

# Simulation and Analysis of a Borehole Transient Electromagnetic Reservoir Monitoring System

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COMSOL  
CONFERENCE  
BOSTON  
2012

Excerpt from the Proceedings of the 2012 COMSOL Conference in Boston

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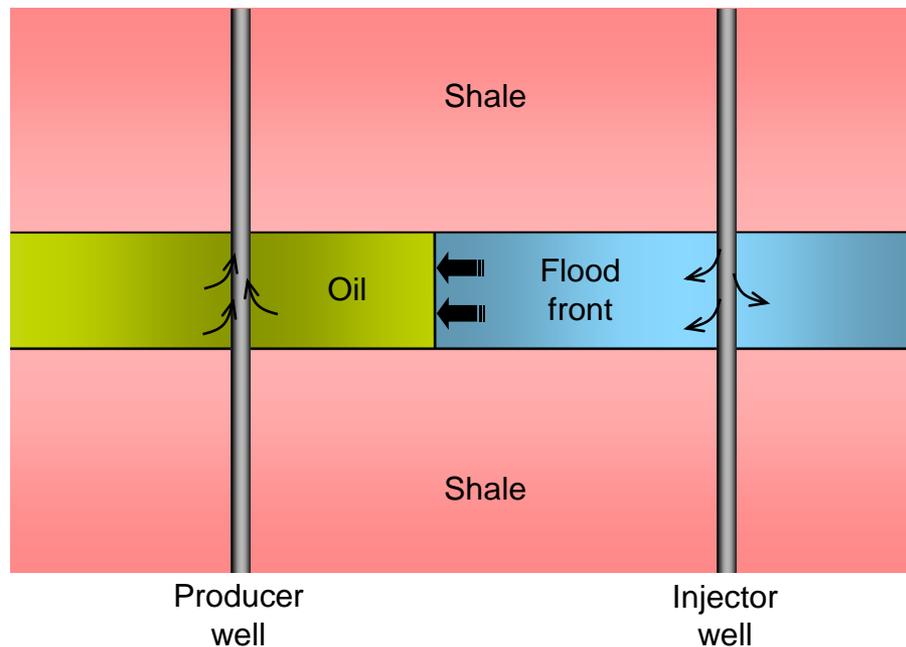


# Outline

- Introduction
- Transient electromagnetics (TEM)
- Borehole TEM reservoir monitoring system
  - Modeling
  - Results
  - Analysis
- Conclusions

# EOR and reservoir monitoring

- EOR—waterflooding, steam flooding, CO<sub>2</sub>-flooding—used in mature oil fields
  - CO<sub>2</sub>-flooding also applied to CCS

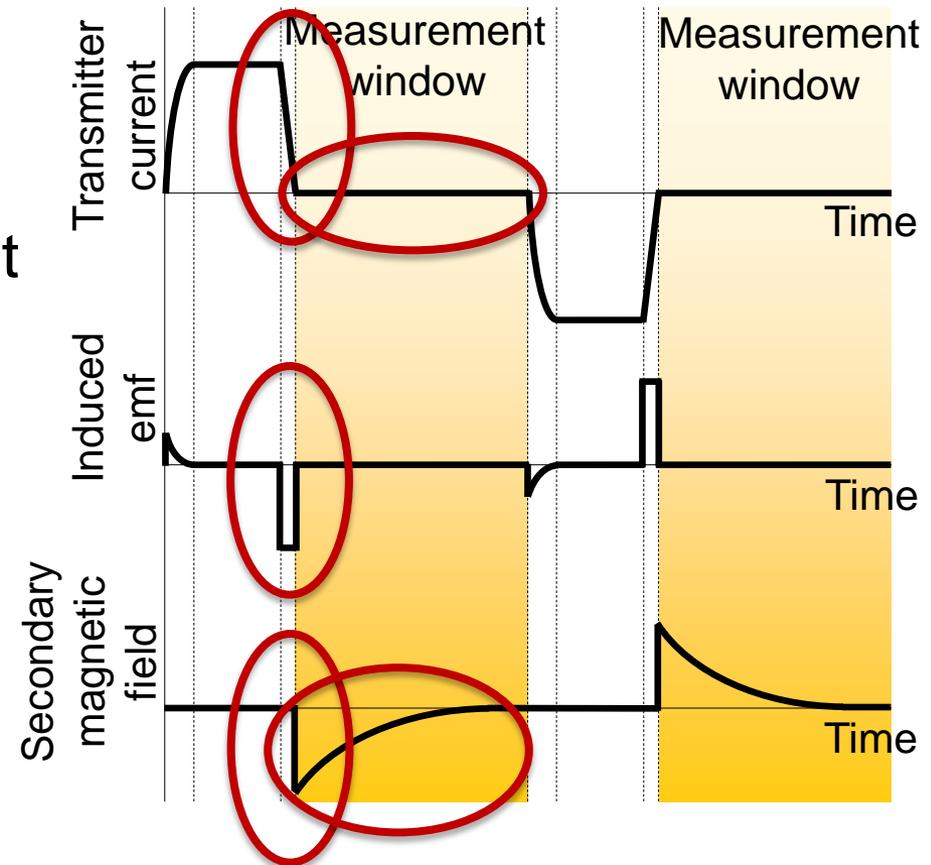


# EOR and reservoir monitoring

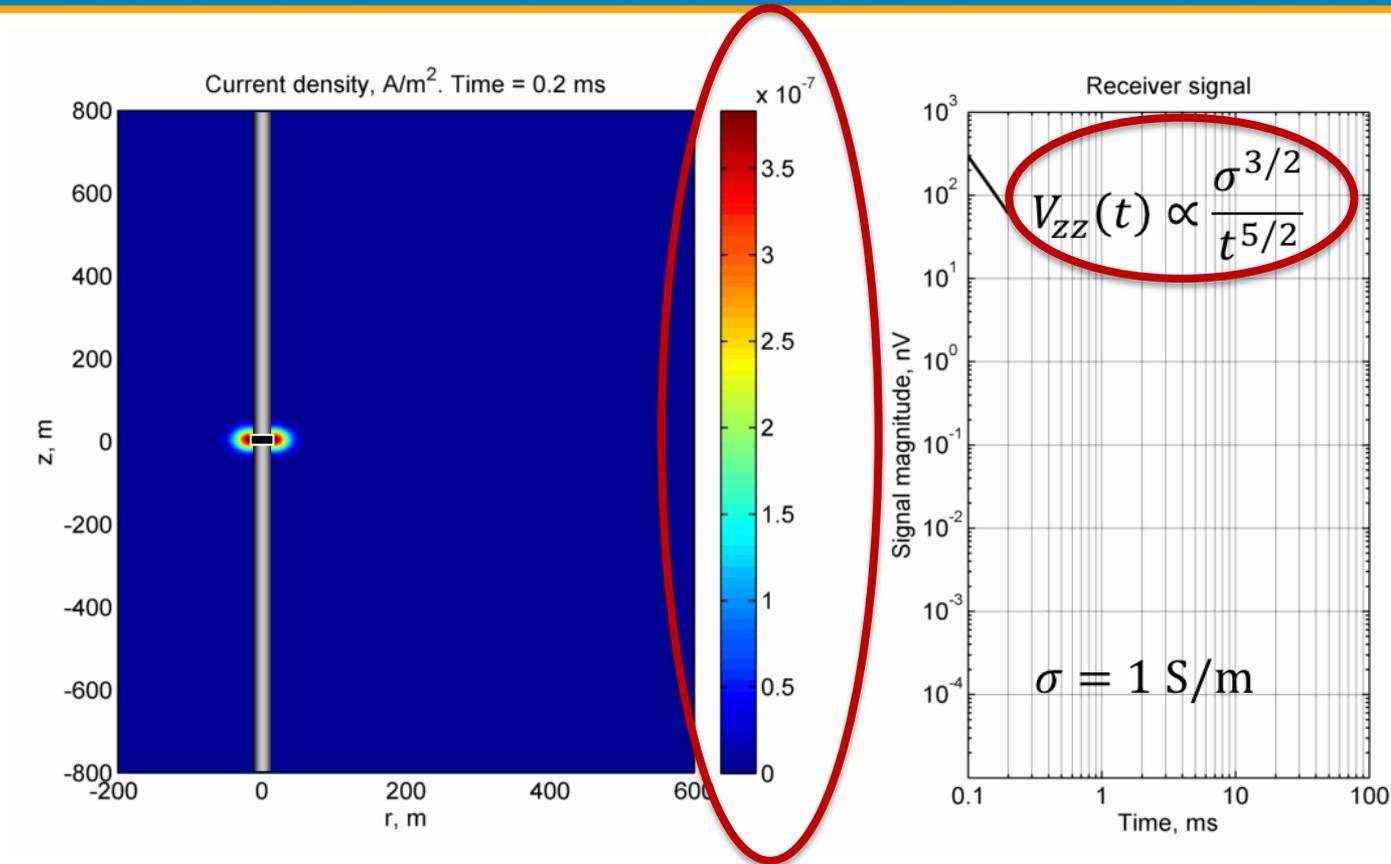
- EOR—waterflooding, steam flooding, CO<sub>2</sub>-flooding—used in mature oil fields
  - CO<sub>2</sub>-flooding also applied to CCS
- Important to map fluid dynamics in reservoir
- Maximize oil recovery efficiency, exploit unswept regions and bypassed pay
- Resistivity contrast among hydrocarbons/water/CO<sub>2</sub>
  - ⇒ **Electromagnetic methods**
- Basin scale > **reservoir scale** > borehole scale

# Transient electromagnetics

- ❑ Broadband excitation
- ❑ Primary (direct) field absent during measurements
- ❑ Diffusing current produces 3D resistivity map



# Transient electromagnetics: EM diffusion



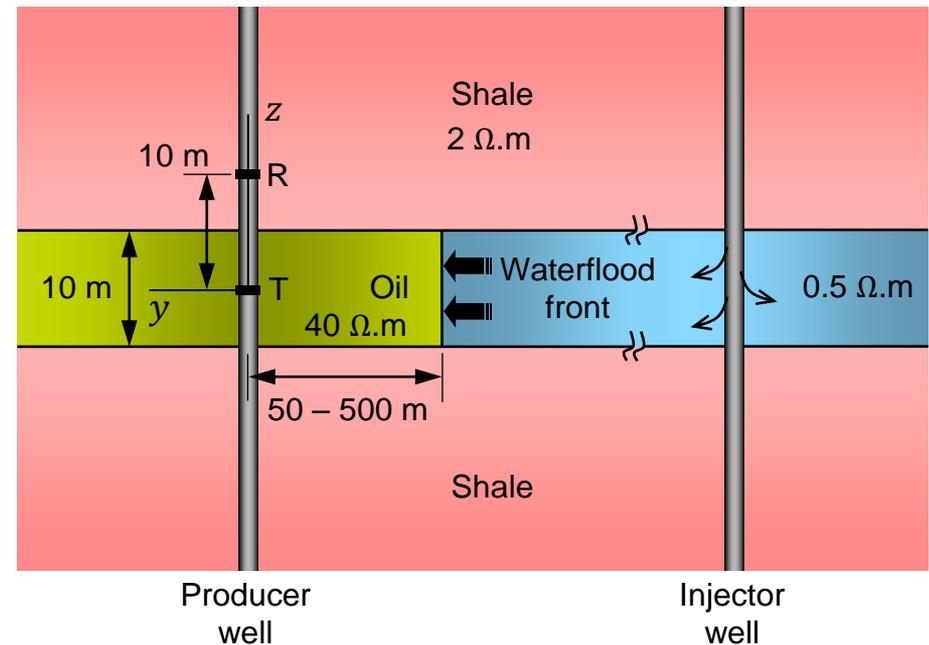
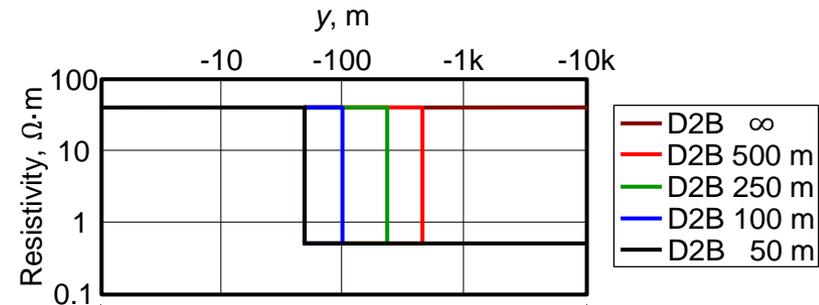
$$\nabla^2 H = \mu\sigma \frac{\partial H}{\partial t} ; r_m(t) = \sqrt{\frac{2t}{\mu\sigma}}$$

- ❑ “Moving Probe” ~ 12.5 miles/s @ 1 ms
- ❑ Resistivity image from single transient

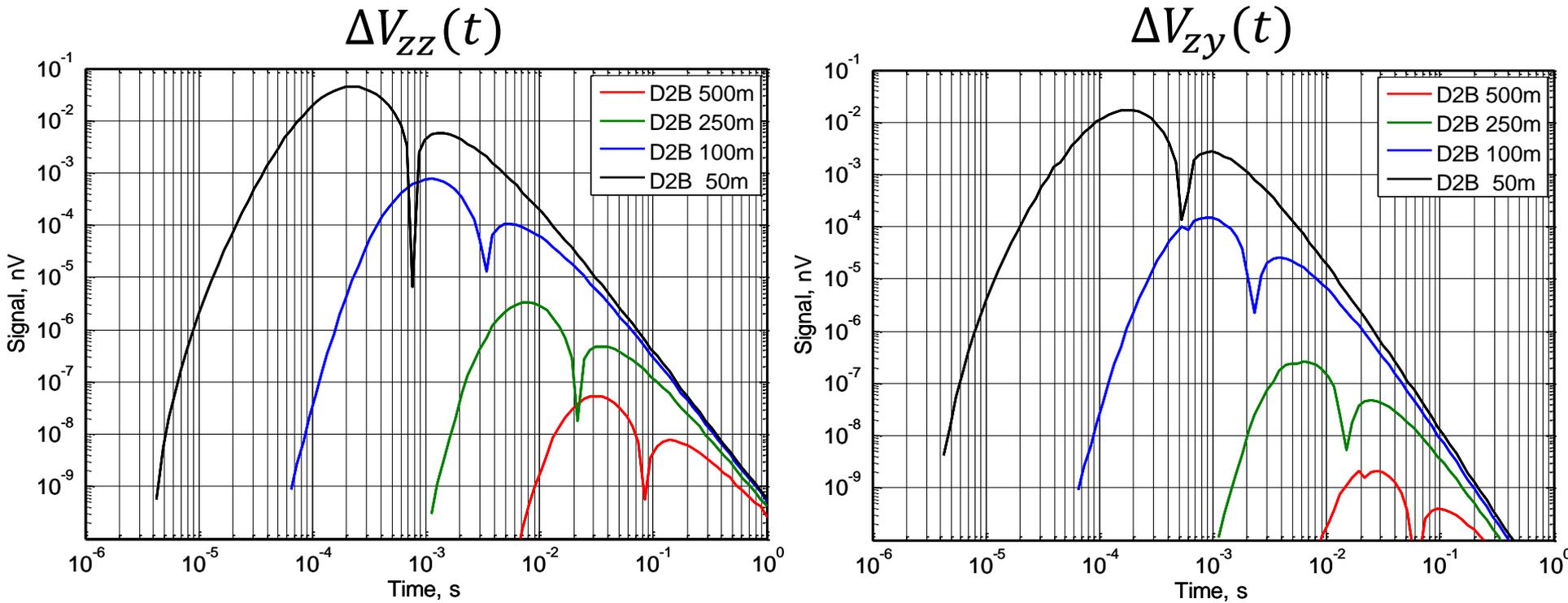
# Modeling: 2D waterflood model

- 10 m thick oil reservoir with advancing planar waterflood front
- Locally non-conductive non-magnetic casing
- Unit Tx/Rx dipoles

$$V(t) = \begin{bmatrix} V_{xx}(t) & V_{xy}(t) & V_{xz}(t) \\ V_{yx}(t) & V_{yy}(t) & V_{yz}(t) \\ V_{zx}(t) & V_{zy}(t) & V_{zz}(t) \end{bmatrix}$$

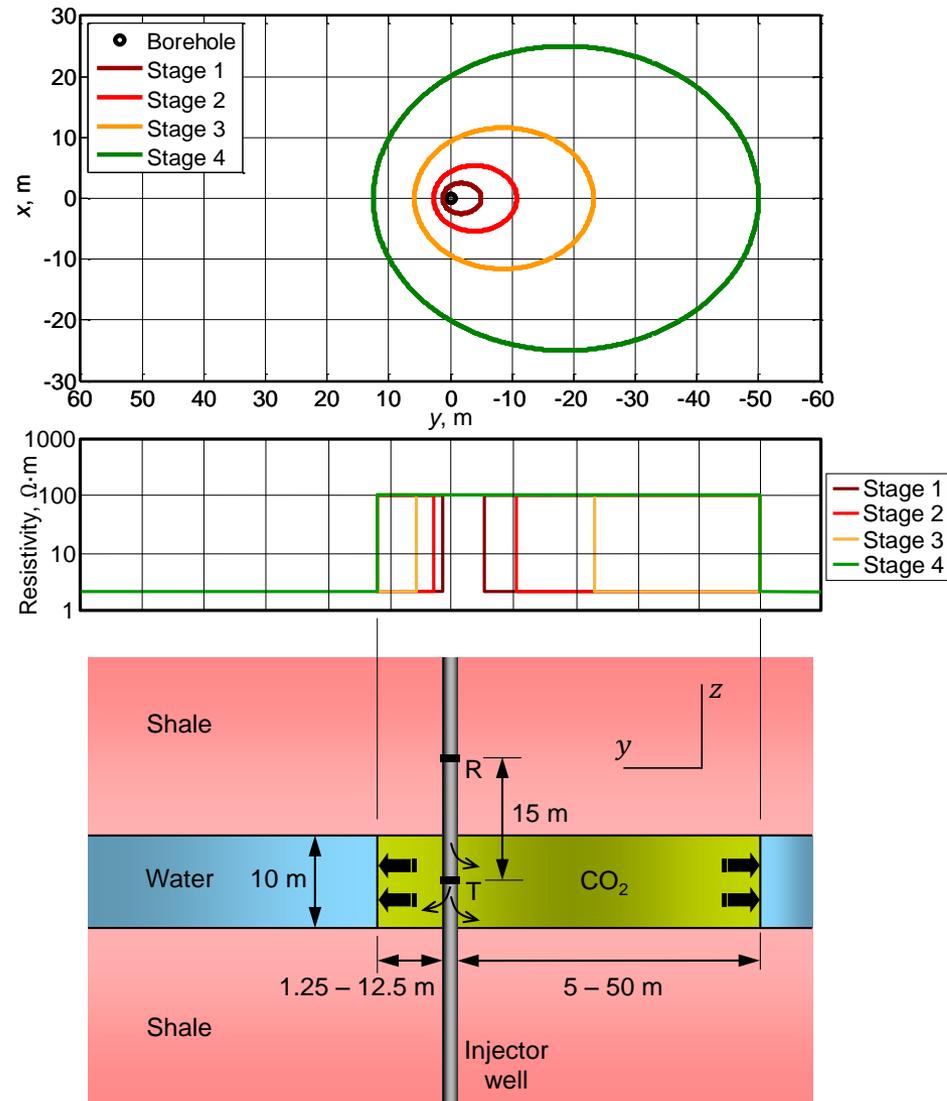


# Results: Time-lapse transient signals

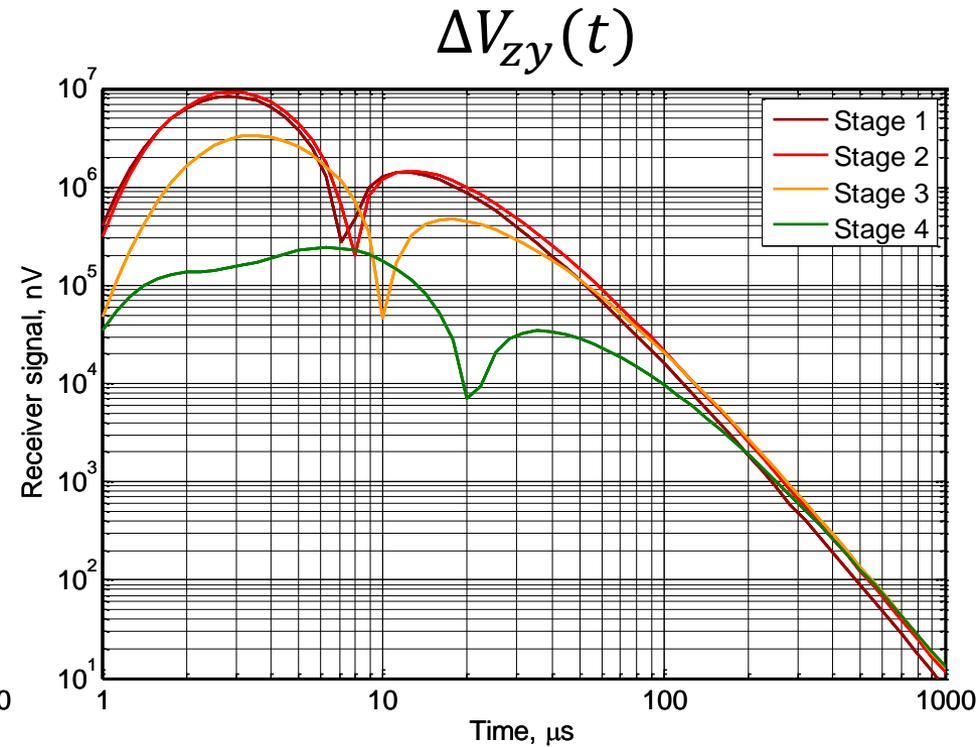
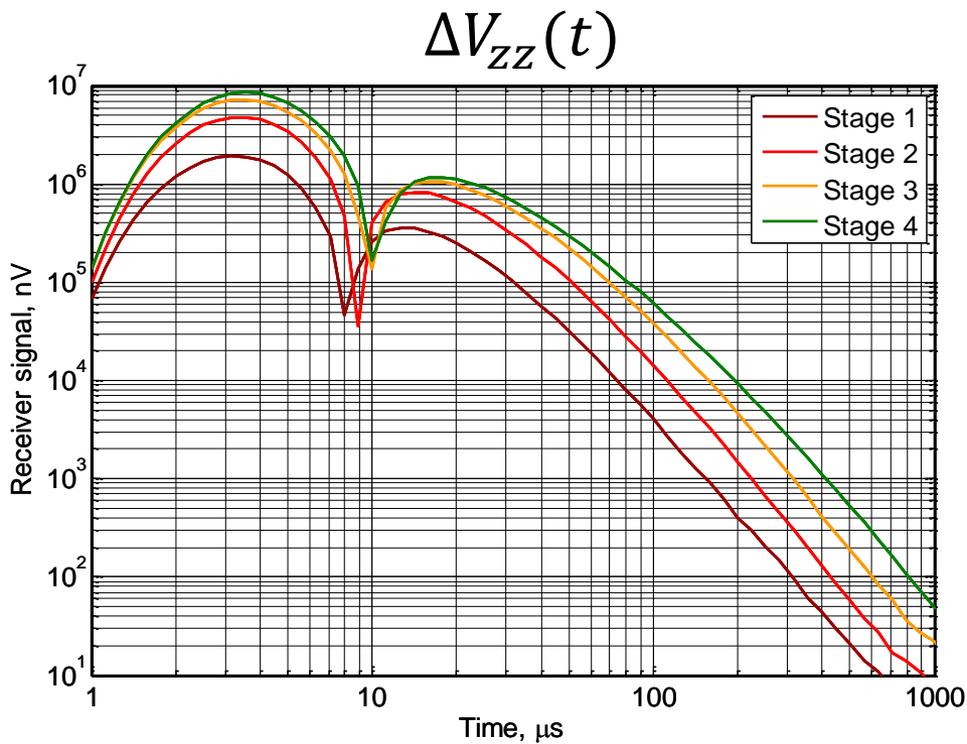


$$\Delta V(t) \Big|_{D2B} = V(t) \Big|_{D2B} - V(t) \Big|_{\infty}$$

# Modeling: 3D CO<sub>2</sub>-flood model

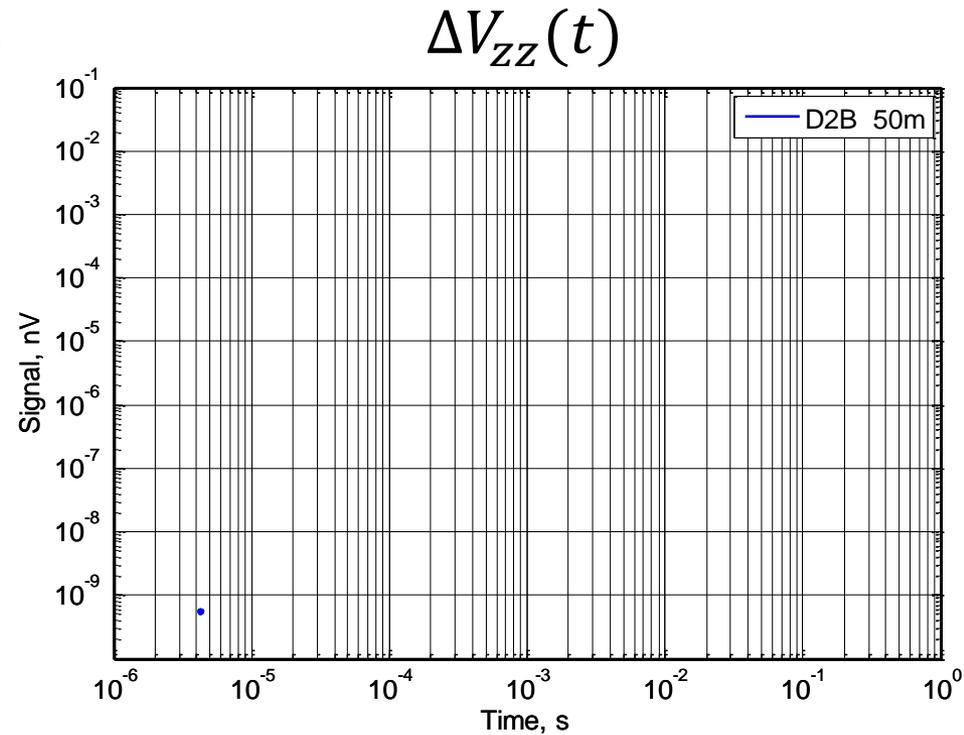
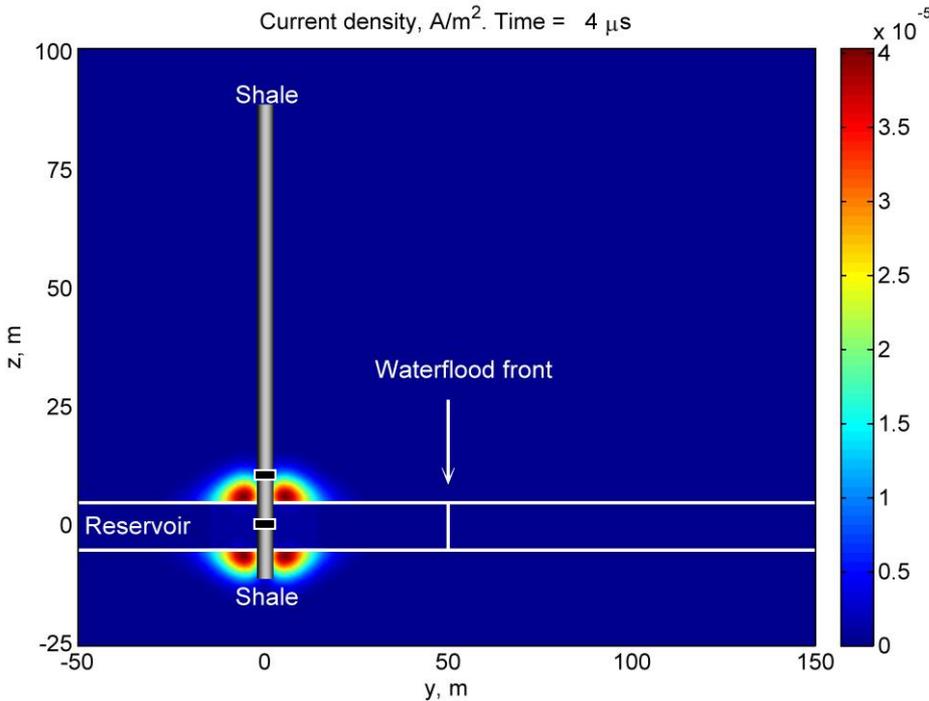


# Results: Time-lapse transient signals

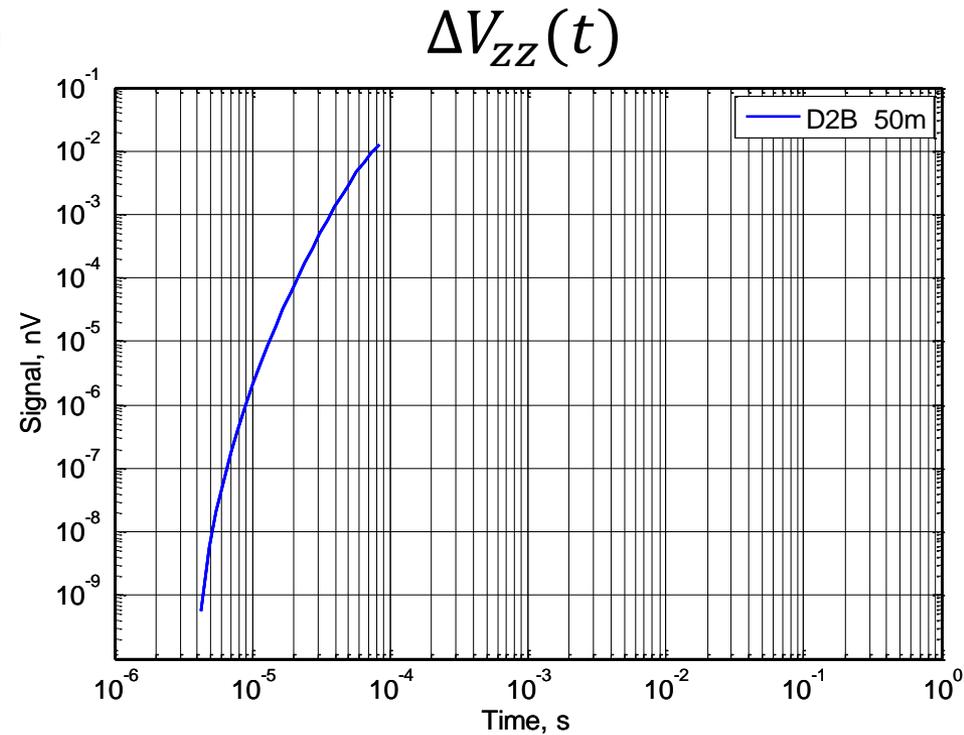
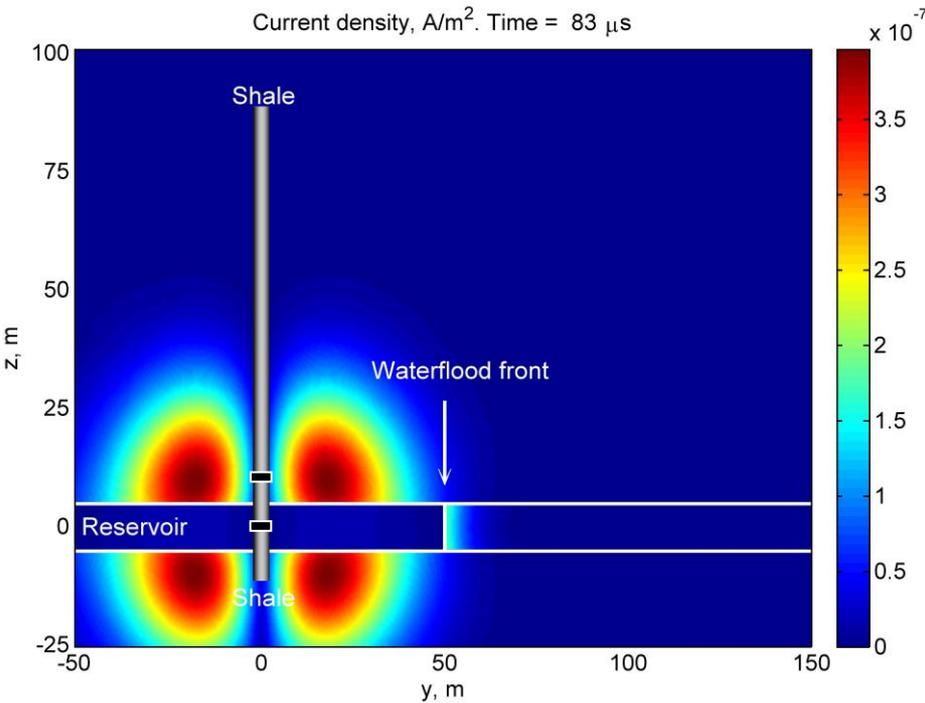


# Analysis: 2D waterflood model. Formation currents for z-transmitter

Current density, A/m<sup>2</sup>. Time = 4 μs

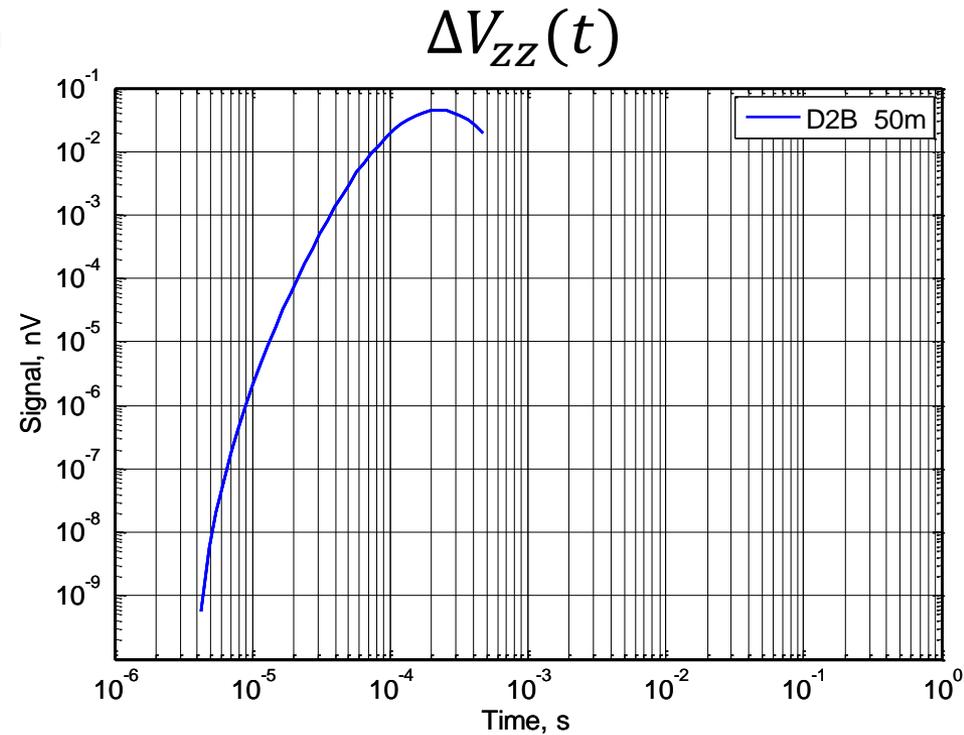
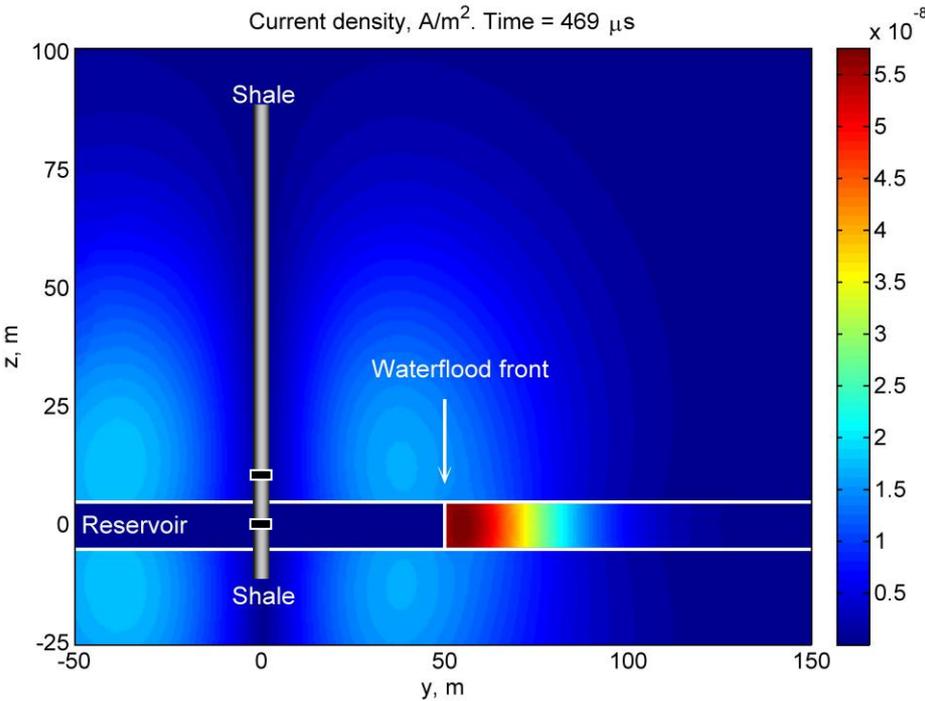


# Analysis: 2D waterflood model. Formation currents for z-transmitter



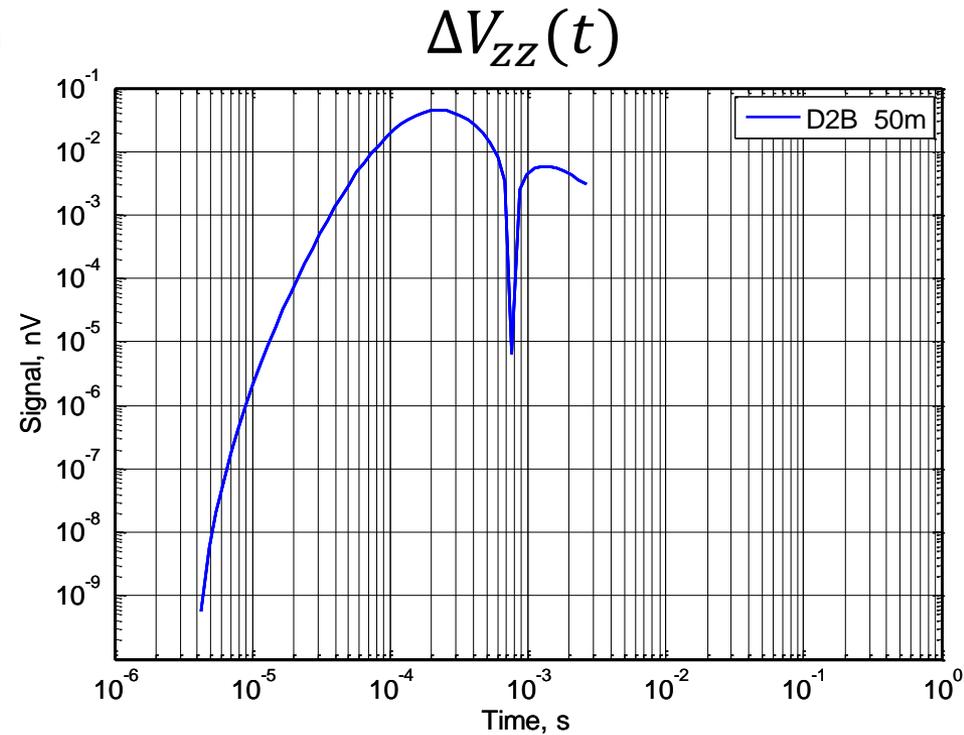
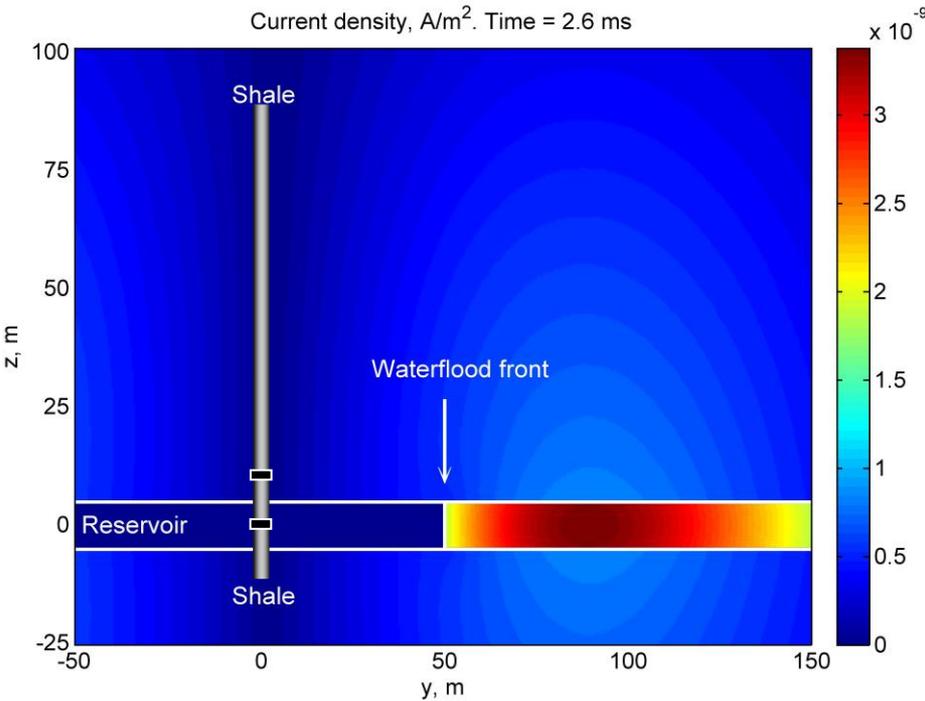
# Analysis: 2D waterflood model. Formation currents for z-transmitter

Current density,  $A/m^2$ . Time = 469  $\mu s$

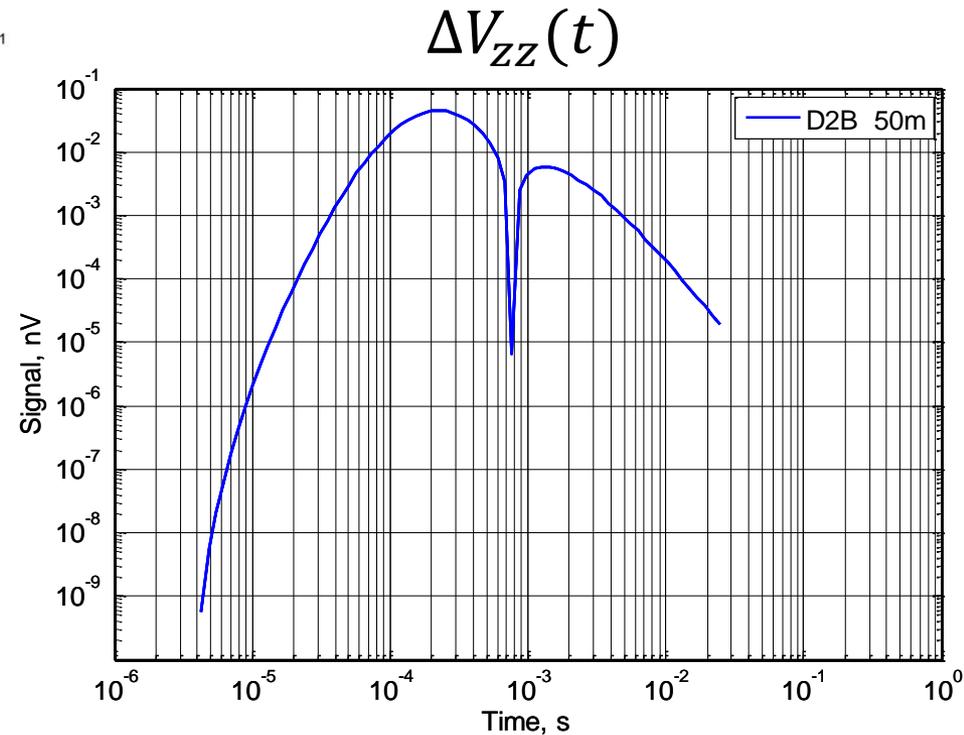
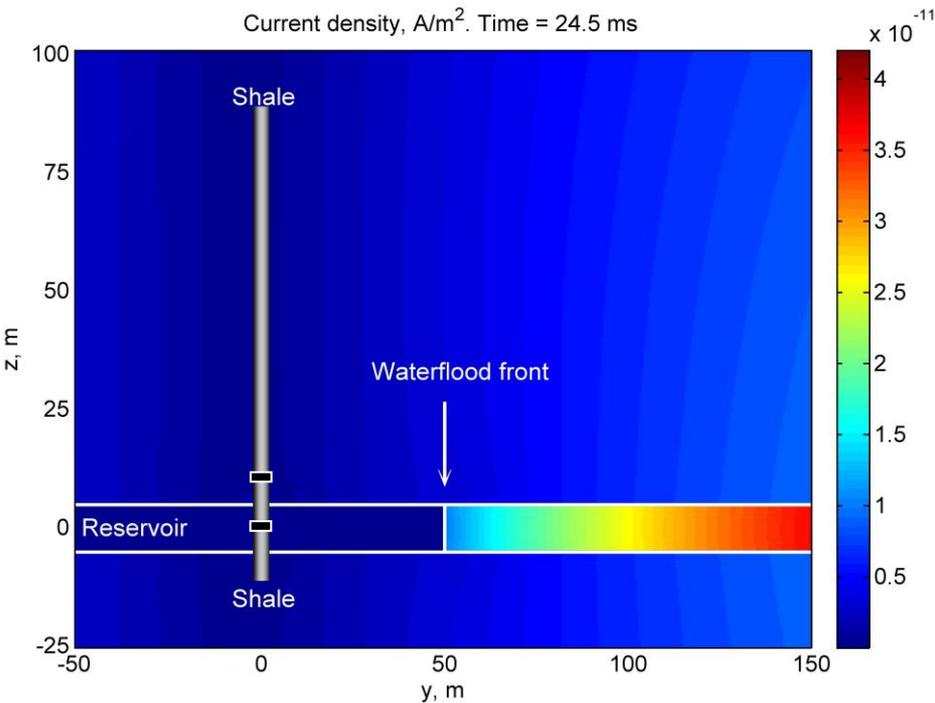


# Analysis: 2D waterflood model. Formation currents for z-transmitter

Current density,  $A/m^2$ . Time = 2.6 ms



# Analysis: 2D waterflood model. Formation currents for z-transmitter



# Conclusions

- ❑ Borehole TEM system capable of resistivity imaging with azimuthal sensitivity
- ❑ Potential to map changes in reservoir fluid distribution over time
- ❑ COMSOL was instrumental in
  - ❑ proving efficacy of borehole TEM technology for reservoir monitoring
  - ❑ delineating behavior of TEM diffusion process in presence of resistivity contrasts
- ❑ Future work:
  - ❑ multi-sensor optimization
  - ❑ multiphysics (porous flow + TEM)