Application of sensitivity analysis in DC resistivity monitoring of SAGD steam chambers

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Outline

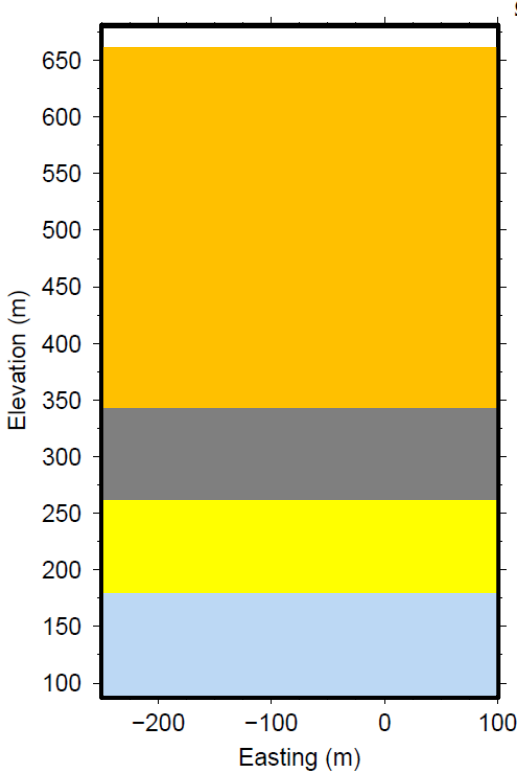
- SAGD and Leismer Demonstration Area
- Survey design
- DC resistivity examples
- EM examples
- Lessons learned

Leismer Demonstration Area

Aspen – talk at 4 pm, this session!

Geology

- Quaternary:
  - Glacial tills, sands, shales
- Clearwater Formation
  - Shales, cap rock
- McMurray Formation - reservoir
  - Upper
  - Middle
  - Lower
- Devonian
  - Limestone



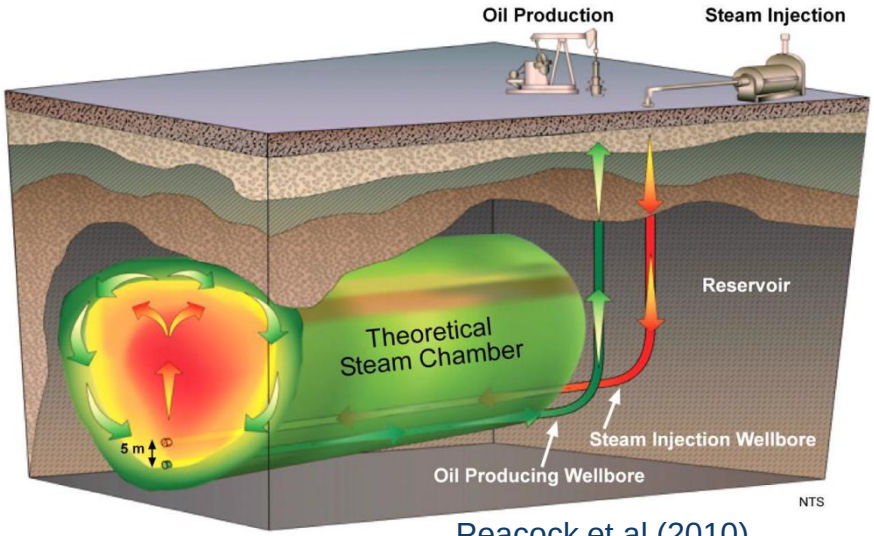
Steam-assisted gravity drainage

- Target: bitumen oil
- Oil is too viscous for conventional recovery; too deep to mine

  → **Steam-assisted gravity drainage**

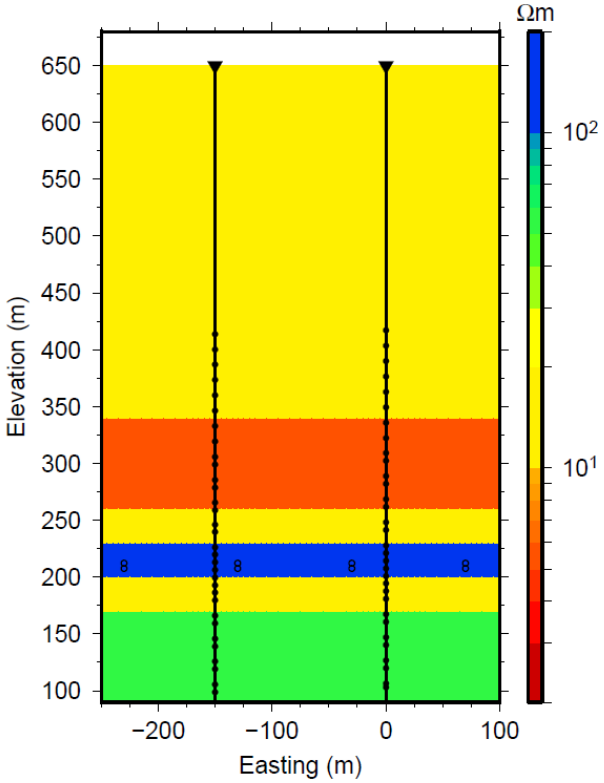
- Decreases the electrical resistivity

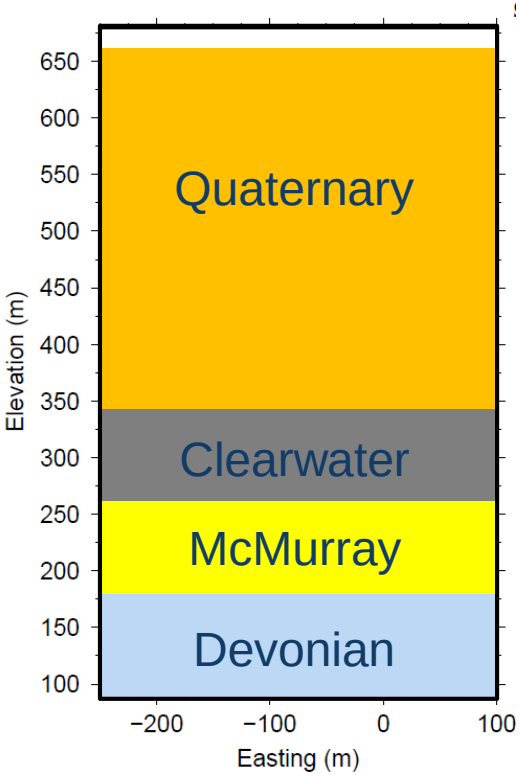
  → **DC resistivity and electromagnetics**



Peacock et al (2010)

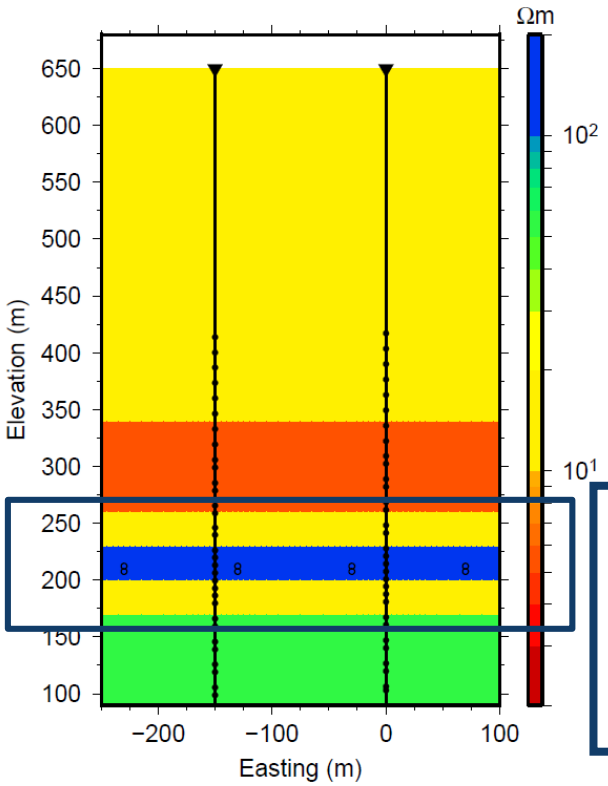
Resistivity model





- Create resistivity model based on geology and baseline survey (Tøndel et al, 2014)

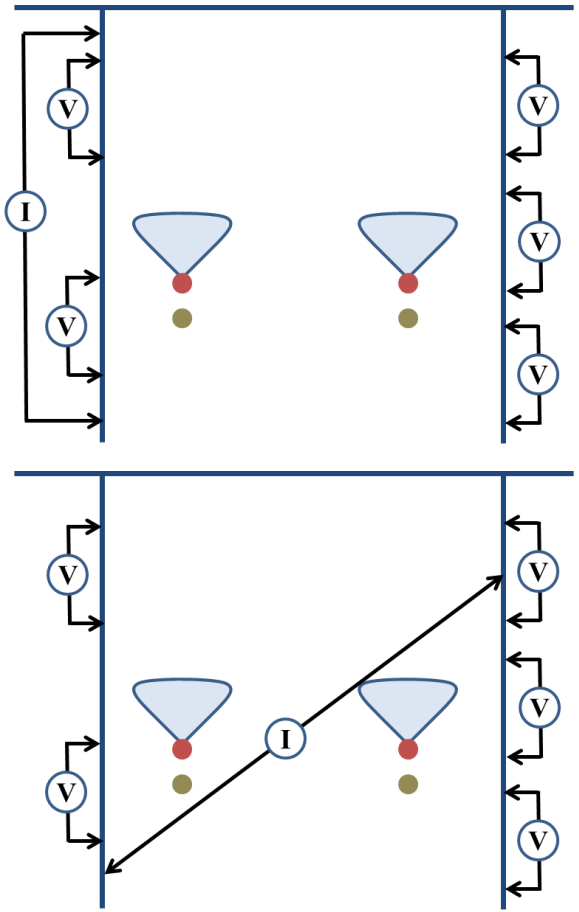
Resistivity model



- 4 horizontal SAGD well pairs
- 2 vertical observation wells
  - Populated with electrodes

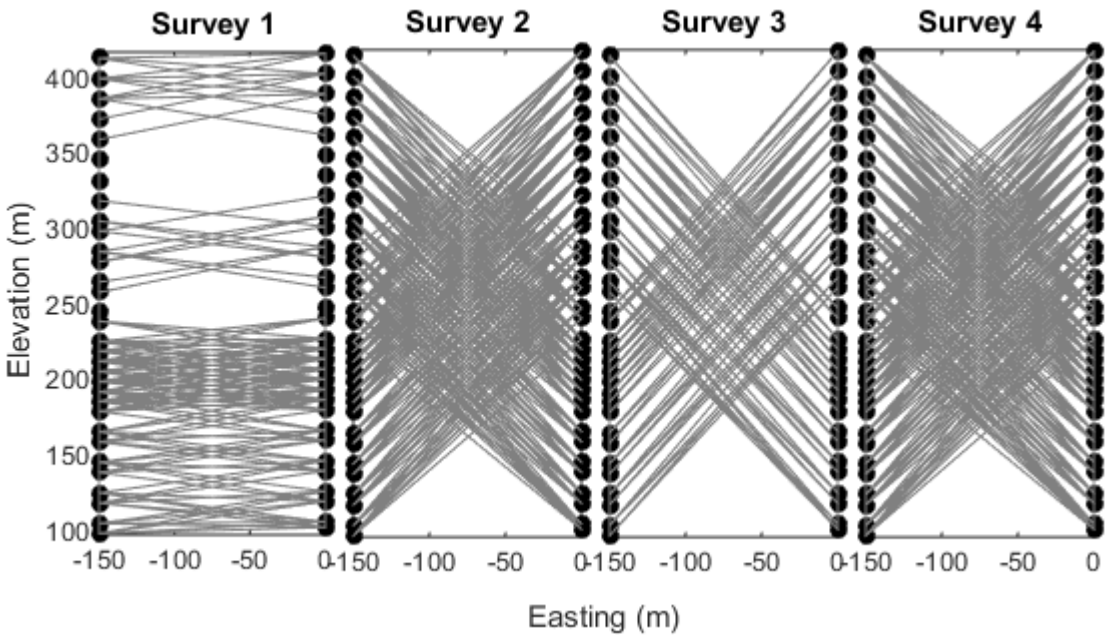
Survey design

- Inductive or galvanic sources
  - Surface or borehole
- Measure electric or magnetic fields
  - Surface or borehole
- Leismer Demonstration Area: test borehole galvanic sources with borehole receivers
  - Crosswell
  - Along-well



Survey design

- 4 crosswell DC resistivity surveys
  - repeated twice every day
- Field results:
  - 80% decrease in resistivity in 2-year period
  - 2 steam chambers
  - Tøndel et al, 2014



Research goal

- Investigate how effective survey design for multiple models
- Improve chamber recovery using electromagnetic methods
- Methodologies: numerical modelling and inversion

Inverse theory

- Forward model

$$\boldsymbol{F}[\boldsymbol{m}] = \boldsymbol{d}$$

- Sensitivity

$$\boldsymbol{J} = \frac{\partial \boldsymbol{F}[\boldsymbol{m}]}{\partial \boldsymbol{m}}$$

- Inversion

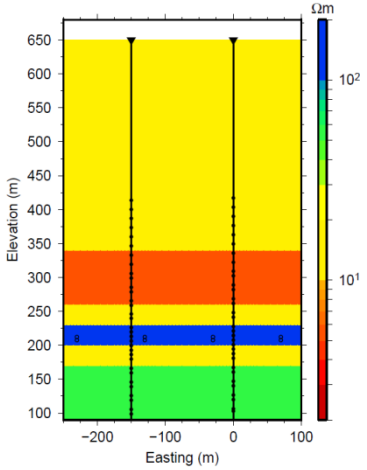
$$\boldsymbol{\phi}(\boldsymbol{m}) = \boldsymbol{\phi_d} + \boldsymbol{\beta}\boldsymbol{\phi_m}(\boldsymbol{m}) = \left\|\boldsymbol{W_d}(\boldsymbol{F}[\boldsymbol{m}] - \boldsymbol{d^{obs}}\right\|_2^2 + \boldsymbol{\beta}\left\|\boldsymbol{W_m}(\boldsymbol{m} - \boldsymbol{m_{ref}}\right\|^2$$

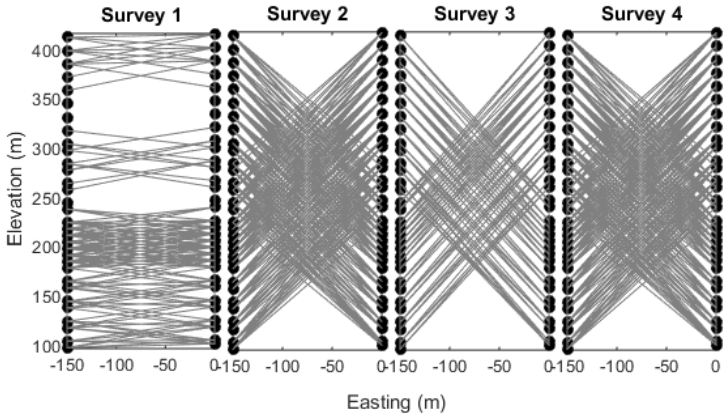
$$\delta \boldsymbol{m} = \left(J^T W_d^T W_d J + \beta W_m^T W_m\right)^{-1}\left[J^T W_d^T W_d\left(\boldsymbol{d}^{obs} - F[\boldsymbol{m}]\right) - \beta W_m^T W_m(\boldsymbol{m}^n - \boldsymbol{m}_{ref})\right]$$

$$\boldsymbol{m}^{n+1} = \boldsymbol{m}^n + \delta \boldsymbol{m}$$

Workflow

- Add steam chambers to the background model
- Forward model data using Leismer surveys
- Add Gaussian noise
- Invert the data





Two things to keep in mind

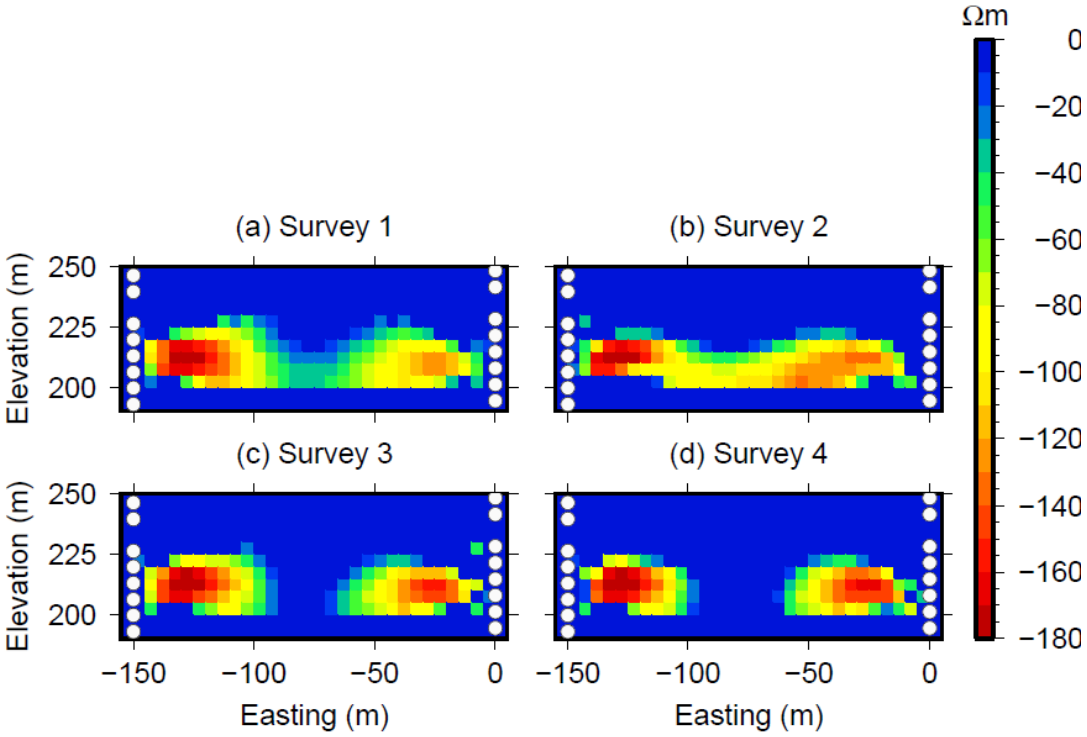
- Purposely **NOT** showing the true synthetic model

- Results are shown as **MODEL DIFFERENCE**

$$\delta m = m^{recovered} - m^{background}$$

DC results: scenario 1

- Each survey recovers 2 anomalies
- Some smearing in Surveys 1 and 2
- Right anomaly has slightly greater change than left anomaly

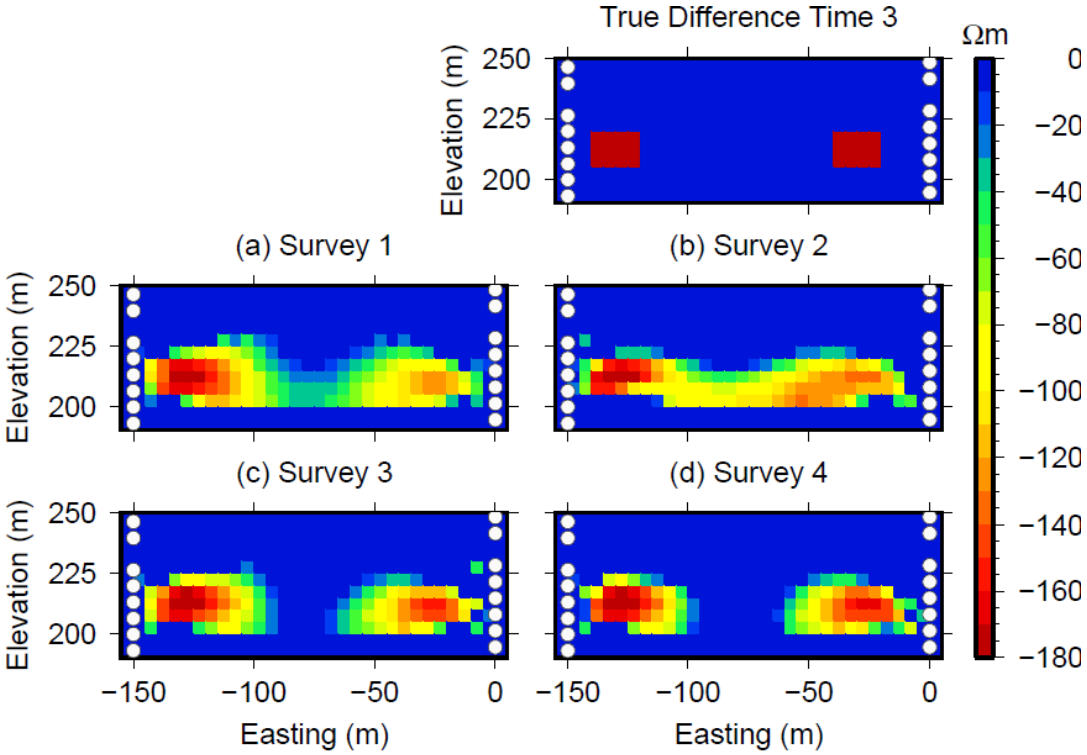


DC results: scenario 1

- Great recovery using Surveys 3 and 4, “ok” recovery using Surveys 1 and 2

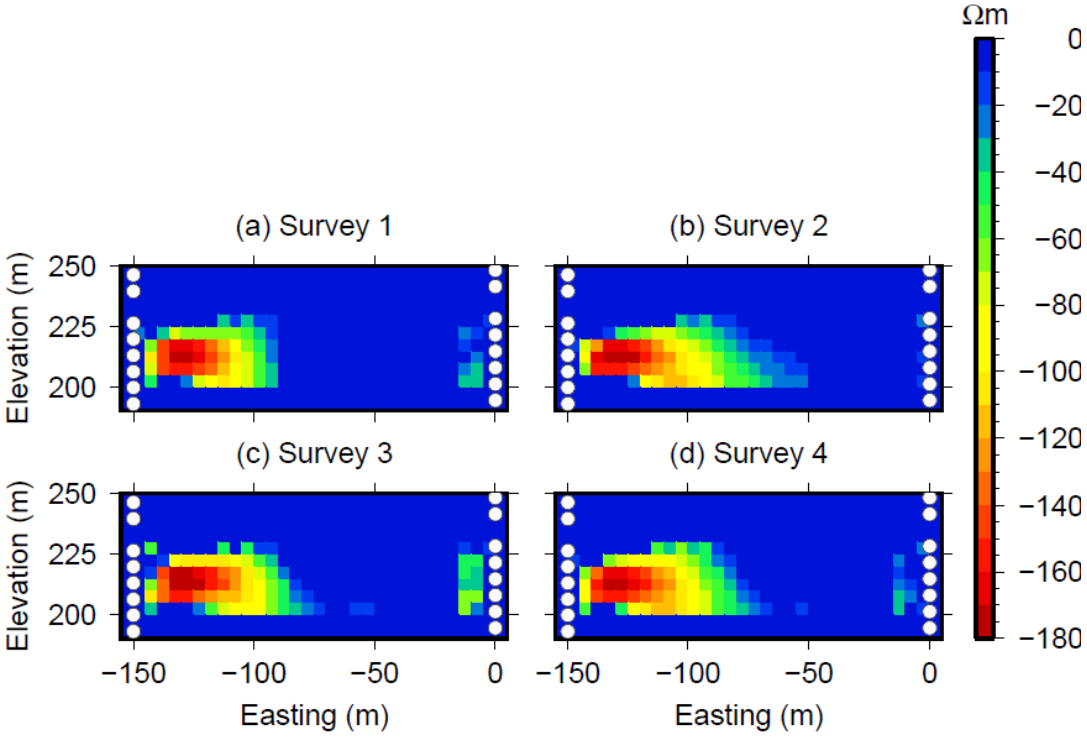
- Results similar to inversion of field data

→ Crosswell DC resistivity works for imaging two steam chambers



DC results: scenario 2

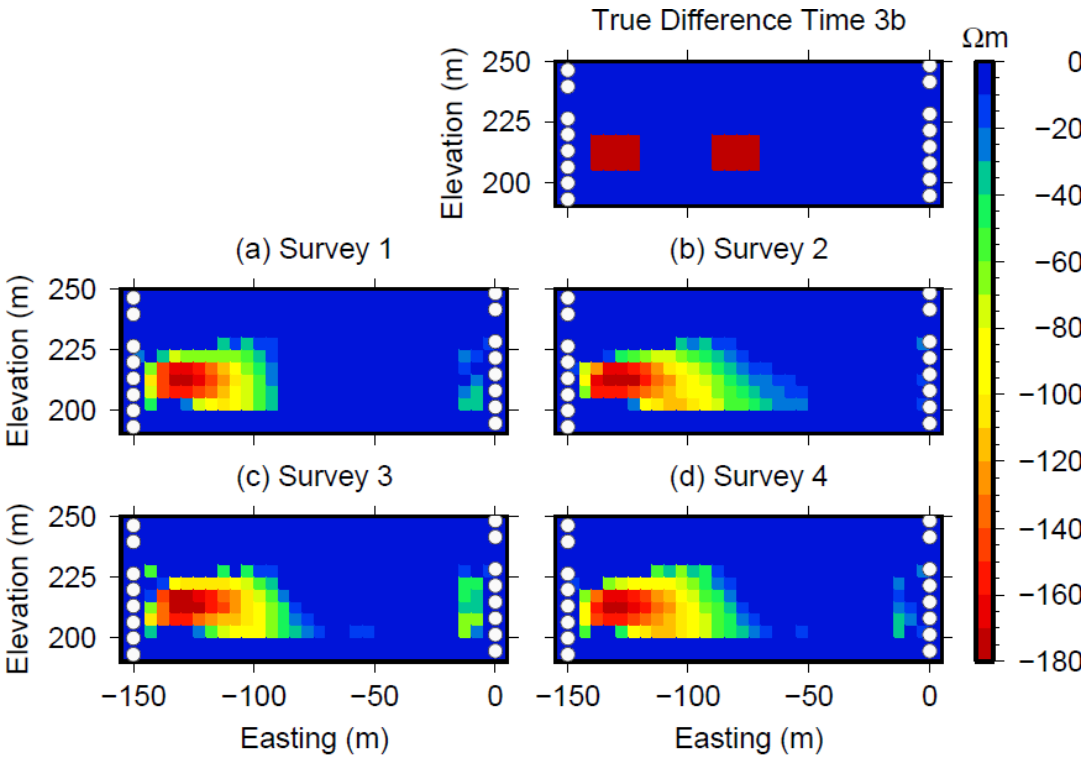
- A different scenario…
- One main anomaly on the left
- Some smearing by Surveys 2 and 4 towards centre



DC results: scenario 2

- A different scenario…
- Inversion does not recover the right chamber!

→ Crosswell DC resistivity does not work for this scenario!



Sensitivity

- Forward model

$$F[\boldsymbol{m}] = \boldsymbol{d}$$

- Inversion

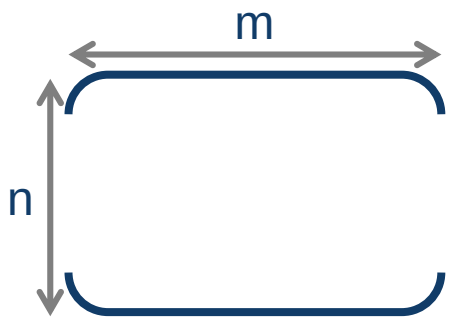
$$\phi(\boldsymbol{m}) = \phi_d + \beta\phi_m(\boldsymbol{m}) = \left\|W_d(F[\boldsymbol{m}] - \boldsymbol{d}^{obs}\right\|_2^2 + \beta\left\|W_m(\boldsymbol{m} - \boldsymbol{m}_{ref}\right\|^2$$

$$\delta\boldsymbol{m} = \left(J^T W_d^T W_d J + \beta W_m^T W_m\right)^{-1}\left[J^T W_d^T W_d\left(\boldsymbol{d}^{obs} - F[\boldsymbol{m}]\right) - \beta W_m^T W_m(\boldsymbol{m}^n - \boldsymbol{m}_{ref})\right]$$

$$\boldsymbol{m}^{n+1} = \boldsymbol{m}^n + \delta\boldsymbol{m}$$

- Sensitivity

$$\boldsymbol{J} = \frac{\partial \boldsymbol{F}[\boldsymbol{m}]}{\partial \boldsymbol{m}}$$



Sensitivity

- Measure of sensitivity

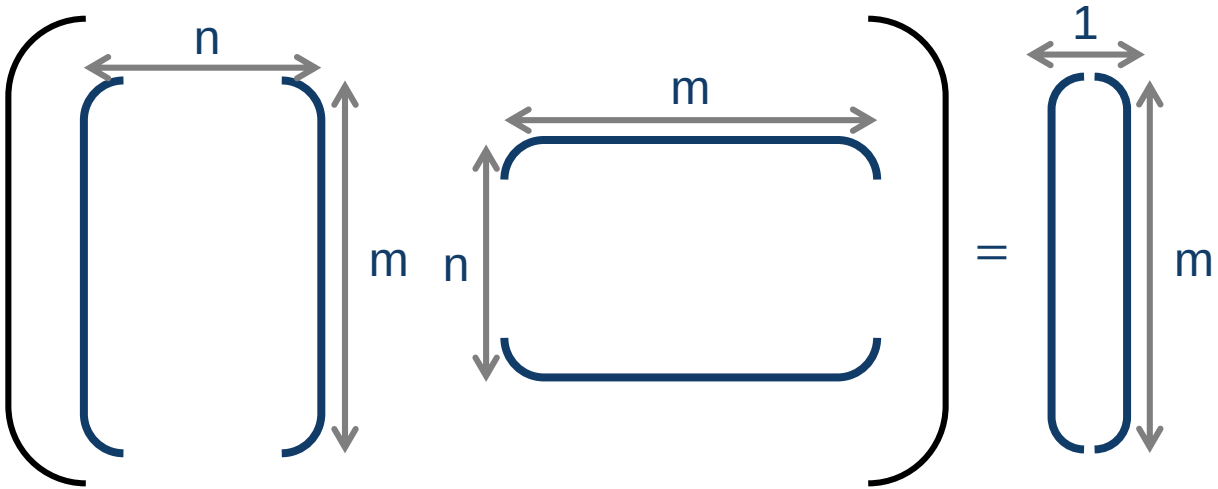
$$D = diag(J^T J)$$

***J* is large.**

- Sensitivity

$$J = \frac{\partial F[\boldsymbol{m}]}{\partial \boldsymbol{m}}$$

$D = diag$



Sensitivity

- Measure of sensitivity

$$D = diag(J^T J)$$

***J* is large.**

- Sensitivity

$$J = \frac{\partial F[\boldsymbol{m}]}{\partial \boldsymbol{m}}$$

- Approximate diagonal: probing

$$D \approx \left[\sum_{k=1}^{p} w_k \odot J^T(Jw_k)\right] \oslash \left[\sum_{k=1}^{p} w_k \odot w_k\right]$$

Two MVPs

Pseudo-random vector

Small number of iterations

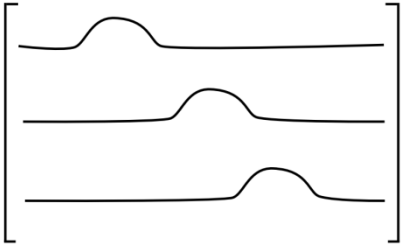
Sensitivity

- How to form pseudo-random vectors?

$$p = 3 \rightarrow \quad w_1 = [1\ 0\ 0\ 1\ 0\ 0\ 1\ \ldots]^T$$
$$w_2 = [0\ 1\ 0\ 0\ 1\ 0\ 0\ \ldots]^T$$
$$w_3 = [0\ 0\ 1\ 0\ 0\ 1\ 0\ \ldots]^T$$

- Sensitivity

$$J = \frac{\partial F[\boldsymbol{m}]}{\partial \boldsymbol{m}}$$

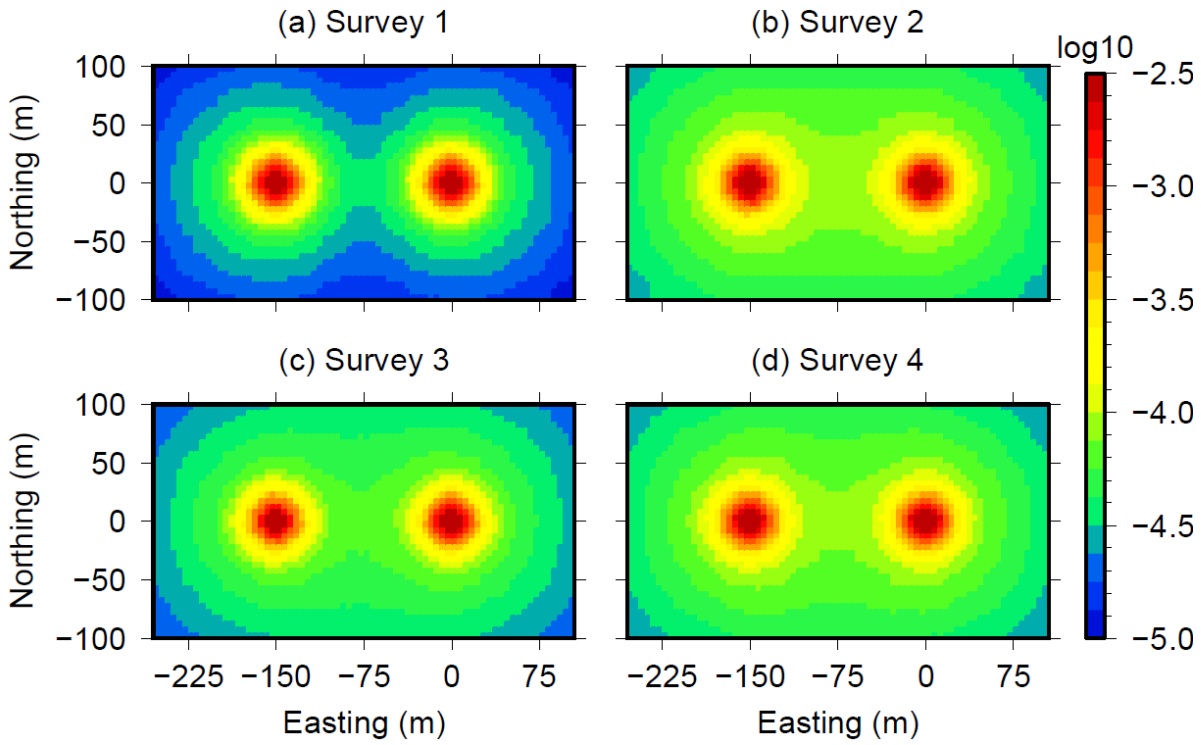


Magnitude of the entries in $J^T J$ decay away from the diagonal.

Note:

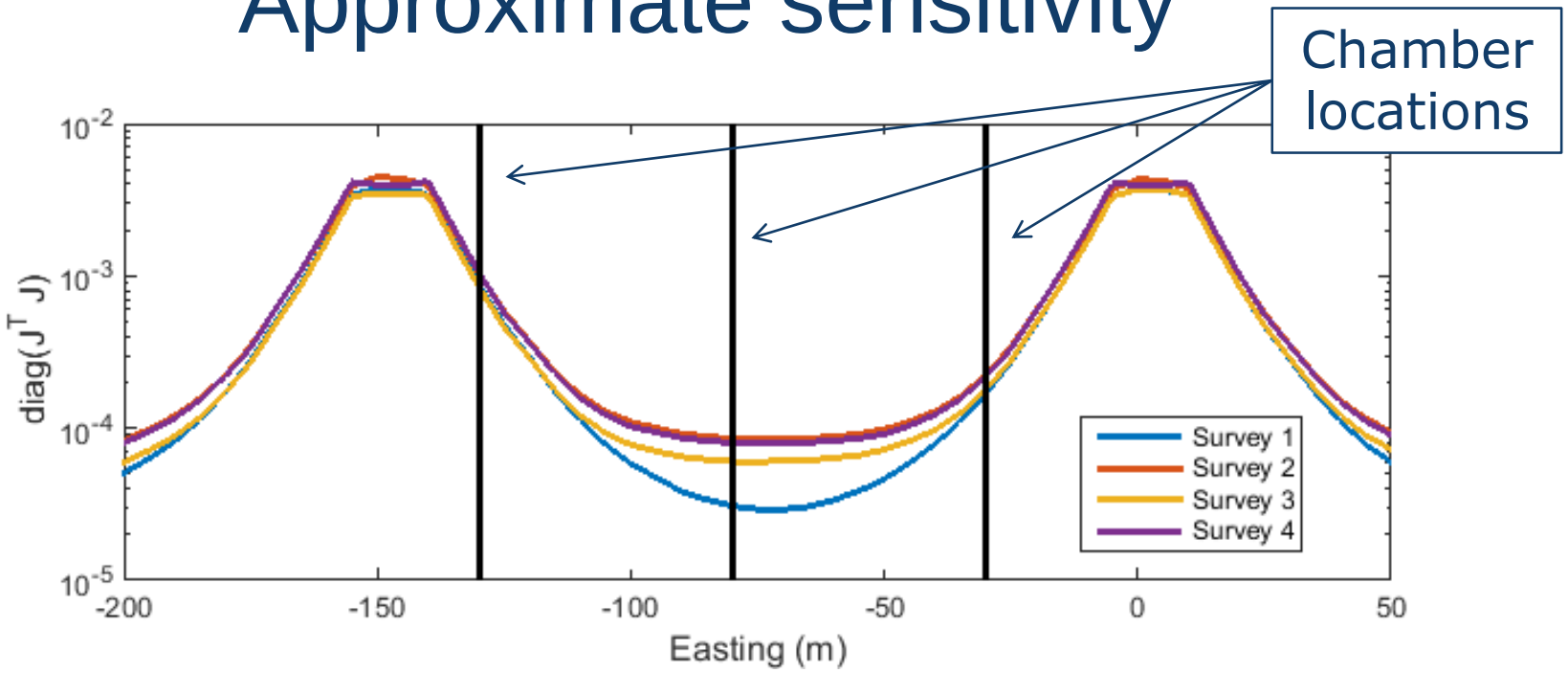
If $p = m$, then $W = I$, and $diag(J^T J)$ is recovered exactly.

Approximate sensitivity



- Sensitivity decreases away from the observation wells
- Different survey → different sensitivity

Approximate sensitivity



- Sensitivity decreases away from the observation wells

Debrief…

- DC resistivity:
  - Limited sensitivity to certain parts of the reservoir
  - Recovery of chambers depends on survey sensitivity

- How to increase sensitivity so that the entire reservoir is monitored?

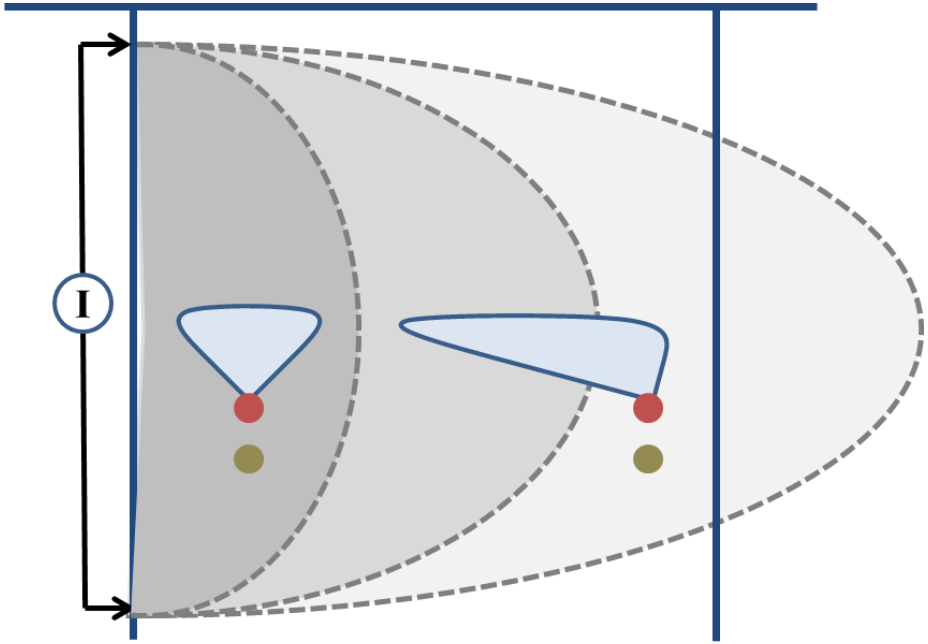
Electromagnetic methods

- Whereas DC resistivity used 1 frequency (f = 0 Hz), EM uses multiple.

$$\nabla \times E + i\mu\omega H = 0$$
$$\nabla \times H - \sigma E = J_e$$

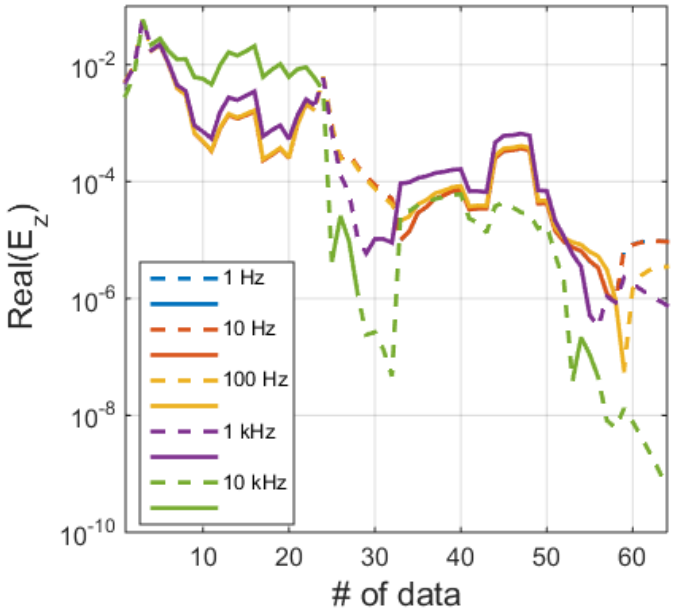
- As frequency increases, skin depth decreases.

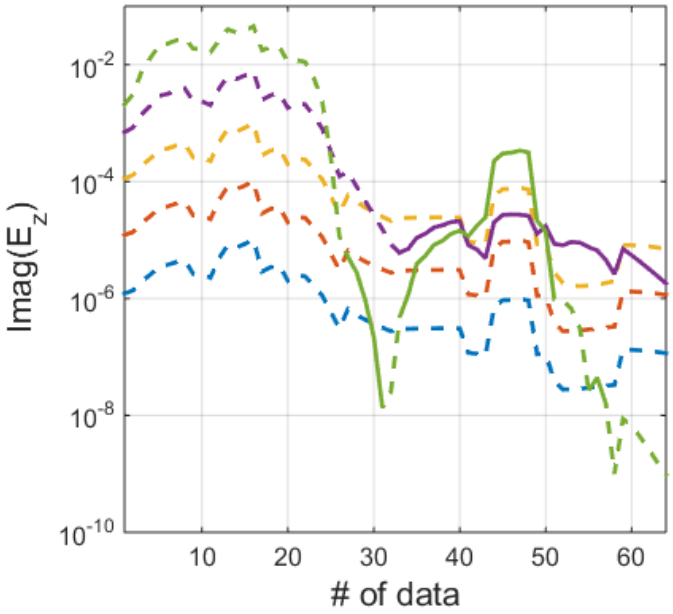
$$d \approx 500 \sqrt{\rho / f}$$



Electromagnetic methods

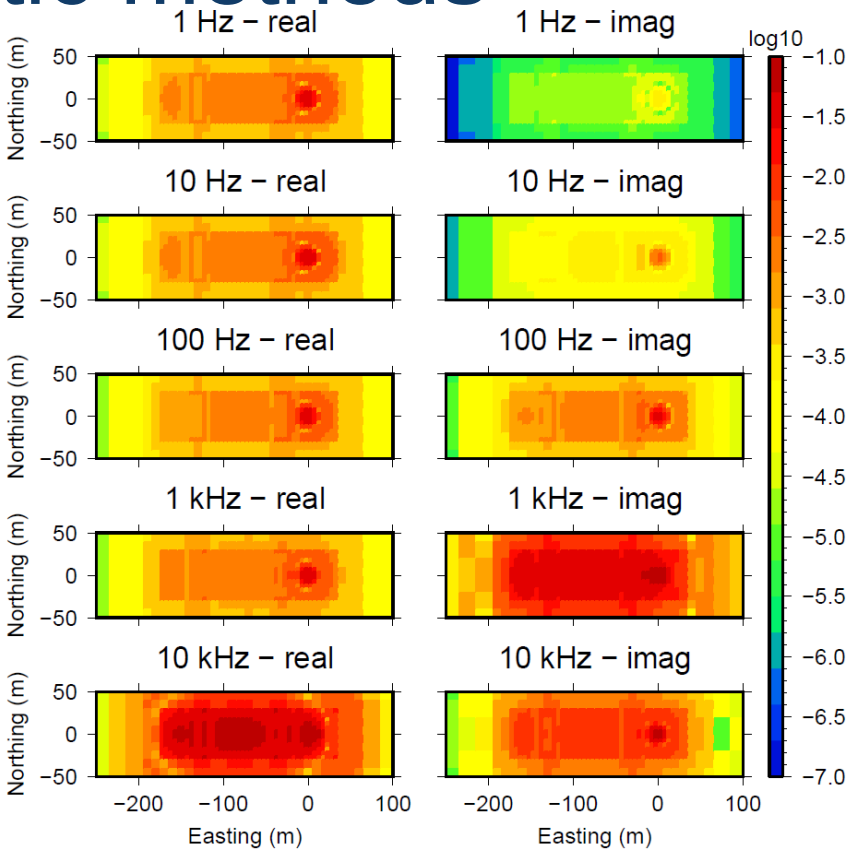
- Whereas DC resistivity used 1 frequency (f = 0 Hz), EM uses multiple.
- Imaginary component increases as frequency increases



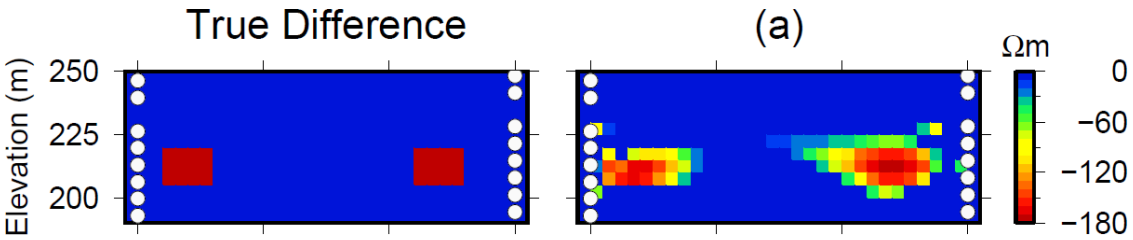


Electromagnetic methods

- Whereas DC resistivity used 1 frequency (f = 0 Hz), EM uses multiple.
- As frequency increases, skin depth decreases.
- Thus, the sensitivity of the survey changes as frequency changes.

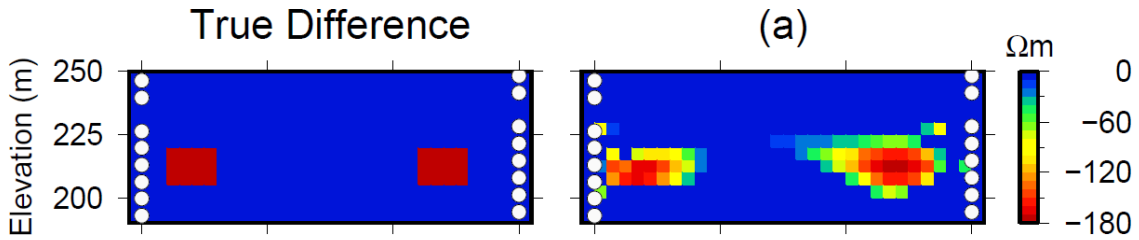


EM multi-frequency results

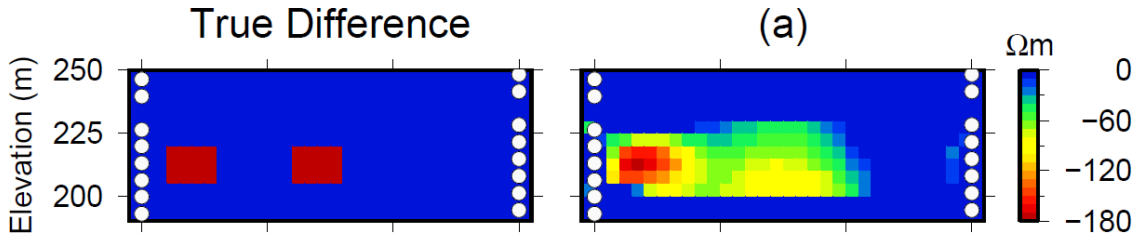


- Multiple frequencies allow the whole region to be adequately sampled

EM multi-frequency results



- Multiple frequencies allow the whole region to be adequately sampled



- Recovery of both chambers in both scenarios!

Debrief…

- DC resistivity:
  - Limited sensitivity to certain parts of the reservoir
  - Recovery of chambers depends on survey sensitivity

- How to increase sensitivity so that the entire reservoir is monitored?
  - Multi-frequency EM allows for better monitoring of the reservoir

Summary

- Crosswell DC surveys are a great way to monitor SAGD steam chamber growth.
- But… the surveys are not sensitive to the whole reservoir.
- By collecting multiple frequencies, recovery of the chambers has improved and,
- Additional confidence that the whole reservoir is monitored.

Thank you!

Questions?

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GIF

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