A New Array System for Multiphysics (MT, LOTEM, & Microseismics) - Focus on Reservoir Monitoring

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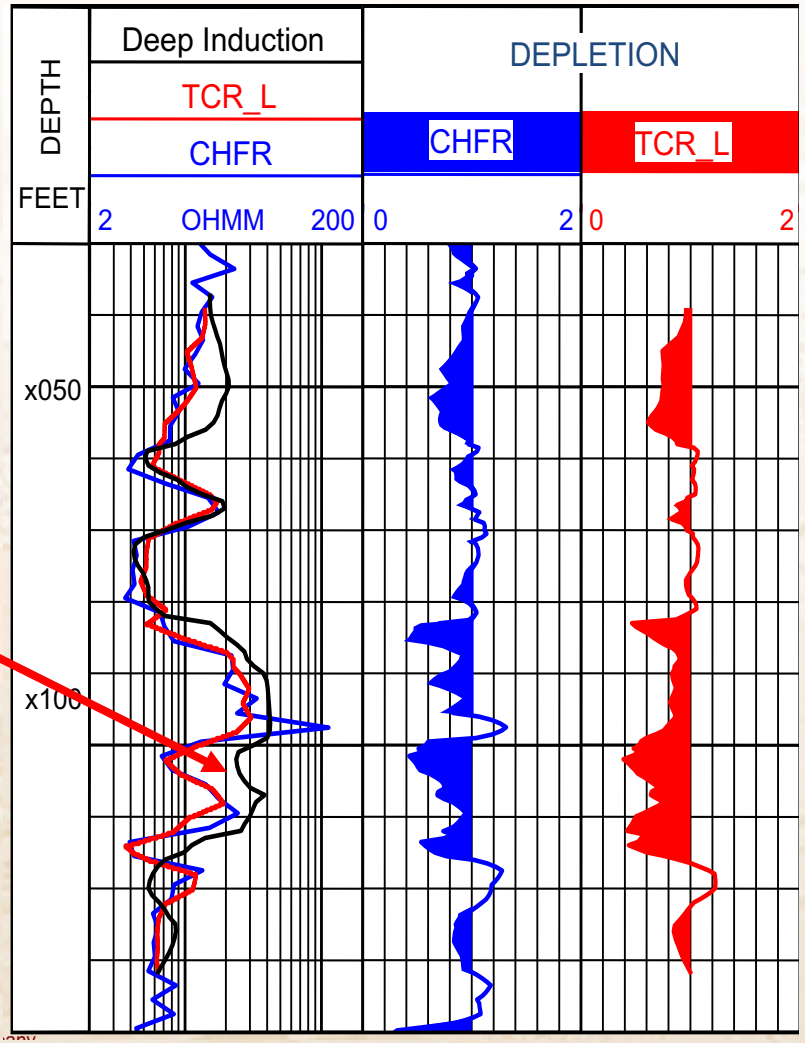
- Introduction to EM monitoring for EOR
- Equipment overview
- Examples:
  - Monitoring
  - SBHT & FSEM
- Conclusion & Recommendation

What is Monitoring & EOR?

Monitoring: Observing reservoir changes with time

Enhanced Oil Recovery (EOR): Using additional stimulation to produce oil

Steam flood reduced 35 Ω-m reservoir resistivity to 7 Ω-m



After Zhou et al., SPWLA 2002

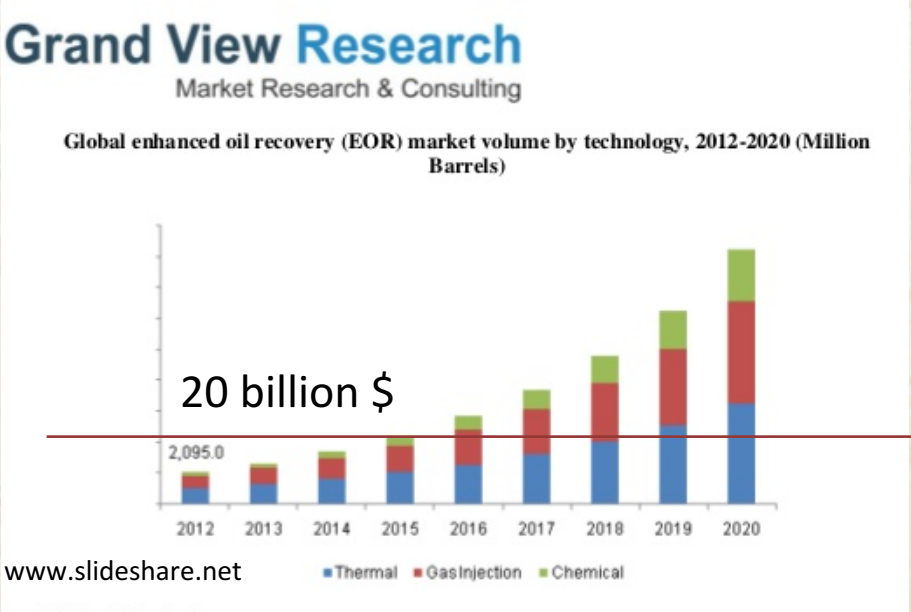
Market overview

- EOR market 2015: 20.4 Billion US $
  - Geophysical data: temperature & pressure
- EOR market predictions 2020:
  - https://globenewswire.com/ - 283 billion US $
  - Conservative 8% growth = 30 billion US $
  - 'more than triple' = 70.6 Billion US $ http://www.environmentalleader.com/

Geophysical data →
ONLY feed forward methods

→ GREAT opportunity

→ ALL cause resistivity contrast



Why electromagnetics (EM) & microseismics?

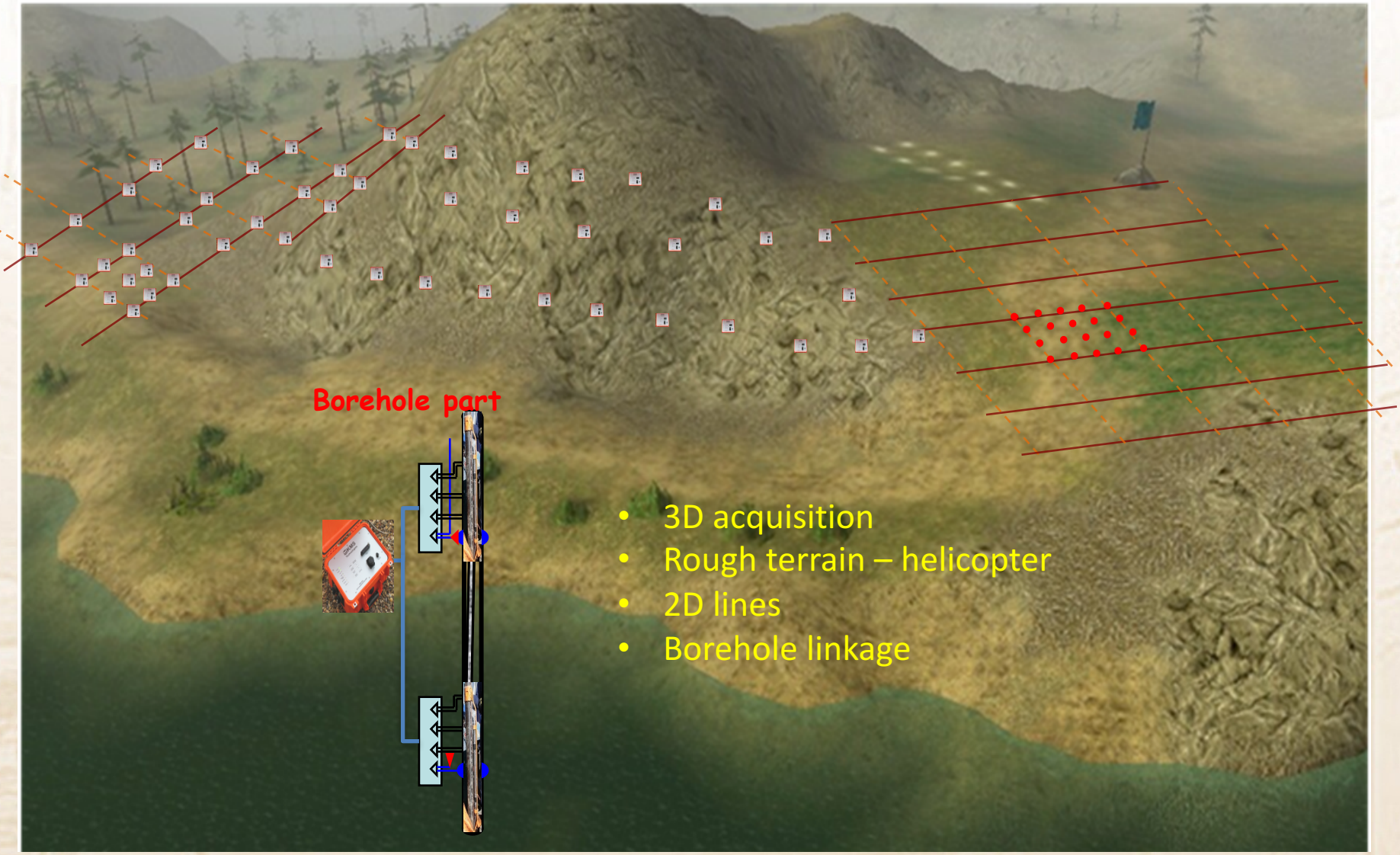
SENSOR CAPABILITY	RESOLVING POWER				
	Distance	Fluid	Surface-to-surface	Surface-to-borehole	Borehole
Seismic	Excellent	Poor	Excellent	Excellent	Ok (more noise)
EM	Ok (5% of depth)	Excellent (water to HC)	Ok	Excellent	Excellent (less noise & distance)
Gravity	Poor	Ok (oil to gas)	Poor	Poor (no source)	Poor (no source)
Strongest Synergy	Seismic	EM/seismic	Seismic/EM/ gravity	Seismic/EM	Seismic/EM/ gravity

With permission of WellDynamics (now Halliburton)

Today's technical advances:

- EM (E & H) & microseismics in **one** unit
- State-of-the-art seismic architecture (node)
  - Wireless array
  - Large memory SD cards
- EM requirements
  - Broad band (DC-80 kHz, low noise, low drift)
  - Multi-components, multi-physics
  - Transition to digital sensors- partial
  - High dynamic range
  - 8 km long range wireless & WIFI (2 types)
  - Autonomous, can record for weeks
  - GPS timing & atomic crystal (marine option)
  - Lower cost
- Processing is seismic software compatible

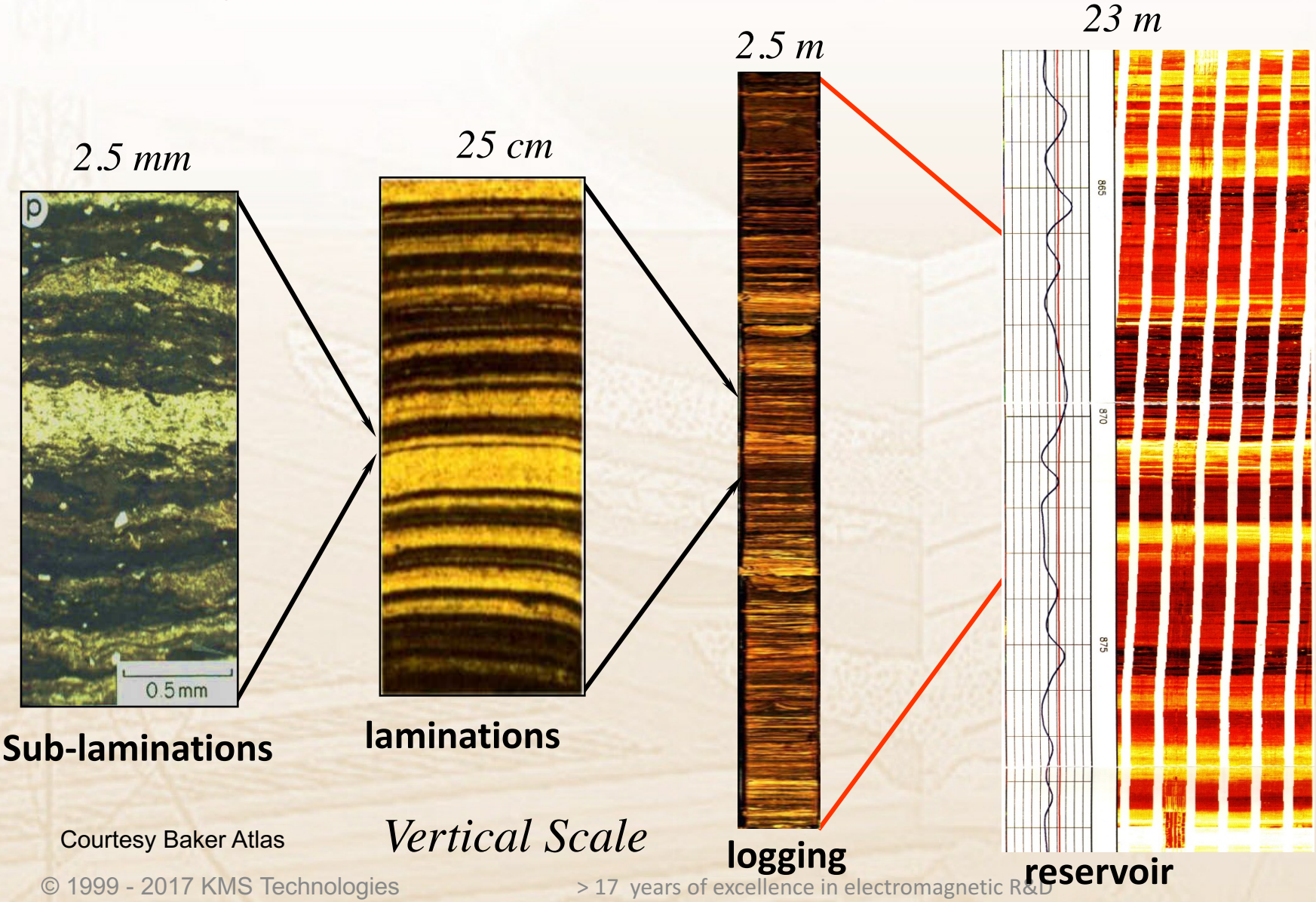
Land acquisition requirements



EM technical status - Monitoring

- Land: technology available, application new
  - Hydrocarbon apps require conductor AND resistor sensitivities
  - Smaller technical challenges: 3D, S/N etc.
  - → integration requires unique TALENTS
- Borehole: standard – all available
  - Induction logs (low resistivities) & Laterologs (higher resistivities)
  - Array tools extend range with large OVERLAP
  - 3D induction
  - Borehole mud gives some limitations (near surface in exploration)
  - Fully integrated into value solutions
- Airborne: conductive targets; not important for monitoring
- Marine: in principle same as land easier science, more difficult operation

Anisotropy is EVERYWHERE – Problem solved



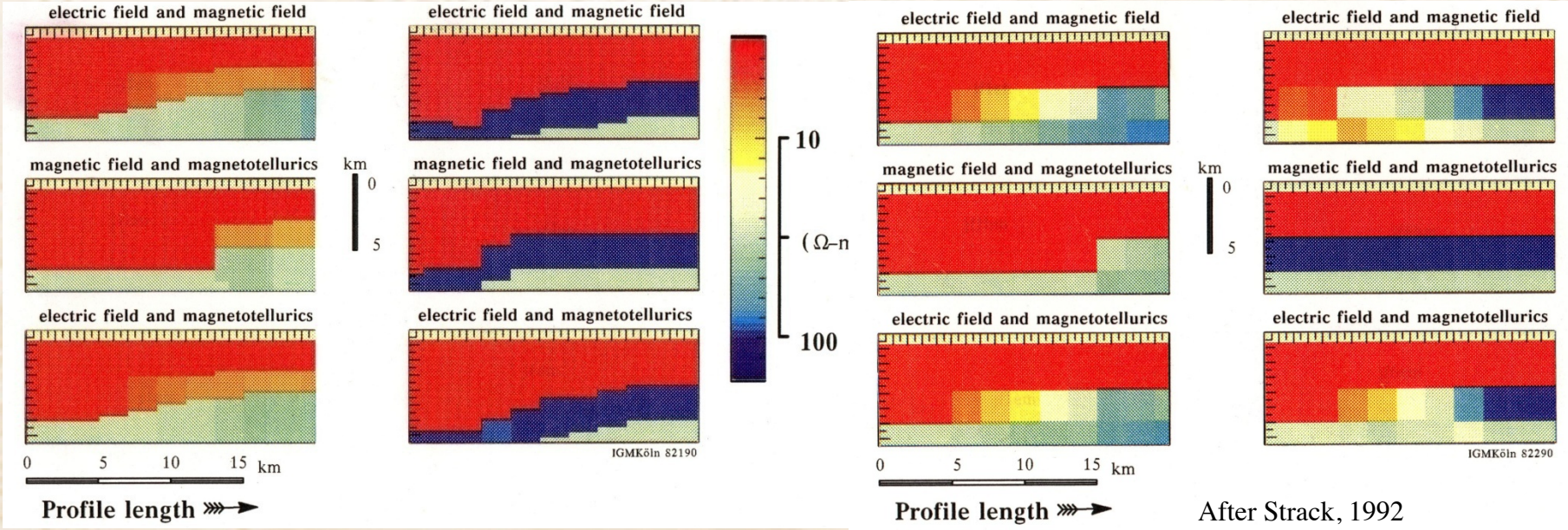
Problem: Mapping porosities in carbonates

EM methods combined

EM constraint by seismic

Start w/ left log

Start w/ right log



After Strack, 1992

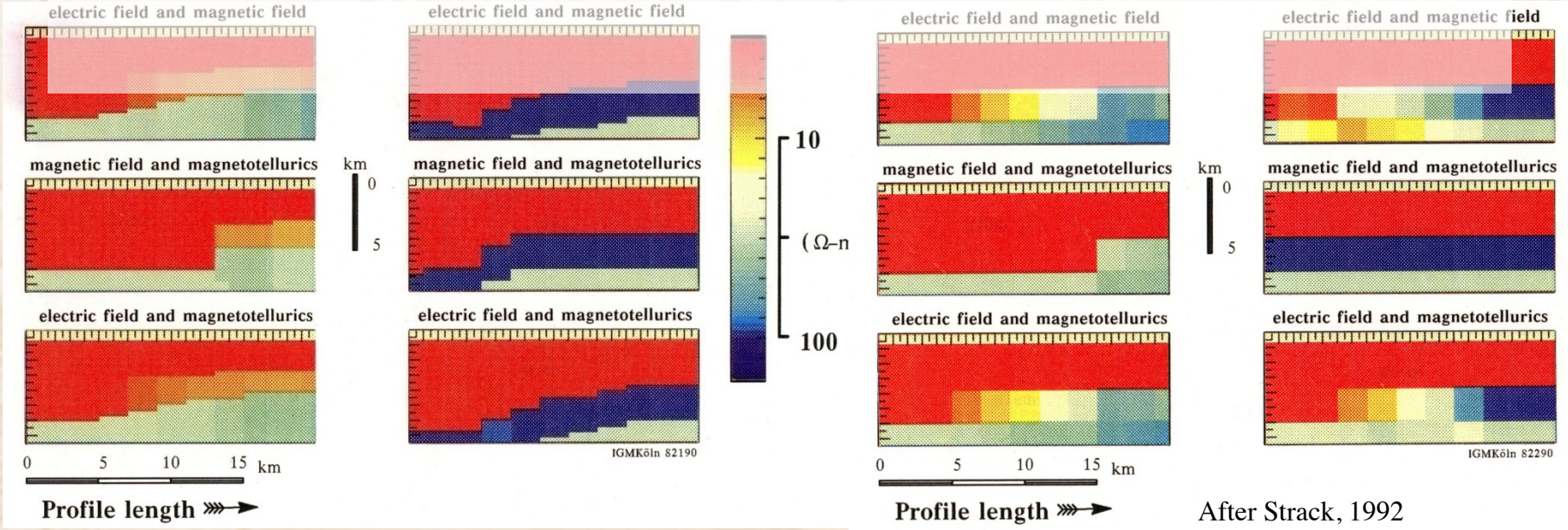
UNBIASED resistivities with contraints from multi-physics II

Problem: Mapping porosities in carbonates

EM methods combined

EM constraint by seismic

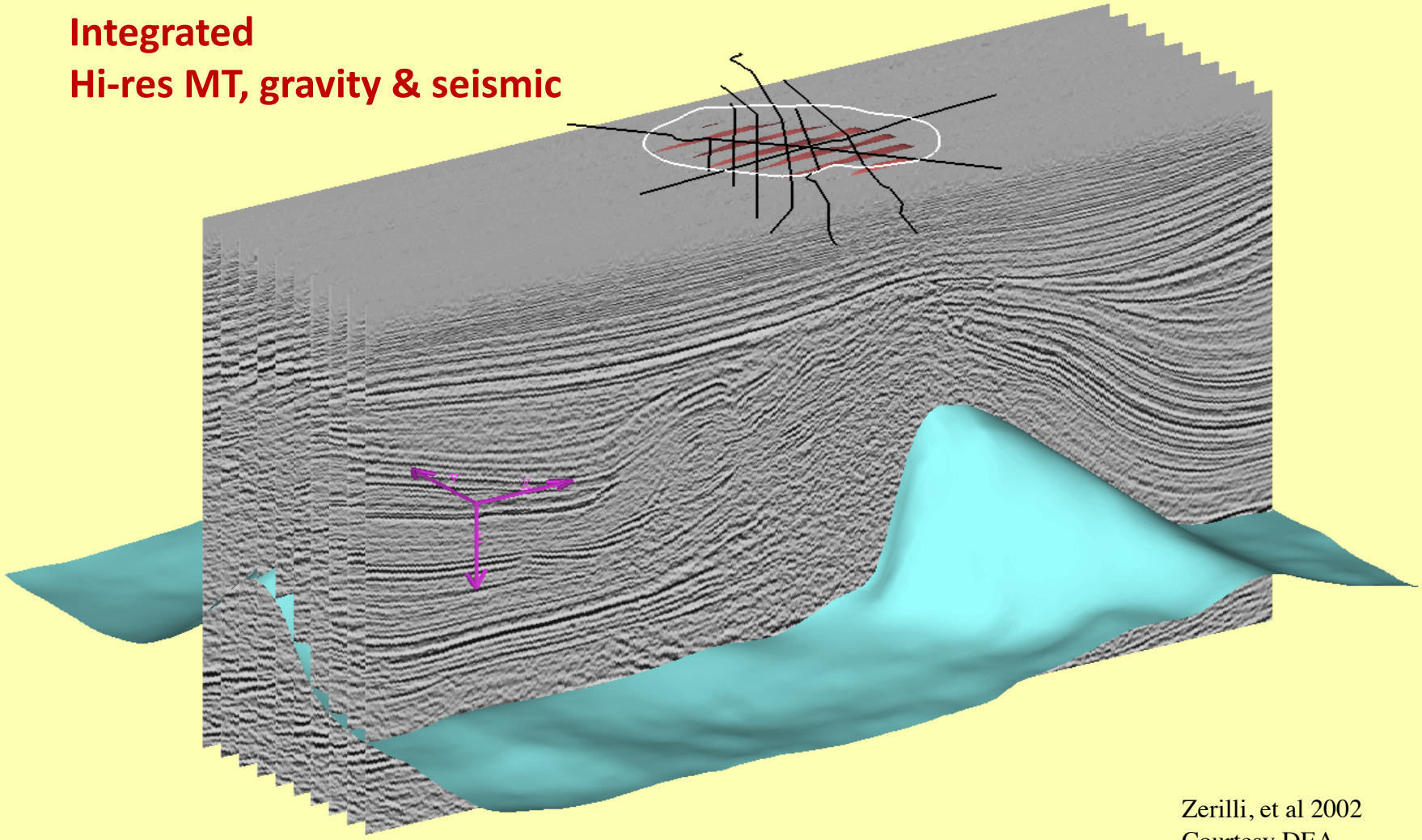
- NEED to constrain geometry → SEISMIC data
- NEED to use E and H → unbiased section



After Strack, 1992

Dense acquisition → better images

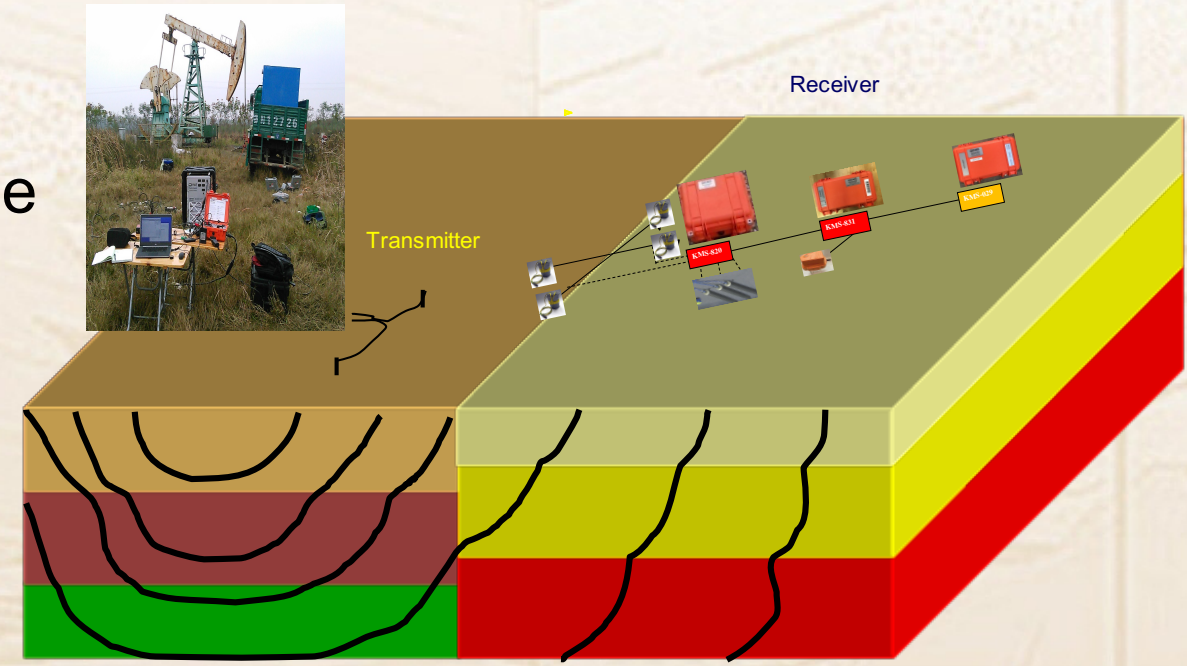
Integrated
Hi-res MT, gravity & seismic



Zerilli, et al 2002
Courtesy DEA

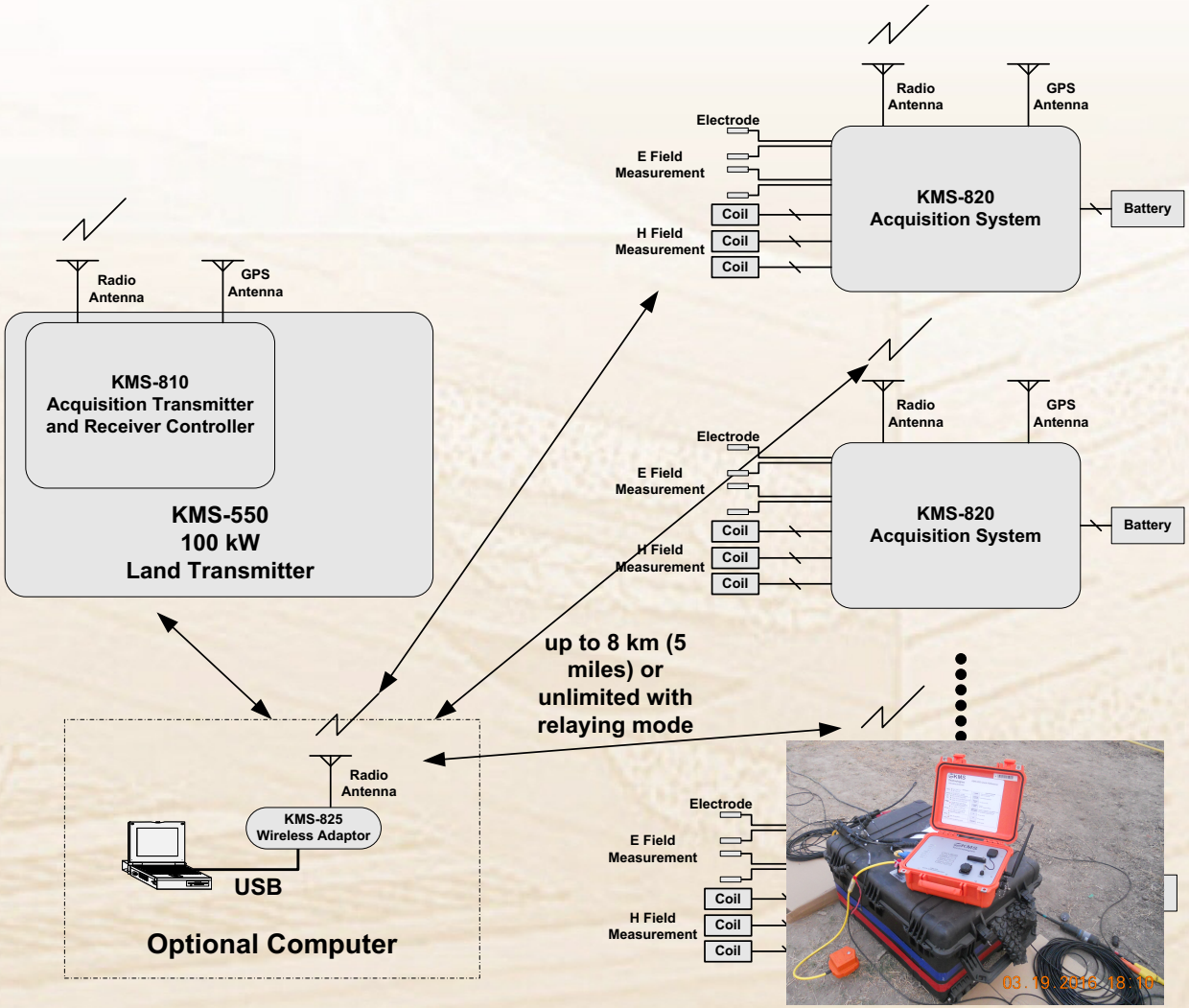
Architecture & hardware

- Introduction to EM monitoring for EOR
- **Equipment overview**
- Examples:
  - Monitoring
  - FSEM & Shallow Borehole
- Conclusion

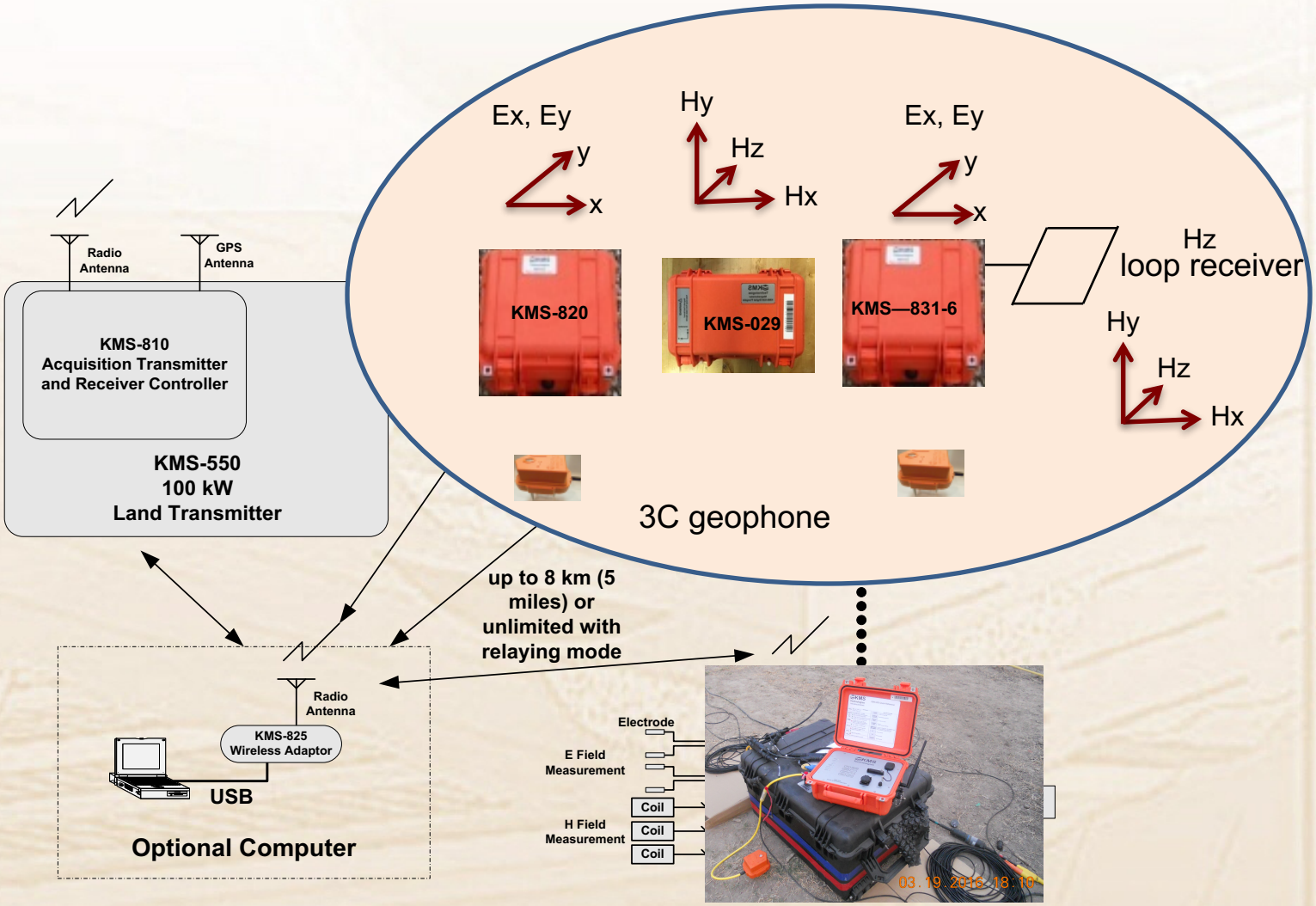


Architecture & hardware: 2016 - 150 KVA transmitter

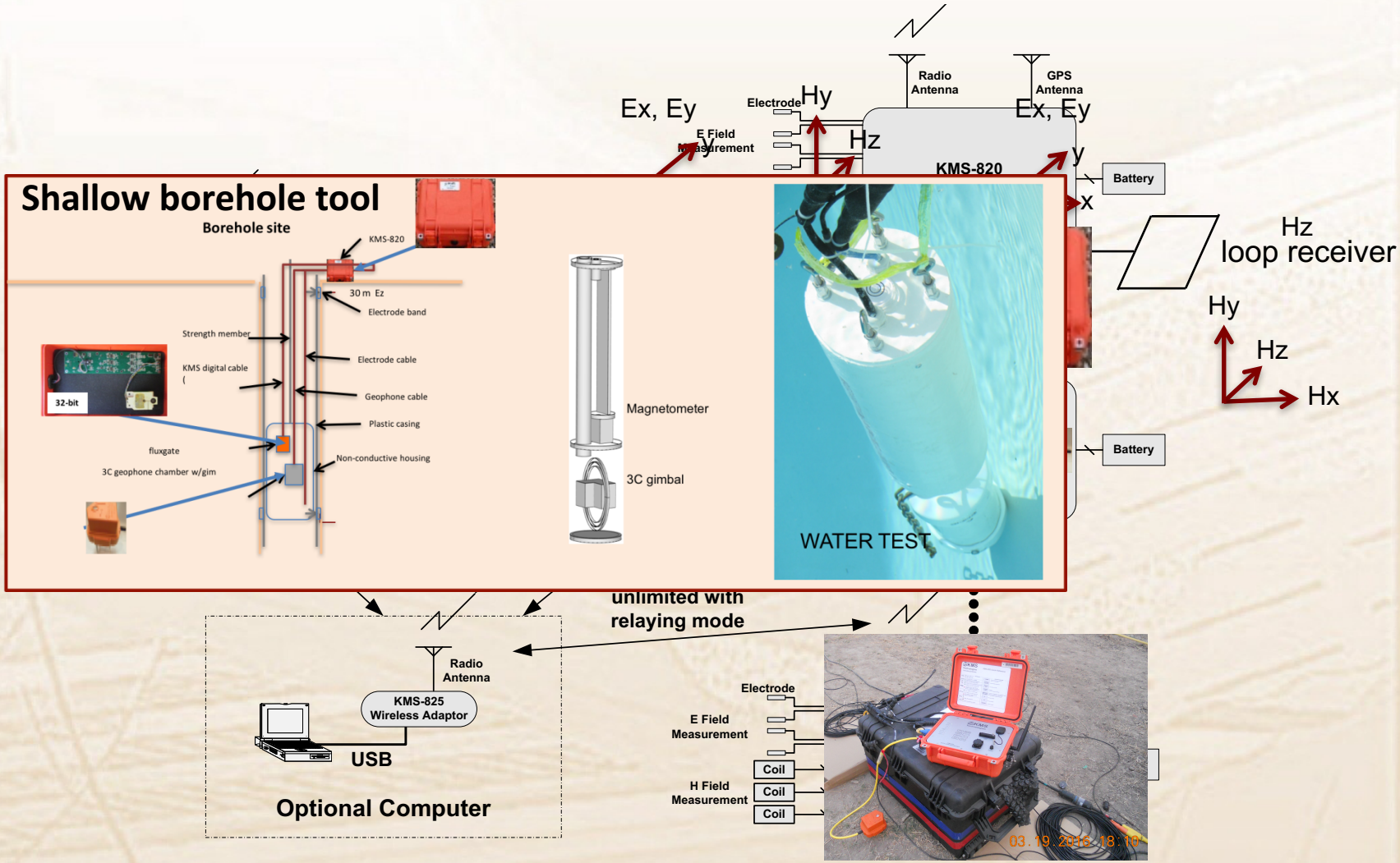
Architecture & hardware: Land & shallow borehole I



Architecture & hardware: Land & shallow borehole II



Architecture & hardware: Land & shallow borehole III



Receiver (KMS-820): for MT & CSEM, transmitter control, MMT

DEEP BOREHOLE

SHALLOW BOREHOLE TOOL

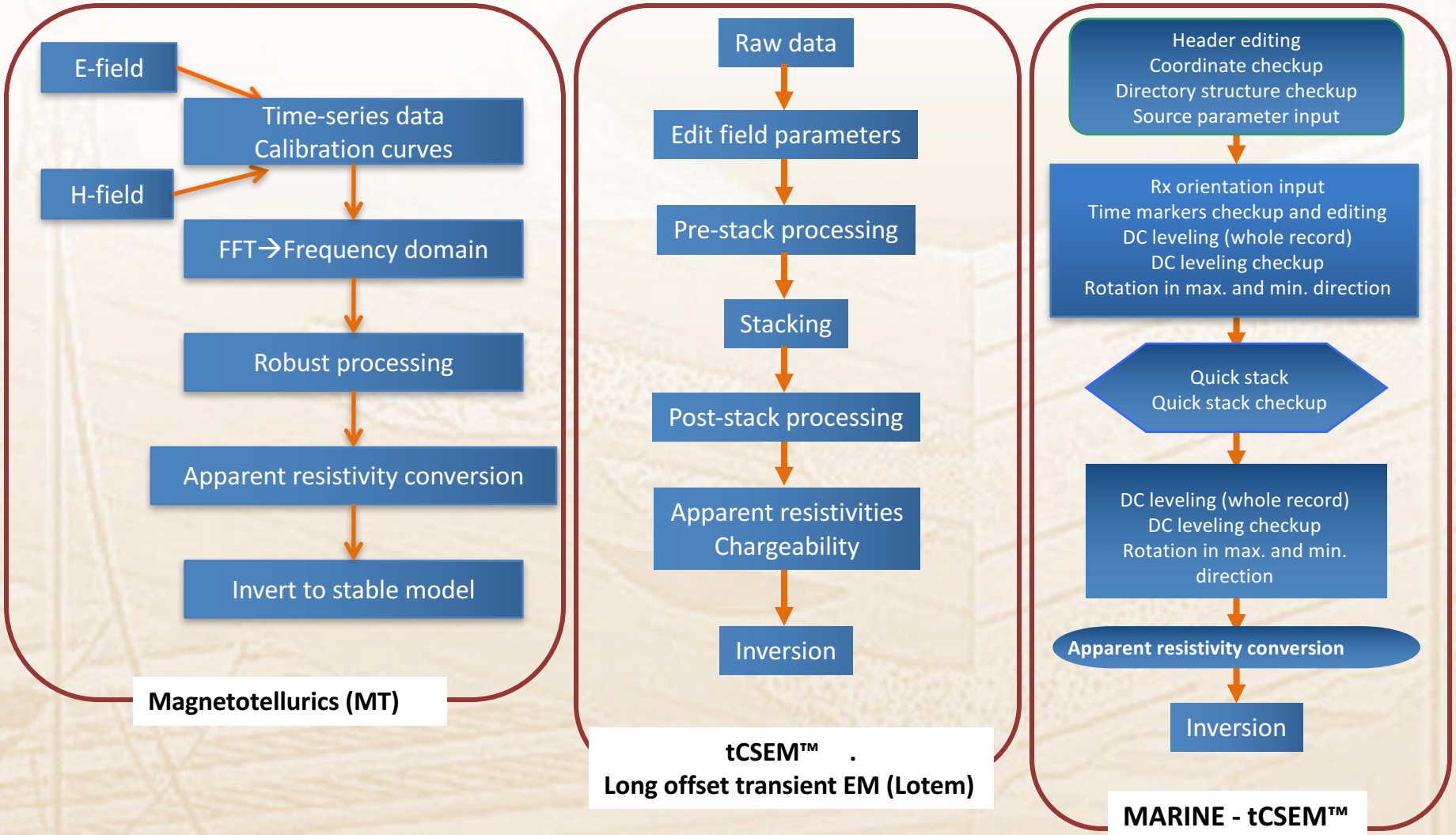
MARINE

Node
on deck

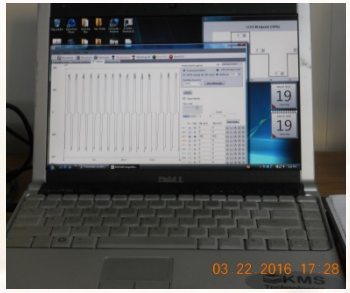
Combined seismic & EM node
For 2 months operation

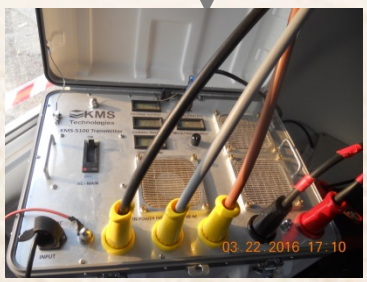
TRANSMITTER

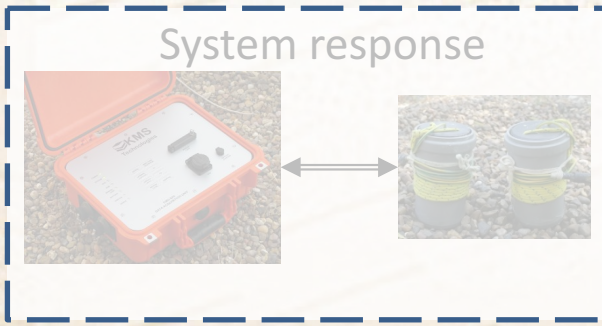
KMS-Pro software: MT, Lotem & marine CSEM



KMS-5100 Transmitter – 100 KVA 2016



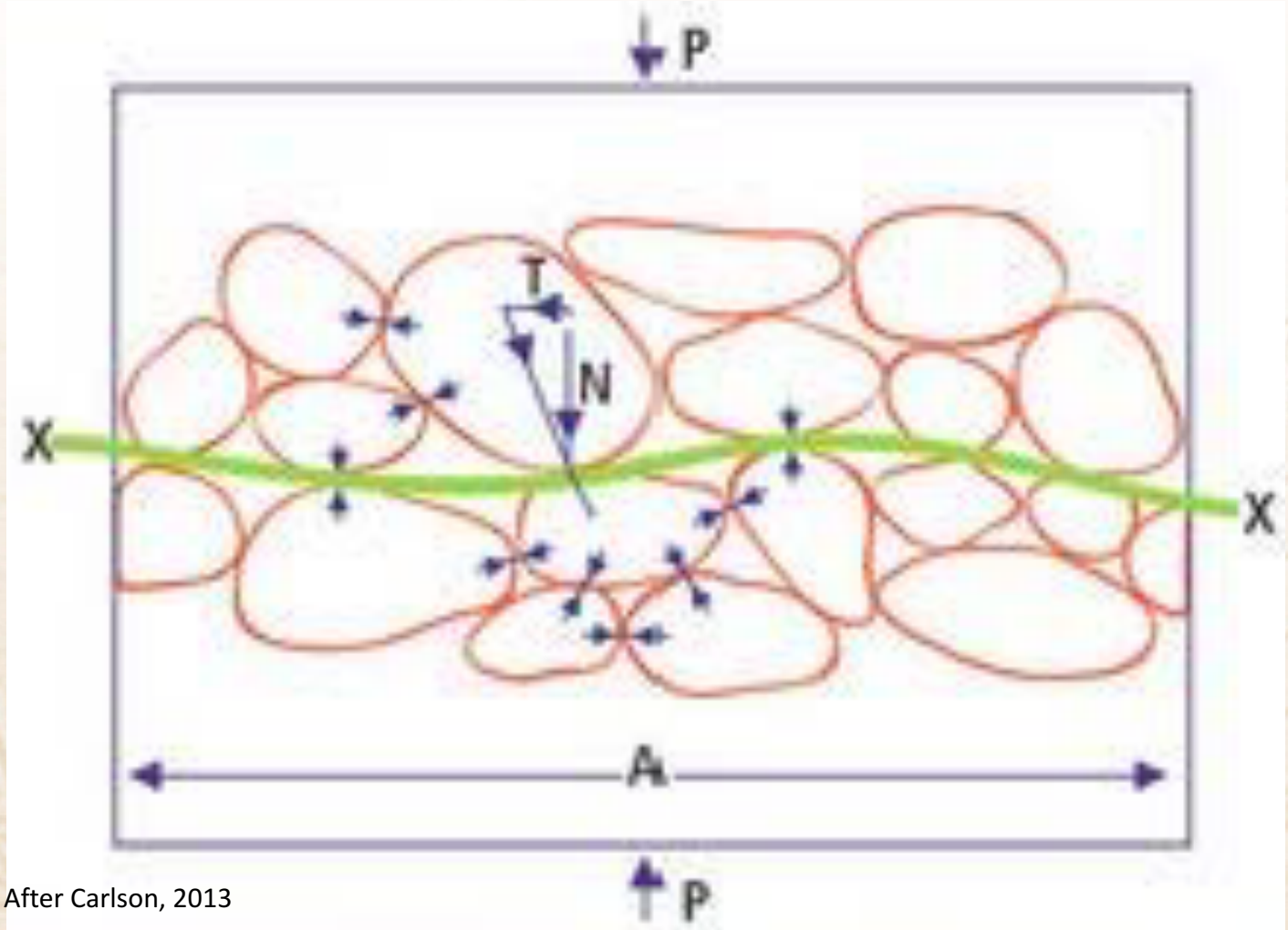




Outline

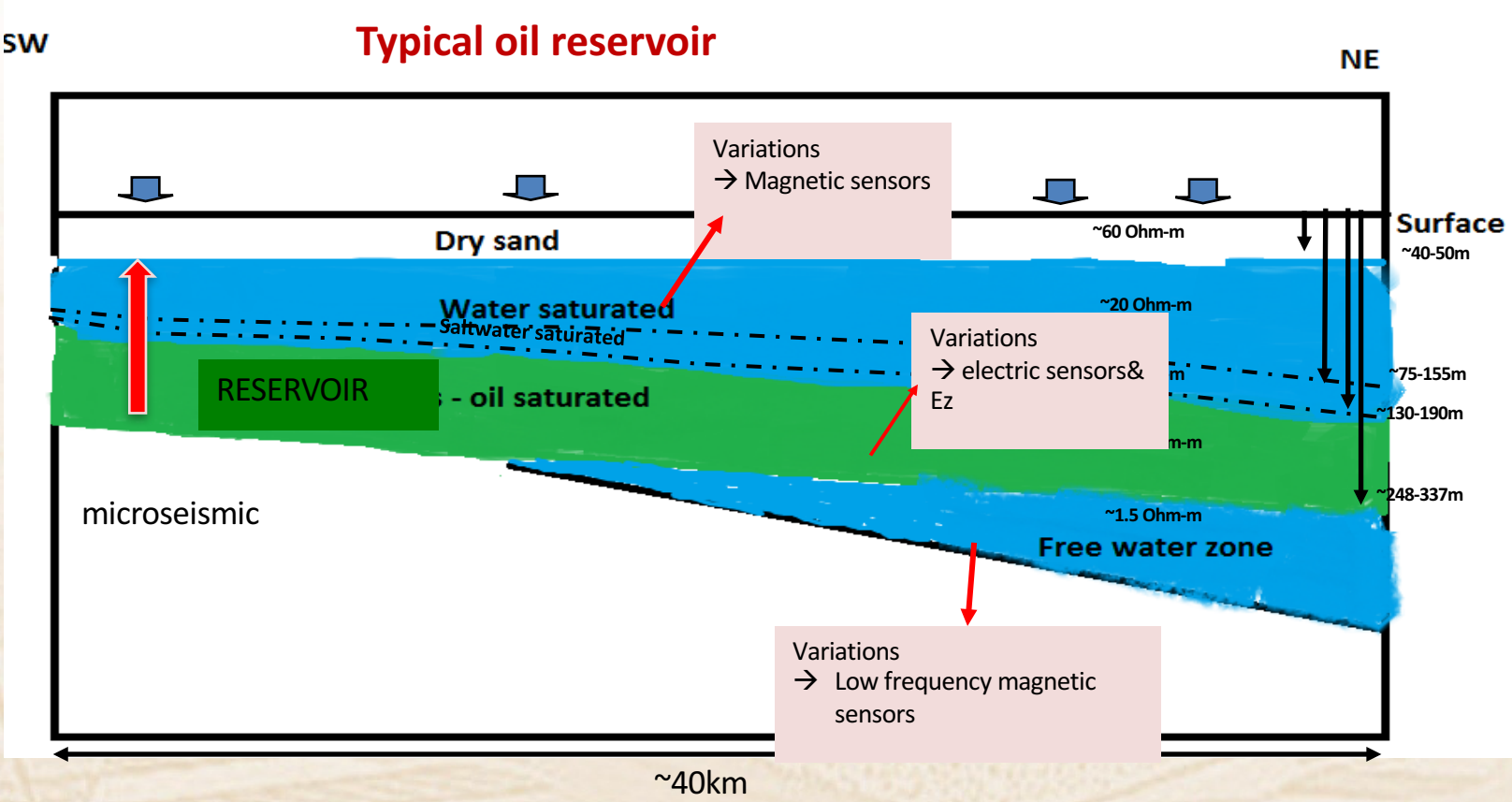
- Objective & history
- Architecture & hardware
- Examples:
  - Monitoring
  - Shallow borehole & FSEM
- Conclusion

Reservoir Monitoring: Fluid variations & Seal integrity

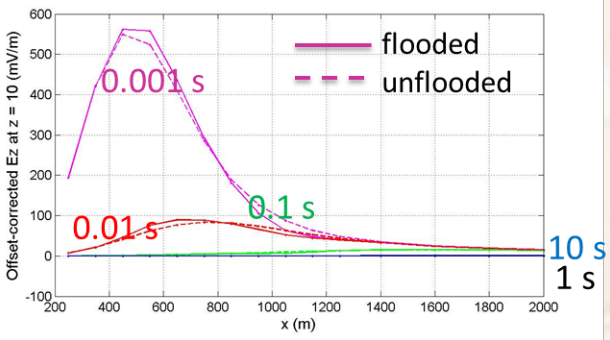


After Carlson, 2013

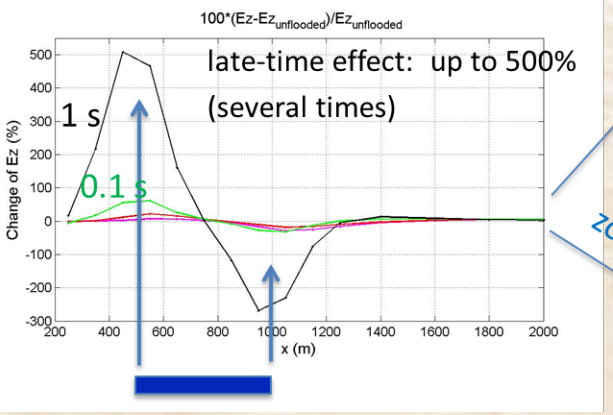
Typical Heavy Oil reservoir → multi-sensor/multi-physics

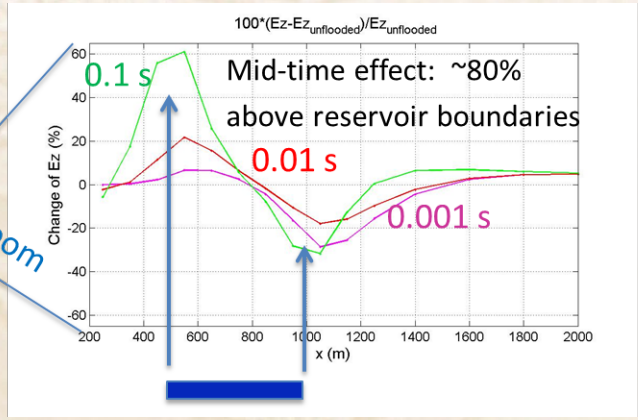


Electric field Ez (z = 10 m)



Water-flooded area contour may be determined with great accuracy





SPE-184089-MS • Integrated Geophysical Reservoir Monitoring for Heavy Oil • Dr. Herminio Passalacqua

Always carry out Feasibility & Noise test FIRST

Monitoring project workflow

Deliverables & objectives

Feasibility & noise test

Input data:
well log data
geologic information
seismic horizons
noise measurements

Verification 3D modeling
benchmarks

Define target variations

Resolution study

Noise data analysis:
noise level, spectra
sensor analysis

Hy - induction coil

Ex –electric field

Pilot study design

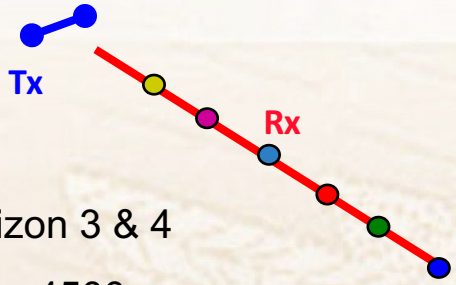
Water Injection well

Production well

KMS-820

KMS-831

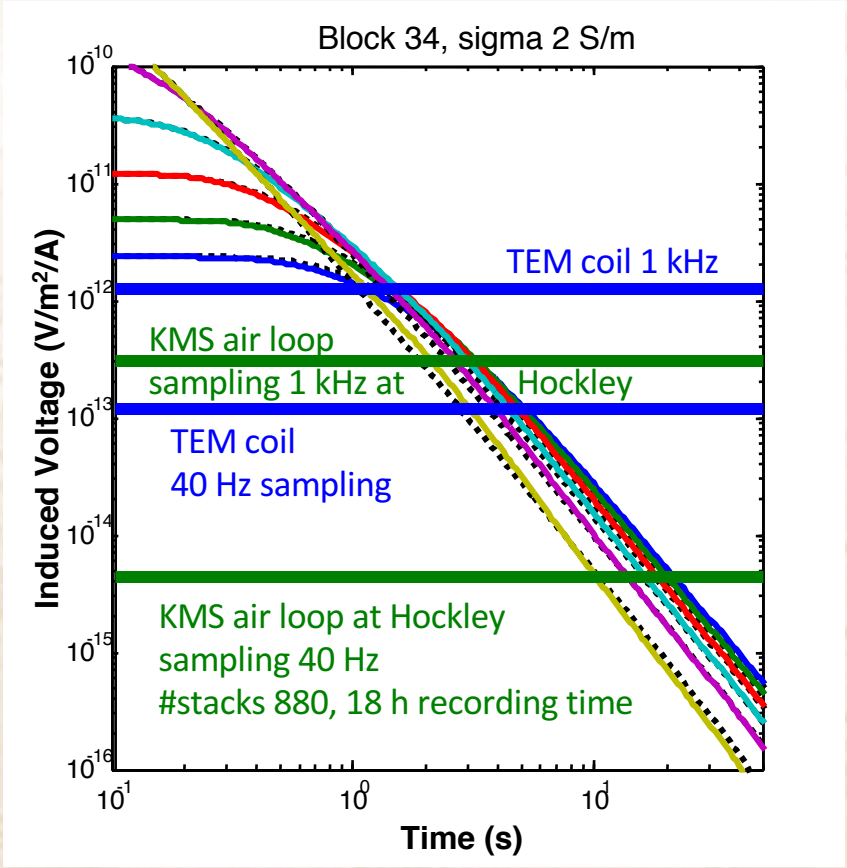
Transients with expected noise levels



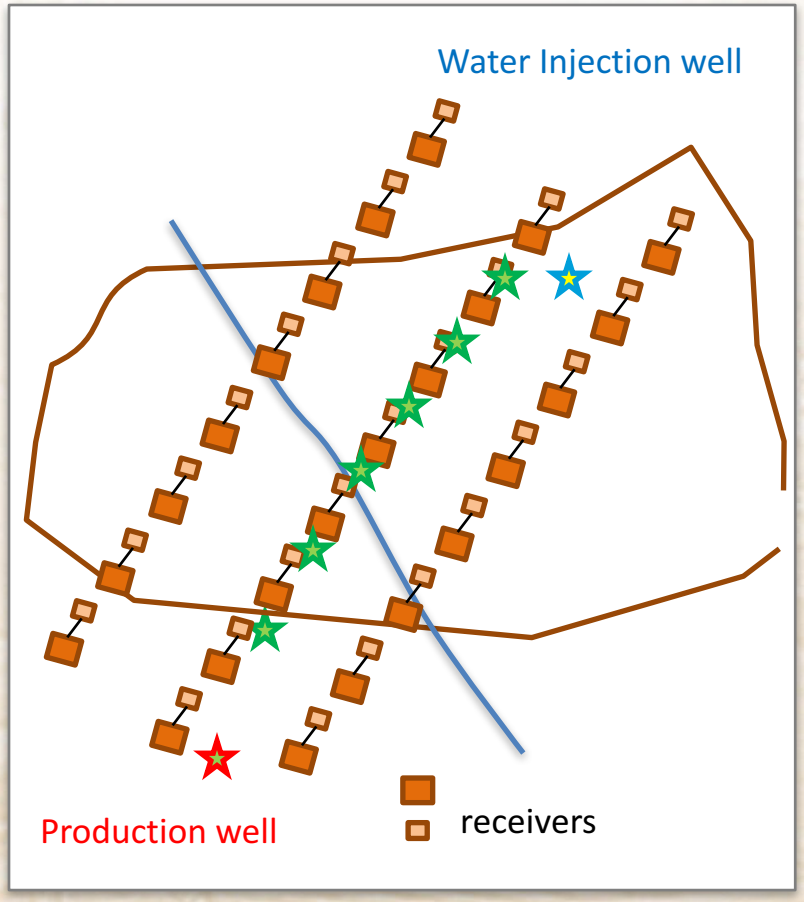
Seismic Horizon 3 & 4

size 6000 m x 4500 m

whole block



Reservoir Monitoring: Example layout design



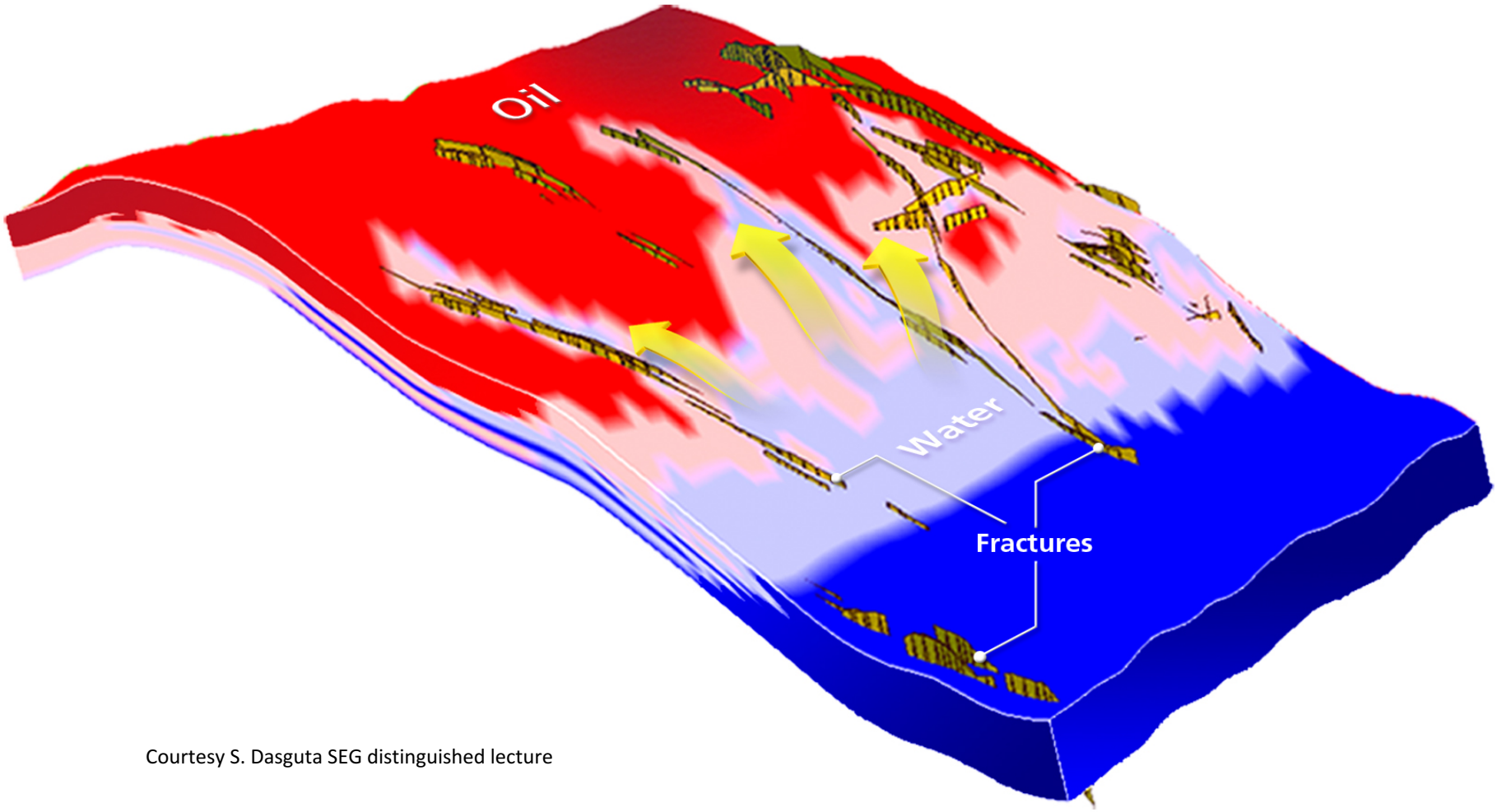
Microseismic sensors

Site	MODULE	Ex-Ey	Ez	Hz	3C fluxgate H	3C geophone
■	KMS-820	x		x	x	x
▪	KMS-831	x				X
★	SBHT	x	x		x	x

E – electric field sensors

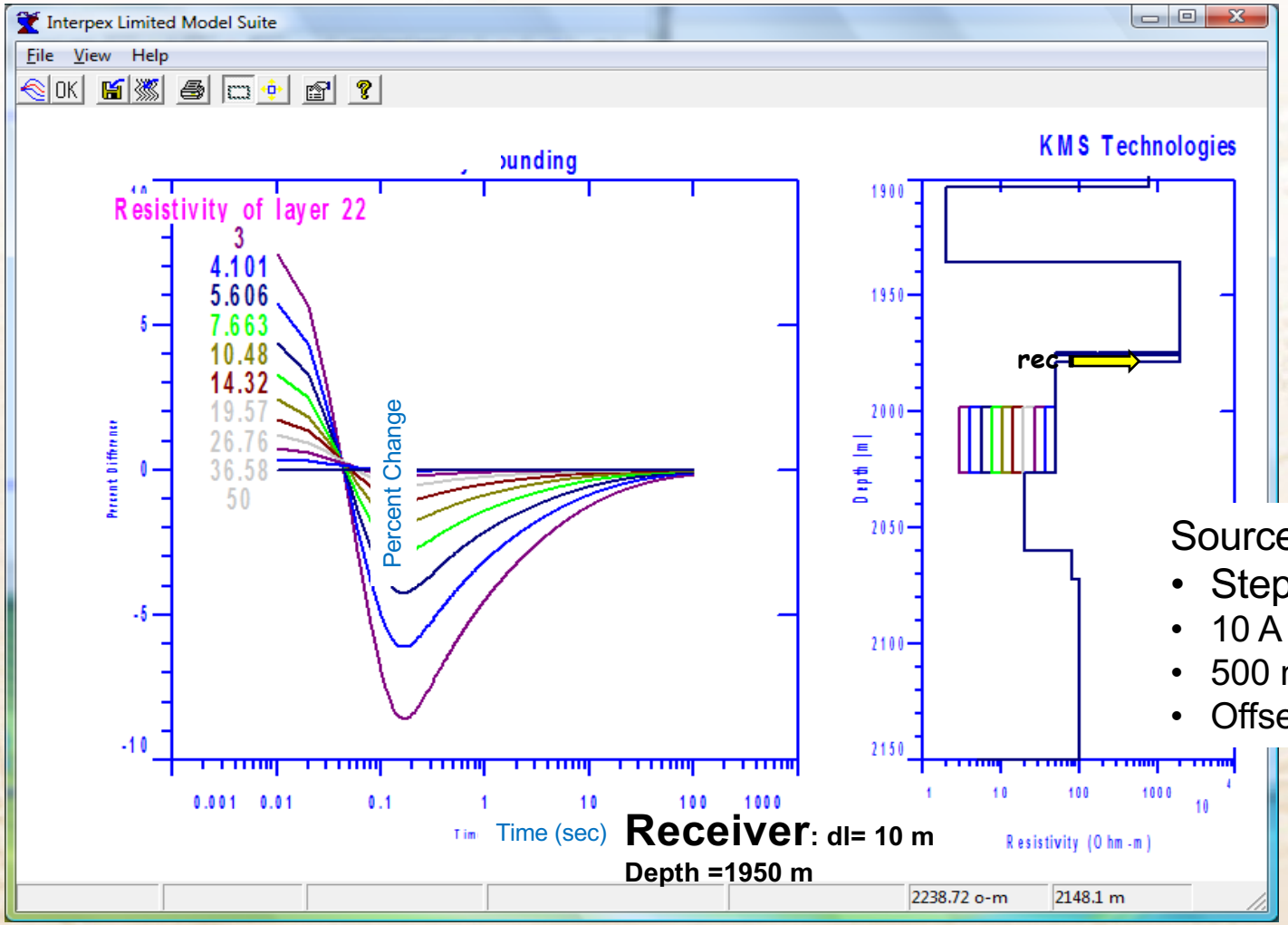
H – magnetic field sensors

Ghawar: Fluid displacement heterogeneity



Courtesy S. Dasguta SEG distinguished lecture

Percent change



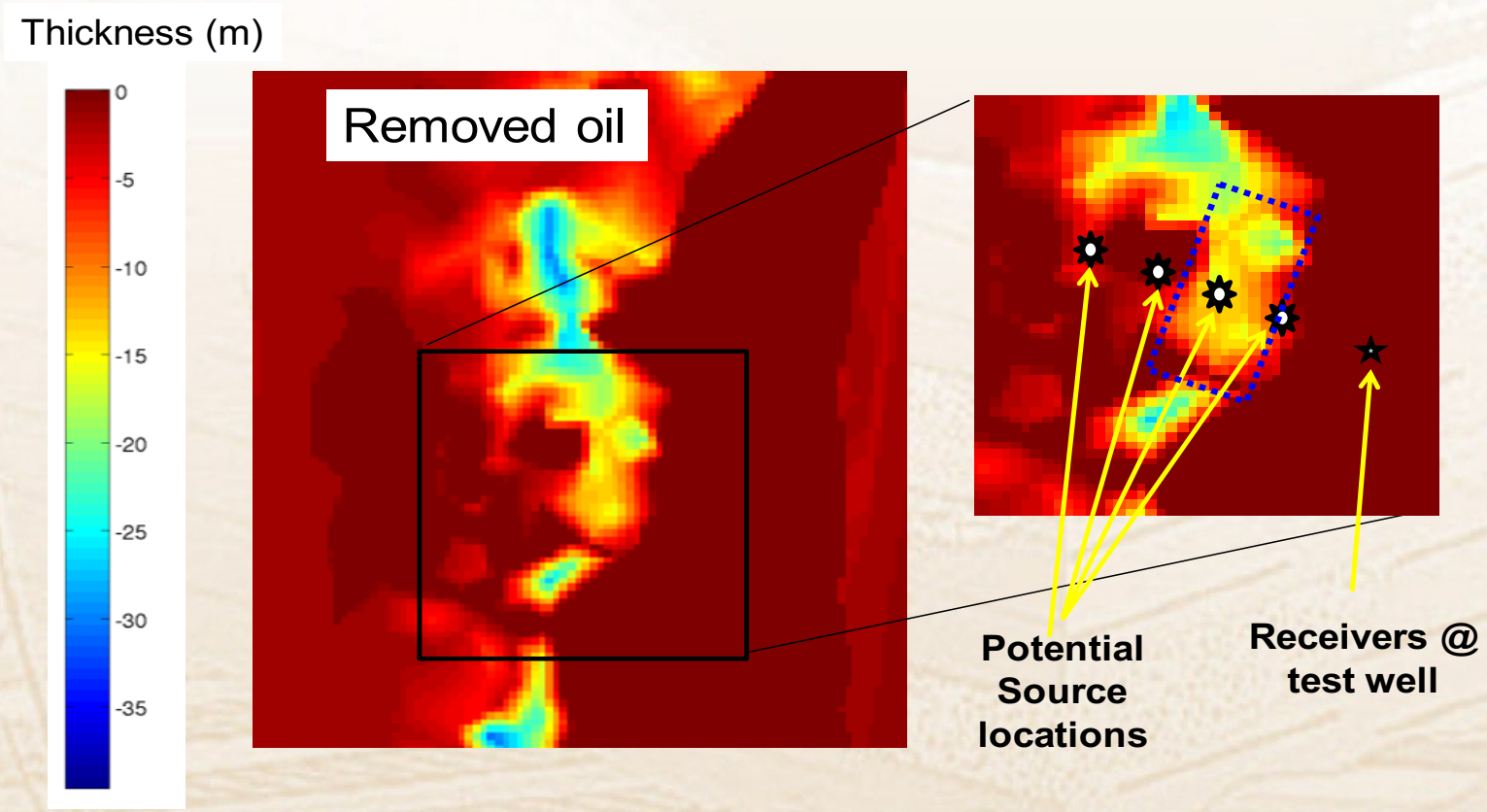
Source:

- Step off
- 10 A
- 500 m
- Offset =1500 m

Receiver: dl= 10 m

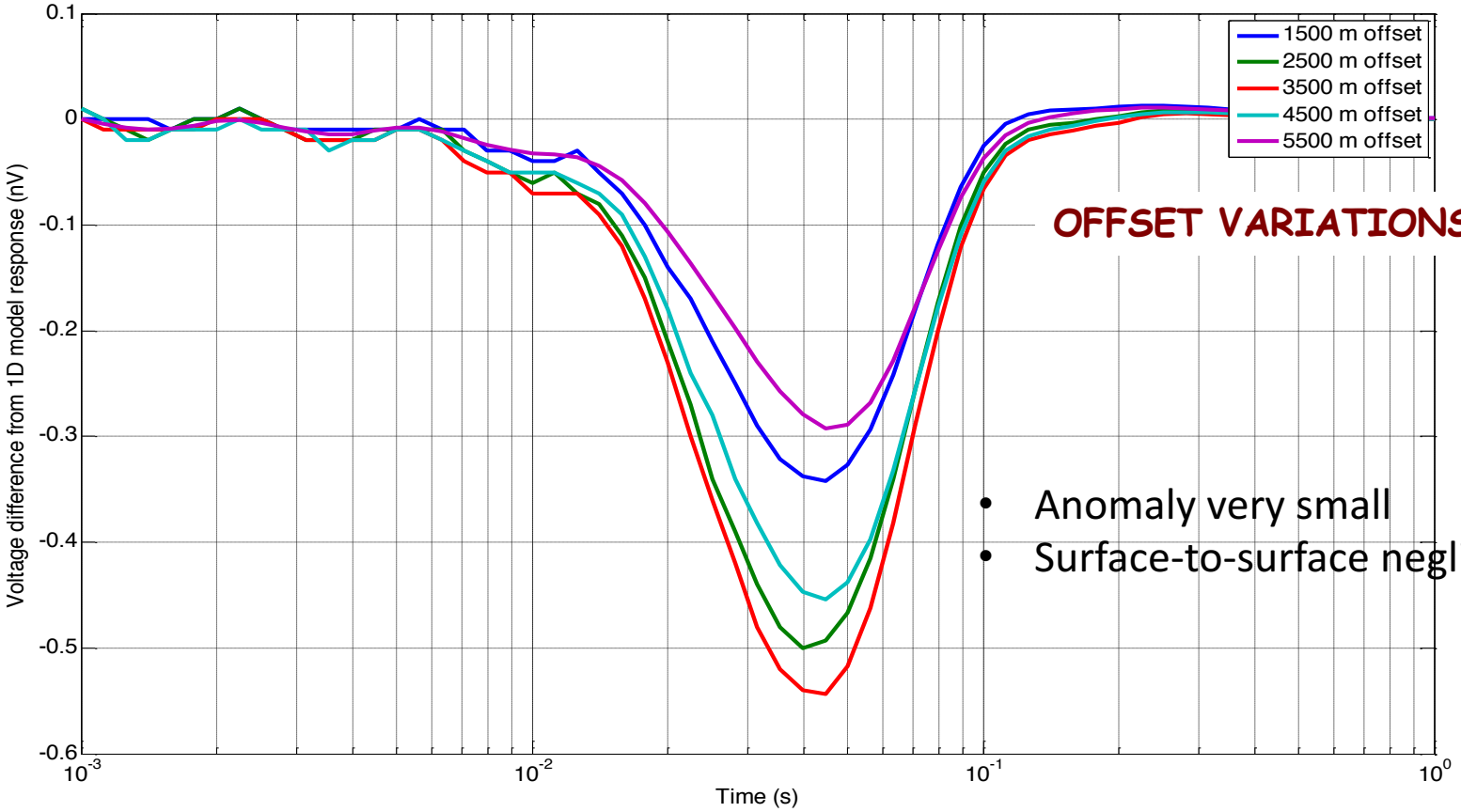
Depth =1950 m

Constructing the block model

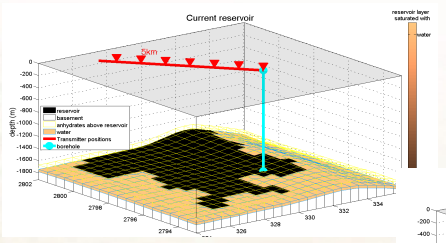


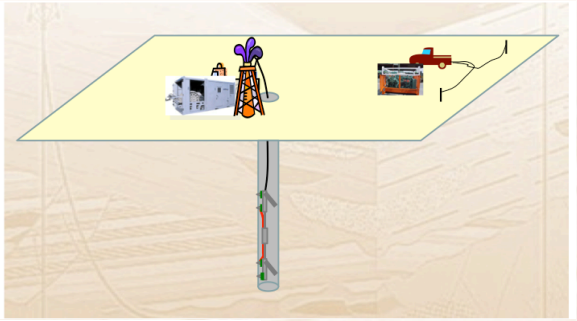
After Colombo et al. 2010

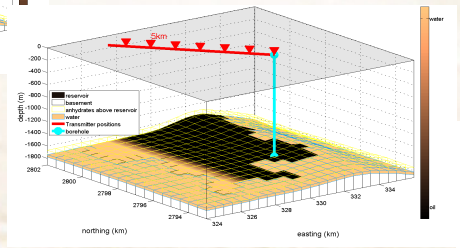
Surface-to-borehole anomaly (%): E_z

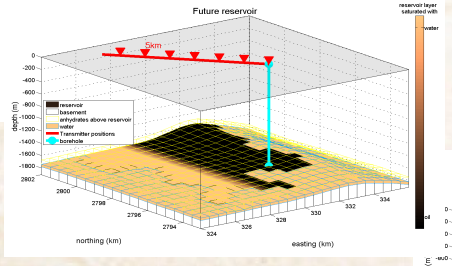


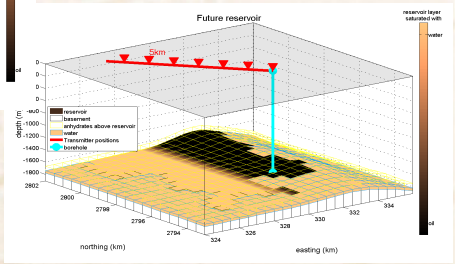
Ghawar: ADD BOREHOLE: Integration!

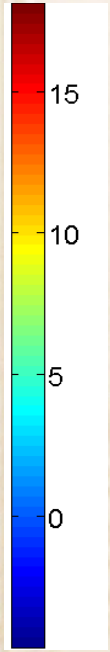


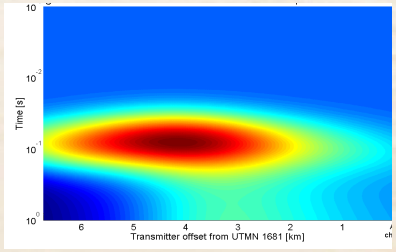




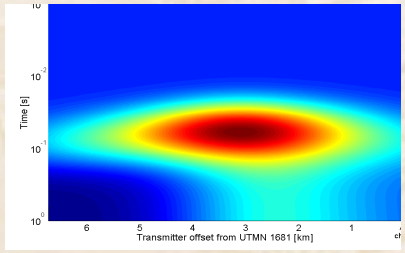


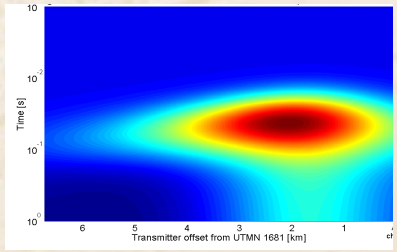






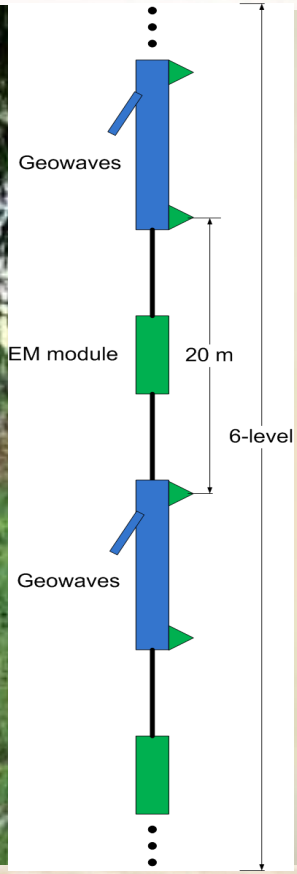
Period of 5 years



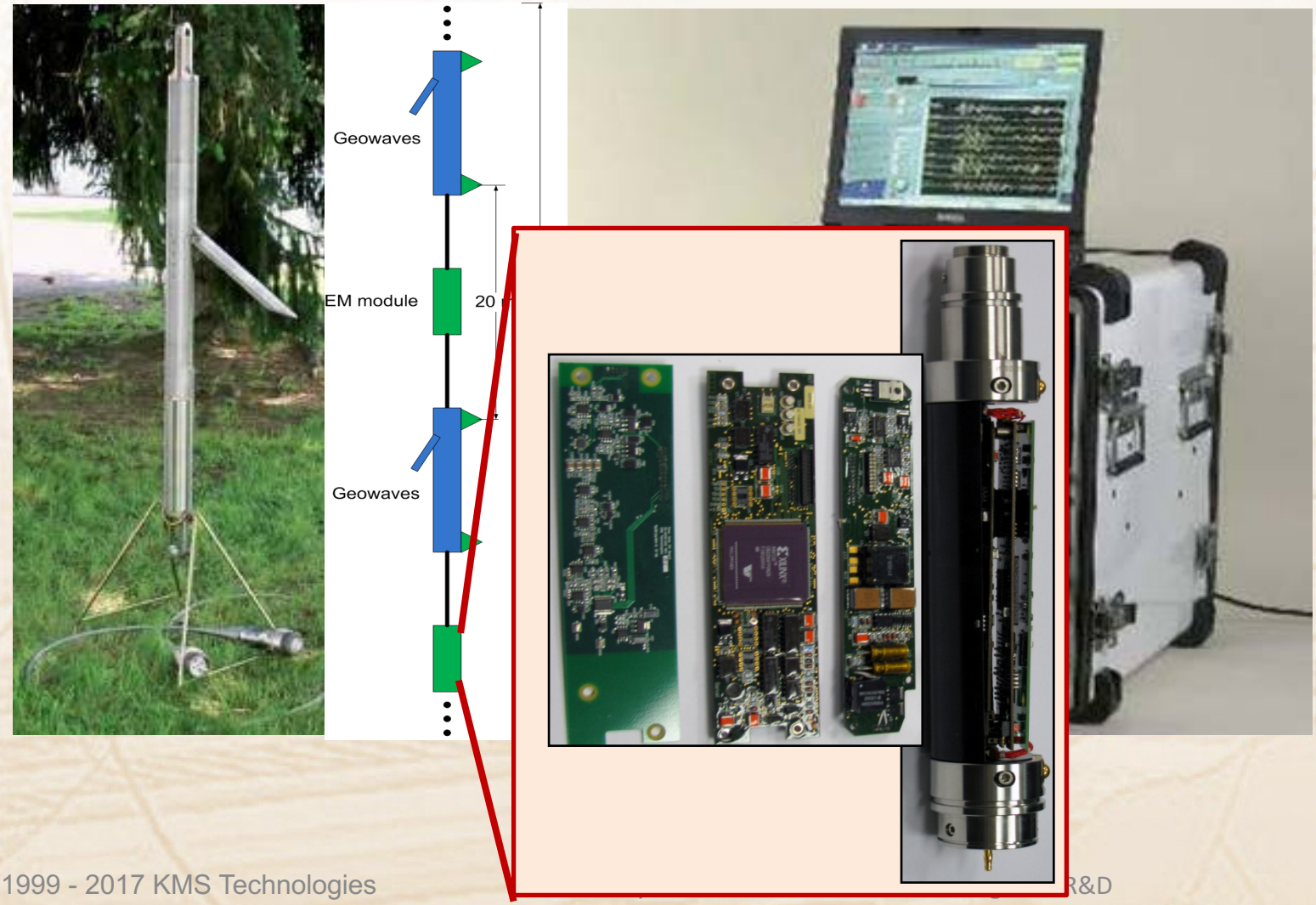


After Colombo et al. 2010

Surface-to-borehole 4C/EM system I



Surface-to-borehole 4C/EM system II



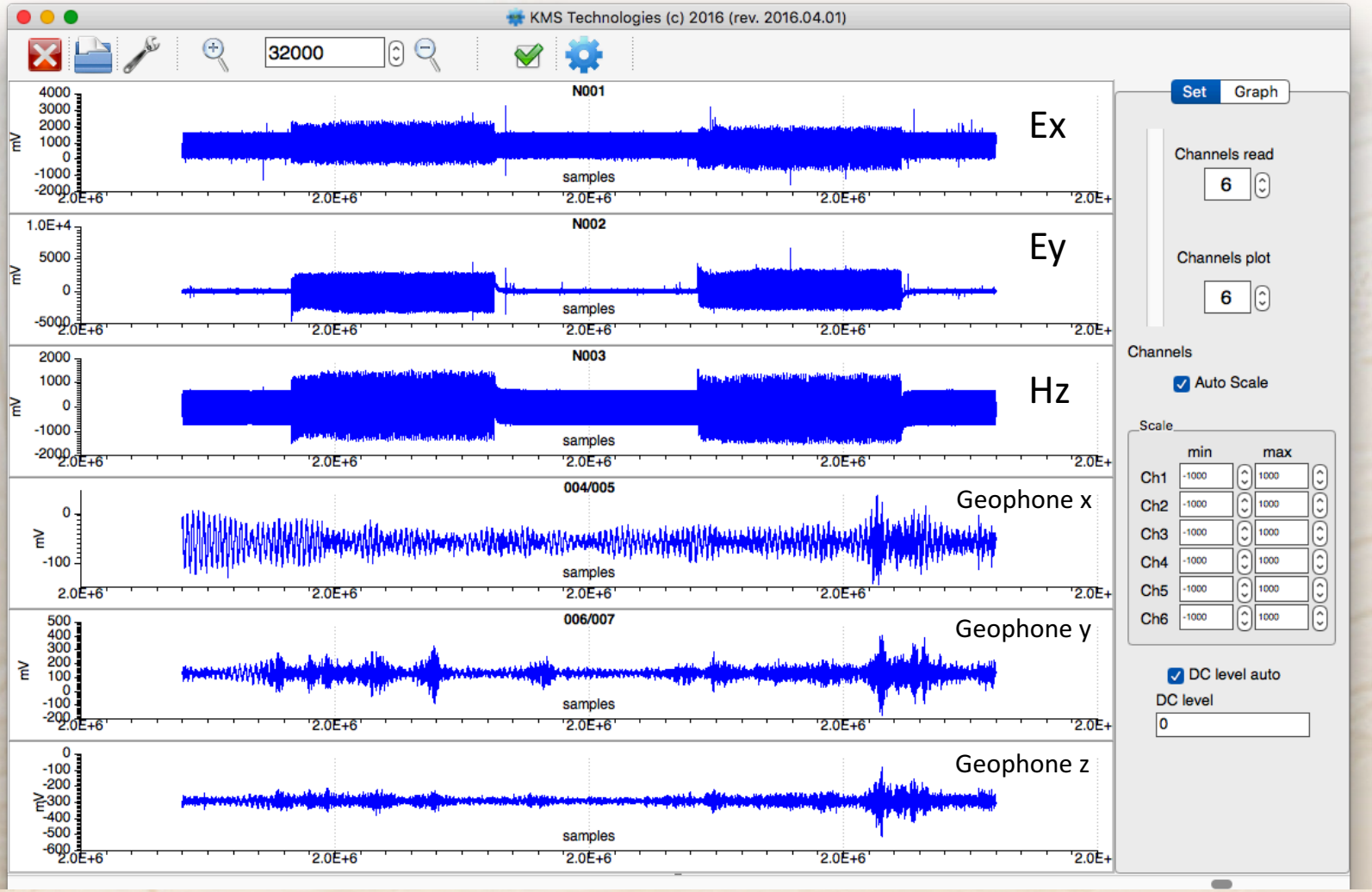
Reservoir Monitoring: 195 channel monitoring system

RESERVOIR MONITORING

ARRAY Electromagnetics

- 195 channels, wifi, wireless or LAN
- 3C magnetic field (DC to 40 kHz)
- 3C microseismic
- 2C electric fields
- Shallow borehole (microseismic/EM)

Reservoir Monitoring: Raw data example: microseismic/EM monitoring



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Reservoir Monitoring comments

- Monitoring
  - Seeing anomaly - Easy
  - Understanding results – complicated
  - Issue 1: Image focus
  - Issue 2: Borehole calibration !!!!!
    - Surface-to-borehole
    - Through Casing

Reservoir Monitoring comments

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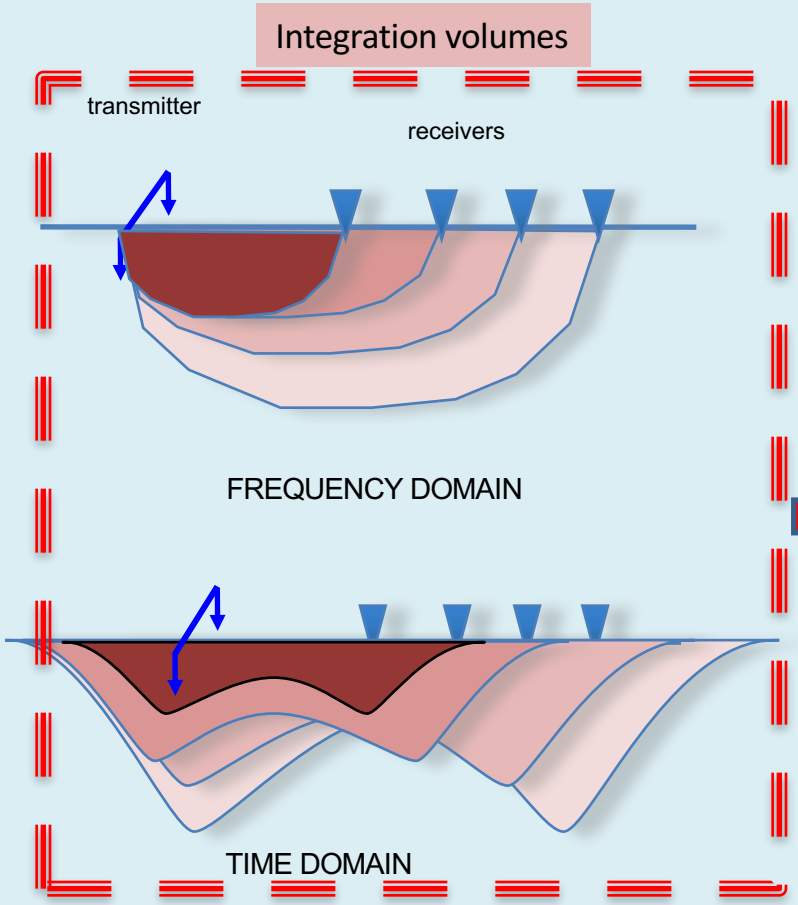
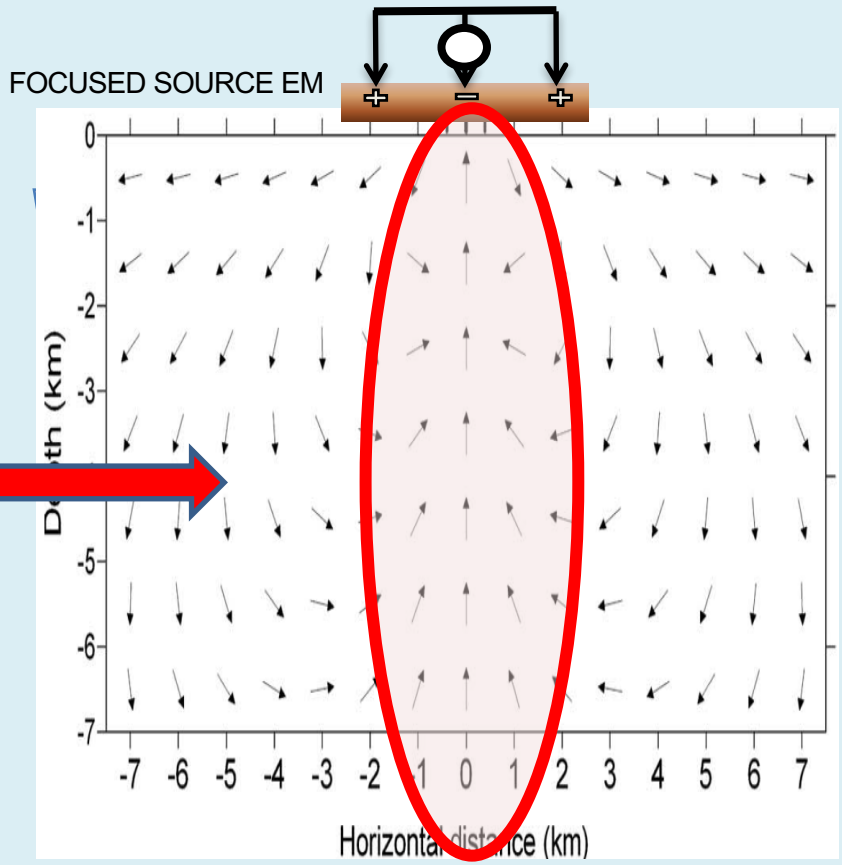
FSEM: Focused source solution to volume imaging



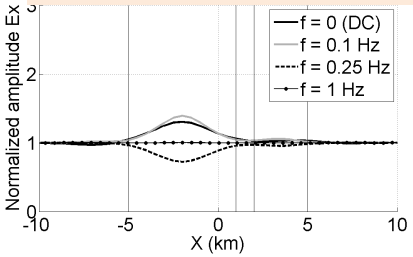


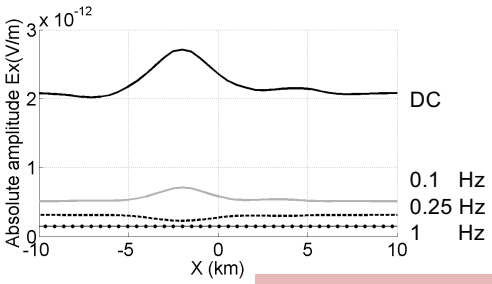
Rykhlinskaya, E., & Davydycheva, S., 2014, U.S. Patent 8,762,062 B2.
Davydycheva, S., 2016, U.S. Patent Application US 2016/0084980 A1.

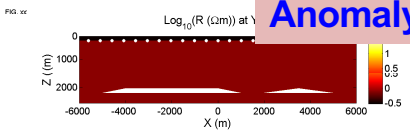
FSEM: Focused source solution to volume imaging

CSEM versus Focused Source

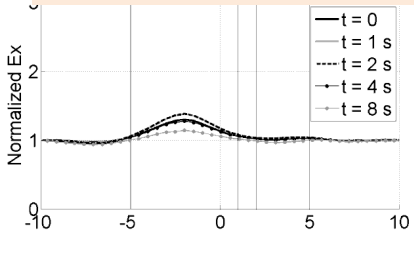
Frequency domain CSEM

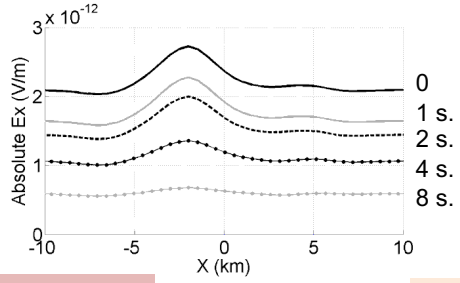


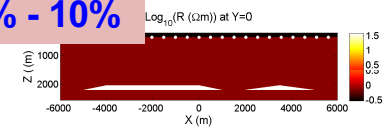




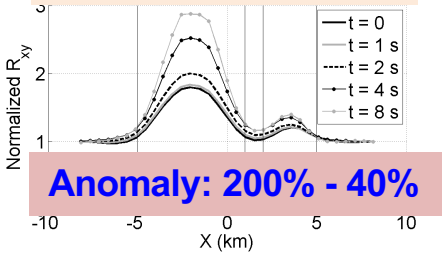
Time domain CSEM



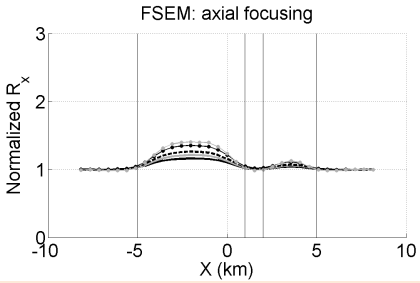




Focused Source EM



Anomaly: 200% - 40%

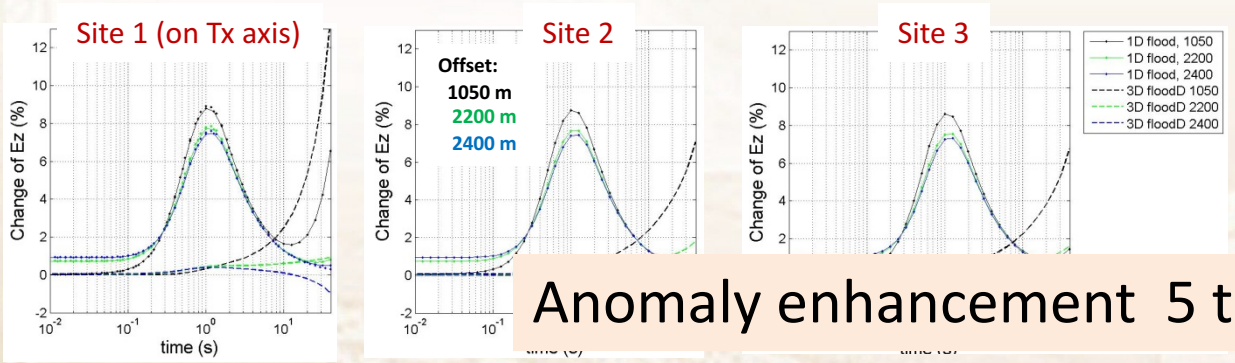


Anomaly: 40% - 10%

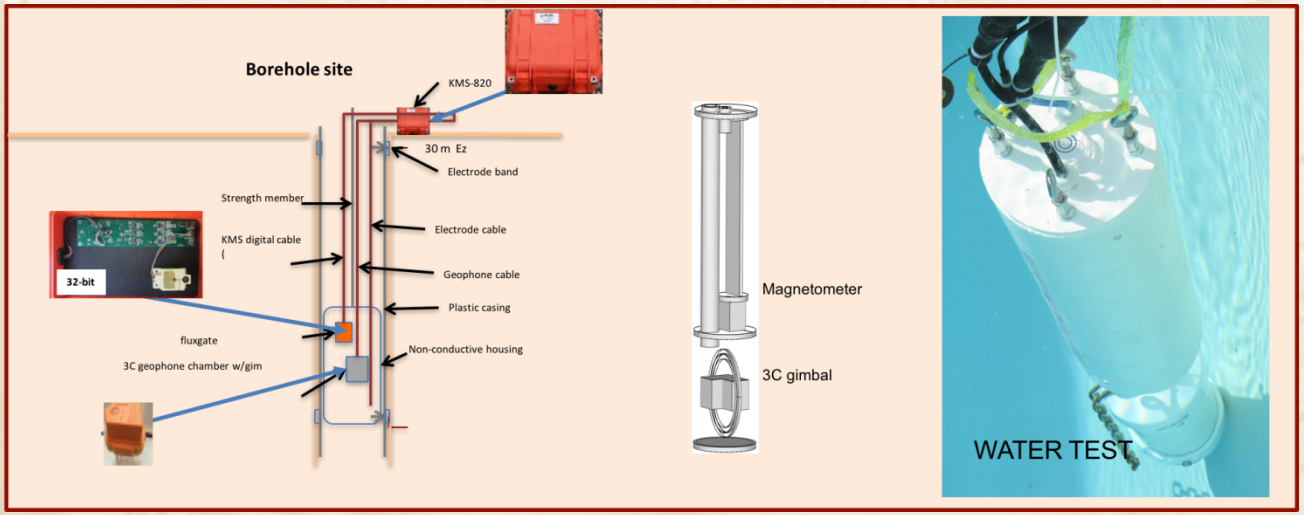
- Smaller reservoir can be detected
- Higher spatial resolution
- Shallow structure removable

Alternative: Shallow borehole tool - Ez

Ez at z = 10 m



Anomaly enhancement 5 times



Reservoir Monitoring comments

- Monitoring
  - Seeing anomaly - Easy
  - Understanding results – complicated
  - Issue 1: Image focus
  - Issue 2: Borehole calibration !!!!!
    - Surface-to-borehole
    - Through Casing

Summary & 5 year vision

- New instruments allow us to re-visit
  - Full anisotropy 3D models √
  - 3D tensor acquisition √
  - Tie to borehole measurements √
- Value recognized (but NOT understood) → PILOT demonstration are required
- 3D models give better inside
- Integration with other methods is key
- Big potential in reservoir monitoring

Acknowledgements