Where does the proppant go?

Examining the application of electromagnetic methods for hydraulic fracture characterization

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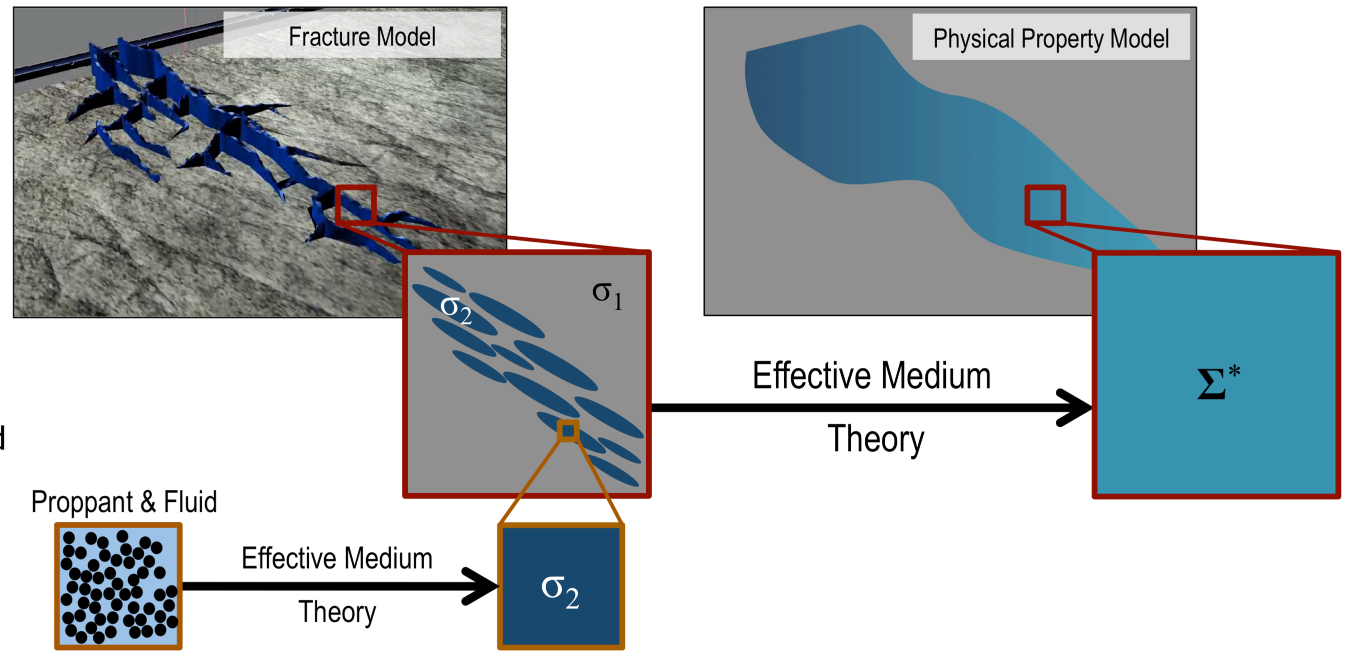
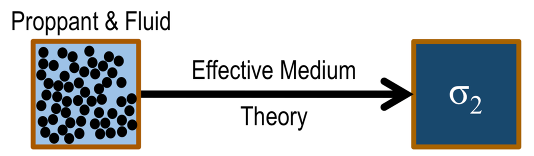
How do we map the propped region of a hydraulically fractured reservoir?

- An electrically conductive proppant can create a physical property contrast between the propped region of the host reservoir
- Physical property model must capture:
  - effect of individual proppant particles
    - µm - mm scale
  - geometry of fractures
    - 10's of meters in height
    - 100's of meters in length
    - mm in width
- Apply effective medium theory in two steps:
  1. Compute σ_2 (scalar) for a proppant-fluid mixture
  2. Compute Σ^* (tensor) for a propped, fractured volume of rock
- Steps 1 and 2: use self-consistent effective medium theory (Bruggeman, 1935). Also described in Torquato (2002), Shafiro & Kachanov (2000), and Berryman & Hoversten (2013)



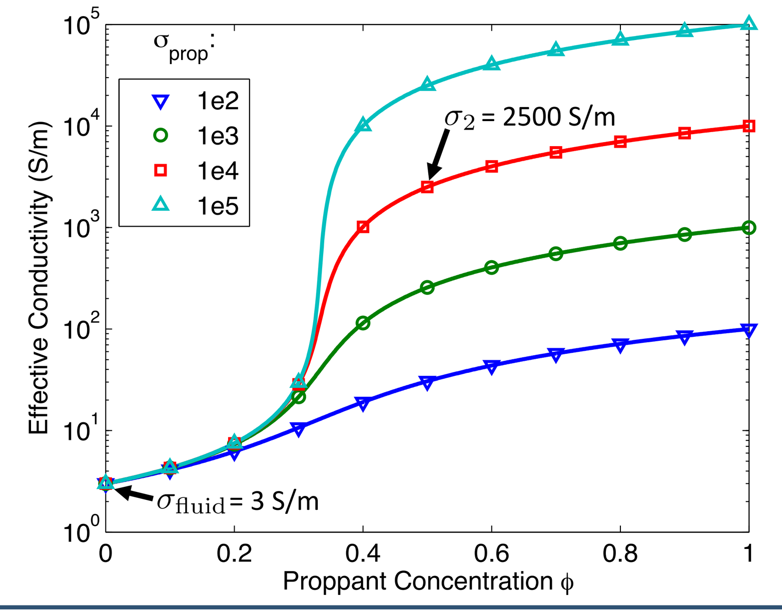
Physical property model for a fractured reservoir

Step 1:

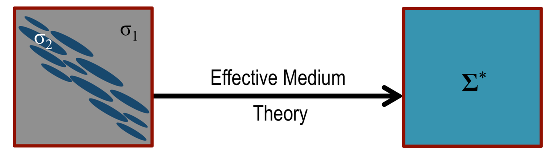


- Assume the fractures are filled with a mixture of
  - fluid
  - electrically conductive proppant
- When the proppant concentration is ϕ~0.3, *percolation* occurs:
  - concentration large enough to form connected, electrically conductive pathways, causing the effective conductivity to rapidly increase
- A mixture of:
  - 50% proppant: σ_{prop} = 10[4] S/m (i.e. graphite)
  - 50% fluid: σ_{fluid} = 3 S/m (i.e. seawater)

  has effective conductivity of 2500 S/m



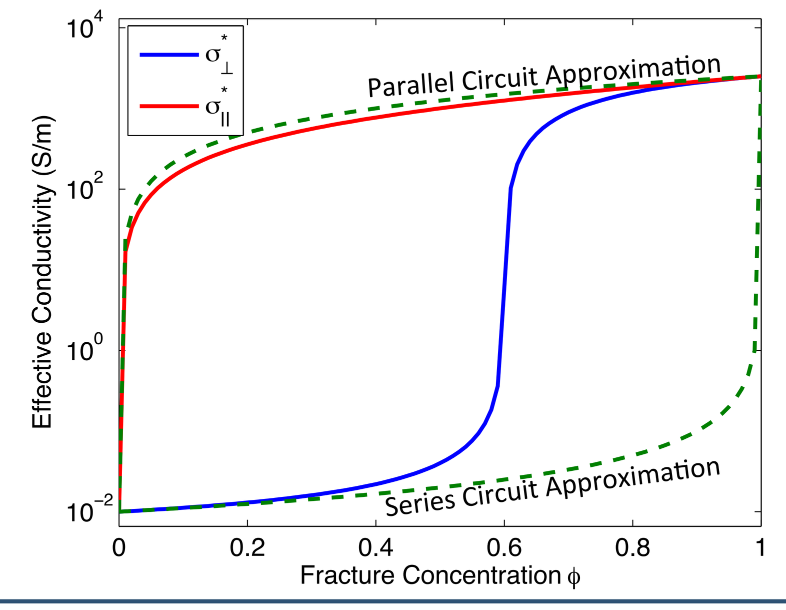
Step 2:



- Propped region of fracture approximated by aligned ellipsoidal cracks (σ_2 = 2500 S/m), in a host reservoir (σ_1 = 0.01 S/m)
- Effective conductivity of a fractured volume of rock is *anisotropic*:

$$\Sigma^* = R^T \begin{pmatrix} \sigma^*_\perp & & \\ & \sigma^*_\parallel & \\ & & \sigma^*_\parallel \end{pmatrix} R$$

  - $\sigma^*_\perp$: conductivity component perpendicular to fractures
  - $\sigma^*_\parallel$: conductivity components parallel to fractures
  - R : rotation tensor
- Magnitudes depend on: σ_1, σ_2, the aspect ratio of the ellipsoids, and their concentration in a given volume of rock.
  - at low concentrations: $\sigma^*_\perp, \sigma^*_\parallel$ approximate conductors in series and in parallel

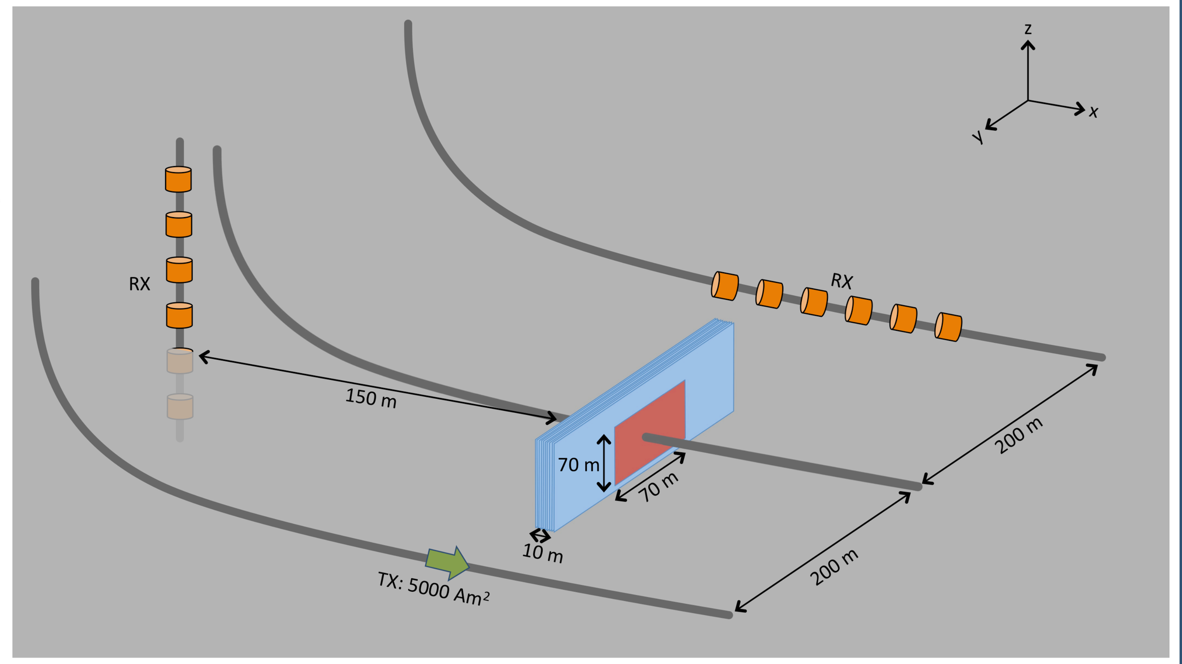


Synthetic Model

- Fracture geometry:
  - 10 fractures spaced evenly along a 10m horizontal segment of the treatment well (on average 1 m apart)
  - Each fracture is 2.5mm wide
  - Propped region of the reservoir (in red): 10m x 70m x 70m, filled with
    - 50% fluid : 3 S/m
    - 50% proppant: 10[4] S/m
  - Uniform background: 0.01 S/m (i.e. shale)
  - Fracture concentration: 2.5×10^{-3} in propped region,

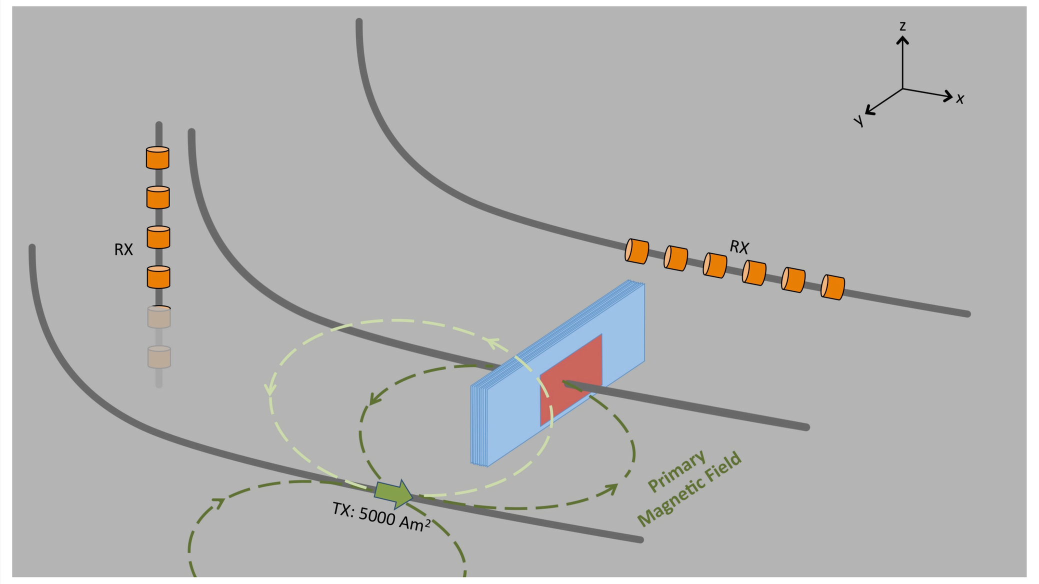
$$\Sigma^* = \begin{pmatrix} \sigma^*_\perp & & \\ & \sigma^*_\parallel & \\ & & \sigma^*_\parallel \end{pmatrix} = \begin{pmatrix} 10^{-2} & & \\ & 4 & \\ & & 4 \end{pmatrix} S/m$$

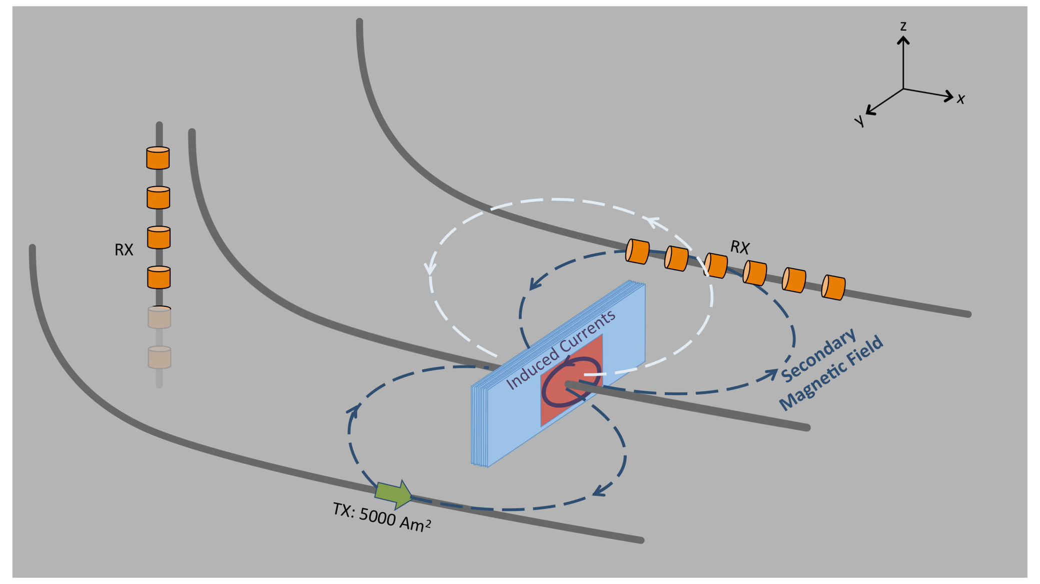
- Multi-well survey:
  - Transmitter: magnetic dipole
    - dipole moment: 5000 Am[2] (Wilt et al., 1995)
    - in horizontal well 200 m from the treatment well
  - Receivers:
    - in a parallel horizontal well 200 m from the treatment well
    - positioned in vertical well located 150 m behind the induced fractures



Electromagnetic Induction

- Transmitter produces a time varying primary magnetic field
- This field excites secondary currents in the propped region of the reservoir
- Secondary currents produce a secondary magnetic field
- Sum of the primary and secondary magnetic fields are measured at the receivers





- To detect electrically conductive proppant, the measured magnetic fields must be:
  - larger in magnitude than the noise floor of the receivers, ~10^{-2} pT (Wilt et al., 1995)
  - different enough from the fields measured in the absence of the fractures, typically larger than 1% of the primary

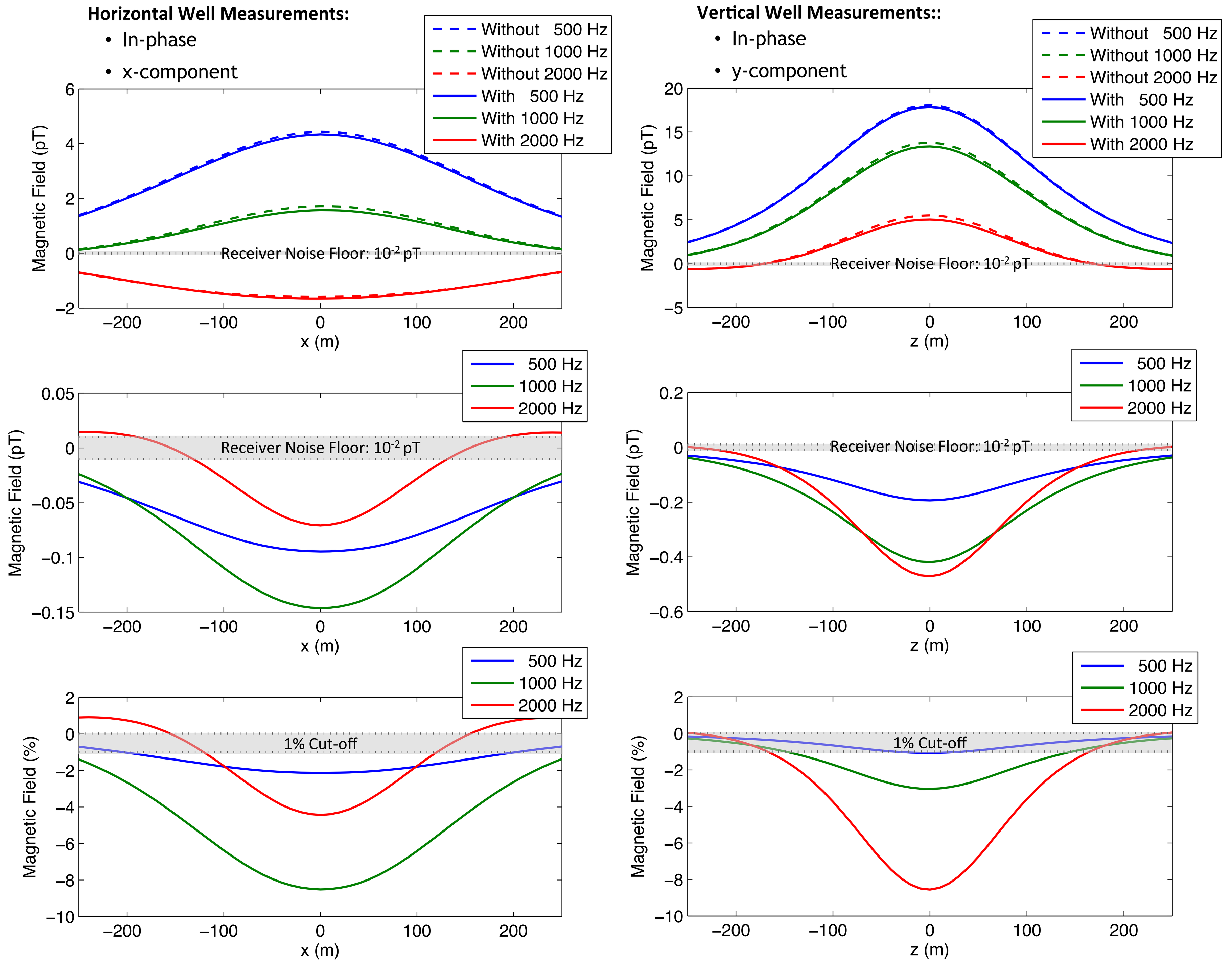
Magnetic Field Responses

- A host of measurements can be taken by each set of receivers:
  - frequency range: 10Hz to 2kHz (Wilt, 2003)
  - x, y, z - components
  - in-phase and quadrature

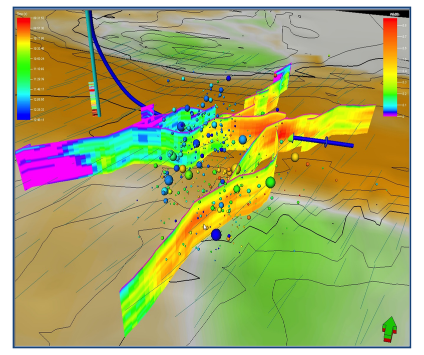
Measured magnetic field with and without propped fracture

Secondary magnetic field

Secondary magnetic field (percentage of primary)



Summary and Outlook



- Electrically conductive proppant can create a physical property contrast between the host reservoir and the propped region of a hydraulically fractured reservoir.
- Build a physical property model using effective medium theory in two steps:
  1. Compute a scalar conductivity for a proppant-fluid mixture
  2. Compute a tensor conductivity for a propped, fractured volume of rock
- Forward-modeled results: the signal is well above the noise level and is significant in percentage of the inducing field
- Moving forward: increase complexity of the fracture models, examine the survey design, and invert the 3D electromagnetic data

Goal: to ascertain whether, and under what conditions, electromagnetic imaging can provide cost effective information about the location of the proppant in a fractured reservoir.

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