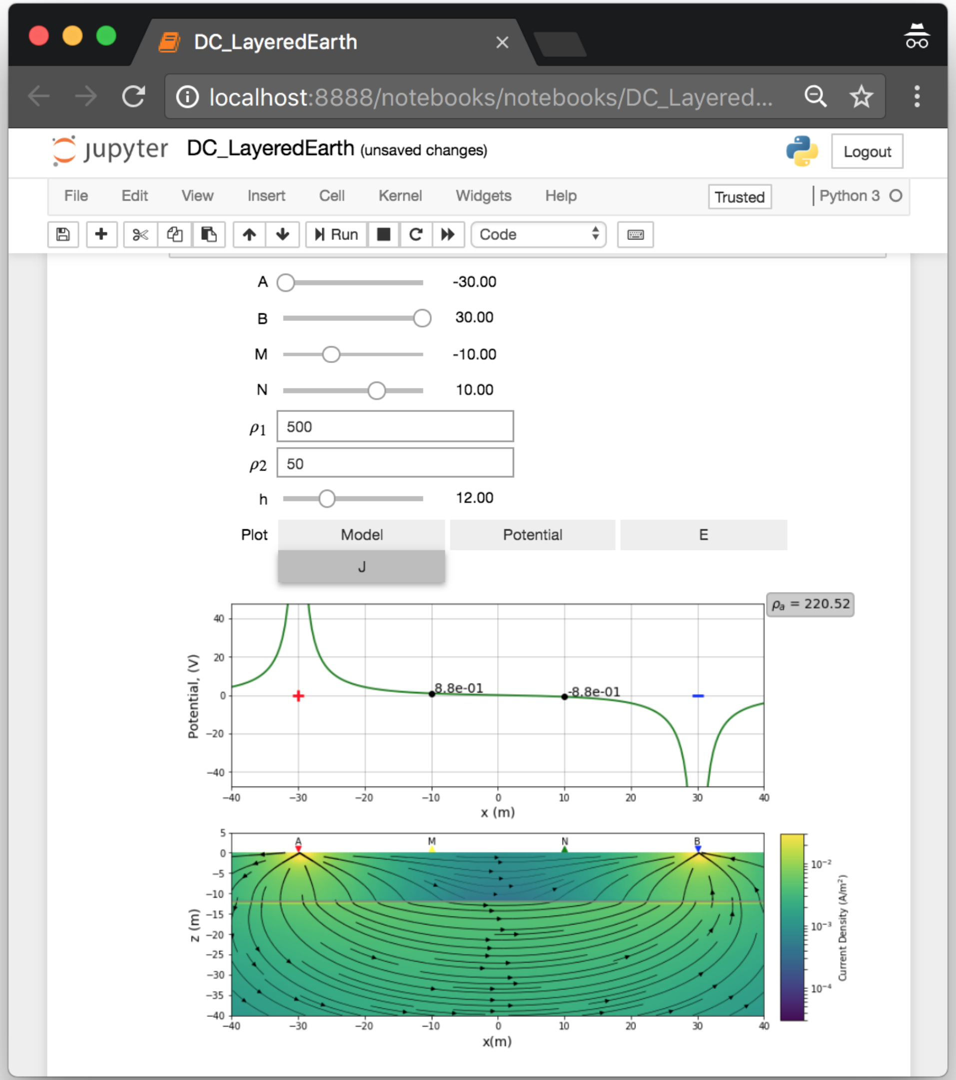
- For inhomogeneous Earth, the apparent resistivity is some complicated averaging of the resistivities of all materials encountered by the currents.
- It can be interpreted as the resistivity that would have been measured if the Earth were homogeneous.

DC Simulation App

Why interactive apps?

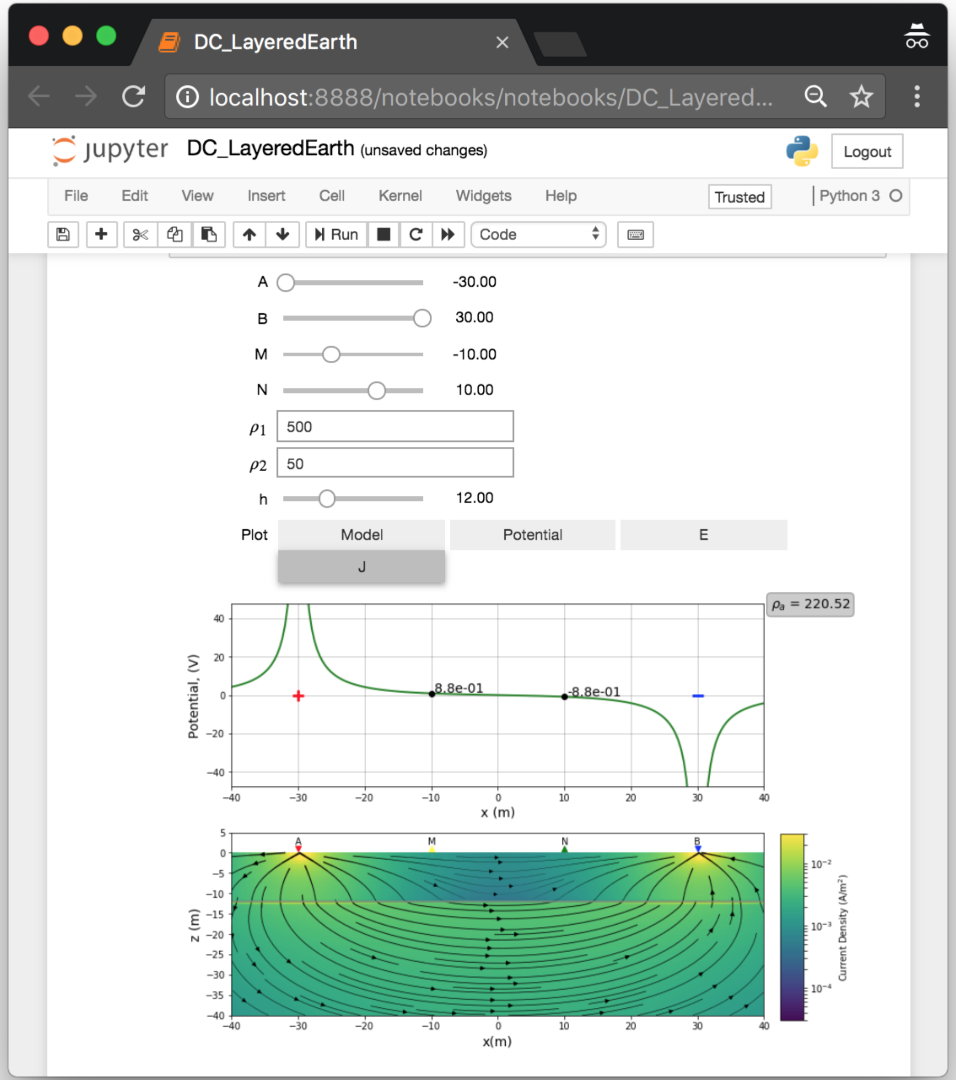
- Visualization aids understanding
- Learn through interaction
  - ask questions and investigate
- Open source:
  - Free to use
  - Welcome contributions!



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

DC Simulation App

- DC_LayeredEarth.ipynb
- Parameters:
  - Layer resistivities
  - Layer thickness
  - Electrode locations
- View:
  - Model
  - Electric potential
  - Electric field
  - Current density



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Current density (optional)

Remember that

$$\nabla \cdot \boldsymbol{J} = -\frac{\partial \rho}{\partial t}$$

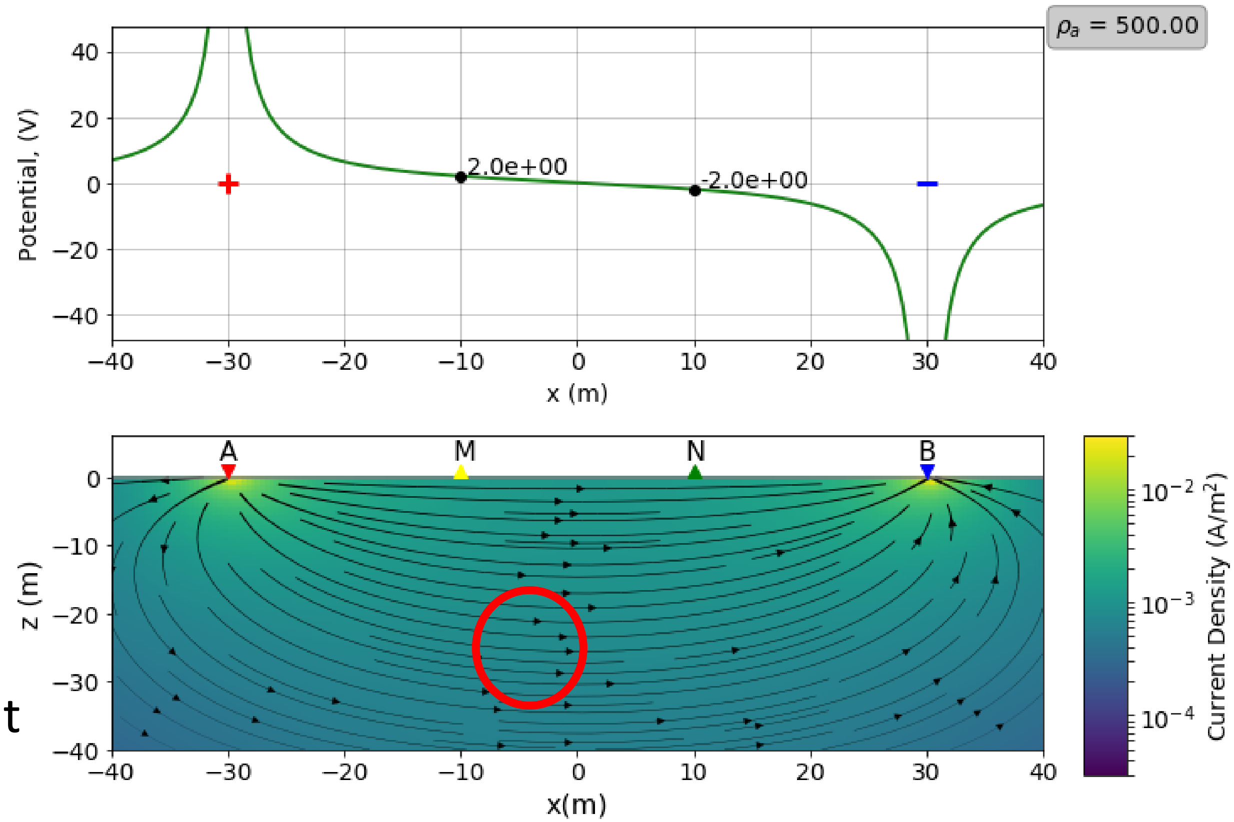
The only place where $\frac{\partial \rho}{\partial t}$ is nonzero is at the current electrodes.

At all other locations,

$$\nabla \cdot \boldsymbol{J} = 0$$

That is, convergence is 0.

That is, all of the current that flows into a volume must be equal to the current flowing out of the volume.



Images generated using DC_LayeredEarth.ipynb. A: -30 m, B: 30 m, M: -10 m, N = 10 m. ρ = 500 Ω·m.

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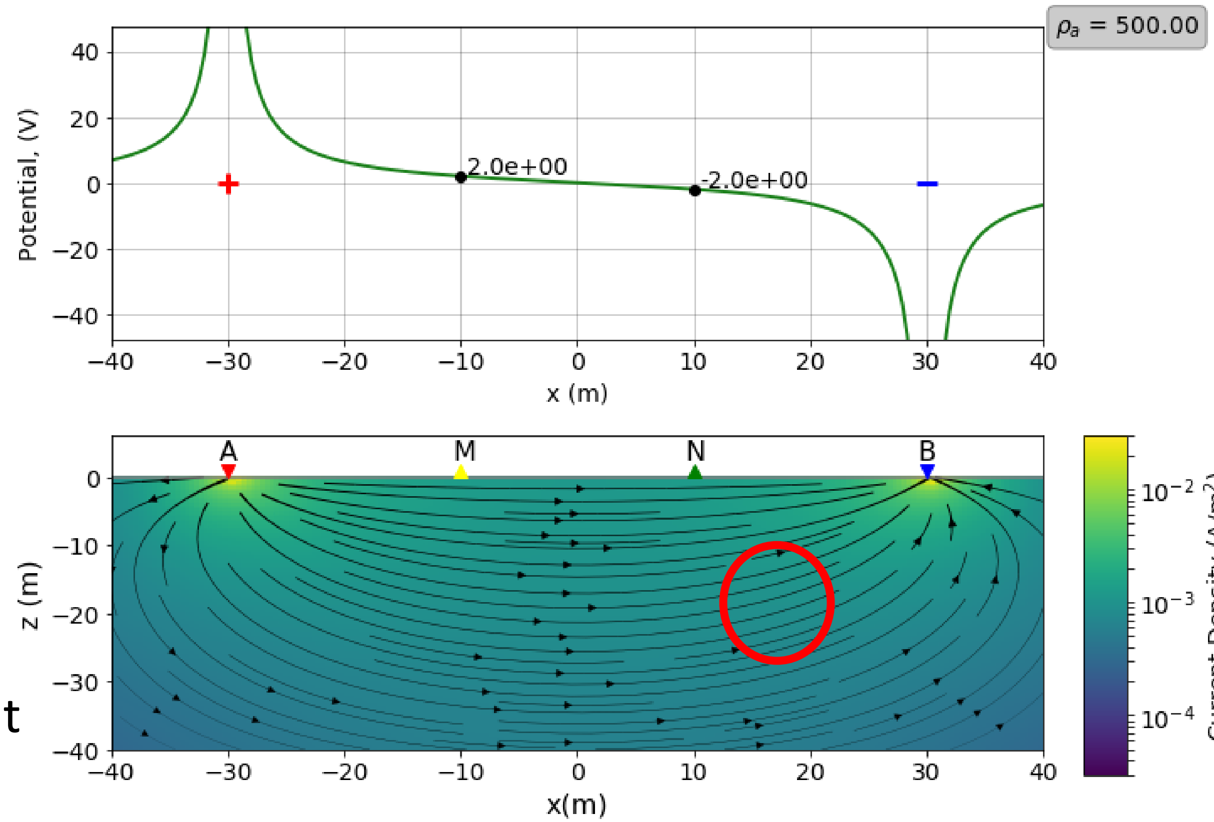

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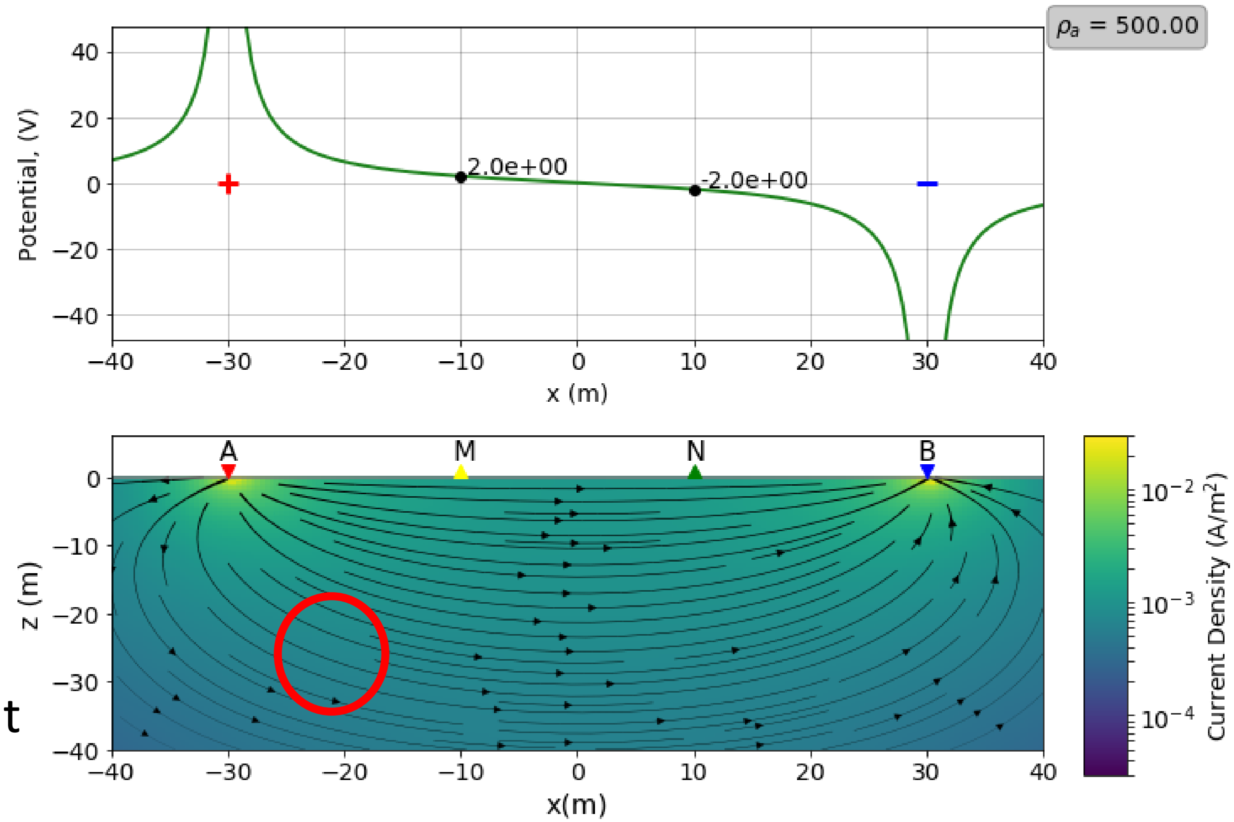

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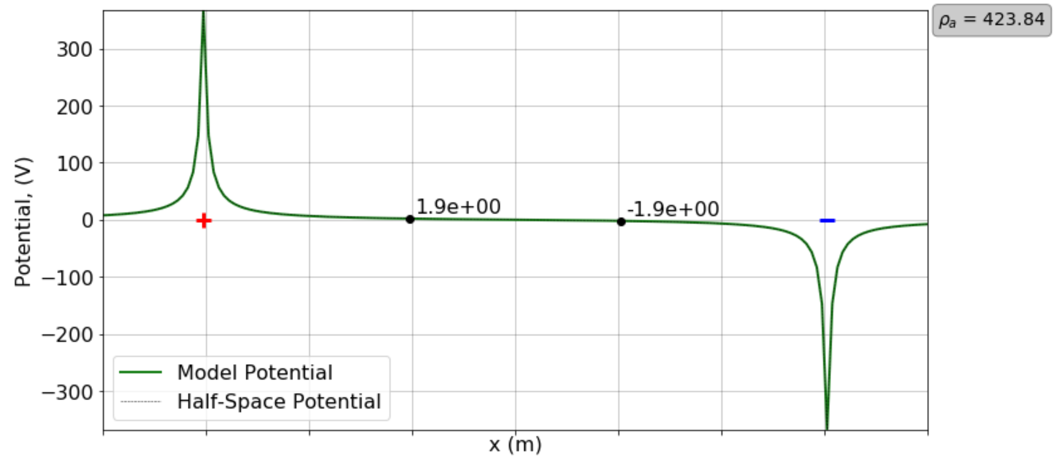
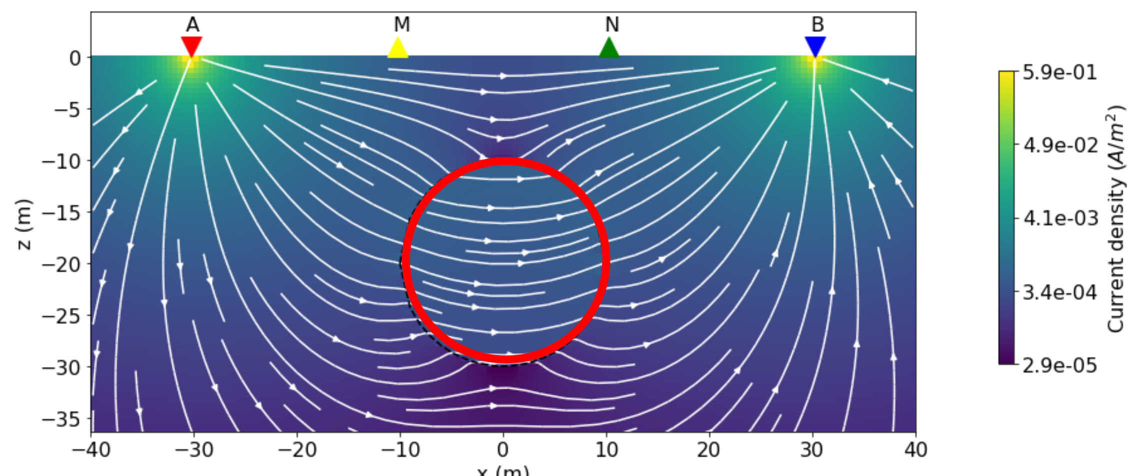


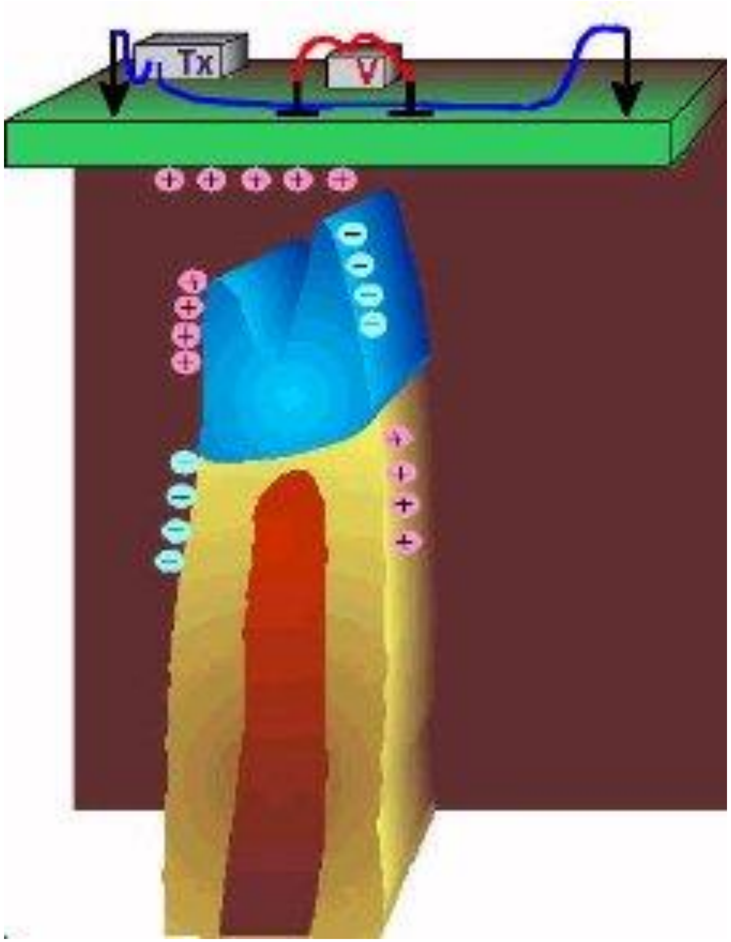


Images generated using DC_Layer_Cylinder_2_5D.ipynb. A: -30.25 m, B: 30.25 m, M: -10.25 m, N = 10.25 m. $\rho 1$ = 500 Ω·m, $\rho 2$ = 50 Ω·m.

Agenda

- Recap
- Two current electrodes
- Apparent resistivity
- Understanding charges

Understanding the charges



Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Some simple math

$$\nabla \cdot \boldsymbol{J} = 0 \longrightarrow J_{1n} = J_{2n}$$

The normal component of current density is continuous.

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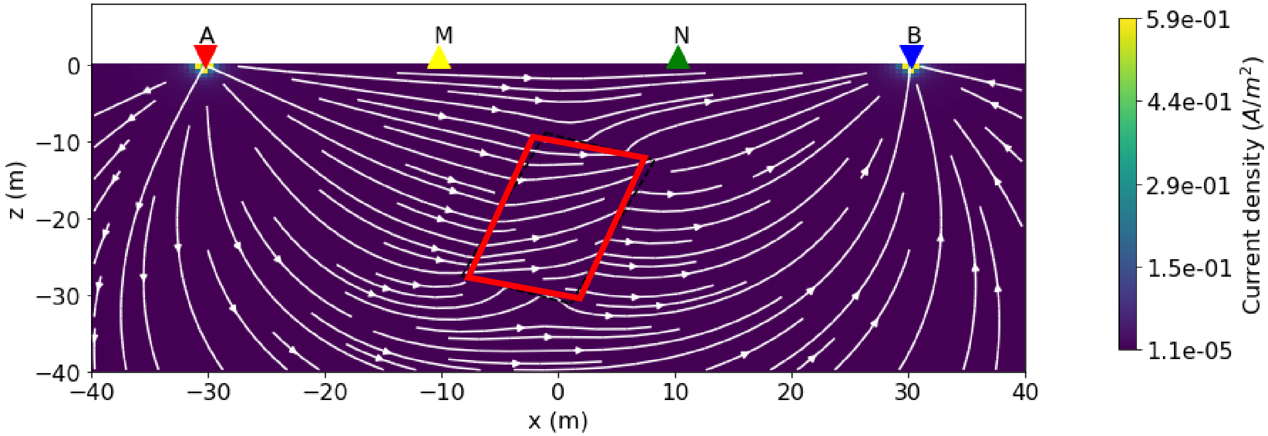

Images generated using DC_Plate2_5D.ipynb. A: -30.25 m, B: 30.25 m, M: -10.25 m, N = 10.25 m. ρ1 = 500 Ω·m, ρ2 = 10 Ω·m. dx = 10, dz=20, xc = 0, zc = -20, theta = 21.

How about the electric field?

$$\nabla \cdot \boldsymbol{J} = 0 \longrightarrow J_{1n} = J_{2n}$$

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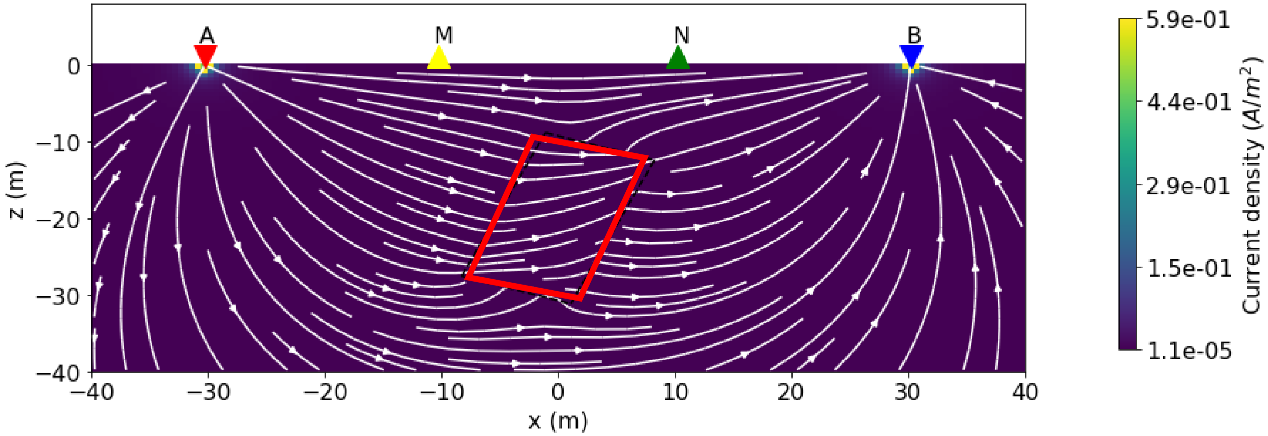

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Then, $\sigma_1 E_{1n} = \sigma_2 E_{2n}$

The normal component of electric field is discontinuous if there is resistivity contrast across some boundary.

What happens when $\sigma_1 \neq \sigma_2$?

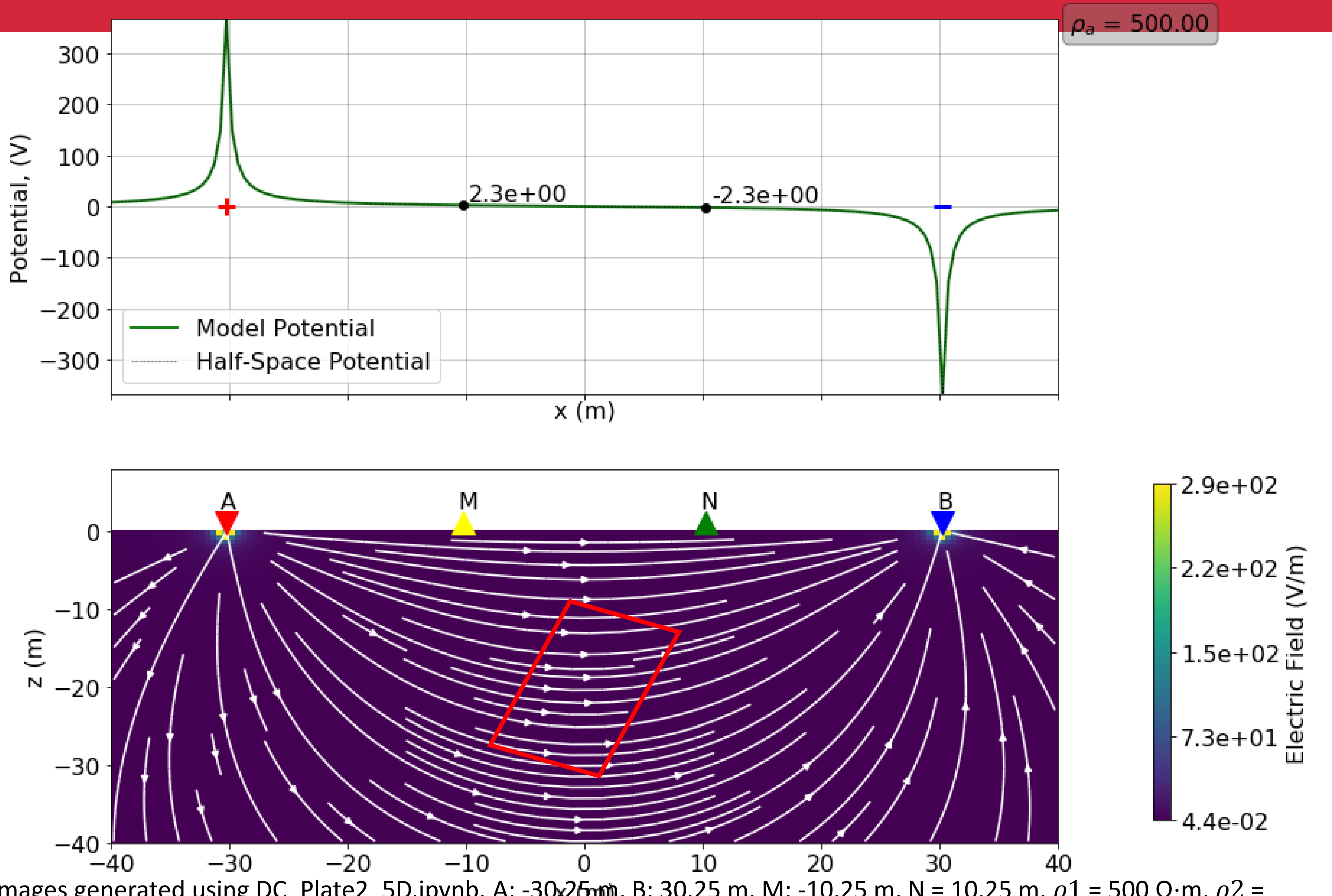
$E_{1n} \neq E_{2n}$!!

How about the tangential component of electric field?

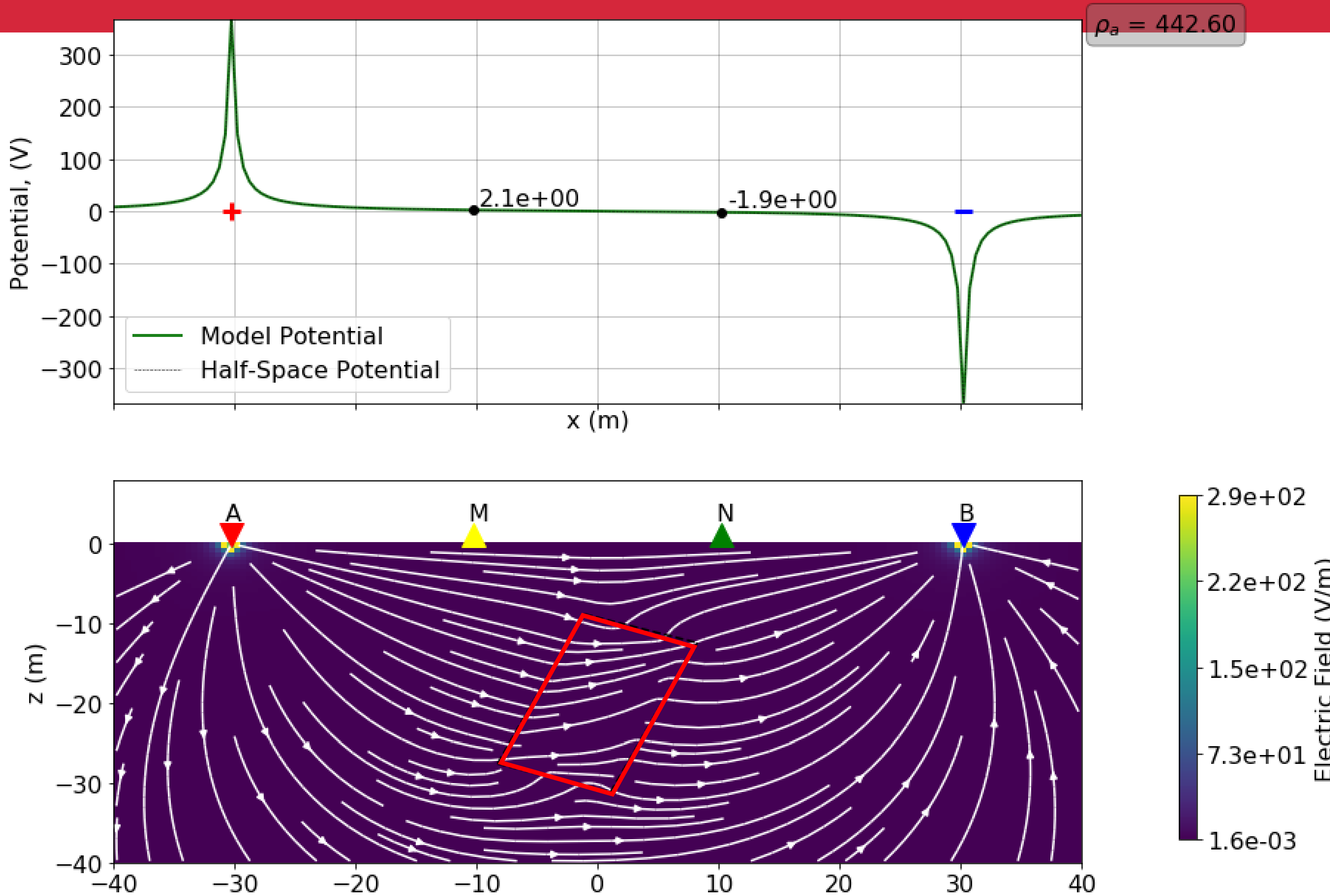
Optional materials

- Short answer:

- Because $\nabla \times \boldsymbol{E} = 0$, $E_{1t} = E_{2t}$



Images generated using DC_Plate2_5D.ipynb. A: -30.25 m, B: 30.25 m, M: -10.25 m, N = 10.25 m. $\rho1$ = 500 Ω·m, $\rho2$ = 500 Ω·m. dx = 10, dz=20, xc = 0, zc = -20, theta = 21.



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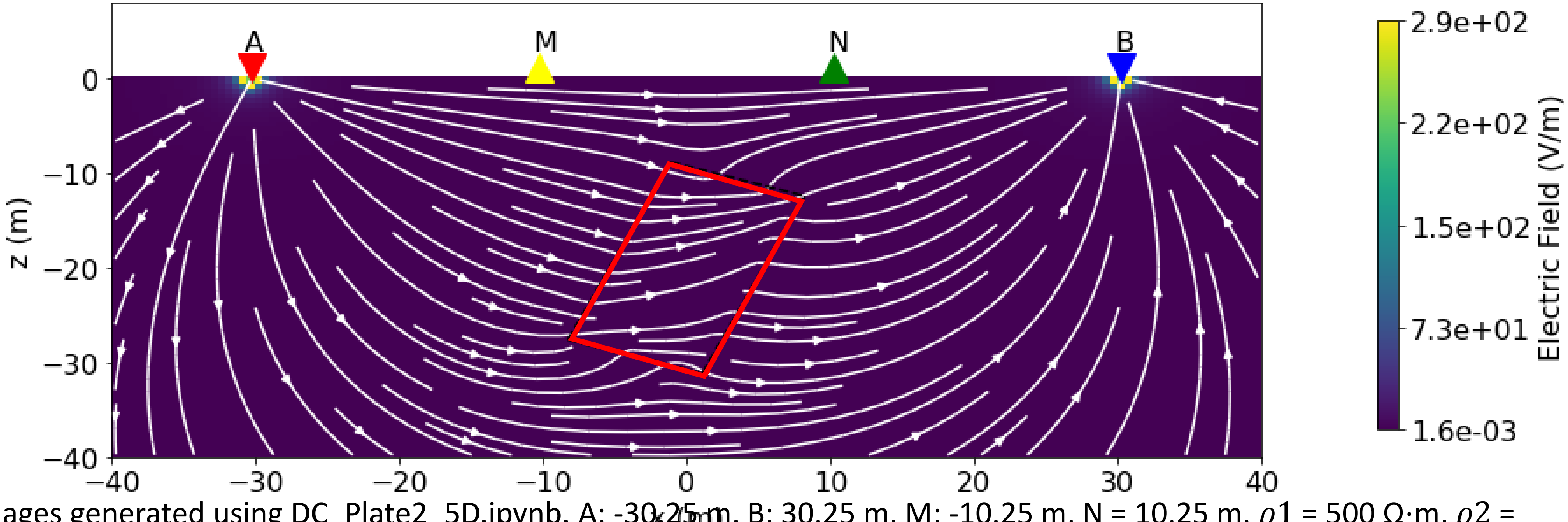
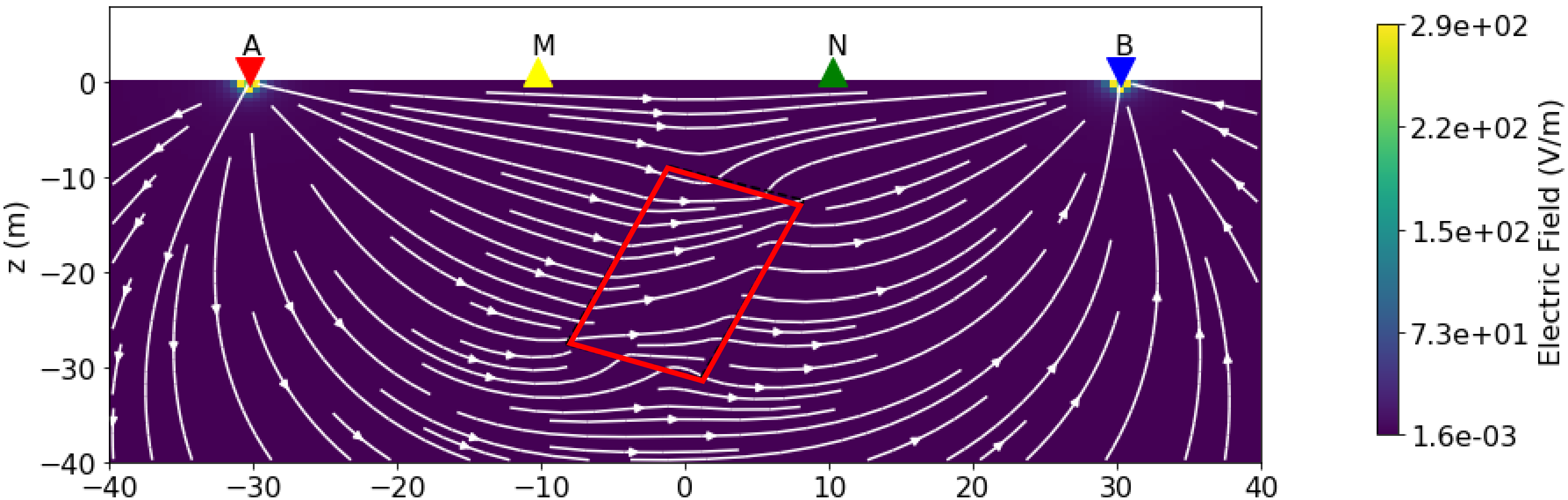
- What could have happened?



Images generated using DC_Plate2_5D.ipynb. A: -30.25 m, B: 30.25 m, M: -10.25 m, N = 10.25 m. $\rho 1$ = 500 Ω·m, $\rho 2$ = 10 Ω·m. dx = 10, dz=20, xc = 0, zc = -20, theta = 21.

- What could have happened?

$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



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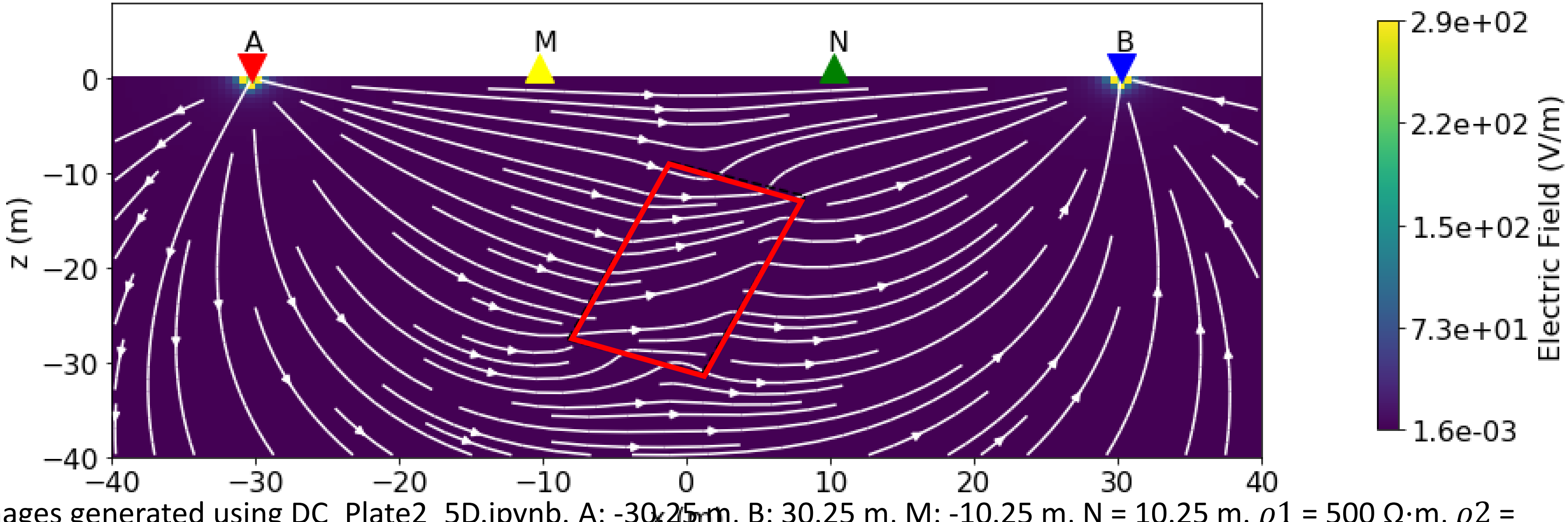
- What could have happened?

- The electric field becomes discontinuous across the boundary.

$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



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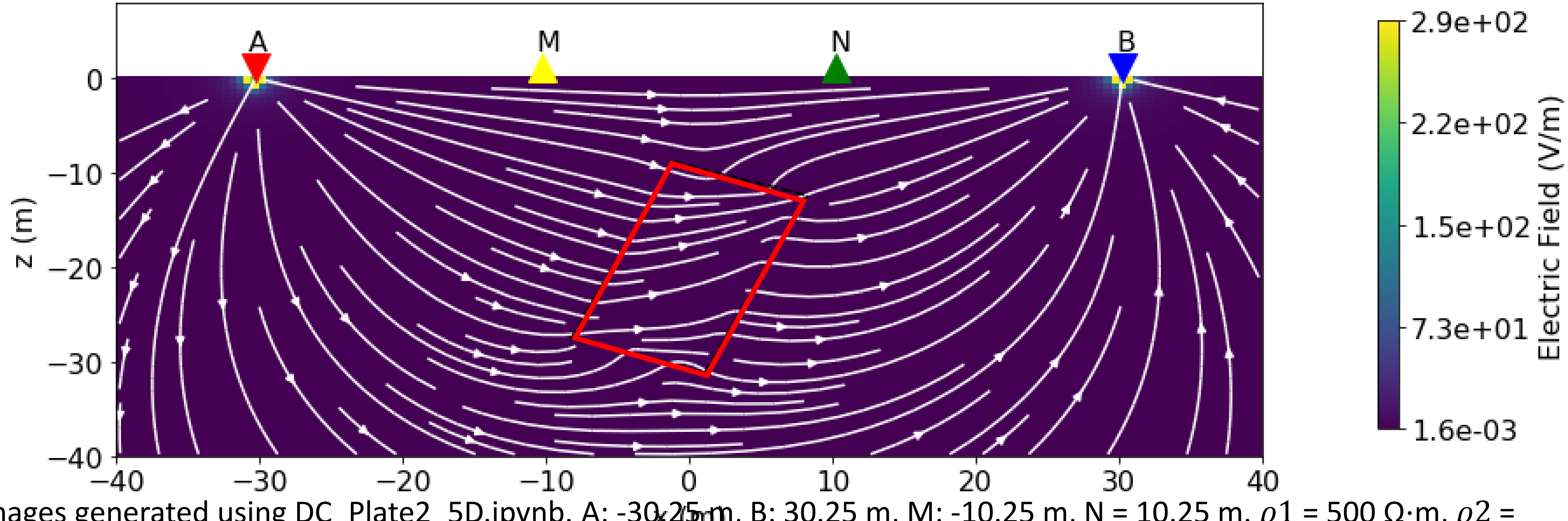
- What could have happened?
- The electric field becomes discontinuous across the boundary.
- What causes the electric field to be discontinuous?

$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



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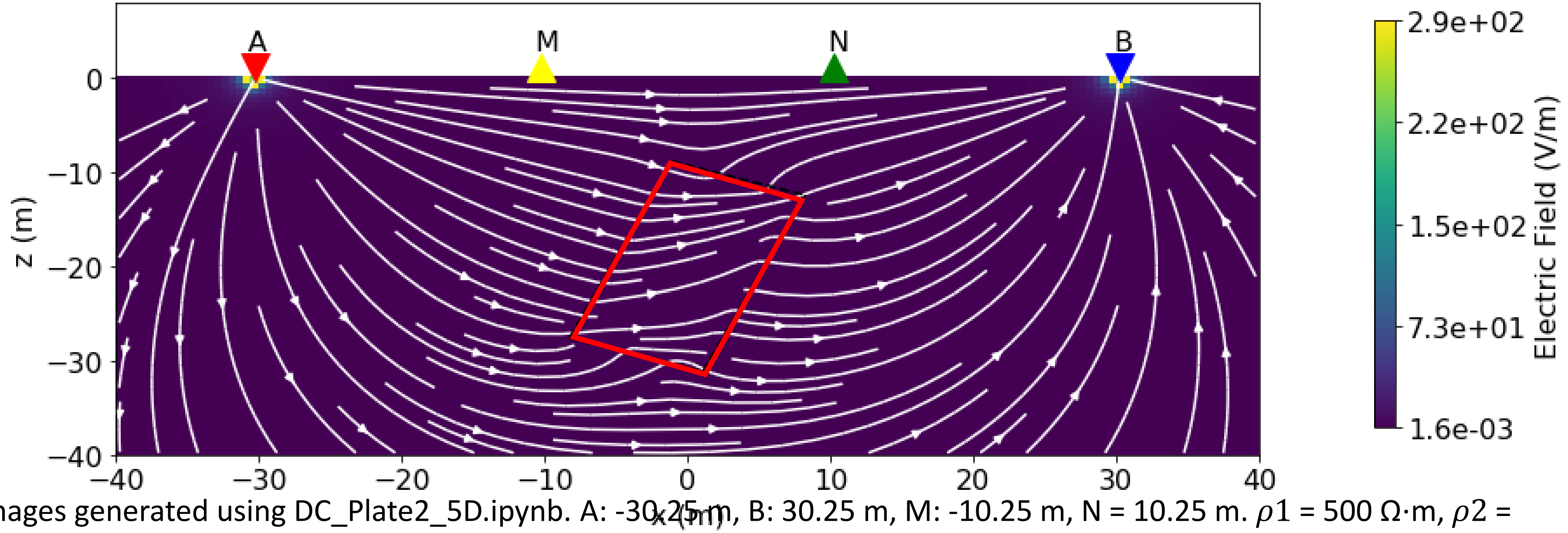
- What could have happened?

- The electric field becomes discontinuous across the boundary.

- What is the easiest way to make the electric field discontinuous?

$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



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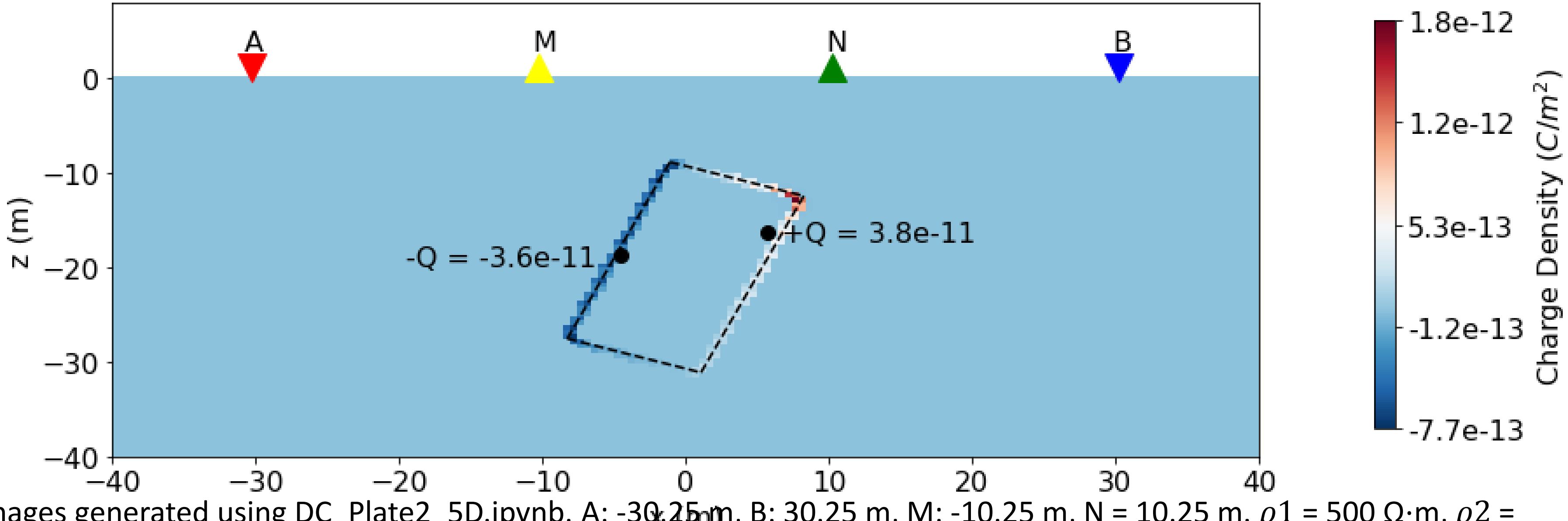
- What could have happened?
- The electric field becomes discontinuous across the boundary.
- What is the easiest way to make the electric field discontinuous?

$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



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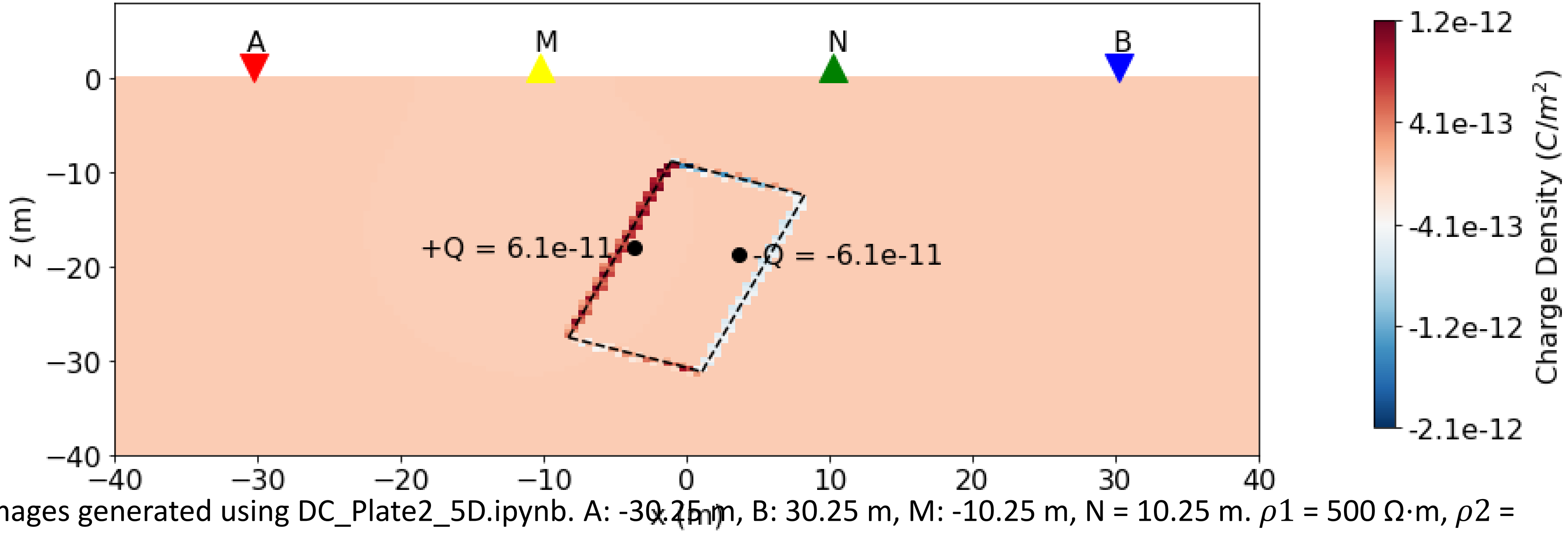
How about a resistor?

- What is the easiest way to make the electric field discontinuous?

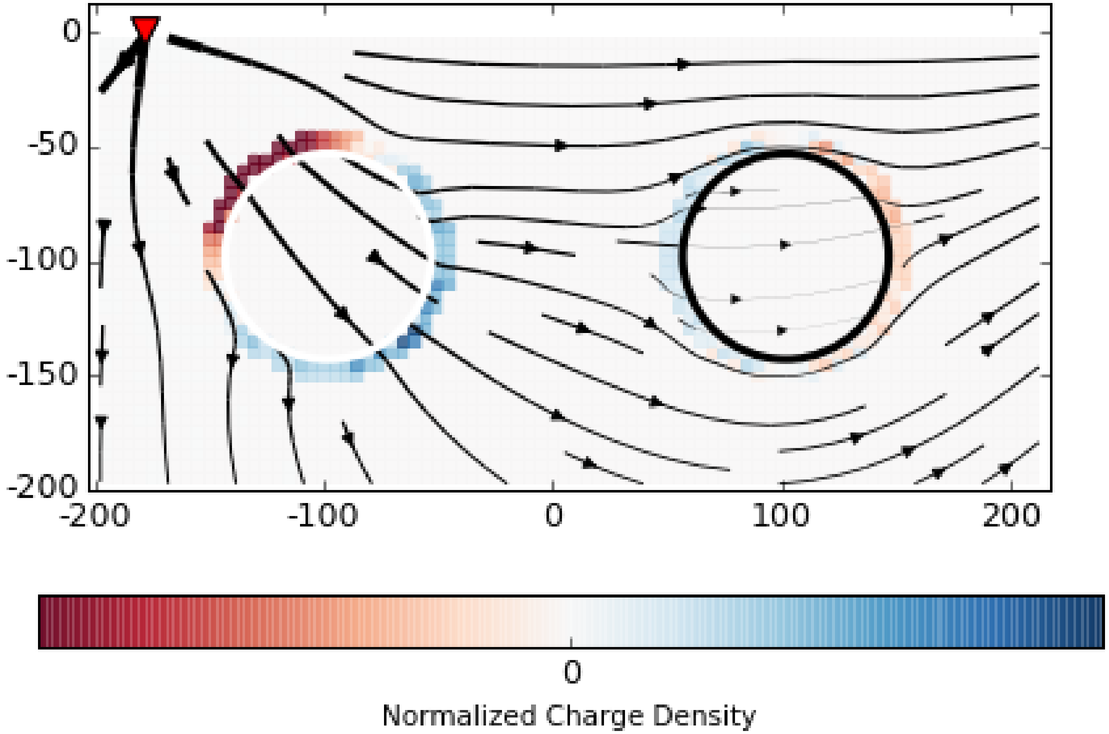
$$\sigma_1 E_{1n} = \sigma_2 E_{2n}$$



Images generated using DC_Plate2_5D.ipynb. A: -30.25 m, B: 30.25 m, M: -10.25 m, N = 10.25 m. $\rho 1$ = 500 Ω·m, $\rho 2$ = 5000 Ω·m. dx = 10, dz=20, xc = 0, zc = -20, theta = 21.

Test

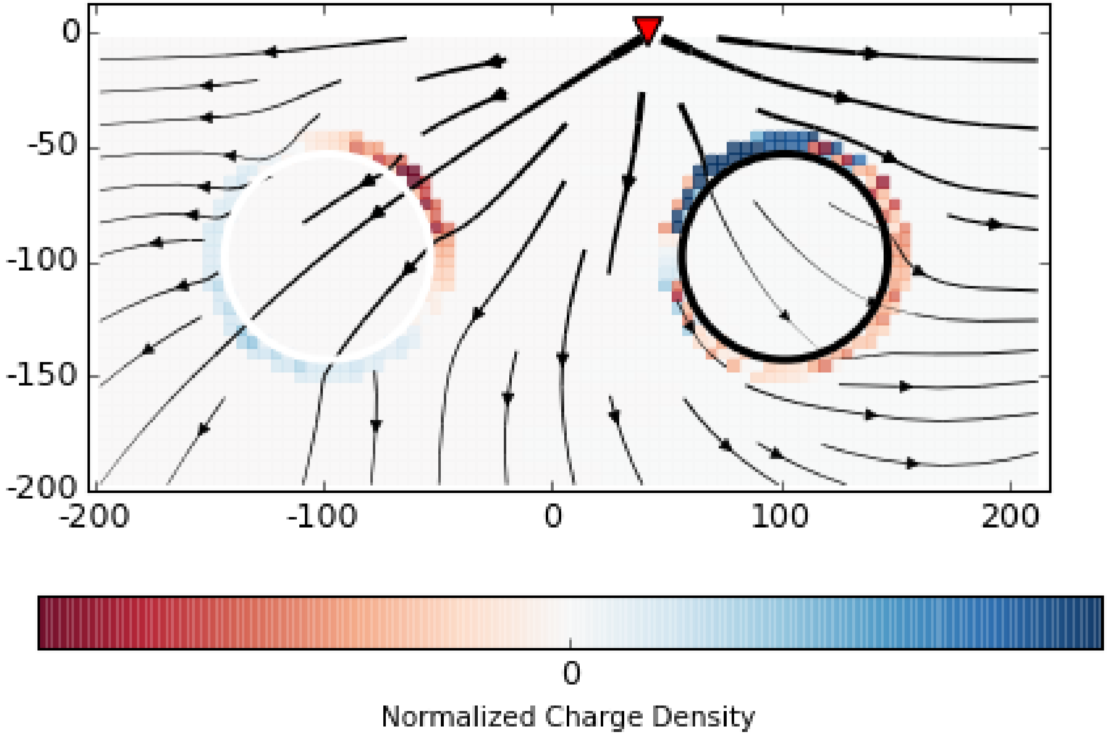
Can you tell which one is conductive and which one is resistive?



https://gpg.geosci.xyz/content/DC_resistivity/DC_basic_principles_heterogeneous_earth.html

Test

Now that you have figured out which one is conductive and which is resistive. What do you think the charges will look like for the following scenario?

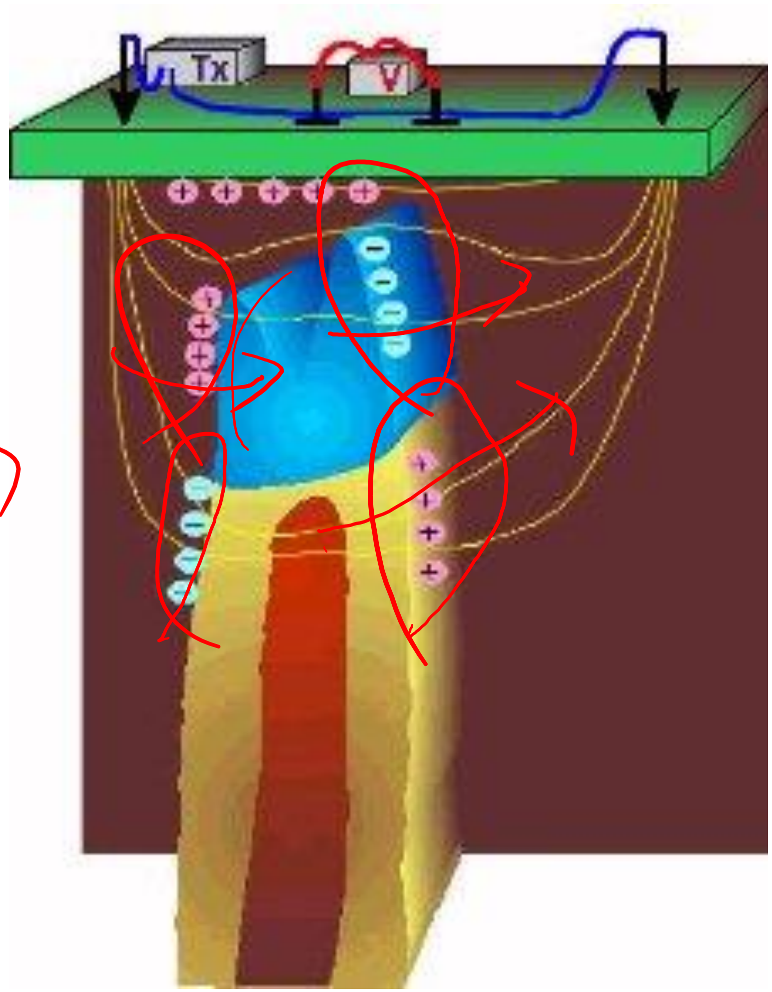


https://gpg.geosci.xyz/content/DC_resistivity/DC_basic_principles_heterogeneous_earth.html

Optional reading materials

- https://gpg.geosci.xyz/content/DC_resistivity/DC_basic_principles_heterogeneous_earth.html

Understanding the charges



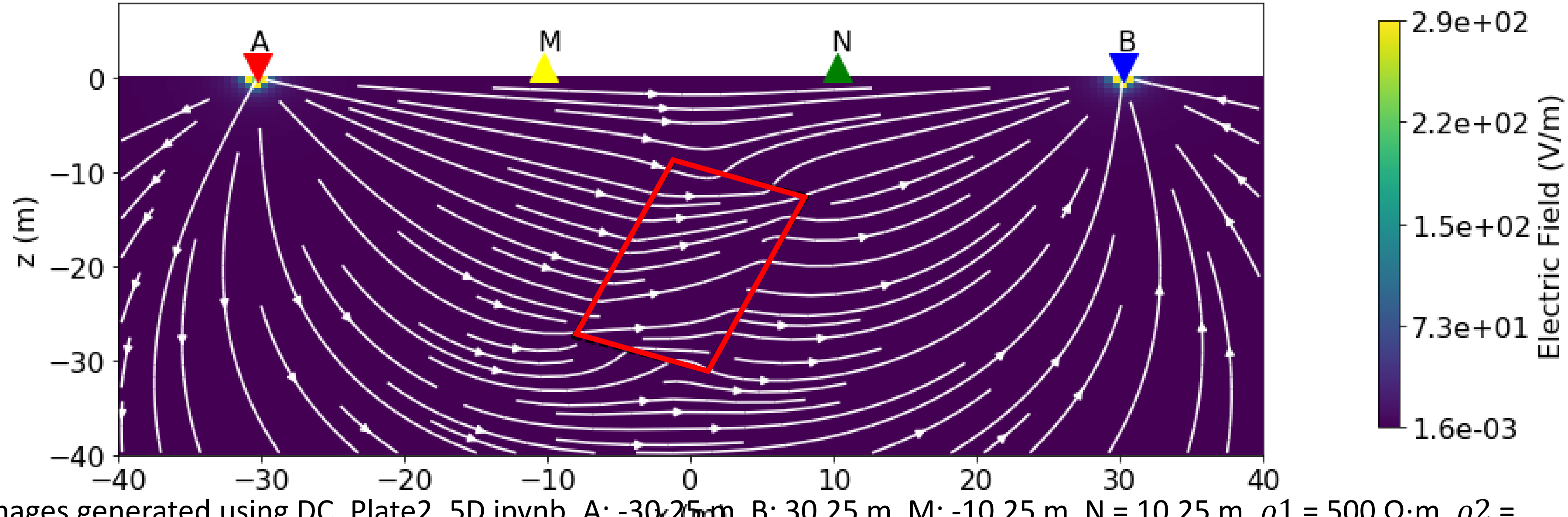
Elura Orebody Electrical resistivities

Rock Type	*Ohm-m*
Overburden	12
Host rocks	200
Gossan	420
Mineralization (pyritic)	0.6
Mineralization (pyrrhotite)	0.6

Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

The rest are optional materials

Understanding the change in directions



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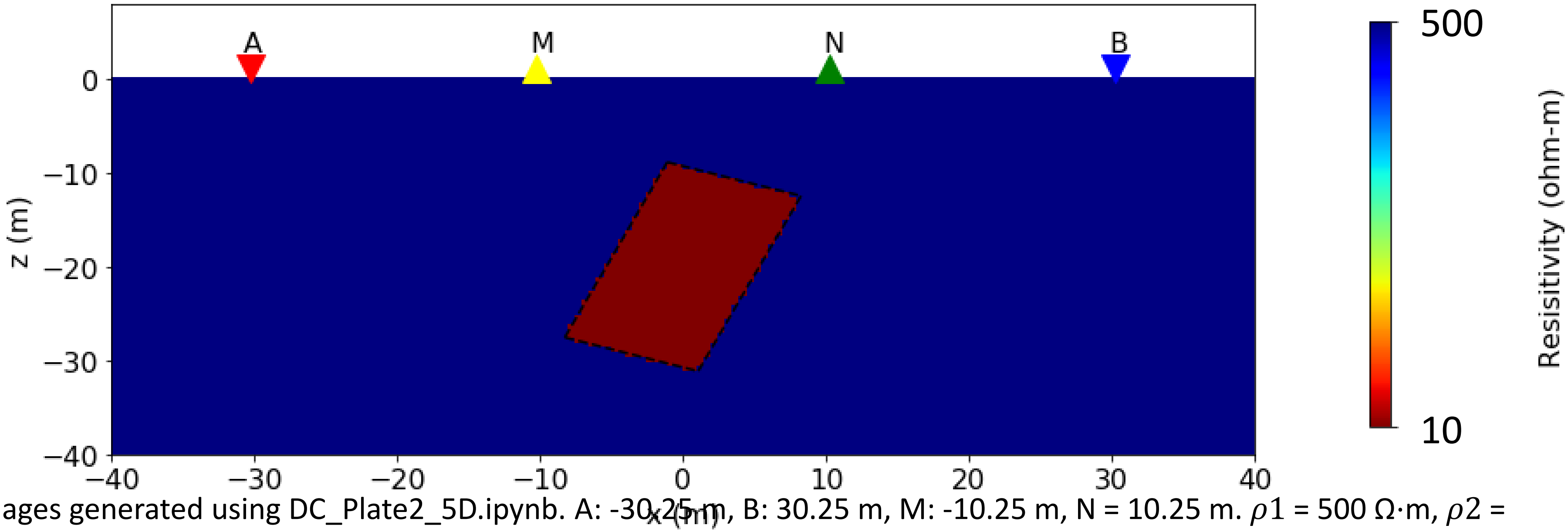

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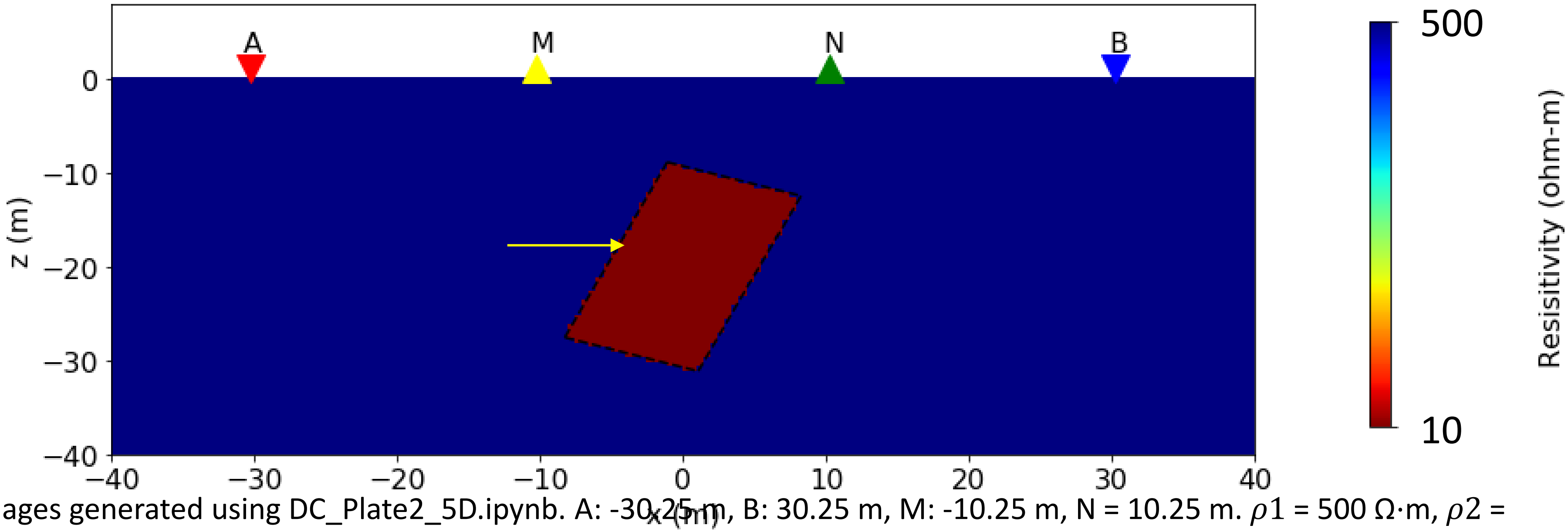

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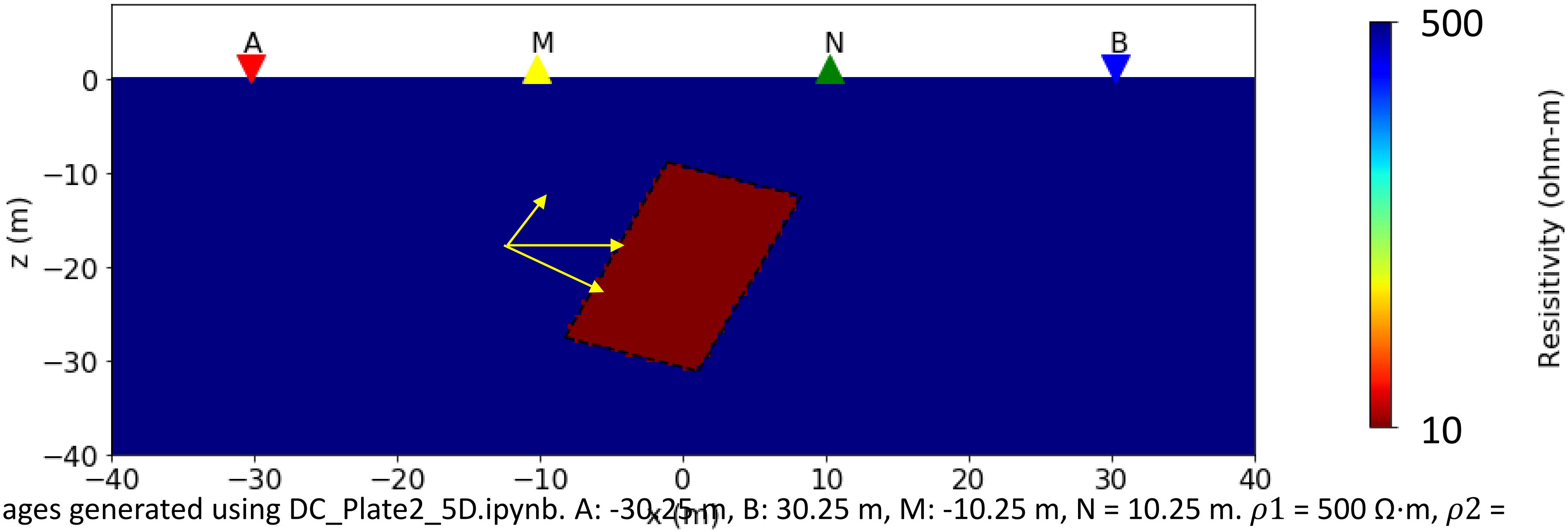

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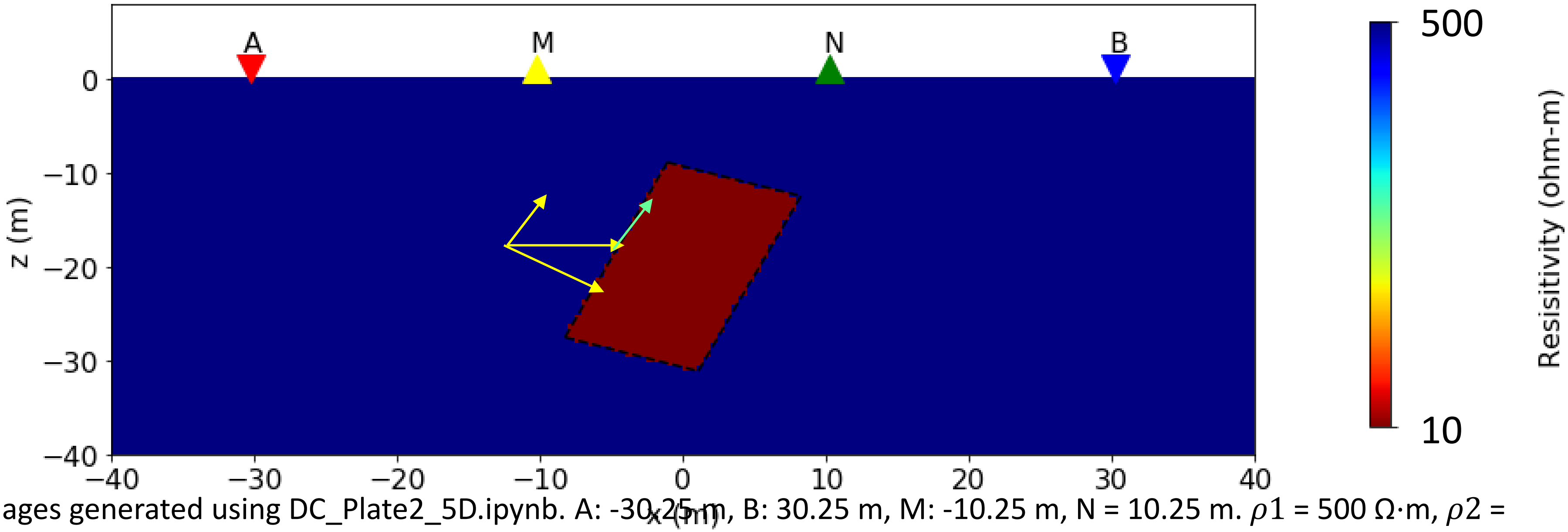

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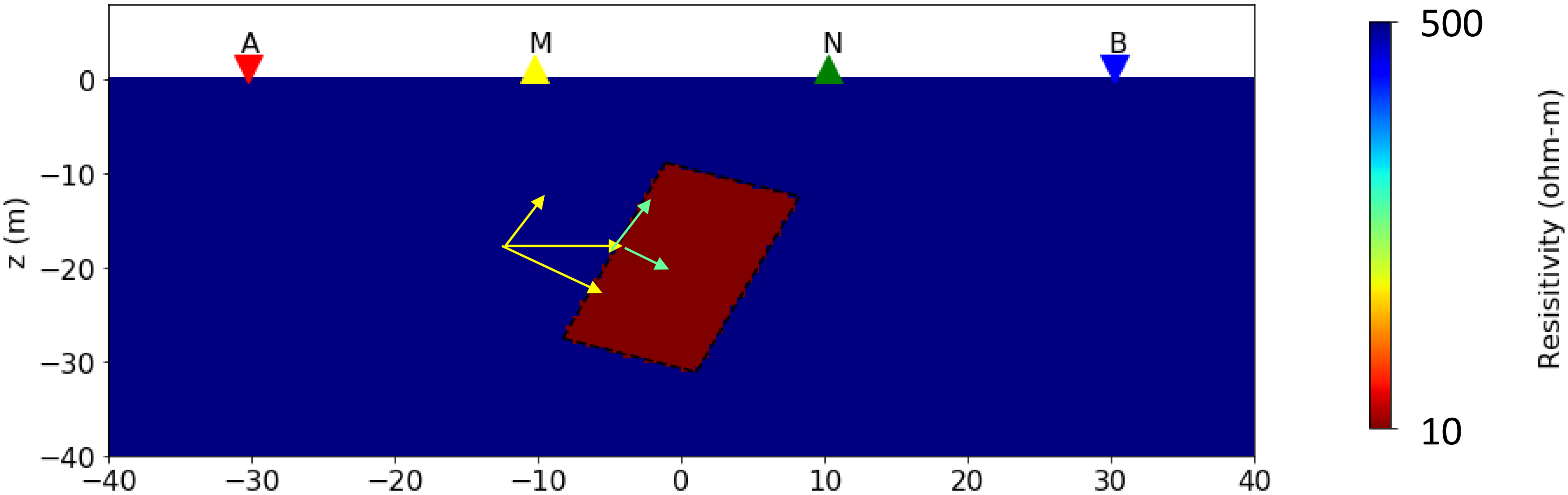

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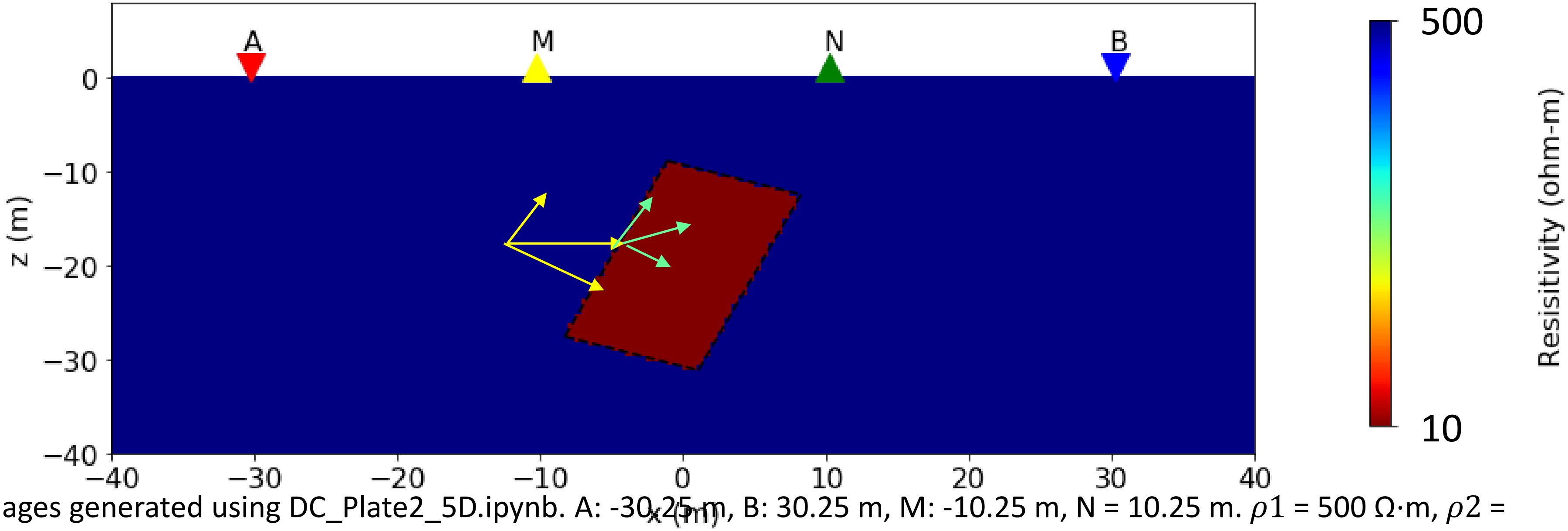

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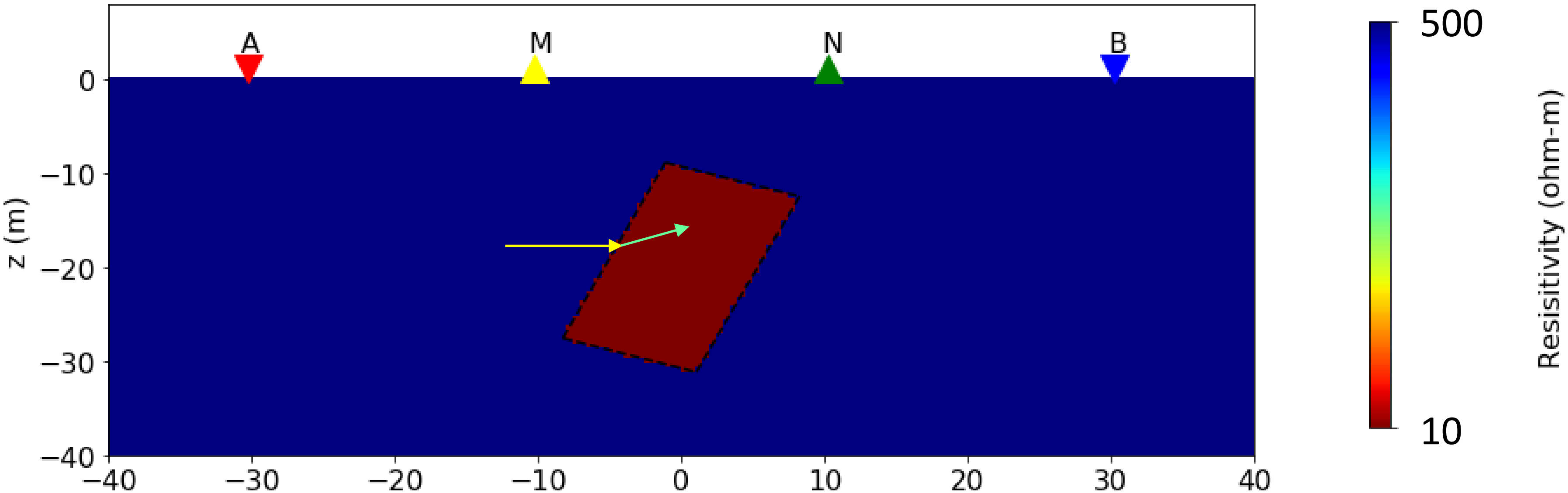

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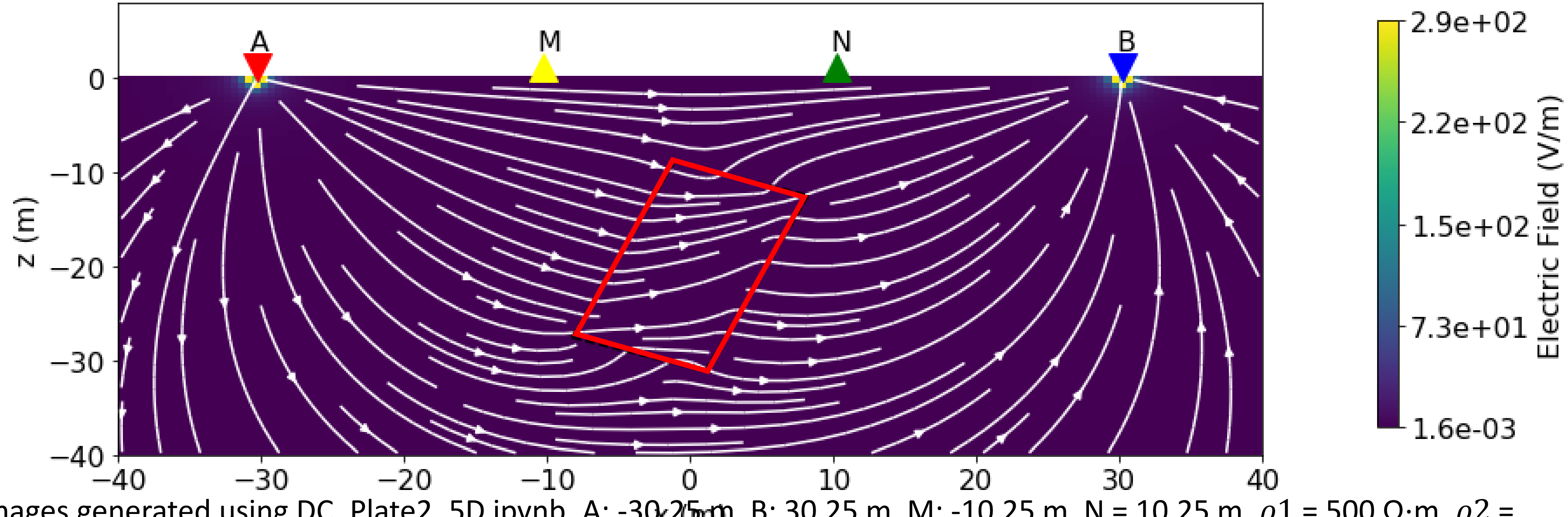

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