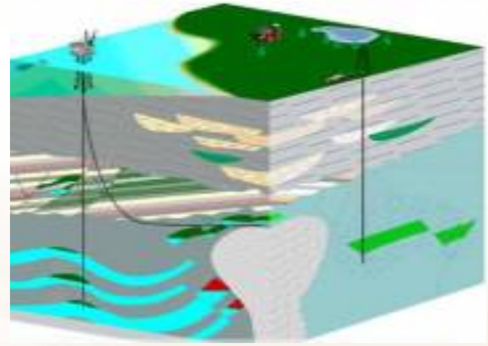


CSEM revisited: shales and reservoir monitoring edited for handout

EAGE 2017, PARIS May 2017

S. Davydycheva[1], I .Geldmacher[1], T. Hanstein[1], **K. Strack[1]**

KMS Technologies

www.KMSTechnologies.com

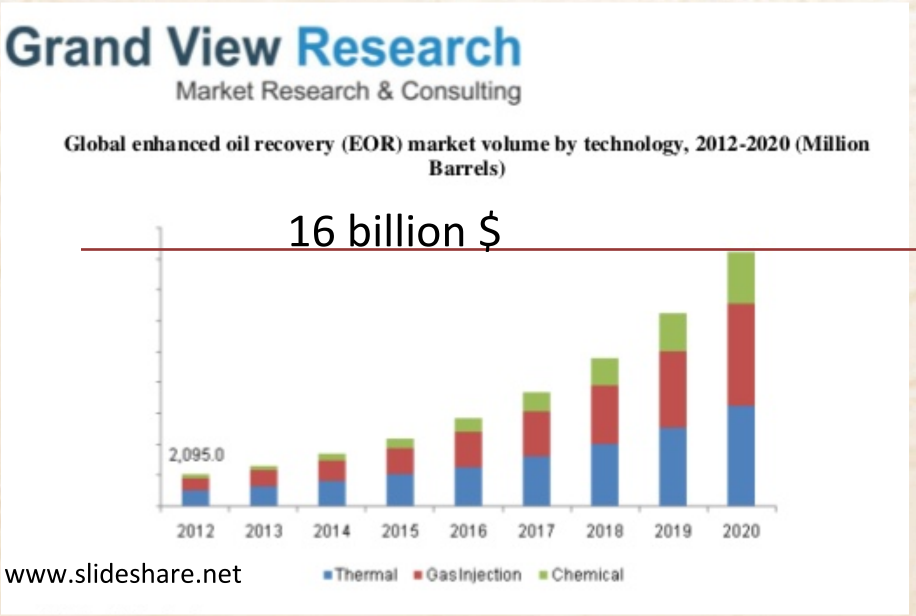
Motivation – our biggest market

- 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

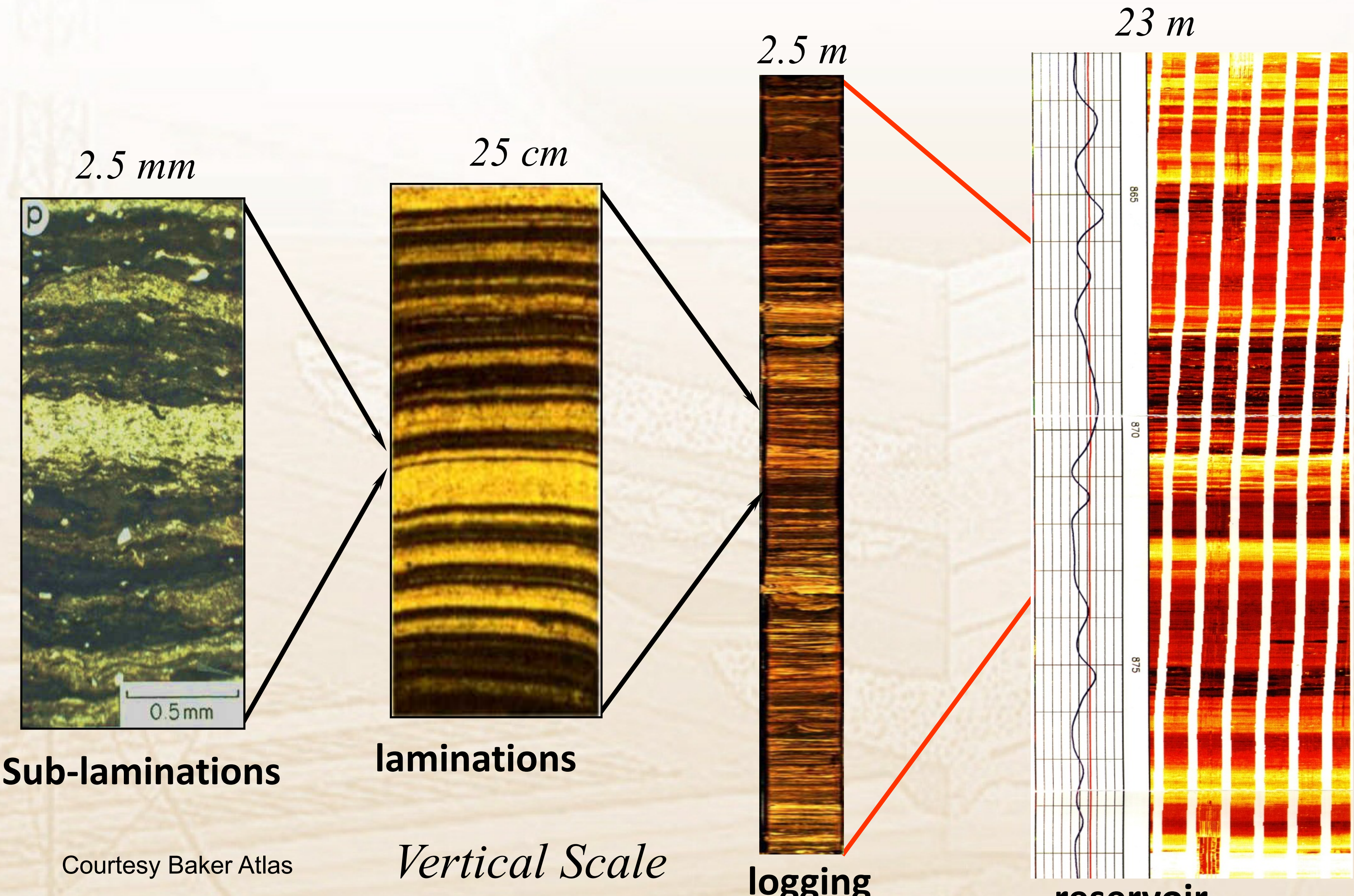
→ ALL cause resistivity contrast



Status of CSEM for reservoir monitoring

- Early work of CSEM for hydrocarbon reservoir monitoring
  - 1980s and 90s Australia (Vozoff et al.), Germany (Strack et al. 1989, Hoerdt et al., 1984, later several Ziolkowski et al. papers) → **frustrating issues with CSEM, no agreement between project partners**
- Issues with CSEM
  1. ANISOTROPY – ANISOTROPY – ANISOTROPY..
  2. Borehole calibration to logs – Solved around 1999 - 3D induction log
  3. Where does the information come from – OFFSET (focusing & measurements Ez - here)
  4. Borehole-to-surface calibration - surface-to-borehole tools (active field - here)
- Our activities:
  - 2004 first surface-borehole integrated monitoring patent: US 06739165
  - 3D Feasibilities: 2000 to present (most continents)
  - Borehole EM prototype 2009
  - Array tensor EM acquisition – commercial since 2010, used in >20 countries
  - Integrated 3D modeling since 2006
  - First successful field trial 2016 in Asia
  - **Shallow 3C EM/microseismic borehole tool 2016 →**
  - **INTEGRATED multi-components/physics borehole/surface monitoring**
- Extendable to fracture & depletion monitoring

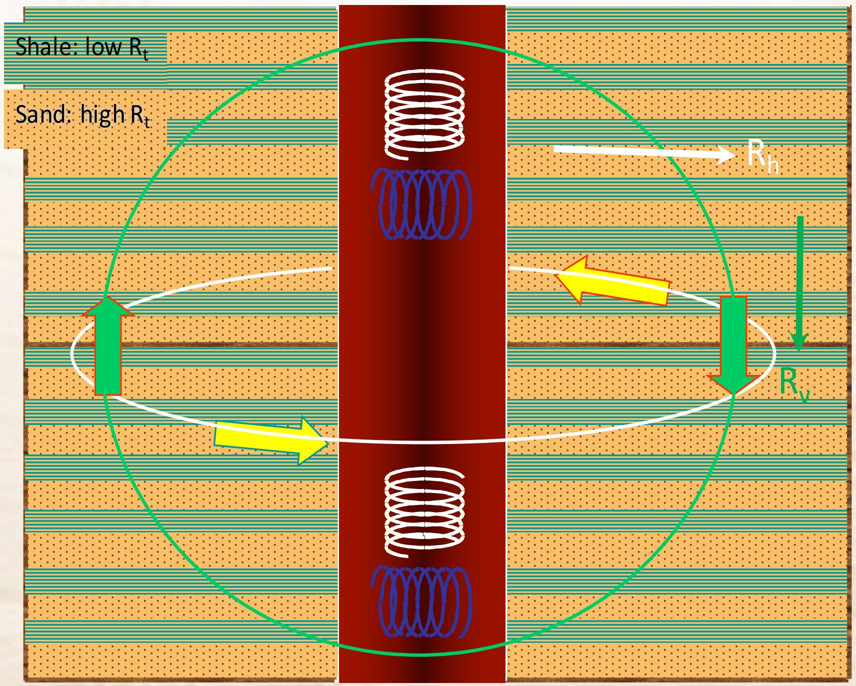
Issue 1: Anisotropy is EVERYWHERE – Problem solved



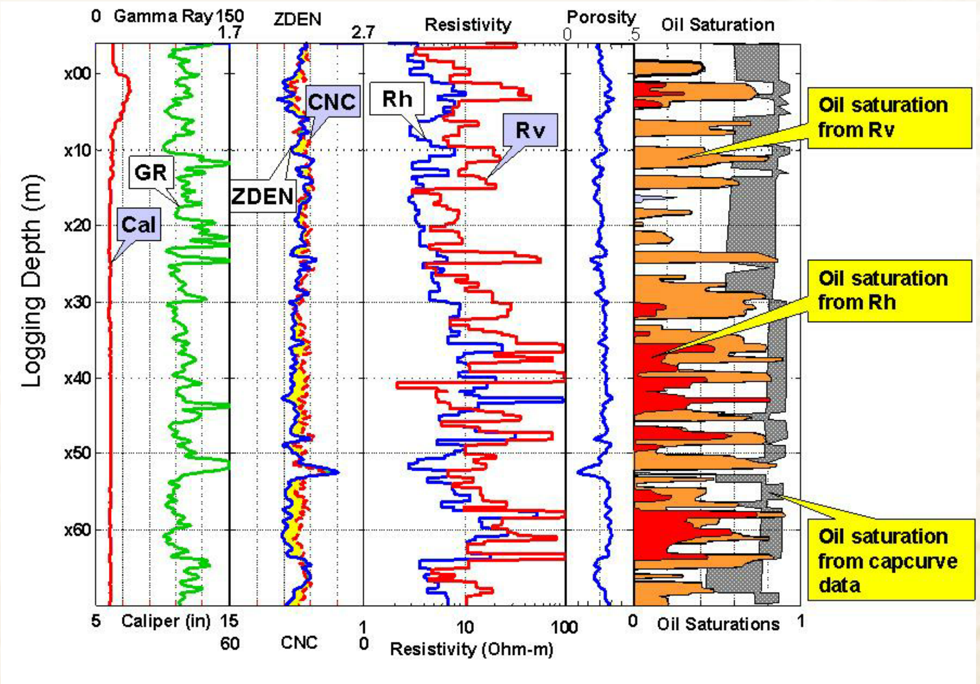
Courtesy Baker Atlas

Issue 3: Anisotropy calibration with 3D Induction logging principle

40 % more reserves → error estimate



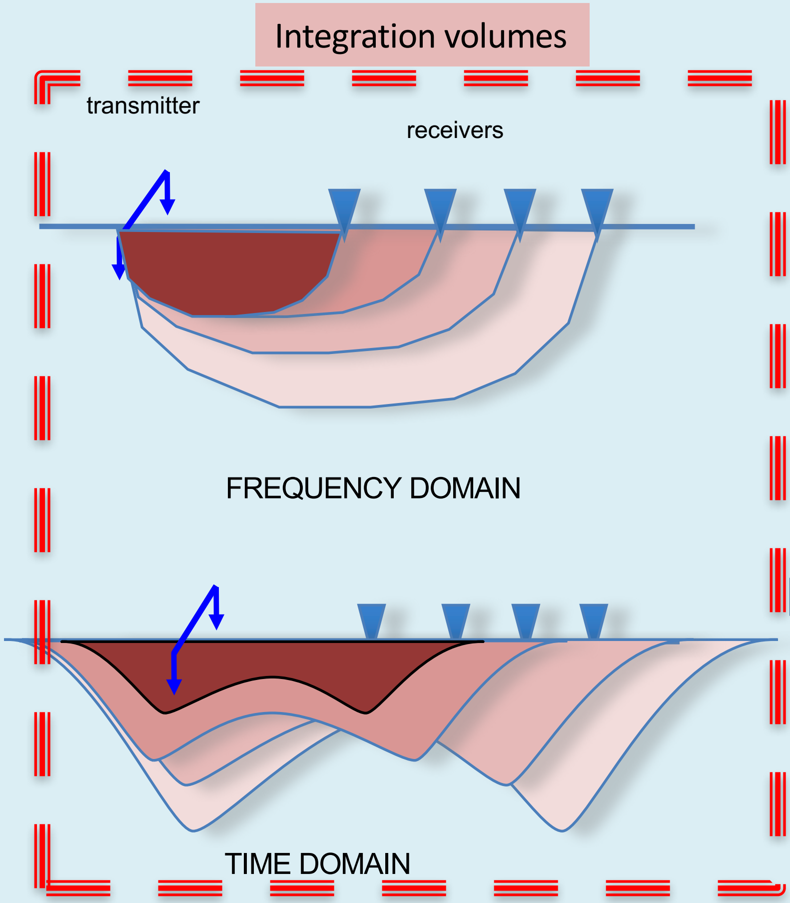
After Kriegshaeuser et al, 2000

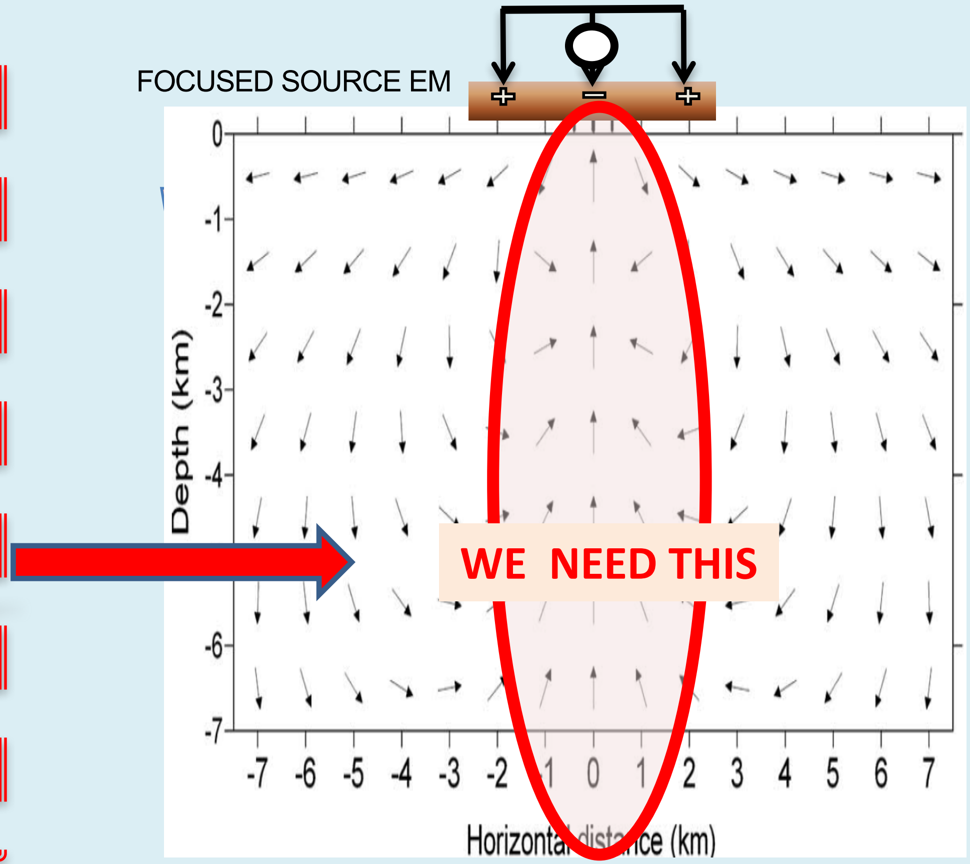


After Yu et al., 2001

40% more oil → without big errors

Issue 3: Where is the information focus?



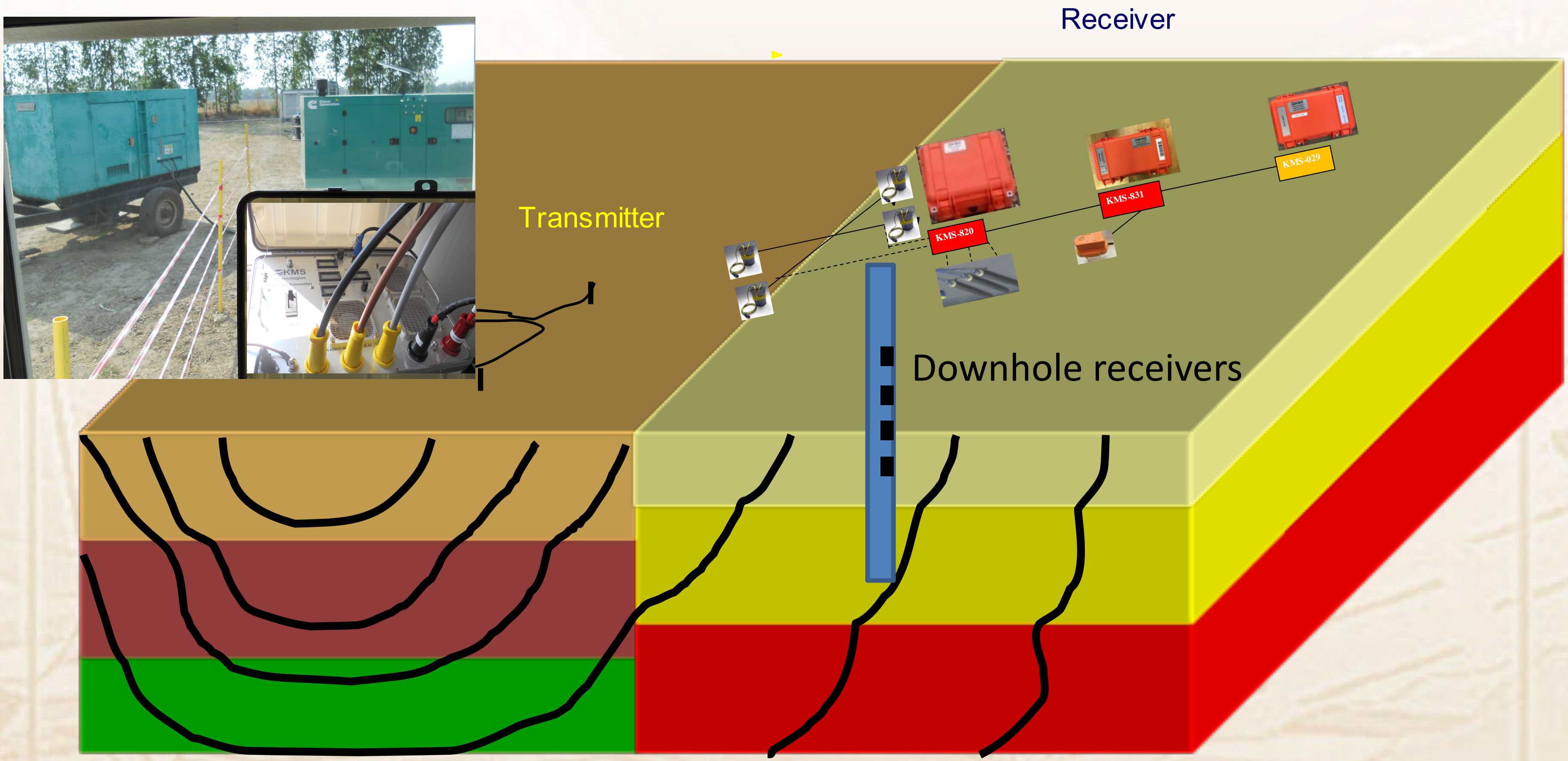


Rykhlinskaya, E., & Davydycheva, S., 2014, U.S. Patent 8,762,062 B2.
Davydycheva, S., 2016, U.S. Patent Application US 2016/0084980 A1.

Issue 4: Surface-to-borehole calibration

- Logs (best 3D) are the ground truth (after log inversion)
- MUST scale to surface from borehole & vice versa
- Boreholes include casings → need through casing measurements (E & H & multi-scale)
- MUST scale to TENSOR surface measurements
- All anisotropic
- → all multi-component in E and H and as FULL tensor

Architecture & hardware setup



Receiver (KMS-820 array system): for MT & CSEM

DEEP BOREHOLE

SHALLOW BOREHOLE TOOL

MARINE

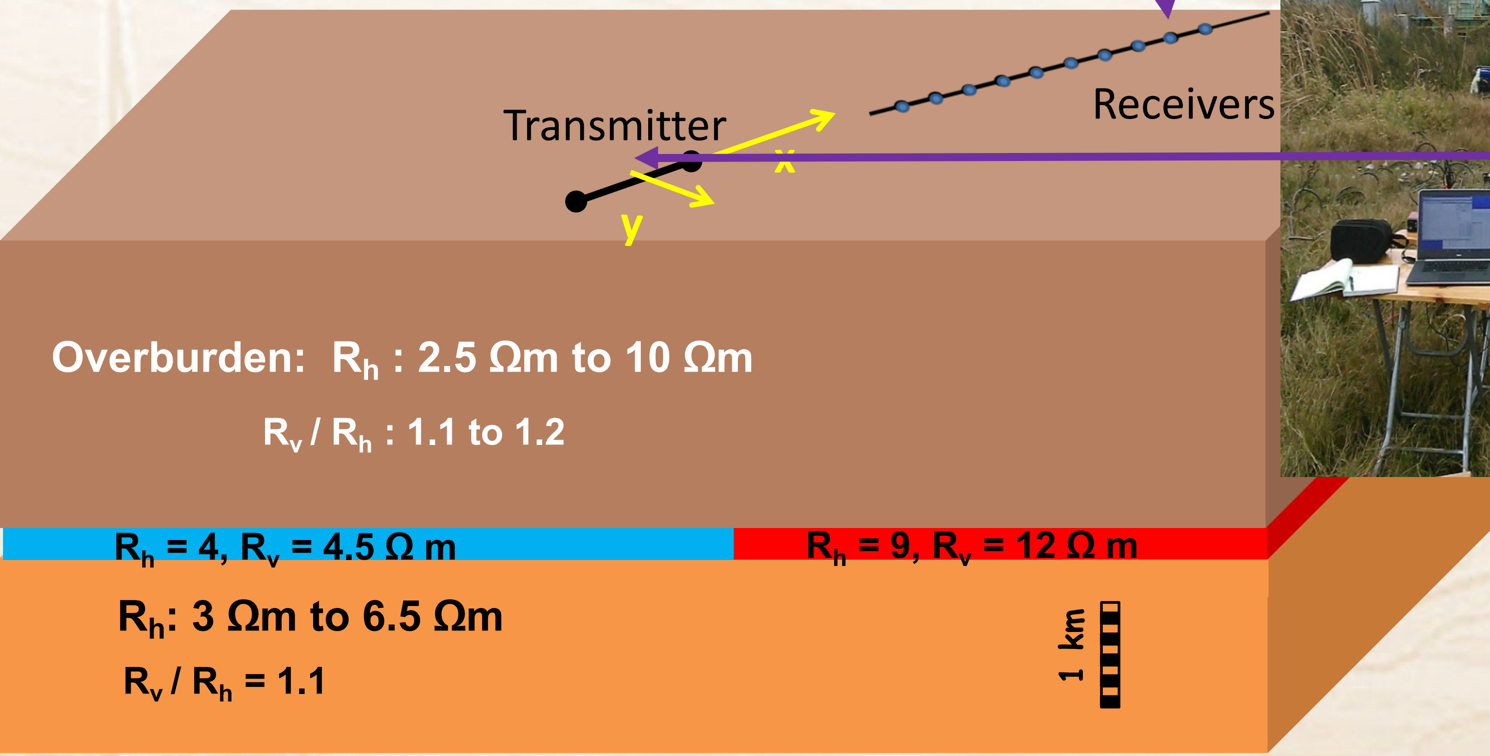
Node
on deck

Combined seismic & EM node
For 2 months operation

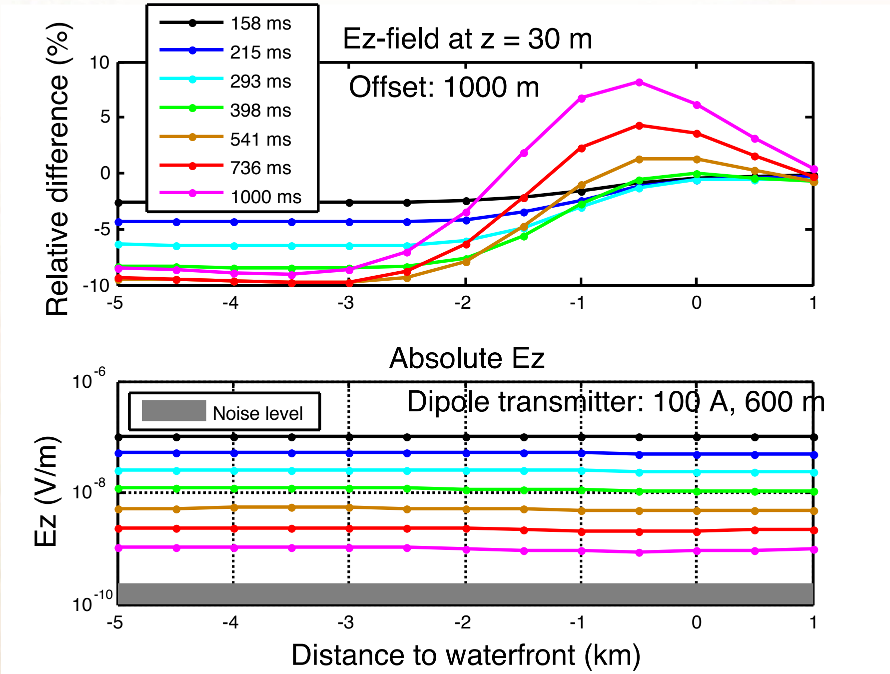
TRANSMITTER

Reservoir monitoring setup in an Asian field

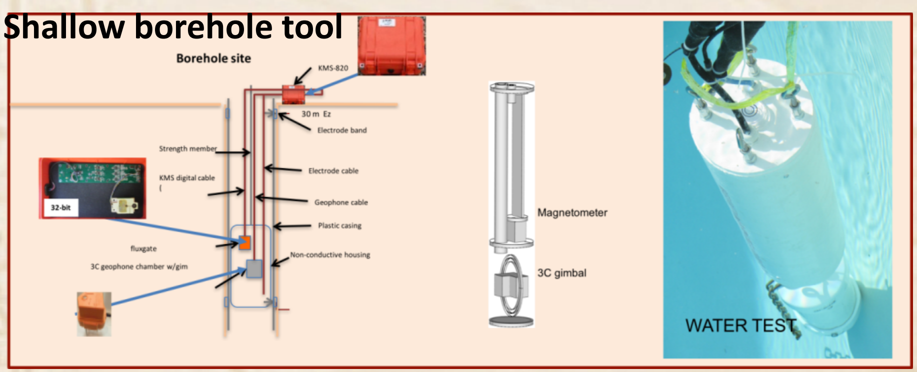
- 3D anisotropic resistivity model; derived from well log
- Monitoring setup: full EM field Ex, Ey, Ez, Bx, By, Bz
  - Shallow borehole tool → vertical component Ez



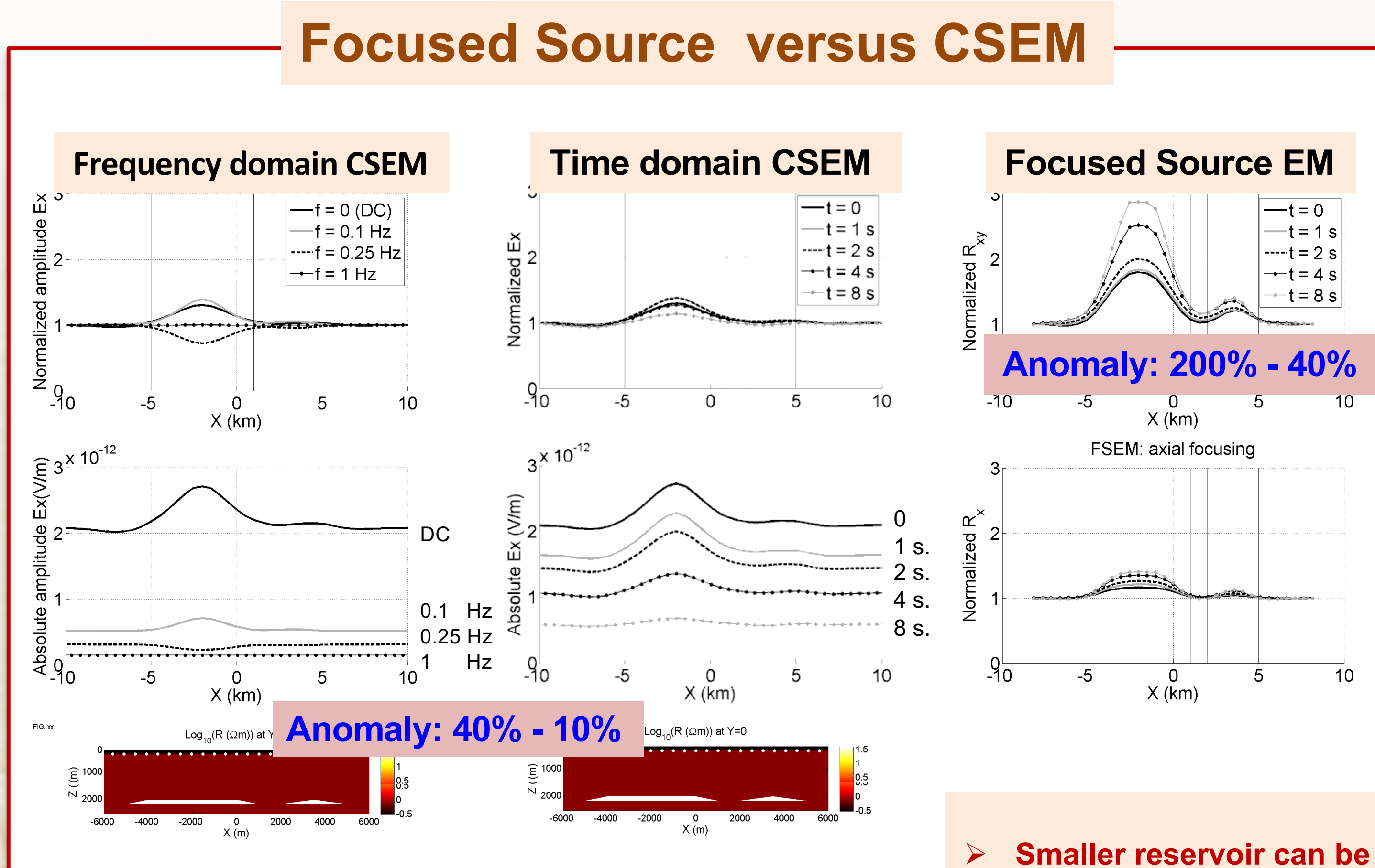
Shallow borehole tool: measure and model Ez component



- Ez: sensitive to deep thin resistors
- Shallow (20-30 m) verstical boreholes
- Example:
  - Rt anisotropy matters!



FSEM: Focused source solution to volume imaging

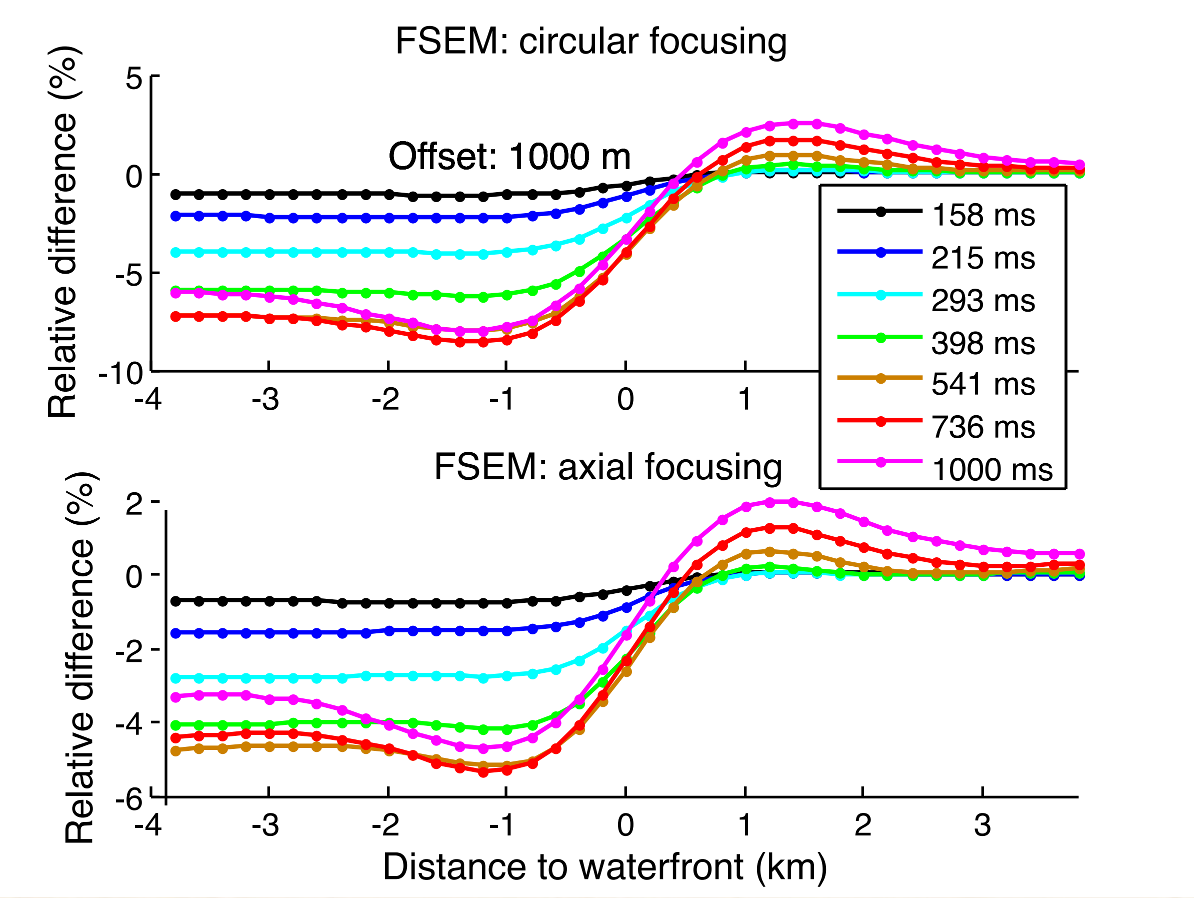


- Anomaly in the order of 40% for the smallest reservoir
- Reservoir layers individually respond!

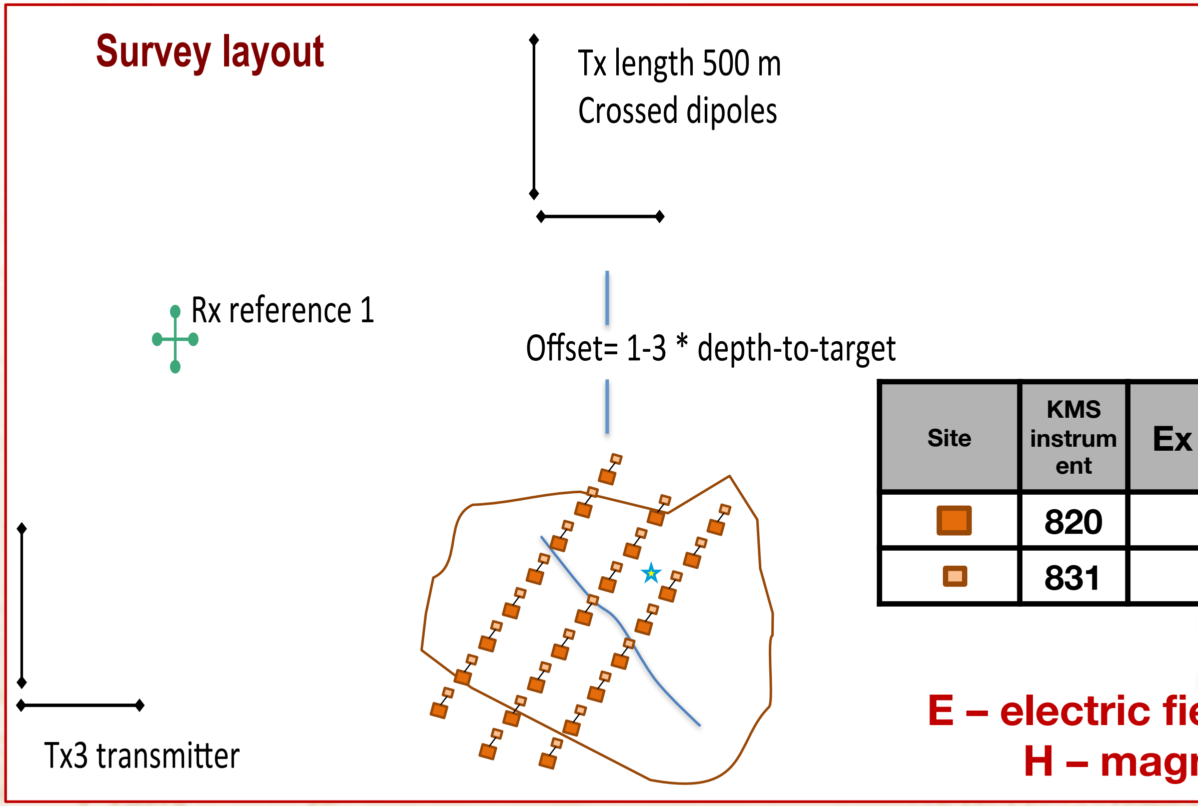
- **Smaller reservoir can be detected**
- **Higher spatial resolution**
- **Shallow structure removable**

FSEM performance on the Asian field example (above)

- Anomaly approx.10%
- Physics similar to Ez (shallow borehole tool)
- More field trials needed



Reservoir Monitoring: Example layout & water flood time lapse result



Microseismic sensors

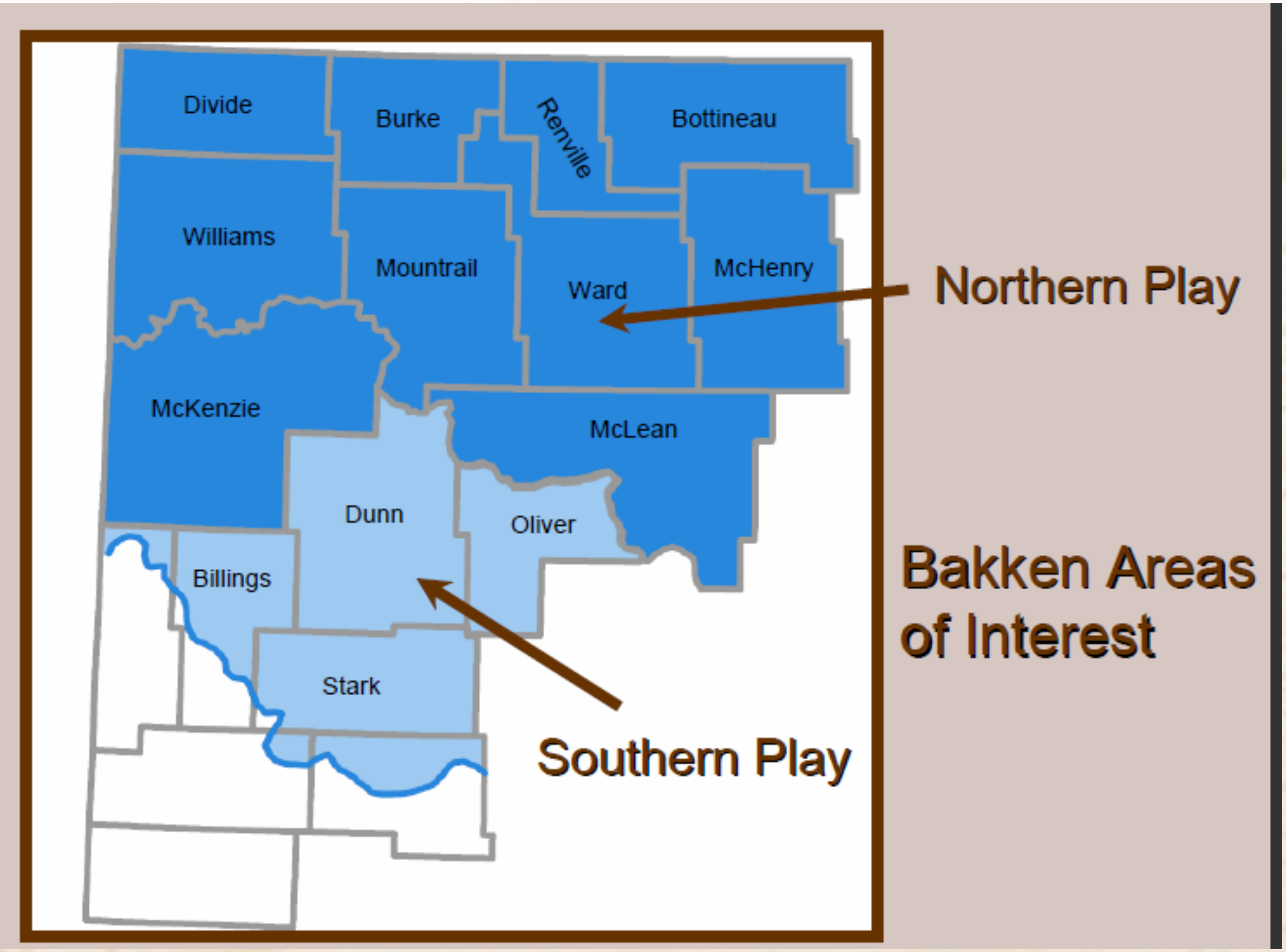
Site	KMS instrument	Ex & Ey	Hz	3C fluxgate H	3C geophone	Shallow borehole tool
■	820	x	x	x	x	x
▫	831	x			x	

E – electric field sensors
H – magnetic field sensors

Shallow Borehole Tool – KMS-888 includes 3C seismic, 3C magnetic & 3C electric sensors

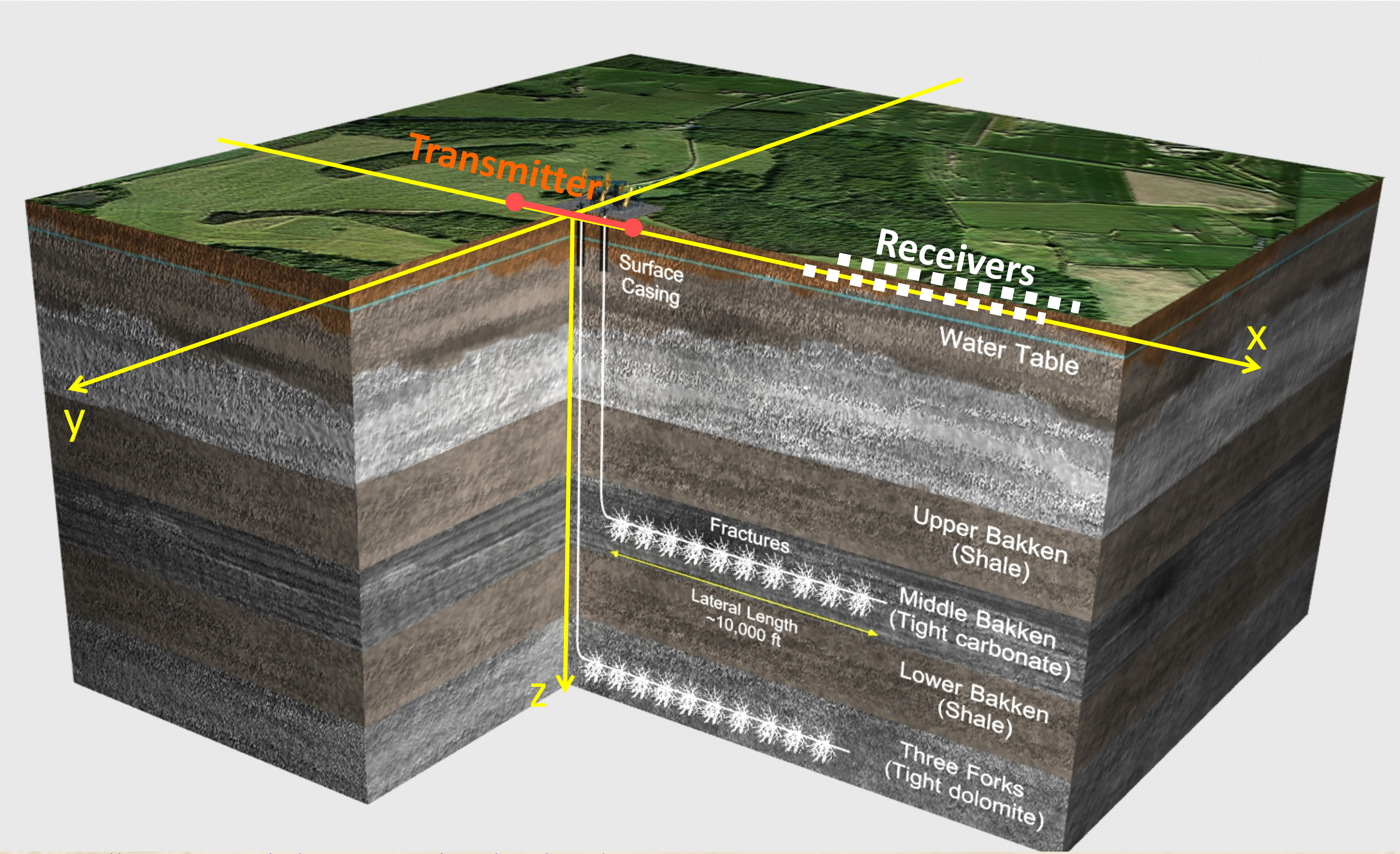
DATA EXAMPLE REMOVED. AND… IT DOES

Hydro-fracturing monitoring application: back to the Bakken



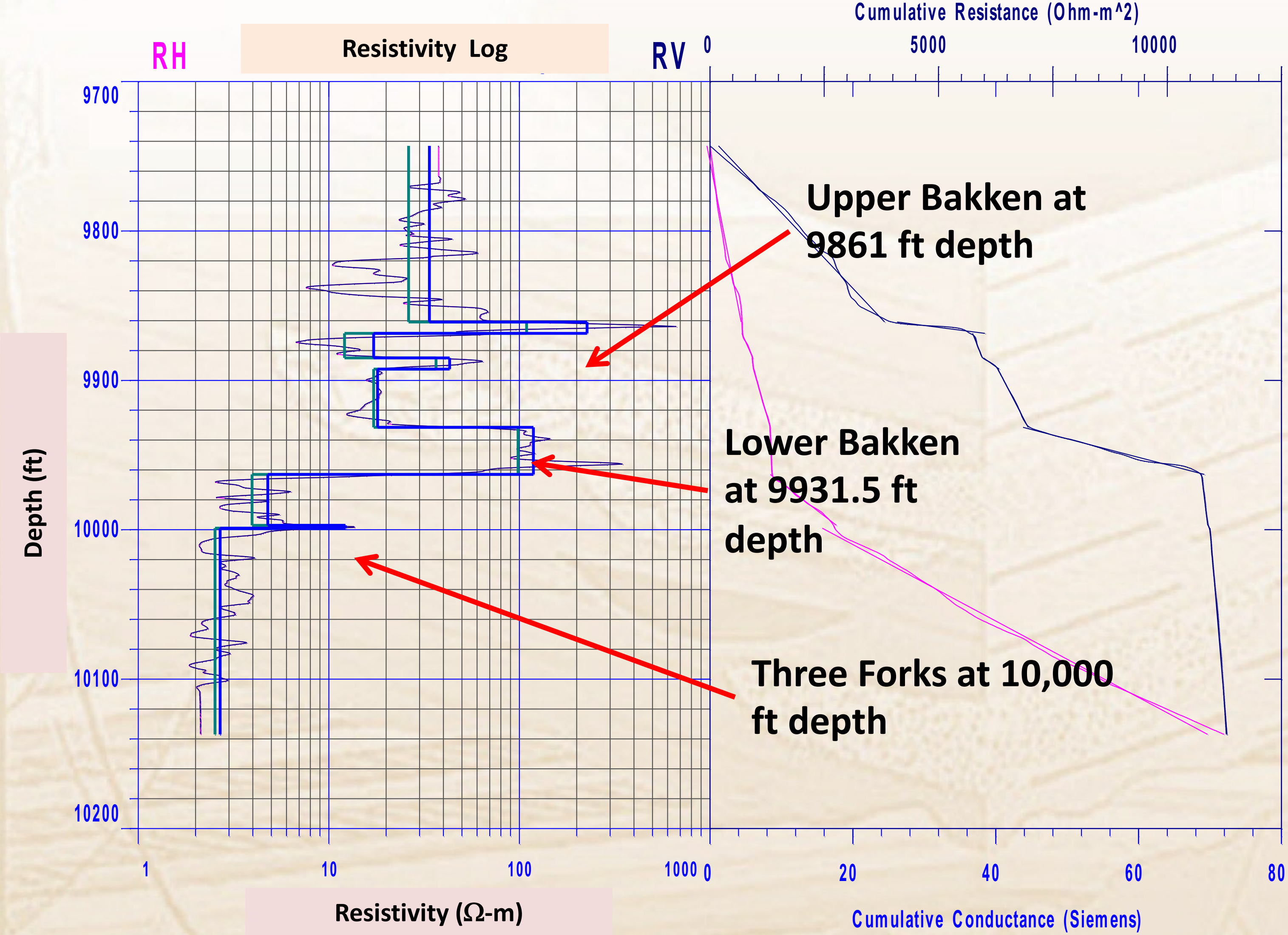
(LaFever, 2010)

Bakken: surface-to-surface EM monitoring setup



http://www.statoil.com/en/NewsAndMedia/News/2011/Pages/XXX16Oct2011.aspx

Derivation of anisotropic background model



Derivation of 1D anisotropic background model

LAYER	RHO-H	RHO-V	THICK,ft	THICK,m	DEPTH,f	DEPTH,m	Formation
1	26.23	33.74	9861	3007.605	9861	3007.605	
2	109.2	227.06	7.5	2.2875	9868.5	3009.893	Upper Bakken
3	12.1	17.2	16.5	5.0325	9885	3014.925	
4	36.55	43.14	7.5	2.2875	9892.5	3017.213	
5	17.22	18.05	39	11.895	9931.5	3029.108	
6	98.56	118.64	31.5	9.6075	9963	3038.715	Lower Bakken
7	3.96	4.78	34	10.37	9997	3049.085	
8	12.1	12.25	2	0.61	9999	3049.695	3 Forks
9	2.53	2.69					

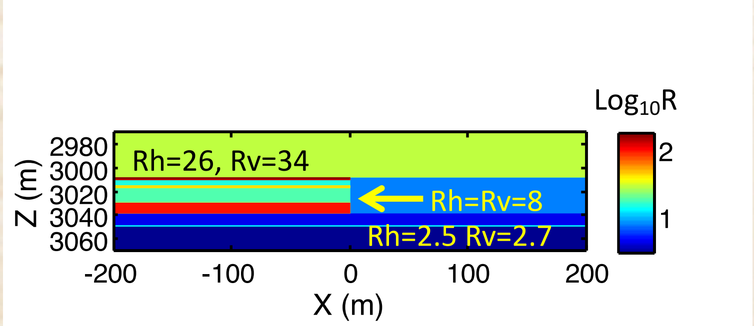
FLOODED

Surface-to-surface EM response before & after hydro-fracturing

- Grounded Tx: current = 150 A, 500 m long
- Offsets = 1000 - 5000 m
- 3D model: rectangular fracture area
- Resistivity:
  - 8 Ωm if sand- & salt-water-based proppant
  - 0.2 Ωm if conductive particles based proppant as **reported by Palish et al.** (SPE 2016, 2017, CARBO Ceramics)

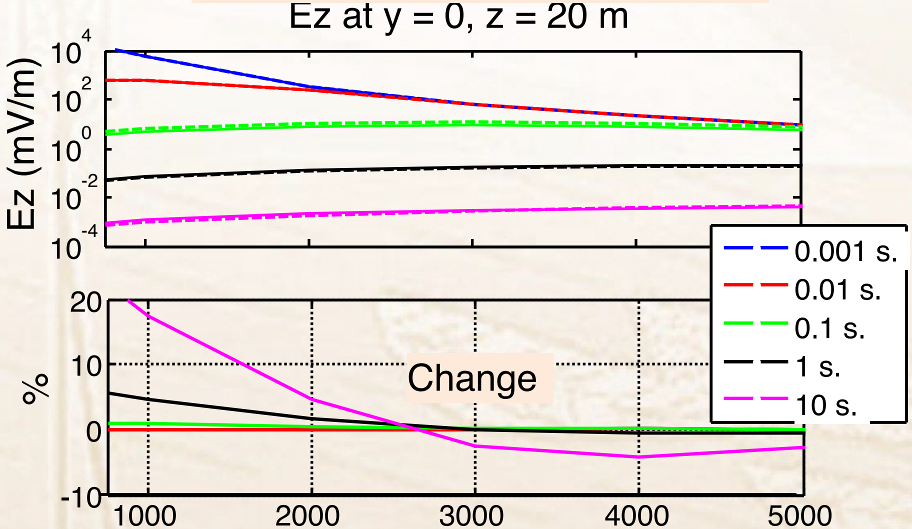
Plan view: Flooded area
3 km long (in x), 400 m in y
Tx: 1 km to the left (at x=-1 km)
Rx all over flooding area,
offsets from 1 to 9 km in x, 0:200 m in y

Side view:

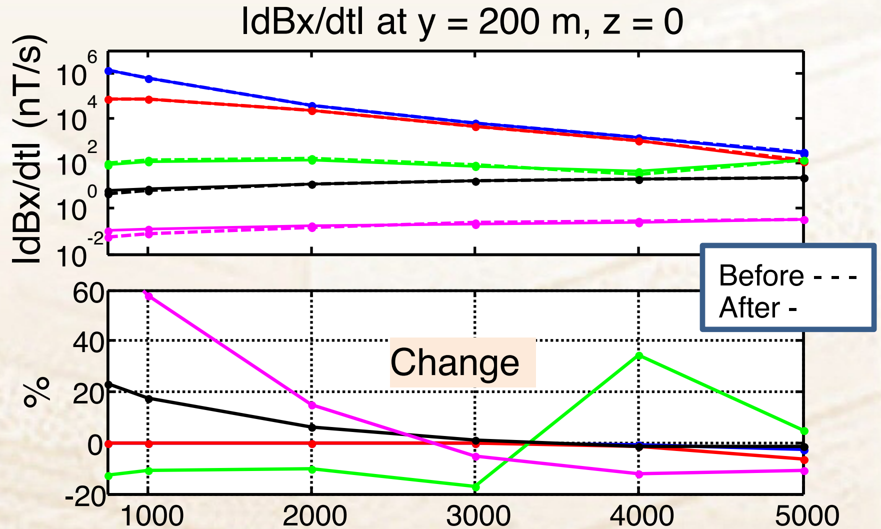


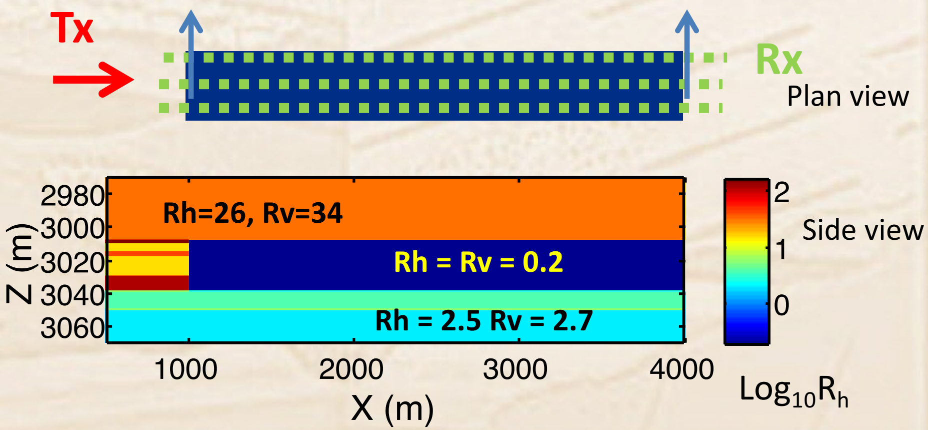
Surface-to-surface 3D-EM response before & after hydro-fracturing

SHALLOW BOREHOLE TOOL



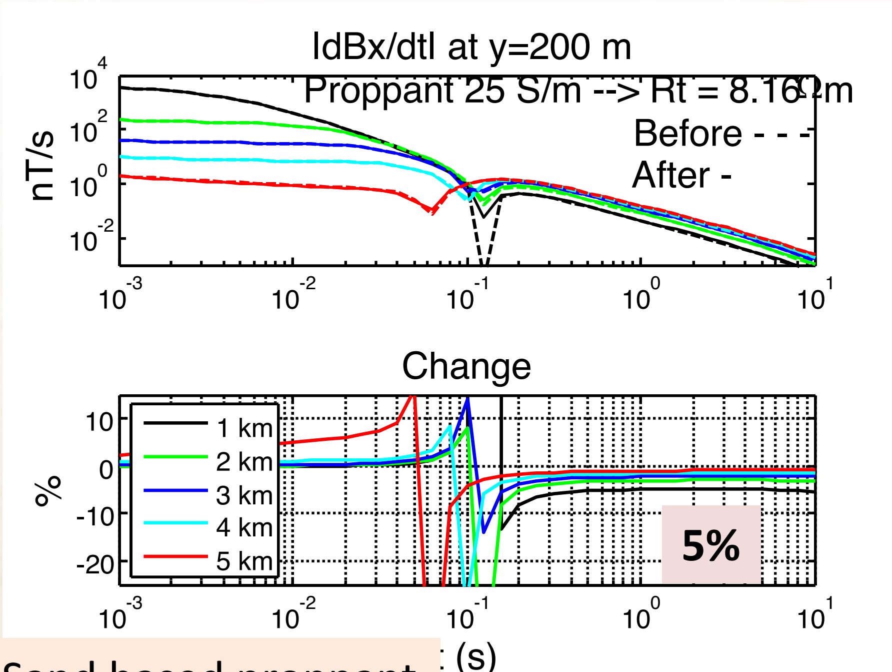
SURFACE-SURFACE



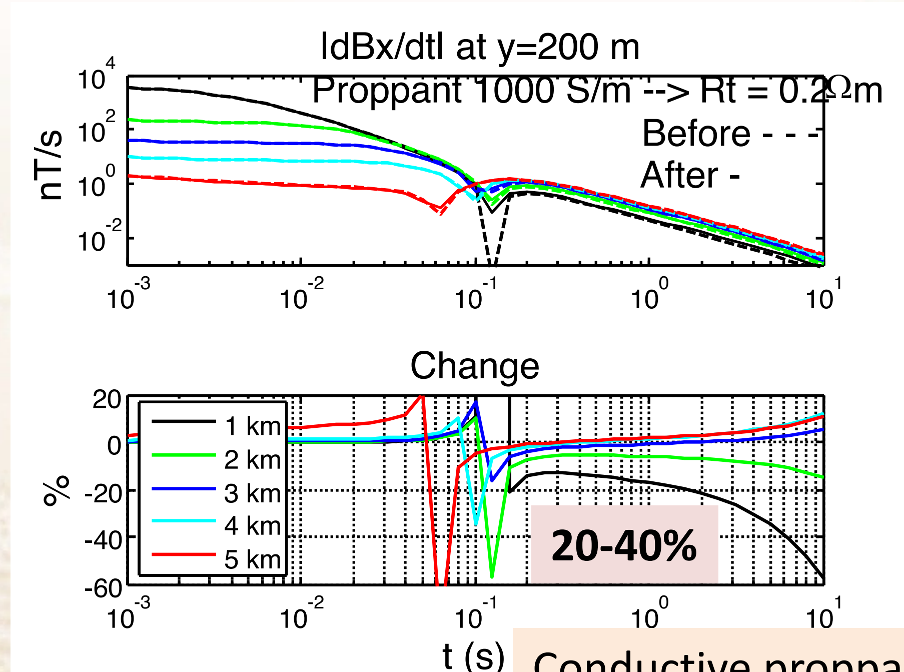


- Conductive-particles-based proppant: → response up to 20-40% above fractured area egdes
- Grounded Tx: current = 150 A, 500 m long

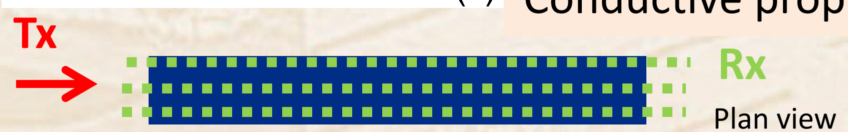
Surface-to-surface 3D-EM: magnetic field before & after hydro-fracturing

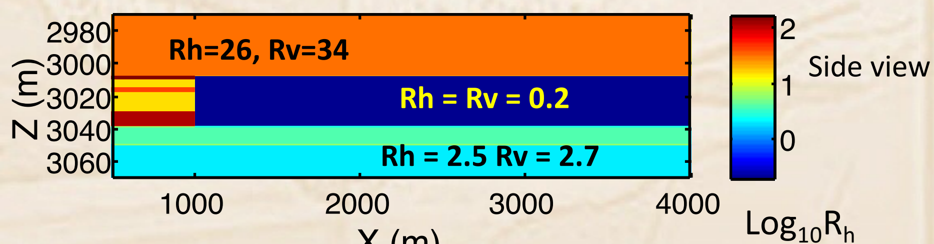


Sand based proppant

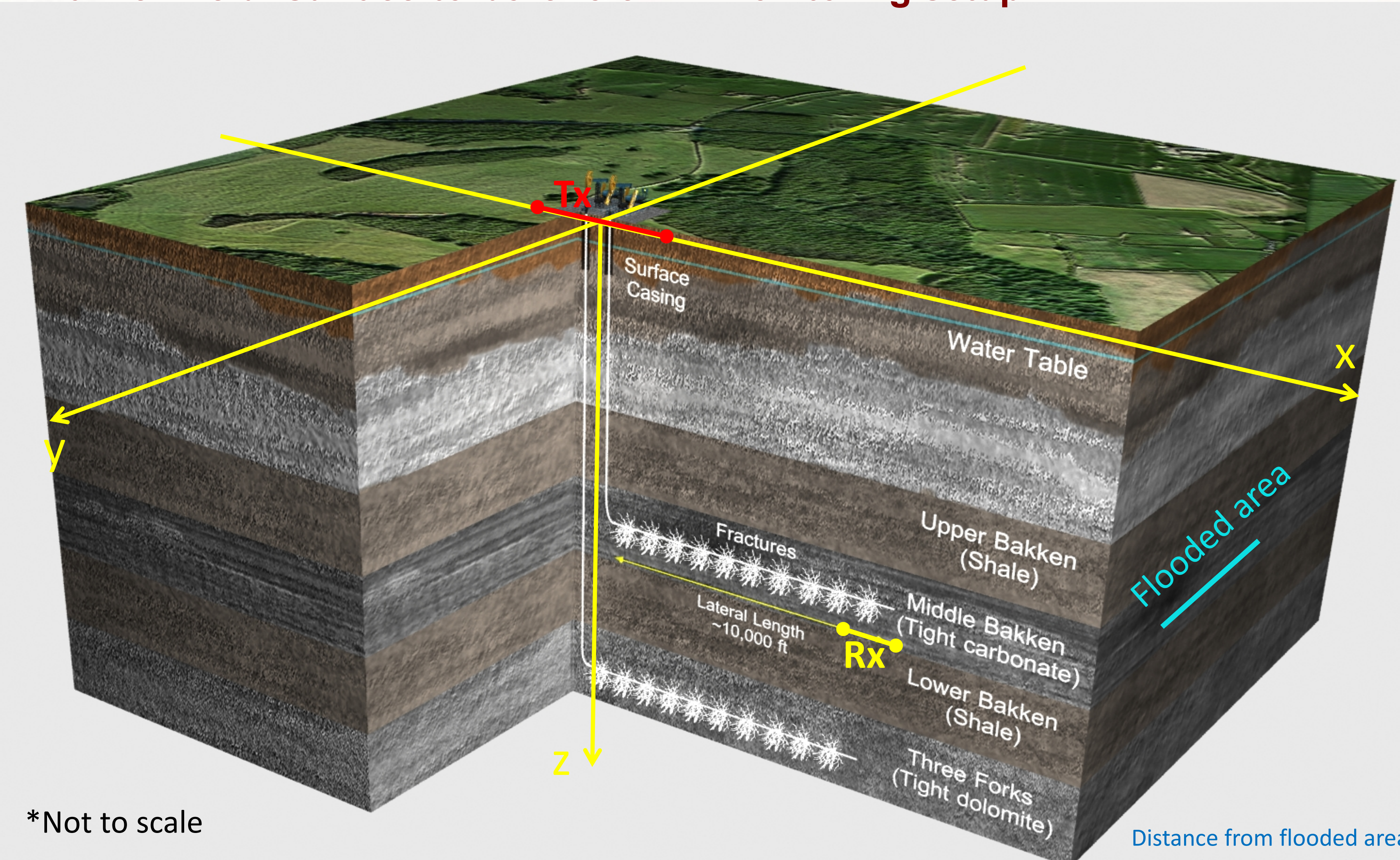


Conductive proppant





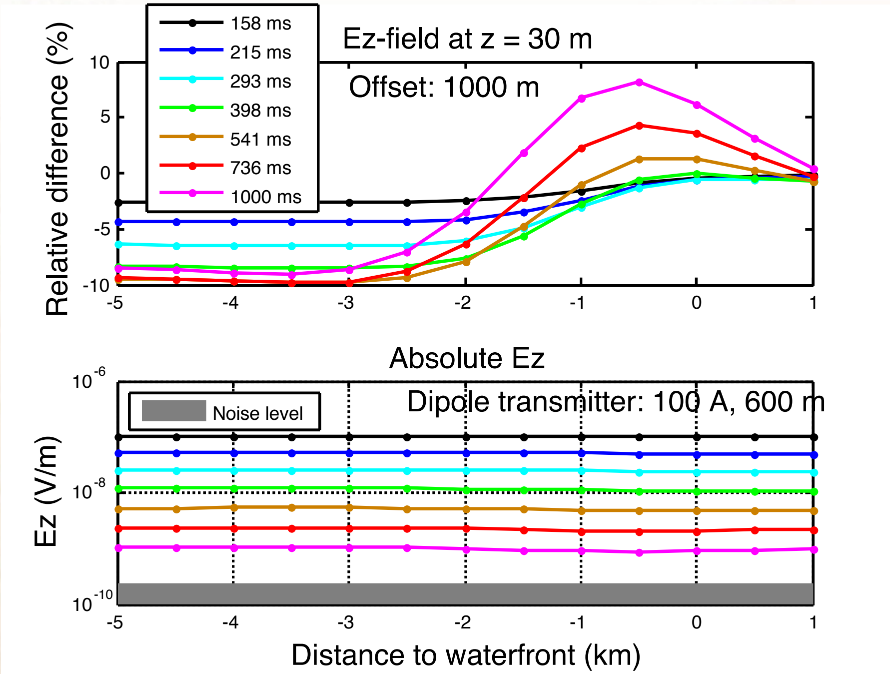
Bakken field: surface-to-borehole EM monitoring setup



http://www.statoil.com/en/NewsAndMedia/News/2011/Pages/XXX16Oct2011.aspx

Distance from flooded area to Rx in observation well varies from 200 m to 0

Shallow borehole tool: measure and model Ez component



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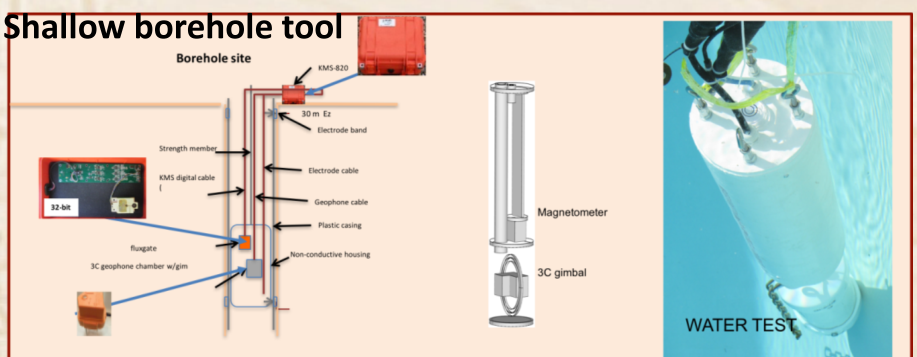
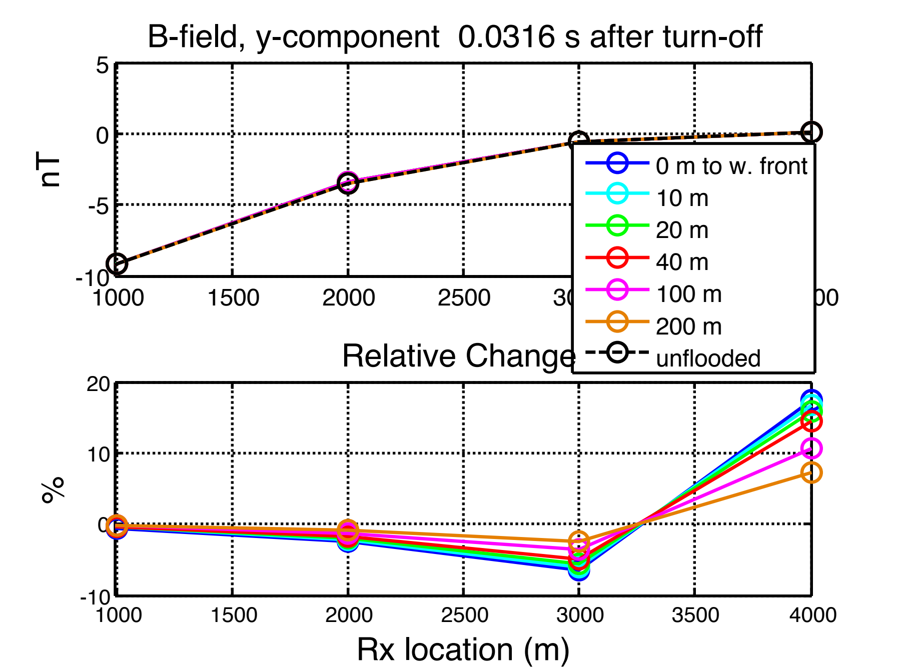
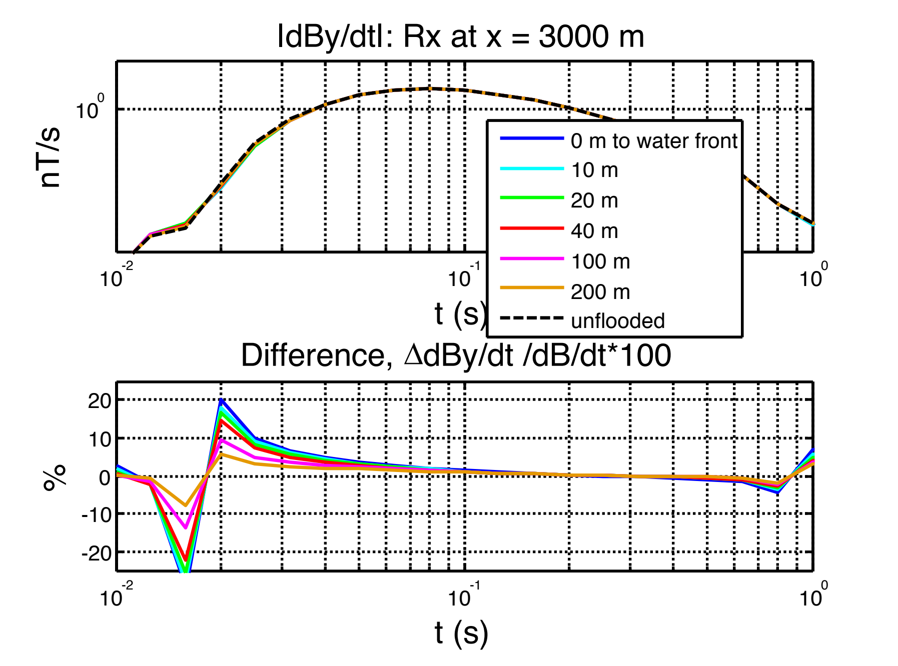


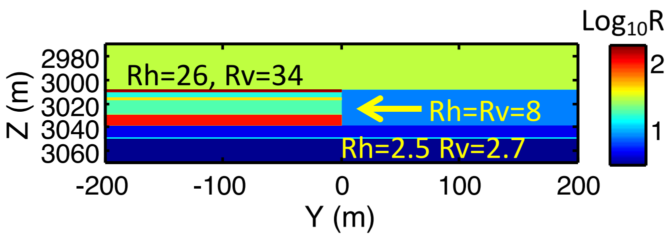
Surface-to-Borehole 3D-EM: Inline Ex – dBy/dt partially flooded

HORIZONTAL WELL → only Bx,By





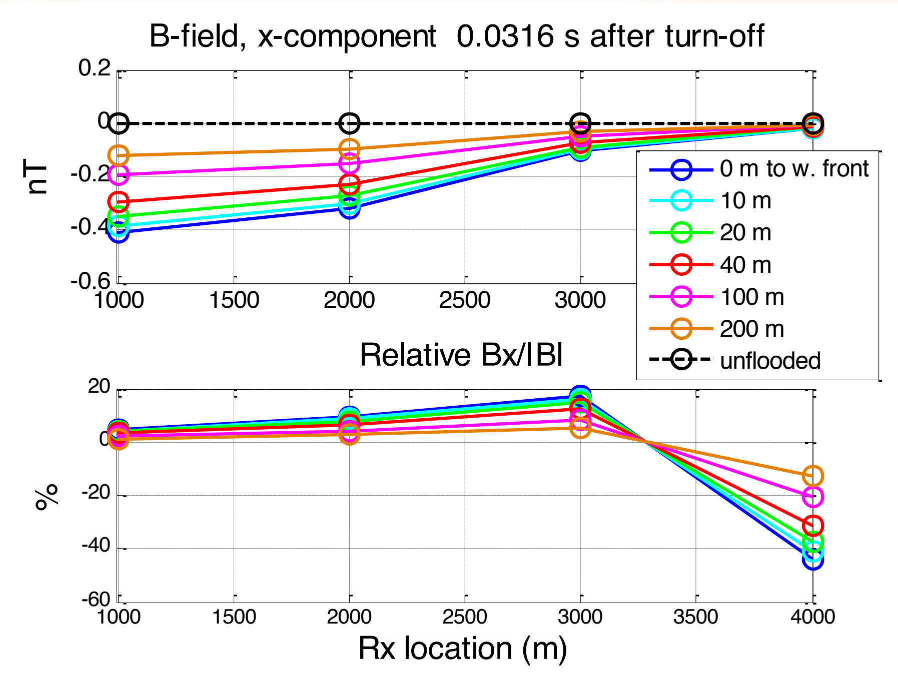
Effect ~10% at 31.6 ms

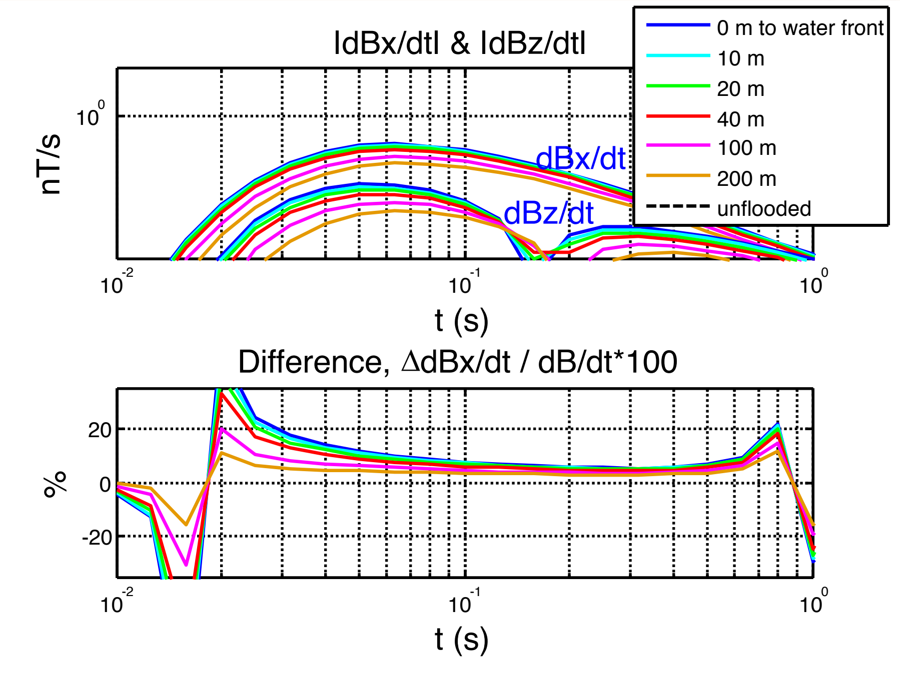


Rx positions:
x varies from 1000 to 4000 m, y = 0,
z = 3033.9 m = 9953.7 ft (in Lower Bakken)

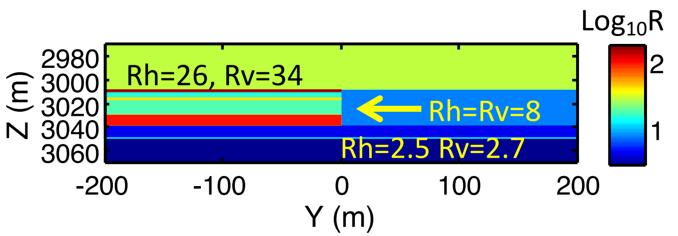
The flooded area:
from 0 to 5000 m in x,
from –500 to variable distance in y (-200:0),
from top Upper Bakken to bottom Lower Bakken (31 m thick) in z.

Surface-to-Borehole 3D-EM: Inline Ex – dBx/dt, dBz/dt partially flooded



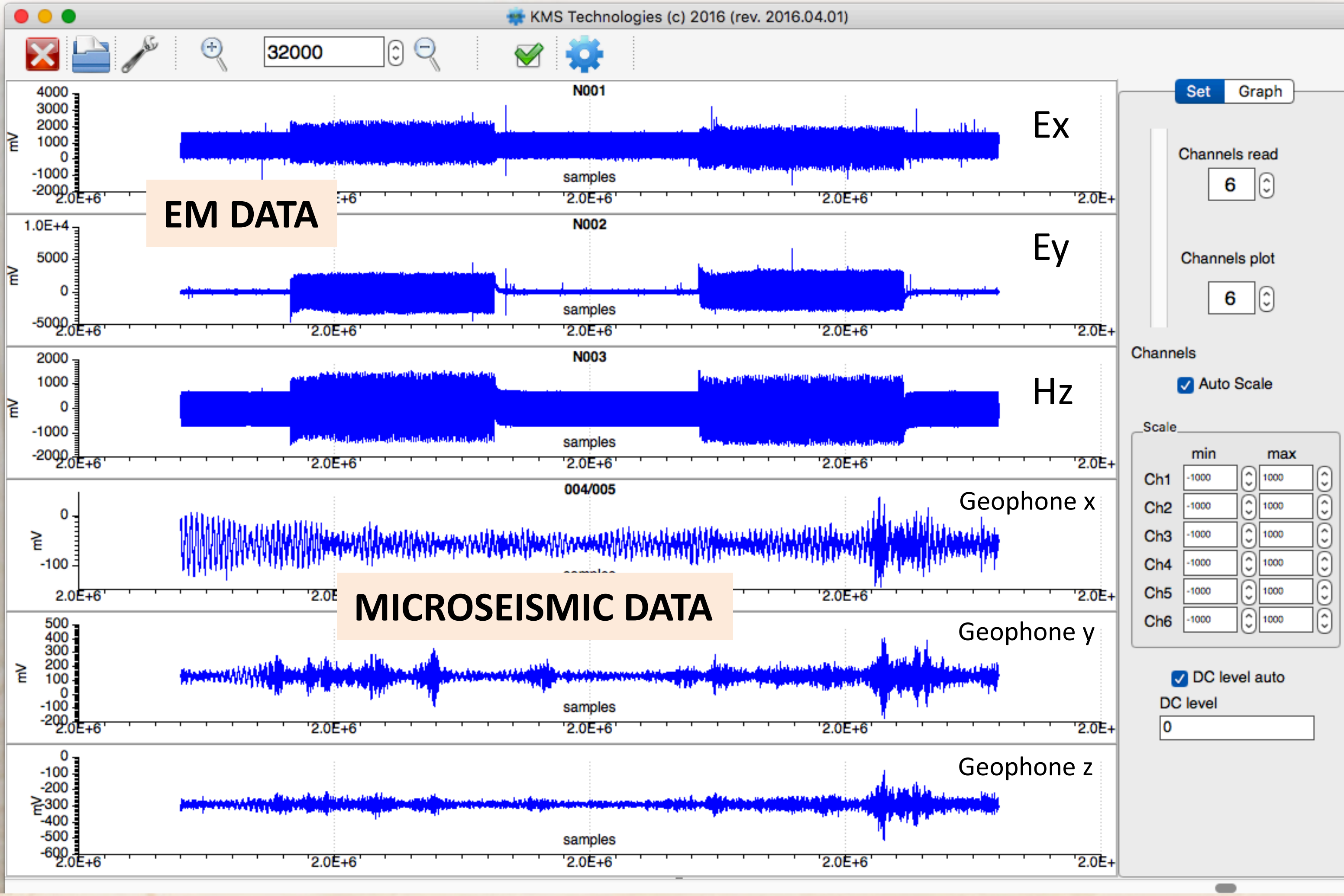


Effect up to 20% at 31.6 ms



HORIZONTAL WELL → only Bx,Bz

Reservoir Monitoring: Real data example: microseismic/EM



Conclusion

- A long path from patent → Feasibility → Hardware → Field trial
- Reservoir monitoring EM & microseismic system available
  - Surface-to-surface full field EM system – fully commercialized
  - Surface-to-borehole full field EM system – in field trial
- Two applications studied
  - Water-flood monitoring for EOR with field trial
  - Hydro-fracturing monitoring – field trial needed
- NEXT:
  - More field pilots
  - Develop deep multi-scale THROUGH CASING borehole tool

Acknowledgements

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...and all KMS staff.

All technology protected by US & Foreign patents
(see KMS Technologies website)