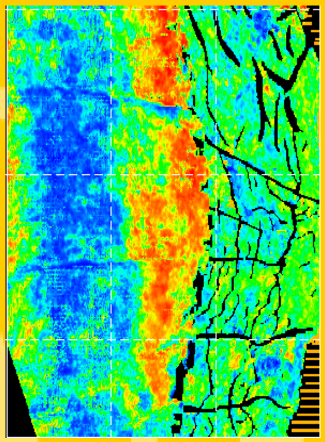
Mork Family Department of
Chemical Engineering and Materials Science

USC Viterbi
School of Engineering

Geophysical Monitoring of Reservoirs



Fred Aminzadeh

SPE- LAS
January 10, 2012

Outline

- Geophysical methods & their sensitivities / applicability
- 4D inversion for pressure, saturation, & permeabilities
- Integrated reservoir model updating & history matching
- Passive seismic for shale reservoir stimulation monitoring
- Applications
- USC Reservoir Monitoring Consortium (RMC)
- Closing

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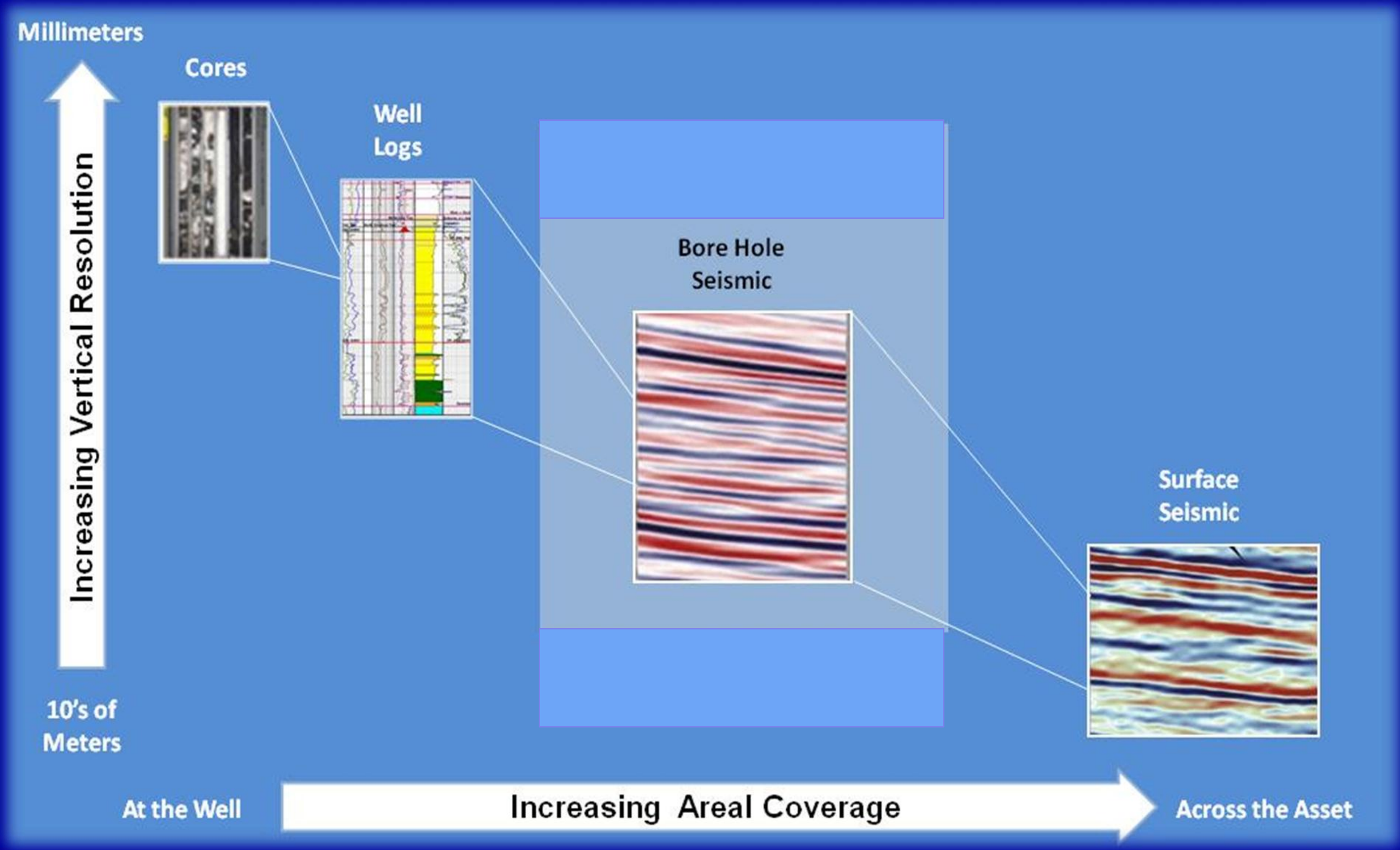
Geophysical tools for reservoir monitoring

Geophysical technique	Physical property measured	Reservoir property inferred
4D surface seismic, VSP, X-well seismic	Changes in amplitude, arrival time, waveform	Fluid saturation, pressure changes
Microseismic or passive seismic	Rock shear failure w/ stress perturbations	Fluid flow pathways flow anisotropy
Borehole & surface EM measurements	Electrical resistivity changes	Saturation 4D changes

Borehole seismic (VSP) bridges the gap between logs & surface seismic



The Physics behind 4D Seismic

- Rock & fluid properties change over time
- Rock & fluid properties affect compressibility and shear strength
- Seismic waves deform rocks by compressing and shearing them

↓

Seismic response changes over time

The Physics behind 4D Seismic (cont.)

- Time-lapse seismic response measured by differences in:
  - local wave front amplitude/energy
  - wave propagation velocity & travel time
  - phase, frequency,, impedance,

    Z= (density x velocity)
  - other physical attributes…

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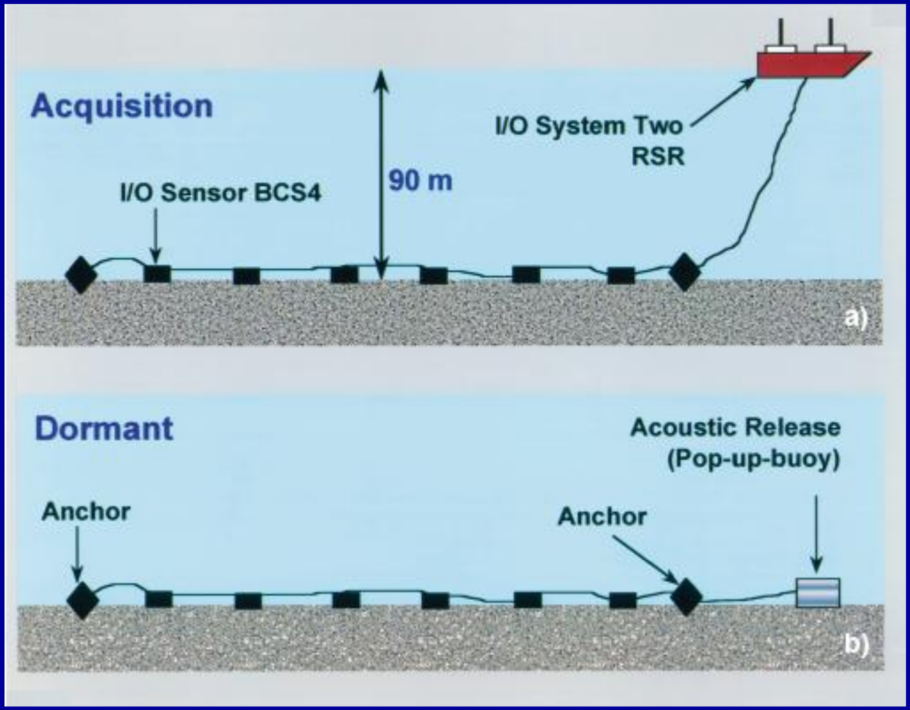
How does 4D seismic work?

- Record seismic data at different times
  - What changed? *Why?*
    - Saturation – *oil-water displacement, gas expulsion,* CO_2 *injection*
    - Pore pressure – *increases at injectors, decreases at producers*
    - Temperature – *steam front movement*
    - Porosity – *pressure depletion*

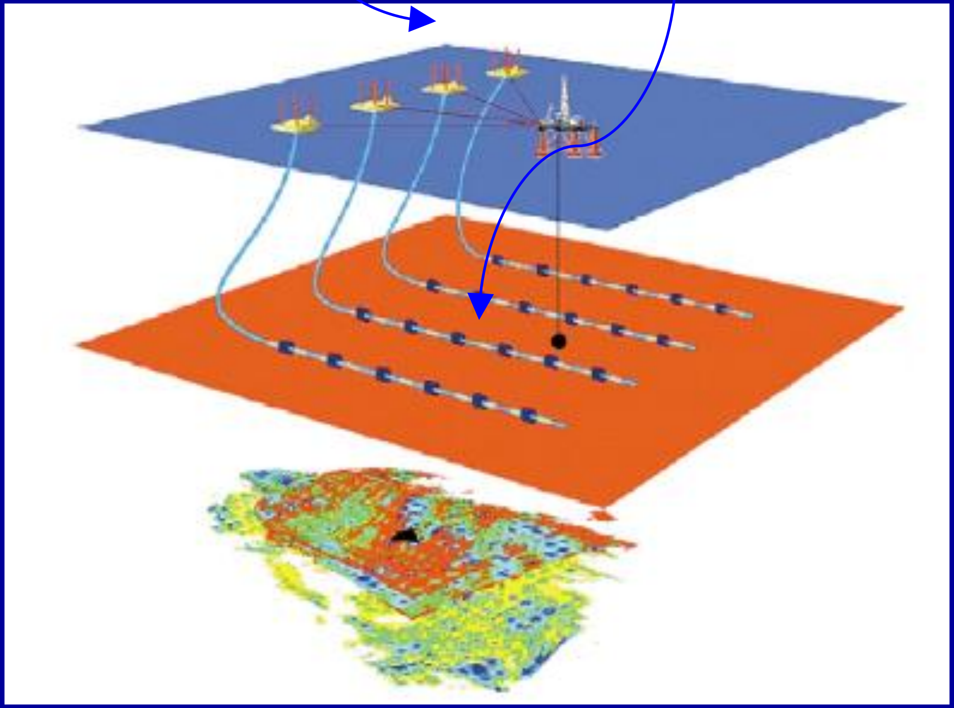
Deployment of Geophysical Monitoring Tools
(Teal South 4D study, GOM)

radio telemetry to rig



Ebrom et al. (1998)

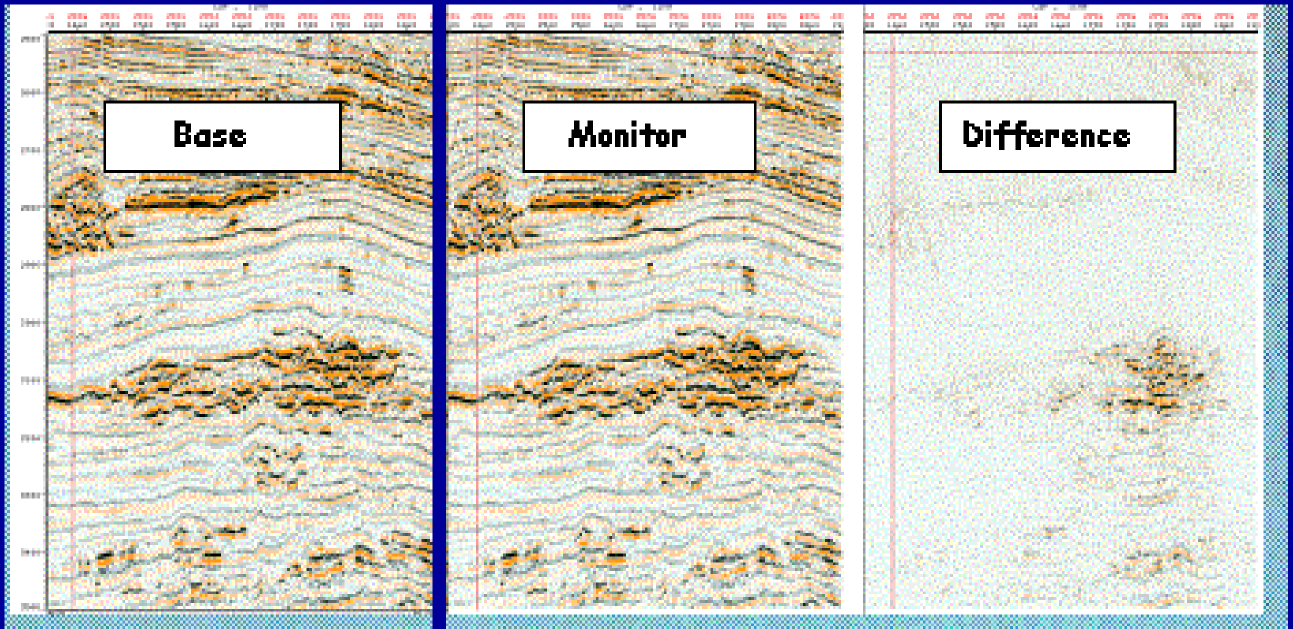
ocean bottom cable (OBC)



Entralgo and Spitz (2001)

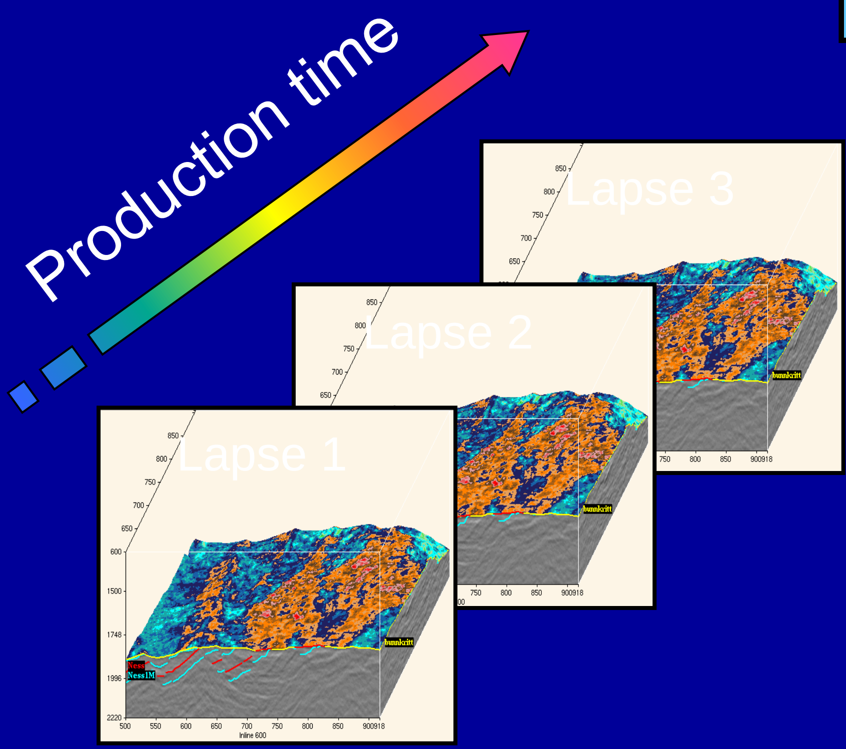
How does 4D seismic work? (cont.)

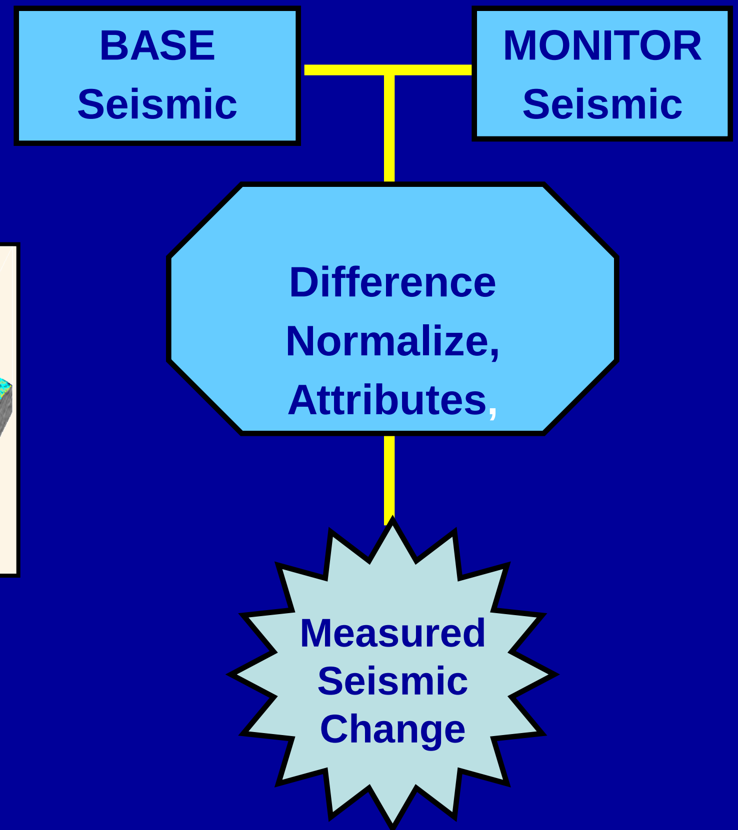
- Differencing time-lapse datasets tells us about fluid changes in the reservoir
  - Qualitative: *Where did the changes take place?*
  - Quantitative: *What changed exactly, and by how much?*



CGGVeritas

4D seismic reservoir monitoring





Fluid saturation

Pressure changes

(Courtesy of Saudi Aramco)

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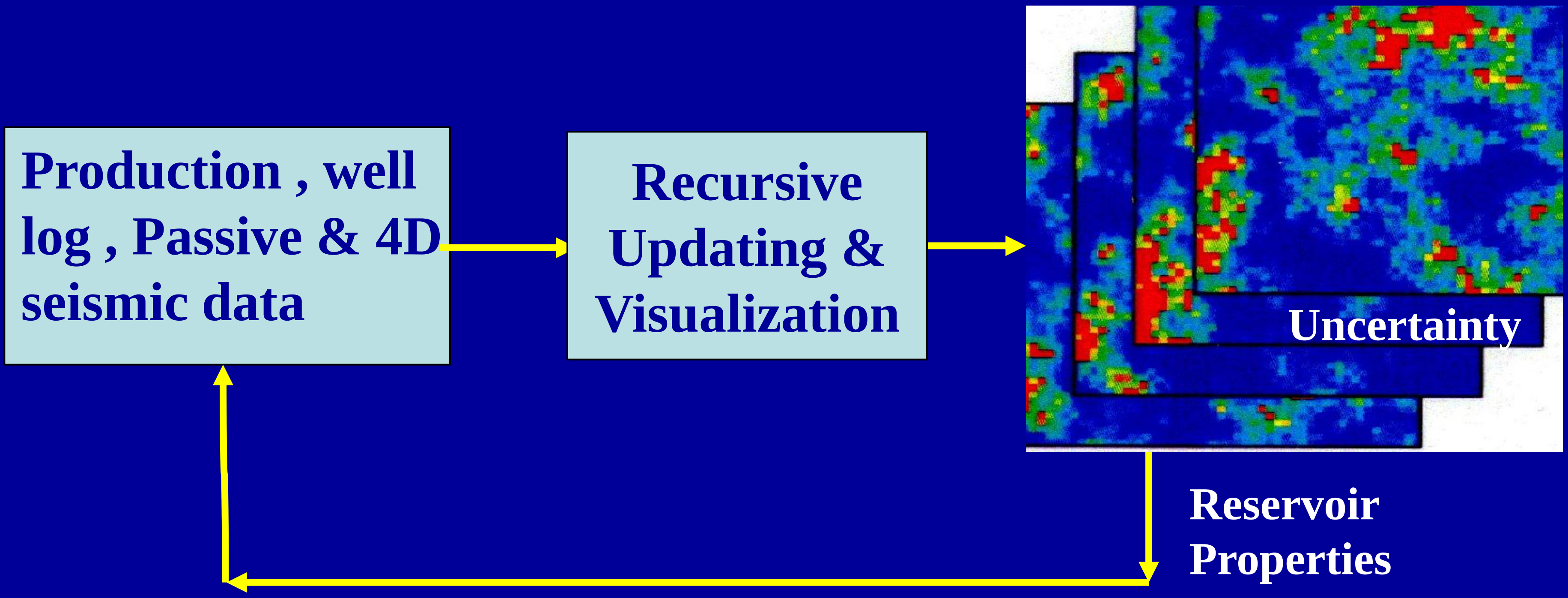
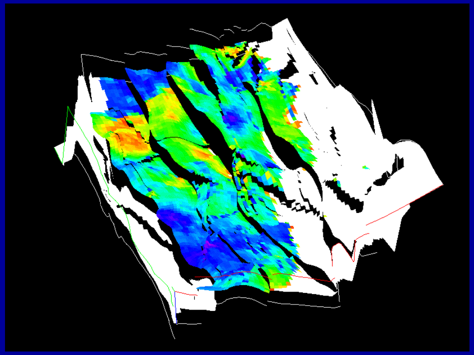
Dynamic Reservoir Model Building



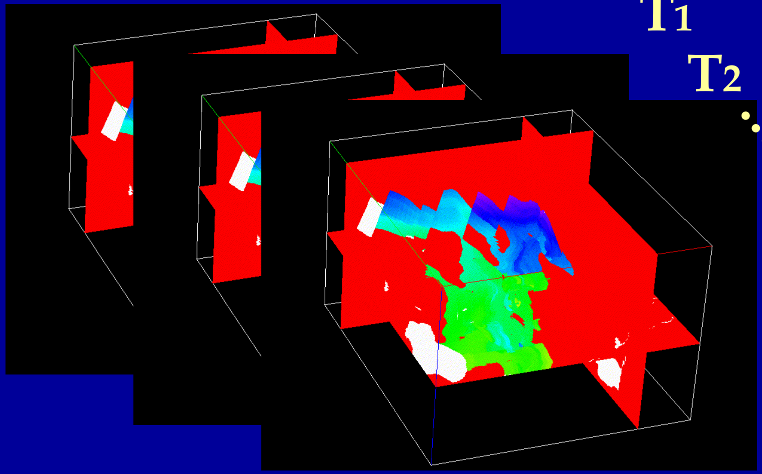
4D Seismic Modeling Flow

Earth Model



Φ, vshale, facies...

Flow Simulation



T_1

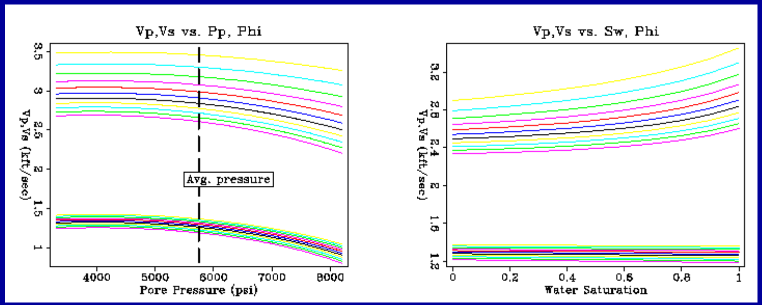
T_2

...

T_N

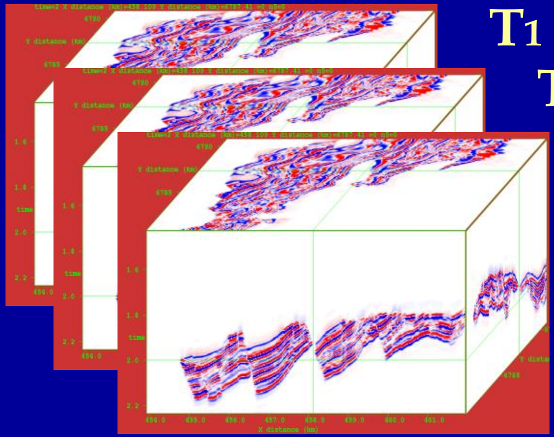
Pp, So, Sw, Sg, Ss, T

Rock Physics



Vp, Vs, ρ

4D Seismic



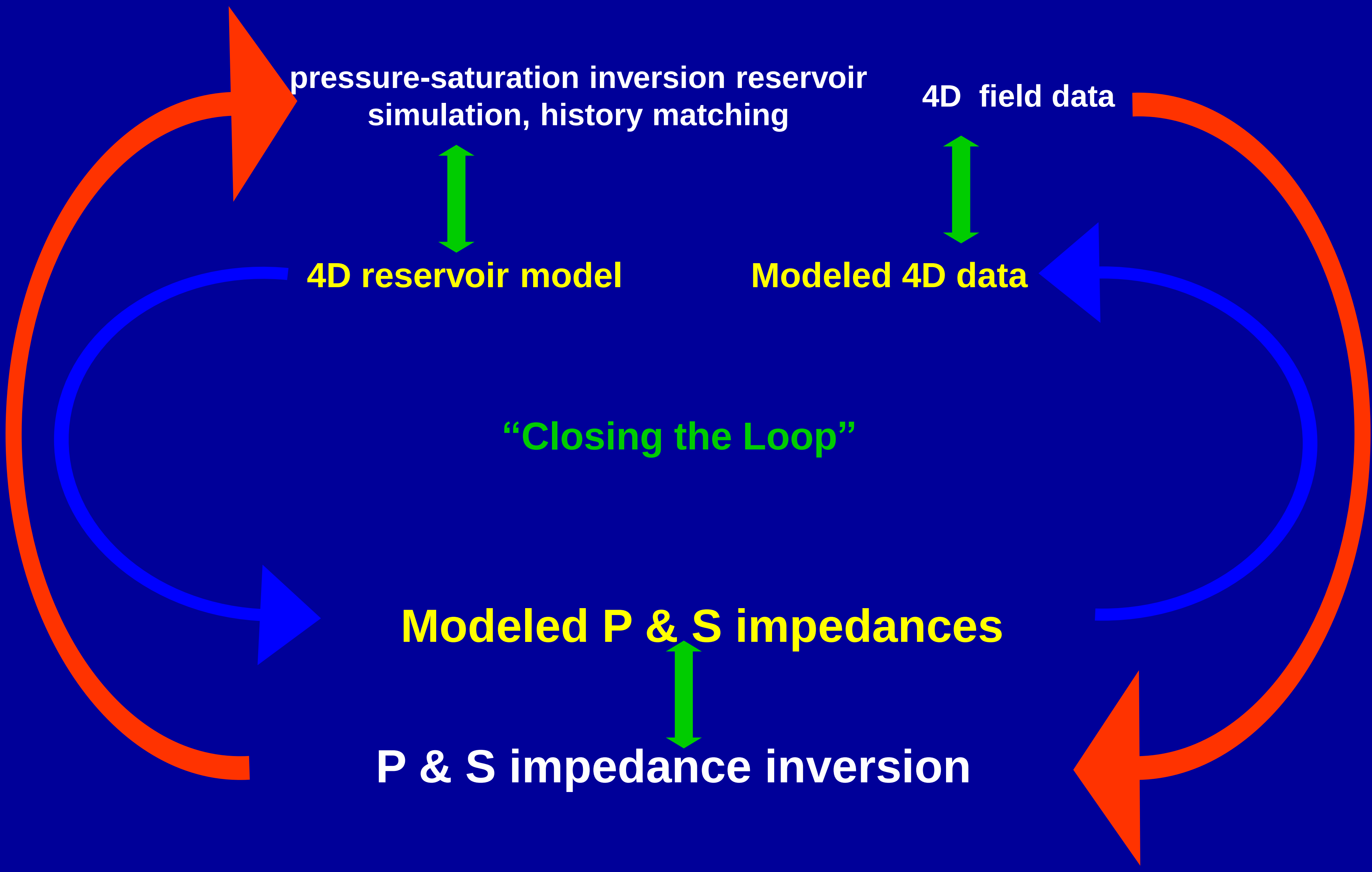
T_1

T_2

....

T_N

4D Modeling/Processing/Inversion



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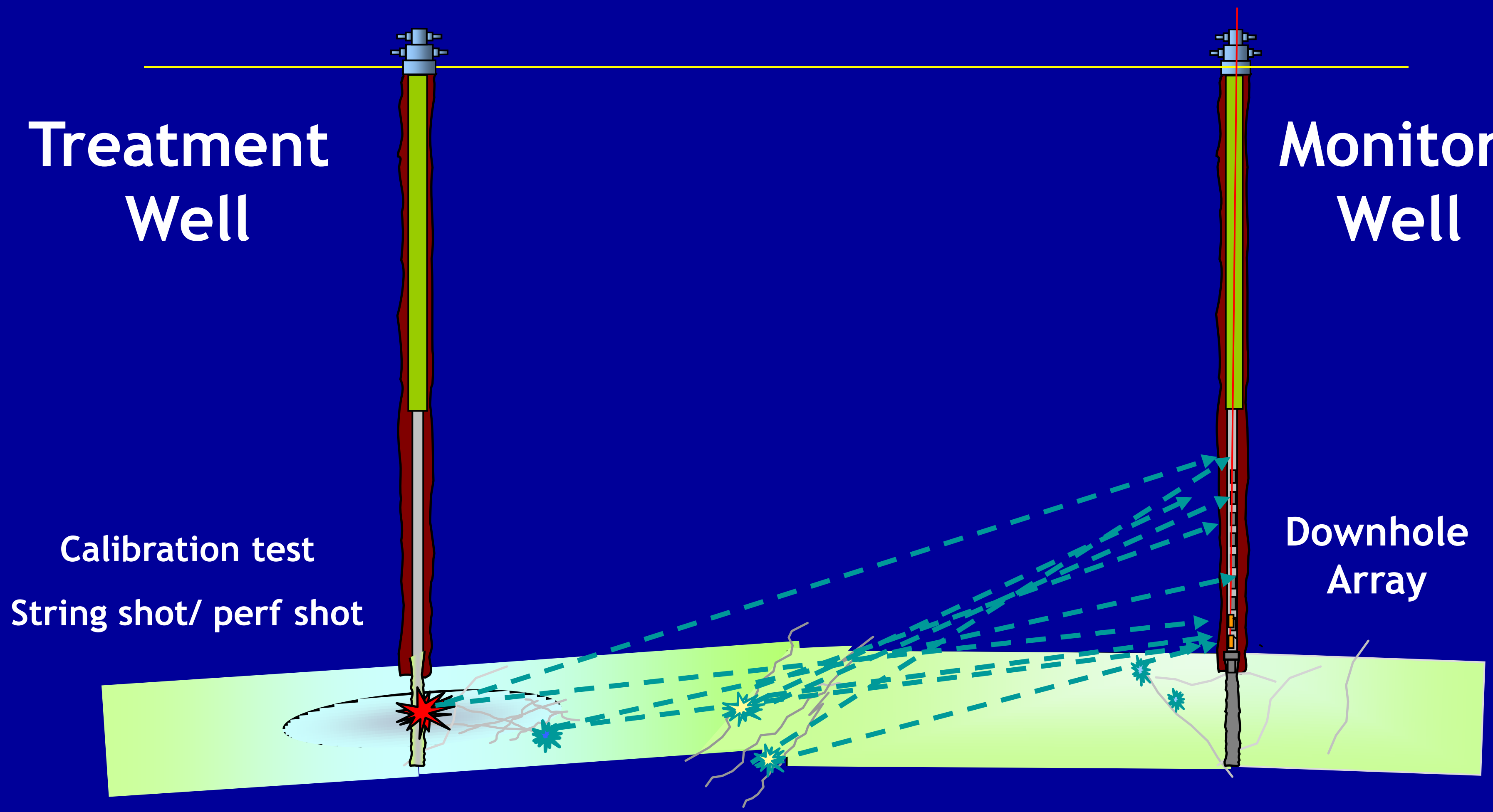
Microseismic monitoring



(Courtesy of Aramco)

Microseismic Monitoring Applications

- Estimate large-scale permeability distribution
- Fracture stimulation optimization
  - pump rate
  - pump pressure,
  - well pattern optimization
  - intervals for multi-stage frac
- Identify areas of potential wellbore instability

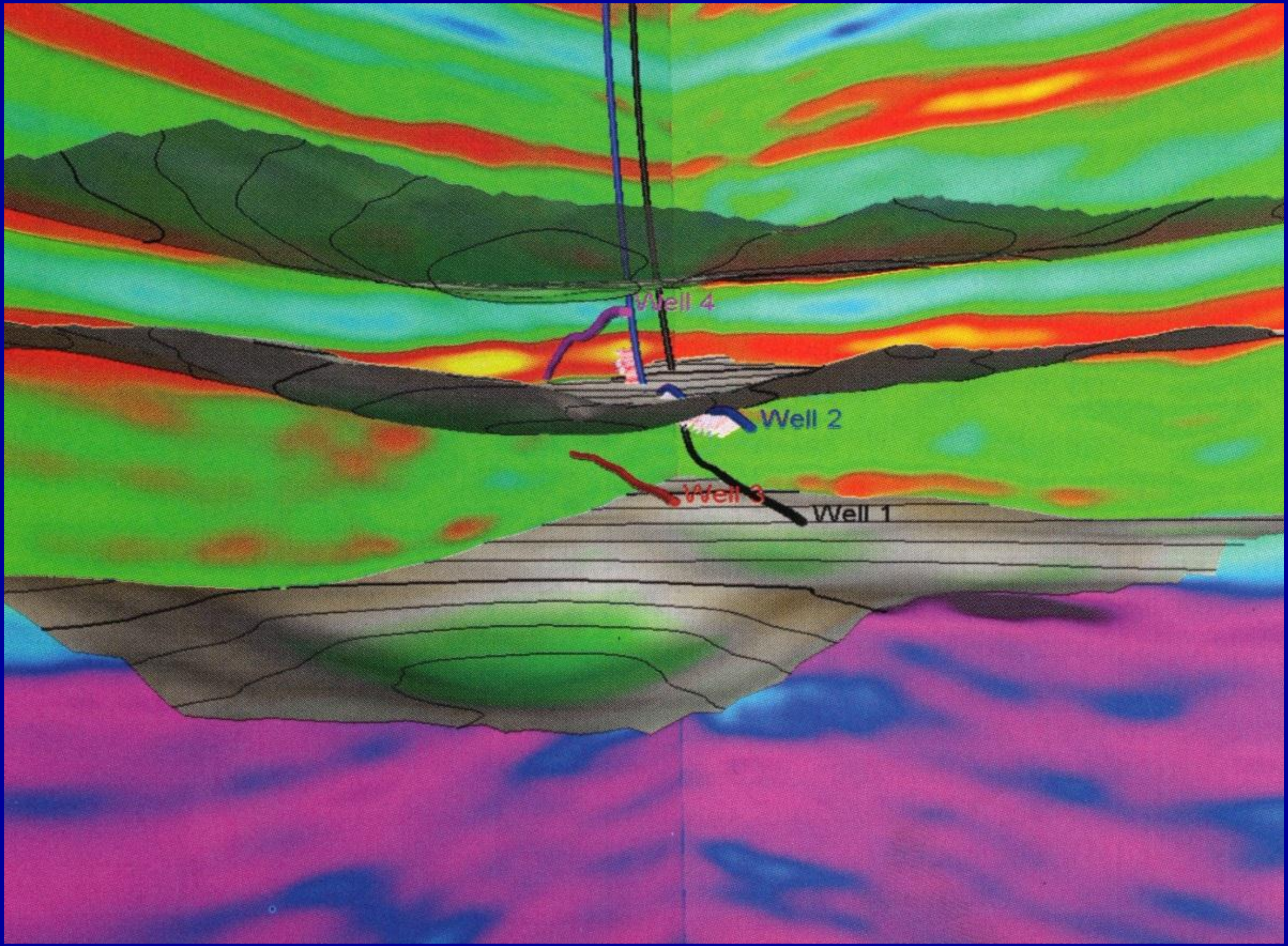
Microseismic Monitoring Applications (cont.)

- Map migration paths in tertiary recovery operations (steam, CO_2) and fluid pressure fronts in real time
- Better understanding of fracture geometry and connectivity
- Determine if existing fractures are reactivated
- Identify reservoir compaction zones
- Determine stress orientation

Multidisciplinary Approach for Hydrofarcking

- **Depth conversion with 3D Seismic and Velocity volume for:**
  - Geosteering
  - Well top information
- **Real time decisions during hydraulic fracturing**
  - Horizons
  - Well top picks
  - Microseismic data analysis.
- **Sonic derived mechanical properties provide insight to the correlation between log and seismic scale information.**

Multidisciplinary Approach for Hydrofarcking



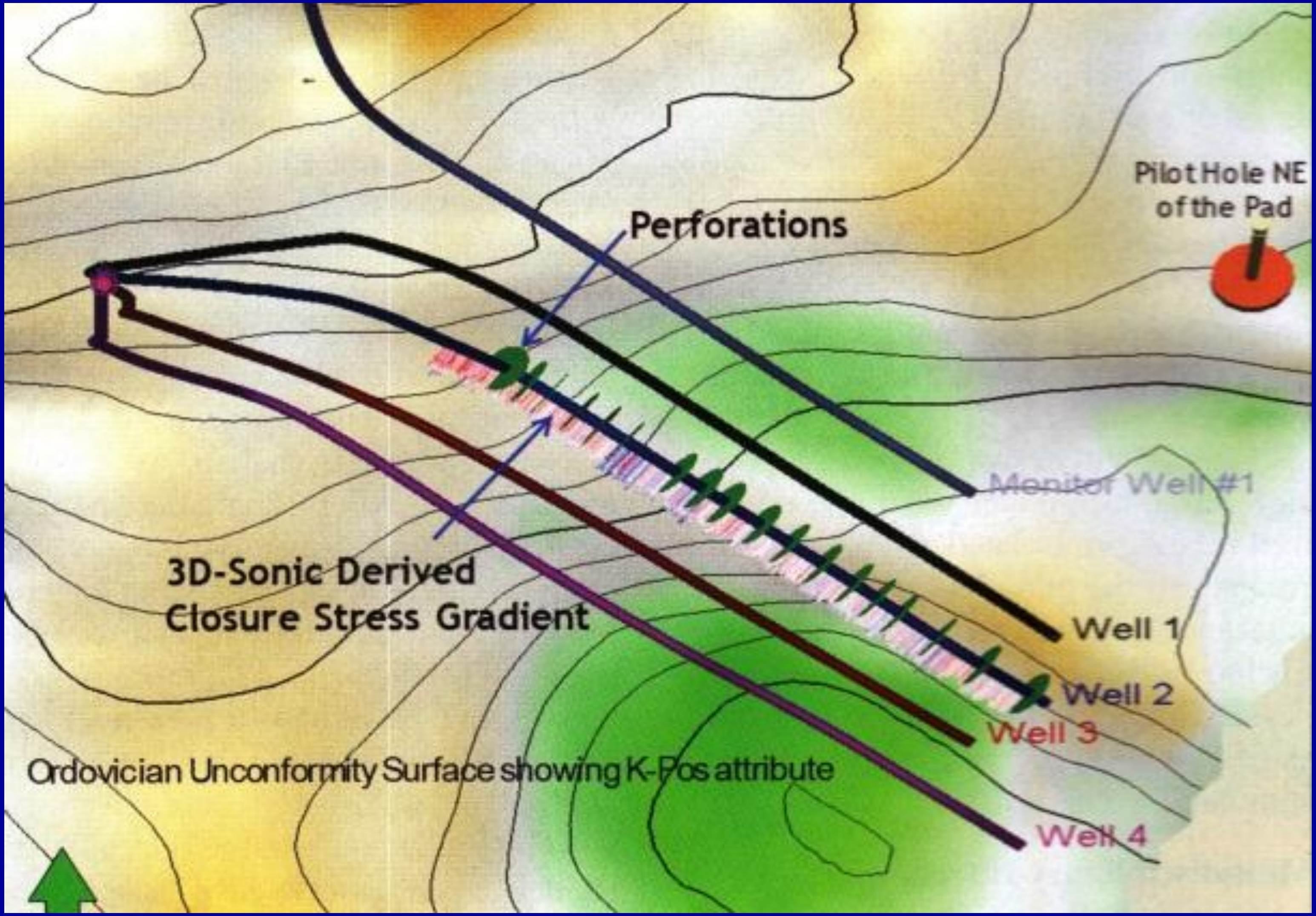
seismic

well top

horizon

well log information

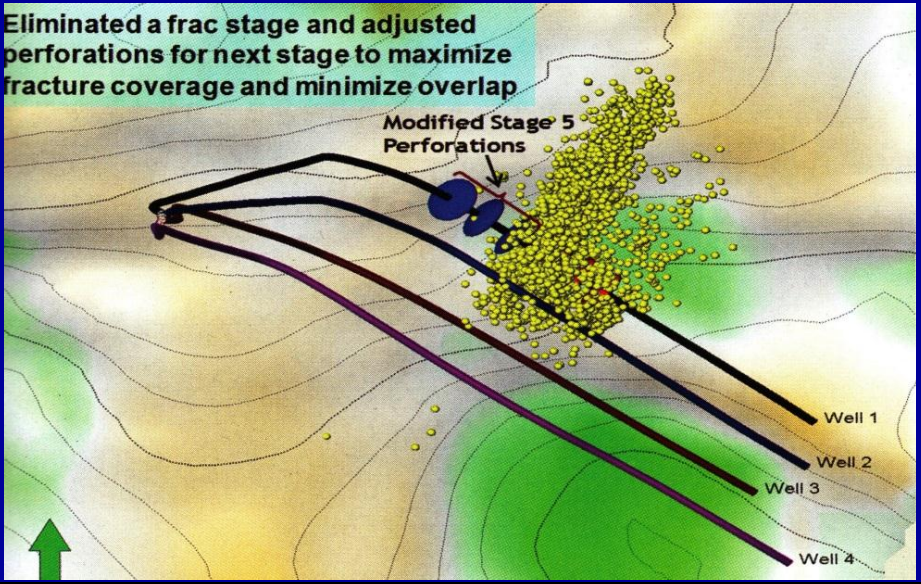
Multidisciplinary Approach for Hydrofarcking

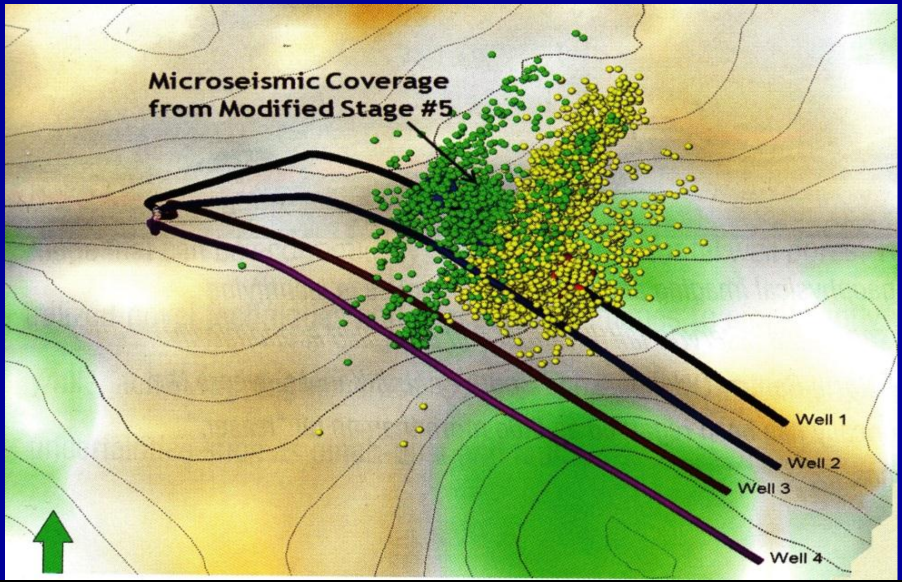


Multidisciplinary Approach for Hydrofarcking

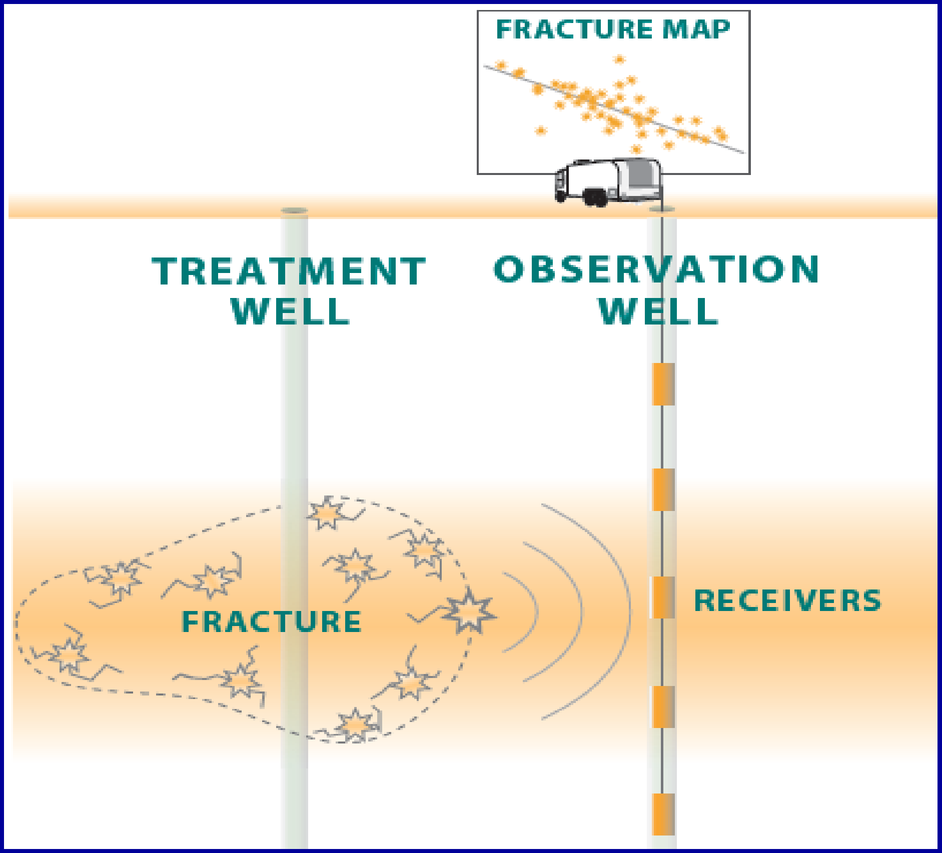
Optimizing staging & perforation design in real time

- Reduces cost by eliminating stages,
- Maximizes the effective stimulation volume

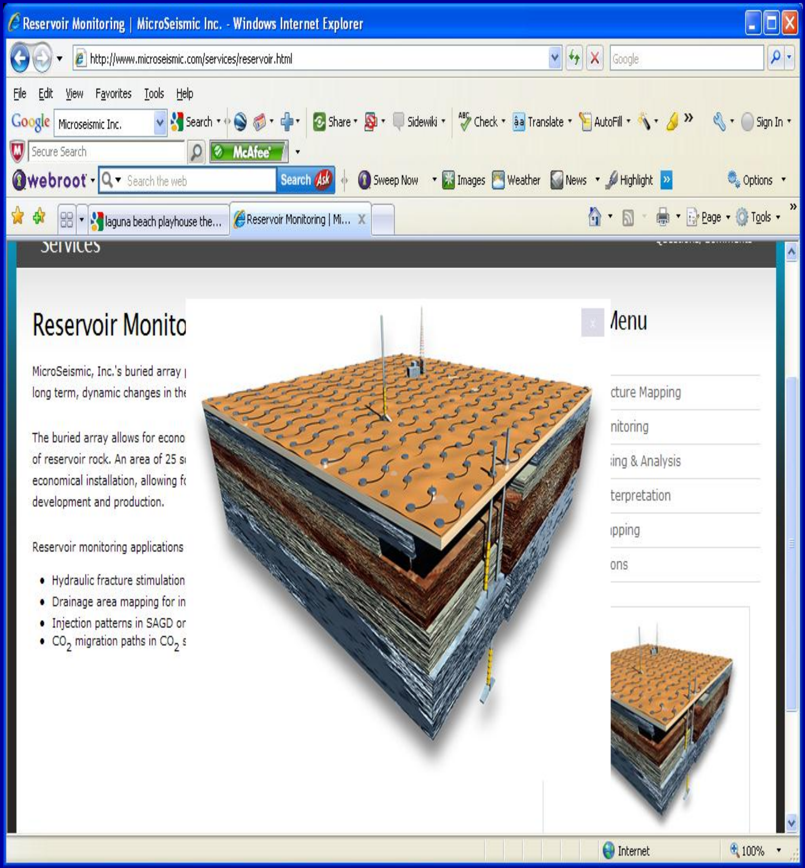




Microseismic monitoring induced fractures

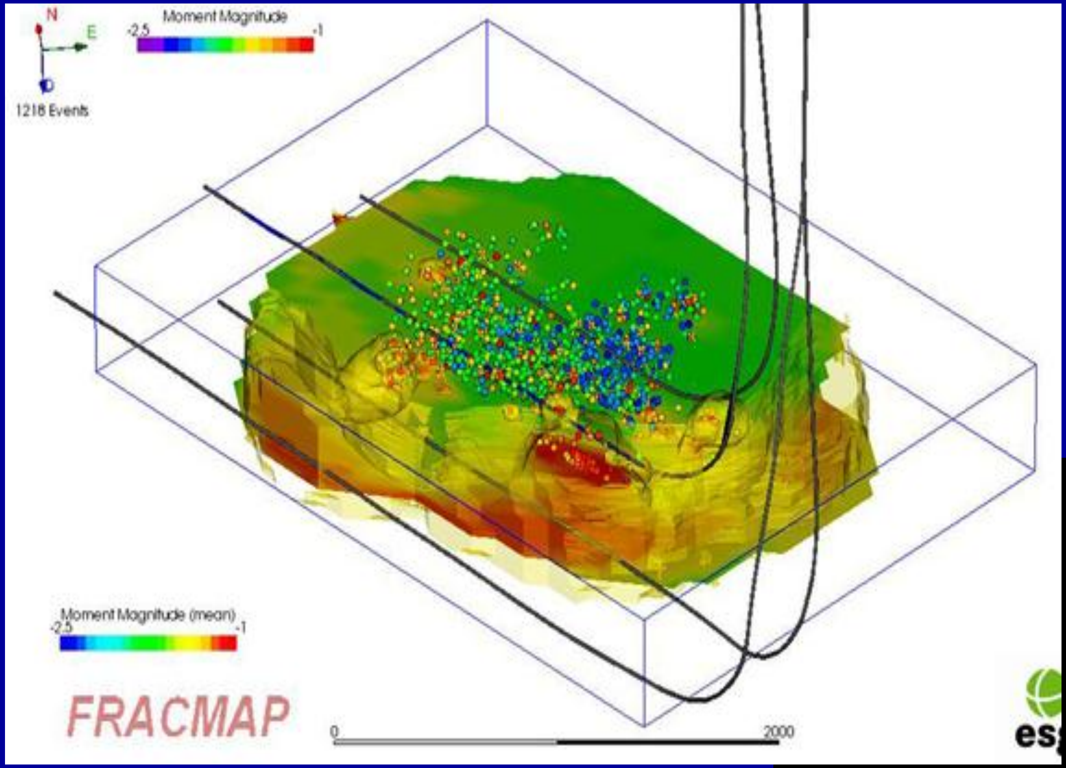


Halliburton

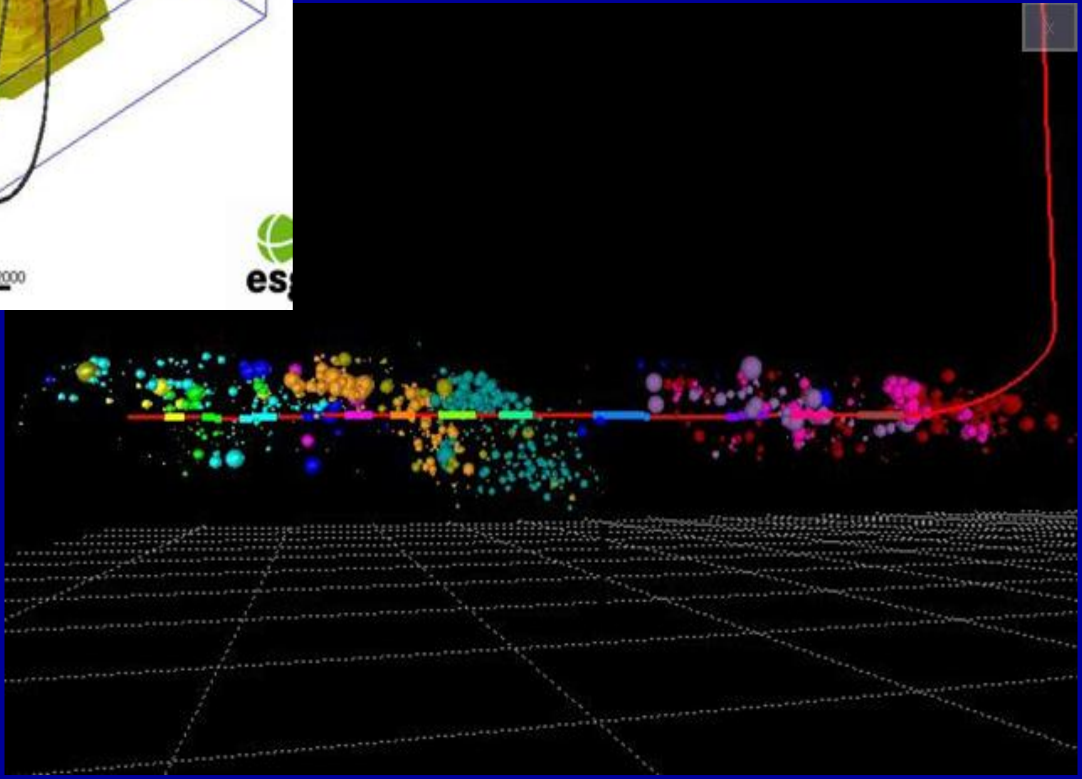


Aramco

Micro-seismic to Monitor Horizontal Well Stimulation



ESG, Inc.



Microseismic, Inc.

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Applications

- Porosity / saturation / permeability change
- CO_2 sequestration & monitoring
- Carbonates
- EOR – Life of field

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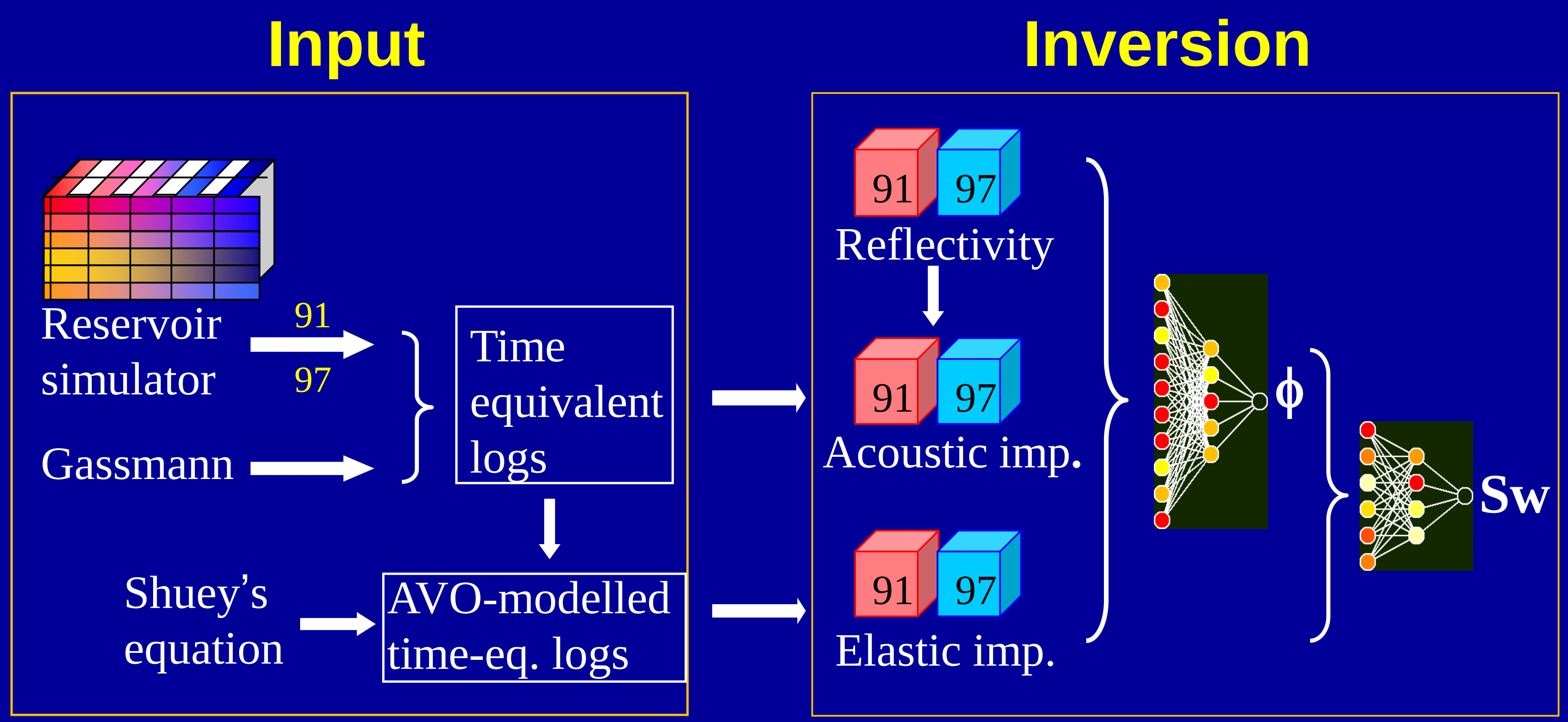
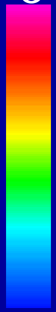
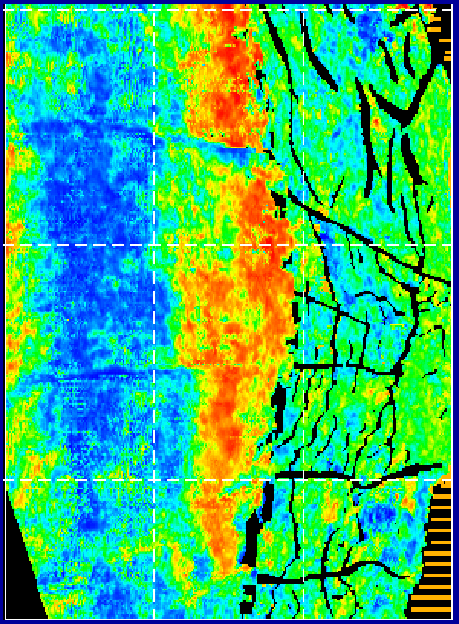
Time-lapse Saturation Inversion



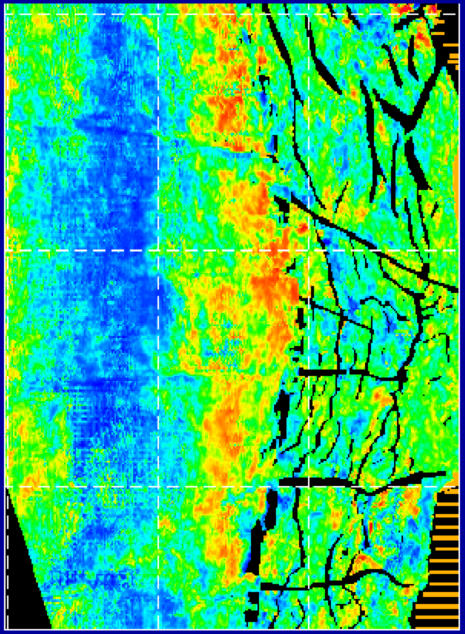
Changes in Water Saturation



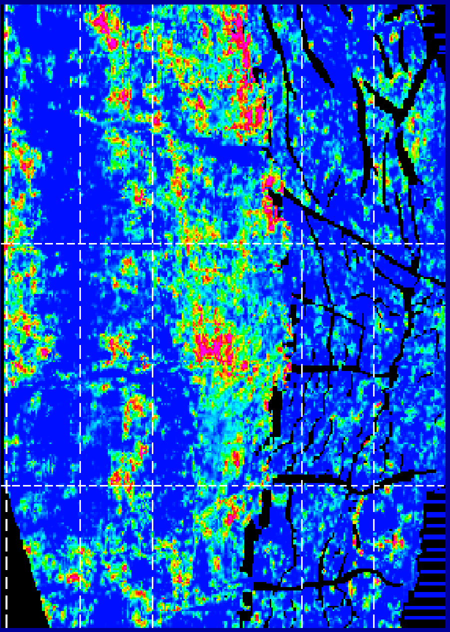
Saturation 91



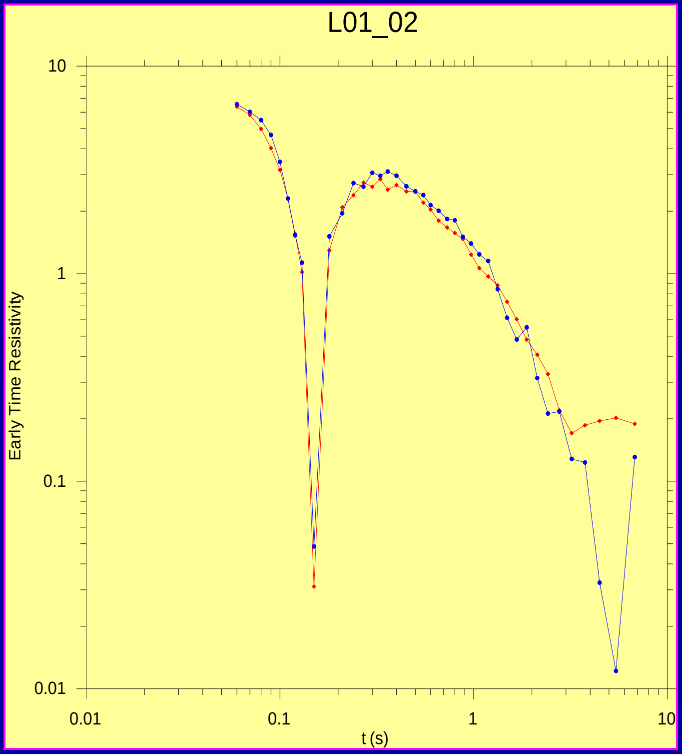
Saturation 97

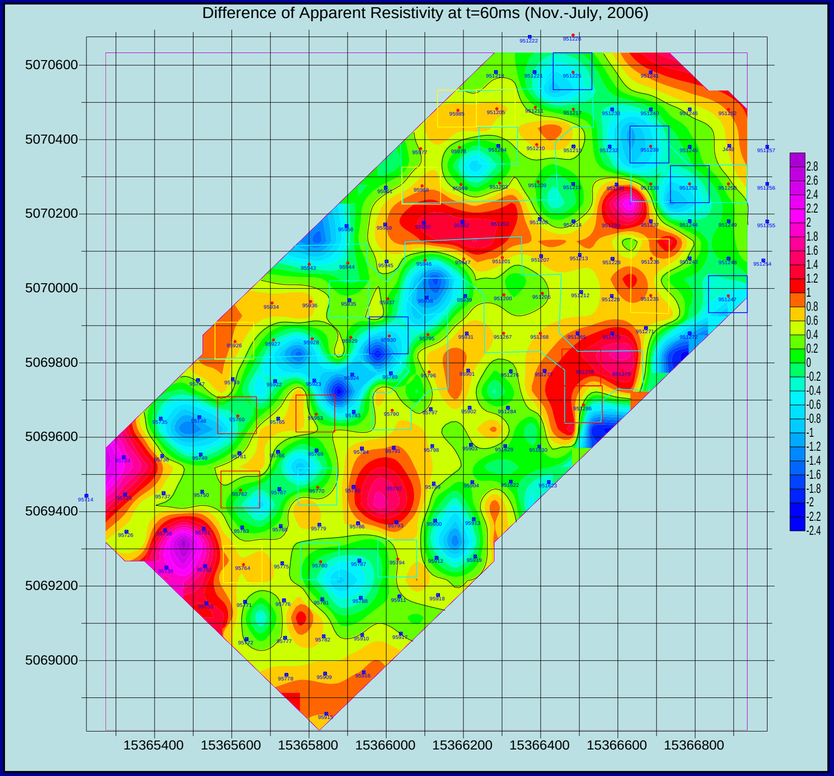


Difference 97 - 91



Time lapse surface TEM for monitoring permeability change, China field test:,





Apparent resistivity- data repeatability

Resistivity differences: permeability; low→ high

Courtesy of KMS Technologies

Applications

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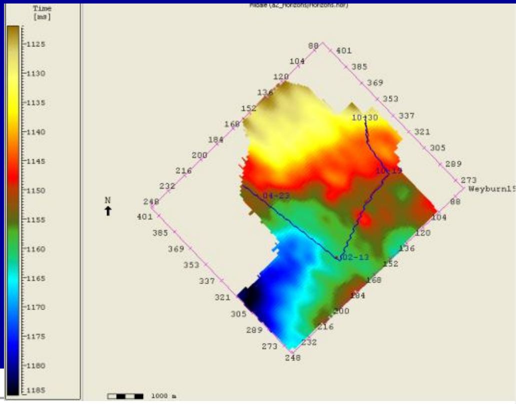
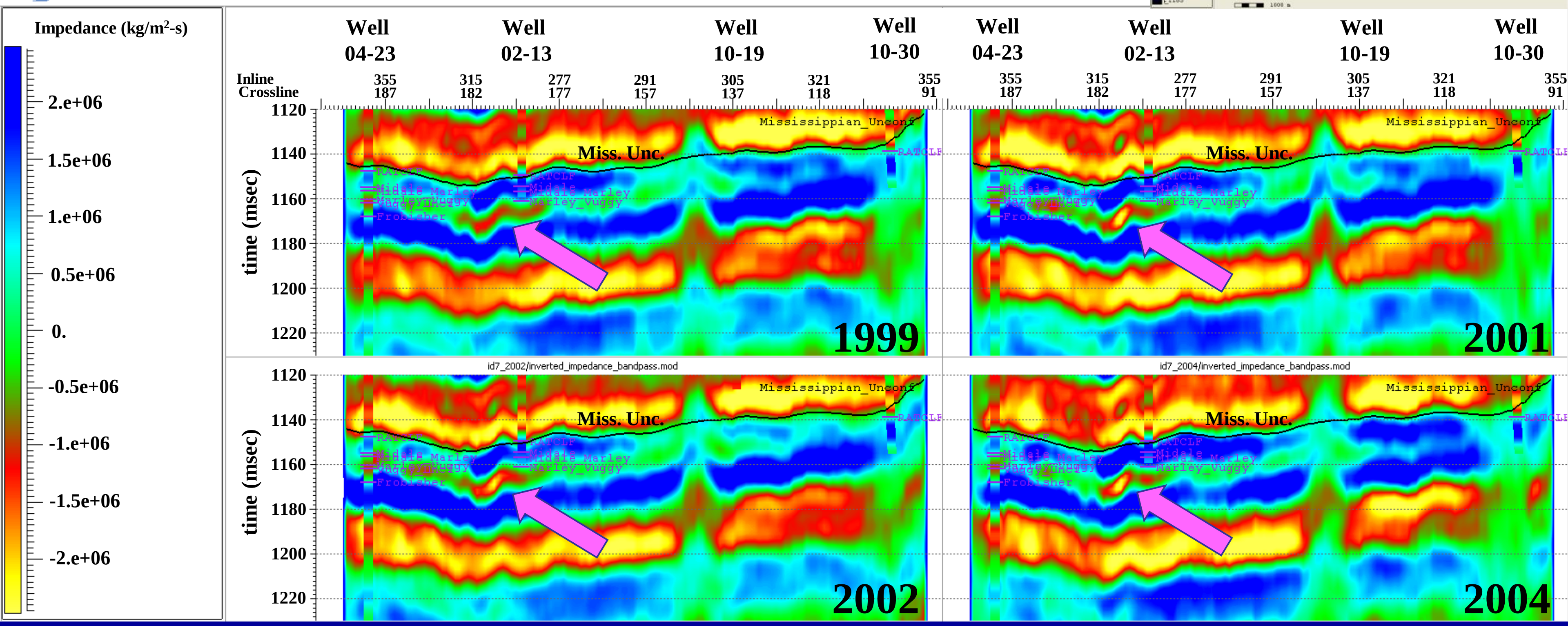
- EOR – Life of field

Monitoring CO_2 Injection

P-impedance along traverse

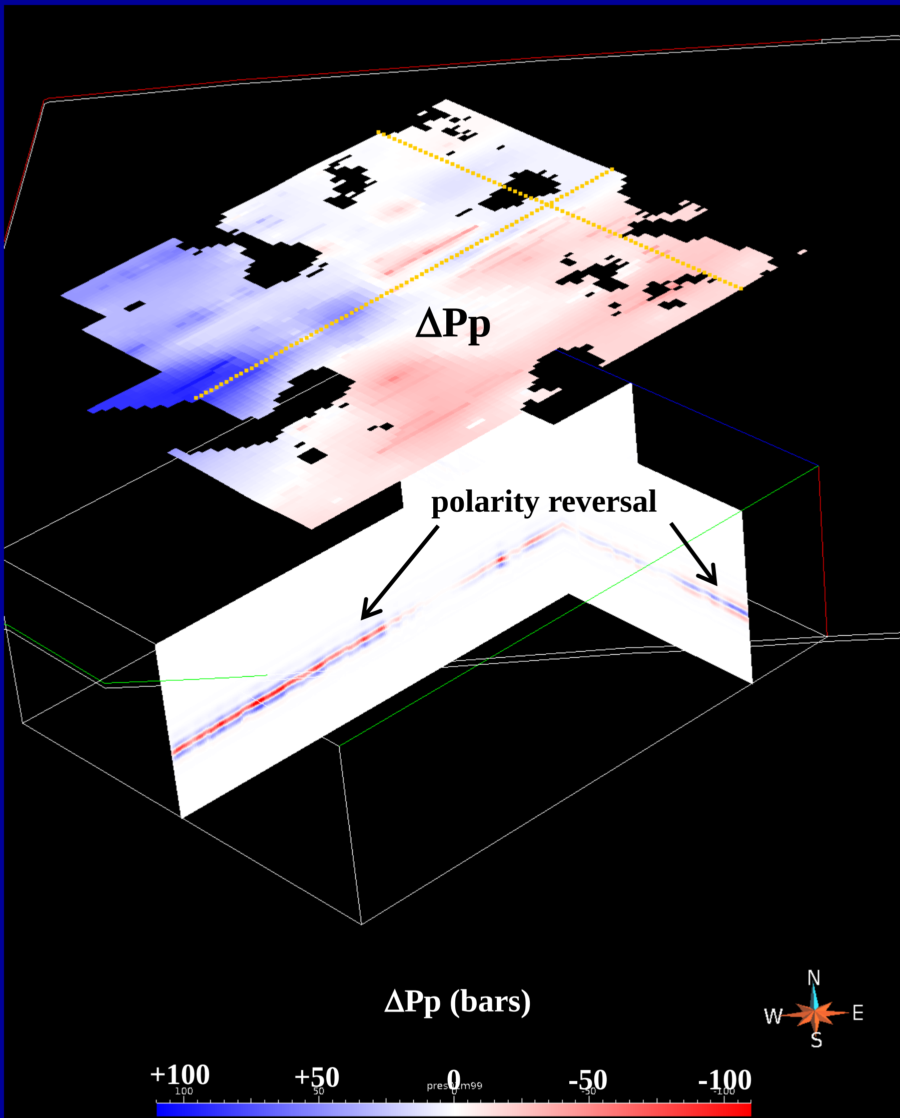
~10% decrease

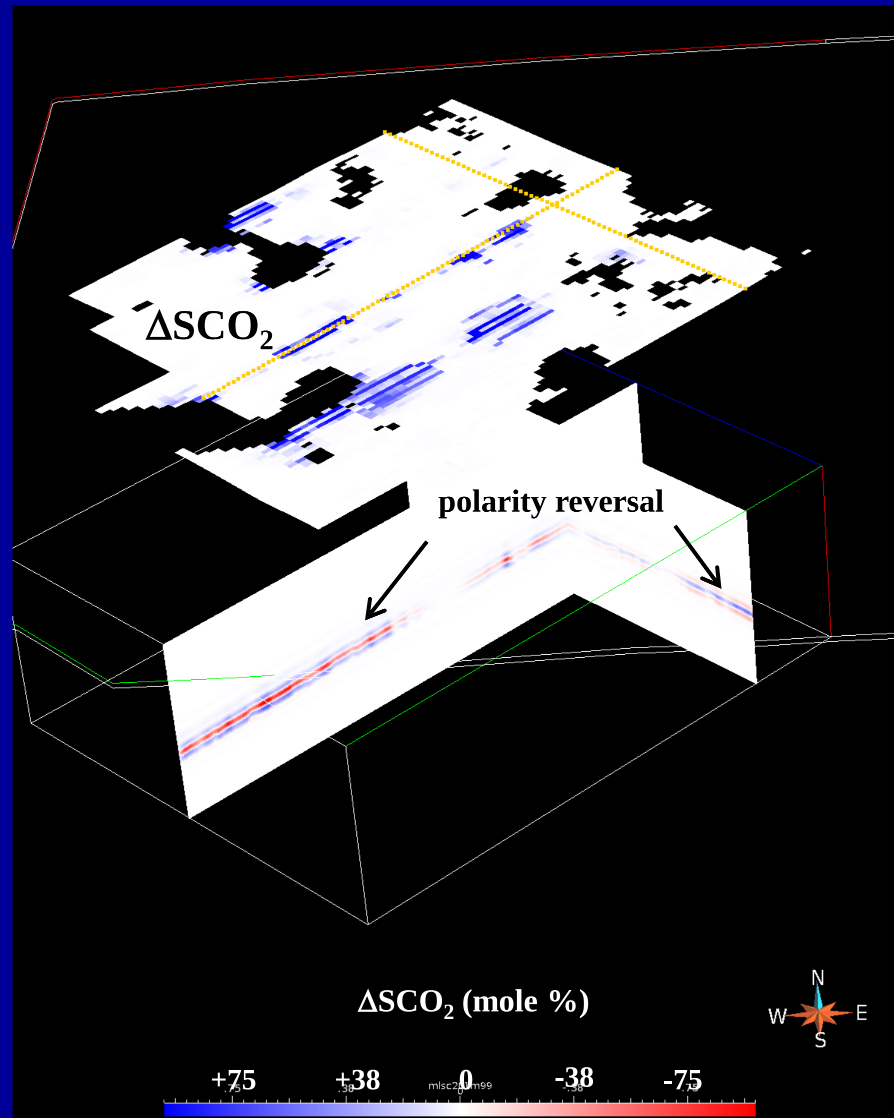




Courtesy Fugro

Monitoring CO_2 Injection
Changes in Reservoir Properties





Courtesy Fugro

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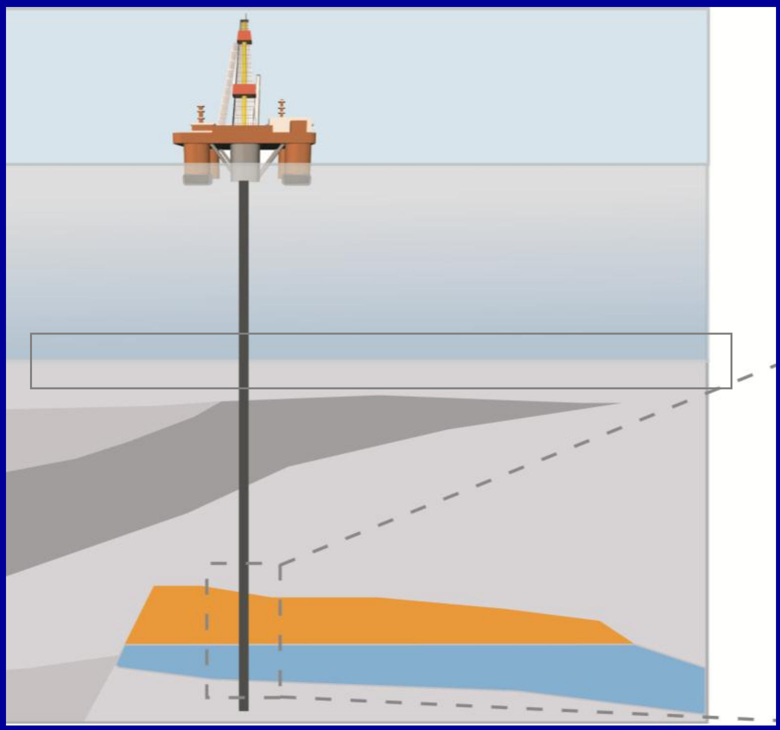
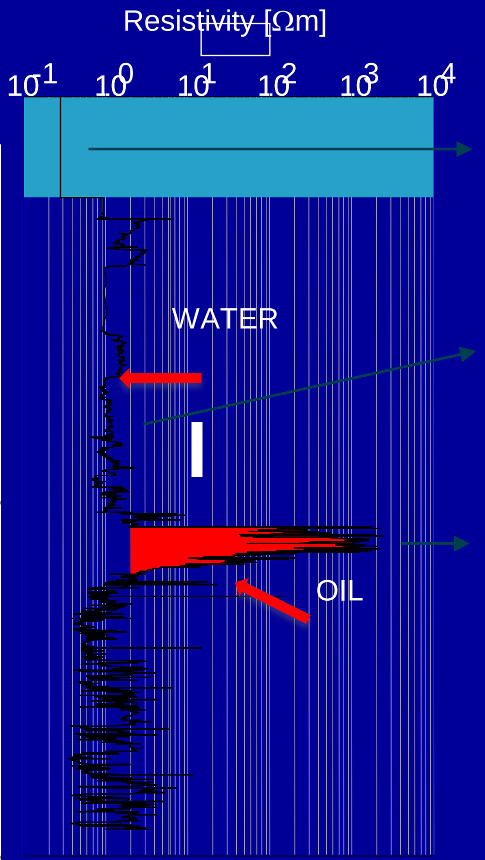
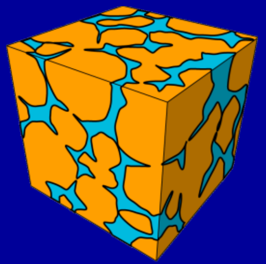
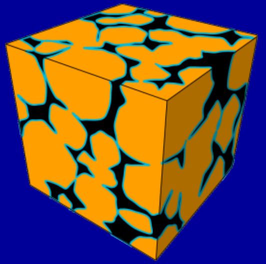
Integrating Seismic, well logs, and EM







Water-bearing sediments: 1 - 2 Ωm

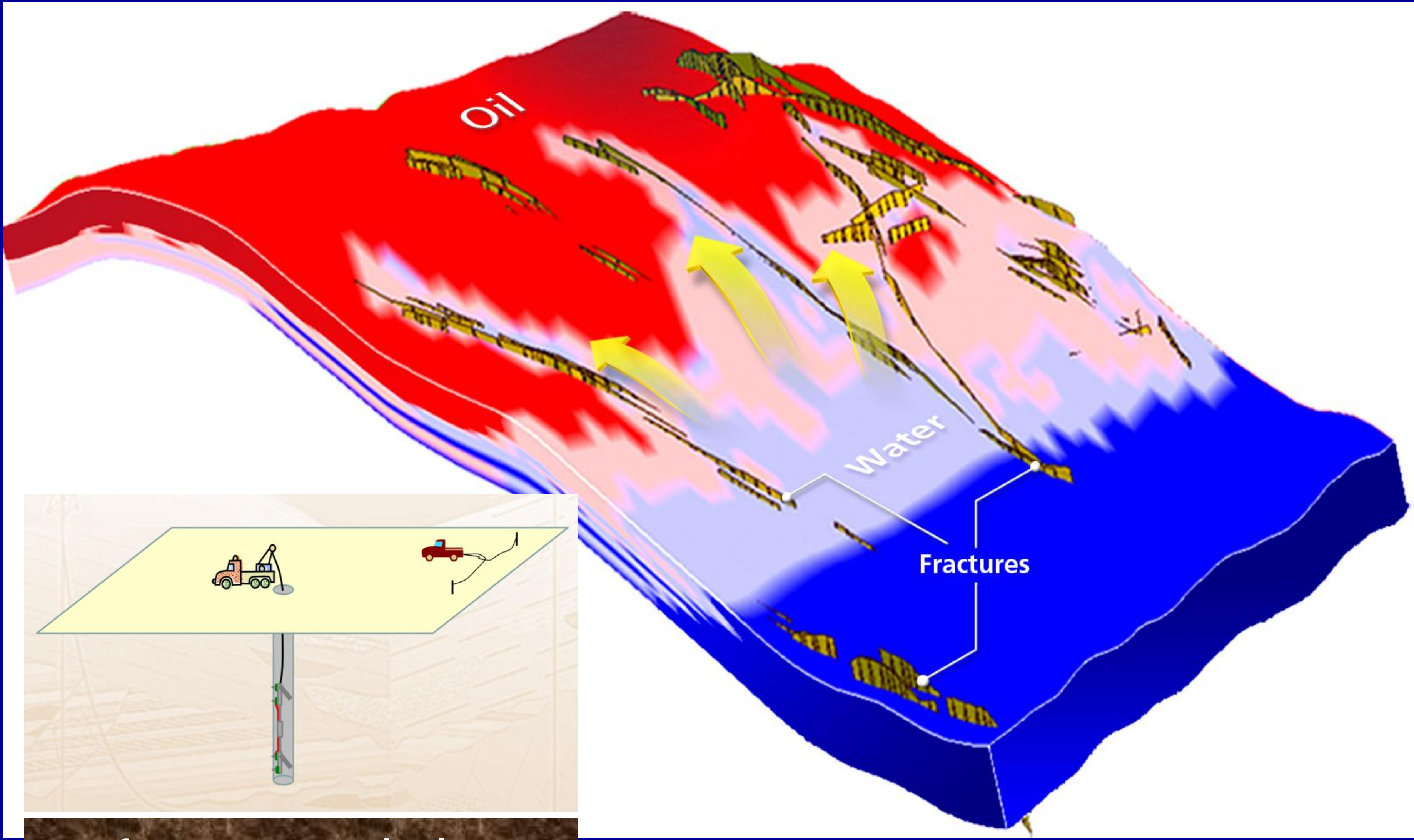


Hydrocarbon reservoirs: 10 - 100 Ωm

Seismic → geologic structure → resistivity log → EM

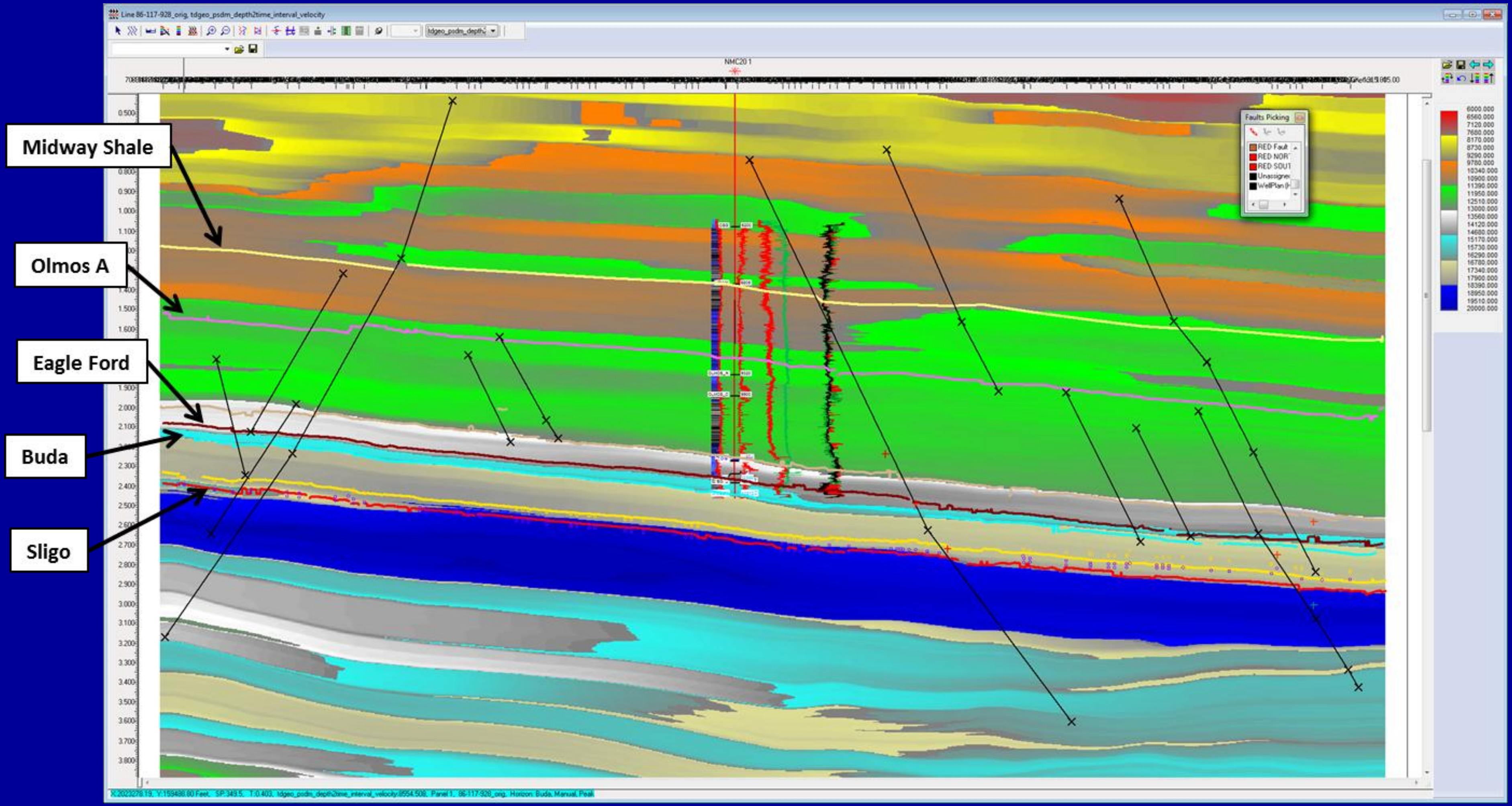
Adopted from EMGS

Fluid displacement heterogeneity



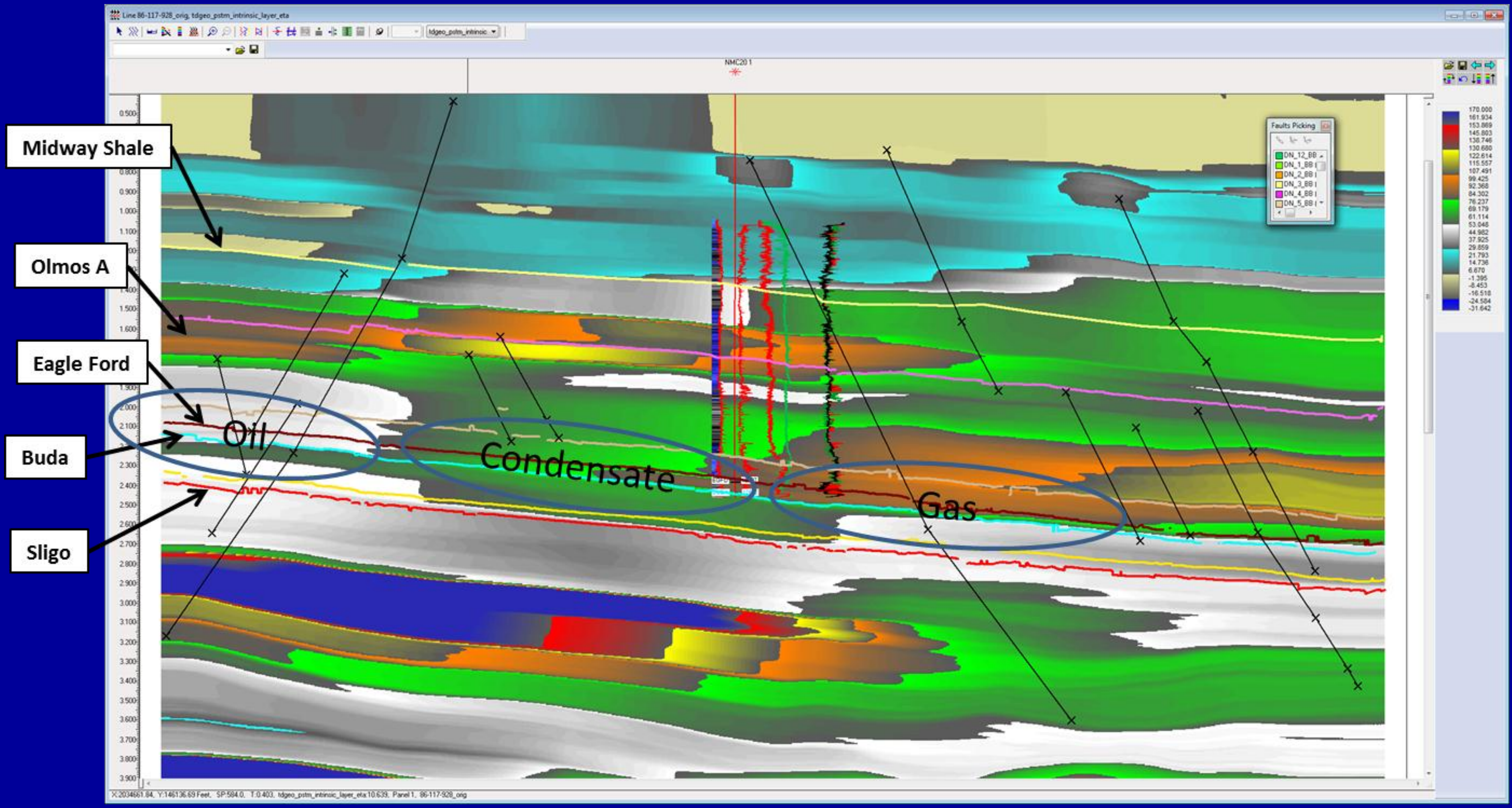
Surface to Borehole EM

Velocity map in a shale reservoir



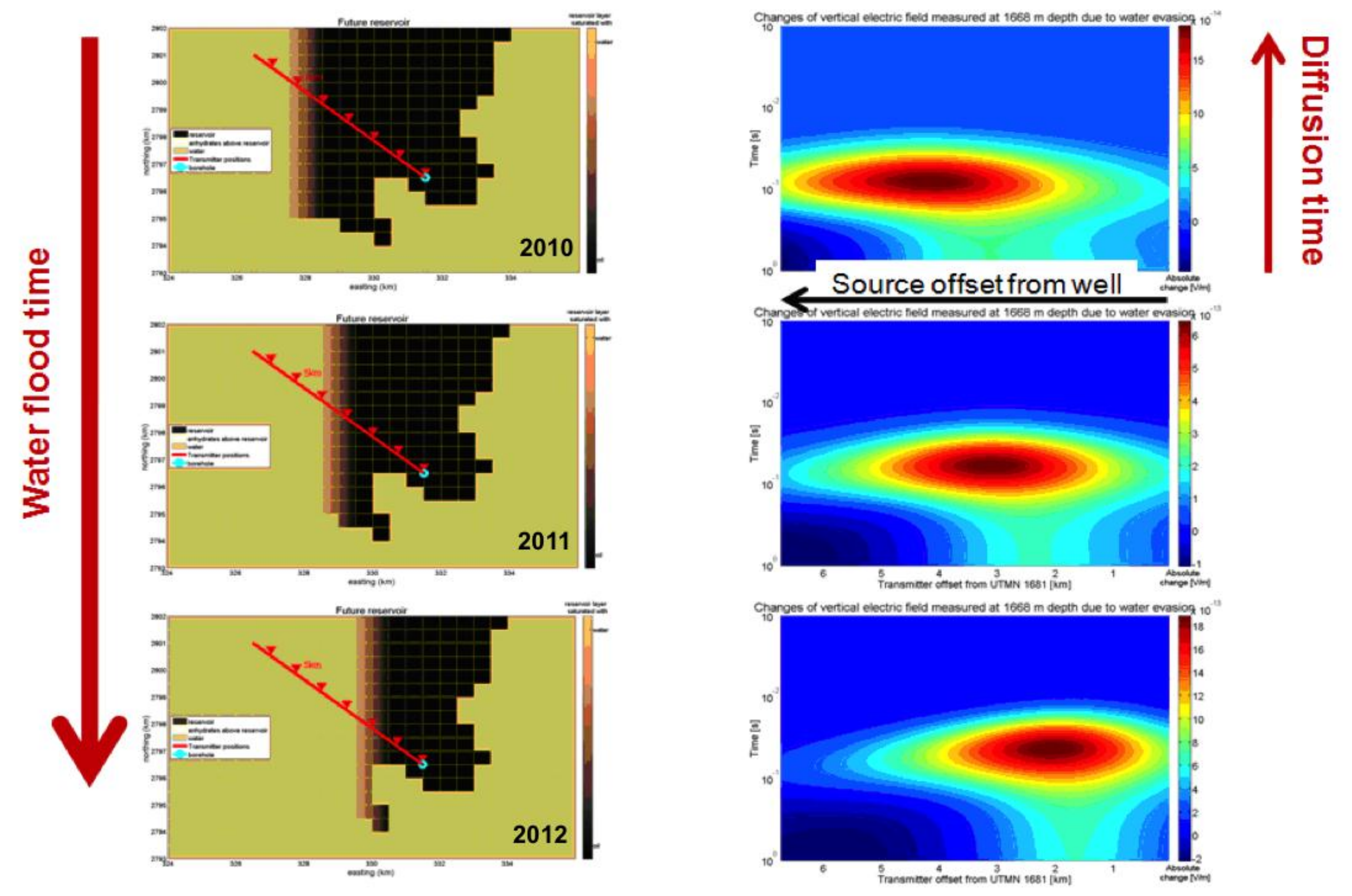
Courtesy of TDGEO

Fluid phase from velocity anisotropy



Courtesy of TDGEO

Application of EM in carbonates (Ghawar field)



After Colombo et al., 2009

Courtesy of KMS Technologies

Applications

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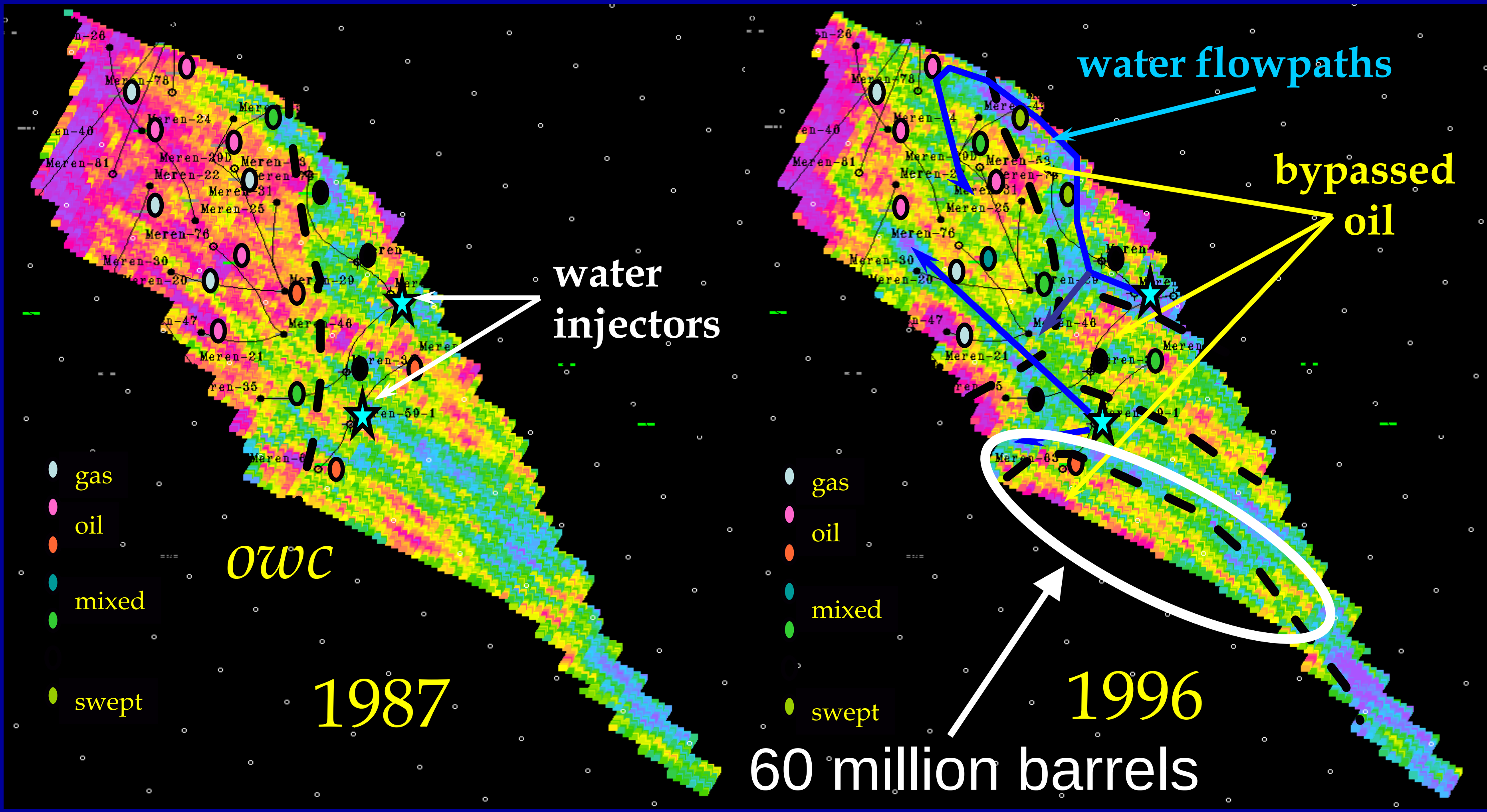
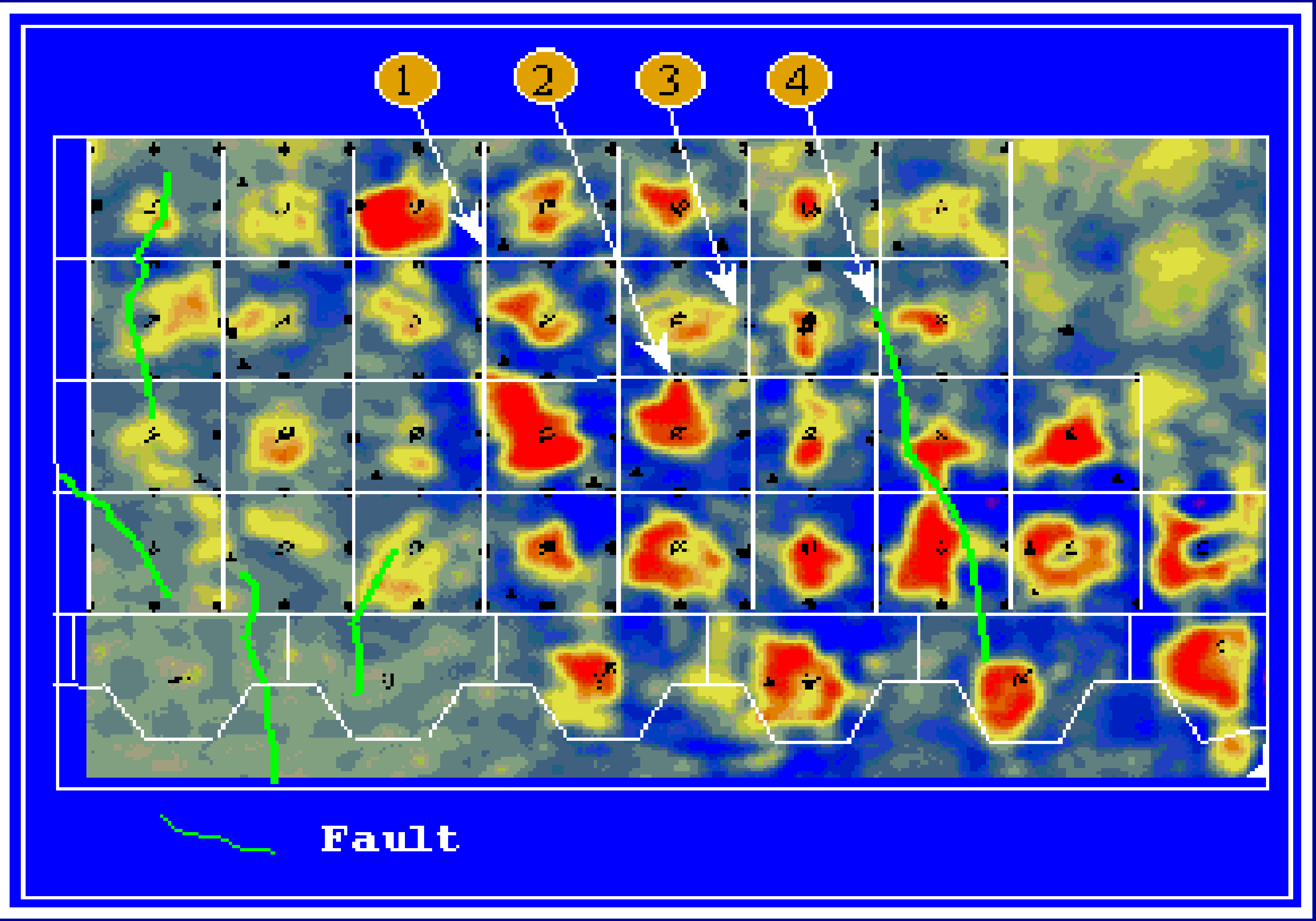
Meren waterflood, Nigeria



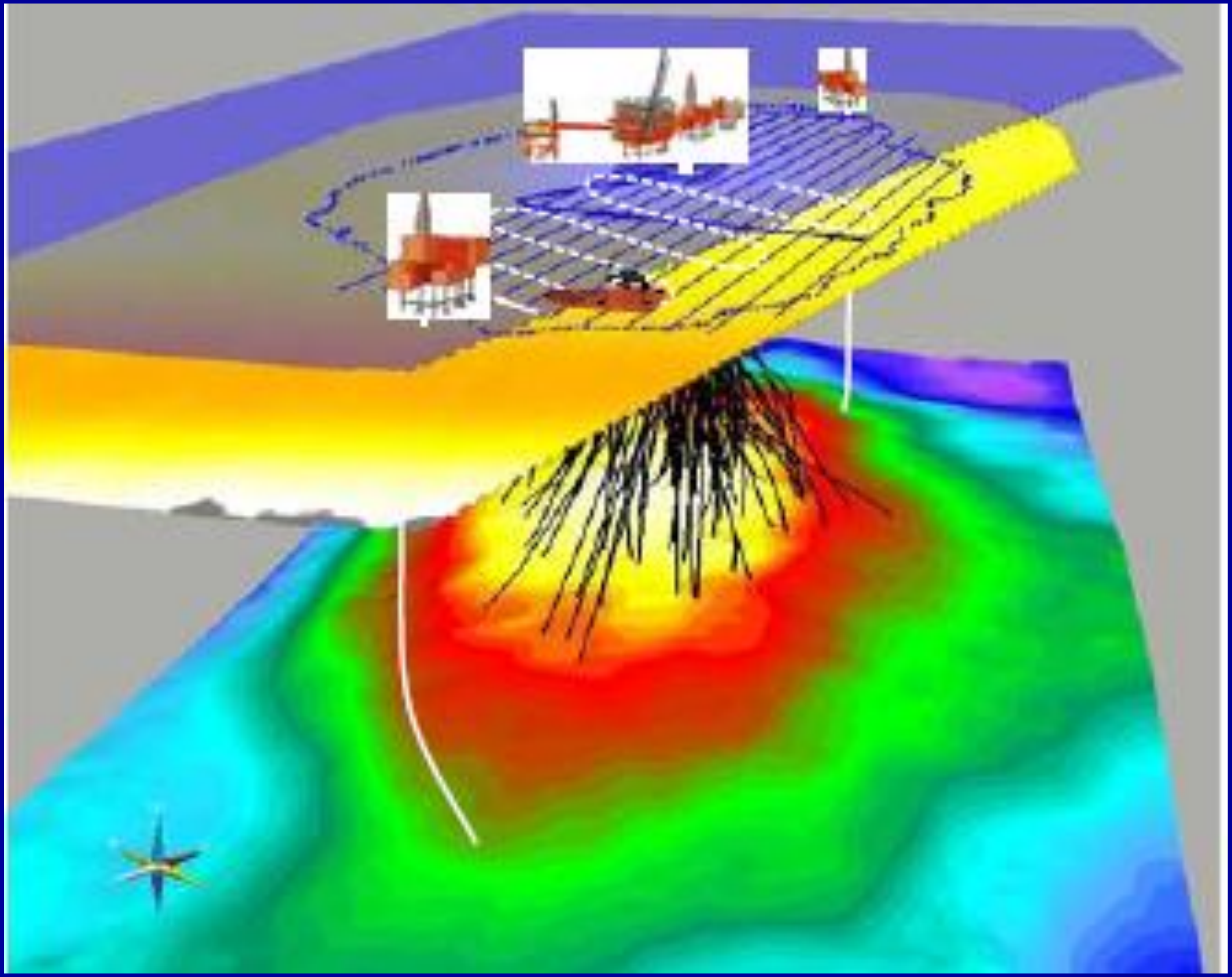
Lumley et al. (1999)

Duri steam-flood, Indonesia



Sigit et al. (1999)

Life-of-field monitoring at Valhall

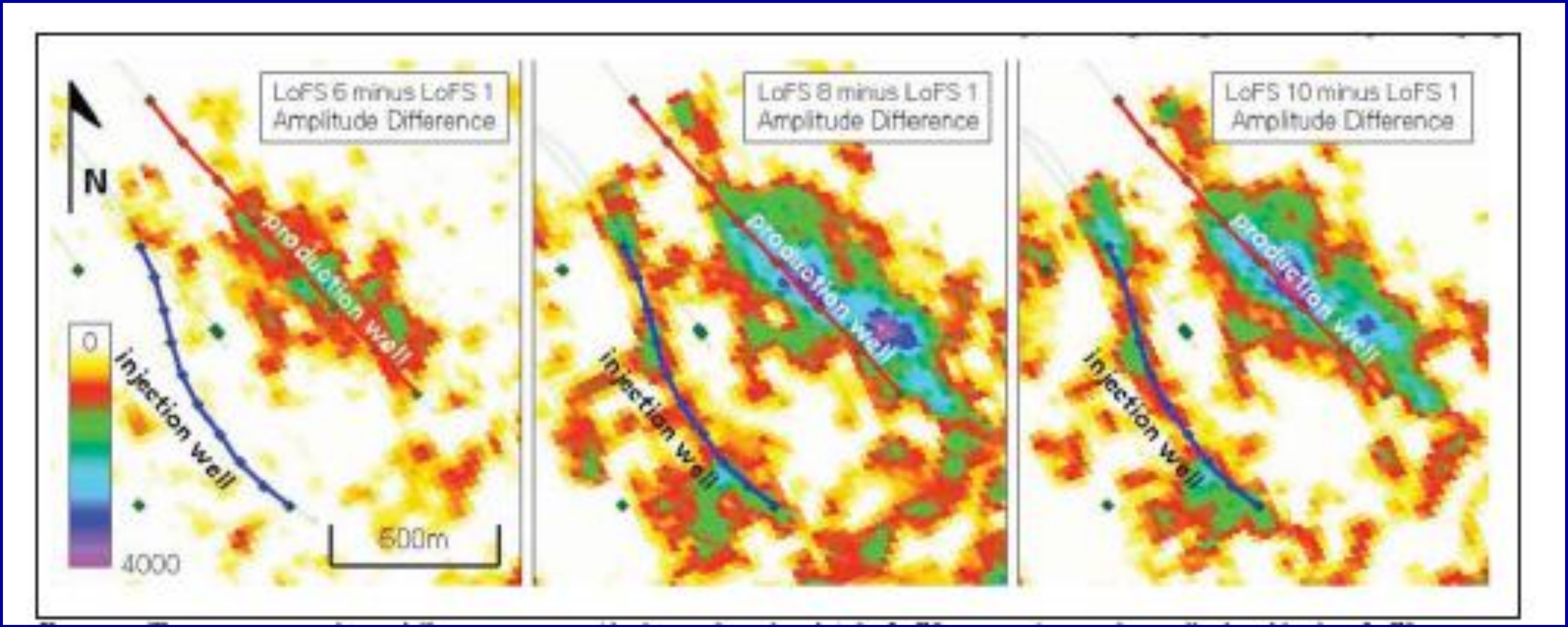


Data Acquisition and Preliminary reservoir model

Barkved (2004)

Life-of-field monitoring at Valhall

Time6-Time1 **Time8-Time1** **Time10-Time1**

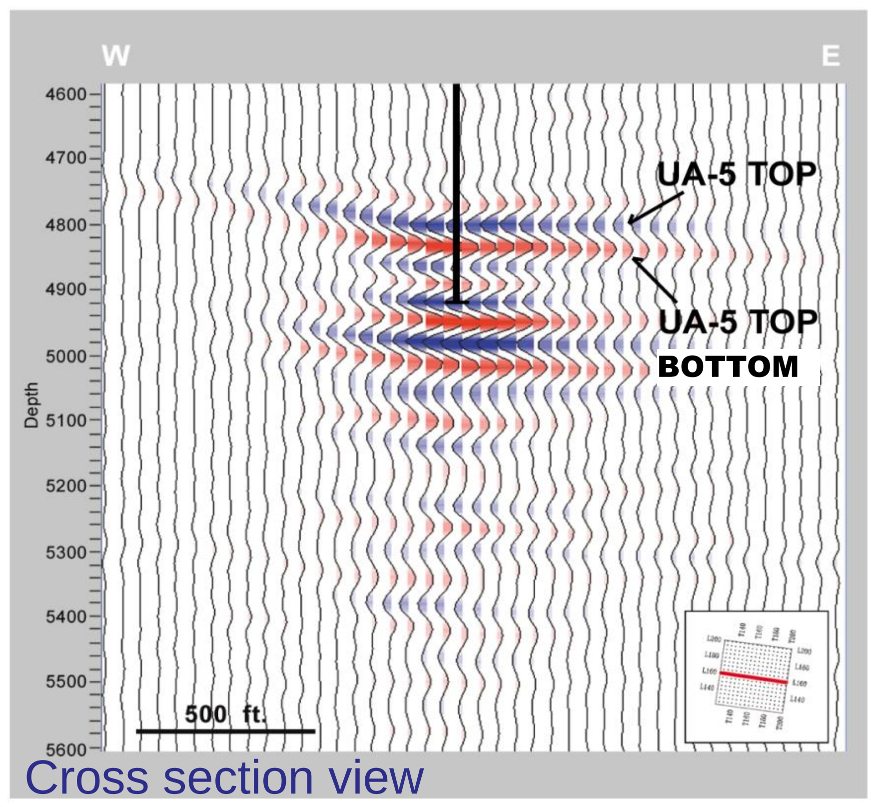


Time 1: (pre-injection)

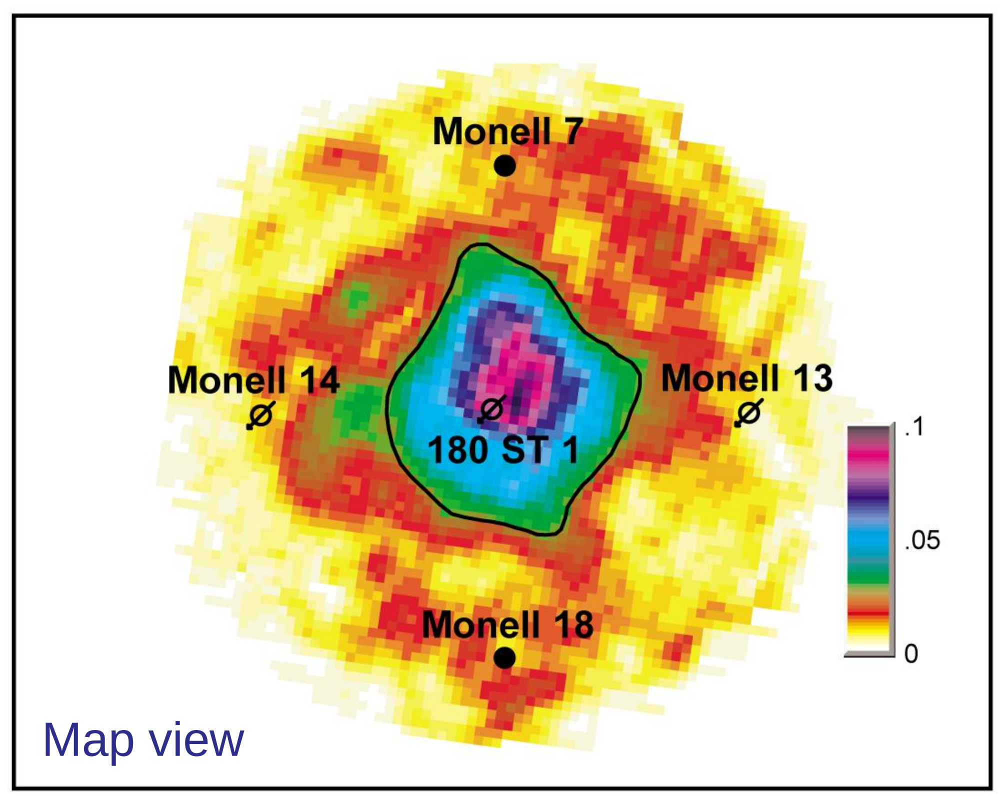
van Gestel et al. (2008)

CO2 Flooding in Monell field, WY

Time-Lapse 3D VSP Survey – 18 Month Amplitude Difference



Cross section view



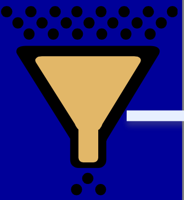
Map view

	Pre CO_2 flood	Peak Production during CO_2 flood
Monell 7	10 bbl/d	80 bbl/d
Monell 18	10 bbl/d	25 bbl/d

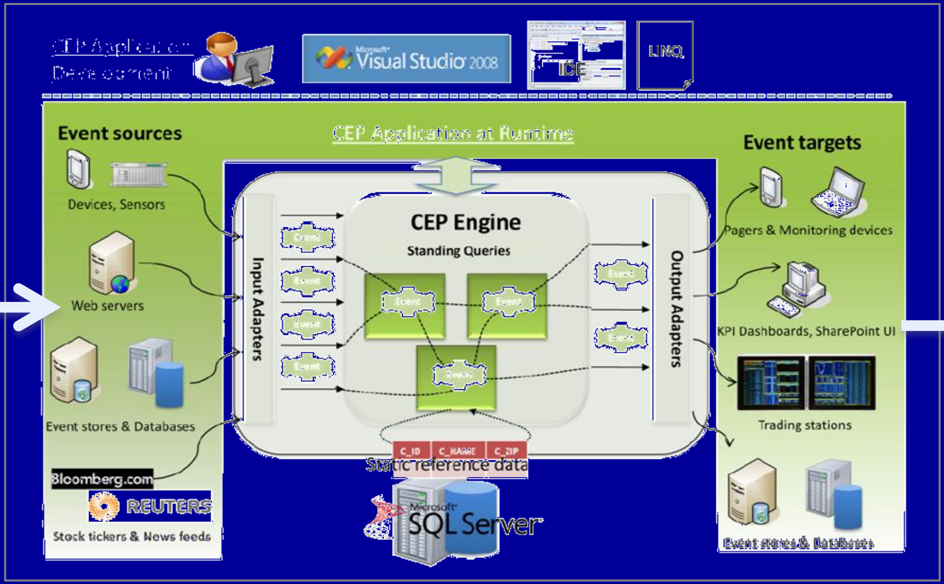
Courtesy of SR2020 Inc.

Real-Time Processing of Reservoir Data Streams

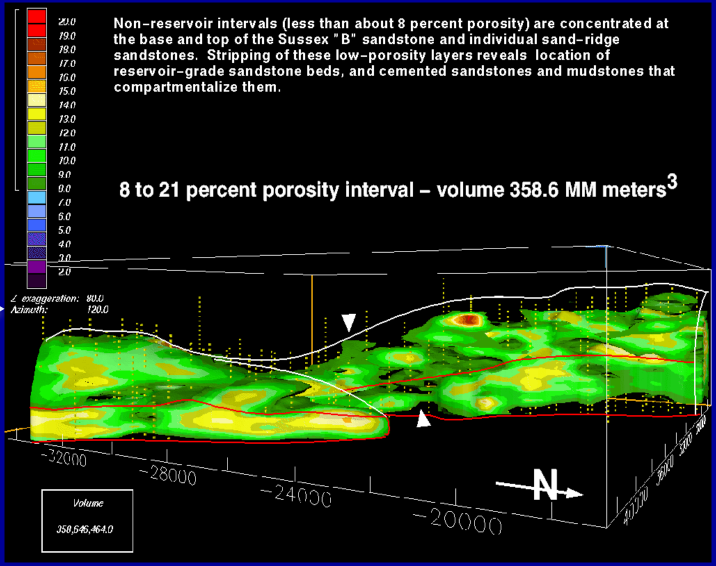
Input Streams



Data Stream Processing Engine



Dynamic Reservoir Characterization



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RMC Projects

Directly Related to Monterey Shale

Indirectly Related to Monterey Shale

Optimize Hydraulic fracturing for shale

Physical Models to monitor reservoir fluid

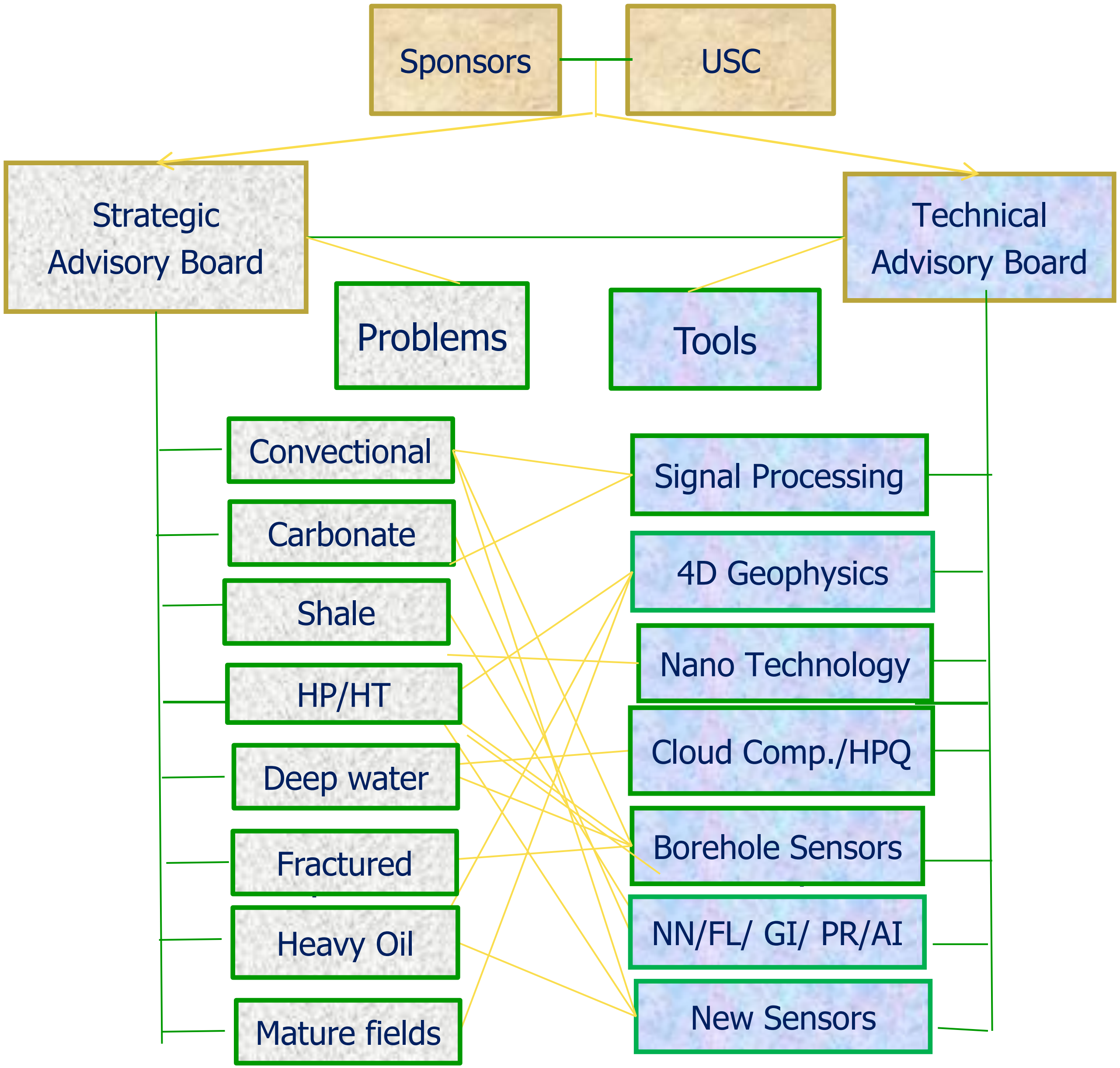
MEQ to Map Reservoir Structure

Time lapse Petrophysics for RM

MEQ & Seismic Integration for Shale Reservoirs

Tomography Based Reservoir Modeling

RMC at a Glance



MEQ & Seismic Integration for Shale Reservoirs

Optimize Hydraulic fracturing for shale

Physical Models to monitor reservoir fluid

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Time lapse Petrophysics for RM

Tomography Based Reservoir Modeling

Integration of microseismic data for reservoir characterization

USC Viterbi School of Engineering

Key Idea - Integration

- Understand the complexity of the fracture networks
- Enhance resolution/ coverage
- Improved reservoir property estimates
- Improve fracture network models and their time lapse growth estimates

Stimulation

Hydraulic fracturing

Acquisition

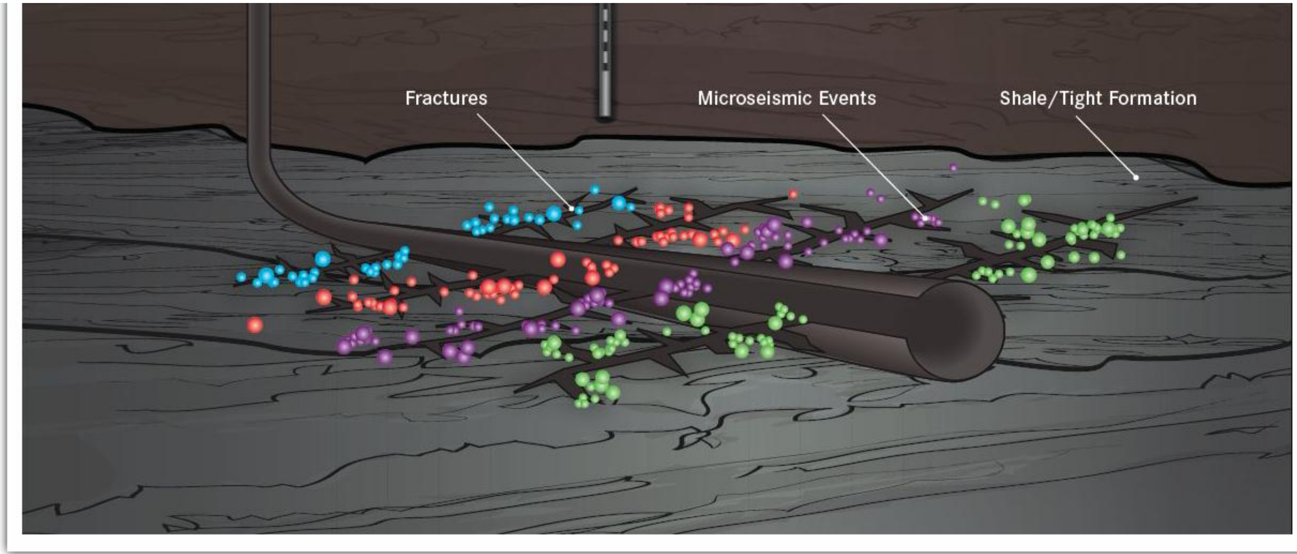
Induced Seismicity

Analysis

- Improved event locations & property estimates
- Integrated analysis – seismic + microseismic
- Accurate property models
- Inverse modeling

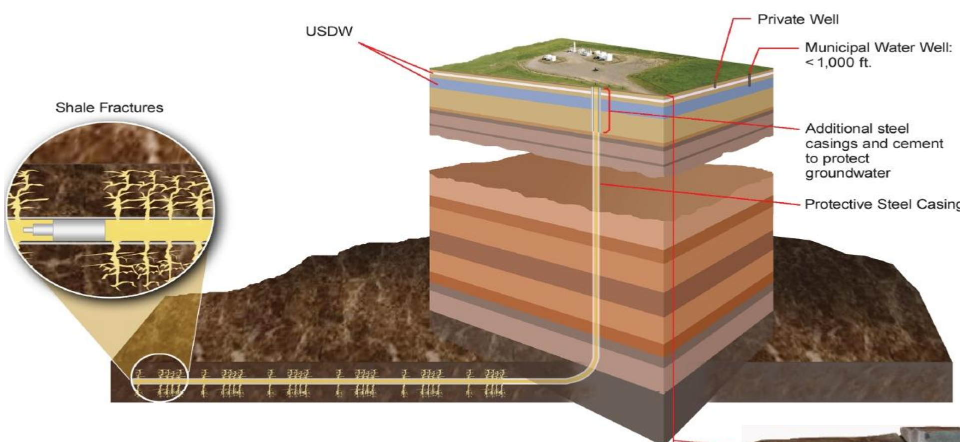
Applications

USC Viterbi
School of Engineering



Fractured Reservoir

- Tight sands
- Shale oil and gas
- Co_2 Sequestration
- Geothermal Reservoir

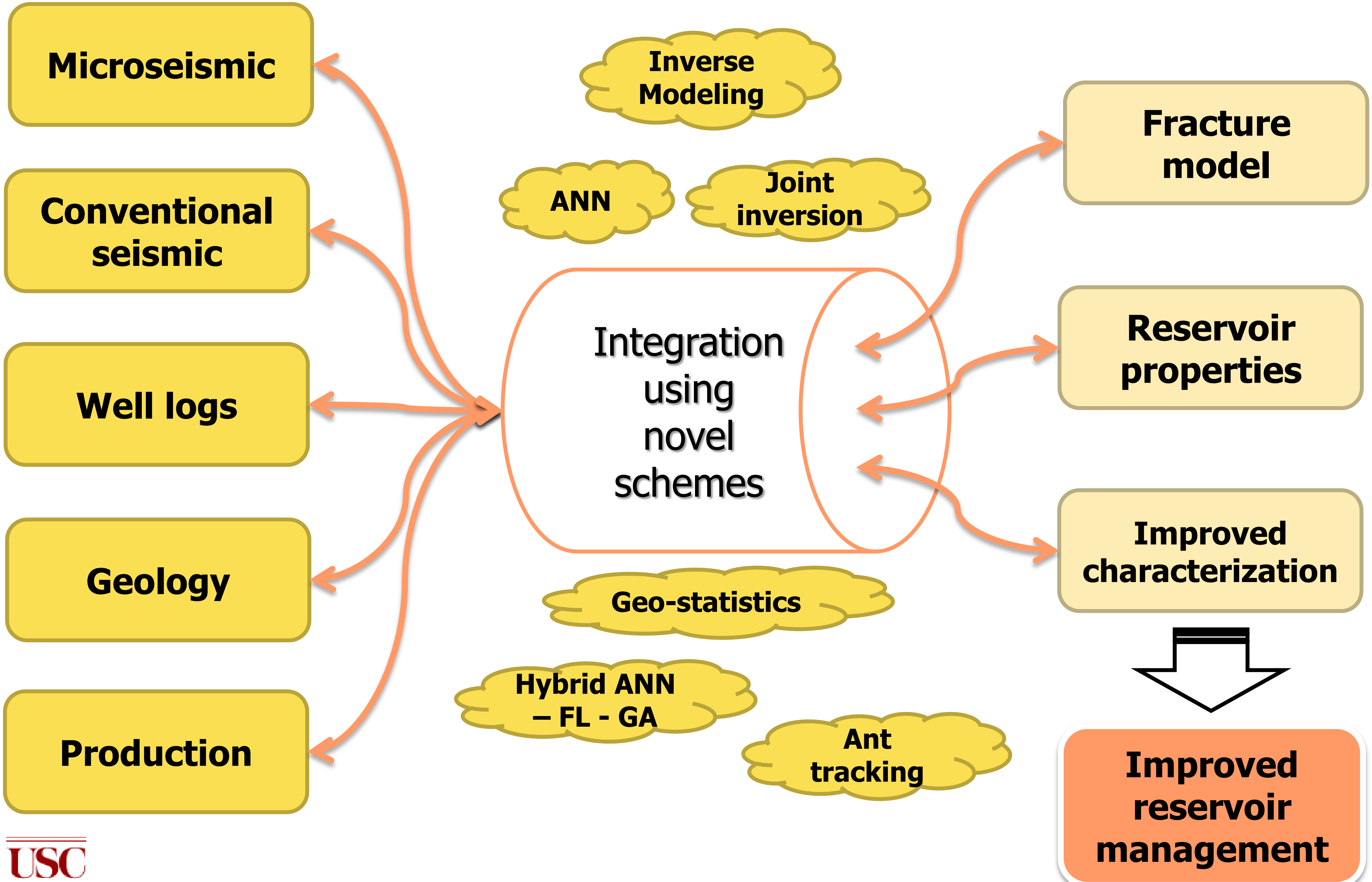


US DOE, Devonian shale gas

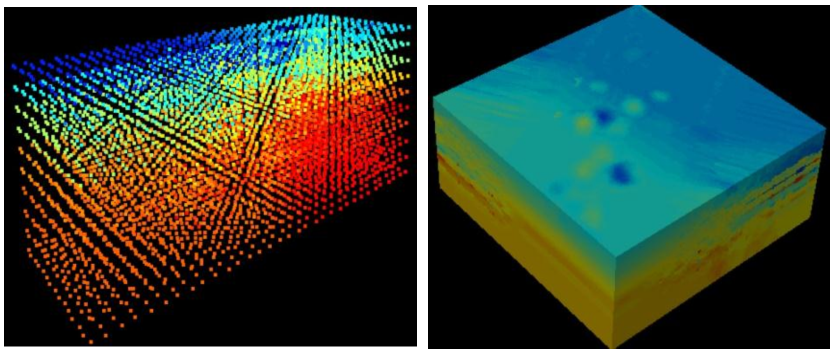
Geothermal
US GS , Geysers and

USC

Overview

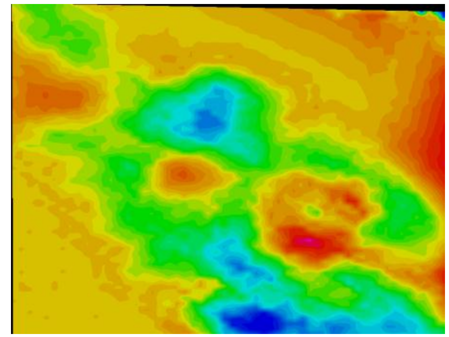

Microseismic
Conventional seismic
Well logs
Geology
Production
Inverse Modeling
ANN
Joint inversion
Integration using novel schemes
Geo-statistics
Hybrid ANN – FL - GA
Ant tracking
Fracture model
Reservoir properties
Improved characterization
Improved reservoir management

Property prediction

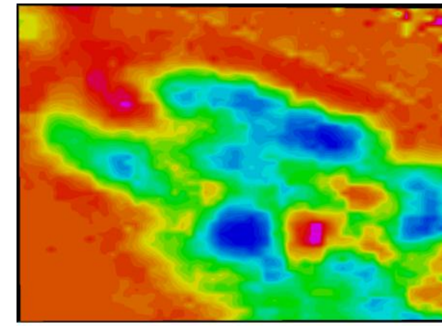


Velocity models from tomographic inversion

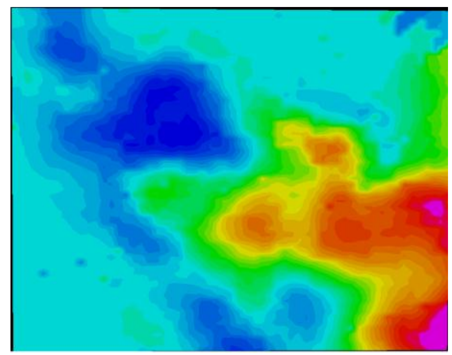
Improved p and s velocity models as a precursor to delineating anomalies and structures of interest and correlate velocity anomalies with fracture swarms and other reservoir properties of interest



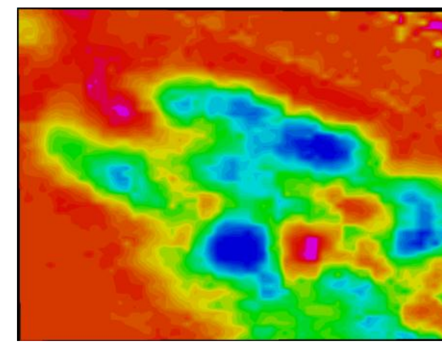
V_p



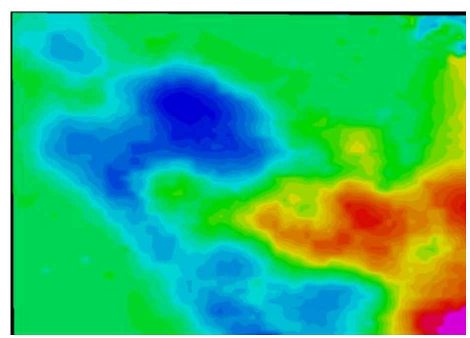
V_p/V_s



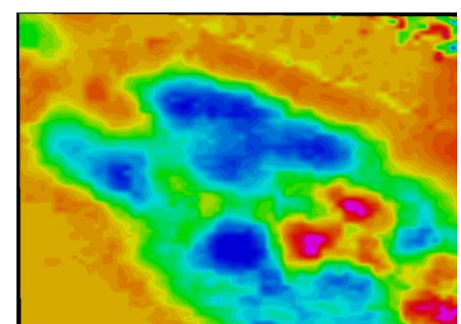
V_s



Poisson's ratio

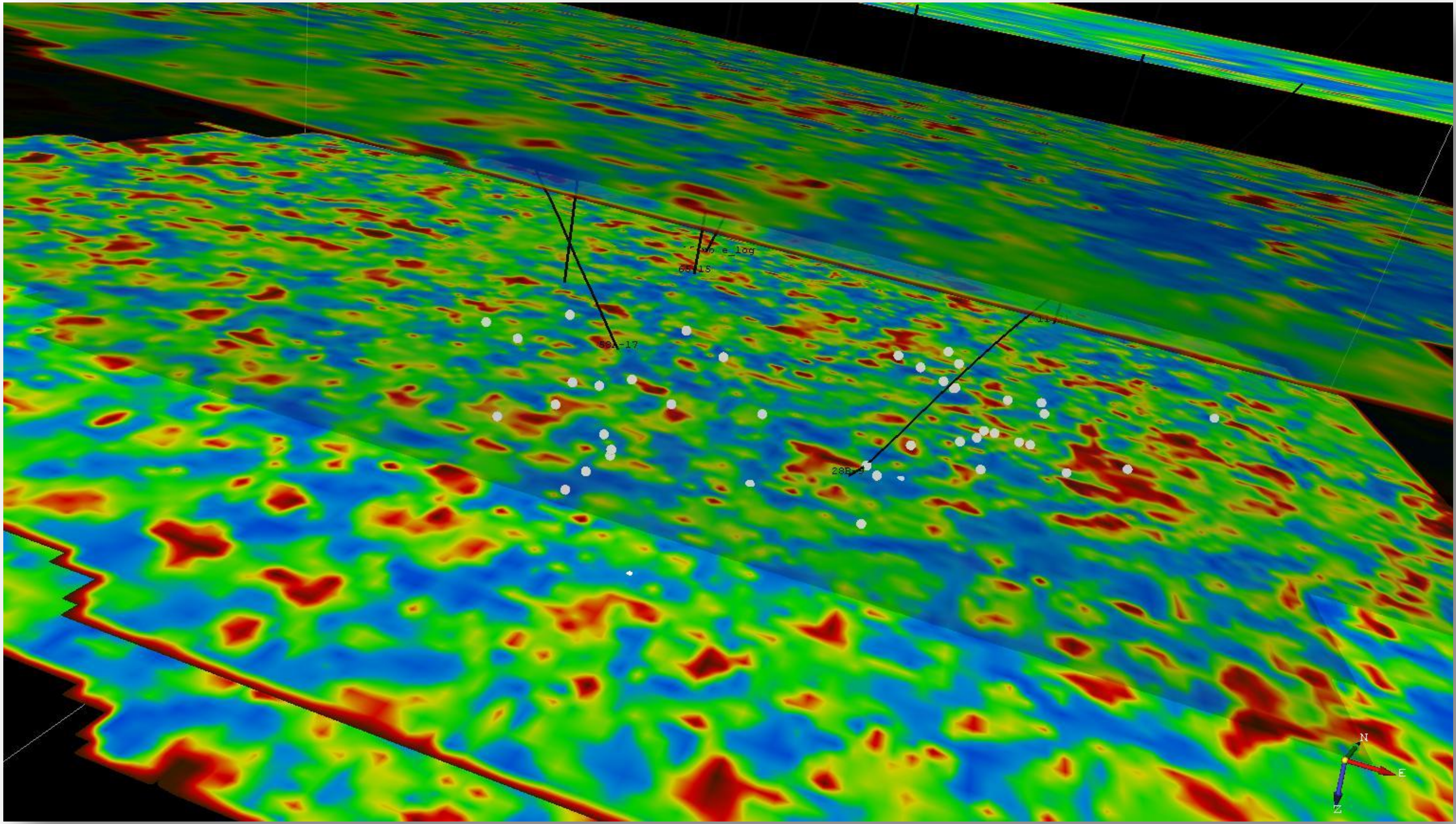


Extensional Stress



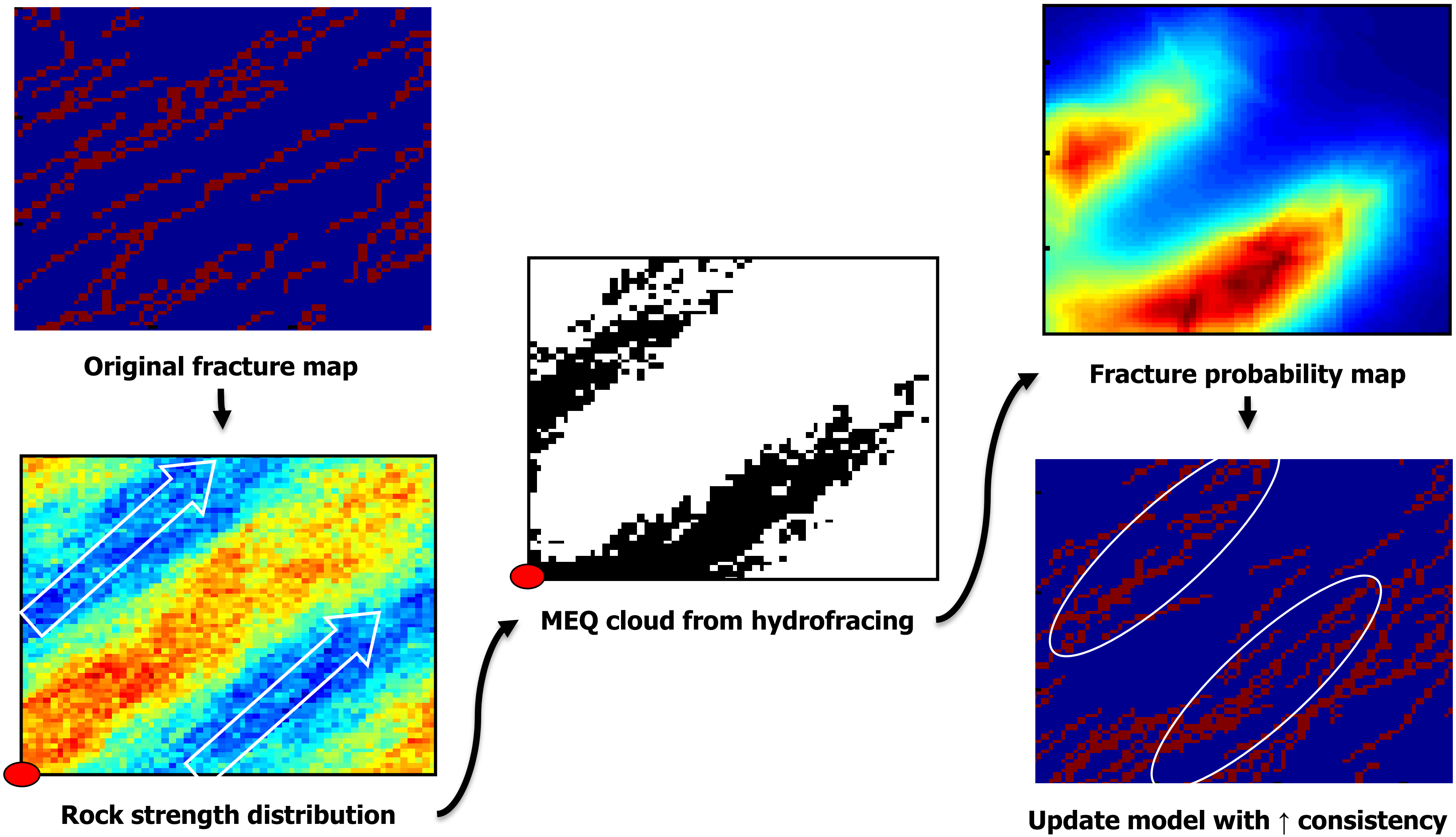
Hydrostatic Stress

Well + Seismic + MEQ



ANN porosity map (seismic attributes & well log data) with observed MEQ activity

Improved fracture models



Integration of MEQ locations and fracture models

MEQ to Map Reservoir Structure

Optimize Hydraulic fracturing for shale

Physical Models to monitor reservoir fluid

Time lapse Petrophysics for RM

MEQ & Seismic Integration for Shale Reservoirs

Tomography Based Reservoir Modeling

Stimulated Seismicity

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- Many geotechnical processes involve the injection of water or gas into the shallow crust.
- Examples: hydrofracking, carbon sequestration, geothermal stimulation.
- These processes often produce many earthquakes, most of which tend to be small ($M \leq 4$). Call this "stimulated seismicity"

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Induced vs. Triggered Seismicity

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Stimulated seismicity can be:

- "induced" if the energy is derived mainly from the injection process itself (by borehole pressure or by thermal contraction produced by cold-water)

- "triggered" if the energy is derived mainly from the release of stored tectonic strain through a mechanical or chemical process that reduces the effective coefficient of friction on fault planes.

Size of Stimulated Events

- The size of induced events is limited by the size of the perturbed region. *A large run-away event is unlikely.*

- The size of triggered events is limited only by the size of faults in the region. *A large run-away event is possible.*

- Induced seismicity can be distinguished from triggered seismicity by the fractal dimension of the hypocenter distribution and the *b*-value in the Gutenberg-Richter frequency-magnitude relation.

Optimize Hydraulic fracturing for shale

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Optimization of Hydraulic Fracturing

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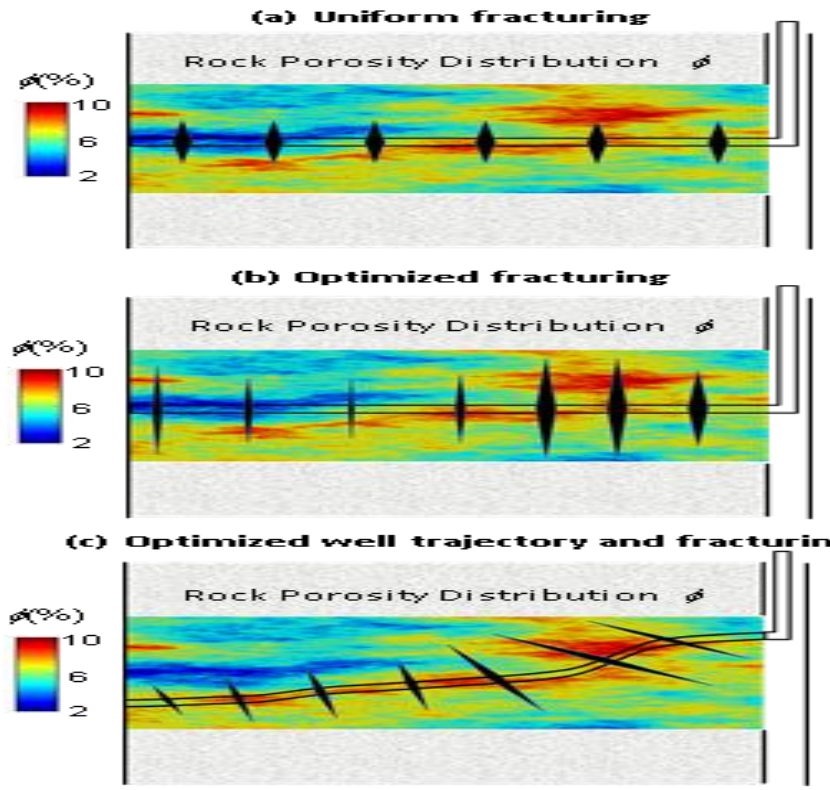
(a) *uniform fracturing;*
(b) *inner loop optimization of fracture locations and intensity;*
(c) *combined optimization of well trajectory and fracture design.*



Plans for Hydro-Fracturing optimization

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- Development of fracturing well trajectory optimization algorithm Development of fracture optimization algorithms to identify fracture intervals and intensity for a fixed well trajectory
- Integration of fracture well trajectory optimization and fracture interval/intensity optimization to develop a hierarchical optimization algorithm.
- Fine-tuning and sensitivity analysis to evaluate the performance of the developed algorithms under geologic uncertainty.
- Preliminary test cases to evaluate the suitability of developed methodology before application to benchmark models and field data.

Physical Models to monitor reservoir fluid

Optimize Hydraulic fracturing for shale

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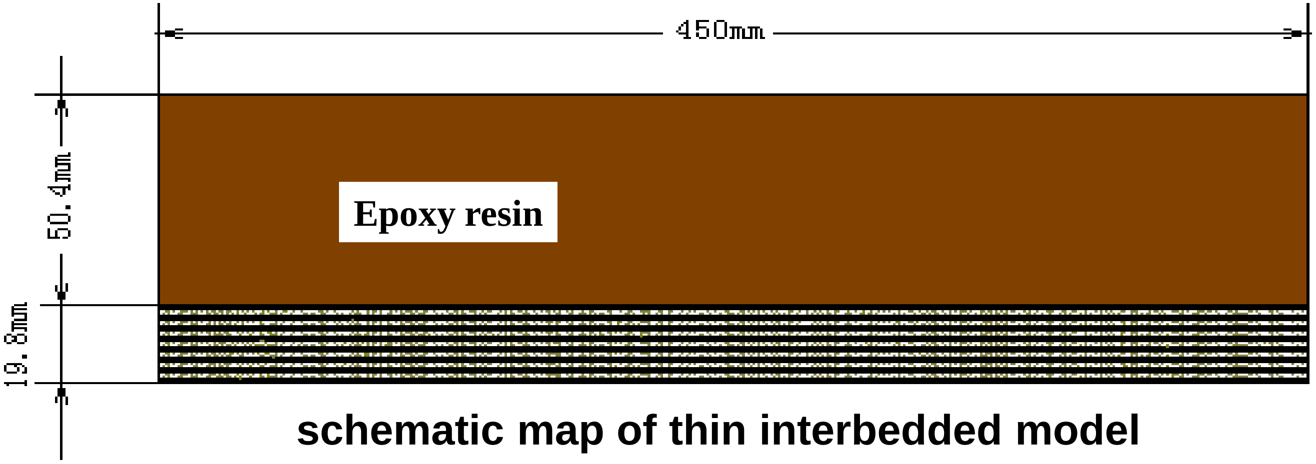
Tomography Based Reservoir Modeling

Model design and data acquisition



schematic map of thin interbedded model

Scaled schematic map of thin interbedded model

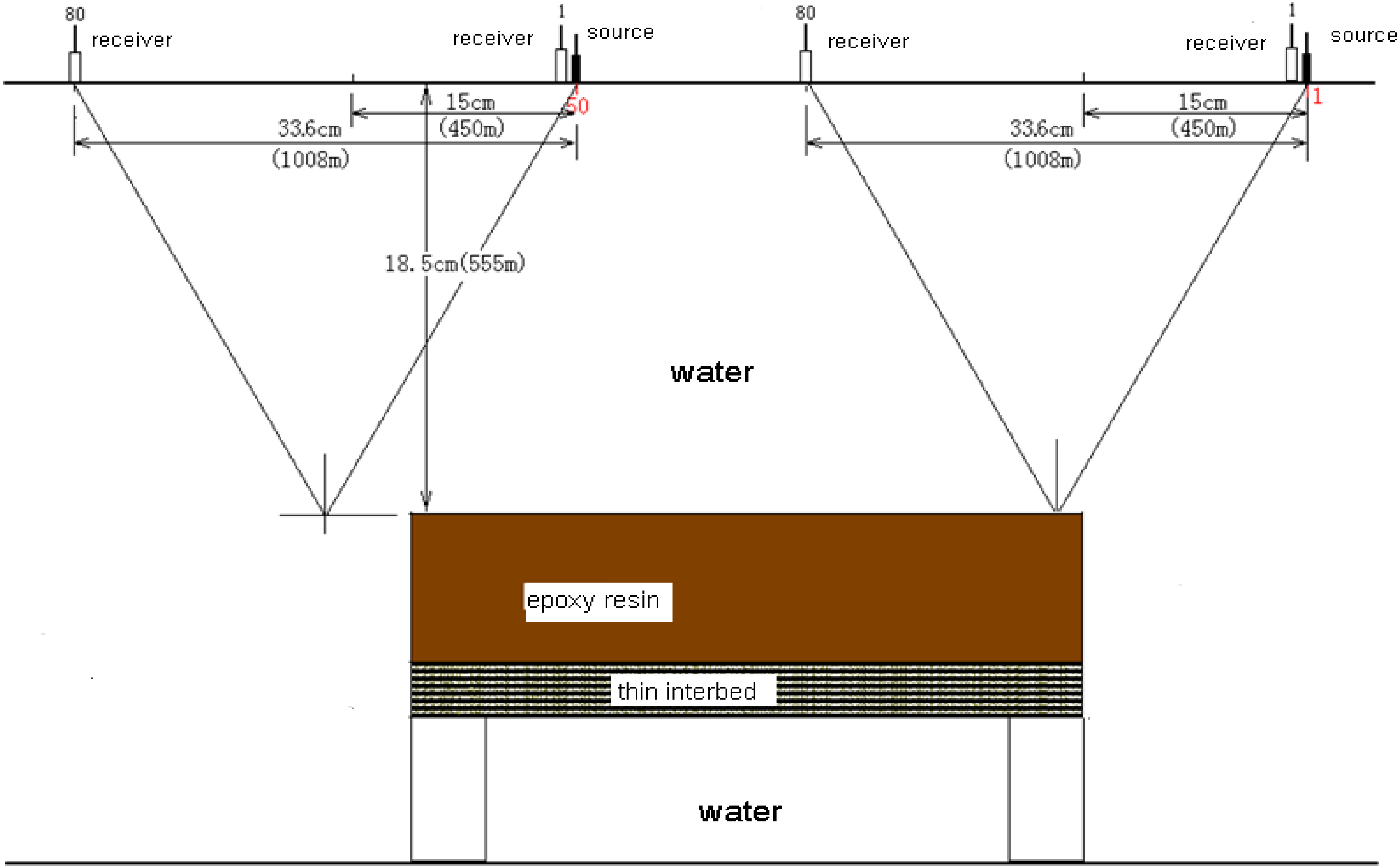
$1.17 g/cm^3$
2440m/s

2580m/s

Consolidate at high pressure and temperature

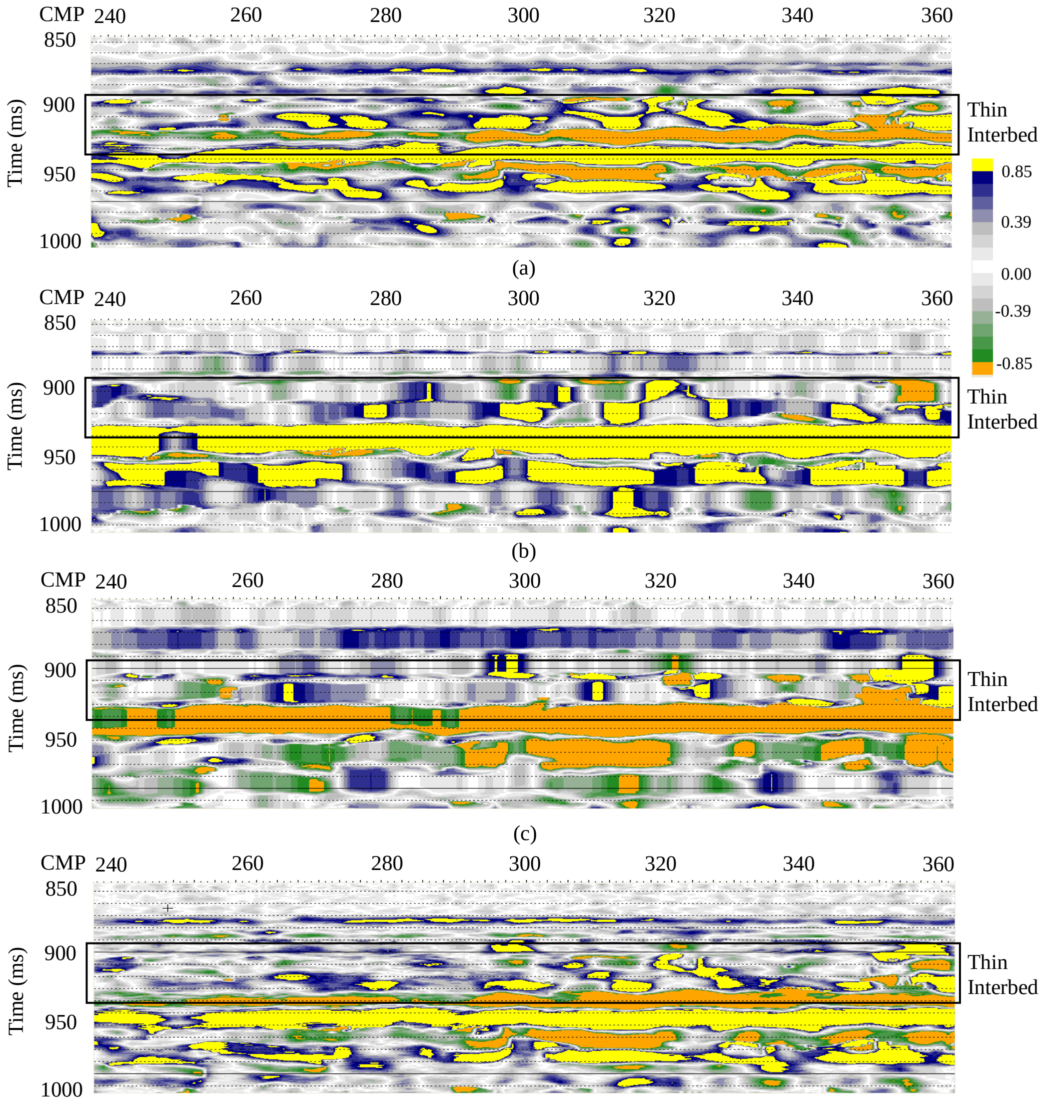
Porosity 17%

Model design and data acquisition



Seismic attribute analysis

Some other differences between water and oil filled amplitudes.



The differences of average amplitude

maximum amplitude

minimum amplitude

midpoint amplitude

Outline

- Geophysical sensitivities
- 4D inversion for pressure, saturation, & permeabilities
- Integrated reservoir model updating & history matching
- Passive seismic for shale reservoir stimulation monitoring
- Applications
- USC Reservoir Monitoring Consortium
- Closing

Closing

- 4D seismic helps monitor changes in reservoir
- Value addition to model updating & history matching
- Passive seismic helps monitoring well stimulation
- Geophysics helps production optimization
- Optimize EOR & reservoir management
- RMC addresses many of the above

Make physical monitoring has the potential to work before large expenditure.

This presentation will be posted at RMC.USC.EDU