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Self-Adaptive hp Finite-Element Simulation of Dual-Laterolog Measurements in Dipping, Invaded, and Anisotropic Formations

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Overview

1. 3D Methodology and Formulation (D. Pardo).

2. Numerical Results:
   Through-Casing Instruments (D. Pardo).
   Induction Instruments (D. Pardo + M. Paszynski).

3. Parallel Implementation (M. Paszynski).

4. Applications: Dual-Laterolog Instruments (M. J. Nam).

5. Multi-Physics: Sonic Instruments (Ch. Michler).

6. Conclusions and Future Work (Ch. Michler).

Outline

- **Methodology.**
- **Introduction to Dual-Laterolog.**
- **Embedded Post-Processing Method.**
- **Verification of 3D methodology for Dual-Laterolog.**
- **Numerical Results:**
  → Dipping, Invaded, Anisotropic Formations.
- **Conclusions.**
- **Future Work.**

Method

Combination of:

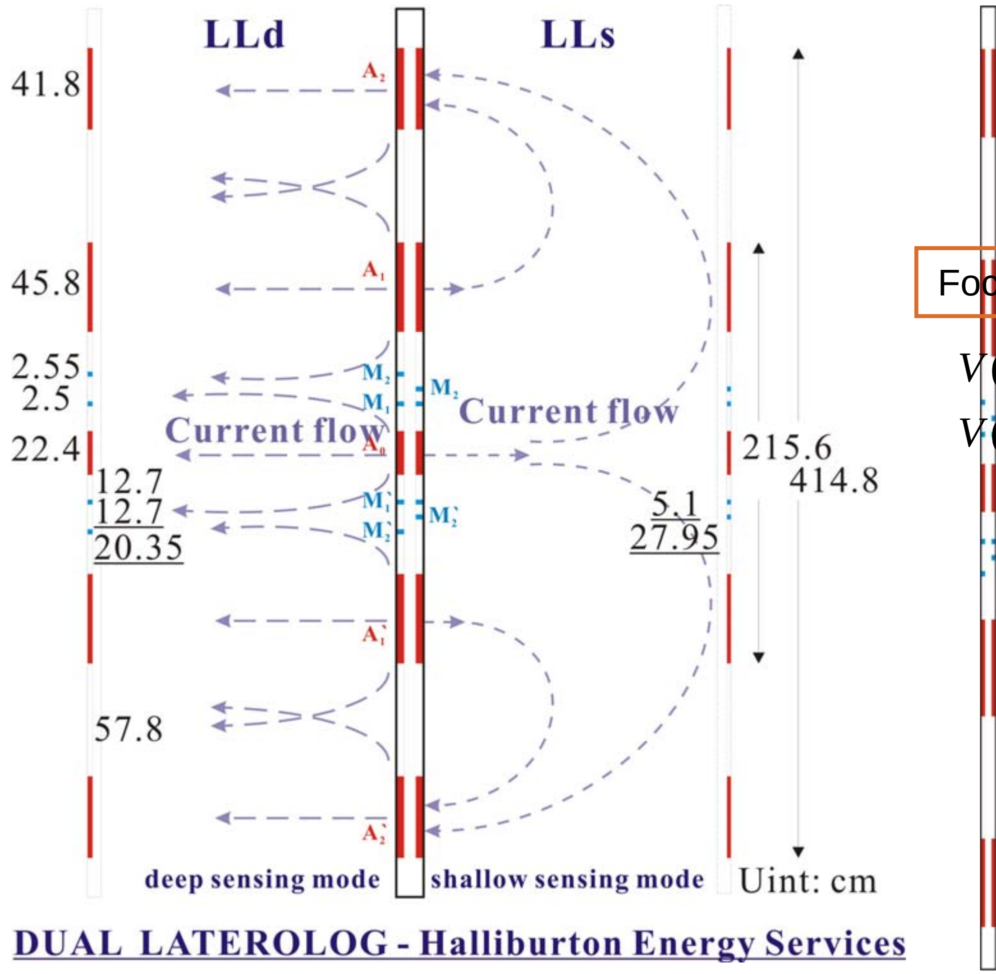
1. A Self-Adaptive Goal-Oriented hp-FEM for DC problems.

2. A Fourier Series Expansion in a Non-Orthogonal System of Coordinates.

3. Embedded Post-Processing Method (EPPM).

Dual-Laterolog

- Description of Tool
- Determination of Intensities (W_j) of Bucking Currents



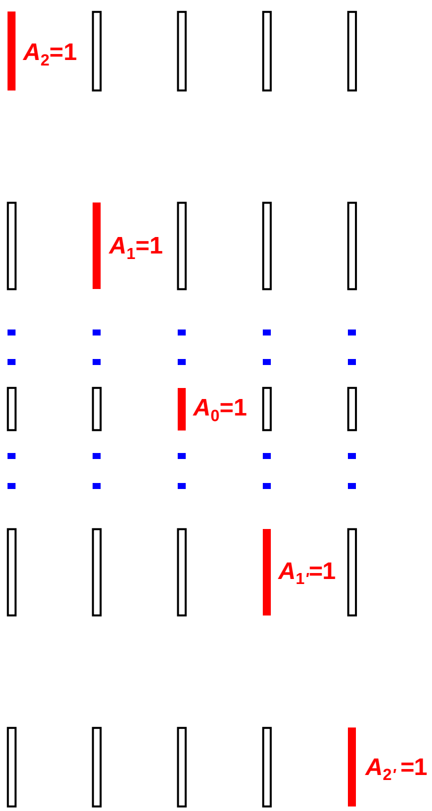
Focusing Conditions

$$V(M_1) = V(M_2)$$

$$V(M_{1'}) = V(M_{2'})$$

Post-Processing Method

Synthetic Focusing (Cozzolino et al, 2007)



(1) Focusing conditions

$$V(M_1) = V(M_2)$$
$$V(M_{1'}) = V(M_{2'})$$

(2) Total potential on M_i

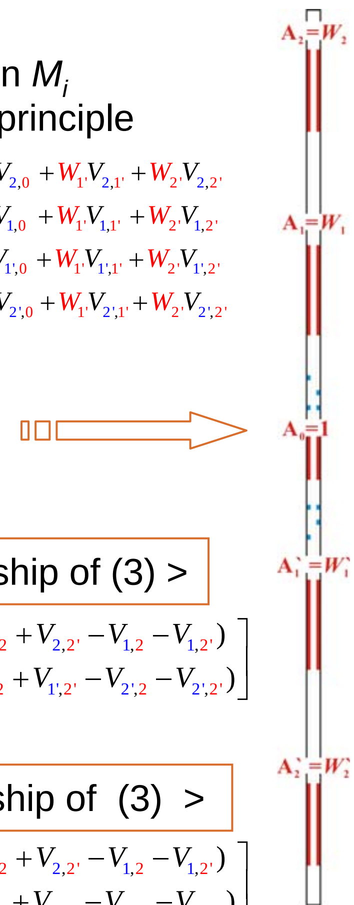
→ Superposition principle

$$V(M_2) = W_2 V_{2,2} + W_1 V_{2,1} + V_{2,0} + W_{1'} V_{2,1'} + W_{2'} V_{2,2'}$$
$$V(M_1) = W_2 V_{1,2} + W_1 V_{1,1} + V_{1,0} + W_{1'} V_{1,1'} + W_{2'} V_{1,2'}$$
$$V(M_{1'}) = W_2 V_{1',2} + W_1 V_{1',1} + V_{1',0} + W_{1'} V_{1',1'} + W_{2'} V_{1',2'}$$
$$V(M_{2'}) = W_2 V_{2',2} + W_1 V_{2',1} + V_{2',0} + W_{1'} V_{2',1'} + W_{2'} V_{2',2'}$$

(3) Relationships between W_j

$$W_2 = (W_1 + c), \quad W_{2'} = (W_{1'} + c) \quad for \ \text{LLd}$$
$$W_2 = -(W_1 + c), \quad W_{2'} = -(W_{1'} + c) \quad for \ \text{LLs}$$

with $c = 0.5$



W_j for LLd: < from (1) and (2) with the LLd relationship of (3) >

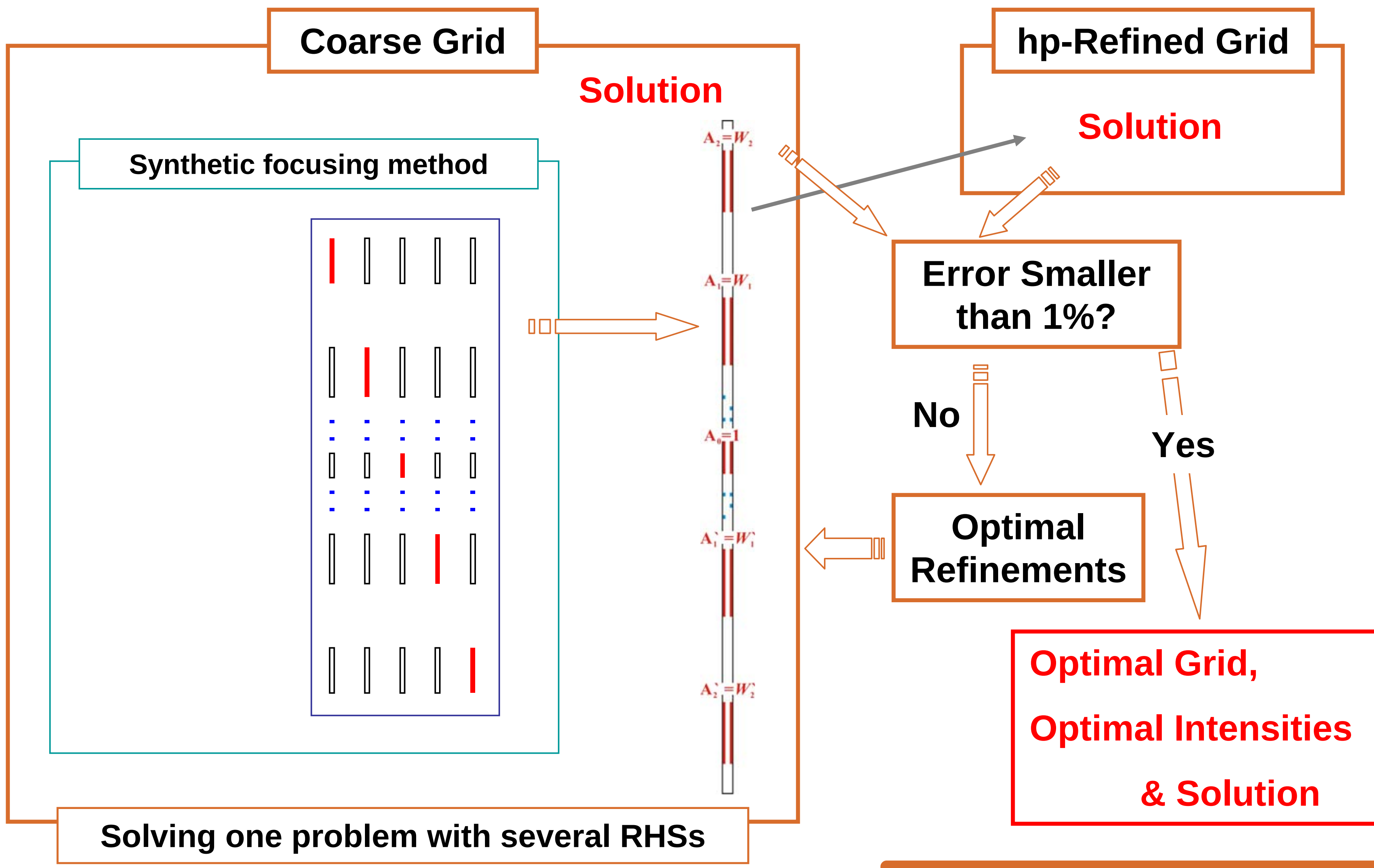
$$\begin{bmatrix} V_{1,2}+V_{1,1}-V_{2,2}-V_{2,1} & V_{1,1'}+V_{1,2'}-V_{2,1'}-V_{2,2'} \\ V_{2',2}+V_{2',1}-V_{1',2}-V_{1',1} & V_{2',1'}+V_{2',2'}-V_{1',1'}-V_{1',2'} \end{bmatrix} \begin{bmatrix} W_1 \\ W_{1'} \end{bmatrix} = \begin{bmatrix} V_{2,0}-V_{1,0}+c(V_{2,2}+V_{2,2'}-V_{1,2}-V_{1,2'}) \\ V_{1',0}-V_{2',0}+c(V_{1',2}+V_{1',2'}-V_{2',2}-V_{2',2'}) \end{bmatrix}$$

W_j for LLs: < from (1) and (2) with the LLs relationship of (3) >

$$\begin{bmatrix} V_{2,2}+V_{1,1}-V_{2,1}-V_{1,2} & V_{2,2'}+V_{1,1'}-V_{1,2'}-V_{2,1'} \\ V_{1',2}+V_{2',1}-V_{1',1}-V_{2',2} & V_{1',2'}+V_{2',1'}-V_{2',2'}-V_{1',1'} \end{bmatrix} \begin{bmatrix} W_1 \\ W_{1'} \end{bmatrix} = \begin{bmatrix} V_{2,0}-V_{1,0}+c(V_{2,2}+V_{2,2'}-V_{1,2}-V_{1,2'}) \\ V_{1',0}-V_{2',0}+c(V_{1',2}+V_{1',2'}-V_{2',2}-V_{2',2'}) \end{bmatrix}$$

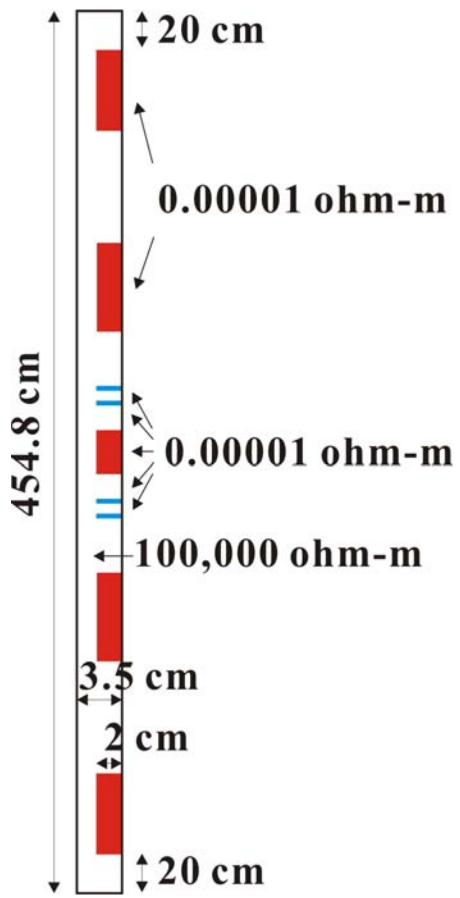
One problem with several RHSs

Embedded Post-Processing Method (EPPM)

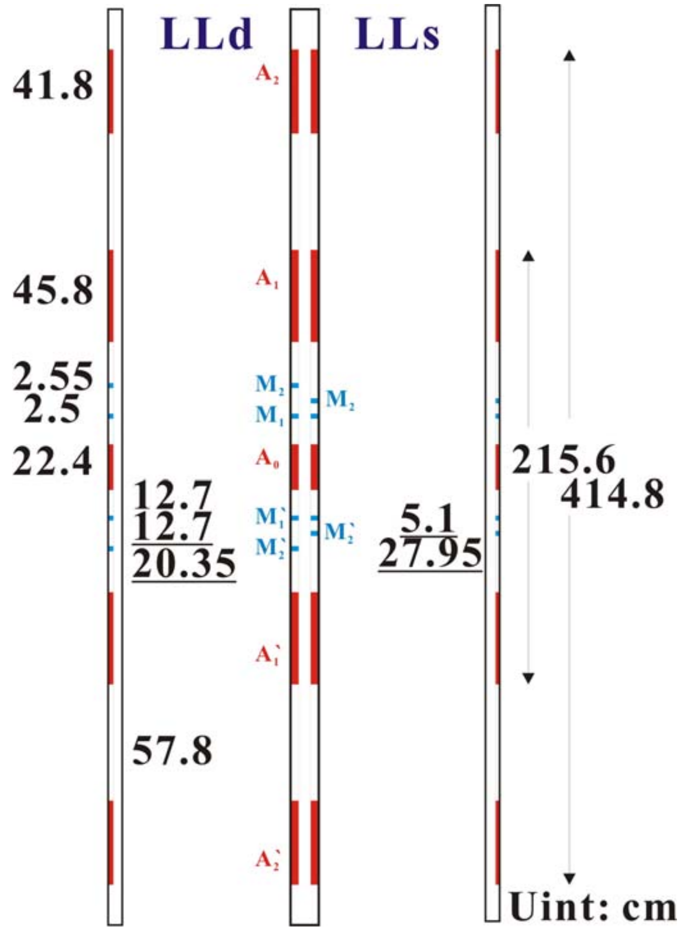


Simulating the DLL tool

Model

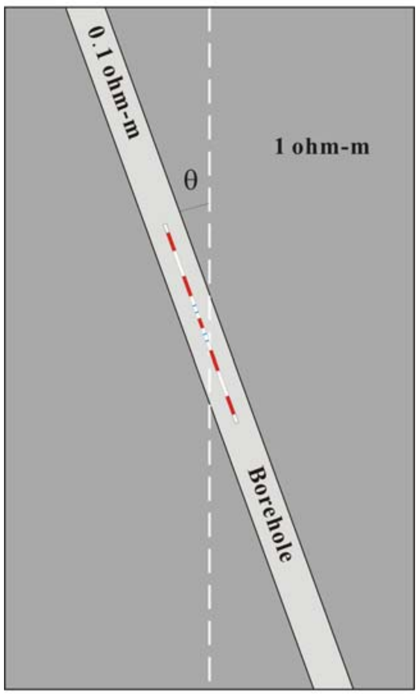


Using the Tool Configuration of Halliburton Energy Services' DLL

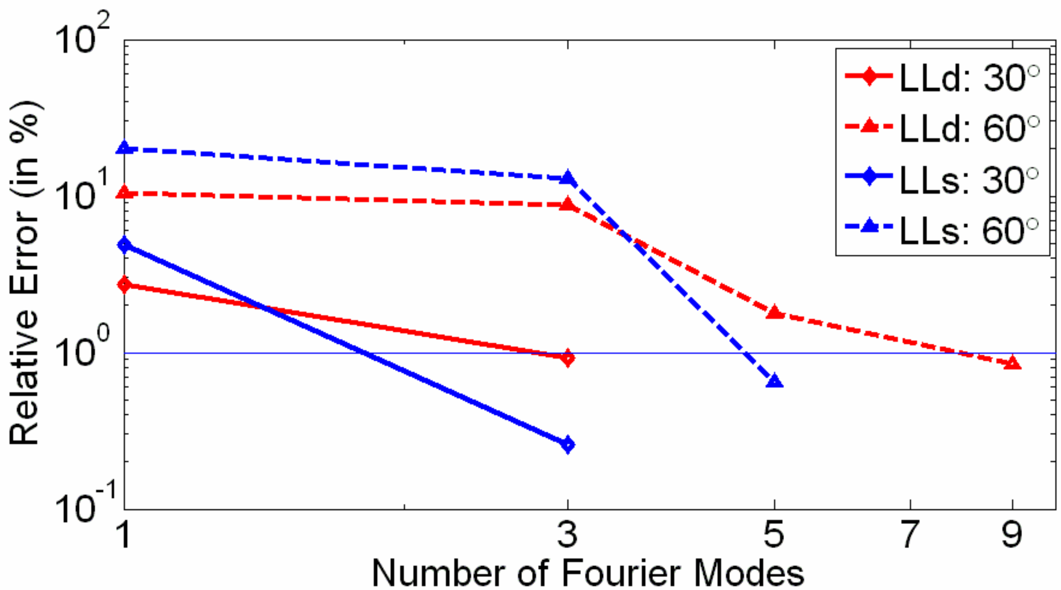


Verification of 3D Simulation

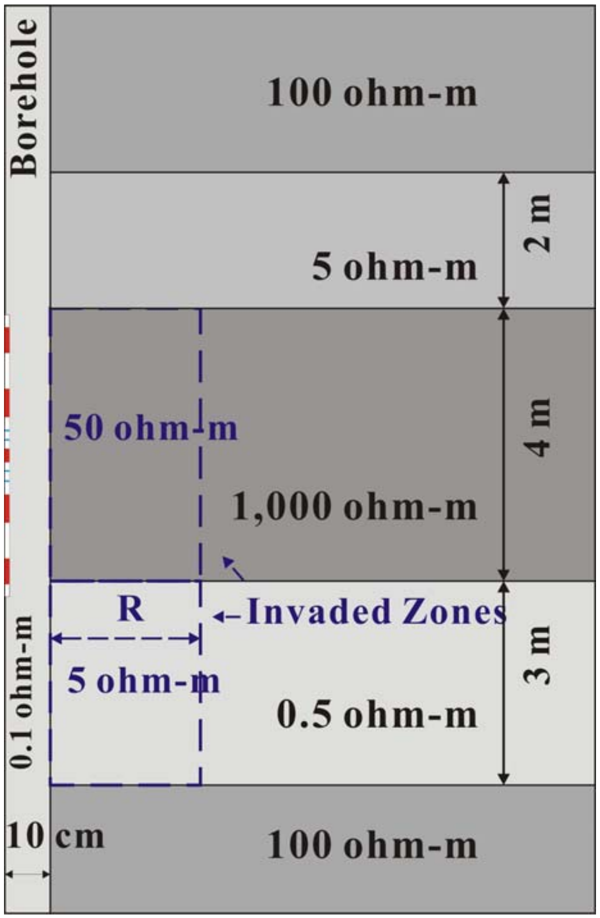
θ = 0, 30 and 60 degrees



Relative errors of laterolog instruments in a homogeneous formation



Model for Numerical Experiments



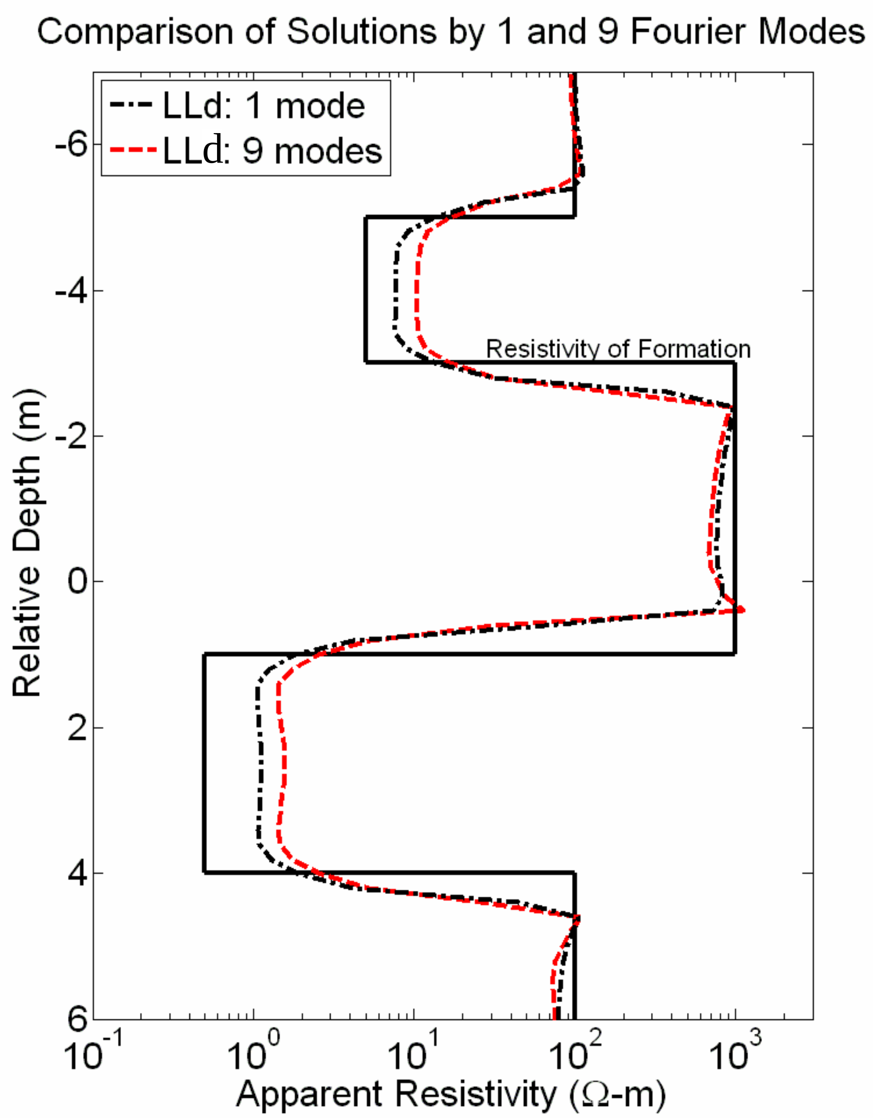
Five layers: 100, 5, 1000, 0.5 and 100 ohm-m from top to bottom

Borehole: 0.1 m in radius
0.1 ohm-m in resistivity

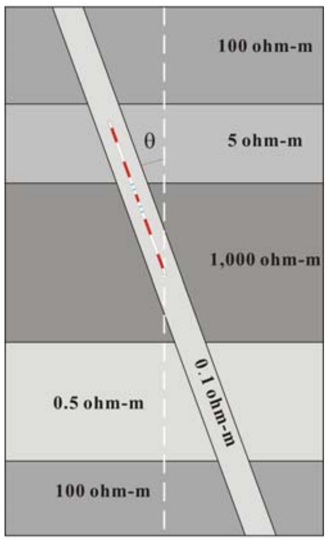
Invasion

Anisotropy

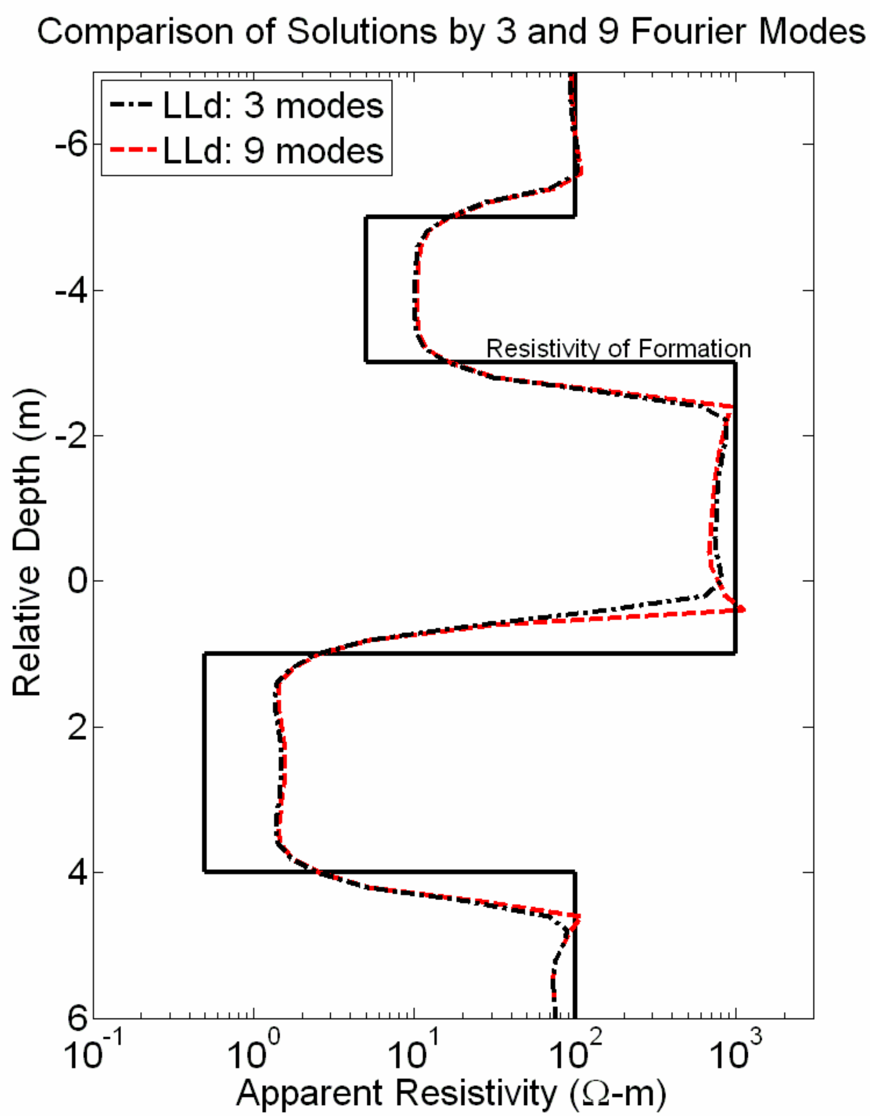
Convergence History of LLd Logs



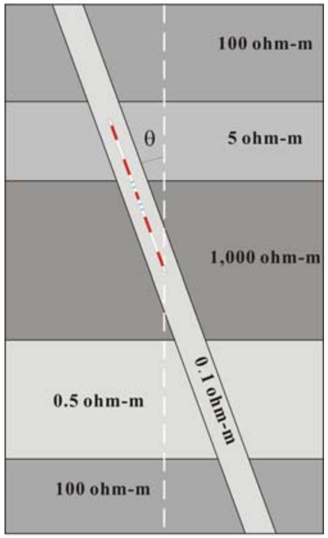
Dip angle: 45 degrees



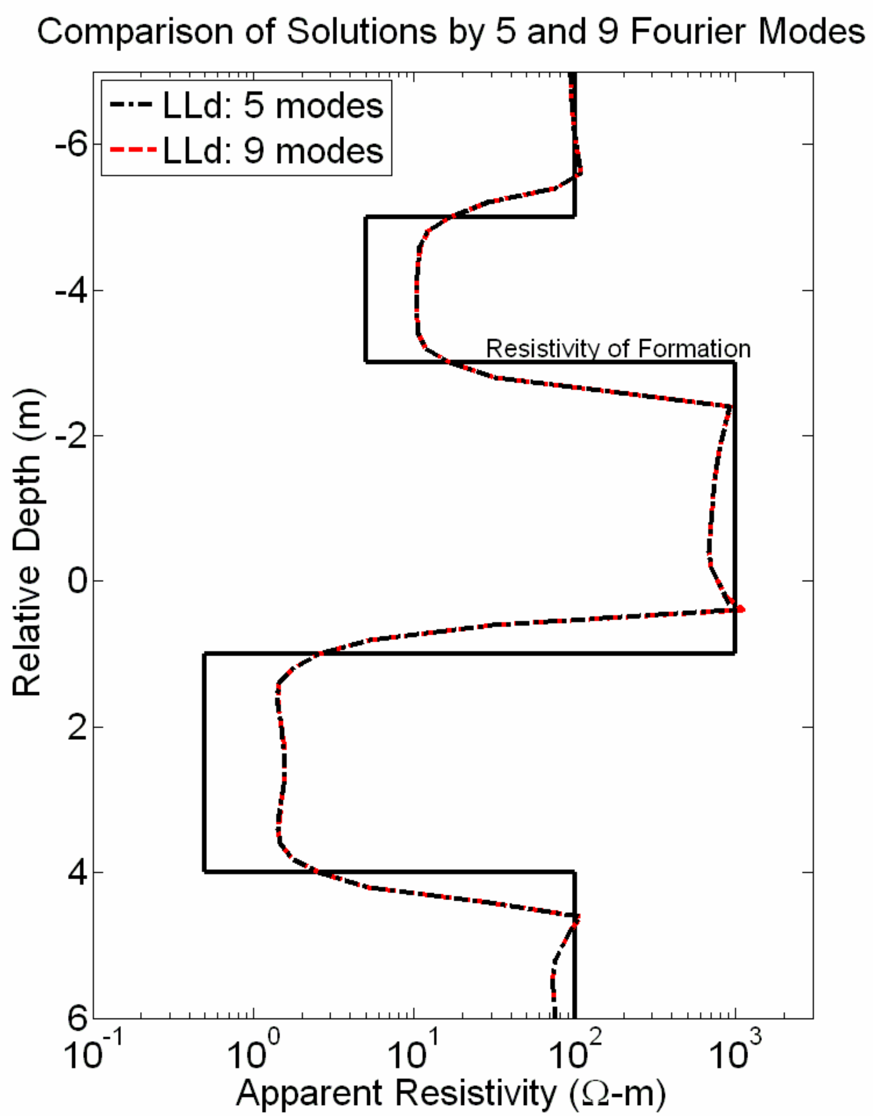
Convergence History of LLd Logs



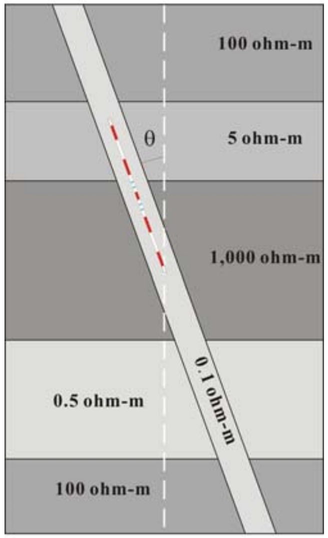
Dip angle: 45 degrees



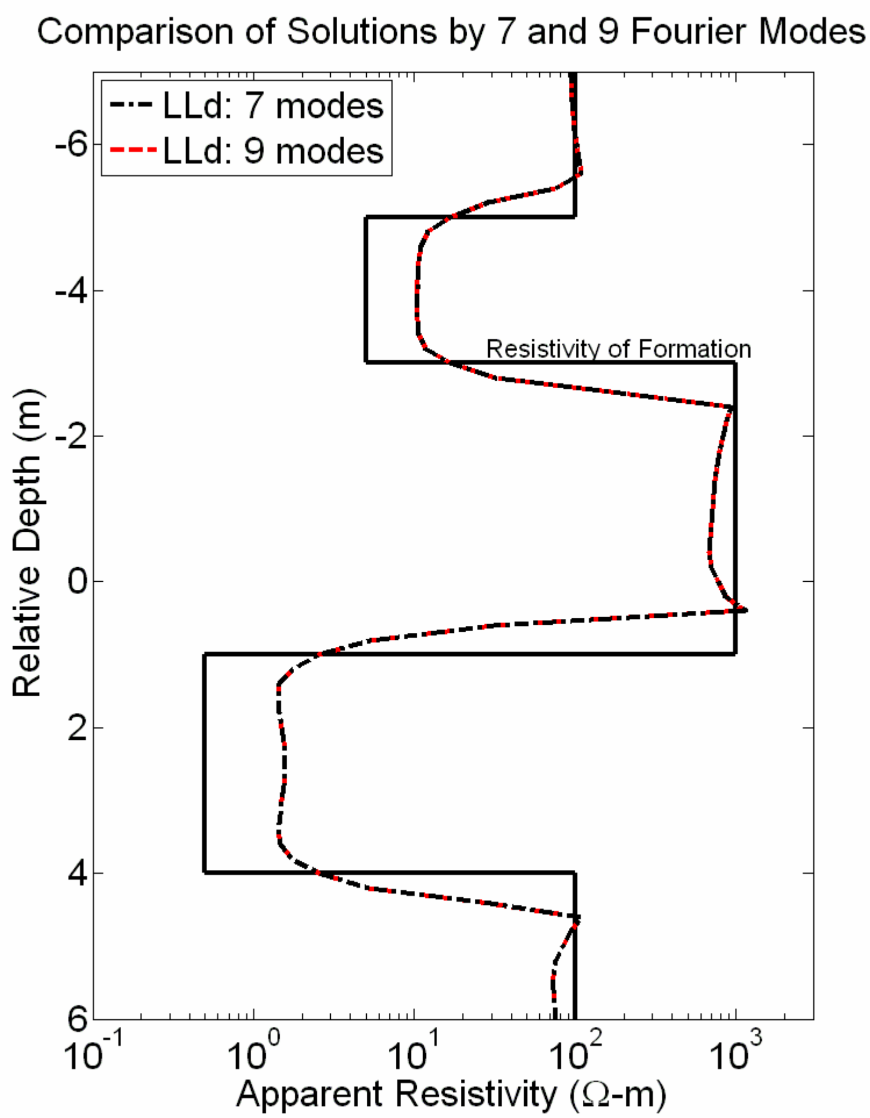
Convergence History of LLd Logs



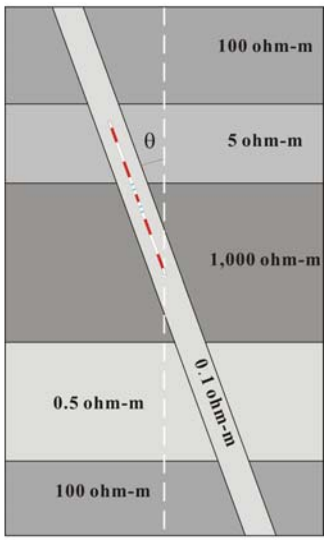
Dip angle: 45 degrees



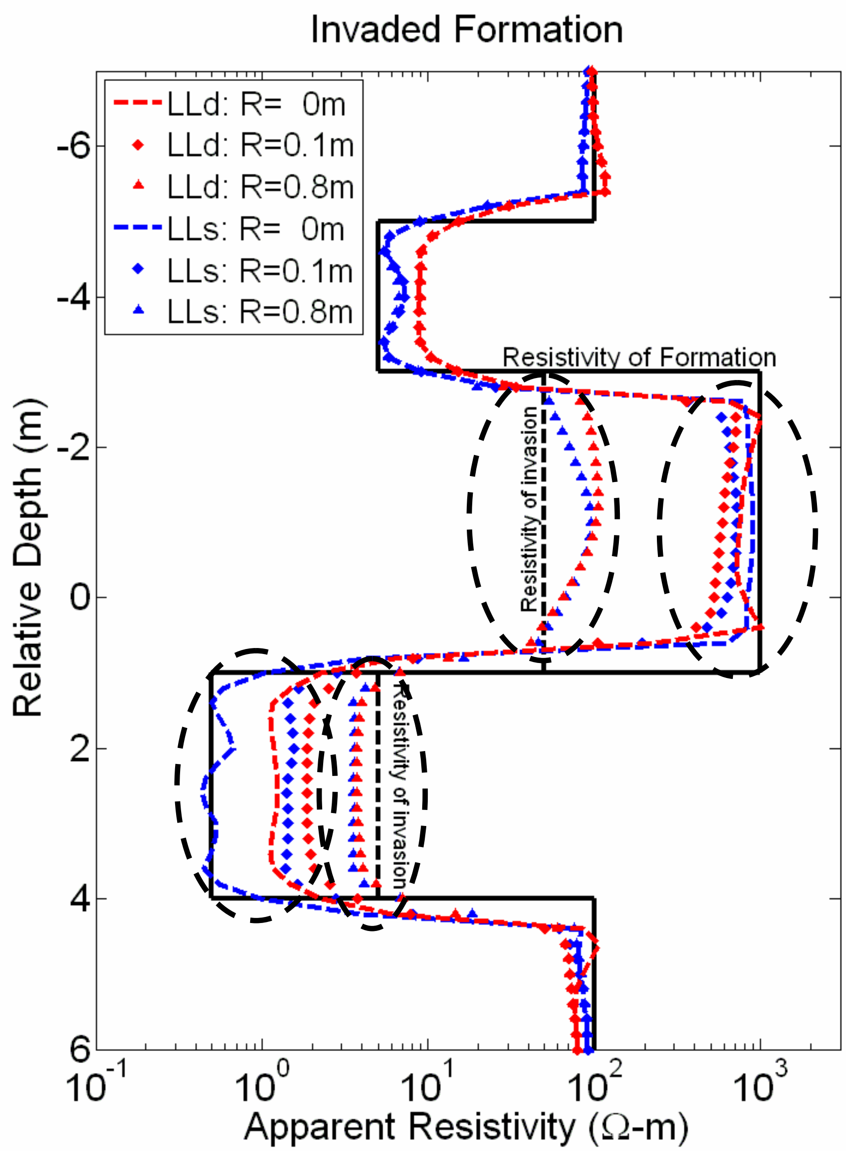
Convergence History of LLd Logs



Dip angle: 45 degrees



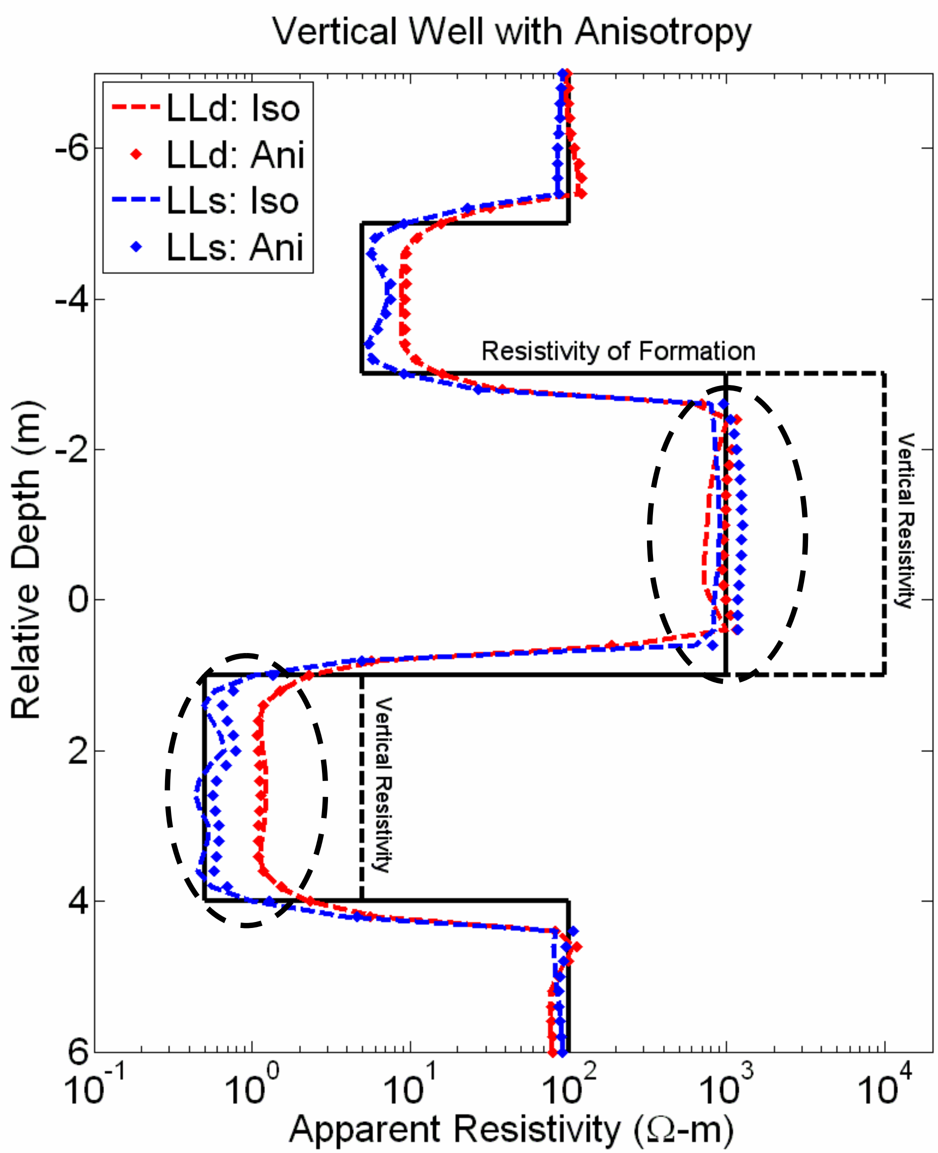
Invaded Formation (Vertical Well)



Effects of adjacent layers:
LLd ↑ in resistive layers
LLs ↑ in conductive layers

Effects of Invasion: LLs ↑

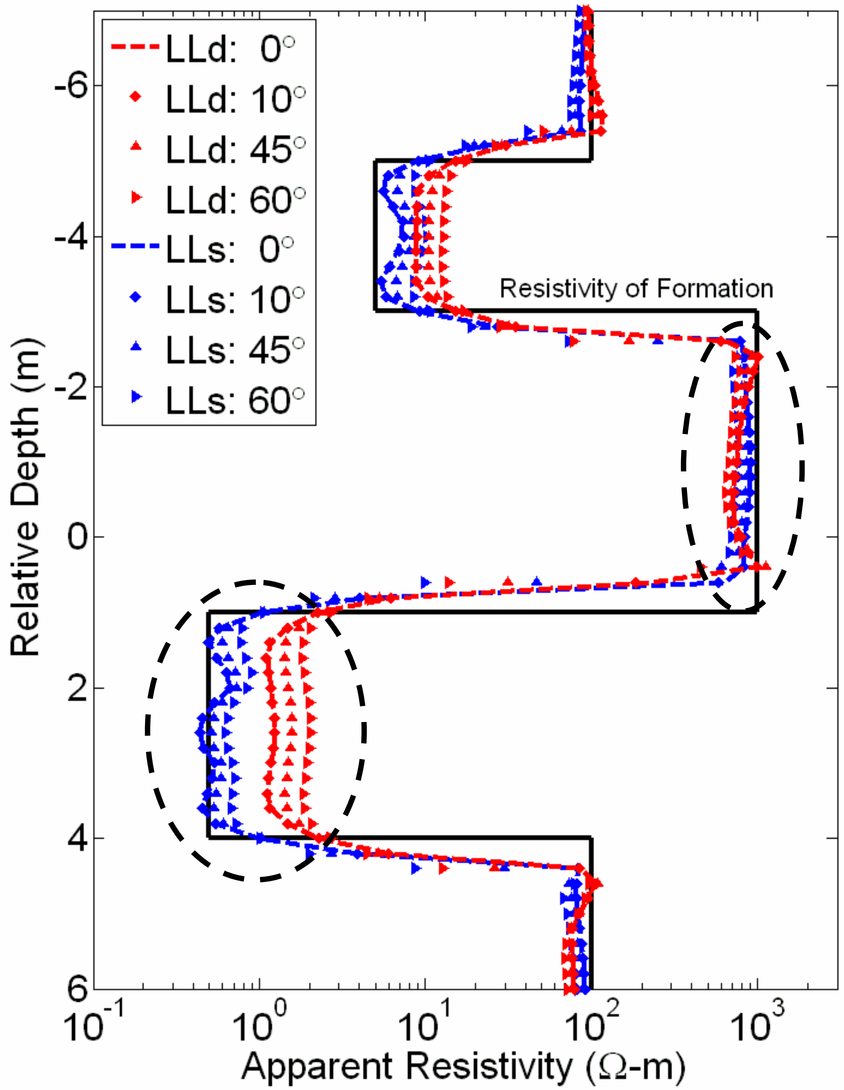
Anisotropic Formation (Vertical Well)



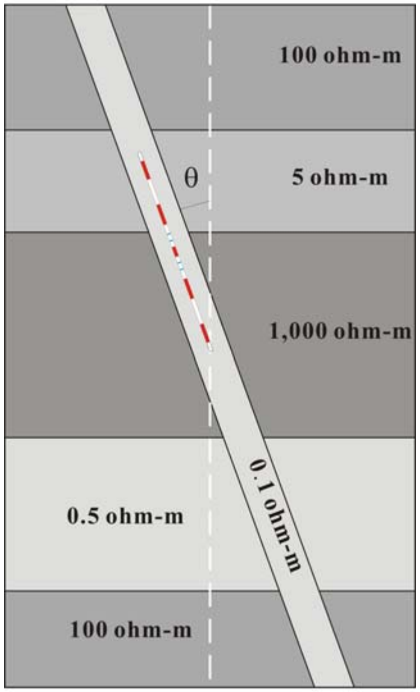
Effects of anisotropy: LLs ↑

LLd: effects of anisotropy are negligible in conductive layer

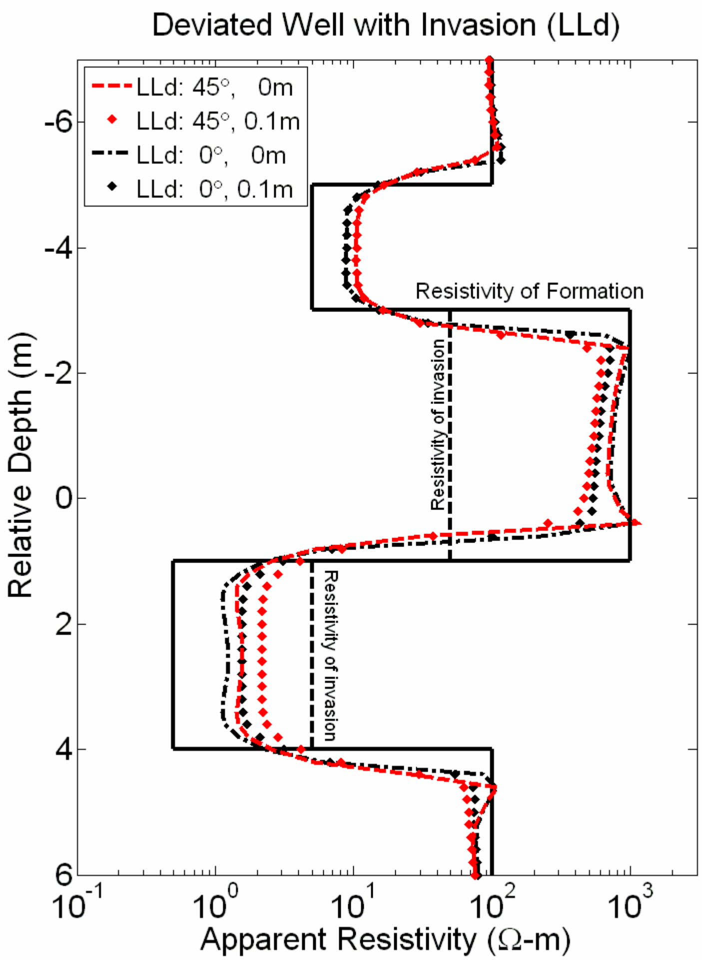
Deviated Well (60, 45 and 10 degrees)

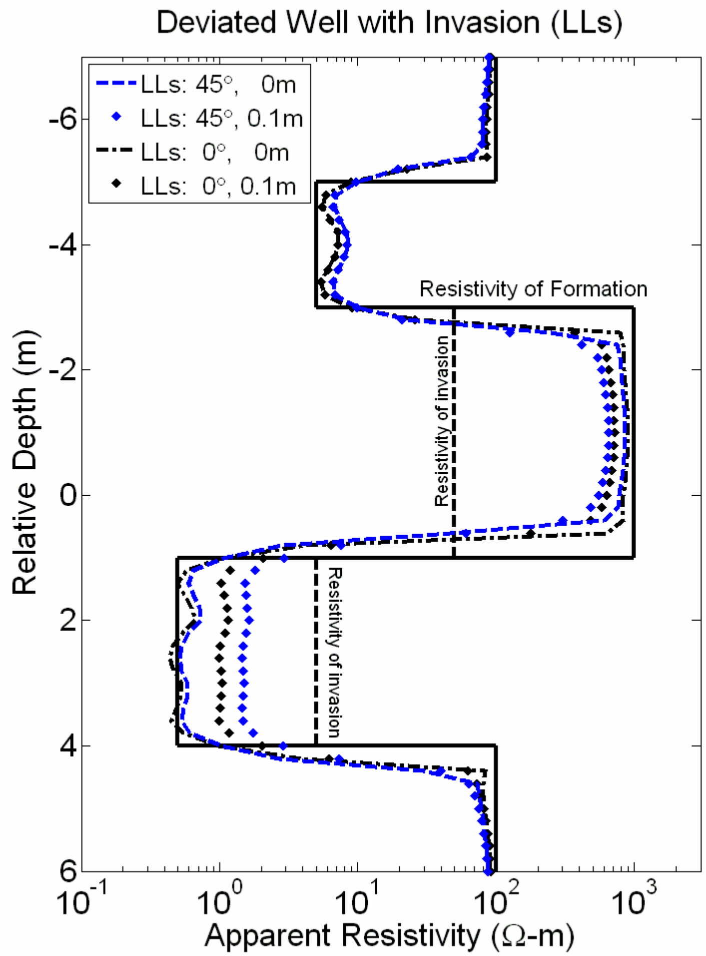


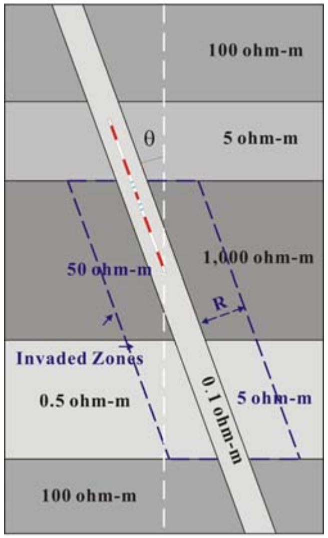
Effects of dip angle: Conductive layer ↑



Invaded Formation (45 degrees)

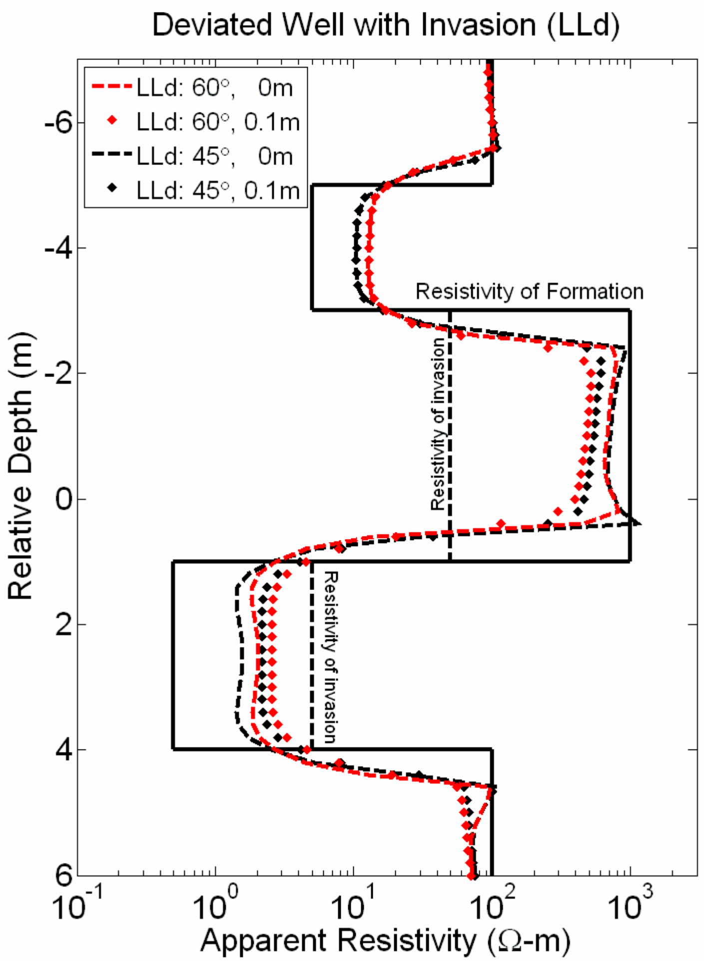


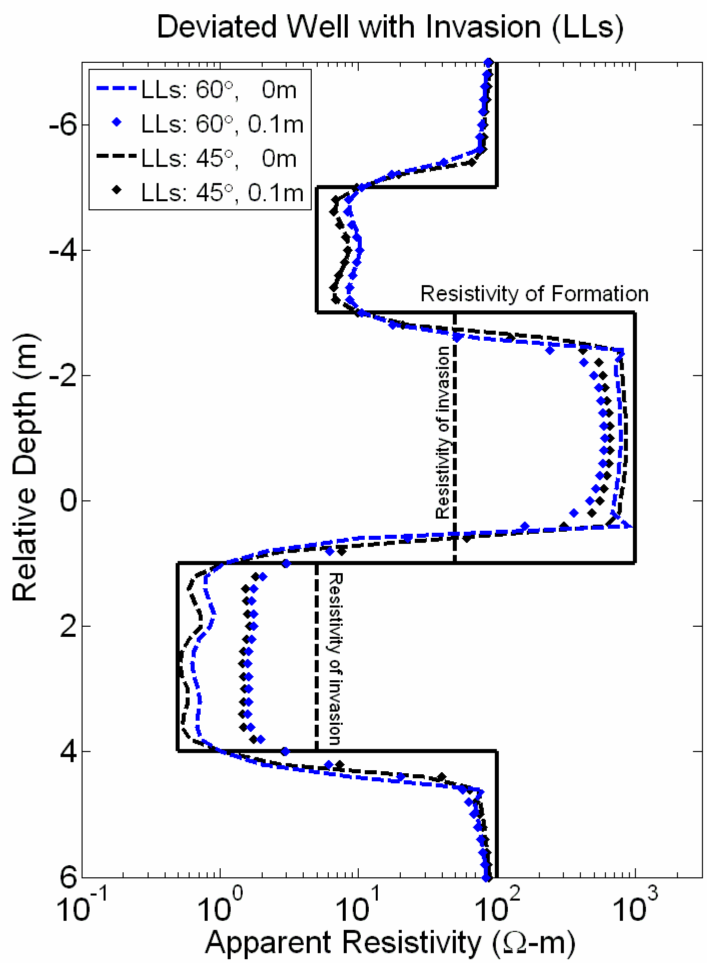


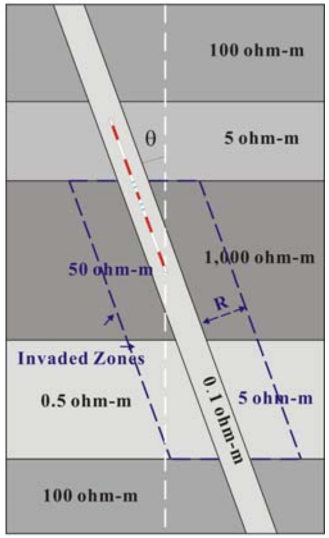


Effects of invasion to LLs: larger in a 45-degree deviated well than in a vertical well in conductive layer

Invaded Formation (60 degrees)

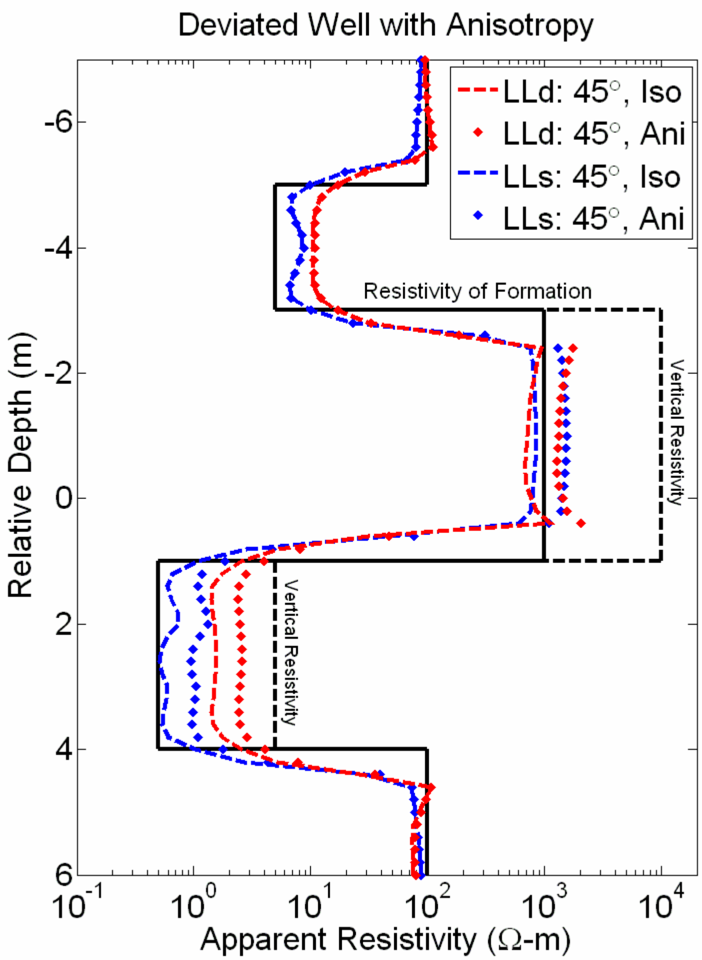


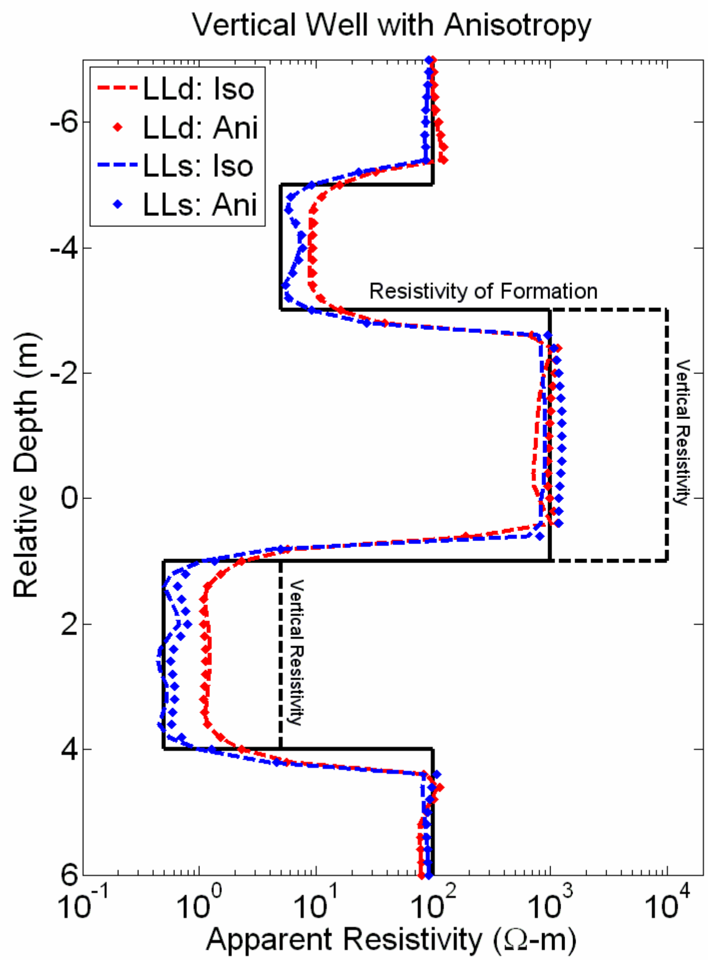


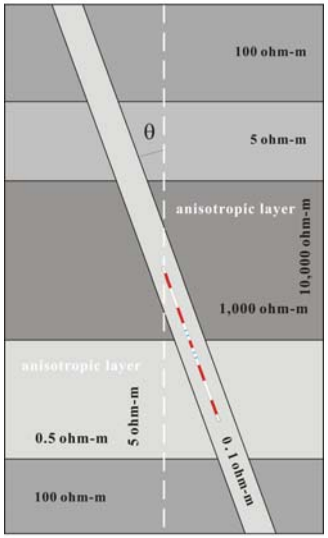


Effects of invasion to LLs: slightly smaller in a 60-degree deviated well than in a 45-degree deviated well in conductive layer

45-degree Deviated Well with Anisotropy

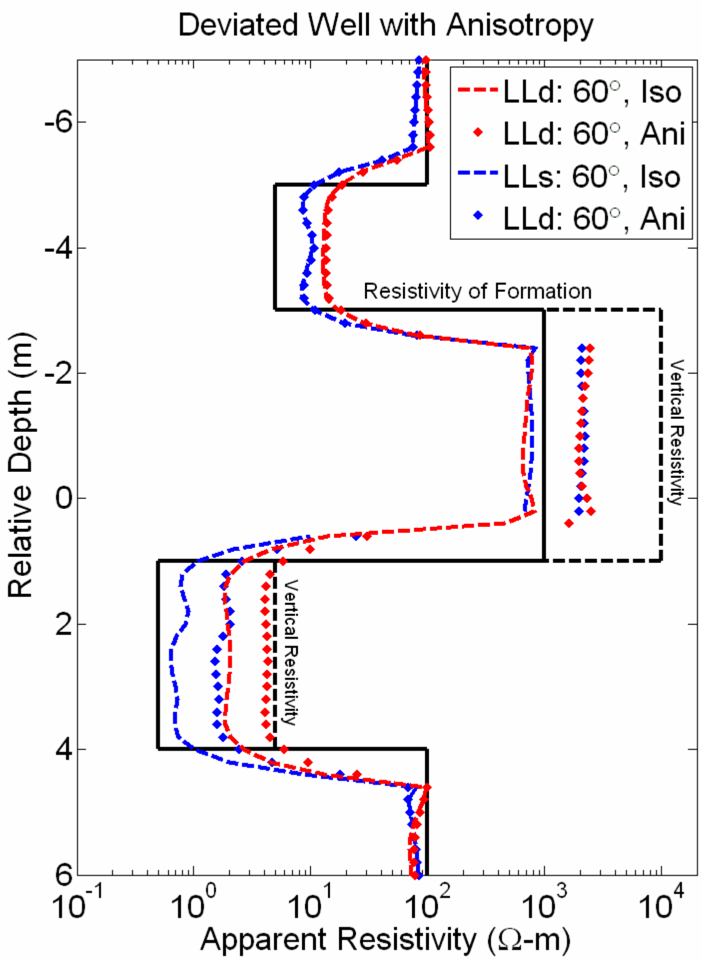


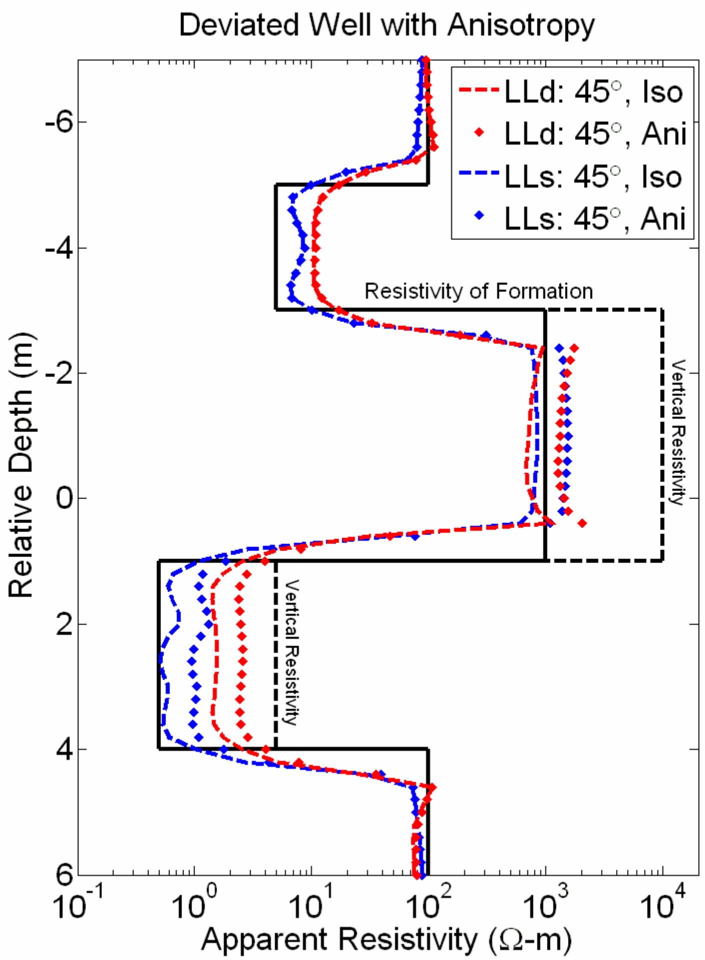


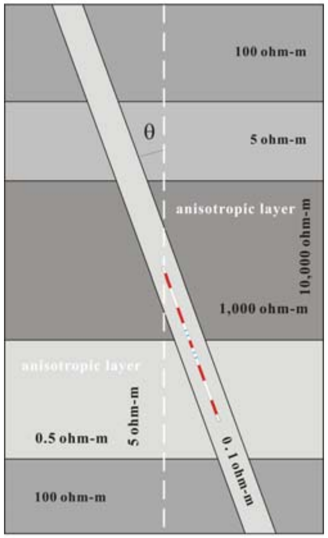


Effects of anisotropy: 45-degree deviated well ↑

60-degree Deviated Well with Anisotropy







Effects of anisotropy: 60-degree deviated well ↑

Conclusions

- We have successfully simulated 3D dual-laterolog measurements by combining the use of a Fourier series expansion in a non-orthogonal system of coordinates with a 2D higher-order self-adaptive hp finite element method.
- We have generated optimal hp finite element grids and optimal intensities of currents for simulation of dual-laterolog measurements using an embedded post-processing technique in the hp finite element method.
- Effects of dip angle are larger in conductive layers than in resistive layers.
- Effects of anisotropy increase as dip angle increases.

Future Work

- **3D Simulation of Non-Zero Frequency Dual-Laterolog Measurements.**

- **User-Friendly Interface.**

- **Development of an Iterative Solver.**

- **Modeling of Real Induction Logging Instruments.**

Acknowledgments

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Anadarko Petroleum Corporation
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bp
Chevron
ConocoPhillips
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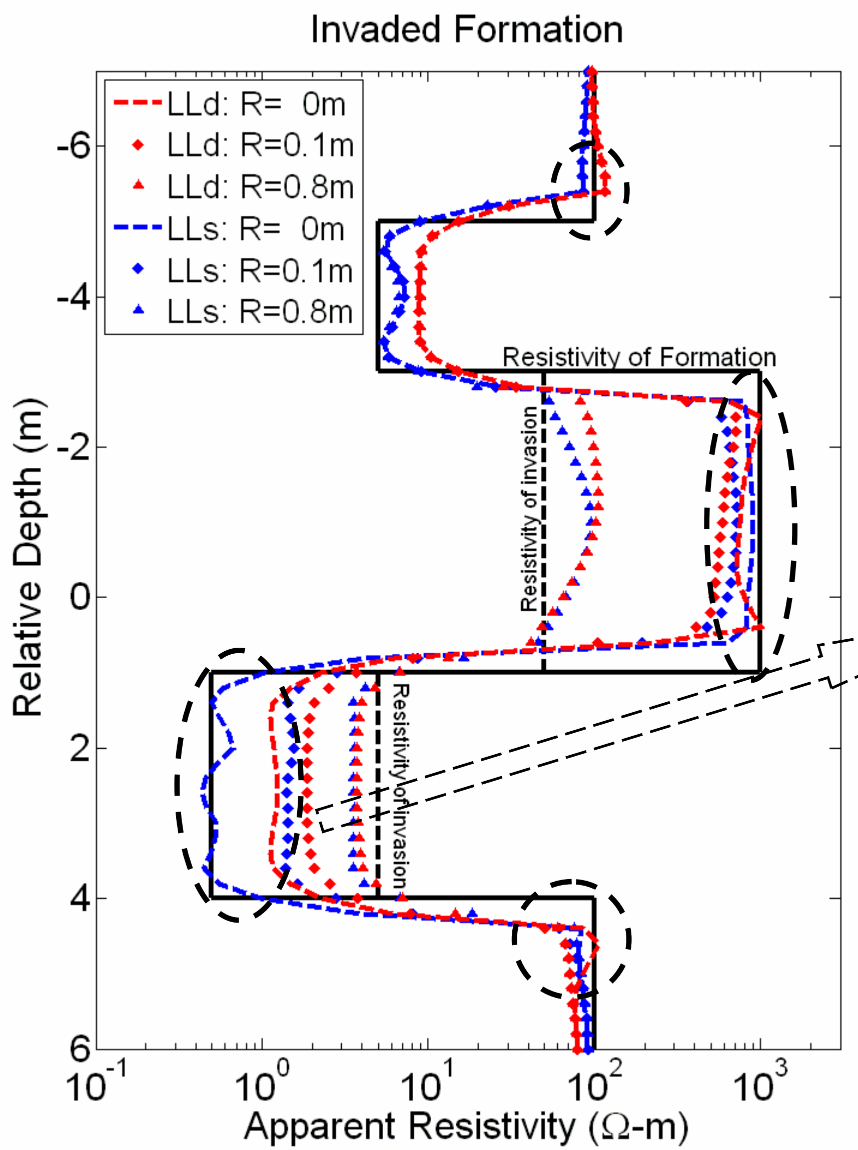
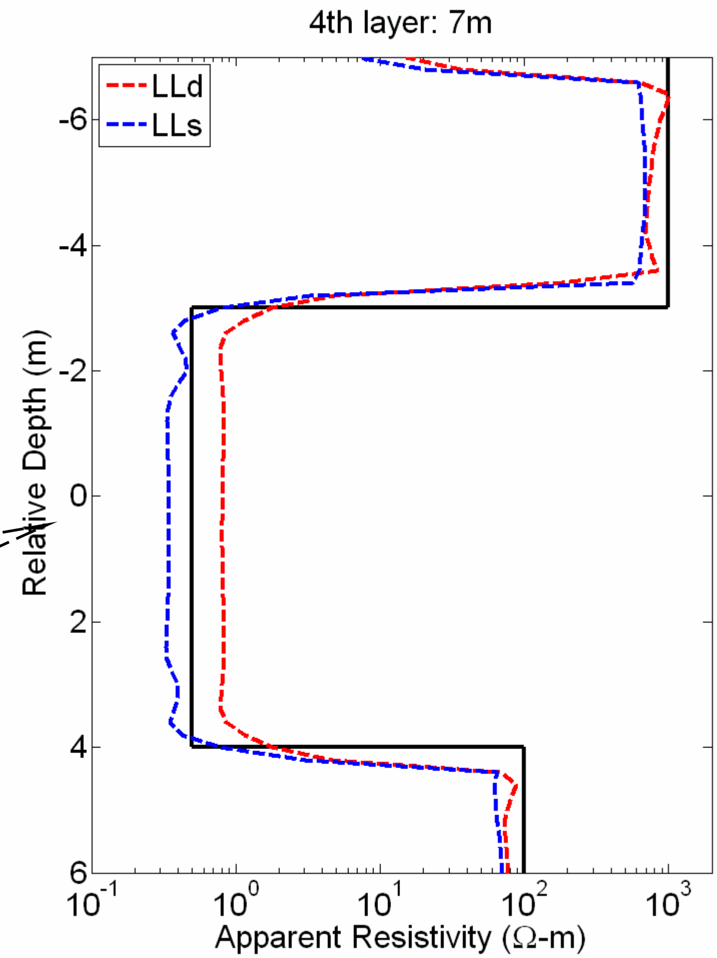
OXY occidental petroleum corporation
BR PETROBRAS
Schlumberger
Shell
STATOIL
TOTAL
Weatherford

Invaded Formation (Vertical Well)





Anisotropic Formation (Vertical Well)