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Presentation

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Borehole Electromagnetics
Theory & Applications

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Borehole Electromagnetics
Theory & Applications

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Outline

• Importance of borehole EM
• The methods
• Cross well examples
• Summary
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Importance of borehole EM

- Resistivity dependence on $\Phi$ & $S_w$ high
- Scaling to reservoir scales
- Signal comes from conductivity contrasts
- Crosswell seismic sensitivity & scale comparable
- Excellent for OWC detection
- Routine log measurement
Resistivity Ranges

Wide ranges = fine parameter distinction

Consolidated sediments:
- Coal
- Slate
- Shale
- Sandstone
- Limestone
- Greywacke
- Dolomite
- Conglomerate

Unconsolidated sediments:
- Glacial silt
- Sand (dunes)
- Sand (valley)
- Marl
- Loess
- Loam
- Clay
- Gravel
Resistivity & velocity versus porosity, brine saturation, temperature.

The scale issue
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The methods

• Classical borehole measurements
  - induction log commercial
  - array induction commercial

• Special applications
  - Deep Logging R&D
  - Cross well commercial trials
  - Single well R&D
Induction log principle

Receiver

Ground loop

Transmitter

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Reserves estimate

DPIL vs. HDIL

Reservoir Thickness: 270 ft
Net Pay (ft) 103.6 130.1
Net Pay 38.4% 48.2%
Por. Feet 15.4 ft 18.9 ft
Hyd. Feet 7.4 ft 9.2 ft

HDIL data allowed 24% more OIIP be booked.
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Cross-well time lapse measurements

Courtesy of EMI Inc.
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Crosswell examples

• The MAIL tool et al.
• Cross well example
• New multi-component tool
Crosswell examples

- The MAIL tool et al.
- Cross well example
- New multi-component tool
Single Hole Systems of EMI

- **MFT250** - mining
  - Single sensor 3 component HF tool
- **MAIL Tool** - geothermal
  - Multiple sensor 3 component tool
- **VEMP Tool** - mining
  - 3 component surface to borehole system
Raising the MAIL Tool in Japan
MAIL results: well DRL61w (0 on section)

Apparent Resistivity Log

Resistivity (ohm-m)

Depth (m)

Commercial Induction Log

High Temp Zone

MAIL tool

Horizontal Field Log

Horizontal field (percent vertical)

Resistivity (ohm-m)

Hy field

Hx field

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Geo-Bilt building blocks
Geo-Bilt tool physics

MAIL needs dipping beds or anisotropy
Crosshole EM

- 1990: LLNL,LBL, and EMI, developed first low frequency crosswell EM System

- Designed to be a 2-D to 3-D extension of EM induction logs; complementary to crosswell seismic logging
Conductivity tomography
Model from Induction Logs

Resistivity (Ω-m)

Depth (m)

0 m 25 m 50 m 90 m
Time lapse view of steam flood

November 1993

April 1994

September 1994

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Single well water flood 3D modeling example
Water Flood Model (Alumbaugh & Wilt)

X-Z Cross Section at Y=0  X-Y Cross Section at Z=0

21 VMD Source Pos. - Three Frequencies/Decade from 1KHz to 100KHz
Forward Model Mesh = 64 x 61 x 66
Inversion Model Mesh = 45 x 45 x 53 : Imaging Region = 30 x 30 x 40

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Initial 3D model (Alumbaugh & Wilt)

Model 1 as shown
Model 2 flipped across the XY planes.

X-Z Cross Section at Y=0

X-Y Cross Section at Z=0

Conductivity (S/m)

- 3.30e-01
- 3.03e-01
- 2.78e-01
- 2.56e-01
- 2.35e-01
- 2.15e-01
- 1.98e-01
- 1.82e-01
- 1.67e-01
- 1.53e-01
- 1.41e-01
- 1.29e-01
- 1.19e-01
- 1.09e-01

Forward Model Mesh = 64 x 61 x 66

21 VMD Source Pos. - Three Frequencies/Decade from 2.1KHz to 210KHz
Forward Modeling Results

Tx-Rx Separation: 10KHz=16m 100KHz=6m (Alumbaugh & Wilt)

Vertical Field

Horizontal Field

Model 1 - 10KHz
Model 2 - 10KHz

Model 1 - 100KHz
Model 2 - 100KHz

Primary - 10KHz
Primary - 100KHz

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3D image results (Alumbaugh & Wilt)

Horizontal Fields Only, Induction Number=3
Whole Space Starting Model - Data Noise=0.2%

X-Z Cross Section at Y=0  X-Y Cross Section at Z=0

Conductivity (S/m)

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Status cross, single well

- All tools frequency domain (TD in mining)
- Cross well:
  - open hole < 500-750 m  commercial trial
  - one casing < 500 m  commercial trial
  - both wells cased  in test phase
  - single well  R&D phase