Cross Well Electromagnetic Imaging for Vadose Zone and Groundwater Characterization

Project Investigators

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Vadose Zone Contaminant Transport

- Poorly understood
- Contaminant transport is controlled by heterogeneous deposits that are geologically chaotic in nature
- Understanding is necessary for proper treatment and stabilization of subsurface contamination at DOE waste sites

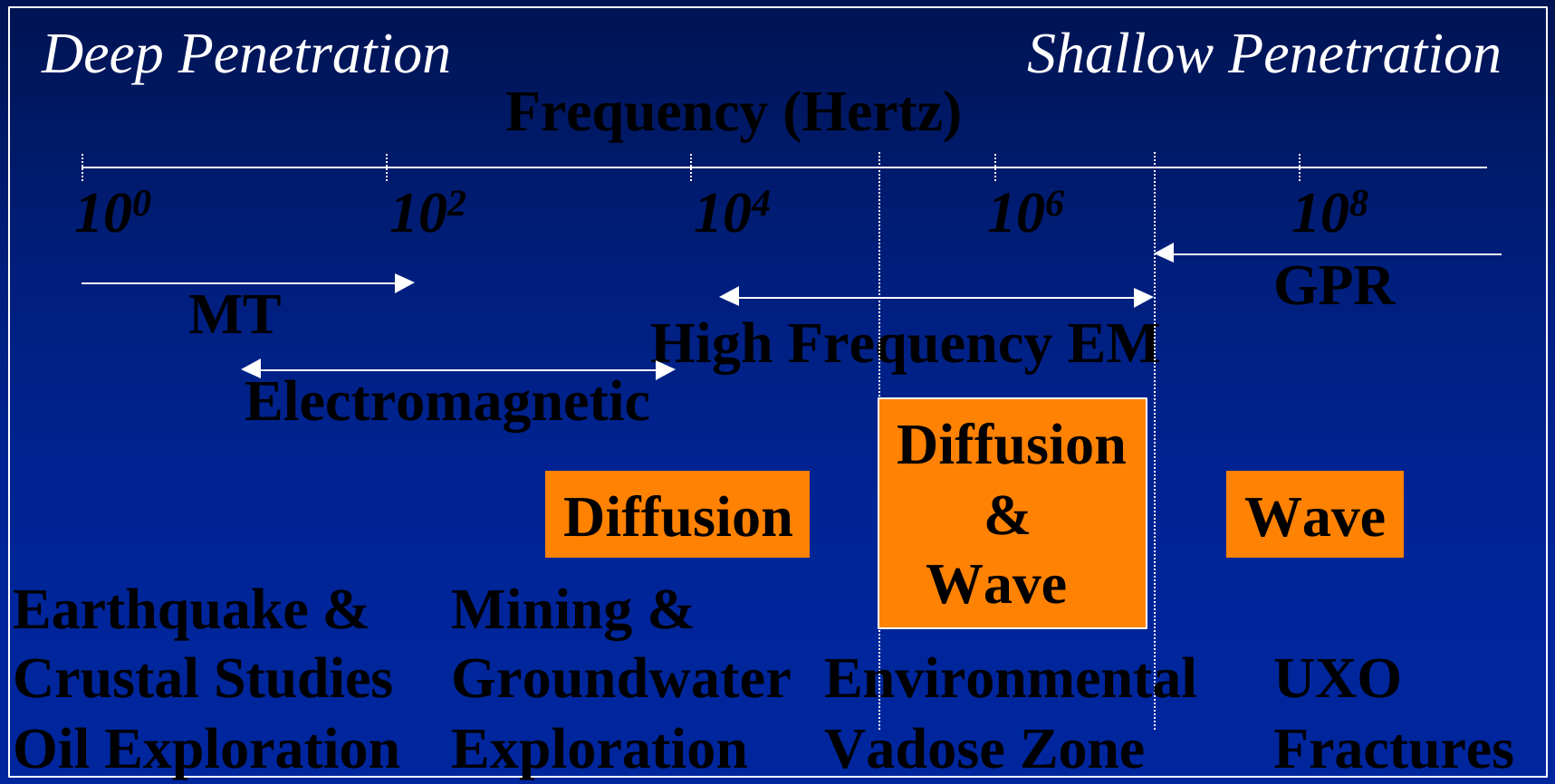
Vadose Zone Characterization

- Mapping of Geological Heterogeneities
- Identification of Transport Pathways
- Location of Contamination

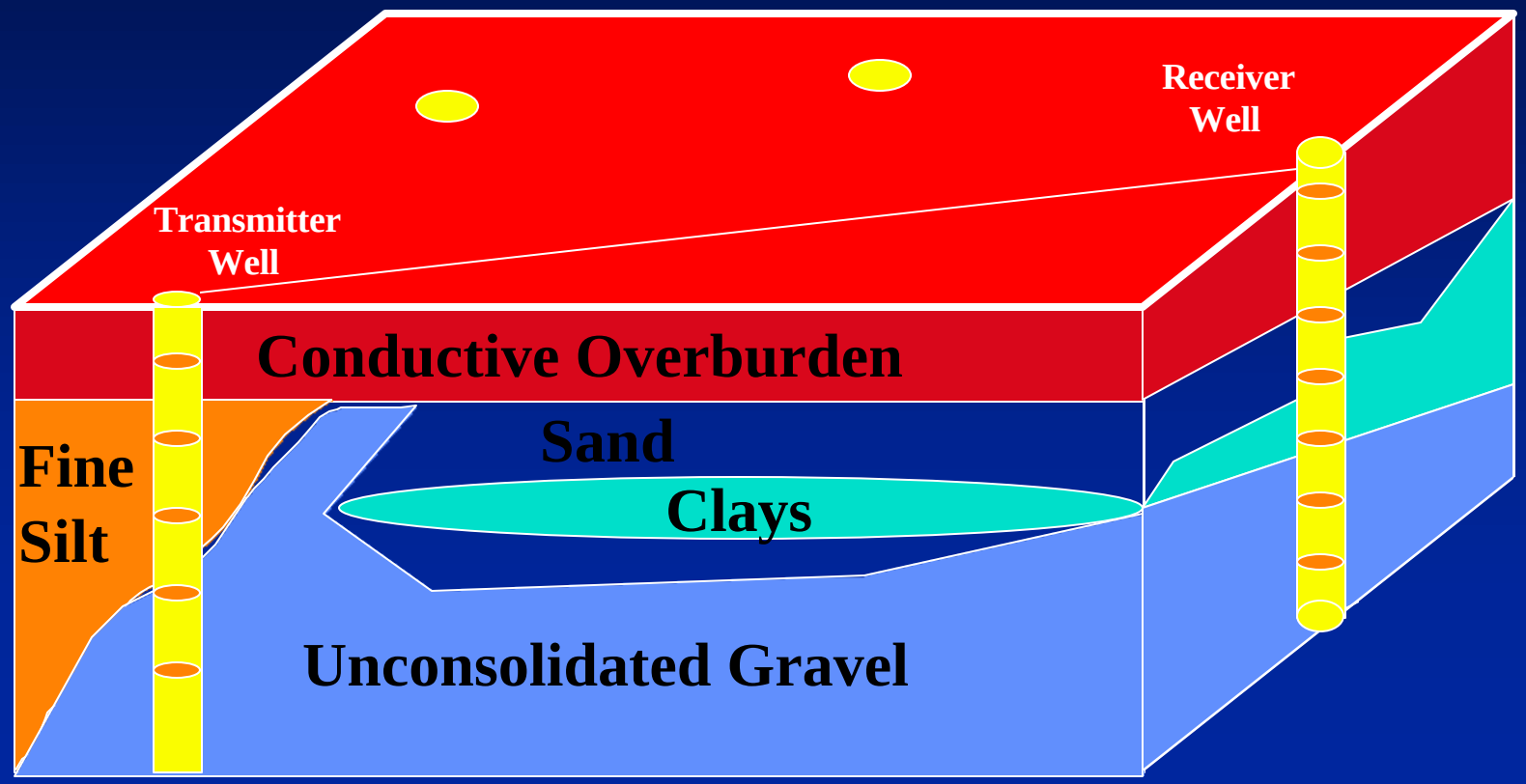
Vadose Zone Characterization using EM Induction Method

- Directly sensitive to fluids in porous media
- Methods detect variations in subsurface
  - → electric conductivity
  - → dielectric permittivity
- A viable alternative to shallow penetrating GPR
- Method employs lower frequency EM fields for penetration
- It is noninvasive; method can utilize wellbores

EM Geophysical Spectrum



Crosswell Electromagnetic Method



Advantages of the Method

- A proven method used in monitoring saturation/conductivity changes
  - in oil field water floods
  - transport pathways for contaminant transport
- Measurements are conducted in boreholes.
  - Yields high resolution imaging between wells.
- Advanced inversion codes already developed and used for data interpretation.

Inversion Methodology

Minimize the cost functional:

$$\varphi = \sum_{j=1}^{2N} \{(\mathbf{d}_j^{\mathbf{obs}} - \mathbf{d}_j^{\mathbf{p}})/e_j\}^2$$

$$+\lambda\,(\mathbf{m}-\mathbf{m}_{\mathbf{ref}})\mathbf{W}^T\,\mathbf{W}(\mathbf{m}-\mathbf{m}_{\mathbf{ref}}).$$

$\mathbf{d}^{obs}$ and $\mathbf{d}^{p}$ are N observed & predicted magnetic fields

$\mathbf{e}$ = data weights

m = M conductivity/dielectric model parameters.

W = $\tilde{N}^2$ operator; constructs a smooth model

λ = tradeoff parameter

The Forward Problem

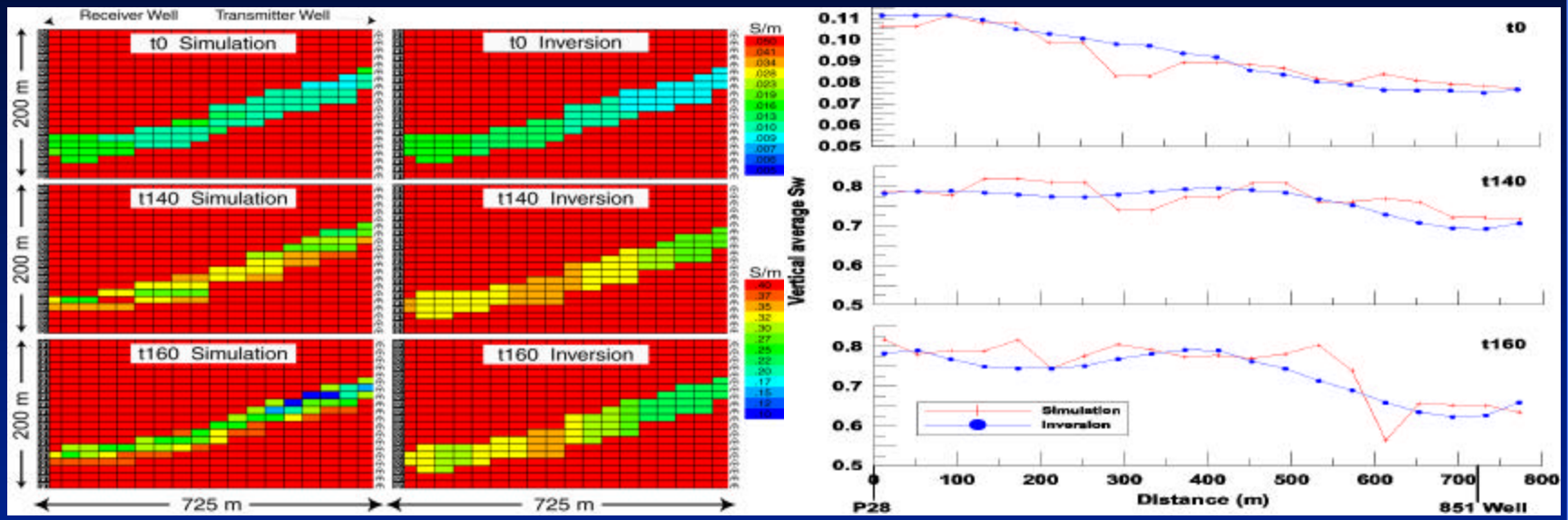
- We require the solution of the electric field vector equation:
  - → $\tilde{N} \times \tilde{N} \times \mathbf{E} + (\omega^2\mu_o\varepsilon - i\omega\mu_o\sigma)\,\mathbf{E} = \mathbf{S}$
  - → **S** depends on the source antenna
  - → equation approximated using finite differences
  - → system solve with iterative Krylov subspace methods
- We also require the magnetic field on the grid
  - → $\mathbf{H} = -\tilde{N} \times \mathbf{E}/i\omega\mu_o$
- Predicted data determined by interpolation
  - → $\mathbf{d}^p = Q\mathbf{H}$

2D Non Linear Gauss-Newton Inversion

- Formulated using the normal equations
- Model update can be computed using direct matrix methods
- Upper and lower bounding constraints on the conductivity/permittivity are included in the minimization process
- A priori information on known structural boundaries can be preserved in the image
- Conductivity/permittivity well logs can be used to constrain the interpretation

Mapping Water Saturation

Snorre Simulation



- Reservoir simulation-geophysical model
- Resistivity vs. Sw from log data
- 2D inversion of numerical2D inversion of numerical data predicts average Sw

EMI Crosswell Field System

- Develop by Electromagnetic Instruments

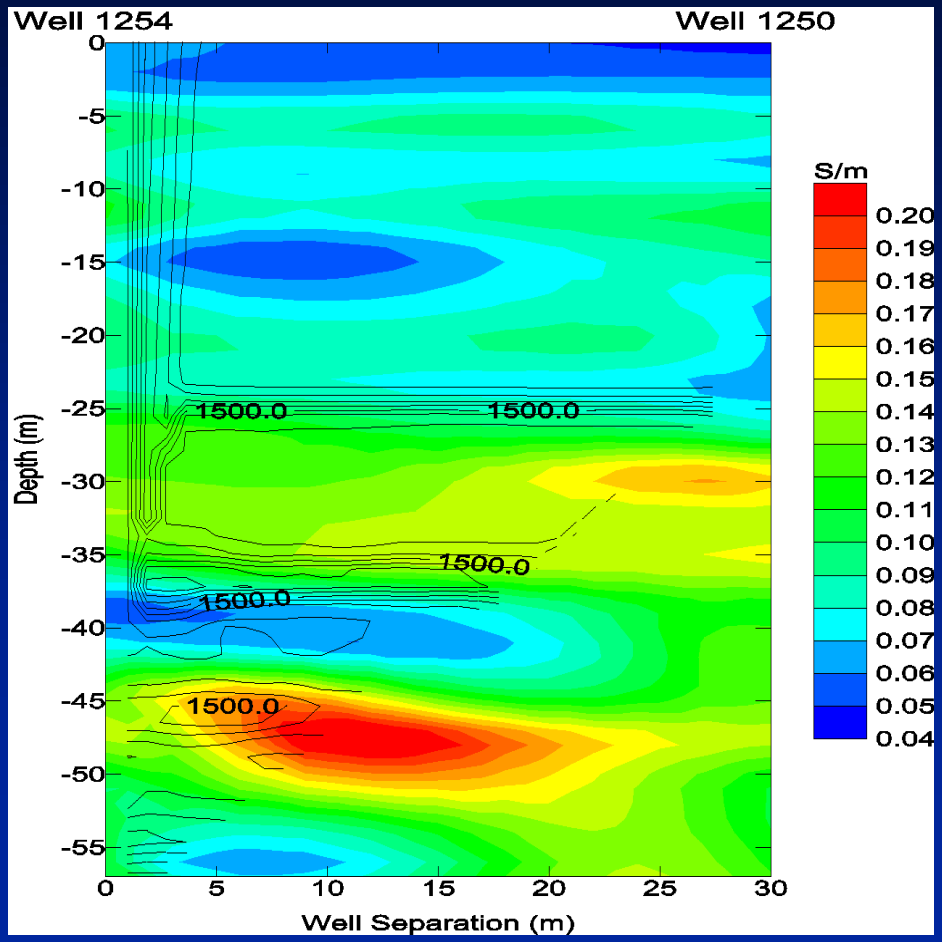
- *Operating Frequencies* (10 Hz to 100 kHz)
- *Transmitter moments of 1000 amps-turns-m^2*
- *Receiver coil sensitivity 1.08e-12 (amp-m) at 50 Hz; even better at higher frequencies*

EMI System

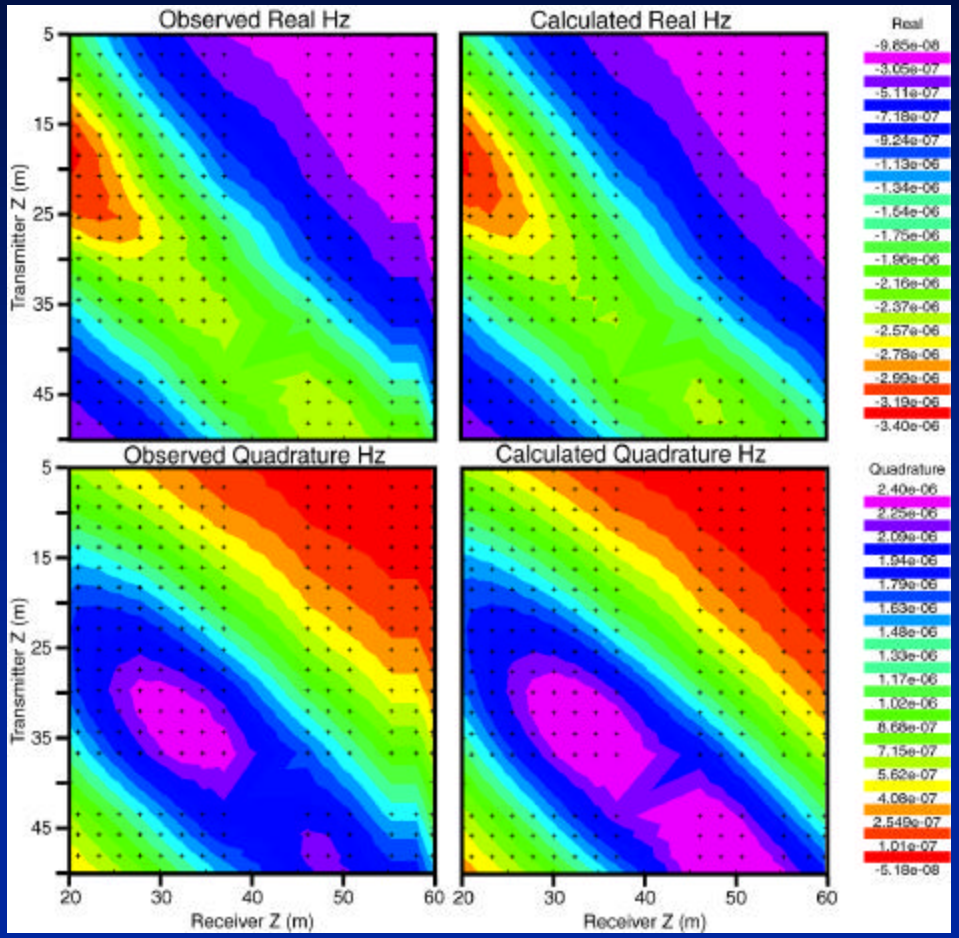
Field Examples

- mapping transport pathways
- water flood experiments at the Lost Hills oil field
- imaging through steel casing
  - **GUDAO (China) and Kern River California Oil Fields**

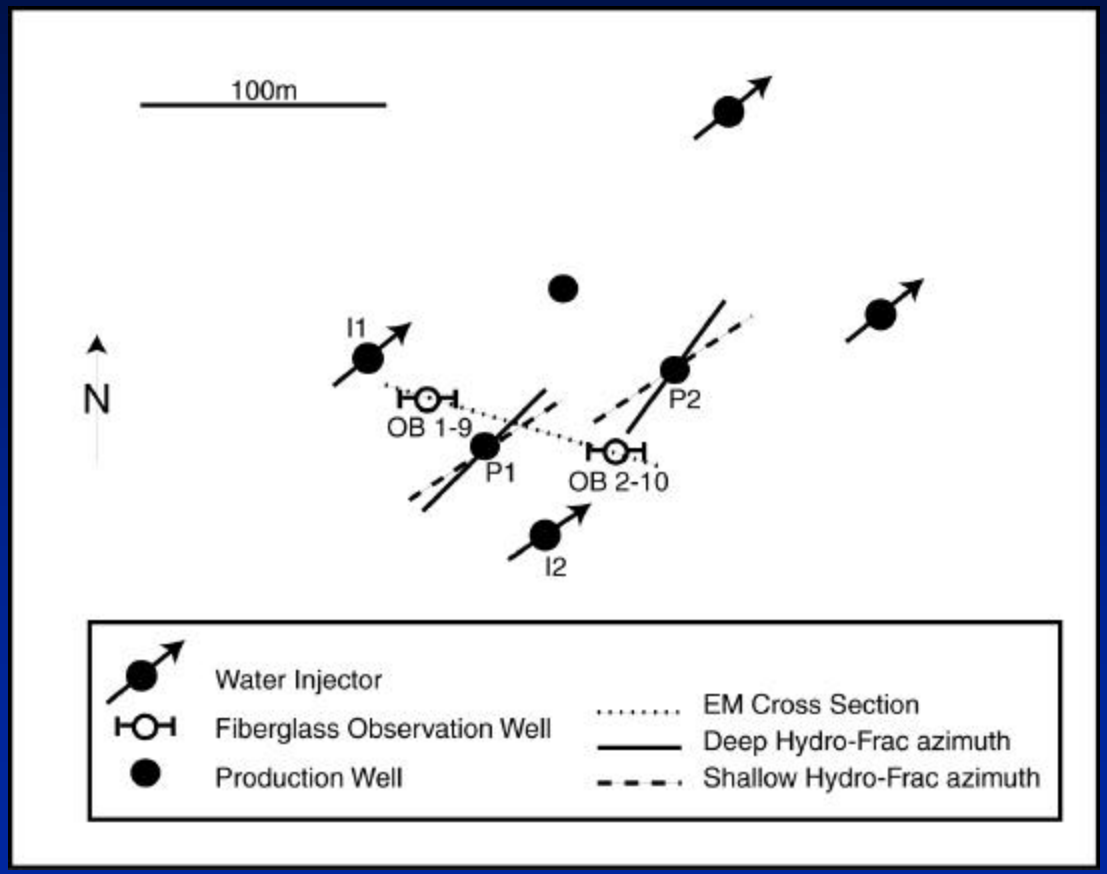
Transport Pathway Characterization



Transport Pathway Imaging (Data Fits)



Petroleum Reservoir Characterization



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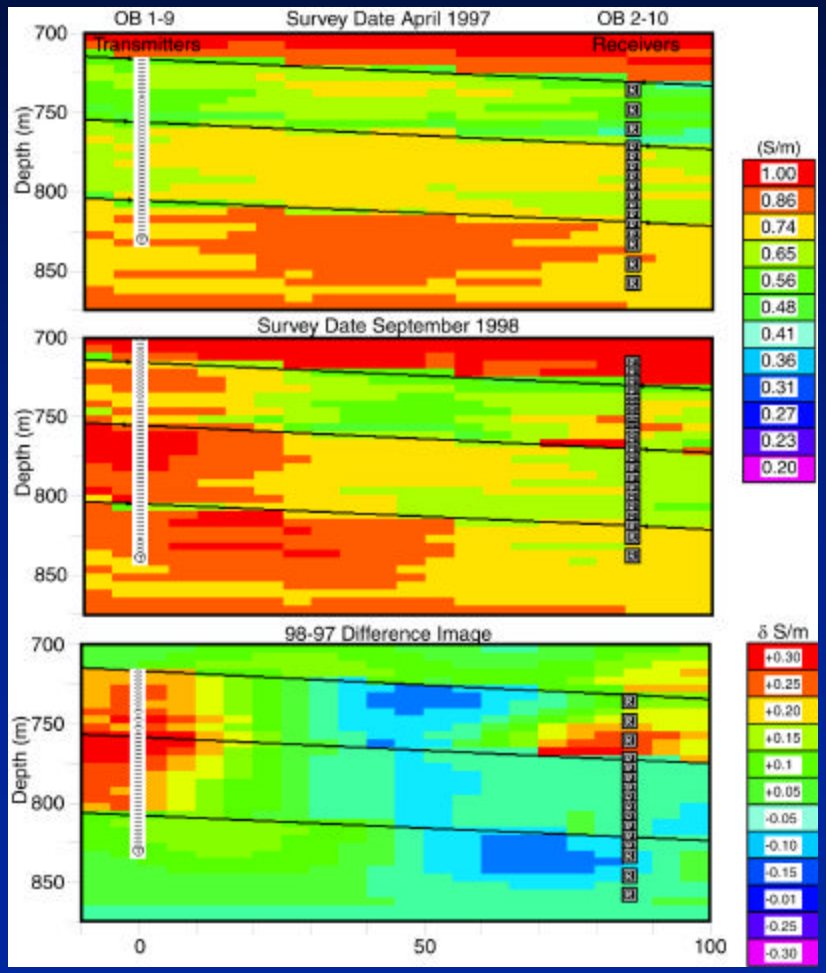
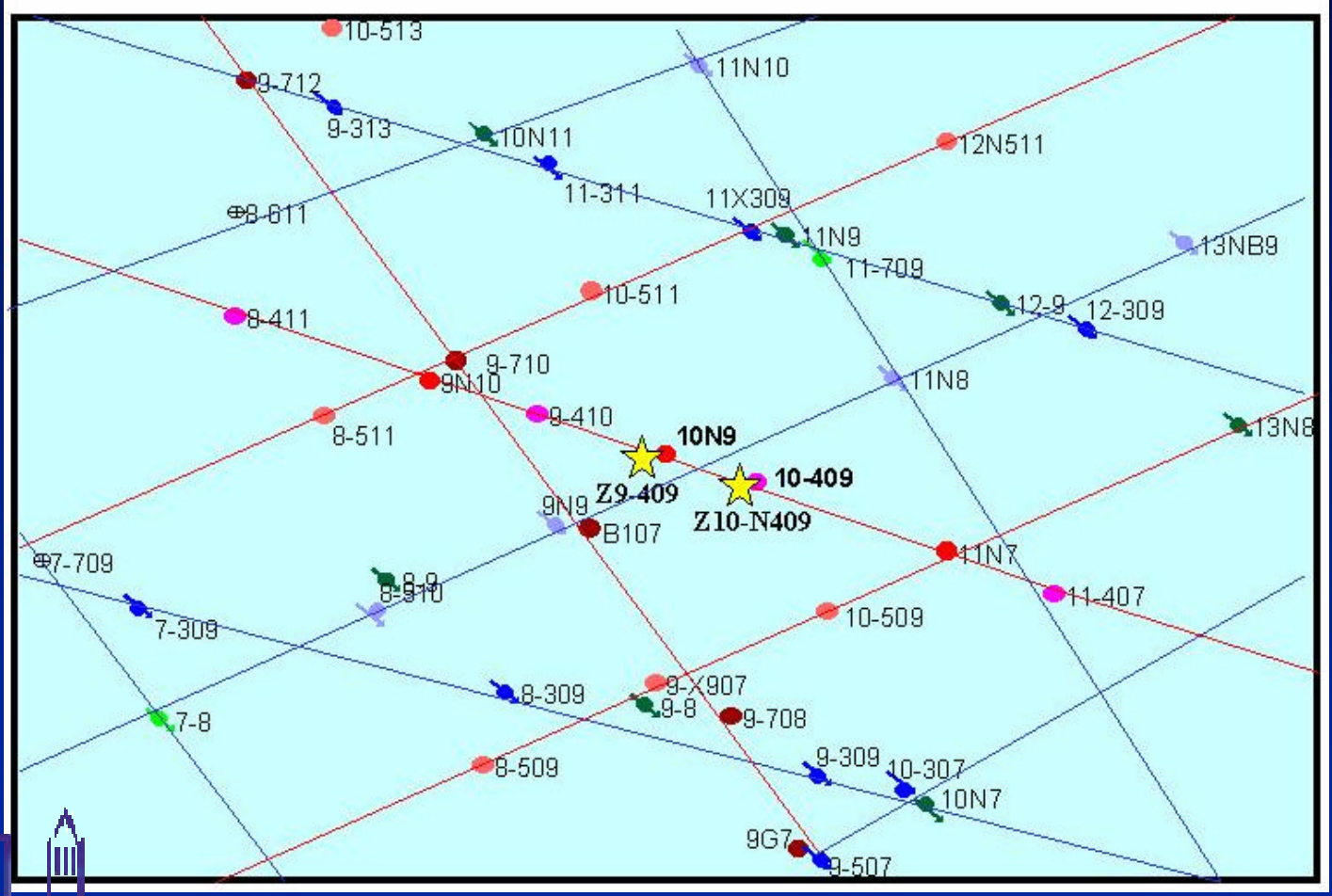
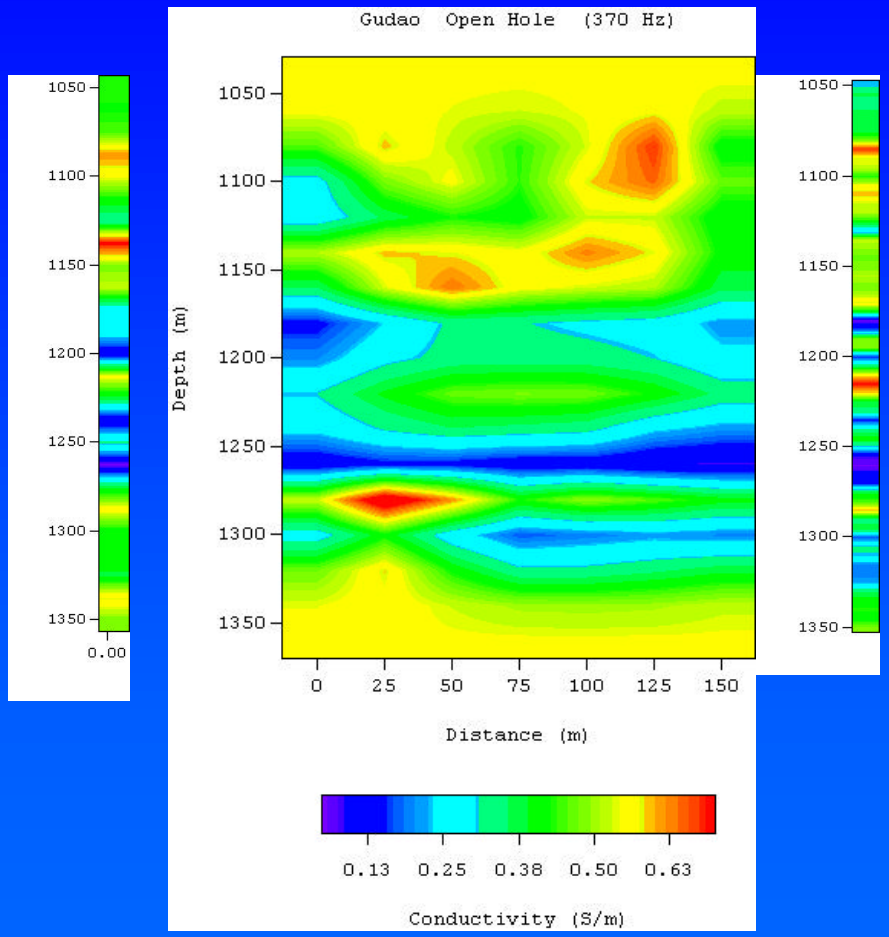


Imaging Through Steel Casing

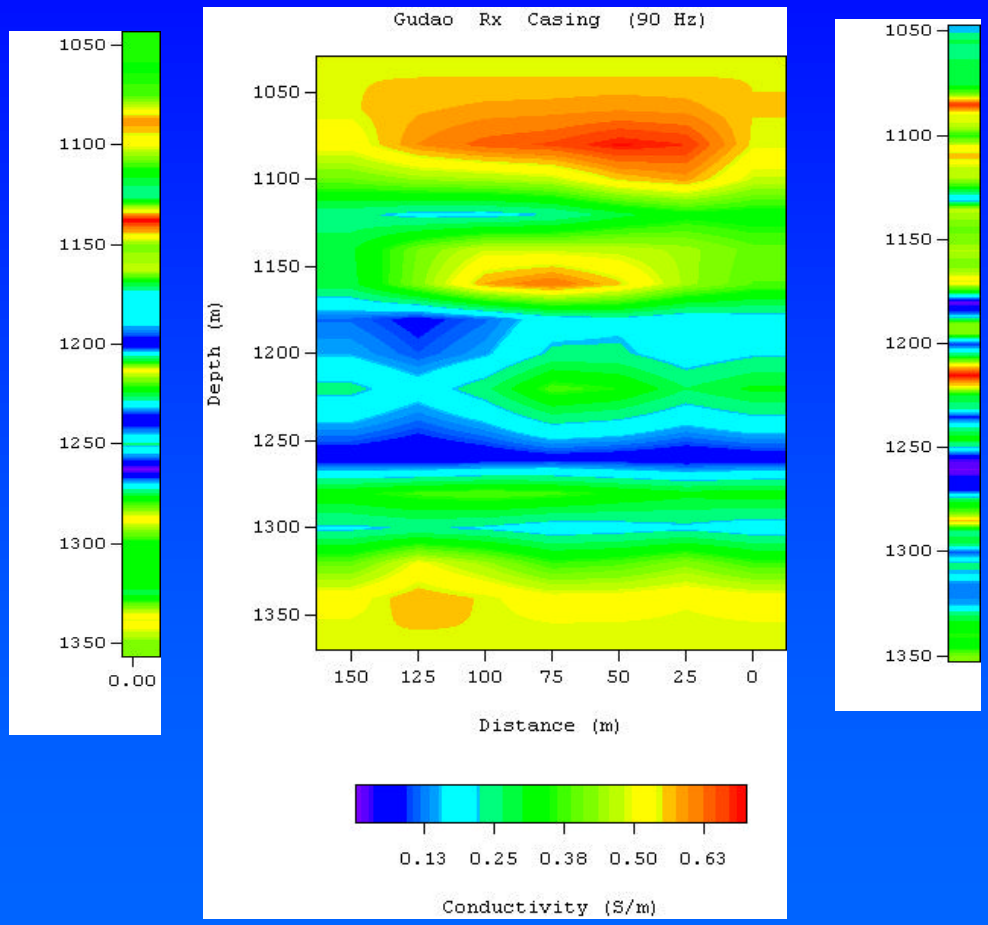
OIL WELL LOCATIONS OF Z-9-409 AREA IN GUDAO OILFIELD



Uncased Image 370 Hz

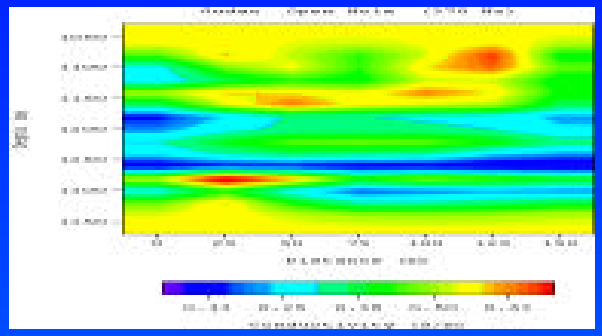


Cased Image 90 Hz

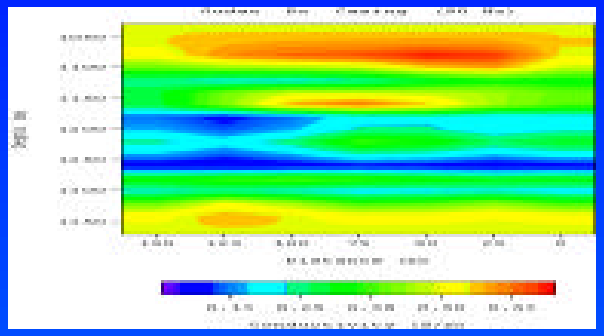


Cased &Uncased Images

GUDAO (China) OILFIELD conductivity imaging through casing



Open hole conductivity image

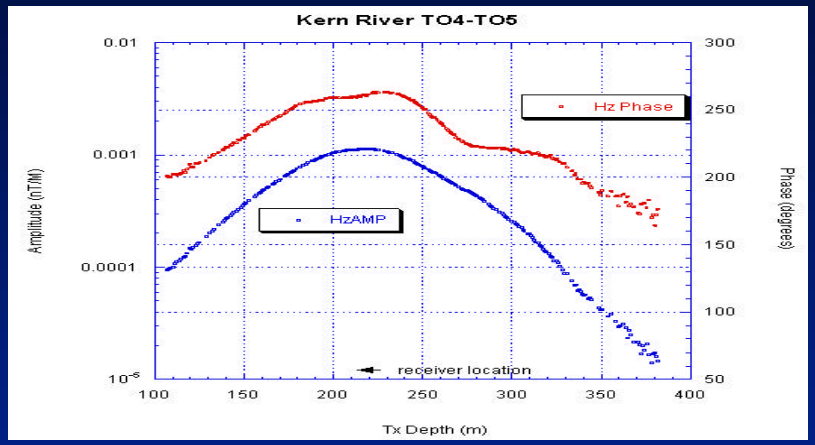


Receiver well cased

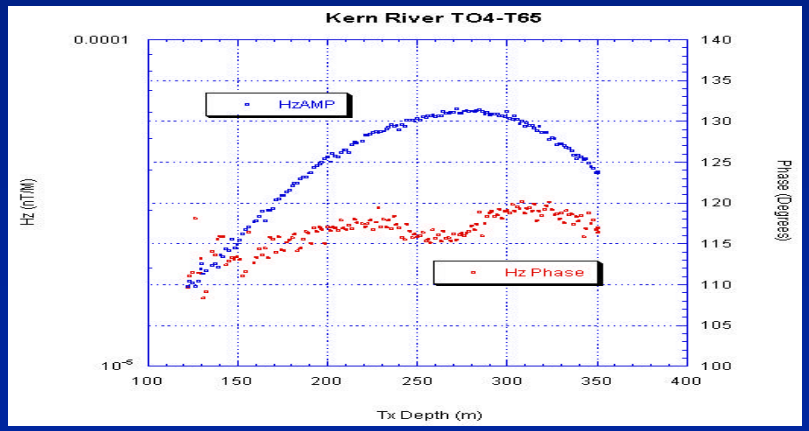
- Open hole image @ 370 Hz
- Cased receiver image @ 90 Hz
- Paten pending on through casing measurements

Kern River Data

- Fiberglass casing standard deviation < 1%
- well separation 114m
- Frequency 759 Hz



- 1 steel casing standard deviations ≅ 3%
- well separation 214m
- Frequency 90 Hz



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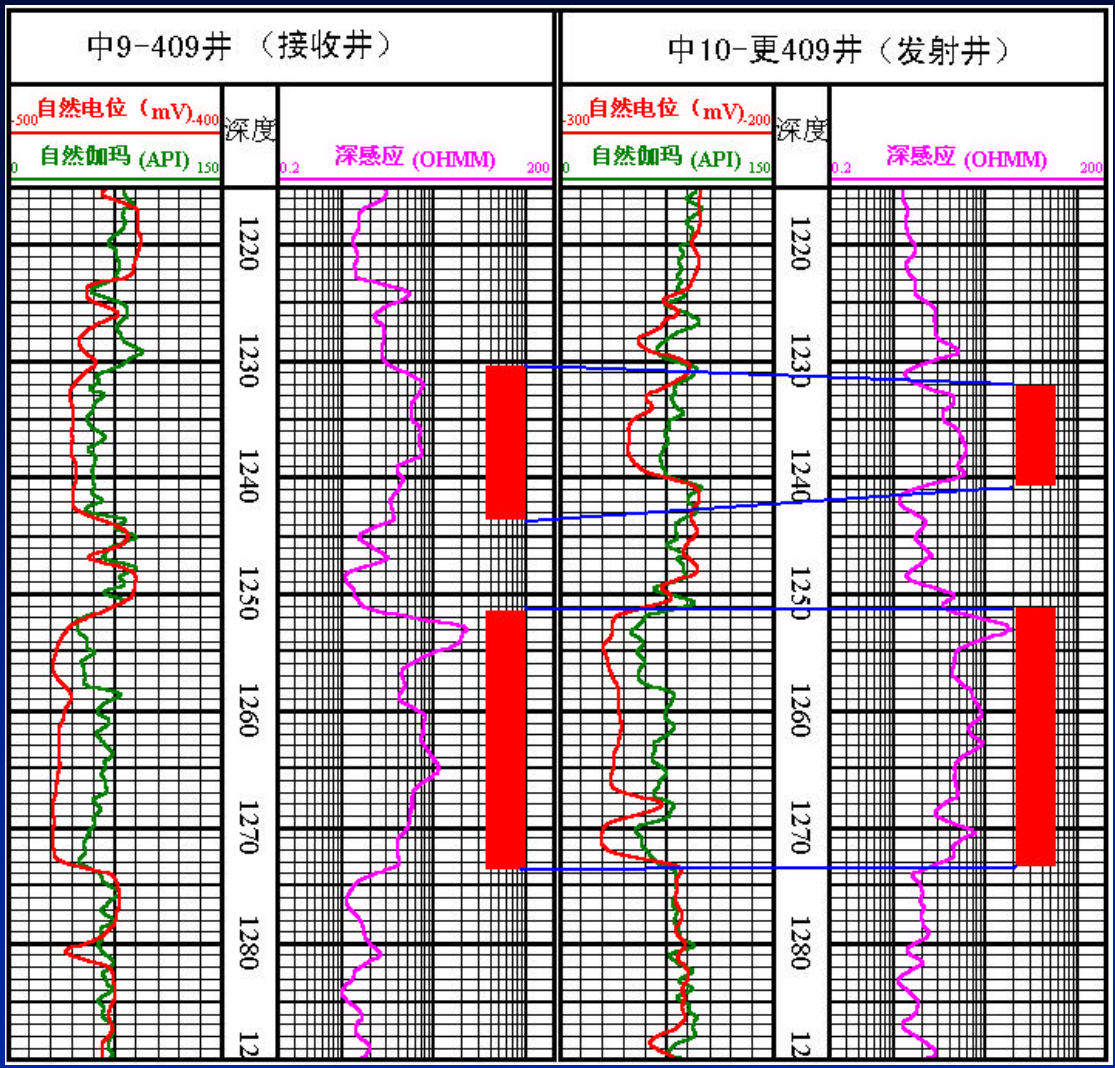
Benefits to DOE & Hanford

- A combined measurement/interpretation package
- Non-invasive
- Measurements possible through steel casing
- High resolution for characterization of the vadose zone
  - larger transport pathways
  - certain types of contamination
  - heterogeneities
- Available for now use at the Hanford Reservation and other DOE facilities

Resistivity Logs