Simulation and Analysis of a Borehole Transient Electromagnetic Reservoir Monitoring System

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COMSOL CONFERENCE BOSTON 2012

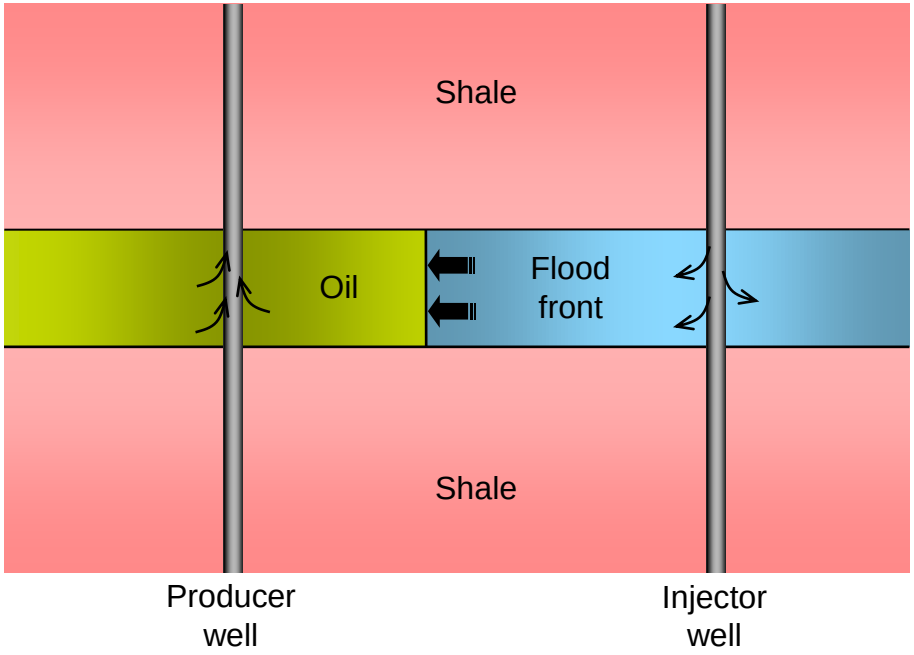
Excerpt from the Proceedings of the 2012 COMSOL Conference in Boston

Outline

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

EOR and reservoir monitoring

- EOR—waterflooding, steam flooding, CO_2-flooding—used in mature oil fields
  - CO_2-flooding also applied to CCS



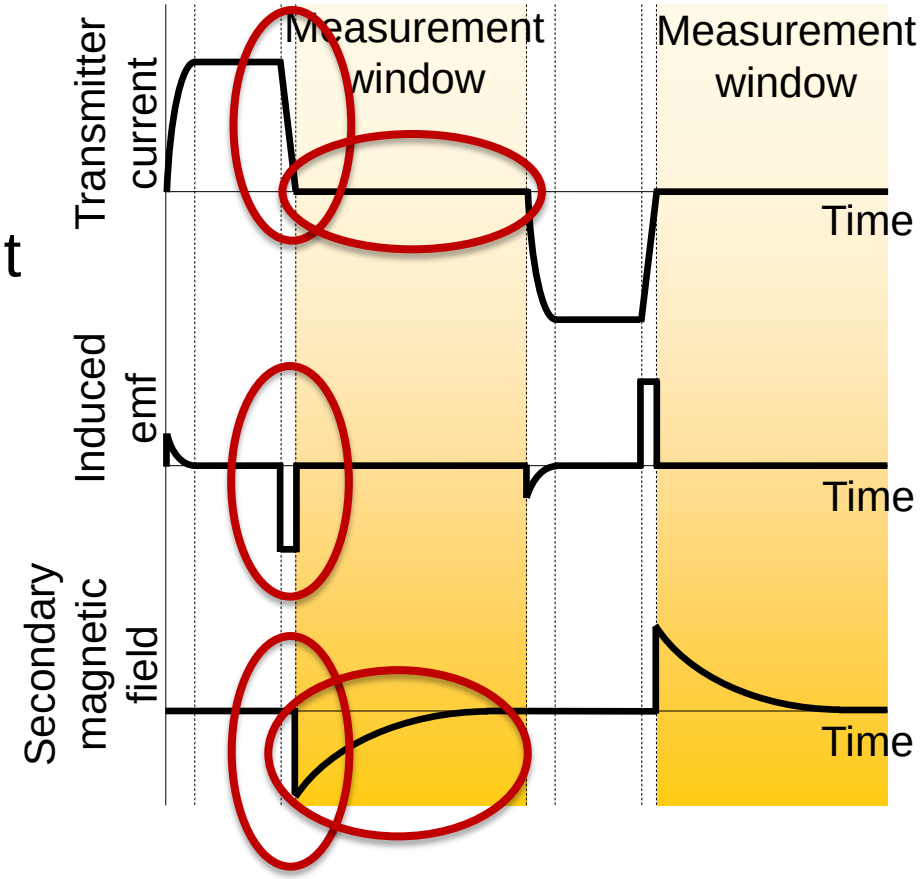
EOR and reservoir monitoring

- EOR—waterflooding, steam flooding, CO_2-flooding—used in mature oil fields
  - CO_2-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_2

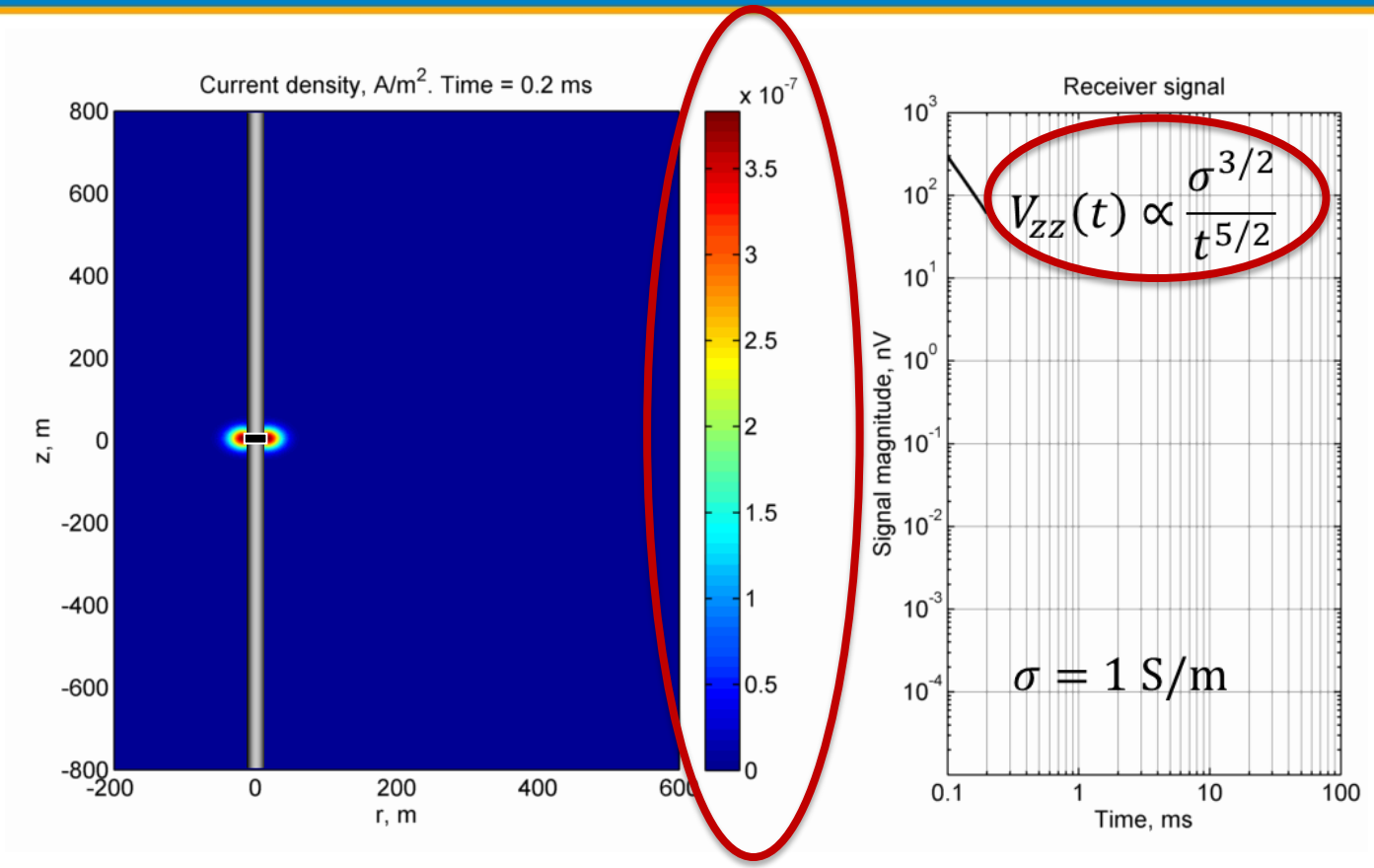
  $\Rightarrow$ **Electromagnetic methods**
- Basin scale > **reservoir scale** > borehole scale

Transient electromagnetics

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



Transient electromagnetics: EM diffusion



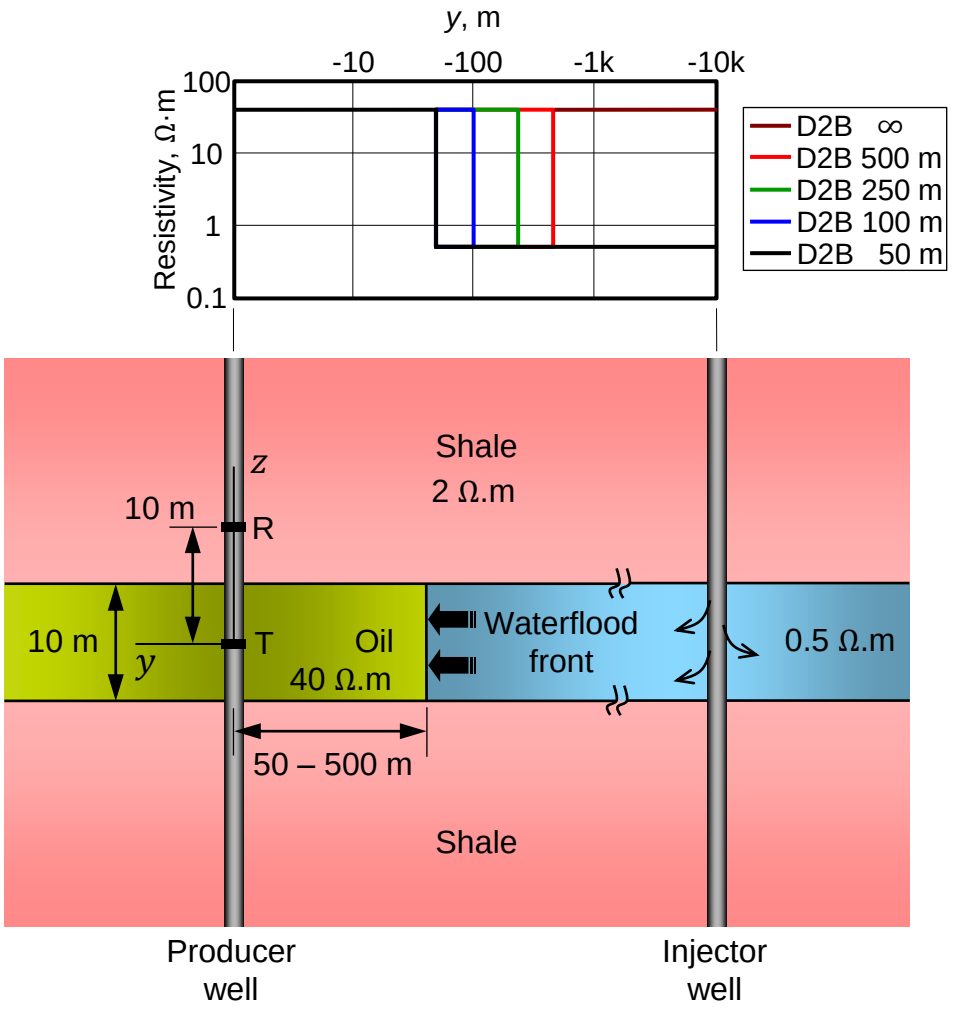
$$\nabla^2 \mathbf{H} = \mu\sigma \frac{\partial \mathbf{H}}{\partial t} \; ; \; r_m(t) = \sqrt{\frac{2t}{\mu\sigma}}$$

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

Modeling: 2D waterflood model

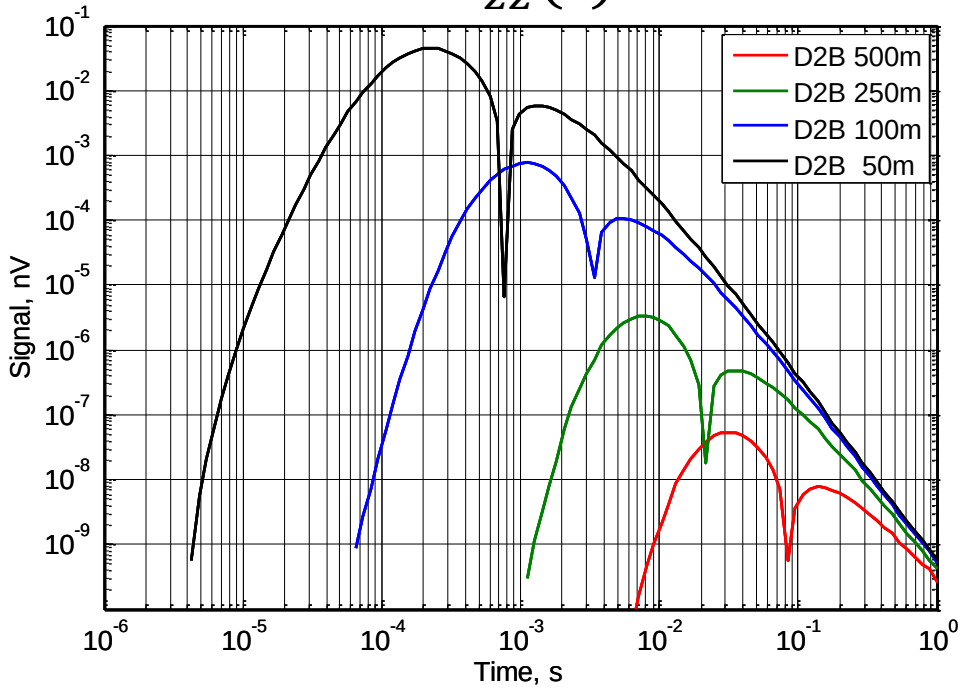
- 10 m thick oil reservoir with advancing planar waterflood front
- Locally non-conductive non-magnetic casing
- Unit Tx/Rx dipoles

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



Results: Time-lapse transient signals

$\Delta V_{zz}(t)$



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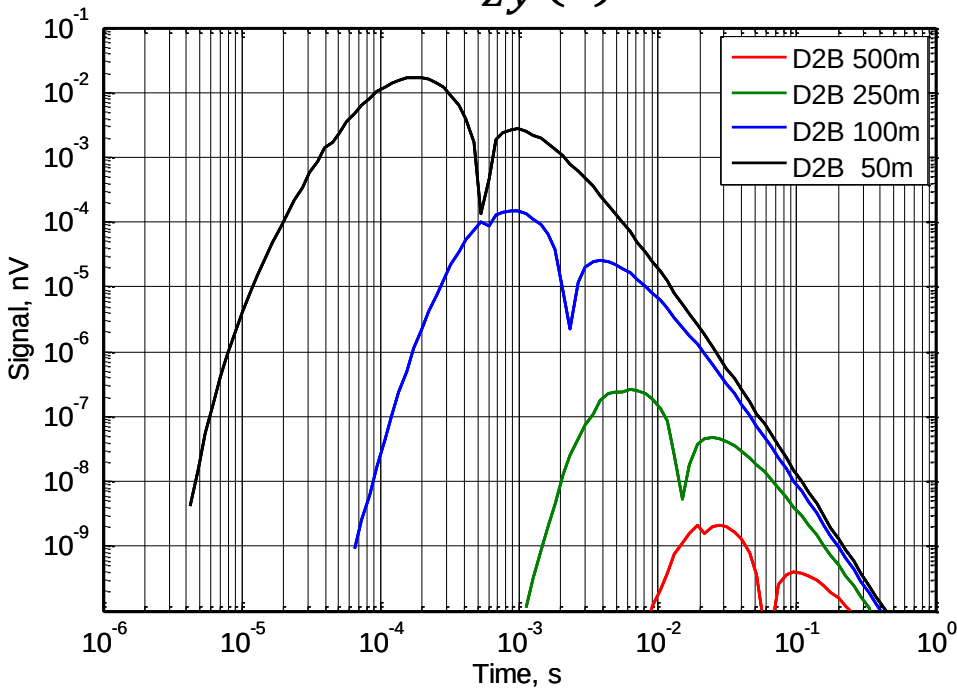
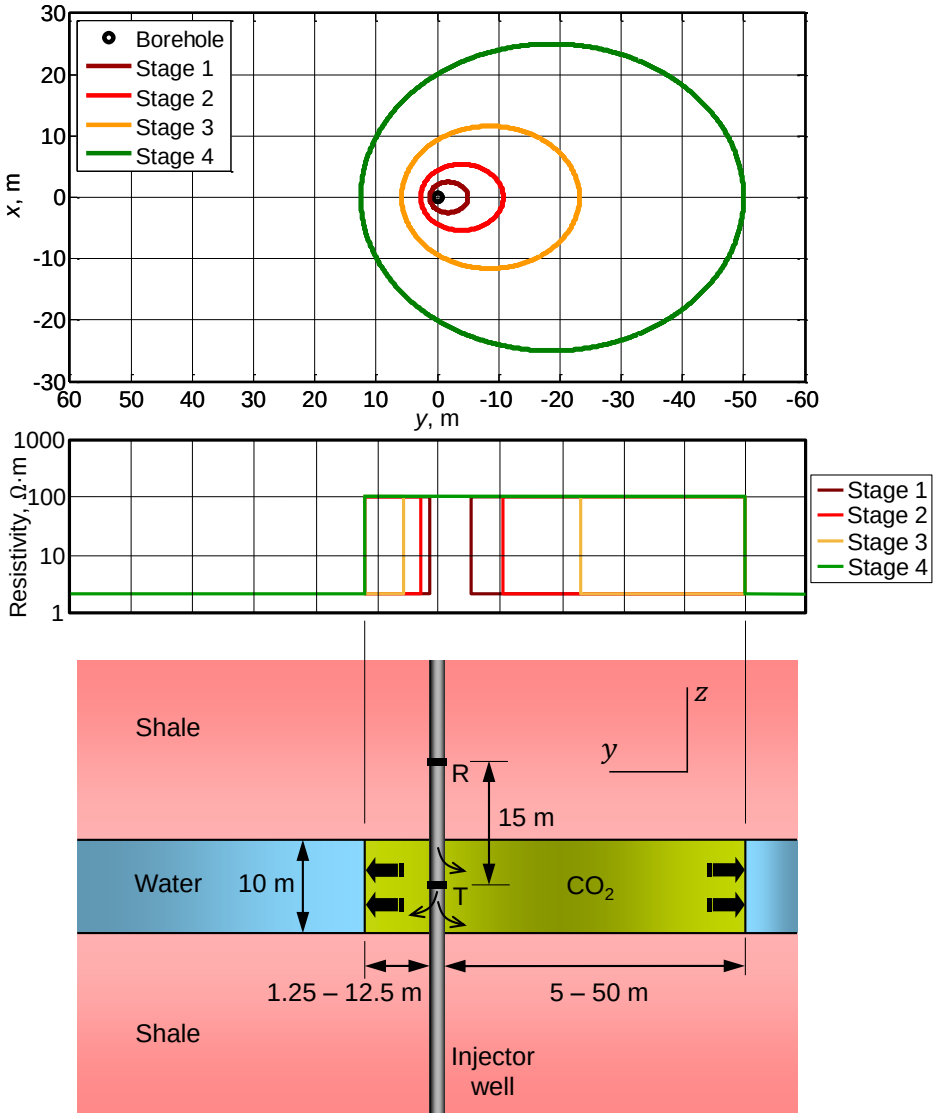


$$\Delta V(t)\Big|_{D2B} = V(t)\Big|_{D2B} - V(t)\Big|_{\infty}$$

Modeling: 3D CO_2-flood model



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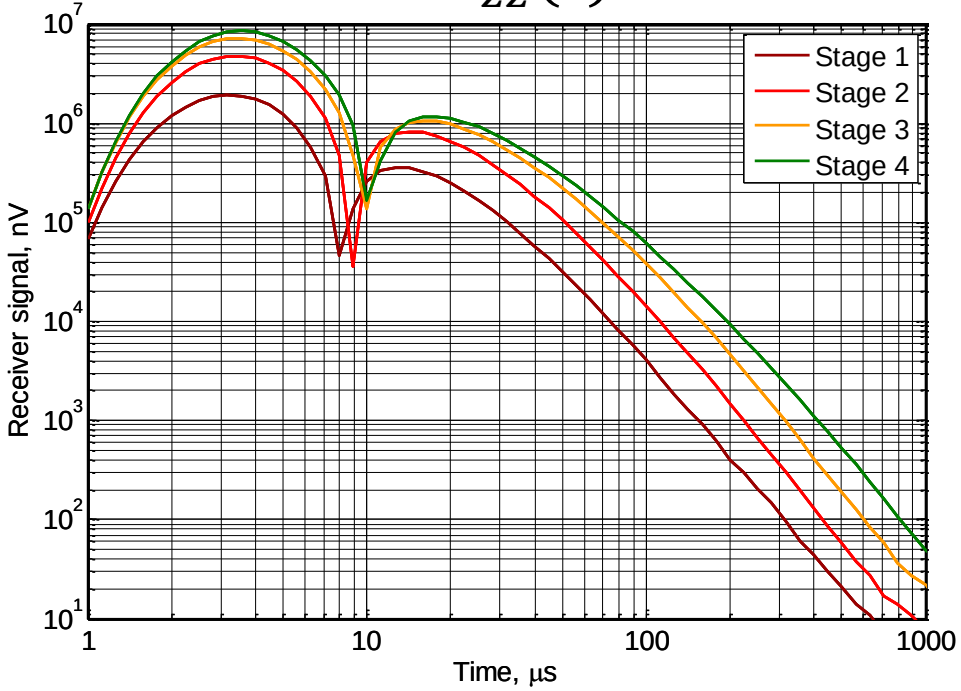

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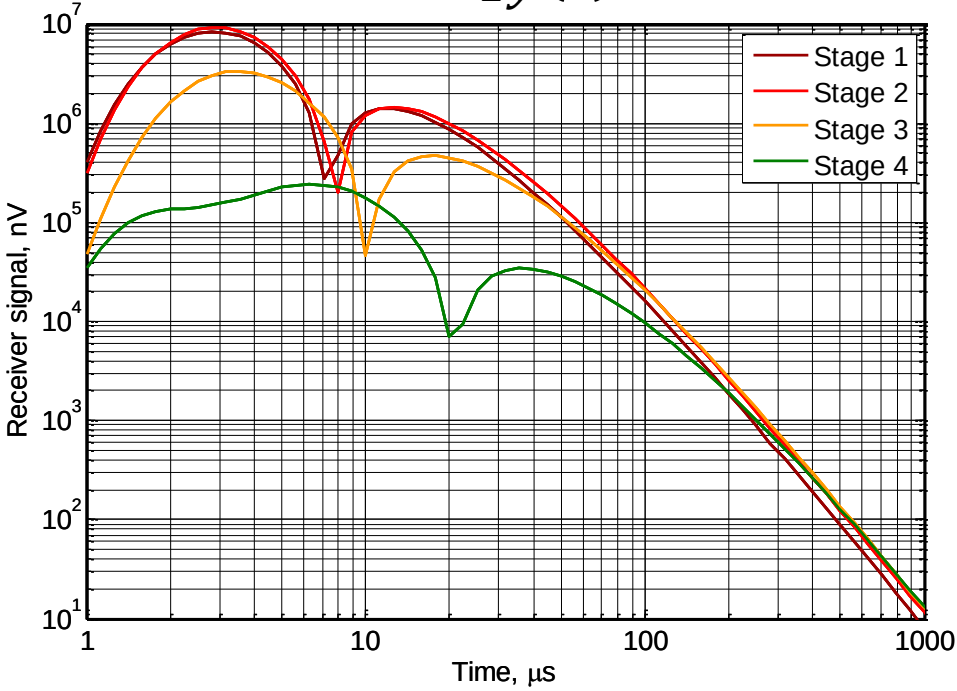
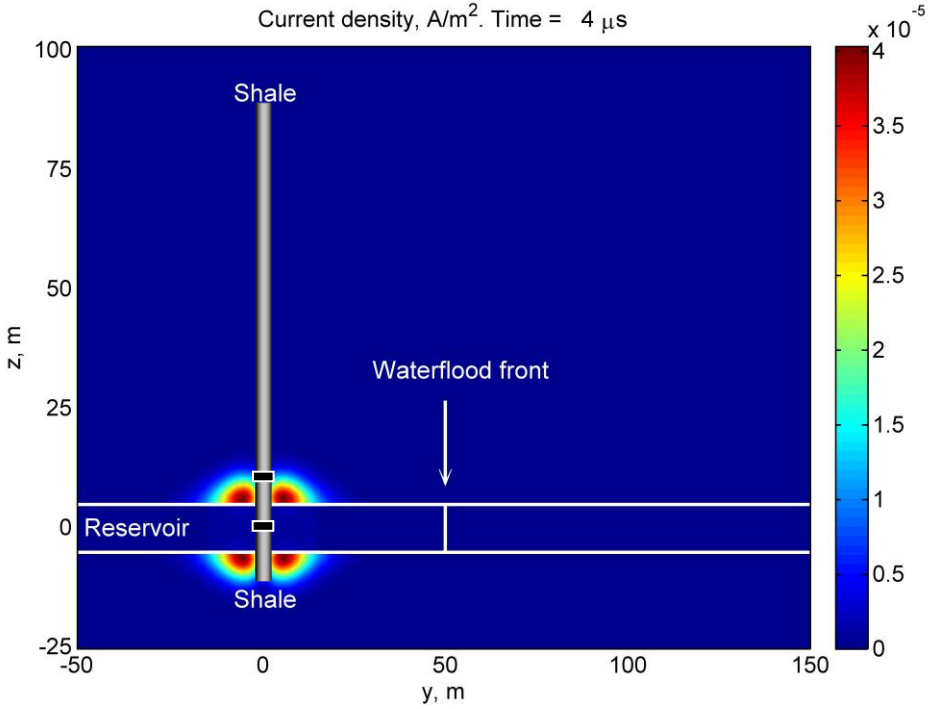


Analysis: 2D waterflood model. Formation currents for z-transmitter



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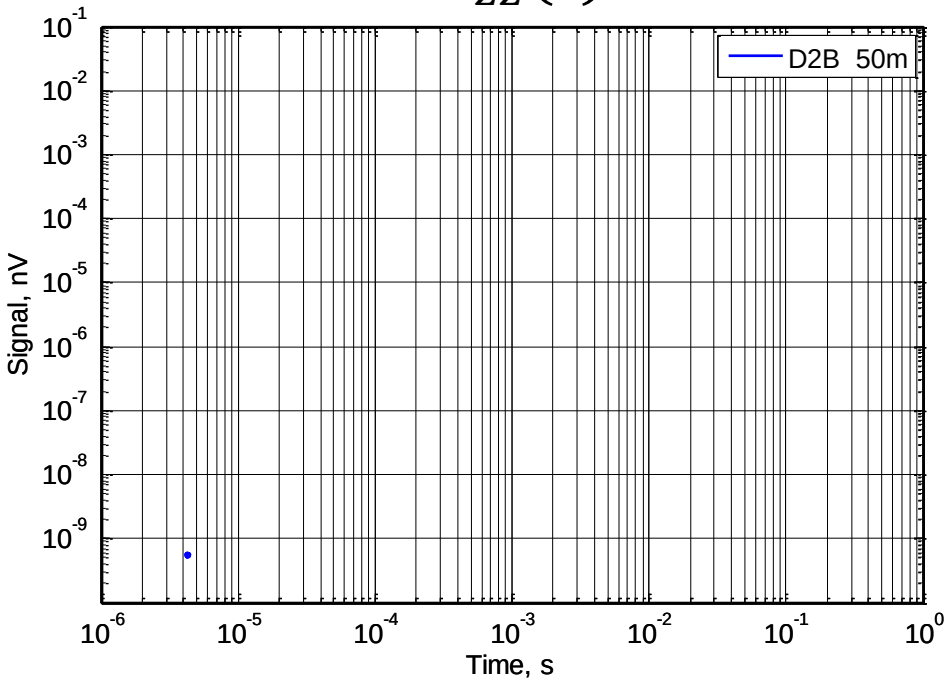

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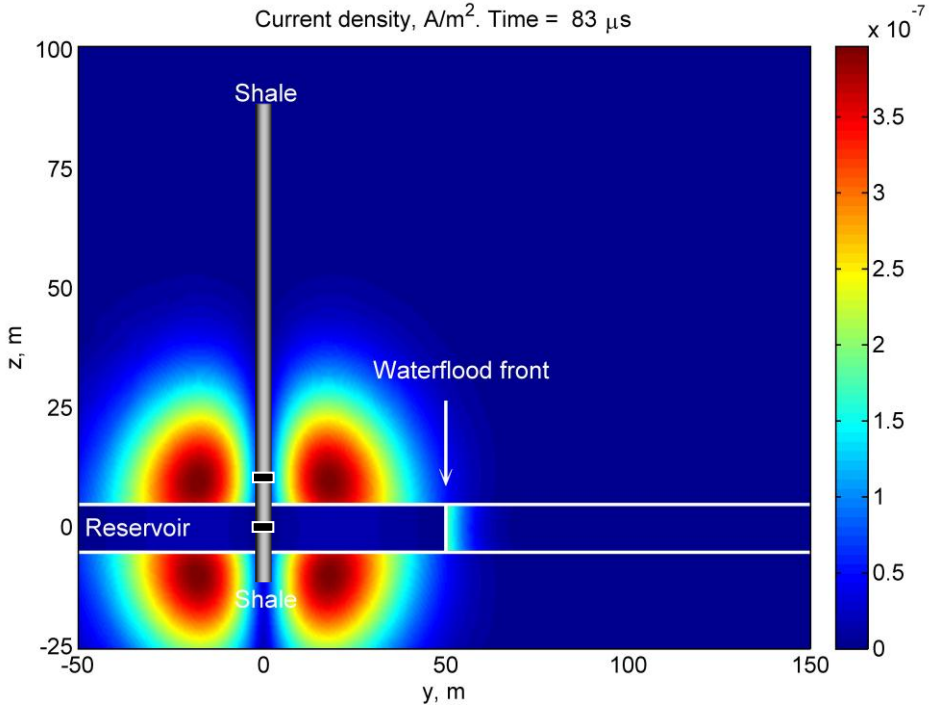

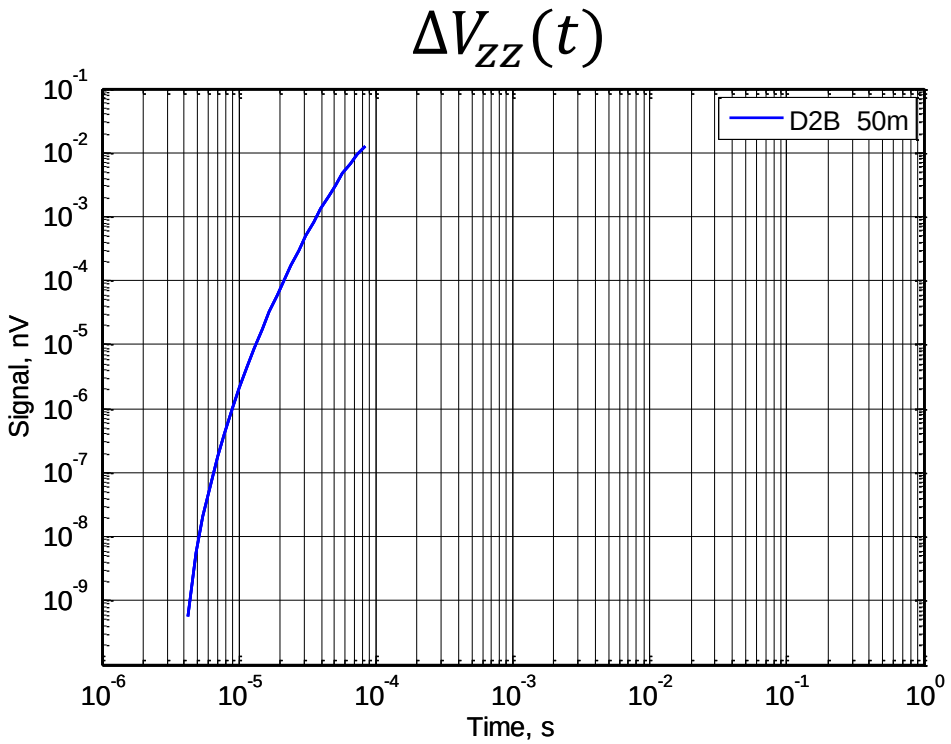

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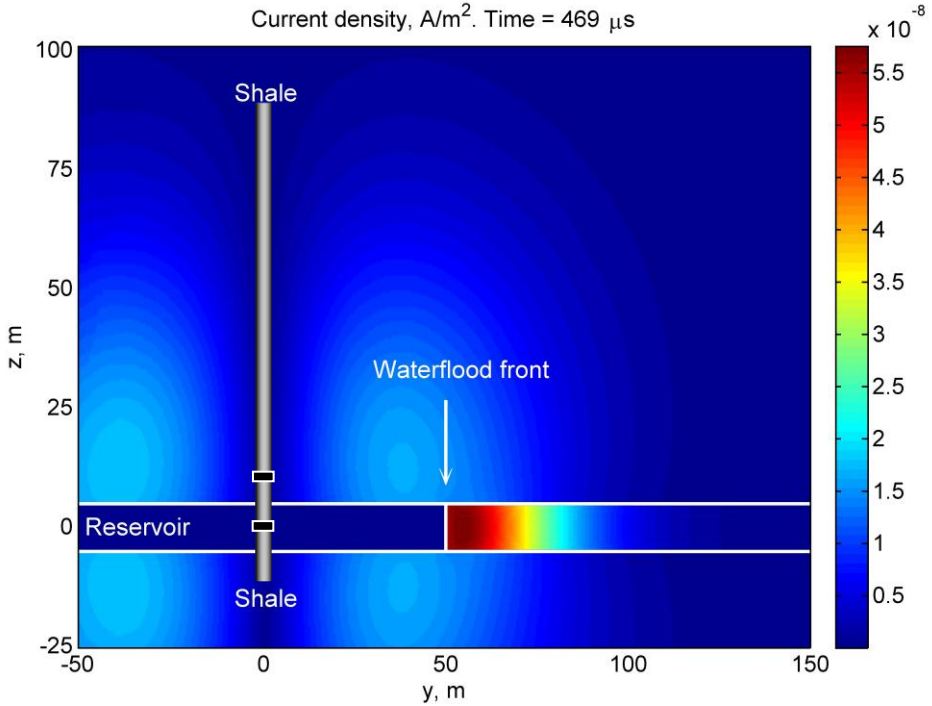

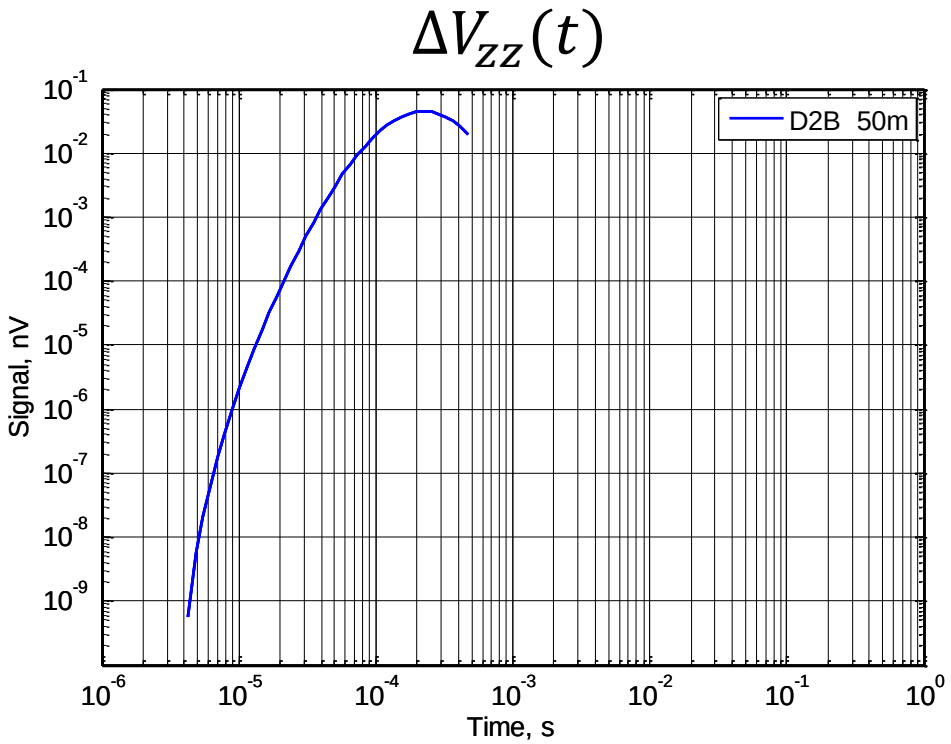

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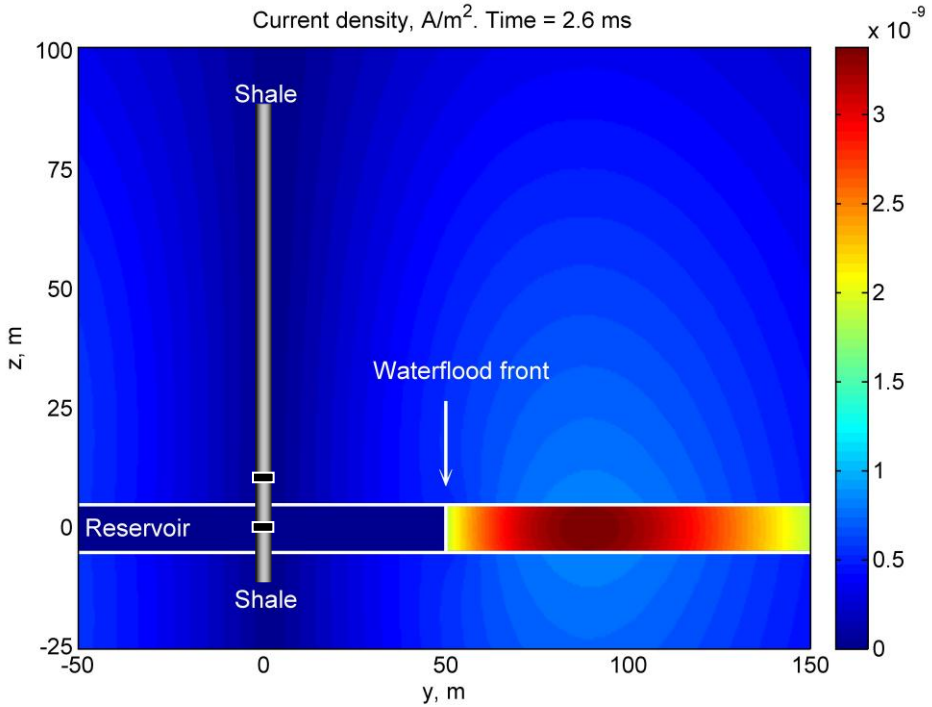

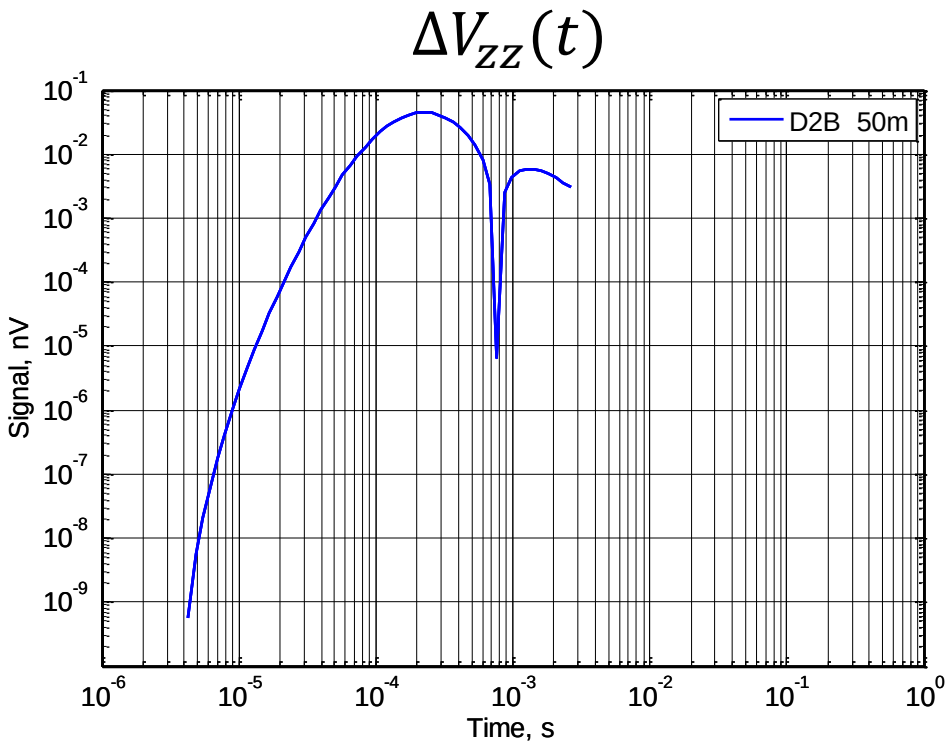

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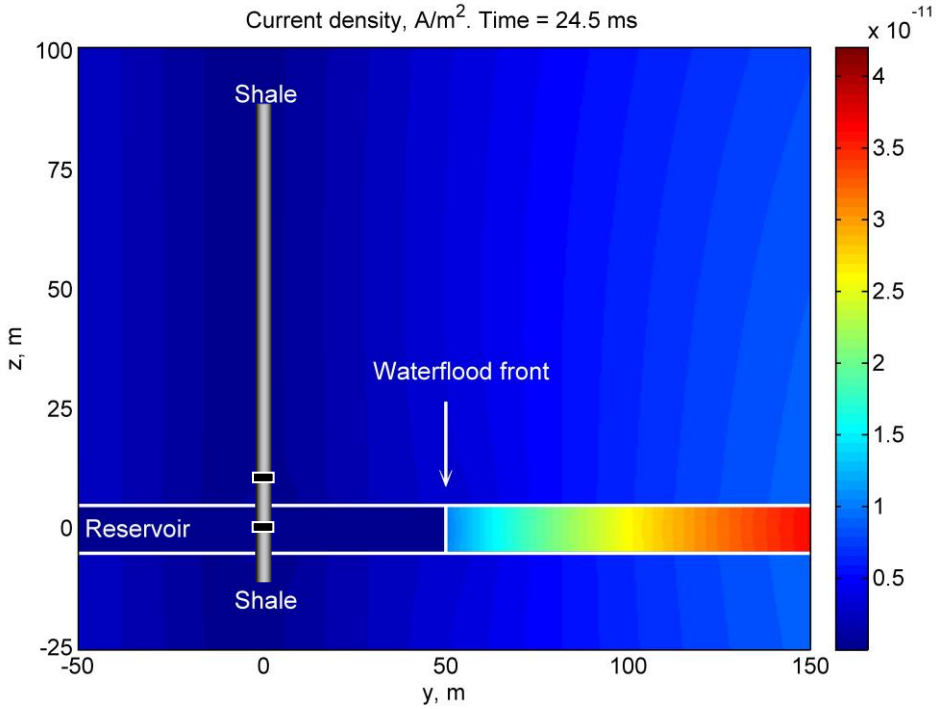

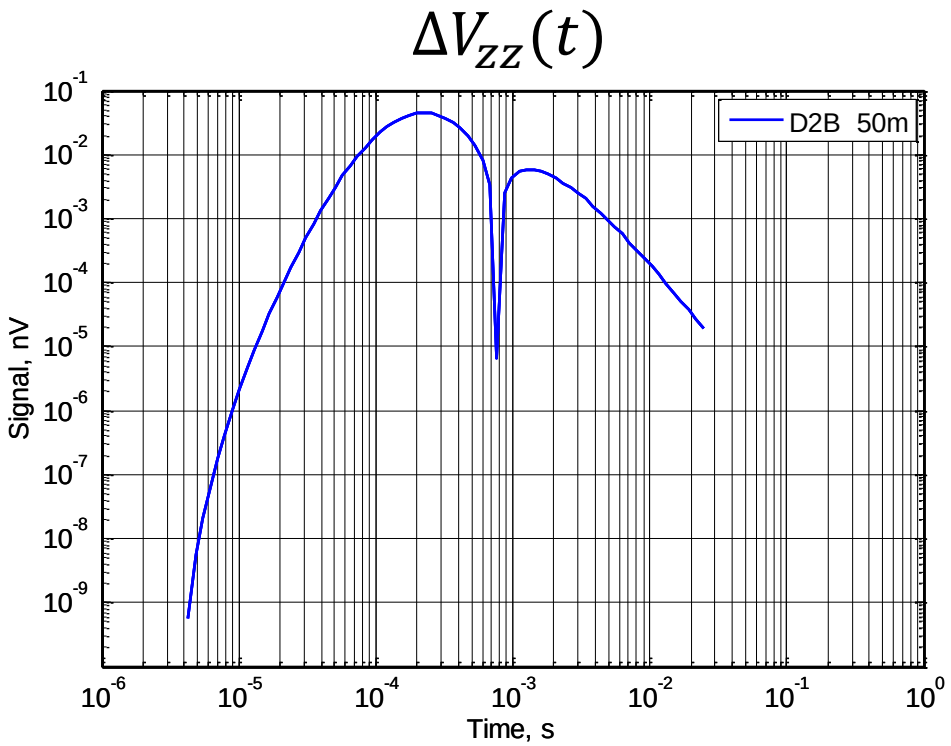

Conclusions

- 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)