SELF-ADAPTIVE *hp* FINITE-ELEMENT SIMULATION OF DC/AC DUAL-LATEROLOG MEASUREMENTS IN DIPPING, INVADED, AND ANISOTROPIC FORMATIONS

M. J. Nam, D. Pardo, and C. Torres-Verdín,
The University of Texas at Austin

***hp*-FEM team: D. Pardo, M. J. Nam, L. Demkowicz, C. Torres-Verdín, V. M. Calo, M. Paszynski, and P. J. Matuszyk**

8th Annual Formation Evaluation Research Consortium Meeting
August 14-15, 2008

THE UNIVERSITY OF TEXAS AT AUSTIN

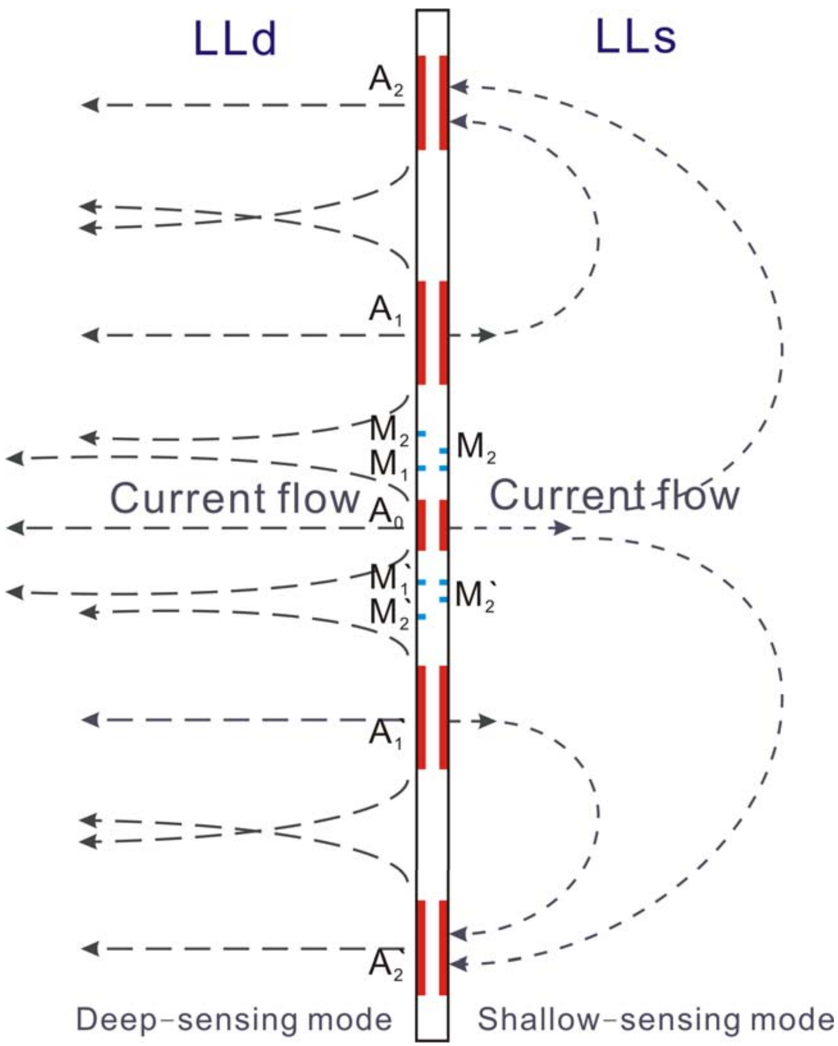
Overview

1. Main Lines of Research and Applications (D. Pardo)
   - Previous work
   - Main features of our technology
2. Application 1: Tri-Axial Induction Instruments (M. J. Nam)
3. Application 2: Dual-Laterolog Instruments (M. J. Nam)
4. Multi-Physics Inversion: (D. Pardo)
5. Sonic Instruments: (L. Demkowicz)

Outline

- Introduction to Dual Laterolog
- Previous Work
- Method
- Numerical Results:
  - Groningen Effects on AC DDL
  - Dipping, Invaded, Anisotropic Formations
  - Eccentricity
- Conclusions

Dual Laterolog

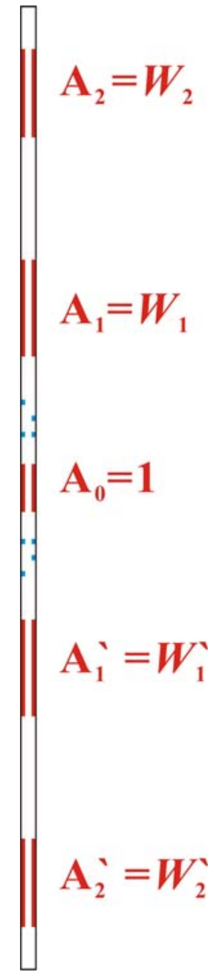


- **Determination of Intensities (W_j) of Bucking Currents**

Focusing Conditions

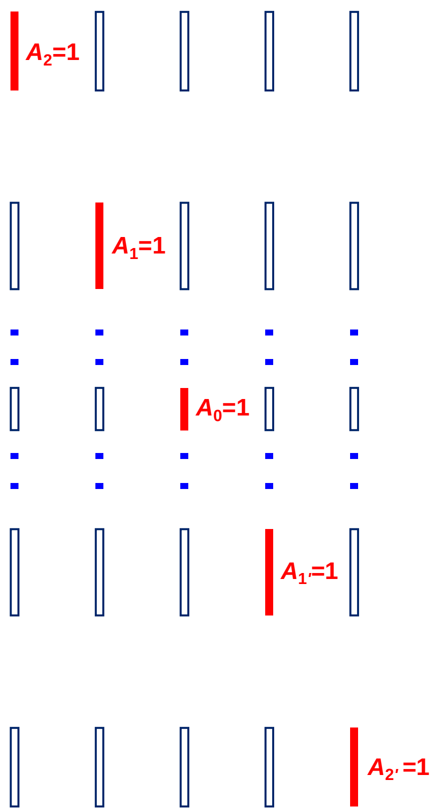
$$V(M_1) = V(M_2)$$

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



Summary from Last Year

Post-Processing Method



(1) Focusing conditions

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

(2) Relationships between W_j

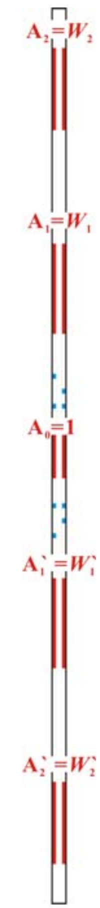
$$W_2 = (W_1 + c), \quad W_{2'} = (W_{1'} + c) \quad \textit{for} \ \text{LLd}$$
$$W_2 = -(W_1 + c), \quad W_{2'} = -(W_{1'} + c) \quad \textit{for} \ \text{LLs}$$

with $c = 0.5$

Total potential on M_i

→ Superposition principle

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



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

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

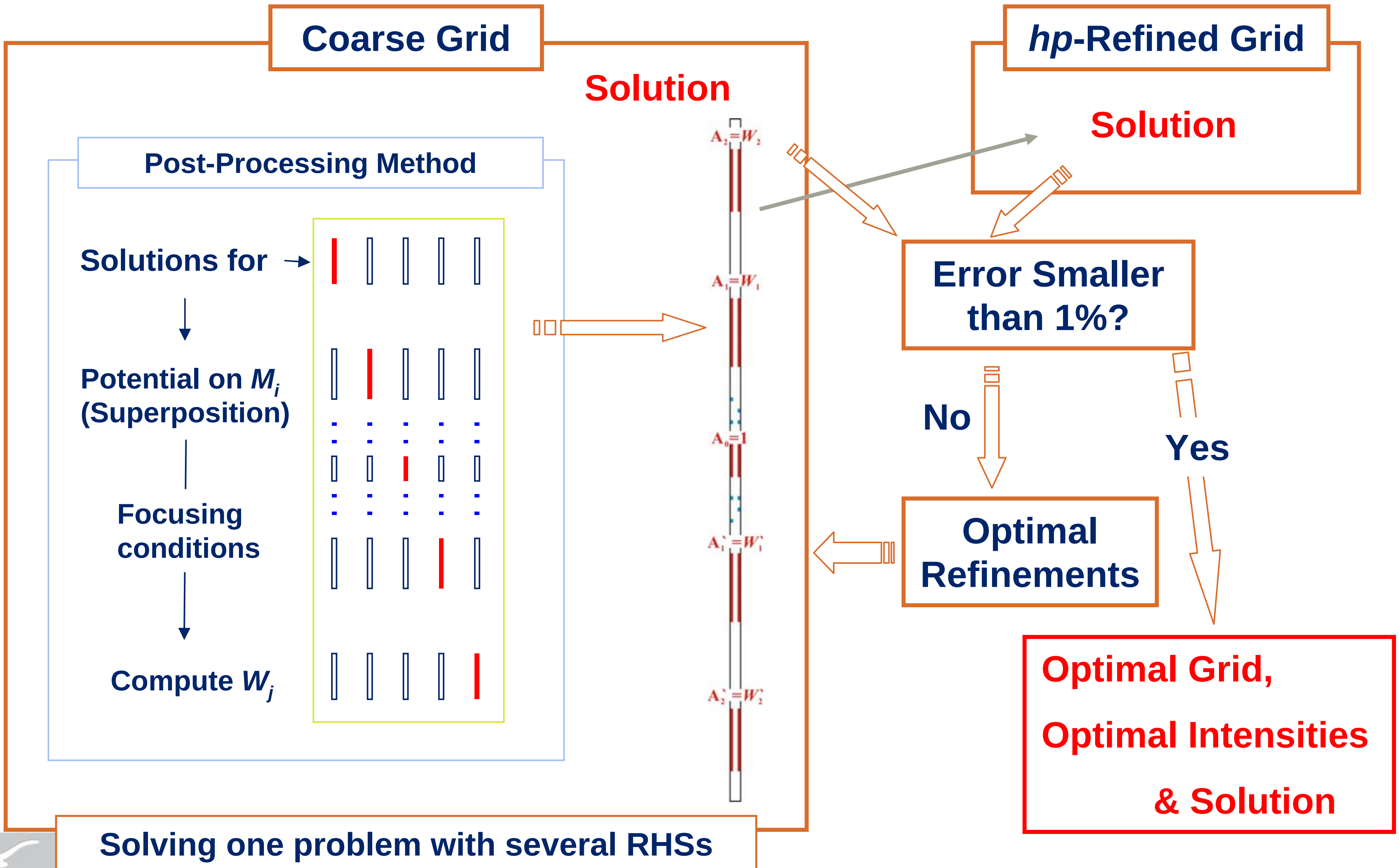
W_j for LLs: < from (1) and (2) with the LLs relationship of (3) >

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

One problem with several RHSs

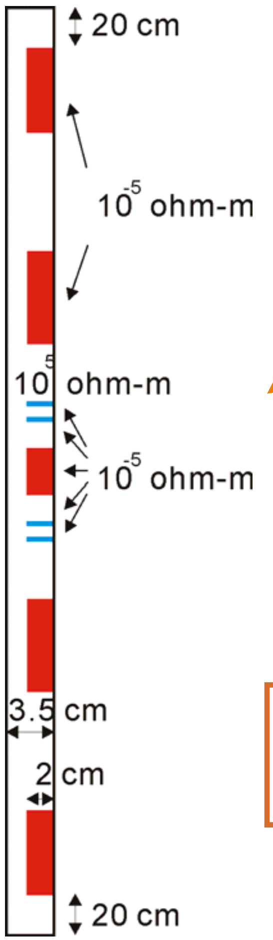
Summary from Last Year

Embedded Post-Processing Method



Summary from Last Year

What we modeled in simulating the DLL tool

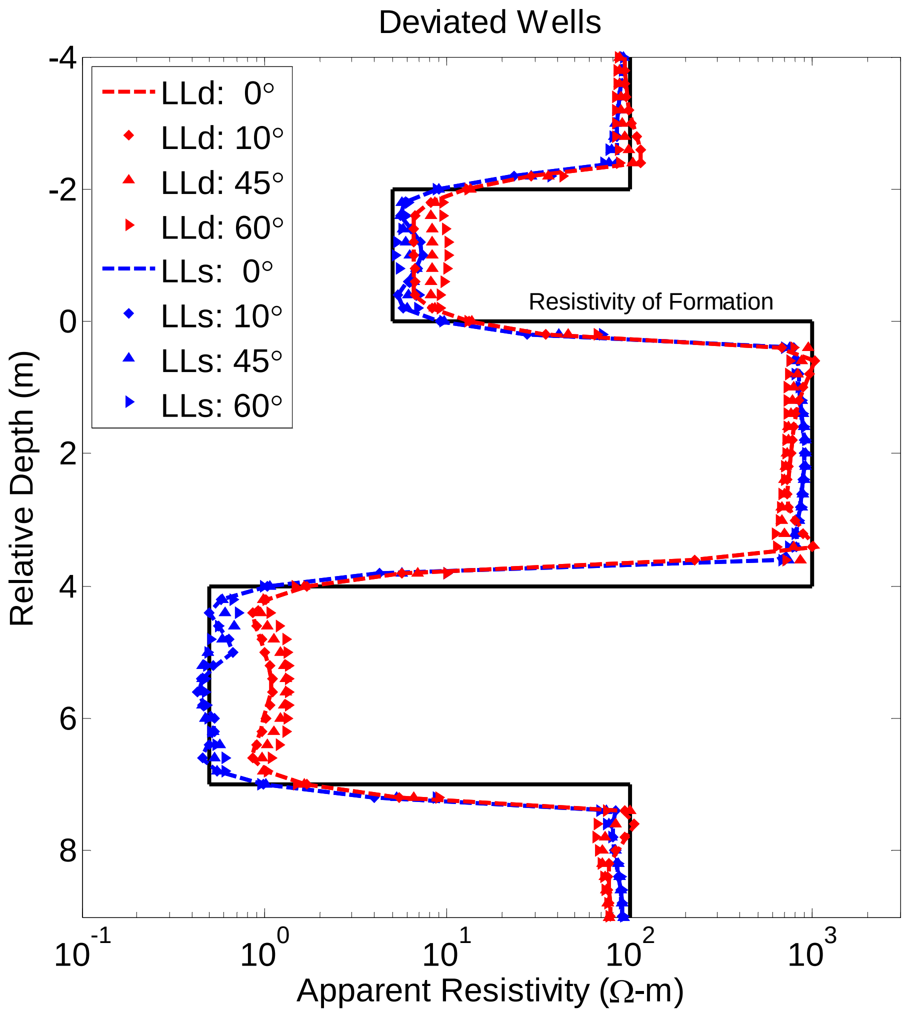


The resistivities and radial lengths of electrode and mandrel.

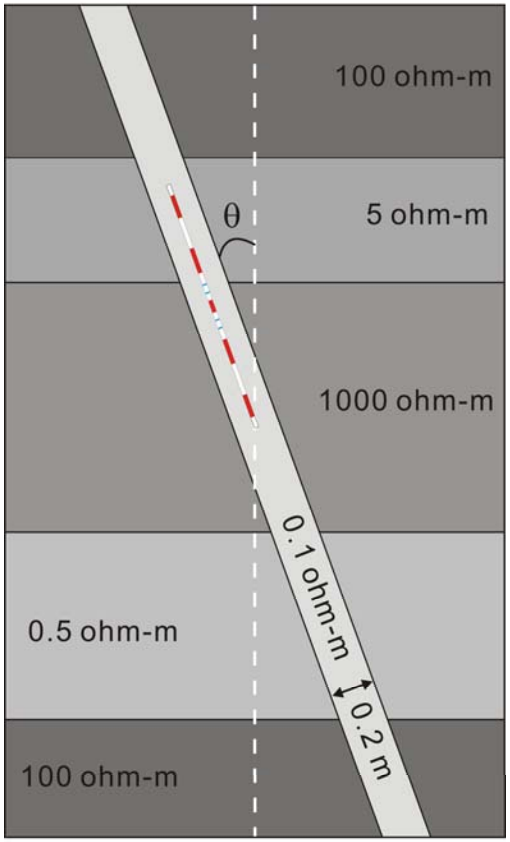
The vertical dimensions and locations of each electrode:
We followed the vertical tool configuration of a commercial tool

Summary from Last Year

Deviated Wells (0, 10, 45, and 60 degrees) at DC

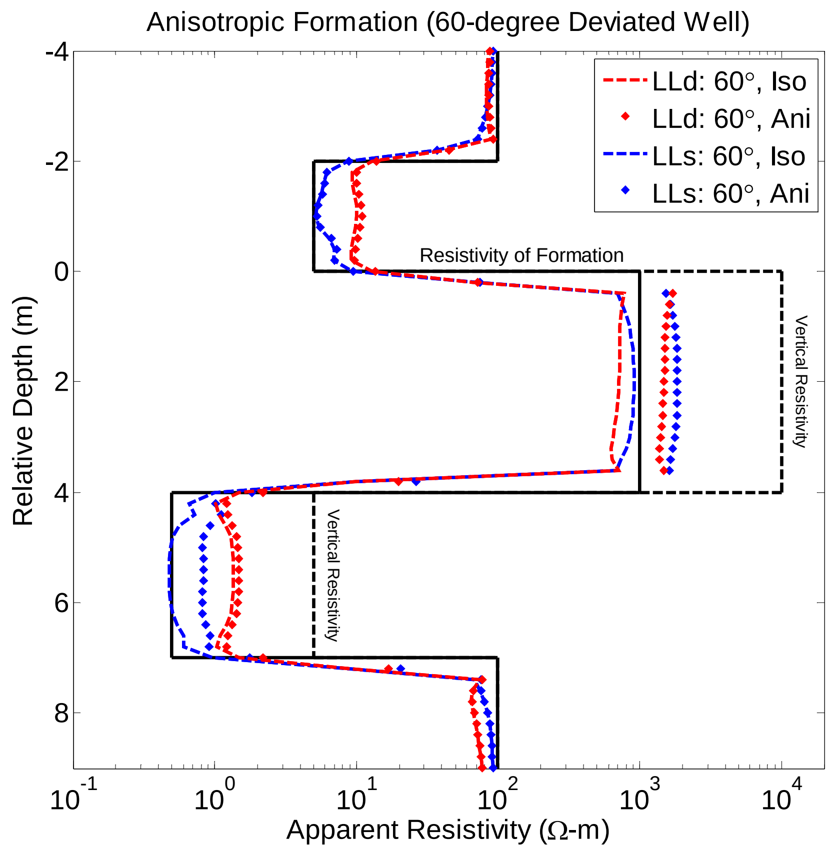


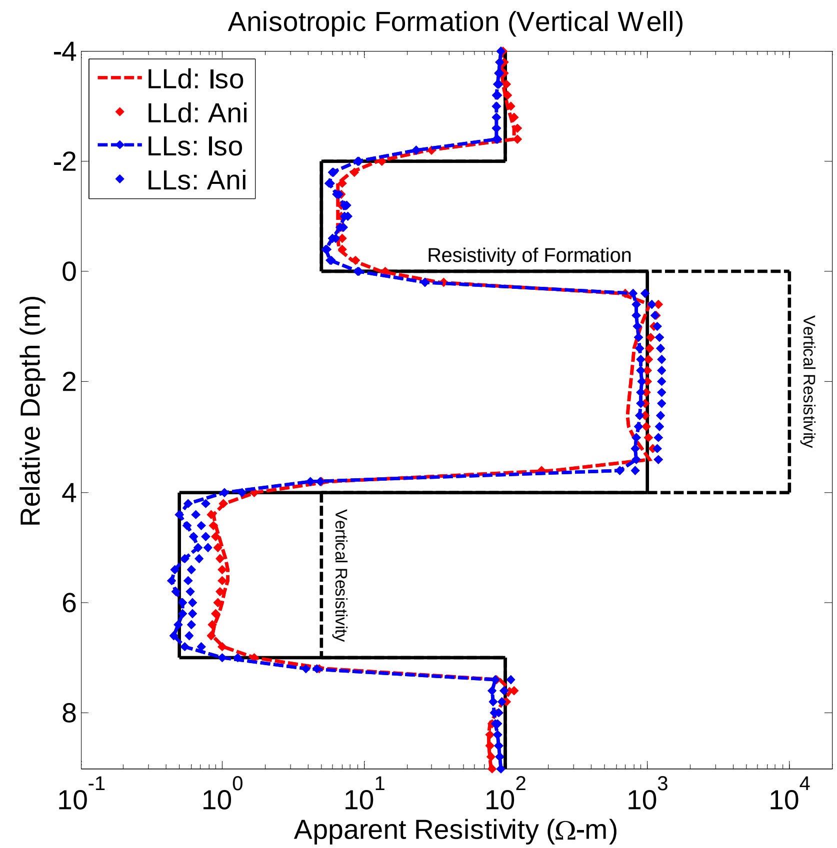
Effects of dip angle:
Thin layer ↑



Summary from Last Year

Anisotropic Formation (60- and 0-degree Deviated Wells) at DC





Effects of anisotropy increase with increase of dip angle

Method for Simulating AC DLL Measurements

Combination of:

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

2. **Embedded Post-Processing Method (EPPM)**

3. **Parallel Implementation**

Simulating AC DLL Measurements 1

Main challenges when simulating AC DLL measurements 1:

Introducing in the AC formulation a source equivalent to $\nabla \cdot J$

To avoid simulating the inner wiring system!!

Simulating AC DLL Measurements 1

Main challenges when simulating AC DLL measurements 1:

Introducing in the AC formulation a source equivalent to ∇·J

Governing equation	Variational formulation

DC

$$\nabla\cdot\left(\sigma\nabla\cdot u\right)=\nabla\cdot\mathbf{J}^{imp}$$

$$<\nabla v,\sigma\nabla u>_{L^2(\Omega)}=<v,\nabla\cdot\mathbf{J}^{imp}>_{L^2(\Omega)}+<v,g>_{L^2(\Gamma_N)}\qquad\forall v\in H^1_D(\Omega)$$

AC

$$\begin{cases}\nabla\times\mathbf{H}=\left(\sigma+j\omega\varepsilon\right)\mathbf{E}+\mathbf{J}\\ \nabla\times\mathbf{E}=-j\omega\mathbf{H}\end{cases}$$

$$<\nabla\times\mathbf{F},\mu^{-1}\nabla\times\mathbf{E}>_{L^2(\Omega)}-<\mathbf{F},\left(\omega^2\varepsilon-j\omega\sigma\right)\mathbf{E}>_{L^2(\Omega)}-<\mathbf{F},\left(\omega^2\varepsilon-j\omega\sigma\right)\nabla p>=$$
$$-j\omega\left\langle\mathbf{F},\mathbf{J}^{imp}\right\rangle_{L^2(\Omega)}+j\omega\left\langle\mathbf{F}_t,\mathbf{J}_S^{imp}\right\rangle_{L^2(\Gamma_H)}\ \to\ 0\qquad\forall\mathbf{F}\in H_{\Gamma_E}(\text{curl};\Omega)$$

Scalar potential eq.→

$$-<\nabla q,\left(\omega^2\varepsilon-j\omega\sigma\right)\mathbf{E}>_{L^2(\Omega)}=$$
$$-j\omega\left\langle\nabla q,\mathbf{J}^{imp}\right\rangle_{L^2(\Omega)}+j\omega\left\langle\nabla q,\mathbf{J}_S^{imp}\right\rangle_{L^2(\Gamma_H)}\ \to\ 0\qquad\forall q\in H^1_D$$

introducing ∇·J

$$j\omega<q,\nabla\cdot\mathbf{J}^{imp}>_{L^2(\Omega)}$$

$$\therefore-<\nabla q,\left(\omega^2\varepsilon-j\omega\sigma\right)\mathbf{E}>_{L^2(\Omega)}=j\omega<q,\nabla\cdot\mathbf{J}^{imp}>_{L^2(\Omega)}\qquad\forall q\in H^1_D$$

Simulating AC DLL Measurements 1

Main challenges when simulating AC DLL measurements 1:

Introducing in the AC formulation a source equivalent to ∇·J

Governing equation	Variational formulation
DC $\nabla \cdot (\sigma \nabla \cdot u) = \nabla \cdot \mathbf{J}^{imp}$	$< \nabla v, \sigma \nabla u >_{L^2(\Omega)} = < v, \nabla \cdot \mathbf{J}^{imp} >_{L^2(\Omega)} + < v, g >_{L^2(\Gamma_N)} \quad \forall v \in H_D^1(\Omega)$
AC $\begin{cases} \nabla \times \mathbf{H} = (\sigma + j\omega\varepsilon)\mathbf{E} + \mathbf{J} \\ \nabla \times \mathbf{E} = -j\omega\mathbf{H} \end{cases}$	

Final AC variational formulations we use:

$$< \nabla \times \mathbf{F}, \mu^{-1} \nabla \times \mathbf{E} >_{L^2(\Omega)} - < \mathbf{F}, (\omega^2 \varepsilon - j\omega\sigma)\mathbf{E} >_{L^2(\Omega)} - < \mathbf{F}, (\omega^2 \varepsilon - j\omega\sigma) \nabla p > = 0 \quad \forall \mathbf{F} \in H_{\Gamma_E}(\text{curl}; \Omega)$$

$$- < \nabla q, (\omega^2 \varepsilon - j\omega\sigma)\mathbf{E} >_{L^2(\Omega)} = j\omega < q, \nabla \cdot \mathbf{J}^{imp} >_{L^2(\Omega)} \quad \forall q \in H_D^1$$

Simulating AC DLL Measurements 2

Main challenges when simulating AC DLL measurements 2:

Simulation of current return at earth surface

1. No current return results in no Groningen effects.

   (Numerical results will be shown)

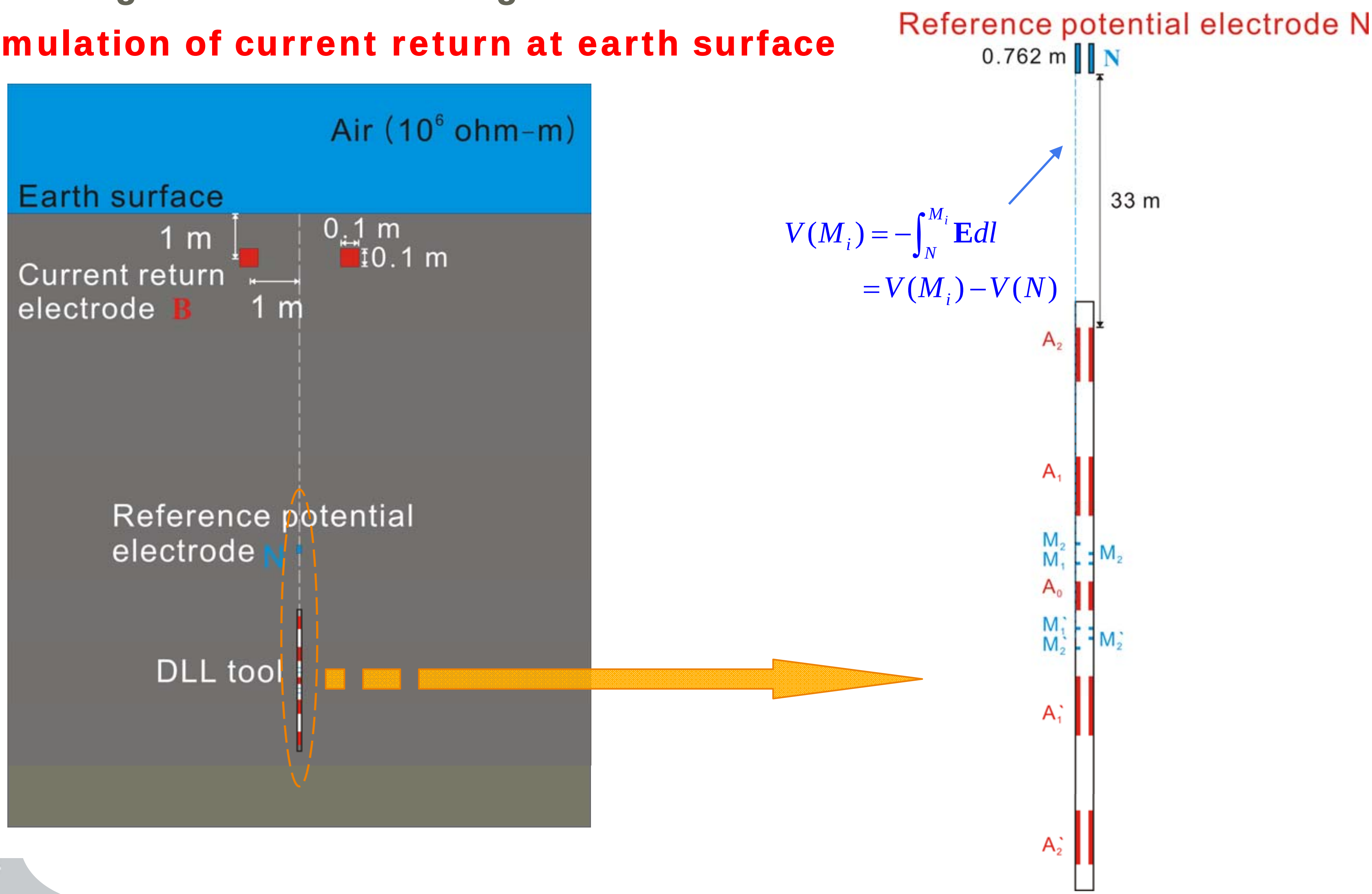
2. We have to simulate the earth surface.

   → Our computing domain is larger than 2 km in the vertical direction.

Simulating AC DLL Measurements 2

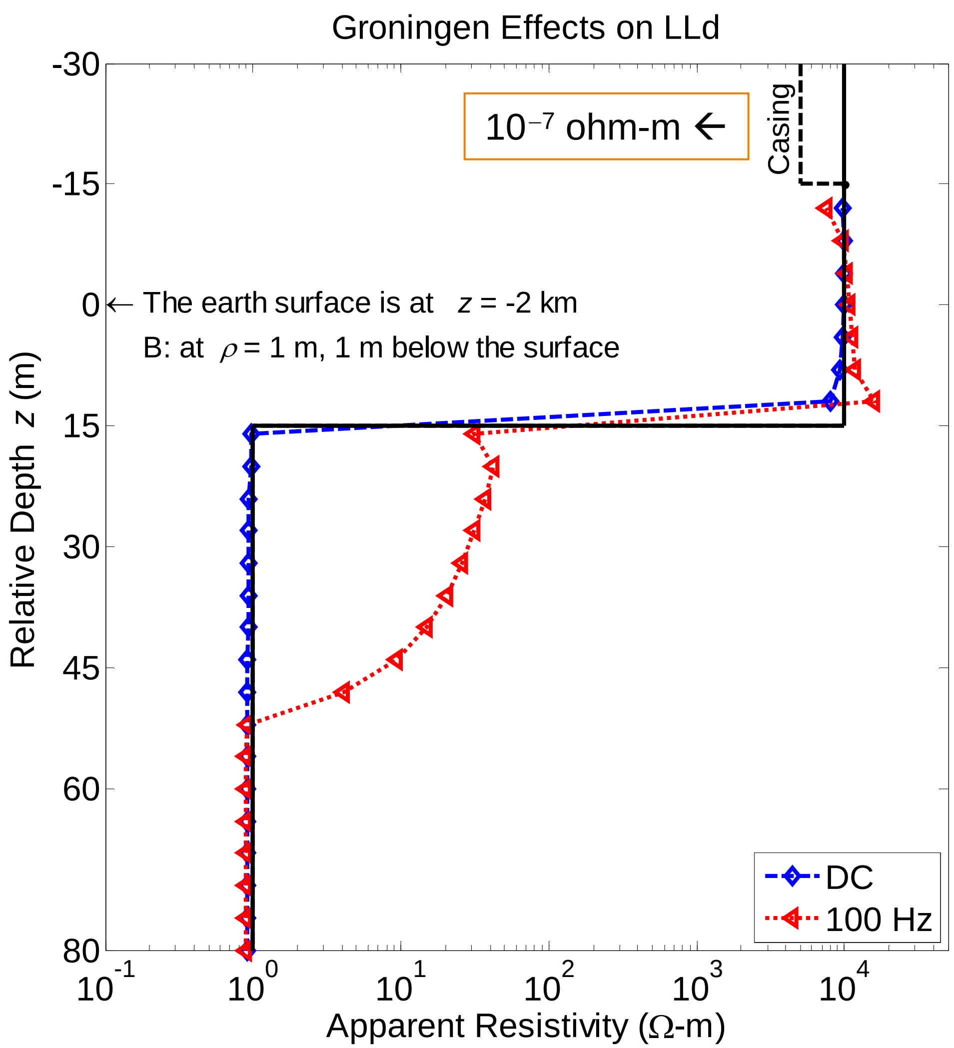
Main challenges when simulating AC DLL measurements 2:

Simulation of current return at earth surface



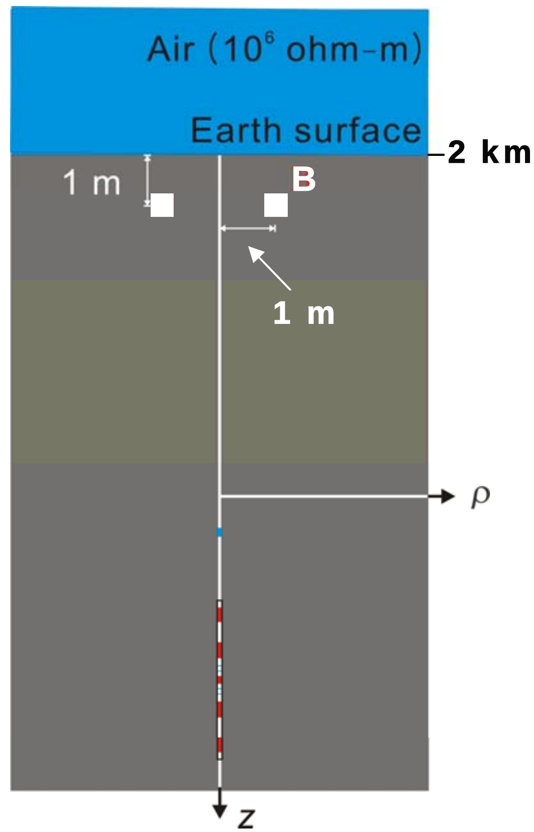
$$V(M_i) = -\int_N^{M_i} \mathbf{E} dl = V(M_i) - V(N)$$

Groningen Effects on LLd at DC and AC

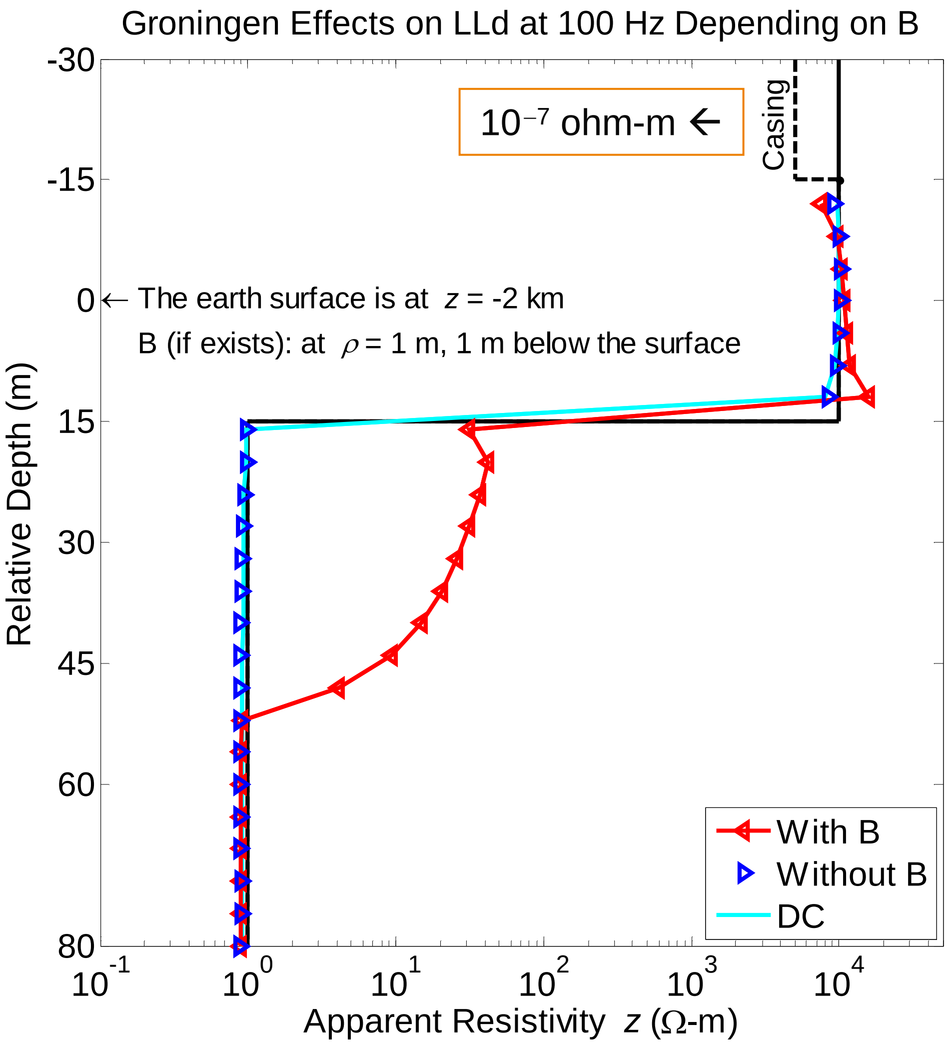


DC: No Groningen effects

AC: Groningen effects

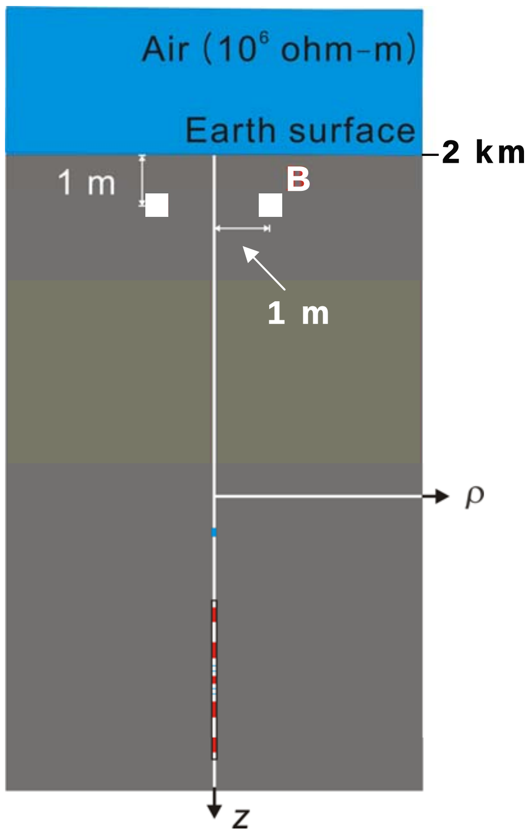


Groningen Effects on LLd at 100 Hz (I)

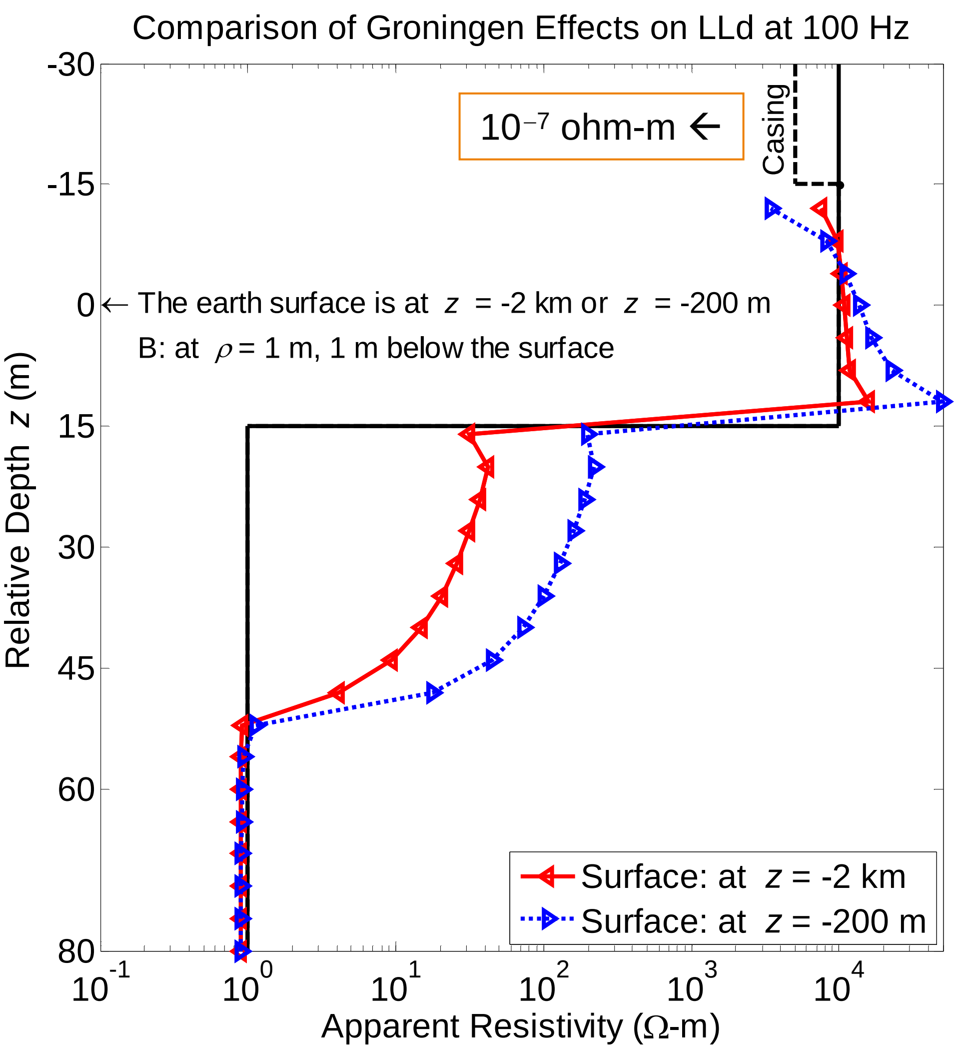


No B:

No Groningen effects

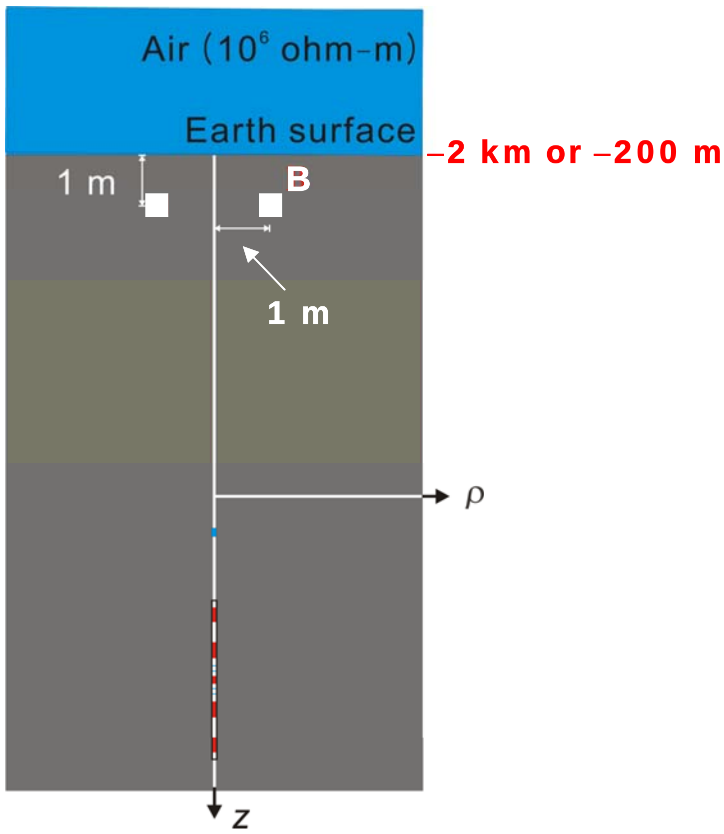


Groningen Effects on LLd at 100 Hz (II)

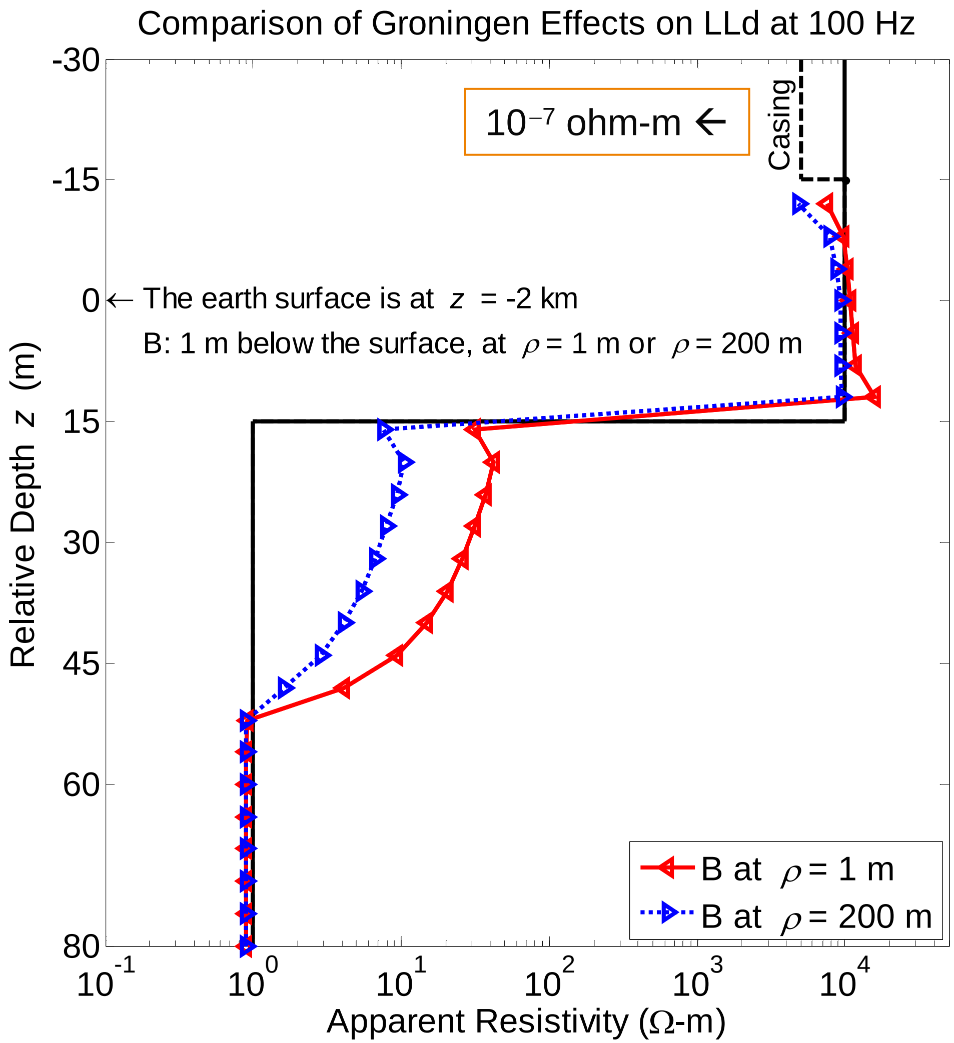


Further B in the *z* direction:

smaller Groningen effects

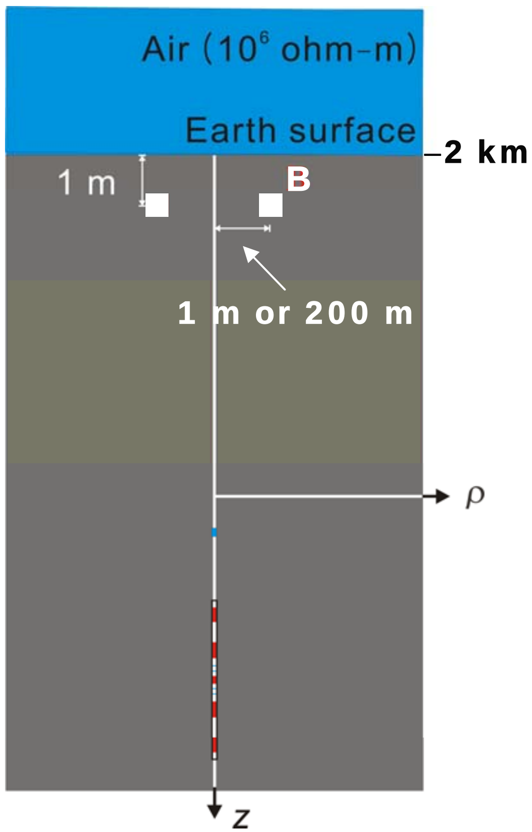


Groningen Effects on LLd at 100 Hz (III)

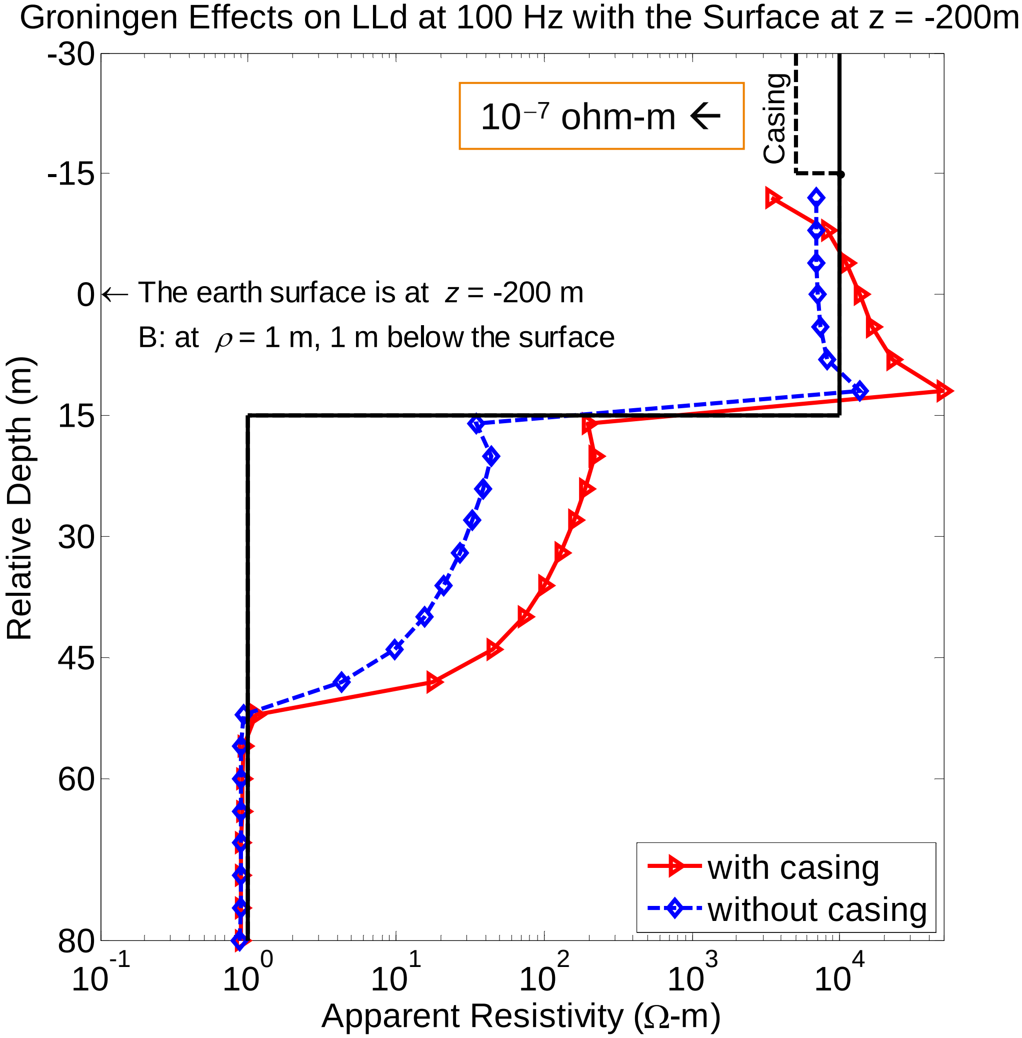


Further B in the ρ direction:

Smaller Groningen effects

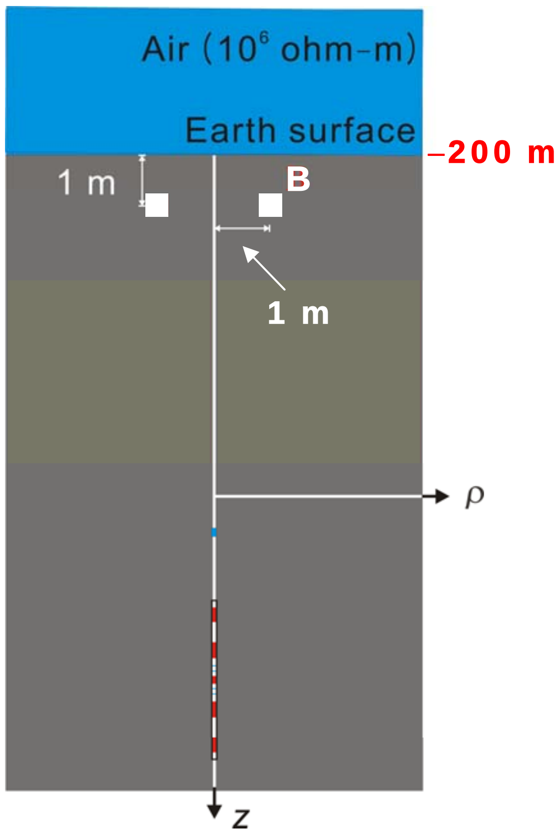


Groningen Effects on LLd at 100 Hz (IV)

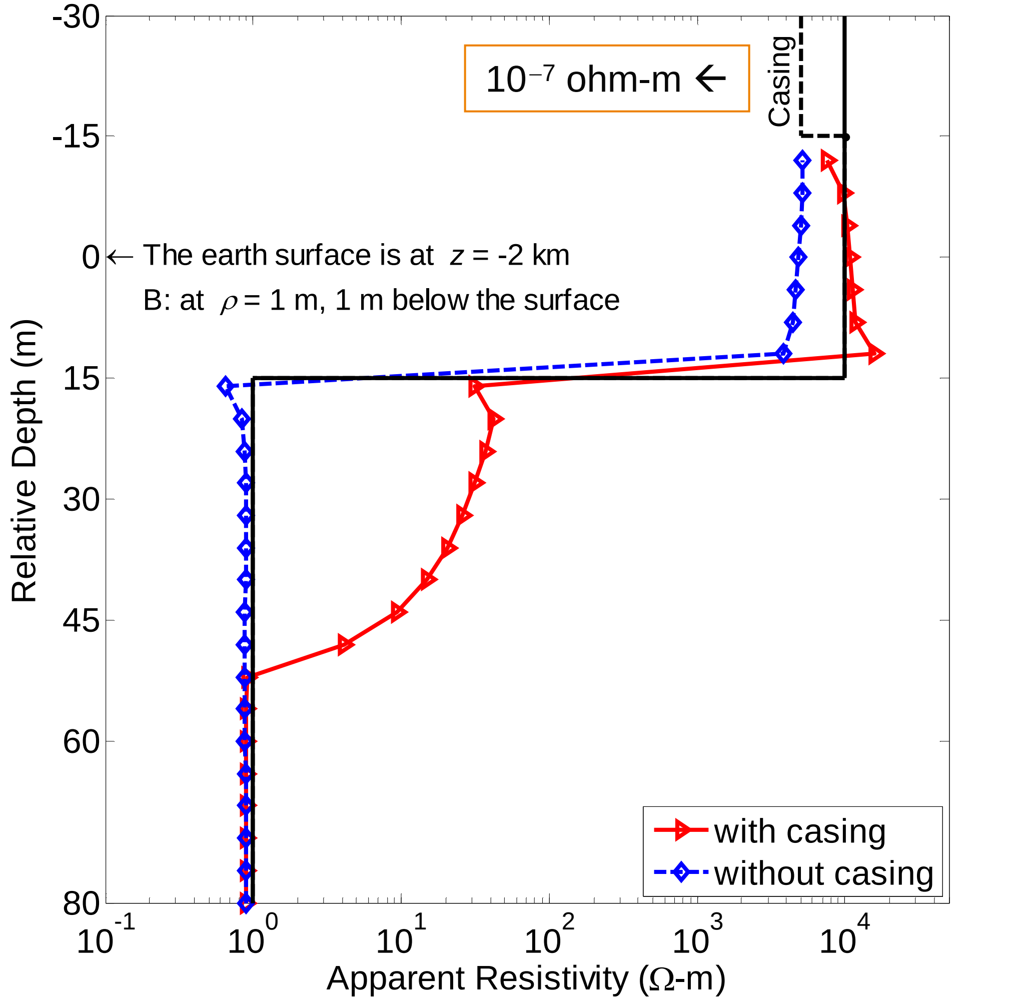


No casing with B 200 m apart:

Smaller Groningen effect

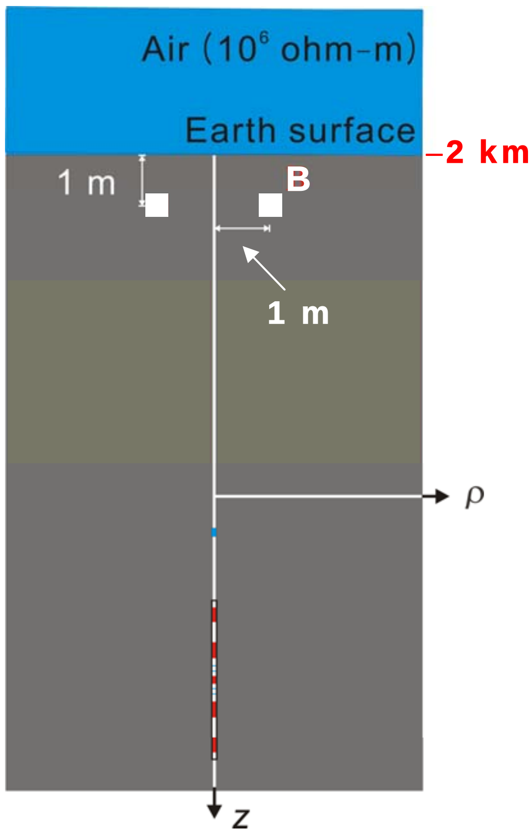


Groningen Effects on LLd at 100 Hz (V)



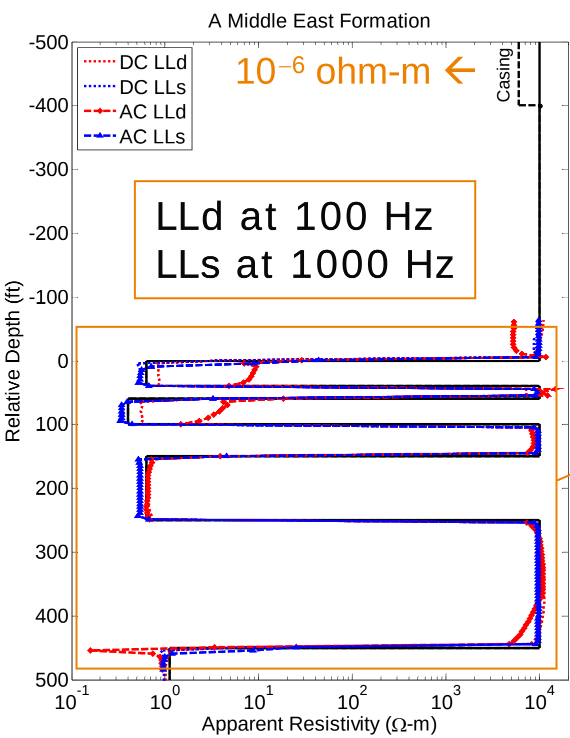
No casing with B 2 km apart:

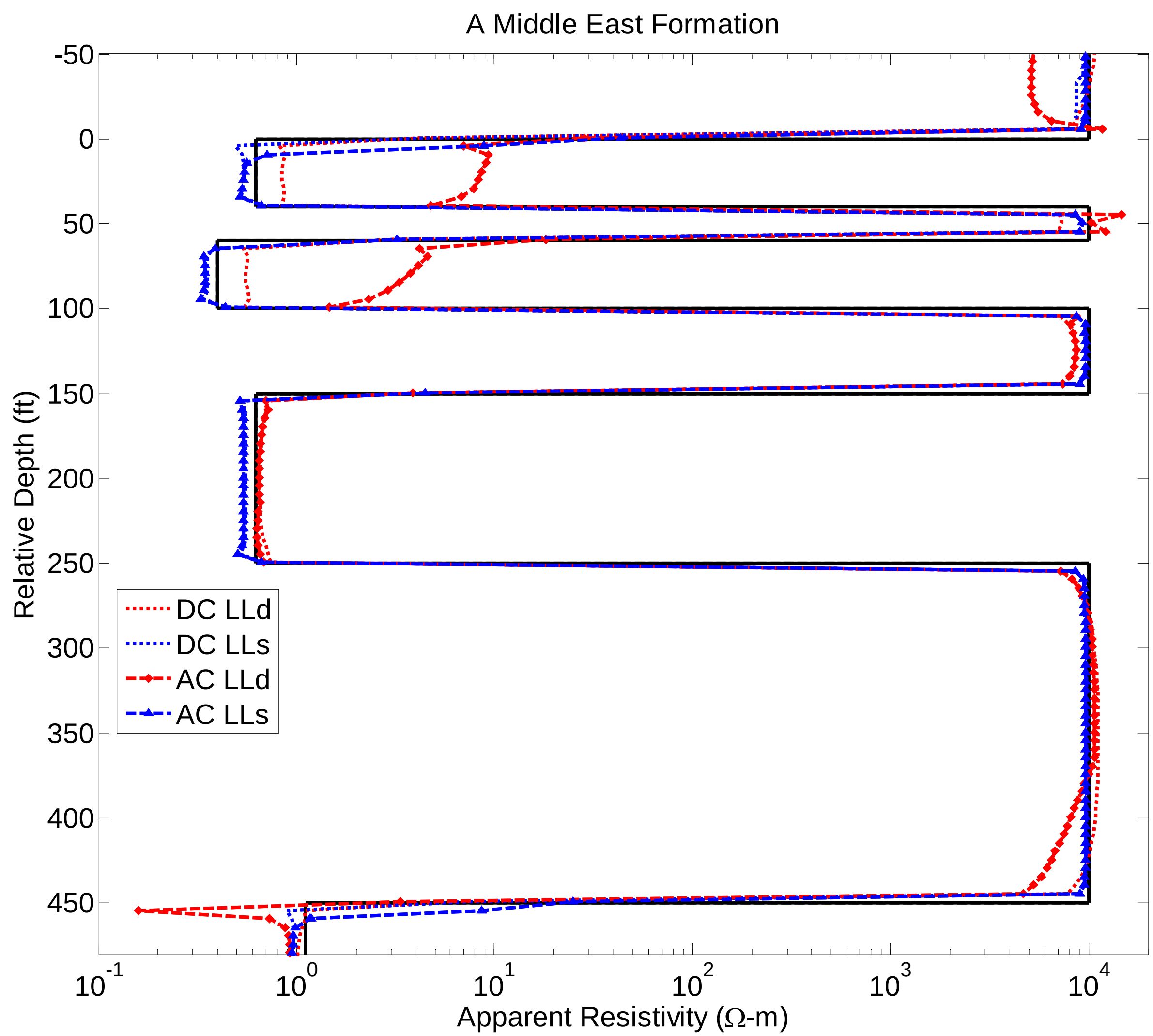
No Groningen effect



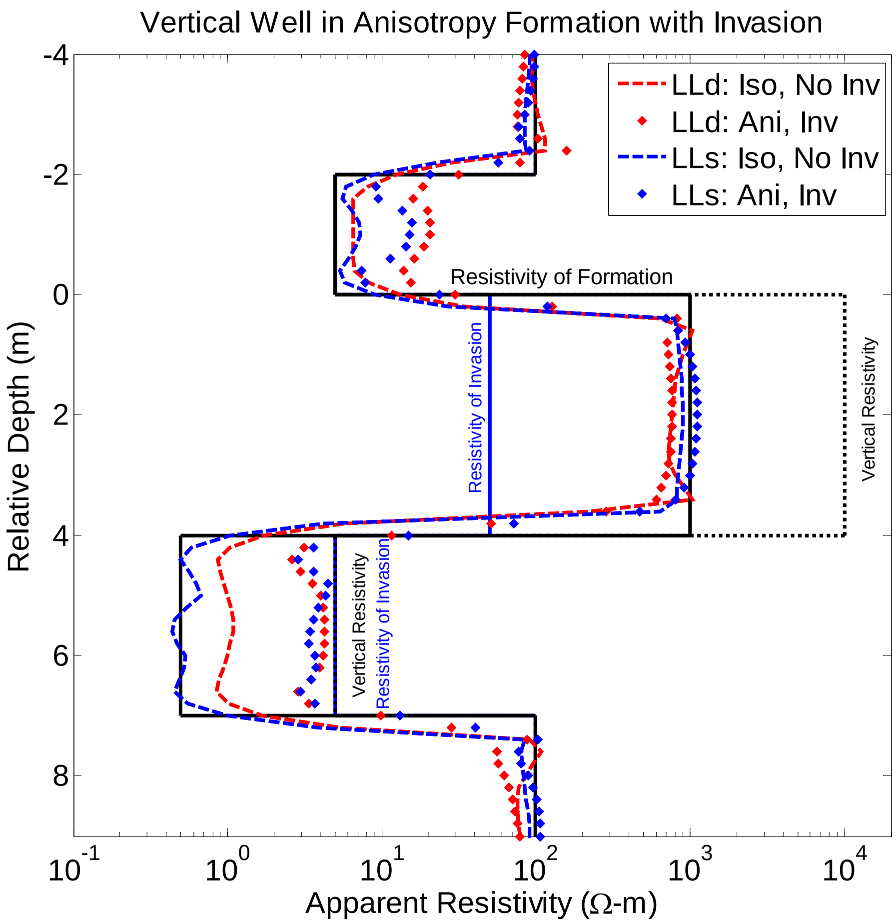
A Middle East Formation Model

Frequency effects on AC DLL measurements

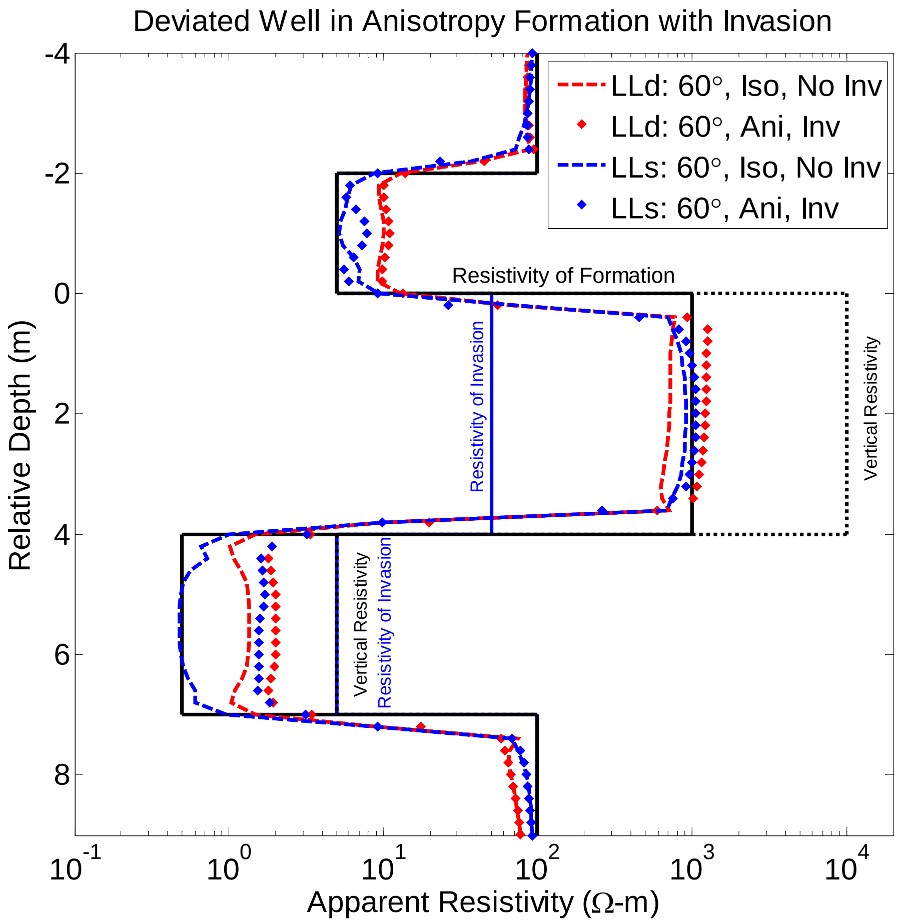




Invaded Anisotropic Formation (DC DLL)

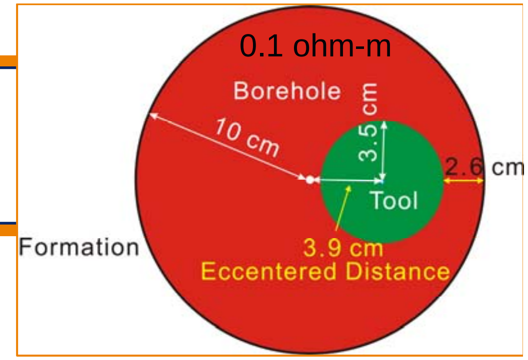


Vertical Well

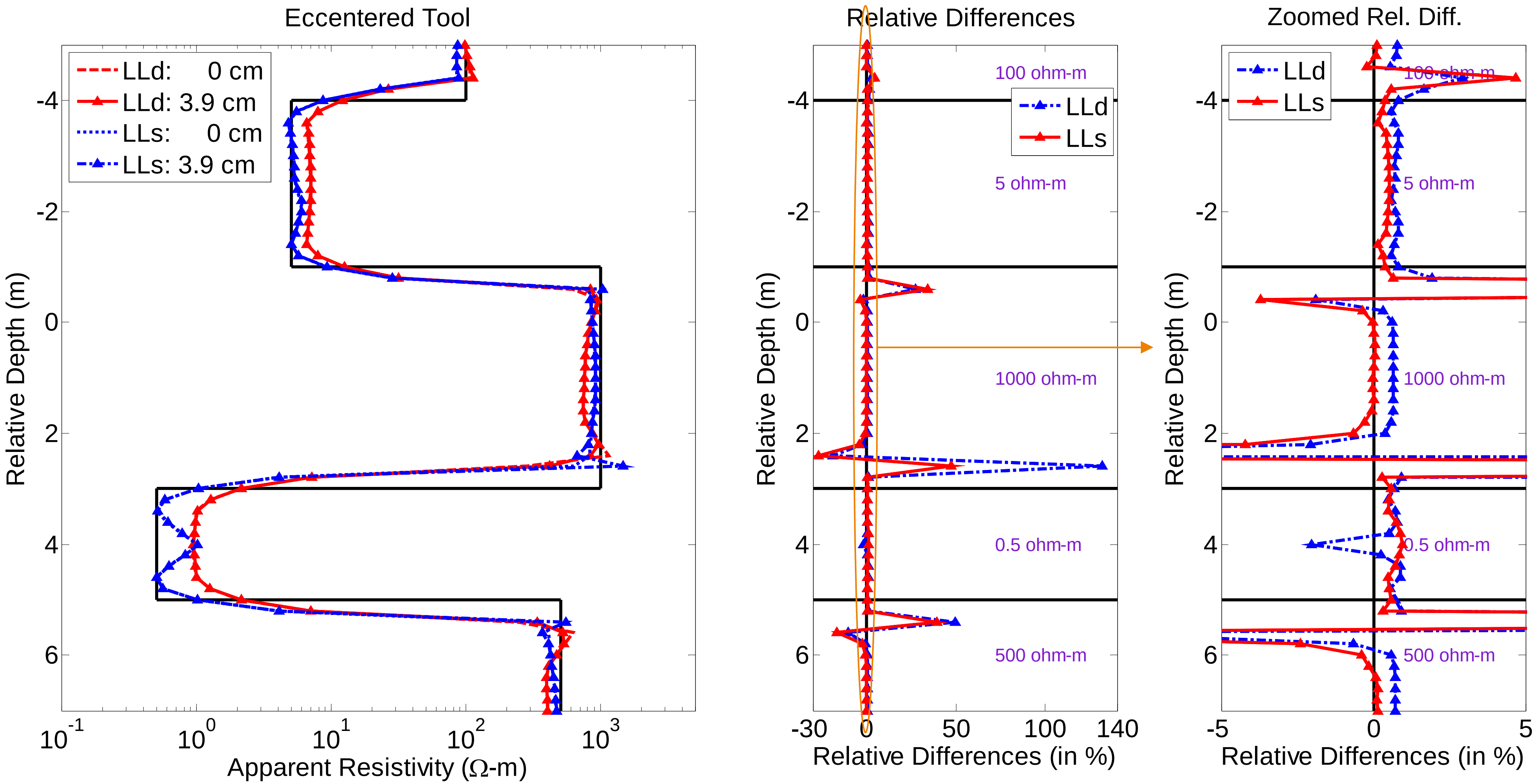


60 degree deviated Well

Eccentered Tool Effects (DC DLL)



Eccentered-tool effects are larger around layer boundaries in resistive layers



Conclusions

- We successfully simulated AC DLL measurements by explicitly incorporating the term $\nabla \cdot J$ for non-zero frequency Maxwell's equations.

- The simulation employed a high-order self-adaptive *hp* finite-element method with an embedded post-processing technique.

- Numerical experiments indicate that the inclusion of a current return electrode is critical to simulate Groningen effects.

- Groningen effects decrease as the current return is placed farther away from either the logging points or the borehole.

Acknowledgements

Sponsors of UT Austin's consortium on Formation Evaluation:

Anadarko Petroleum Corporation
ارامكو السعودية Saudi Aramco
Baker Hughes Baker Atlas
bhpbilliton
bp
Chevron
ConocoPhillips
Agip
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ExxonMobil
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