Large-scale Numerical Simulation of Reservoir Monitoring – SEAM Time Lapse

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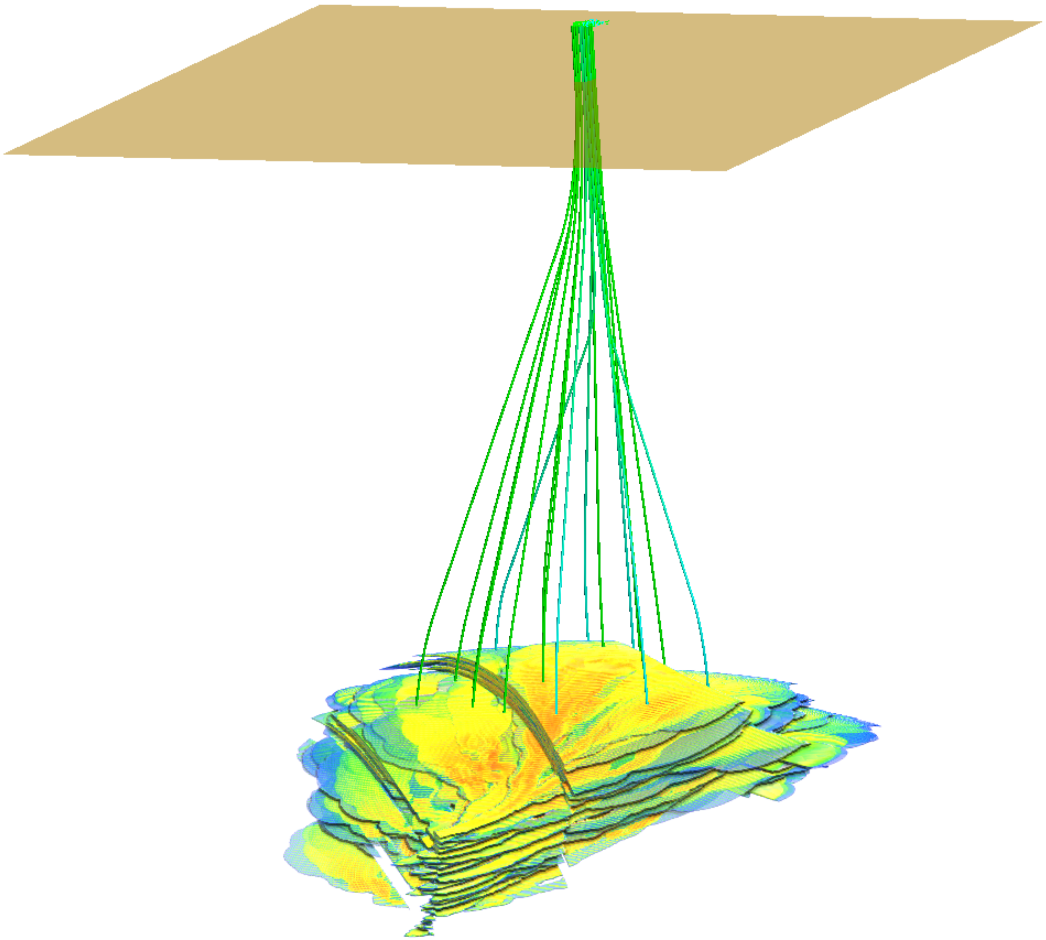

First EAGE Workshop on Practical Reservoir Monitoring
Amsterdam, The Netherlands
6 – 9 March 2017

Background

- **SEAM Time Lapse was 6-month pilot project on simulation of reservoir monitoring**, funded jointly by SEAM and the U.S. National Energy Technology Laboratory (NETL). The project's goal was to study the effects of reservoir development on pore pressure distributions and their monitoring by geophysical remote sensing.
  - **The Time-Lapse project ran from May to September 2016** as an extension of the SEAM Pressure Prediction and Hazard Avoidance Project, which was funded by NETL to build and simulate basin models that can help predict overpressure zones in the Gulf of Mexico.
- **The project set out to answer several questions:**
  - Can modern **reservoir simulation methods for coupled flow and geomechanics** handle the detailed, large-scale geologic models used to simulate geophysical surveys of reservoirs by seismic, EM and gravity methods?
  - What **types of detail are needed in the geologic models and the (simulated) production scenario** to reproduce the subtle effects that are seen in time-lapse geophysical surveys of real oil fields?
  - Are the inversion and petrophysical models good enough to **tie the effects back to changes in the rocks, pore fluids and pressures**?

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SEAM

SEG Advanced Modeling Corporation

An industry research cooperative

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Outline

- Geologic and reservoir model
- Reservoir production scenario
- Coupled flow and geomechanical reservoir simulations
- Time-lapse geophysical simulations: seismic, gravity, (CSEM, MT)
- Lessons learned

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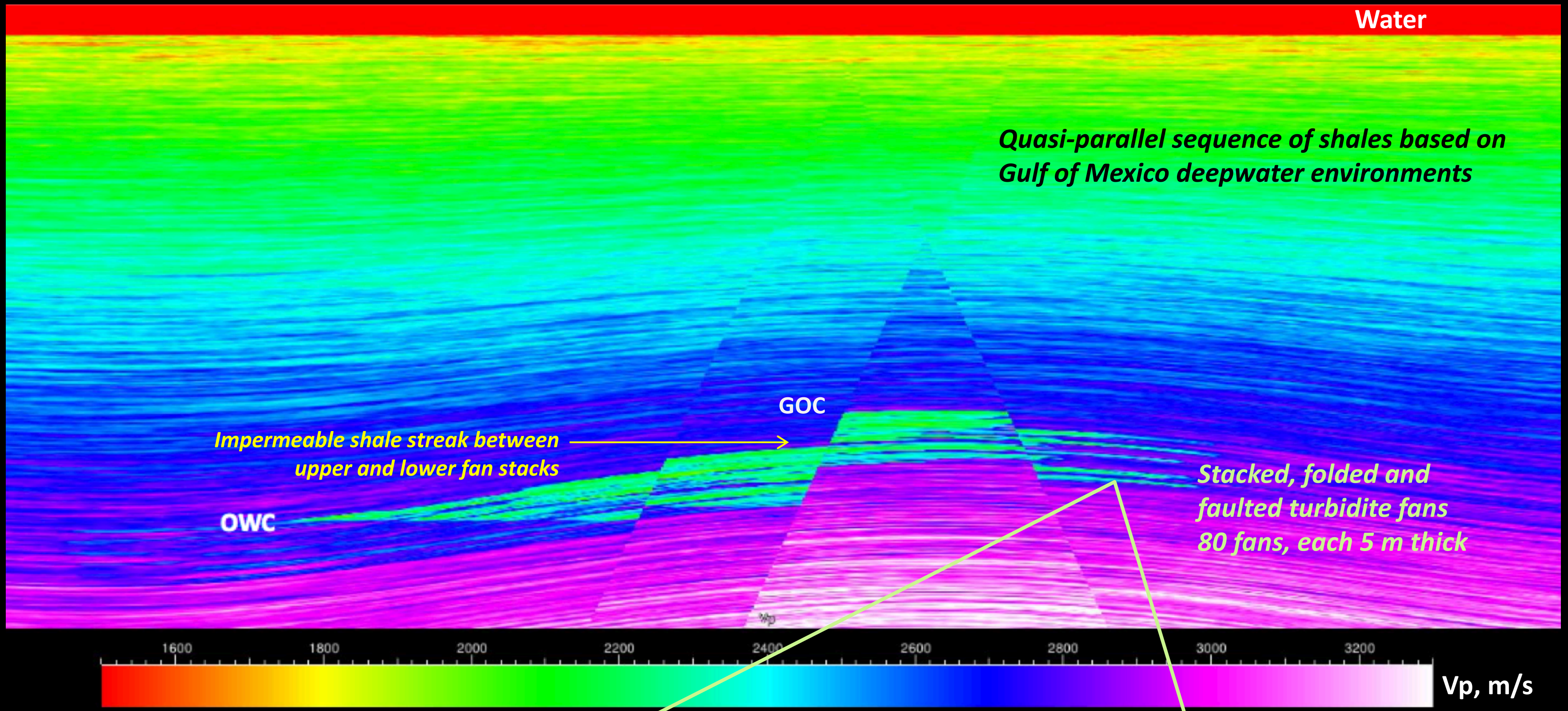
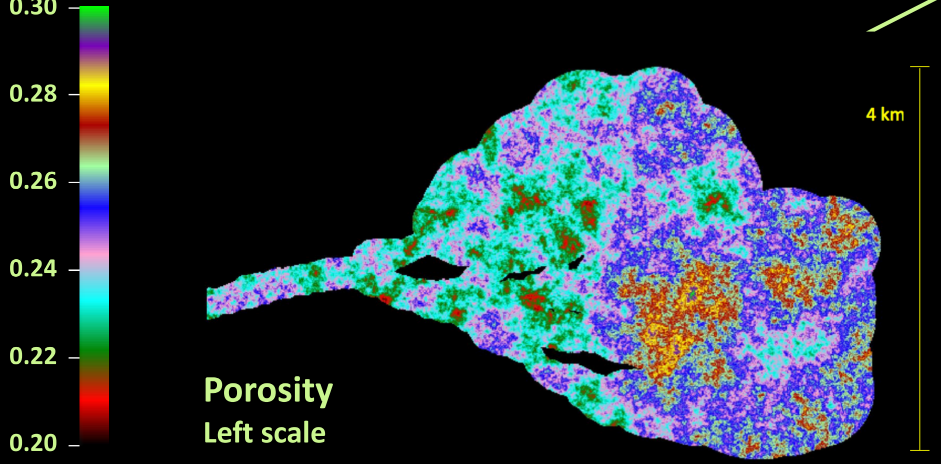
SEAM Time Lapse Geologic Model

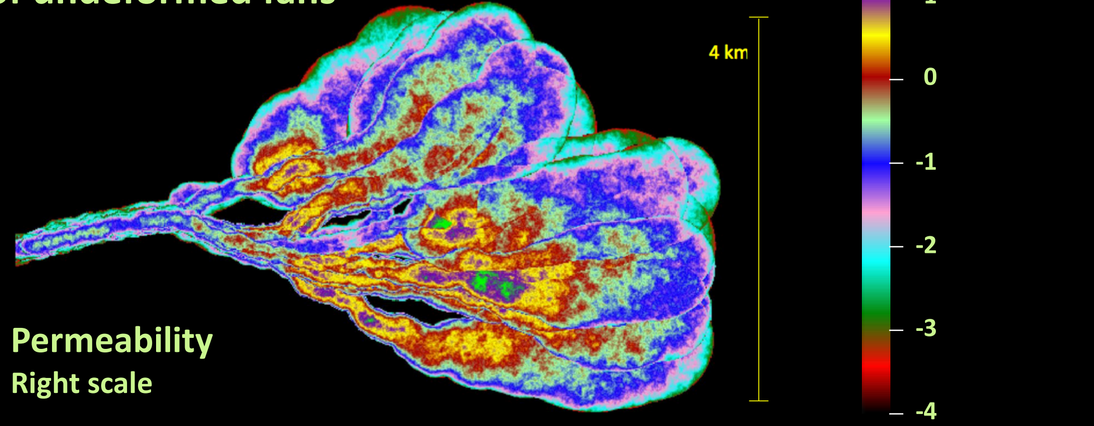
12.5 km ×
12.5 km ×
5.0 km

1000 ×
1000 ×
2000 cells



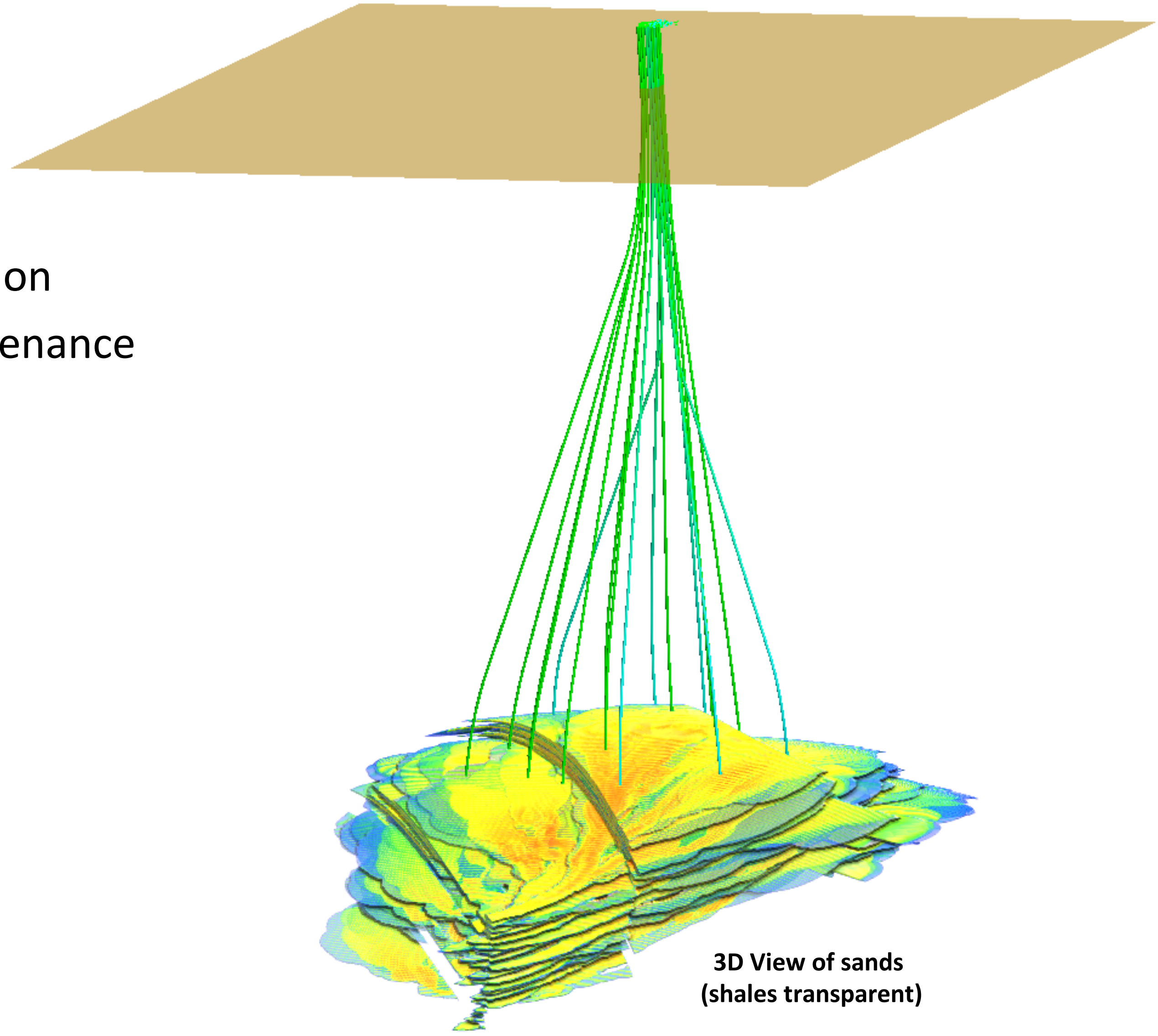
Plan views of undeformed fans





Simulated production plan

- **Design the simulation to realistically create 4D effects of depletion and injection over a timespan of 1 to 3 years from first oil:**
  – Gas exsolution, water replacing oil, gas to oil production
  – Pressure drop, pressure increase, and pressure maintenance
  – Geomechanical responses to depletion and injection
- **Main variables**
  – Fault Compartments
  – Location of Producers/Injectors
  – Comingling Zones
  – Injection/Production rates
  – Timing of Production and Shut-In
- **For simplicity, all wells brought on at time zero**



3D View of sands (shales transparent)

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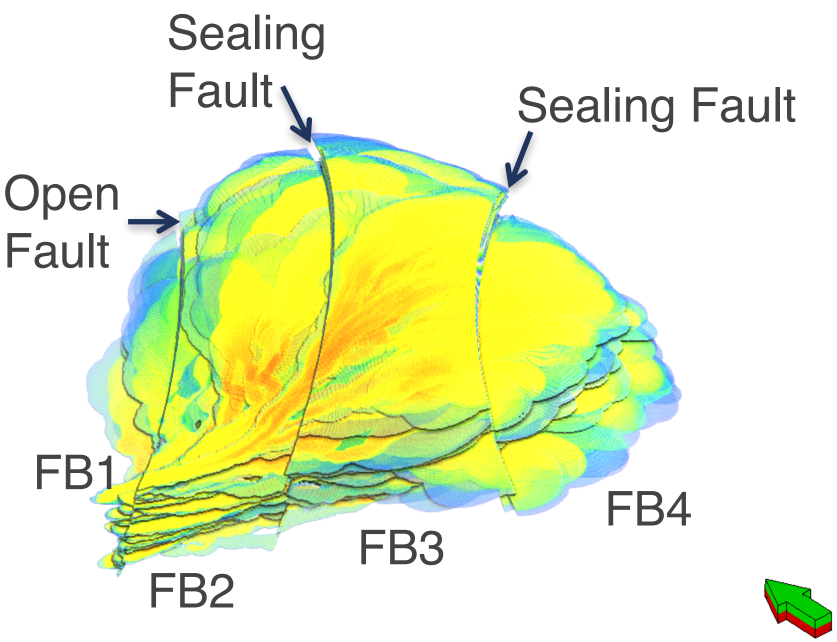
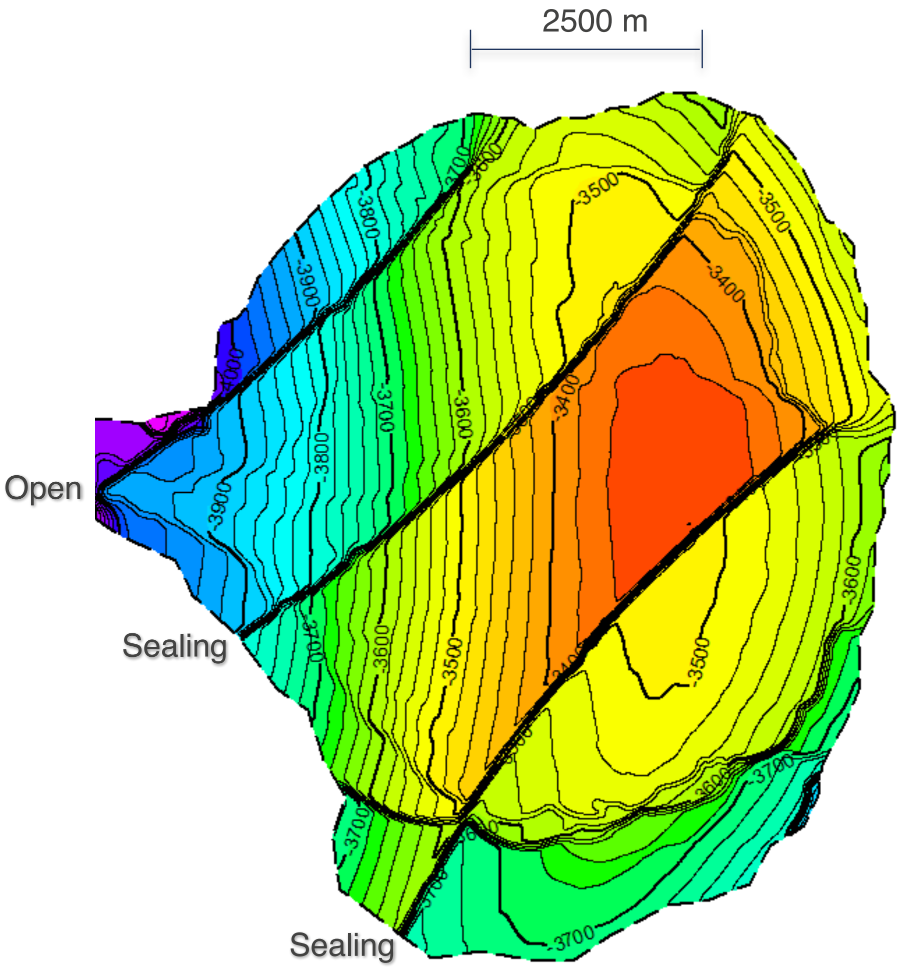
Faulted Compartments

4 Fault Blocks
3 Reservoir Compartments



3D View of Sands
(shales transparent)



Top Reservoir Structure Map
20-m contour interval

Sealed faults allow testing of different production scenarios in each reservoir compartment.

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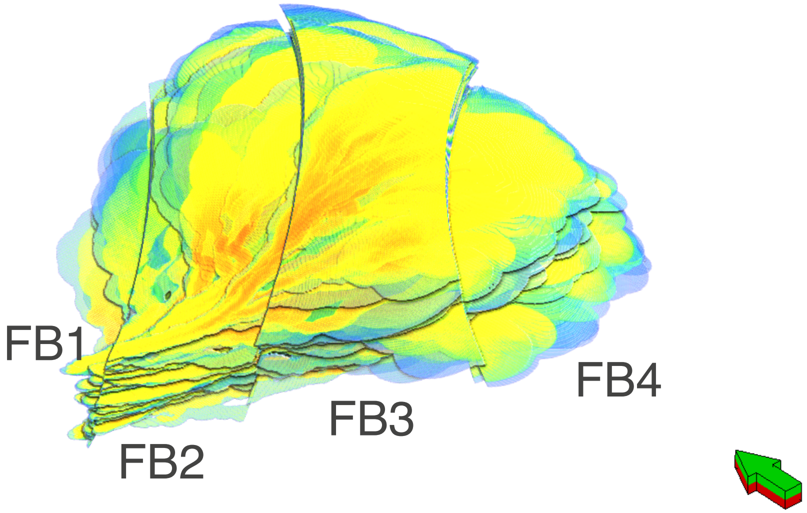
Depletion Plan

Reservoir Compartments

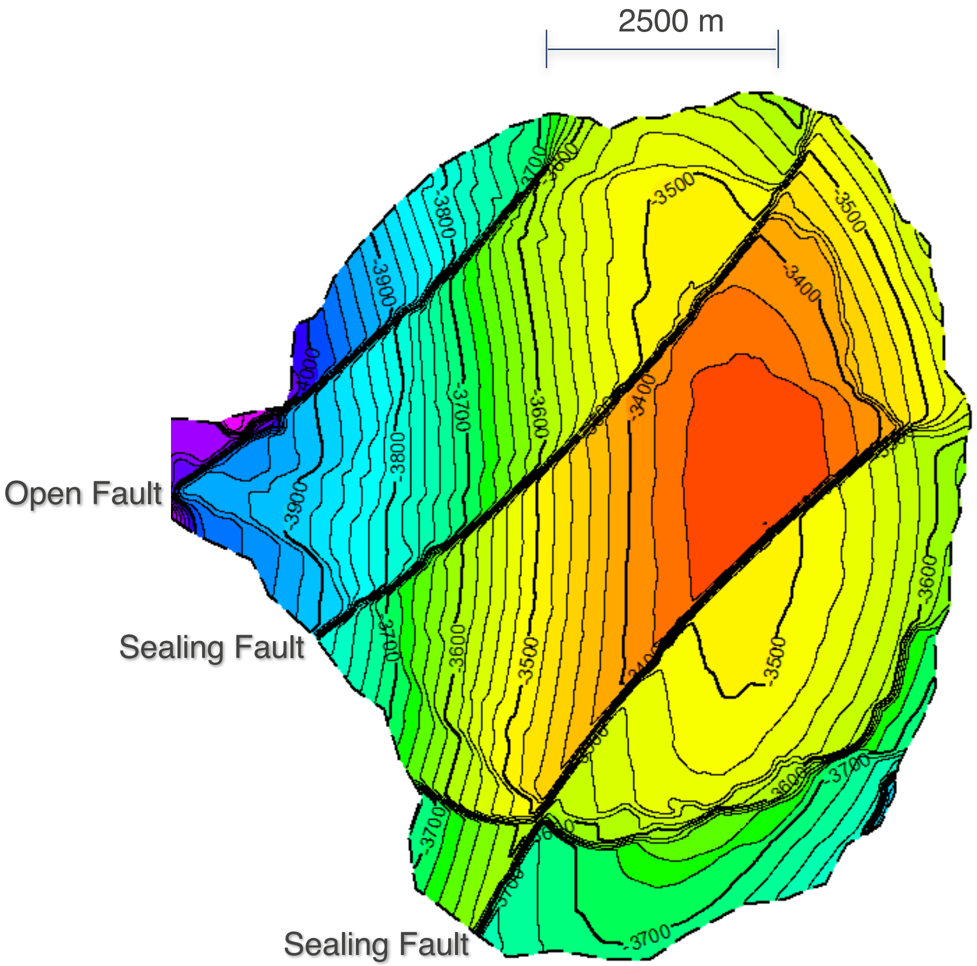
FB1 & FB2: Depletion Only

FB3: Depletion with Injection

FB4: Over Injection with Depletion



3D View of Sands
(shales transparent)



Top Reservoir Structure Map
20-m contour interval

Production plan is designed to isolate geomechanical effects in waterflood and depletion only scenarios.

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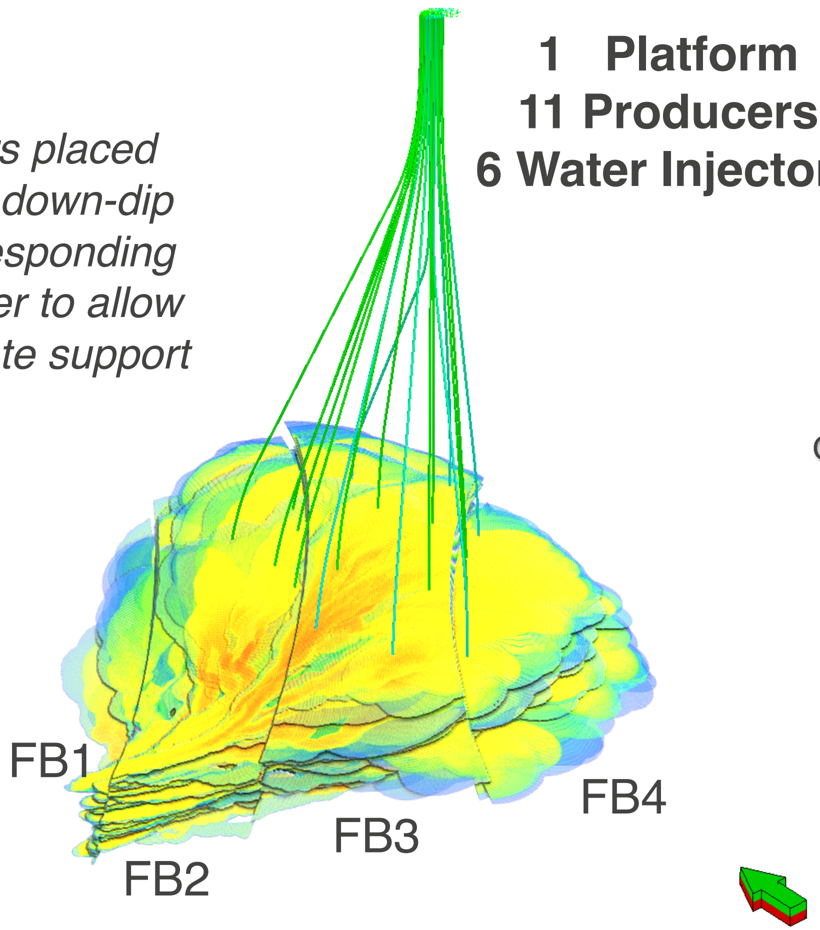
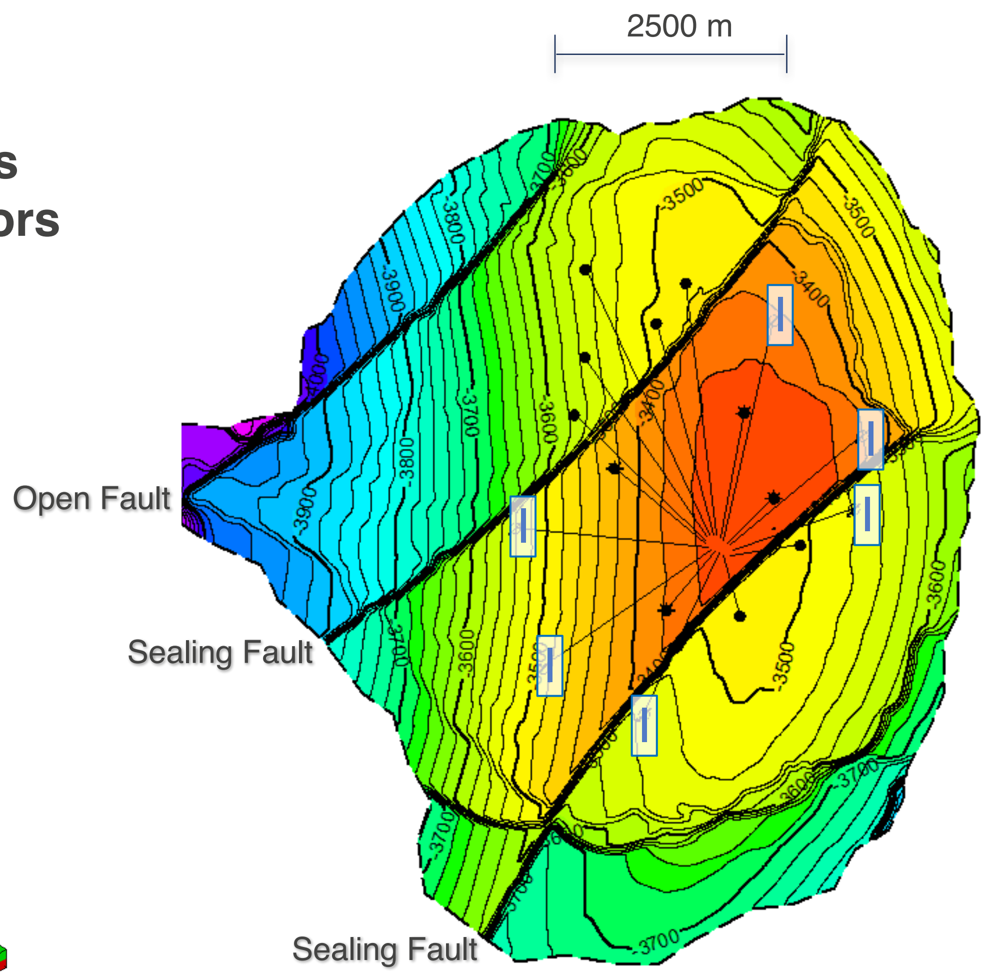
Wells and Production Timing

Injectors placed 1-2 km down-dip of corresponding producer to allow adequate support

1 Platform
11 Producers
6 Water Injectors



3D View of Sands
(shales transparent)



Top Reservoir Structure Map
20-m contour interval

Production Timing

All wells were turned on at zero time (time of baseline survey).

A "hurricane" shut-in of 2 weeks was simulated after 1 year.

Monitor geophysical surveys were simulated before the start and after 2 years 3.5 months of production.

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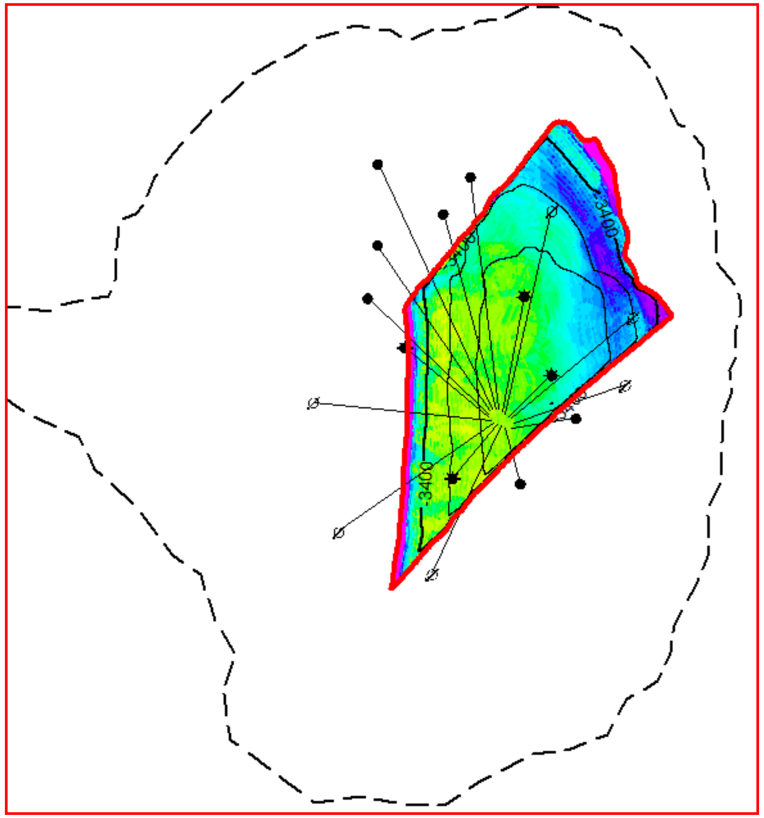
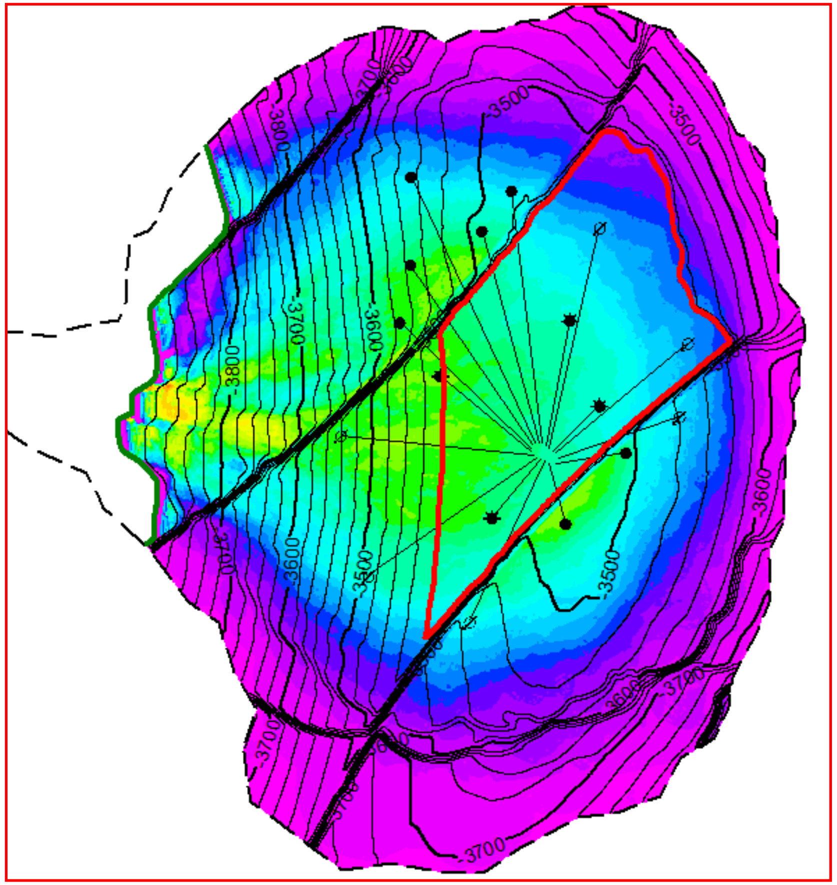
The reservoir fluid model was a synthetic 3-phase model with black oil (API 35), water and gas, with PVT relationships generated from standard correlations observed for Gulf of Mexico conditions.



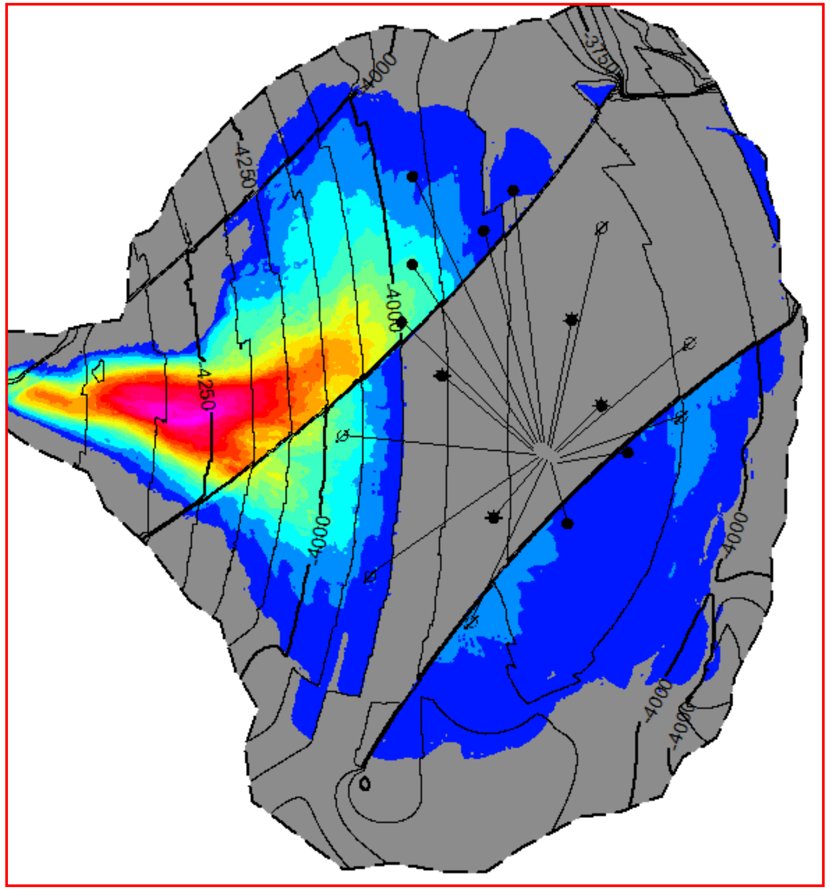
Gas Leg

Up to 125 m thick (TVT)
Middle Fault Block (FB3)
High N:G
$S_w = 0.20$
$S_o = 0.07$
$S_g = 0.73$



Oil Leg

Up to 480 m thick (TVT)
All Fault Blocks
Range of N:G
$S_w = 0.20$
$S_o = 0.80$
$S_g = 0.00$



Water Leg

Up to 125 m thick
Middle Fault Block (FB3)
High N:G

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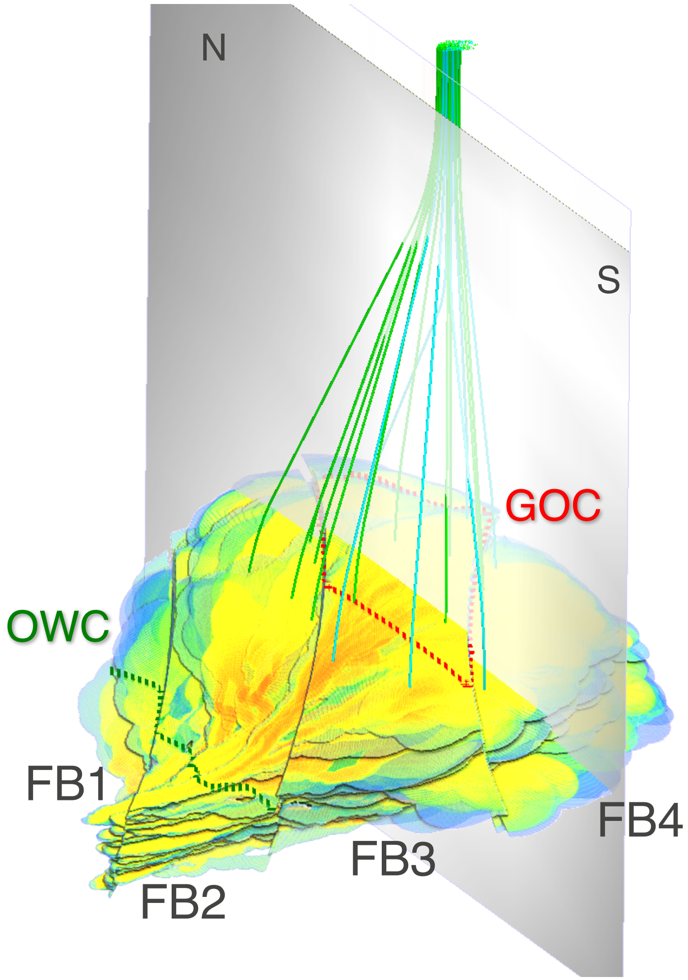
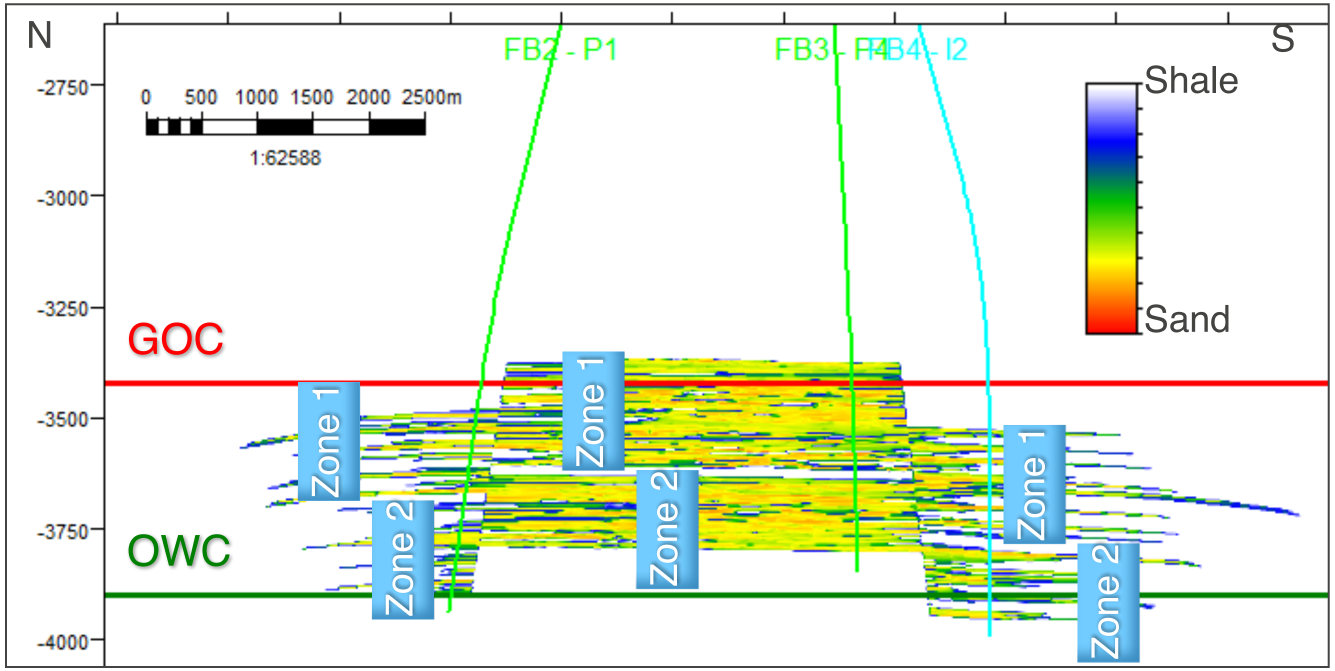
Completions



3D View of Sands
(shales transparent)

Arbitrary Vertical Section through Reservoir



Zone 1 and Zone 2 are commingled for production and injection

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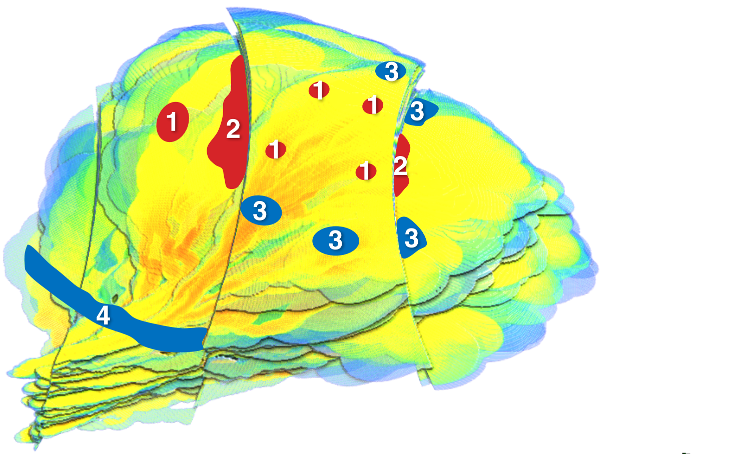
Conceptual 4D Response

Saturation Changes

Oil Leg 4D Softening/Hardening

1 Softening due to gas exsolution
2 Softening due to gas exsolution and mobilization to create updip gas cap
3 Hardening due to water injection
4 Hardening due to water replacing oil at OWC

*Softening due to oil replacing water
*Hardening due to gas pressuring up to oil



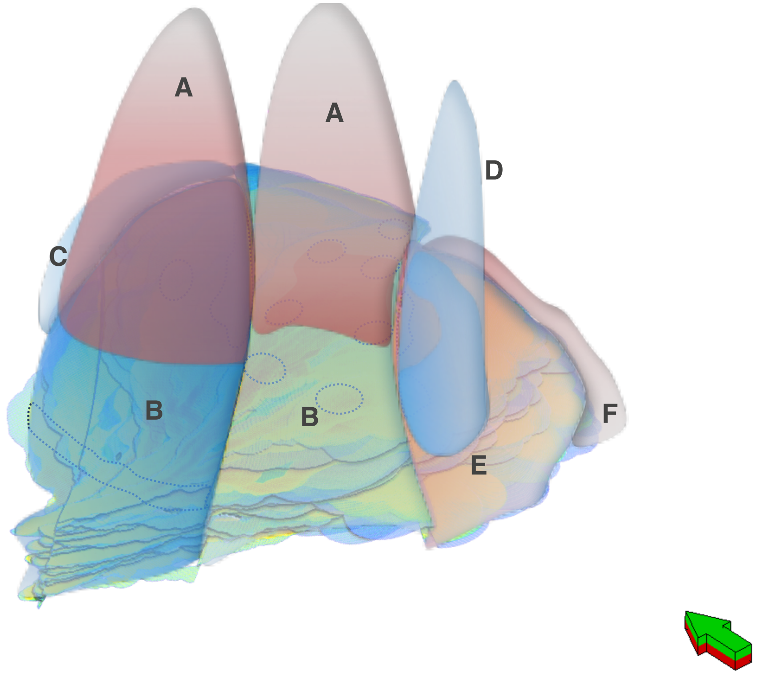
3D View of Sands
(shales transparent)

Geomechanical Changes

Overburden + Reservoir 4D Softening/Hardening

A. Overburden dilation (stress arching)
B. Reservoir compaction
C. Stress transfer to sideburden (small compaction)
D. Overburden compaction
E. Reservoir expansion due to injection
F. Stress transfer to sideburden (small dilation)

*Underburden response not shown



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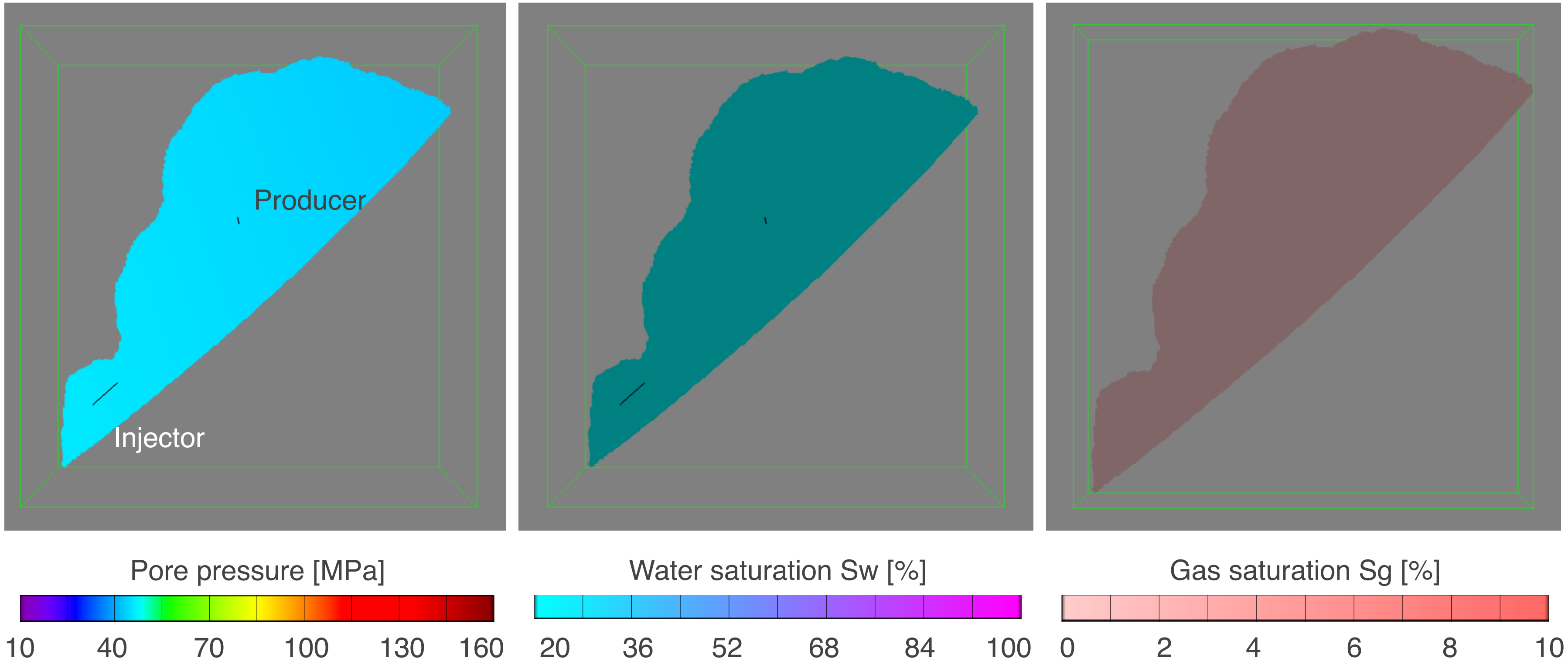
Reservoir Simulations

01-Jun.-2016: Start



1 MPa ≈ 145 psi

Connate water saturation = 0.2 (20%)

The slide sequence to follow shows a test run isolating one of the reservoir compartments (Fault Block 2), to study the effects of pressure variations on dissolved gas near the injector and producer wells.

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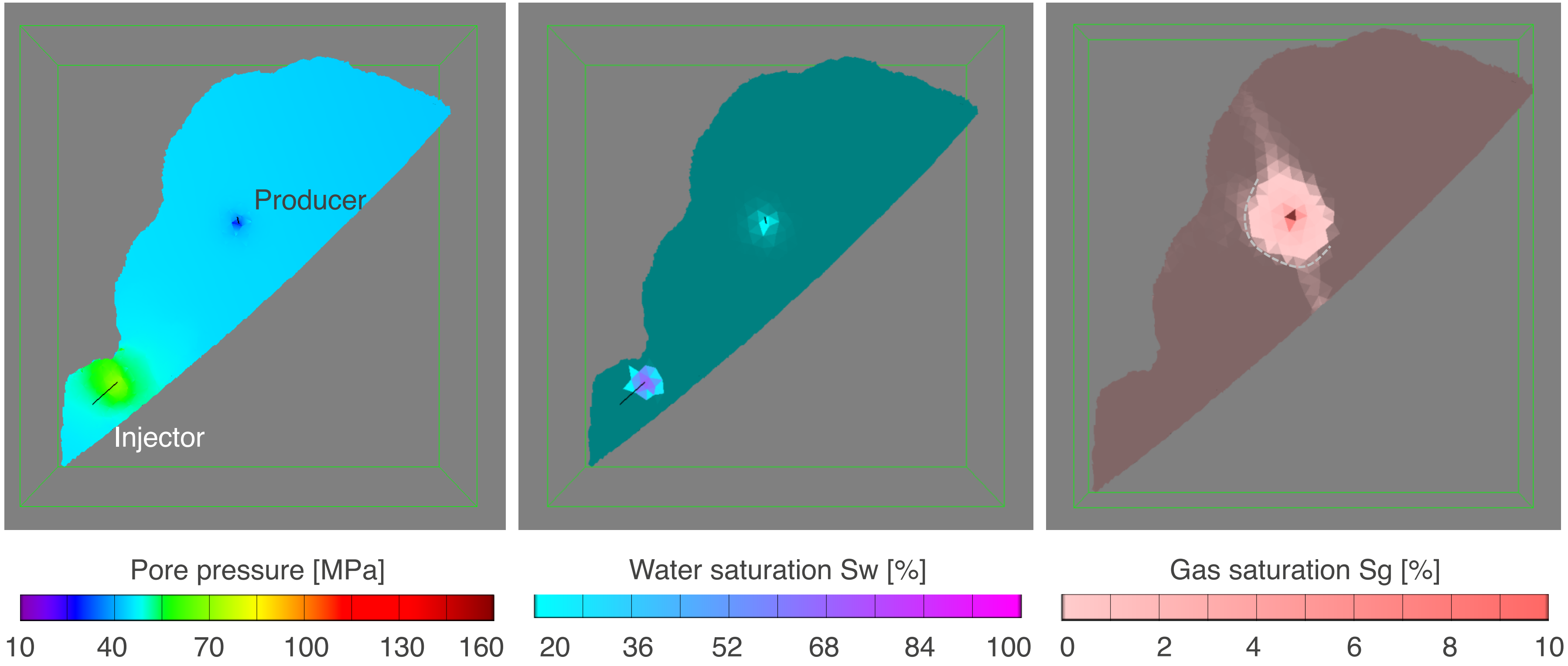
Reservoir Simulations

01-Jul.-2016: 01 month production



1 MPa ≈ 145 psi

Reservoir at bubble point pressure: Gas comes out of solution as soon as production starts.

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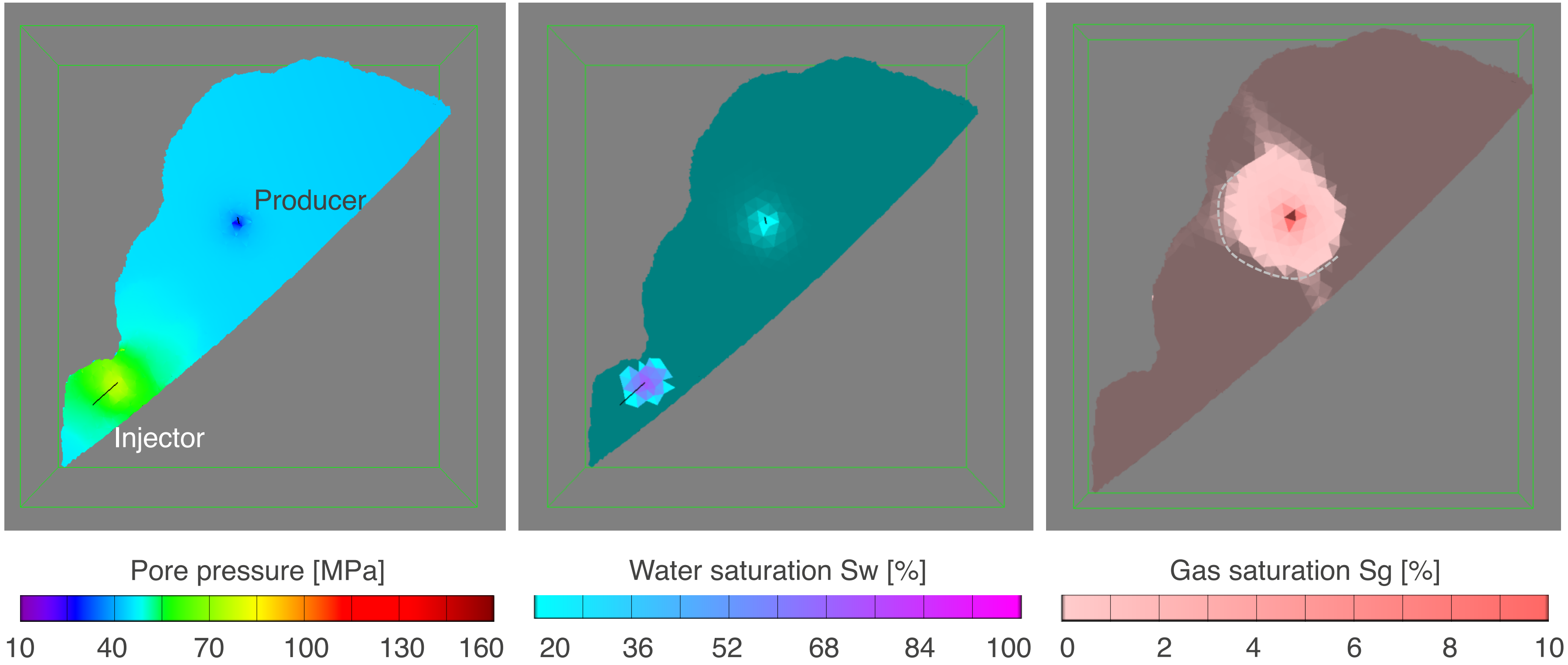
Reservoir Simulations

01-Aug.-2016: 02 month production



1 MPa ≈ 145 psi

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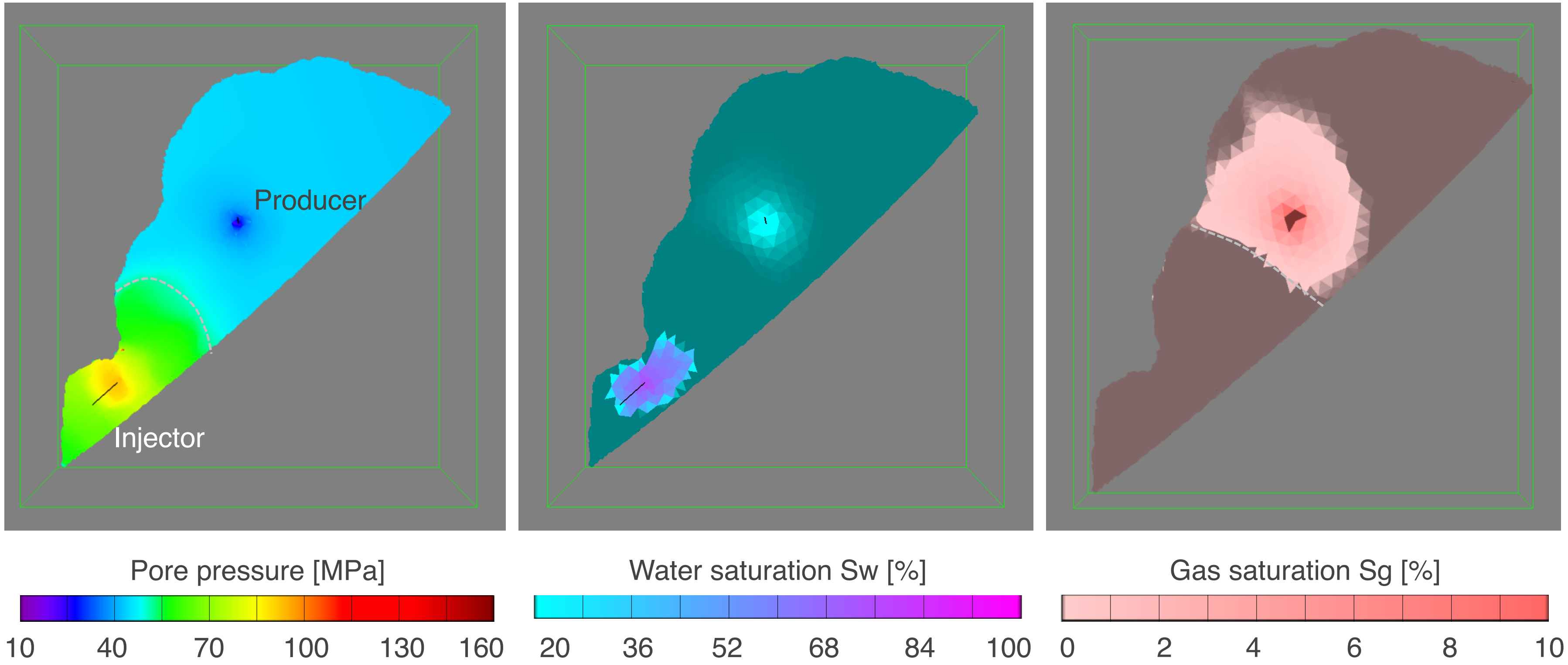
Reservoir Simulations

01-Dec.-2016: 06 month production



1 MPa ≈ 145 psi

Note the sharp saturation fronts (Sw and Sg) and smooth pressure front.

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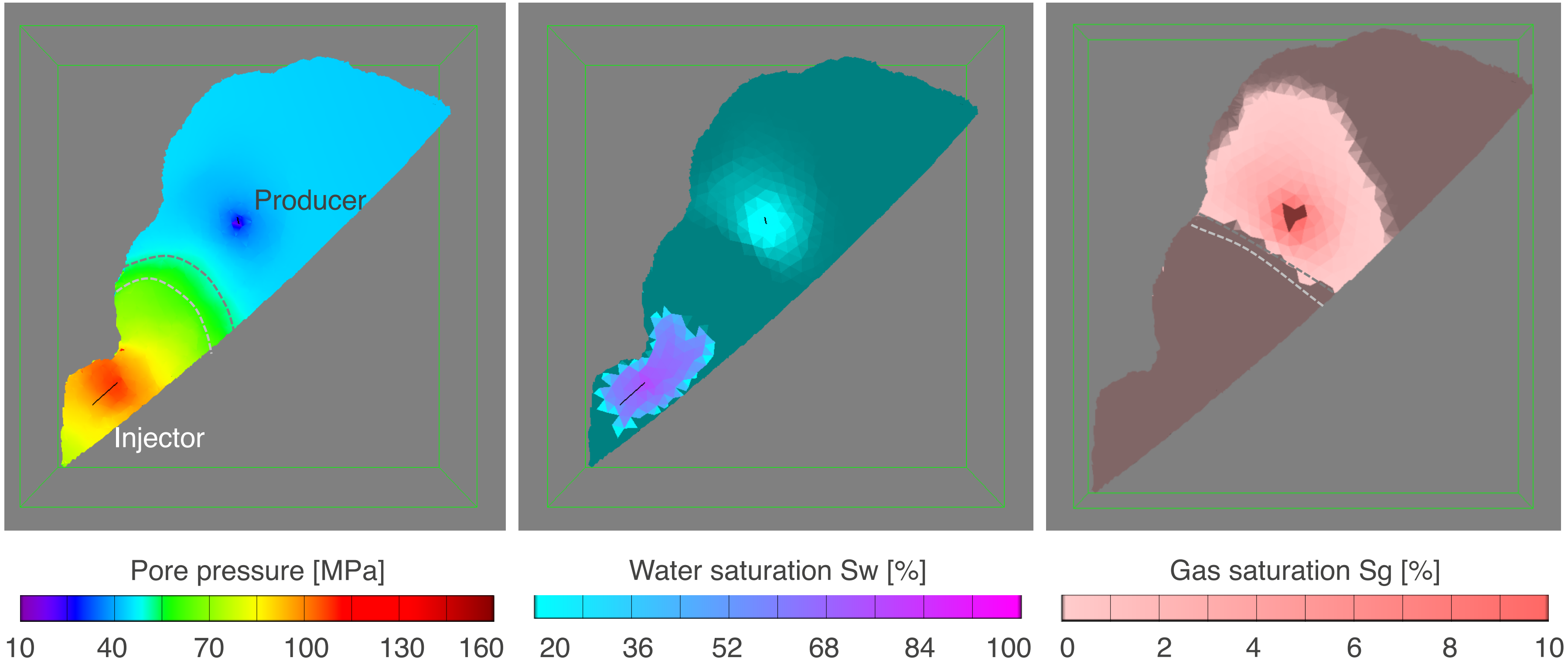
Reservoir Simulations

01-Jun.-2017: 12 month production



1 MPa ≈ 145 psi

Pressure front reaches gas front and forces gas back into solution.
Gas front retracts towards North-East

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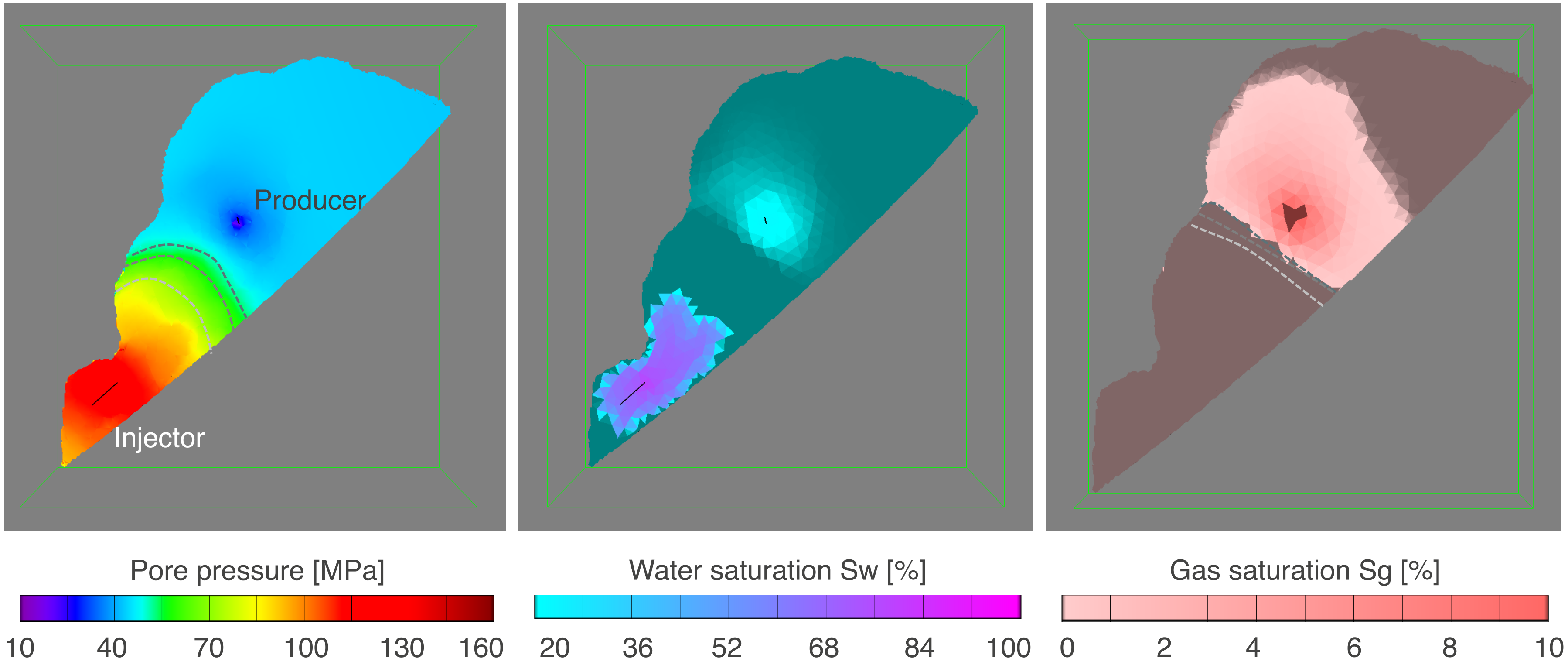
Reservoir Simulations

01-Dec.-2017: 18 month production



1 MPa ≈ 145 psi

Pressure front continues to force gas back into solution.

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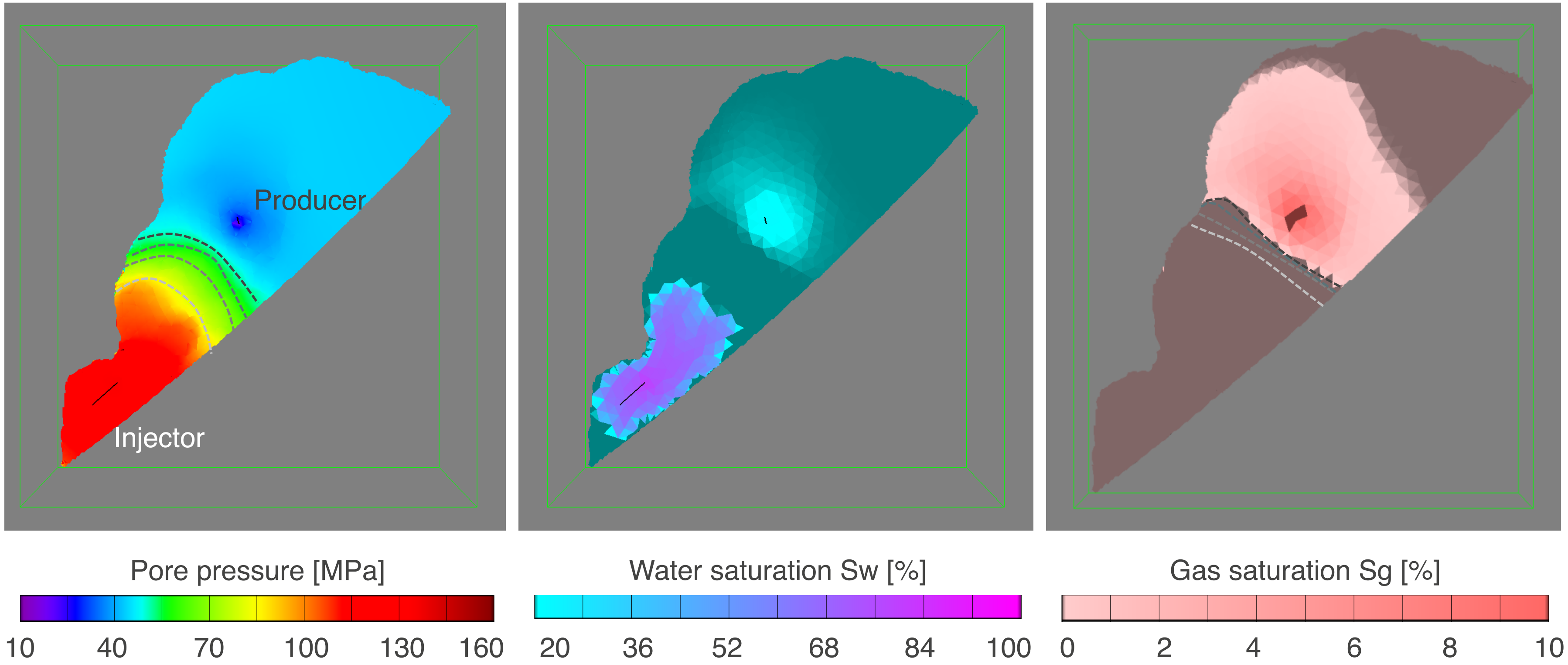
Reservoir Simulations

01-Jun.-2018: 24 month production



1 MPa ≈ 145 psi

Small increase in water saturation around producer

Production causes pressure drop at producer and reduction in pore space.
Water has higher bulk modulus (i.e., is less compressible) than oil and gas.
Water takes up a slightly larger percentage of pore space after reduction in porosity.

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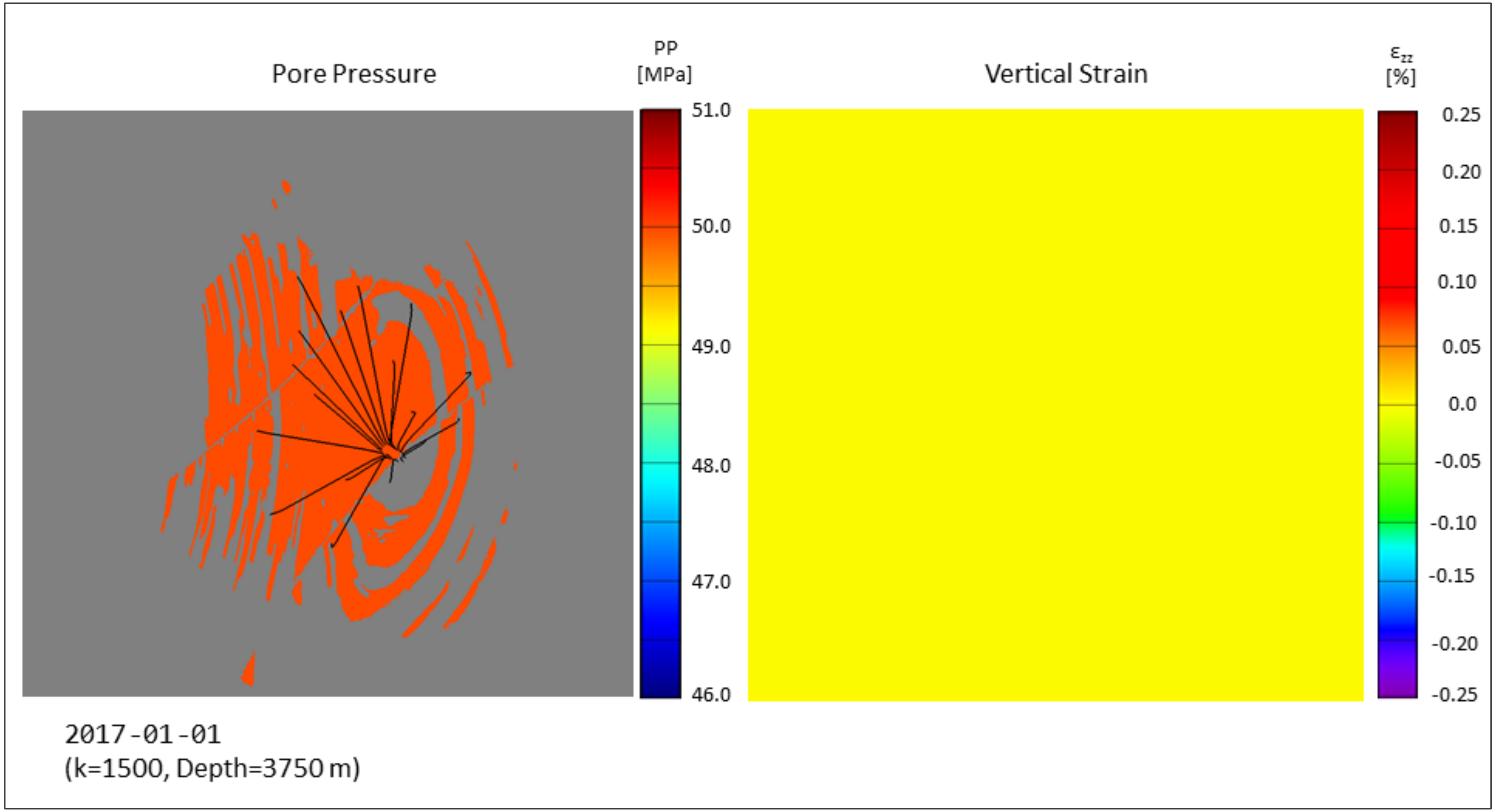
Full Model Time-Lapse Movie



MOVIE

Horizontal slice through middle of reservoir (3750 m)

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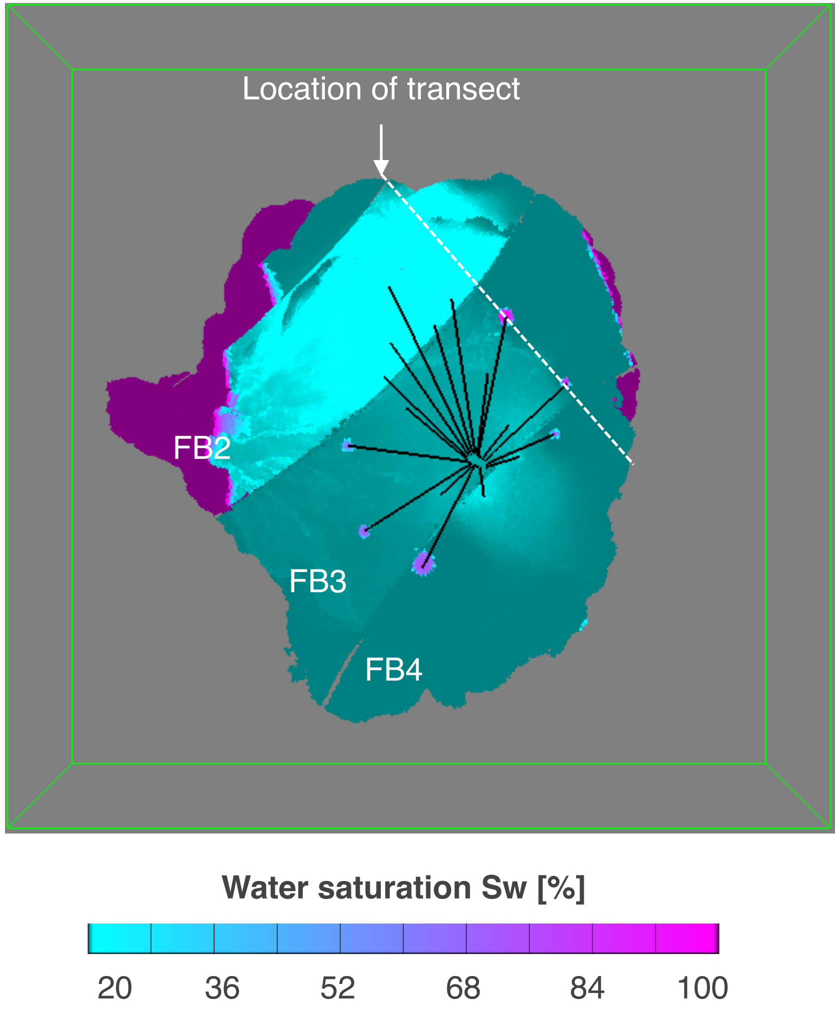
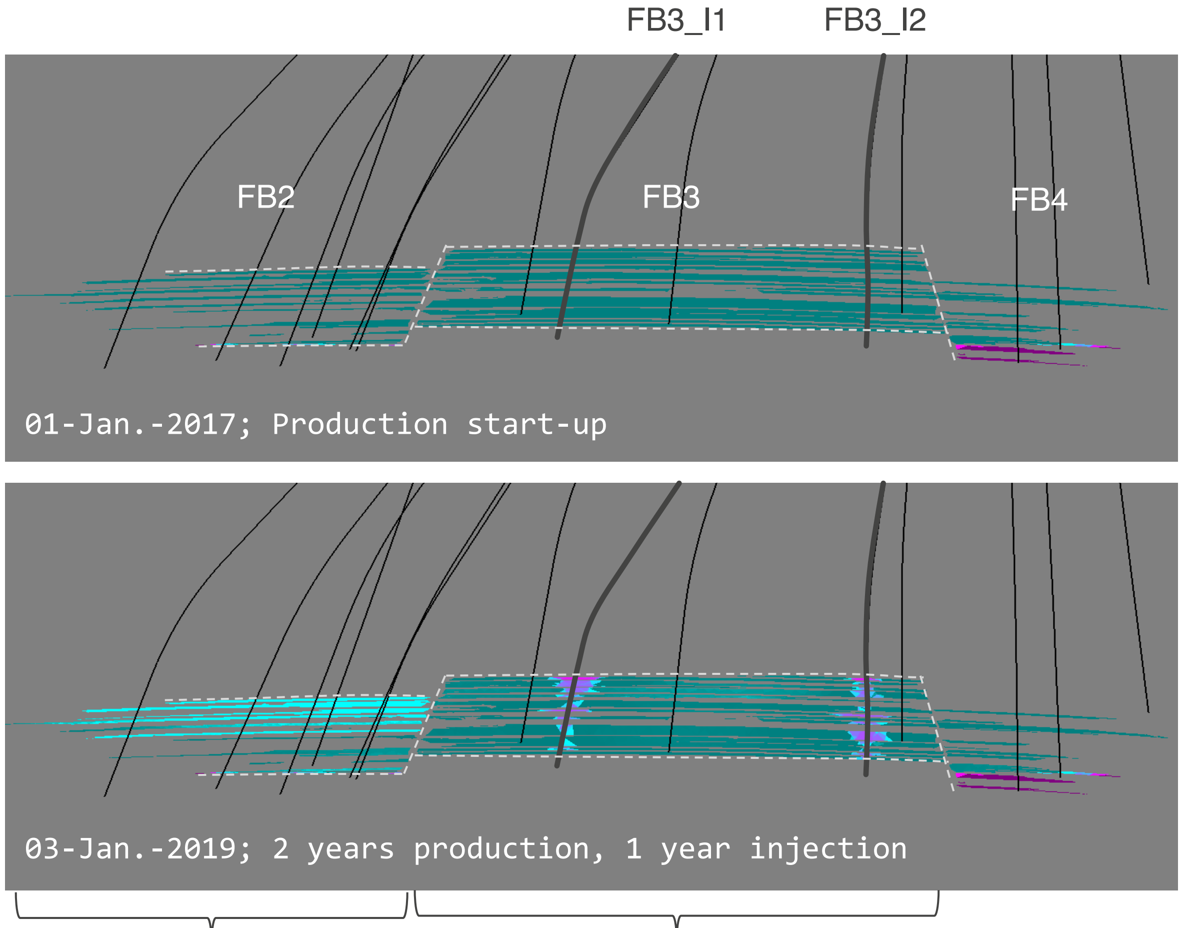
Time-Lapse Changes: Sw





Fault block 2 (FB2):

- Primary production
- Pressure drop with gas coming out of solution
- Compaction and subsidence

Fault block 3 (FB3):

- Transect through two injectors
- Water front causes pressure increase
- Gas forced back into solution
- Reservoir dilation of sandstones, and compaction of interlayered shales

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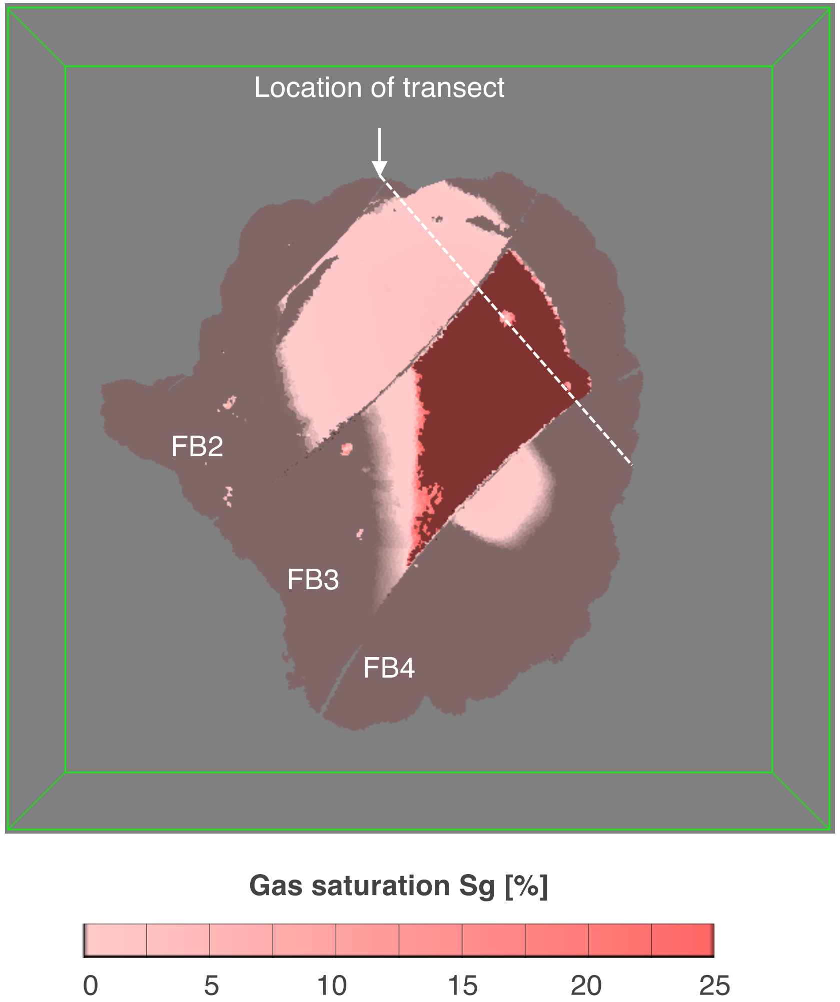
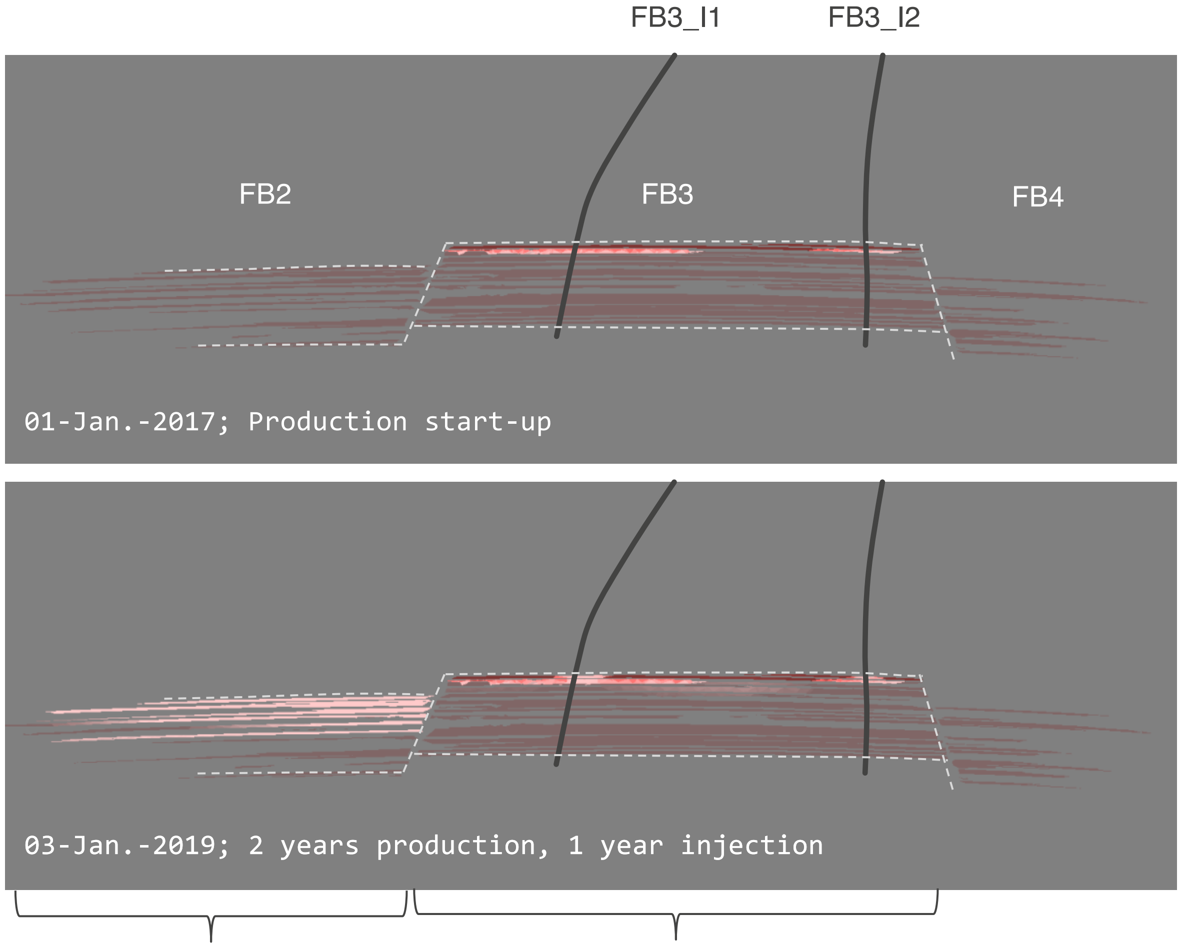
Time-Lapse Changes: Sg





Fault block 2 (FB2):
- Primary production
- Pressure drop with gas coming out of solution
- Compaction and subsidence

Fault block 3 (FB3):
- Transect through two injectors
- Water front causes pressure increase
- Gas forced back into solution
- Reservoir dilation of sandstones, and compaction of interlayered shales

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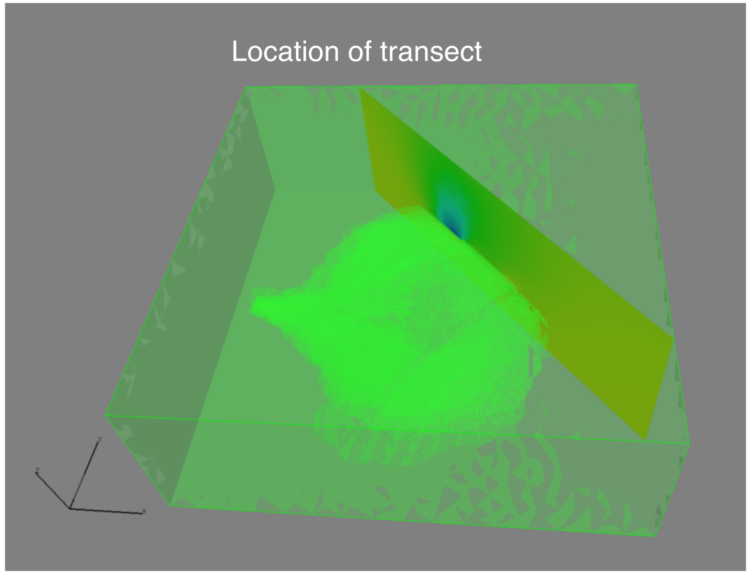
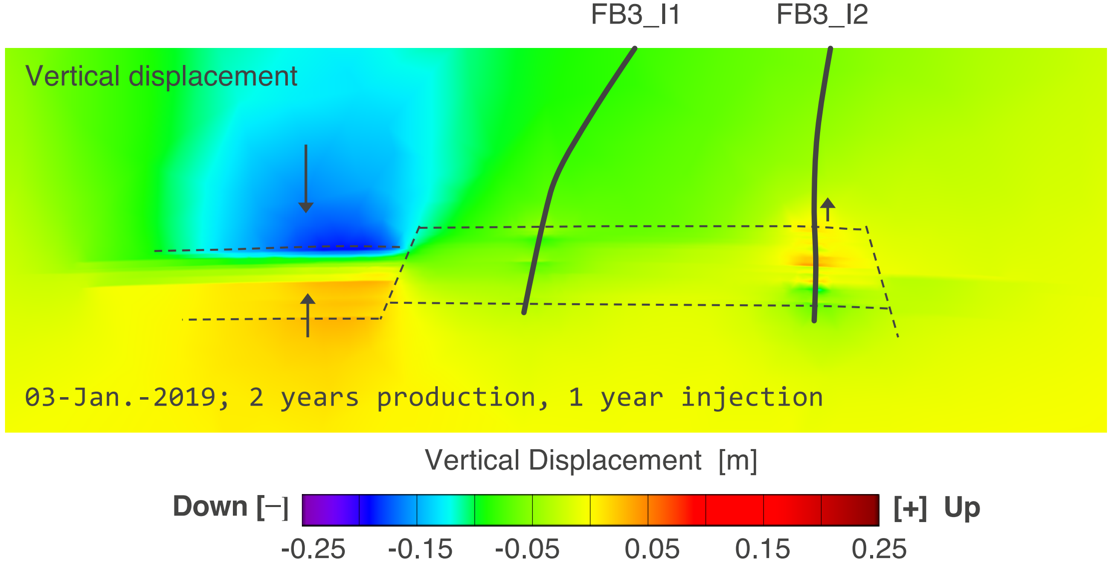
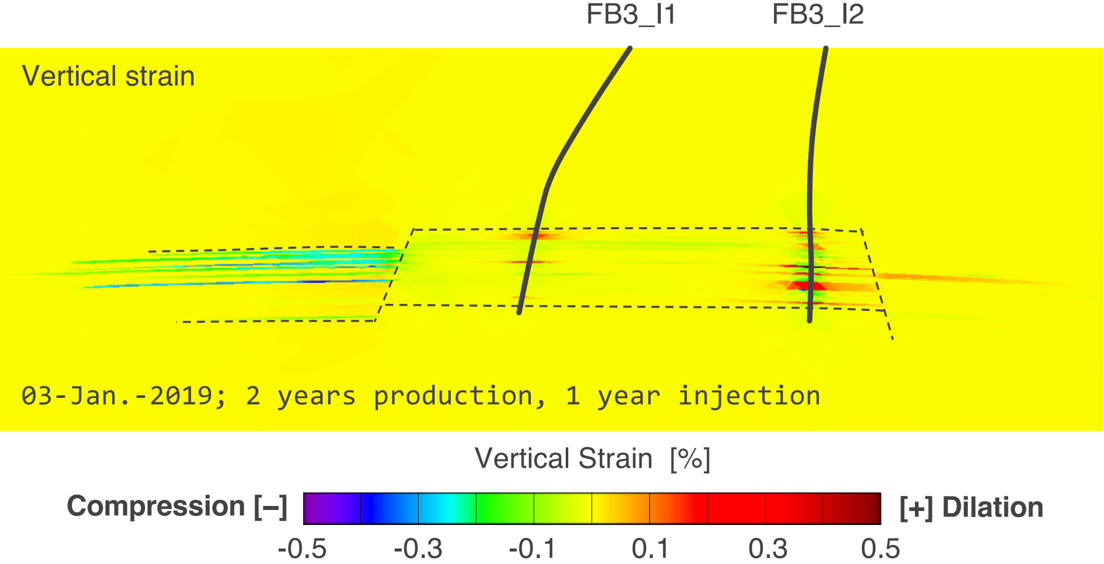
Time-Lapse Changes: Displacement







Key messages

Preserving stratigraphy in the numerical model is key to accuracy

Primary production: *Sands compact, shales dilate*

Near injection wells: *Sands dilate, shales compact*

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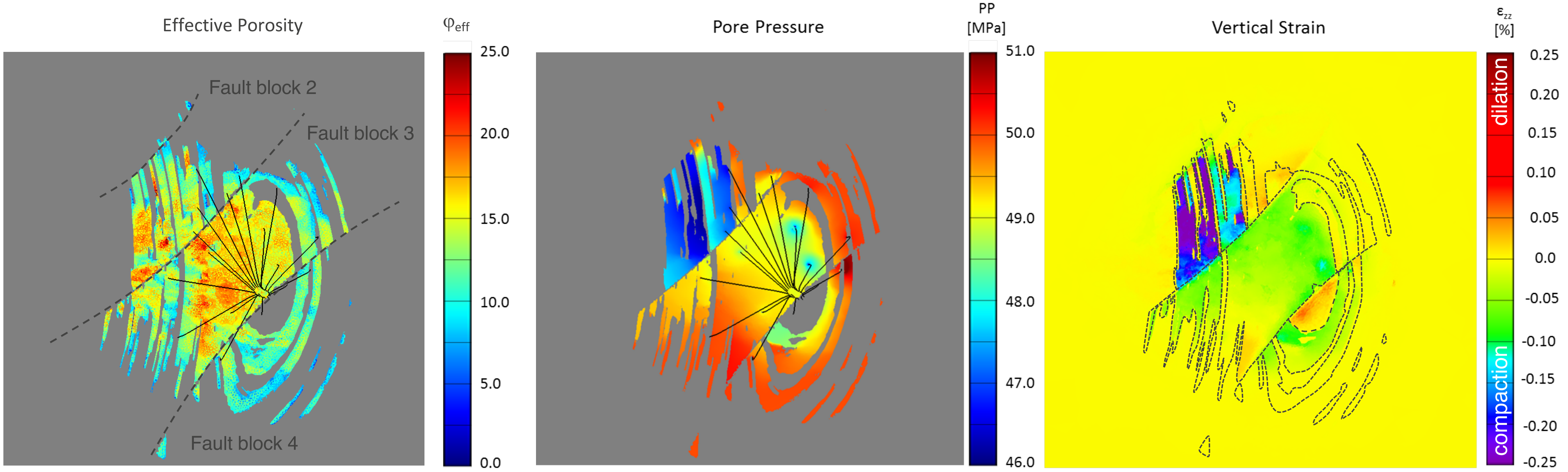
Time-stamp for time-lapse seismic simulations

2 years 3.5 months of field production



2019-05-08
(k=1500, Depth=3750 m)

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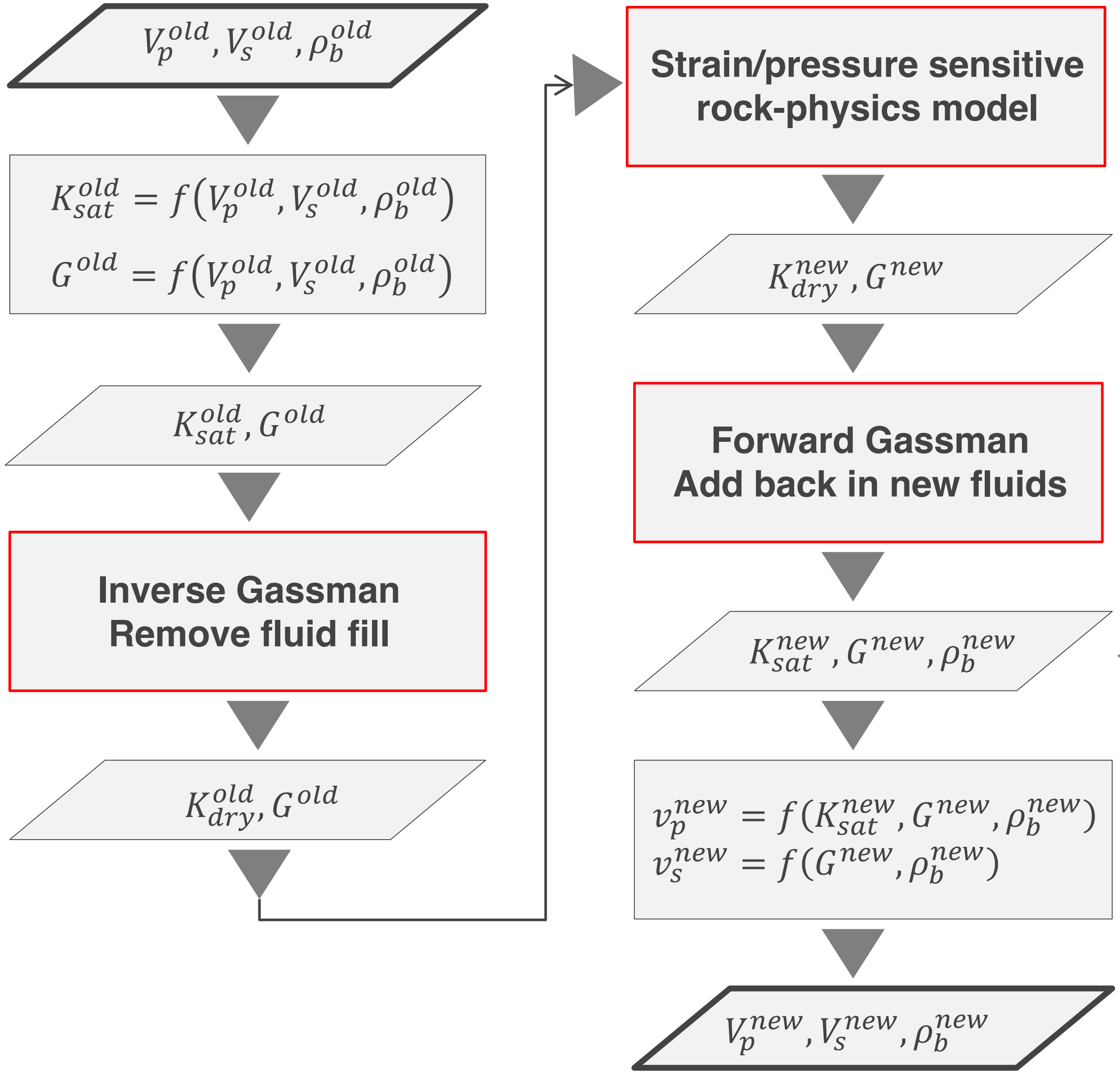
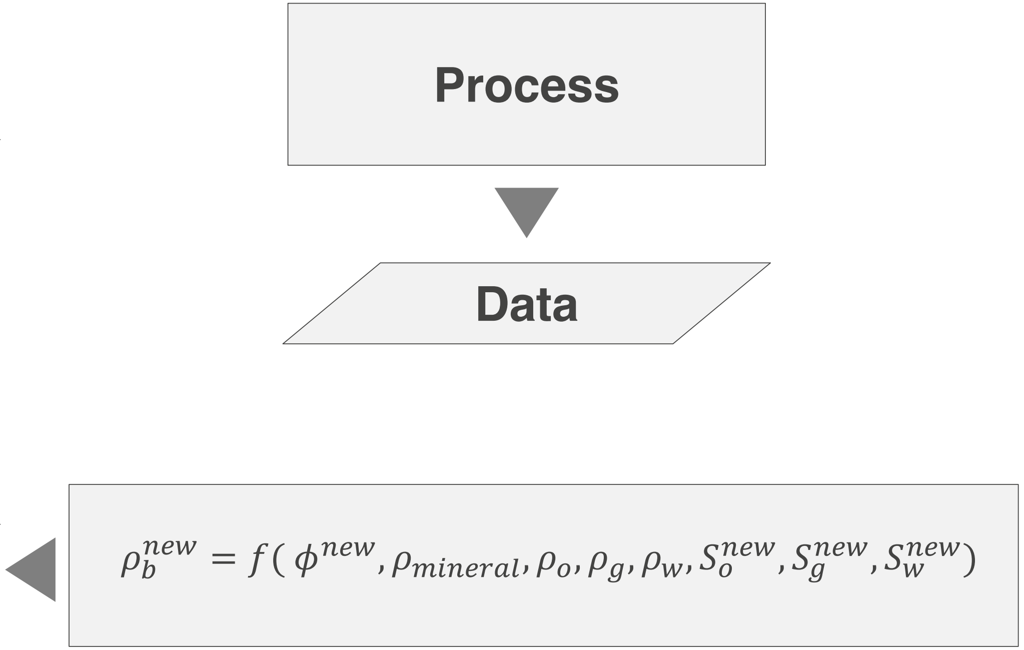
Updating the Rock Physics





Reservoir changes exported to property cubes

Rock physics model applied on property cubes

Displacements applied to nodes in seismic finite-element grid

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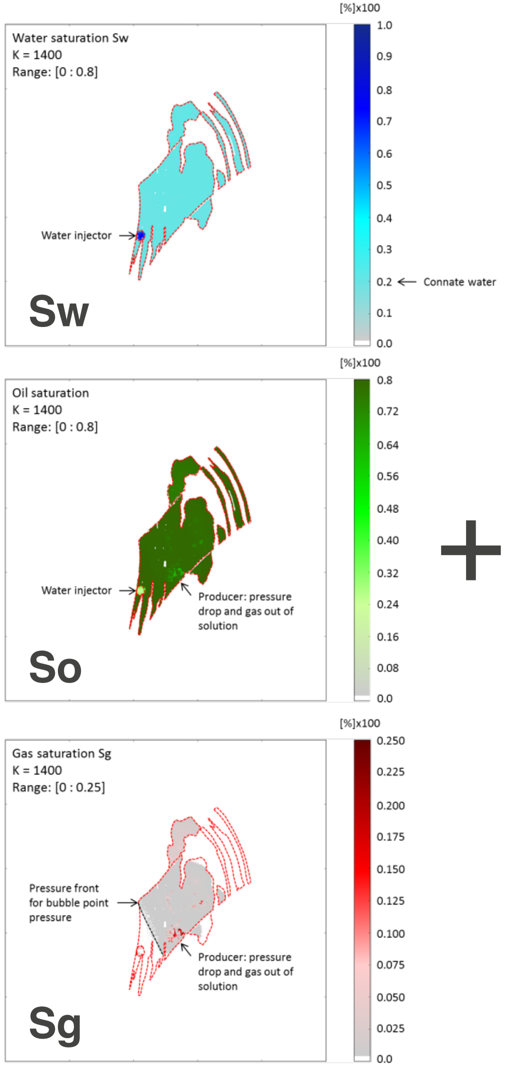
Updating the Rock Physics

SATURATION CHANGES



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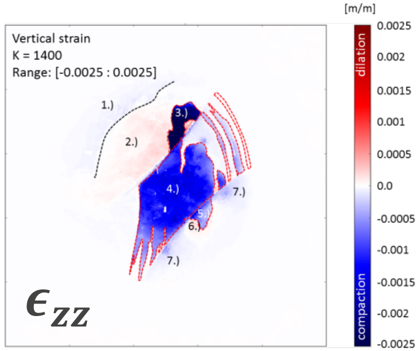
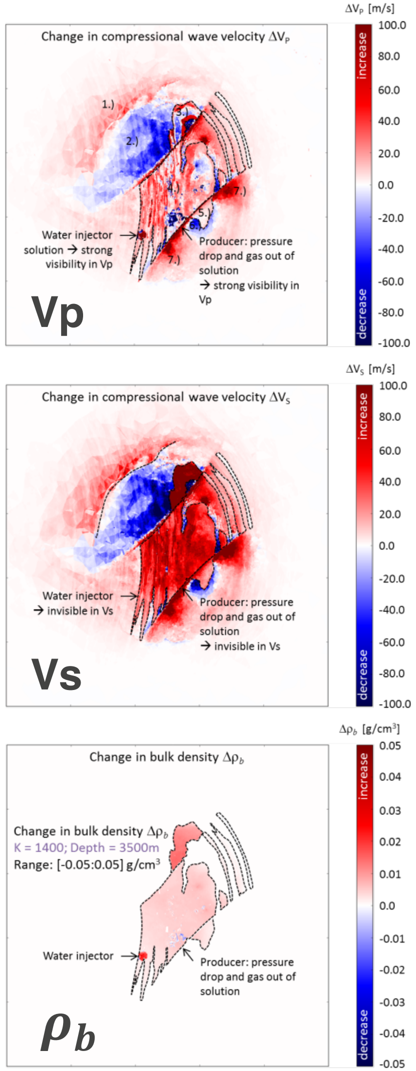
GEOMECHANICAL CHANGES



ELASTIC CHANGES



Elastic Model Updates

Gassman fluid substitution ensures that high-porosity rocks show a stronger effect of fluid substitution than low-porosity rocks.

Making the pressure sensitivity of elastic moduli a function of effective porosity gives a near-constant strain sensitivity ($\Delta V/V$) and a constant R-factor (Hatchell and Bourne, 2005).

Hatchell P and Bourne S, 2005, "Rocks under strain: Strain-induced time-lapse time shifts are observed for depleting reservoirs," *The Leading Edge* **24**, 1222–1225.

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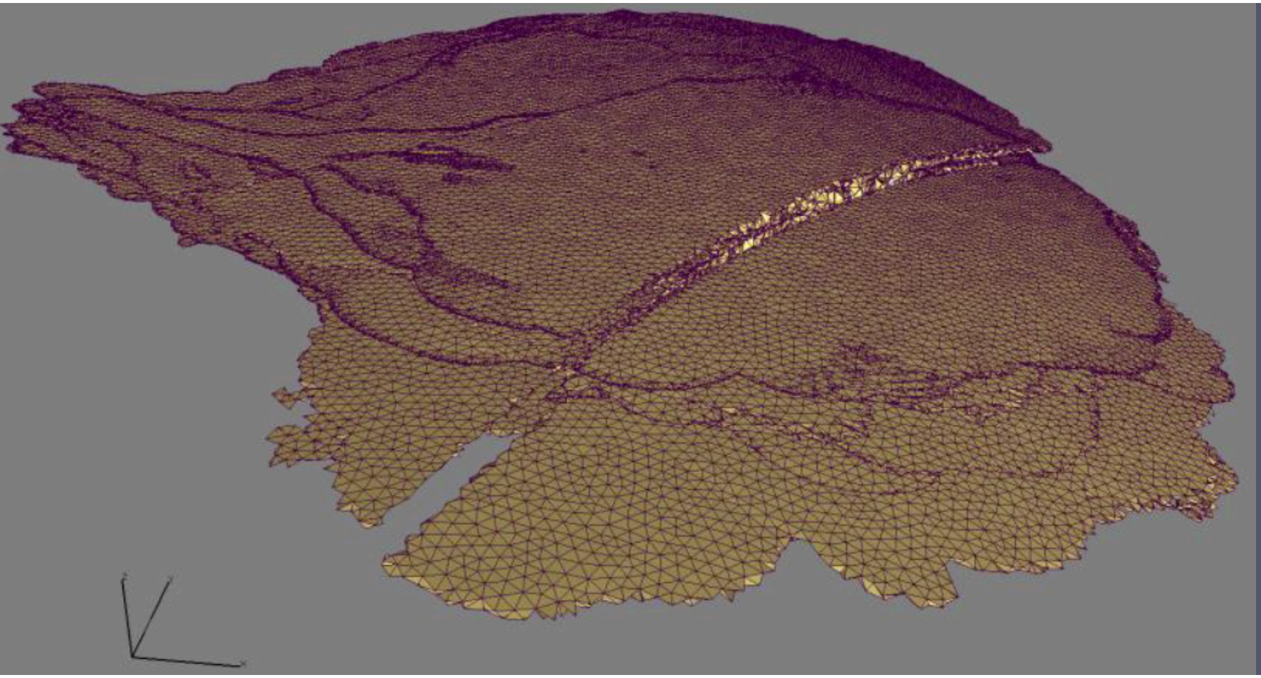
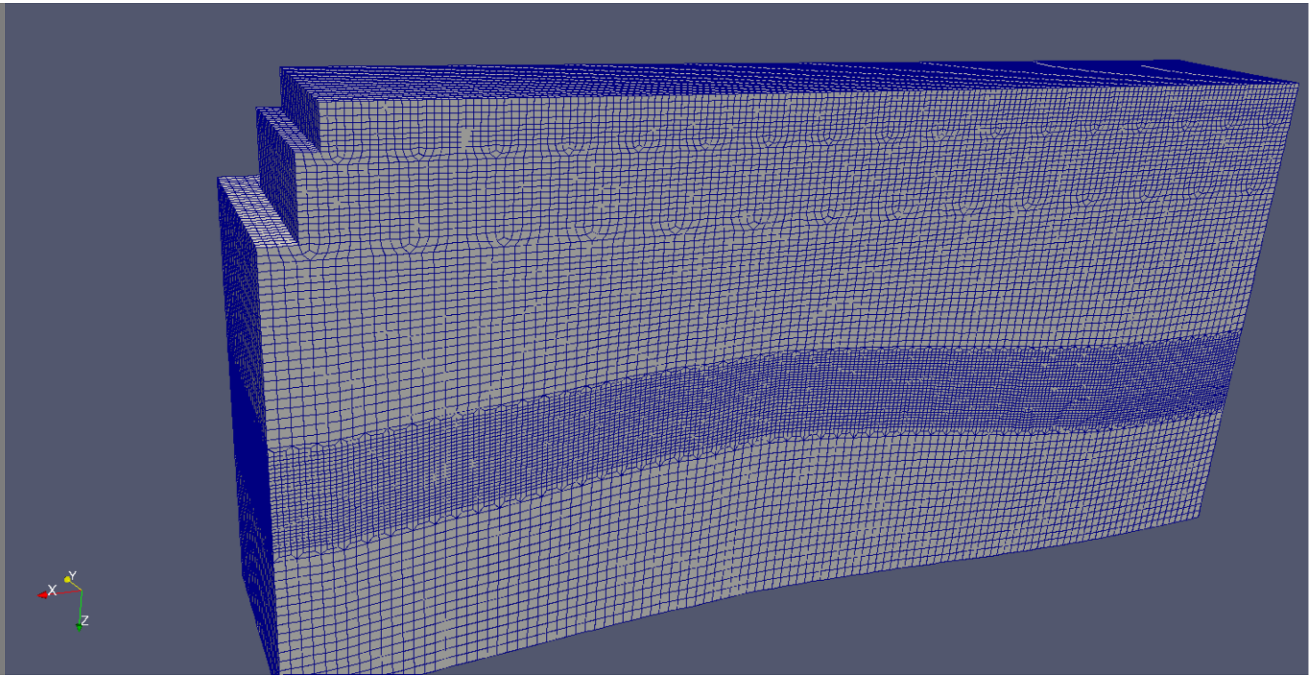
Conforming Finite-Element Grids

Finite-element grids were created separately for the reservoir (flow + geomechanics) and the seismic simulations. These grids were designed to conform to key geologic features that determined the responses for each simulation: facies distributions for the reservoir simulation and structural elements for the seismic simulation. Cross-scaling between the grids was done via the digital geologic model, which was built at a resolution suitable for both sets of simulations. Cross-scaling between reservoir and geophysical numerical simulations is ripe for further research using multi-scale finite-element techniques.



Finite element grid of turbidite stack for reservoir modeling



Finite element grid of geologic structure for seismic modeling

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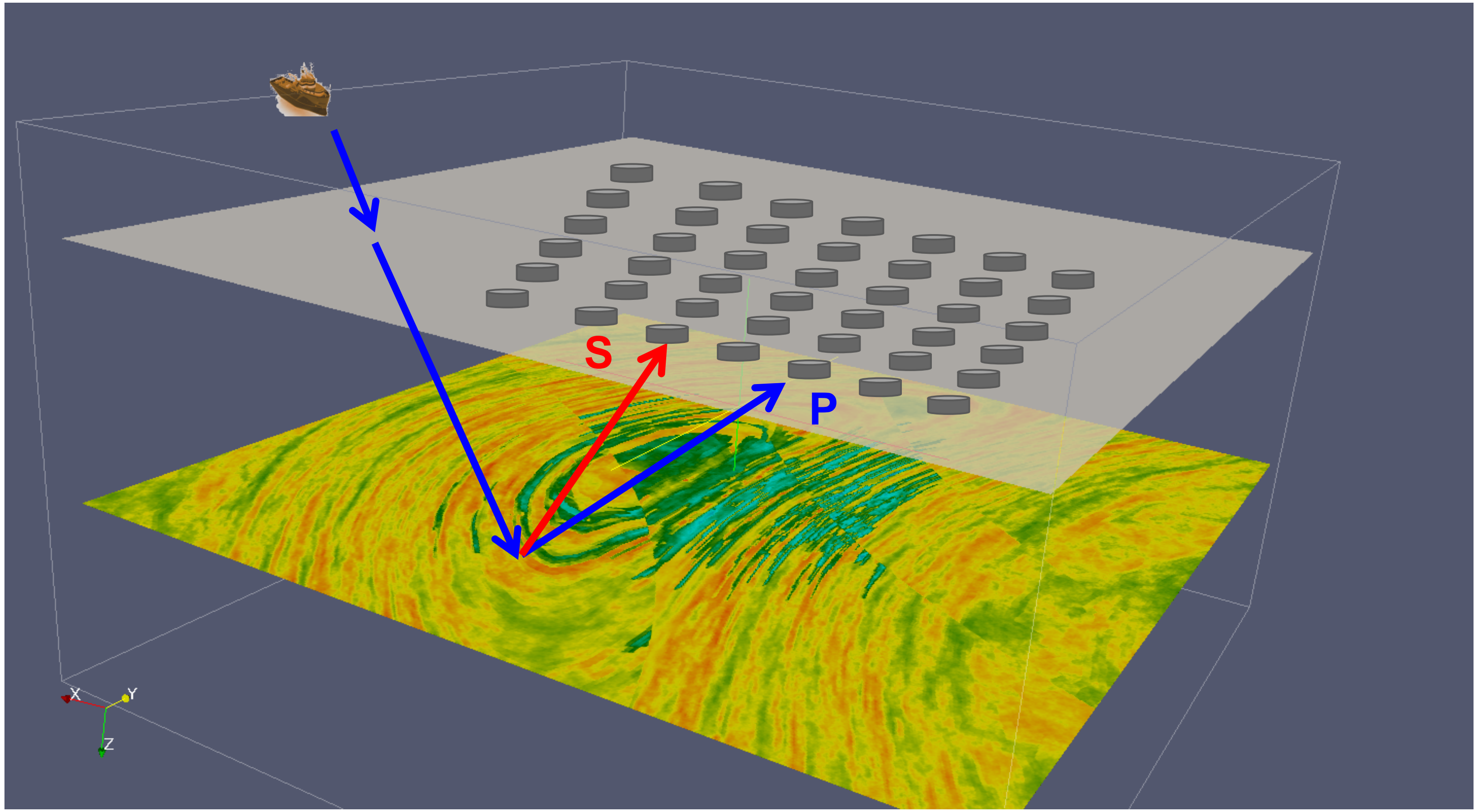
Seismic acquisition

Ocean Bottom Node (OBN) geometry



Seismic Survey Parameters

- 45 Hz source wavelet
- 175 m node spacing
  3600 nodes (60×60, x and y)
- Shots everywhere in region
  [0,12 500]×[0,12 500]
  at 25 m spacing
  200 m above sea bottom
- 7 second pressure records
  (time and budget constraints)
- Computational aperture is the full model for all shots
- **Absorbing upper boundary**
  No surface-multiple ghost

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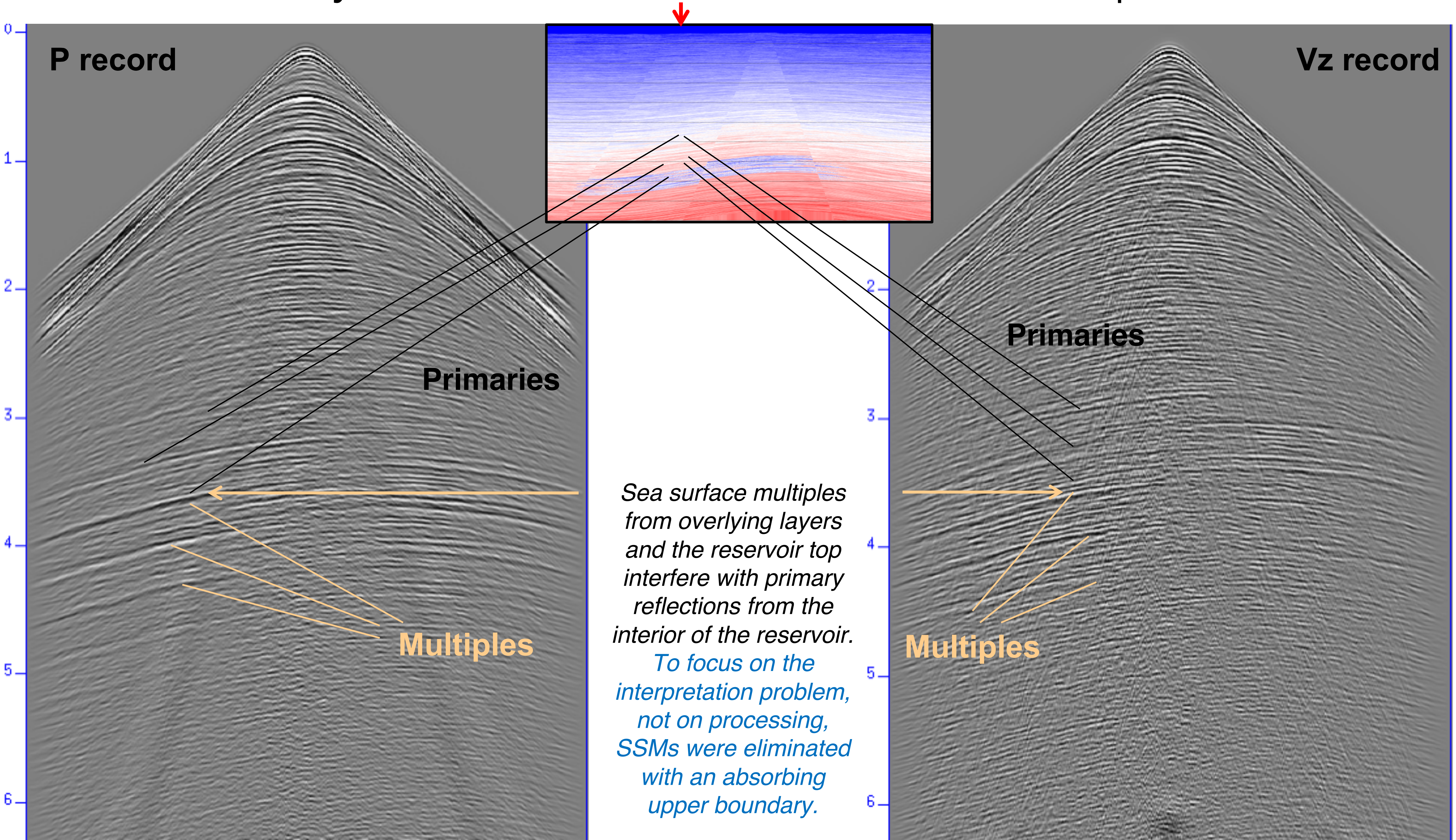
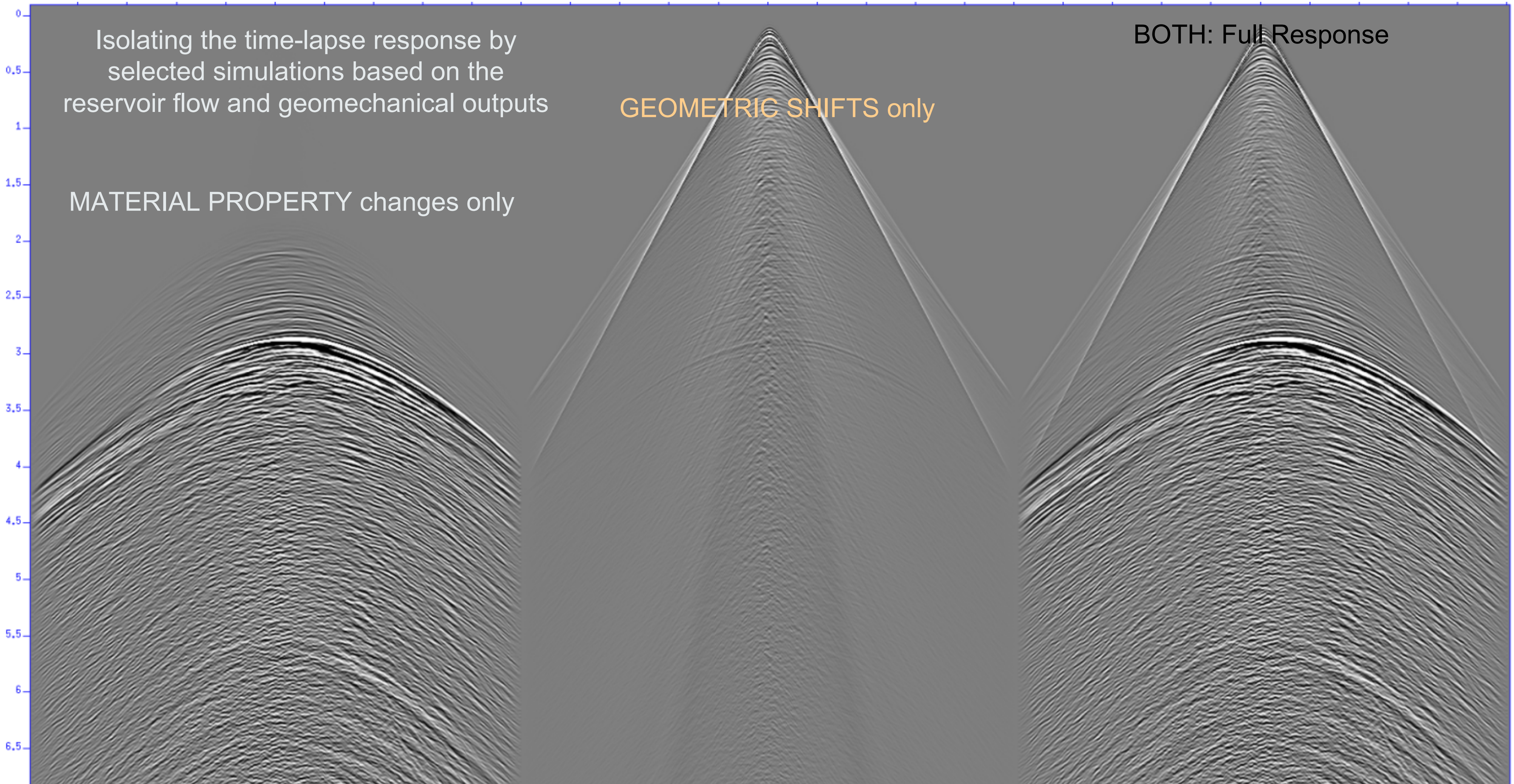
Why eliminate the free-surface multiple?



Sea surface multiples from overlying layers and the reservoir top interfere with primary reflections from the interior of the reservoir.

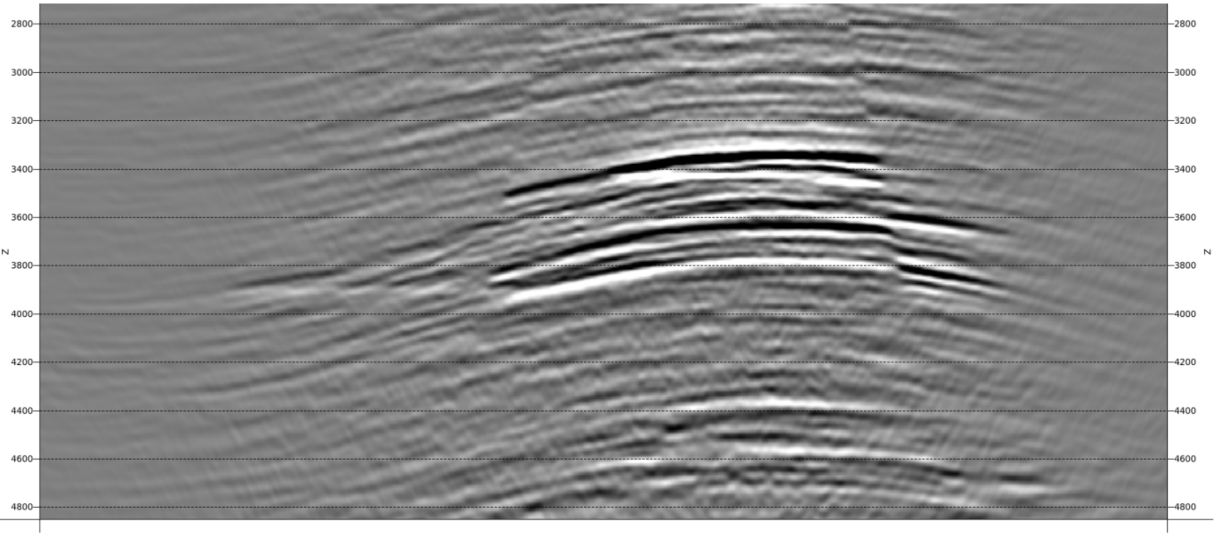
To focus on the interpretation problem, not on processing, SSMs were eliminated with an absorbing upper boundary.

Time-Lapse Seismic Responses (After–Before)

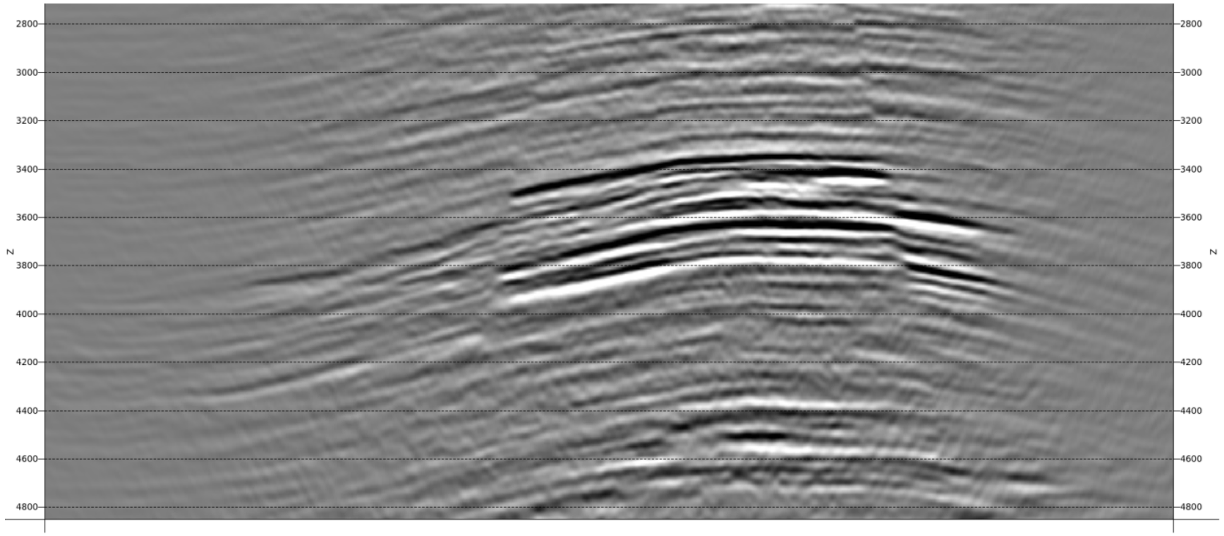


Time-Lapse Images at Reservoir Level

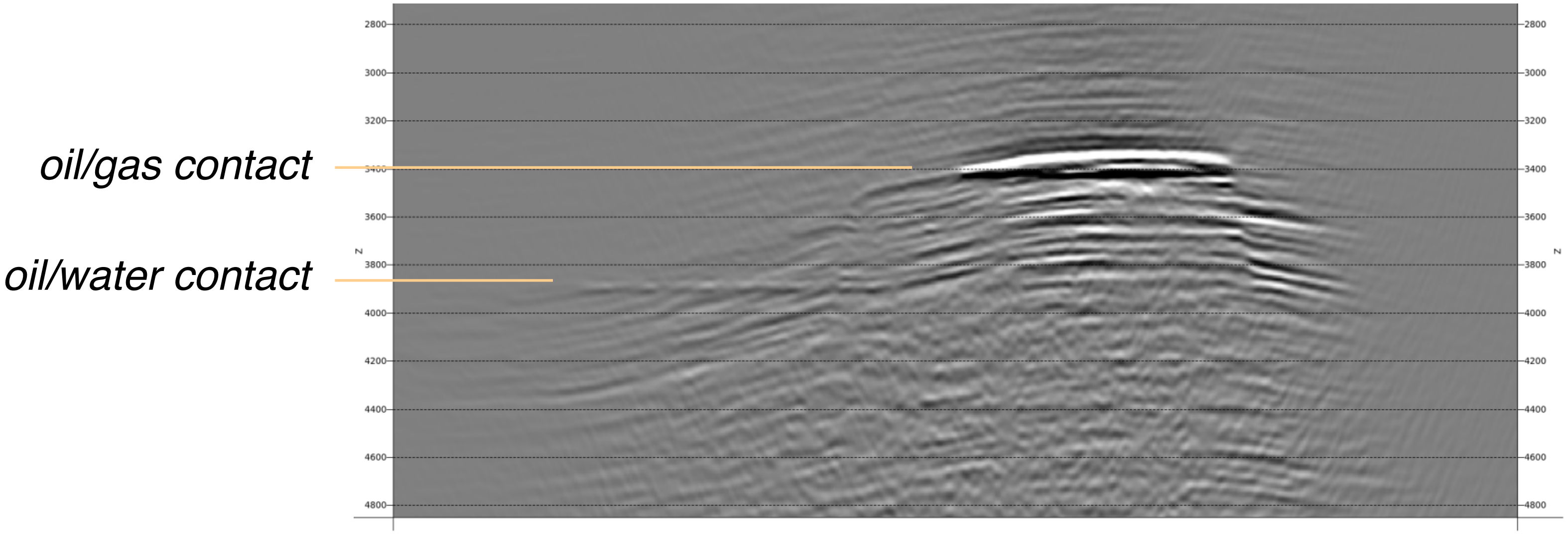
Before production



After production

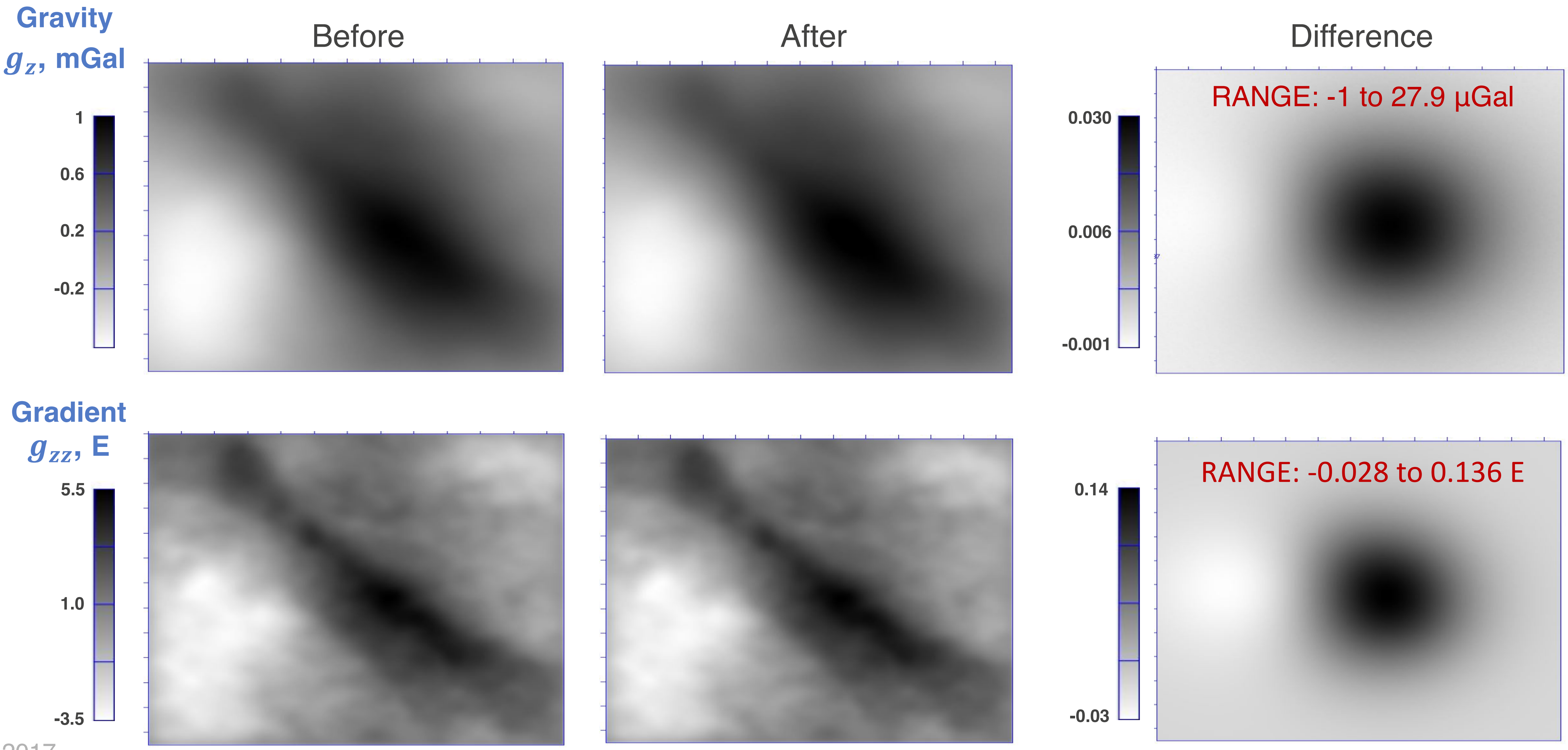


Difference



Airborne Gravity

30 m above sea level



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Lessons Learned

- **Modern numerical methods can simulate time-lapse surveys with realistic detail**.
  - Use of finite-element numerical methods for both reservoir (flow + geomechanics) and seismic simulation helps in creating digital models that conform to realistic geology ("shrink wrapping finite-element grids to facies"), but there are still research issues in cross-scaling between the reservoir and seismic grids.
- **4D conceptual models and field examples are needed to develop more refined simulation plans to highlight 4D pressure and geomechanical effects.**
  - Allow plenty of time to fine-tune simulated production plans: a large fraction of the project time was spent on trial runs of to determine the flow rates necessary to achieve realistic pressure and deformation effects.
  - *"Walk before we run": Start with simple models, work with more complex scenarios once experience is gained.*
- **More and better petrophysical models are needed to translate flow and deformation effects to geophysical parameter models.**
  - Empirical models are available for clastic reservoirs and overburden, but still require careful calibration. Carbonates are an open field. Better theoretical tools are needed to understand changes: For this model, seismic and gravity showed detectable time-lapse responses; CSEM and MT time-lapse responses were below the noise.

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Next Steps

- **SEAM Life of Field is a new multi-year, multidisciplinary project** aimed at improving workflows and interpretation methodologies used to **manage the full life of a field**.
  - Build larger, more detailed and **more realistic clastic models**: shallow and deepwater, subsalt
  - Begin to understand the **time-lapse response of carbonate models**: carbonate platform, lacustrine
  - Simulate the full life of a field over a **30-year production lifetime** with more complex scenarios
  - Build better petrophysical models to **calibrate observed time-lapse changes** in real reservoirs
  - Understand the **value of geophysical remote sensing**, including by downhole measurements, in workflows for reservoir management, over a reservoir's lifetime
  - Look at other applications: **carbon sequestration, gas storage, management of water reservoirs**
- **SEG/SEAM and SPE are continuing the technical collaboration in Life of Field, along with 7 member companies. New partners are welcome.**

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