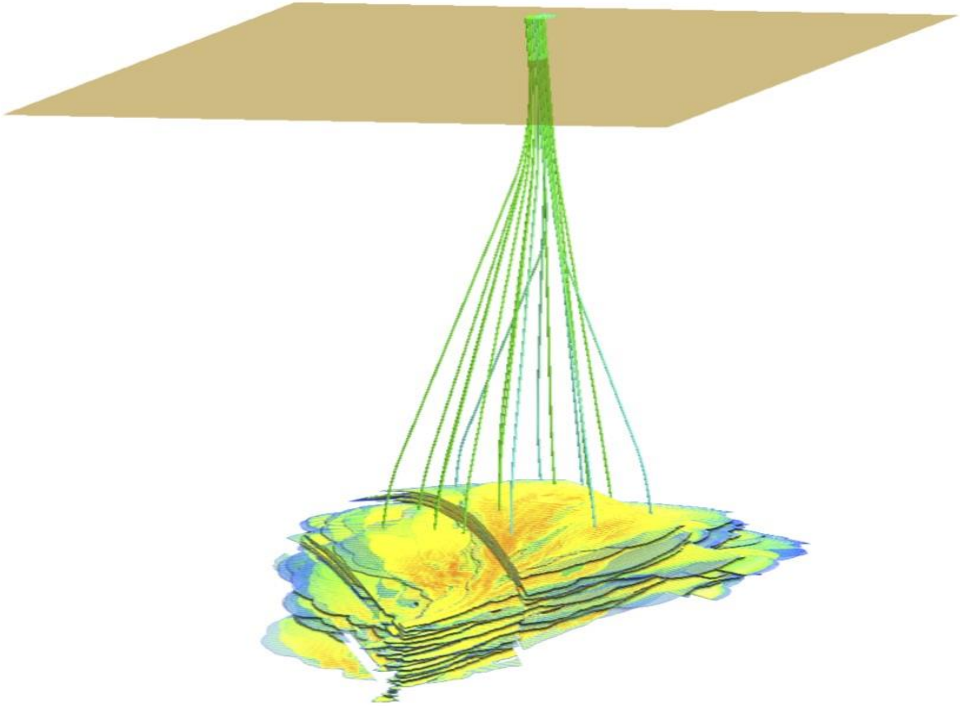
Large-scale Numerical Simulation of Reservoir Monitoring – SEAM Time Lapse



S. Oppert, J. Stefani, *Chevron Energy Technology Company*
V. Artus, *SPE (Kappa Engineering)*
J. Herwanger, P. Popov, A. Bottrill, *MP Geomechanics (Ikon Science)*
L. Tan, W. Hu, J. Liu, *Advanced Geophysical Technology*
W. Abriel, R. Detomo, W. Barkhouse, *SEG*
M. Oristaglio, *SEAM (Yale University)*
J. Paffenholz, *Fairfield Geotechnologies, SEAM Board*

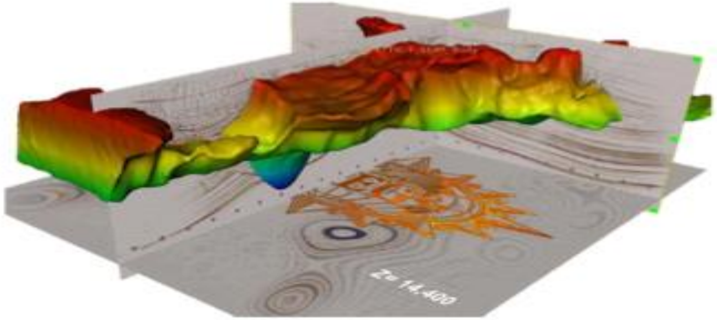
SEG ADVANCED MODELING
10 Years of Success in Advanced Modeling

SEAM: SEG Advanced Modeling Corp.

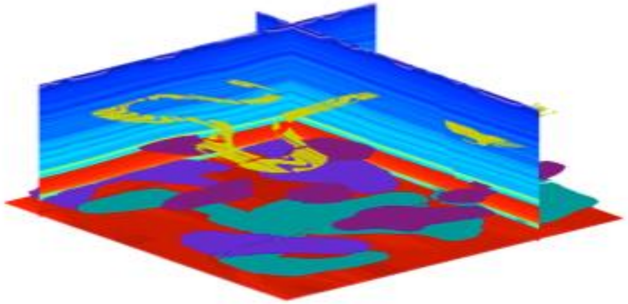
- **Non–profit corporation; subsidy of SEG ; established 2007**
- **Focused on industry challenges at a scale not normally feasible for single organizations or academic consortia**
- **SEAM is SEG's co-operative research organization**
  - Projects directed by Member companies
  - Participants frame project tasks & carry out certain tasks as volunteers
  - 3rd parties, contracted through open bidding, carry out major model-building and/or simulation tasks
  - Project Manager under contract to SEAM manages each project

SEAM Projects to Date

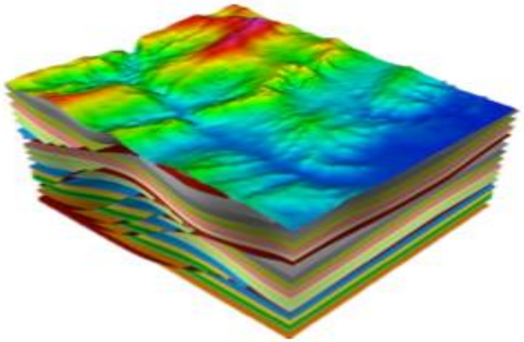
GULF OF MEXICO SUBSALT MODEL



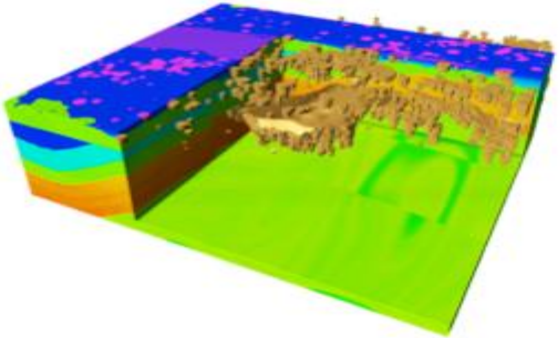
BARRETT UNCONVENTIONAL MODEL



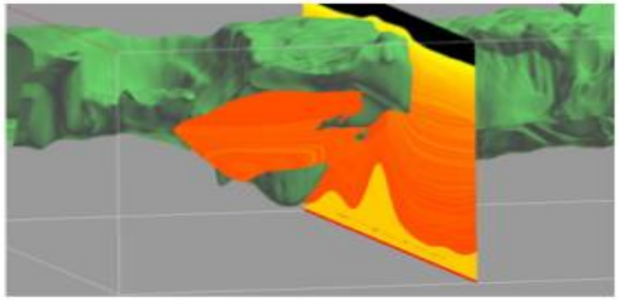
FOOTHILLS MODEL



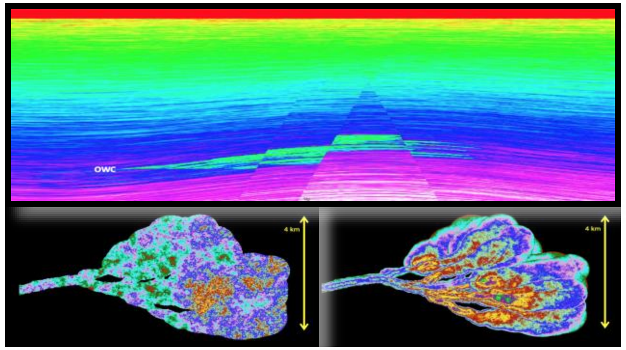
ARID MODEL



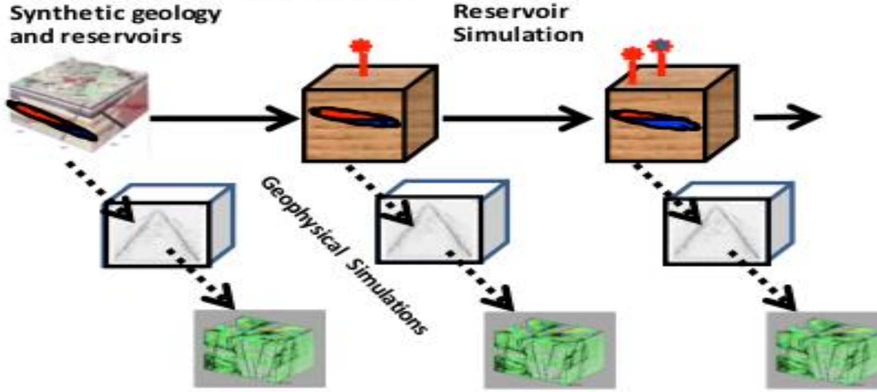
PORE PRESSURE



TIME LAPSE PILOT



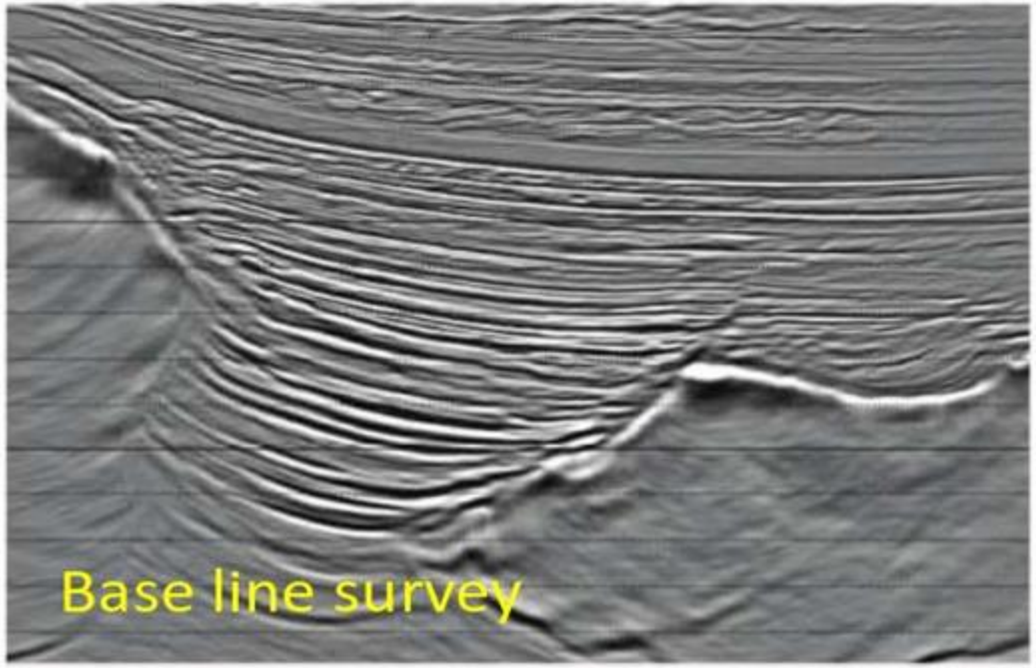
LIFE OF FIELD

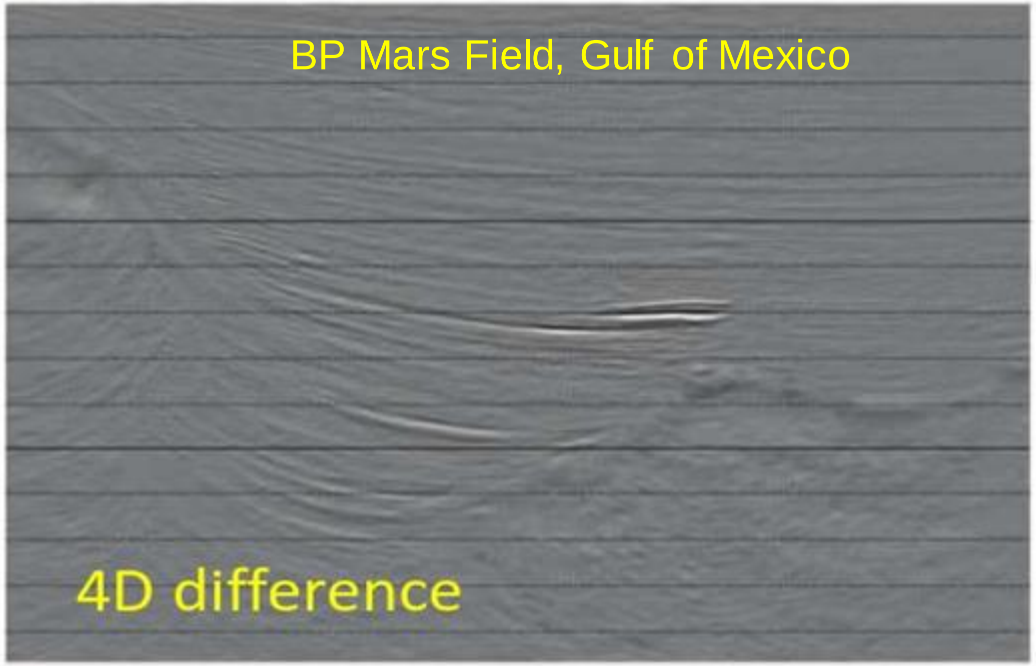


SEAM Life of Field (LoF)

- Geologic model building and synthetic seismic modeling aimed at *improving the workflows* used in managing the *life of an oil field*
  - *linking Geology, Reservoir Engineering, Rock Physics, Geomechanics, and Geophysics*
- Field management simulation to calibrate sensitivity of time lapse survey responses (seismic, G&M, electrical) to reservoir changes
  - *gas, oil, and water saturations, pressures, and reservoir compaction*
- Research tool to develop work flow for Life of Field processing where the results can be compared to known ground truth
  - *flight simulator for reservoir engineering*
- Framework for investigating CO_2 sequestration

Can modern numerical methods simulate changes in the geometry and physical properties of a reservoir over time — the changes in the rocks, pore fluids, and pressures that accompany reservoir flow and production — **in a realistic way and well enough** to explain and predict the subtle effects that are seen in time-lapse geophysical surveys of real oil fields?





"…high repeatability with an NRMS of 6%." (Stopin et al., 2011, EAGE)

SEAM Time Lapse Pilot Project

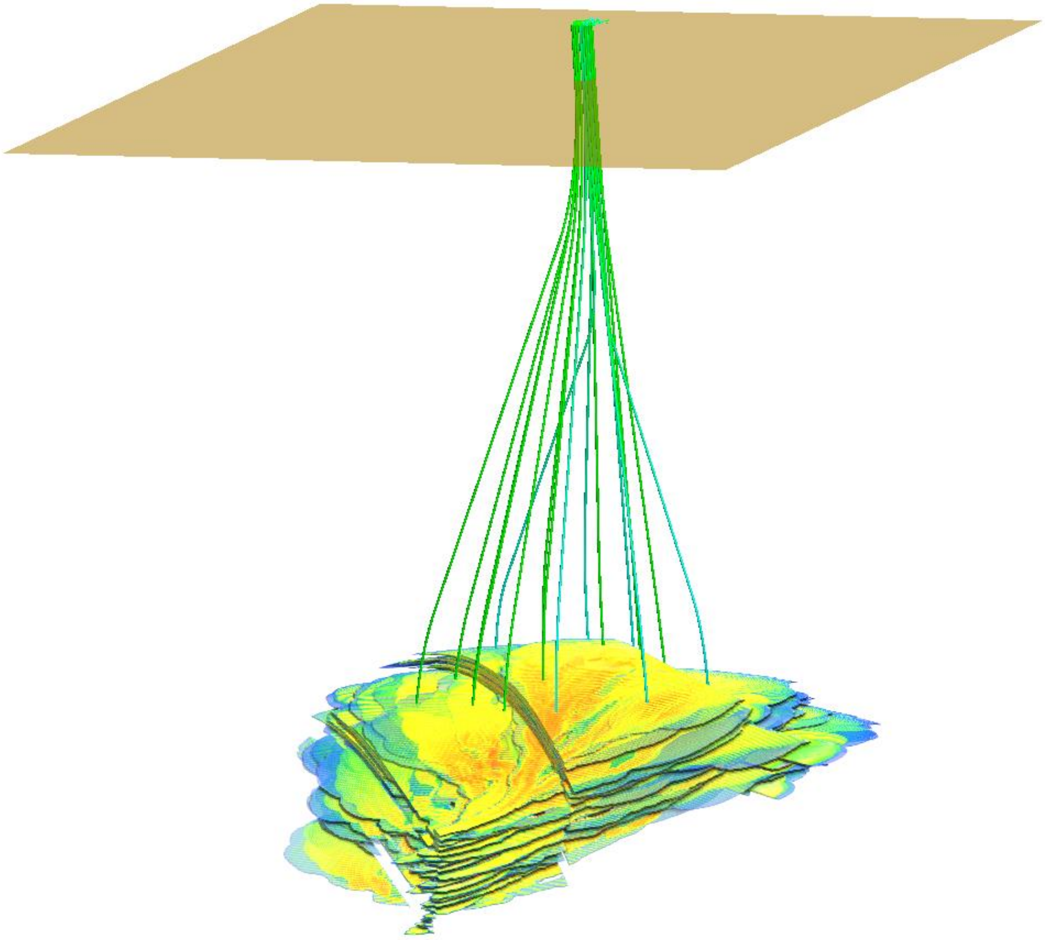
- Geologic model building
- Gridding
- Geomechanics and fluid flow modeling
- Seismic simulations

Design and Construction of the Geologic / Reservoir Model

Joe Stefani*

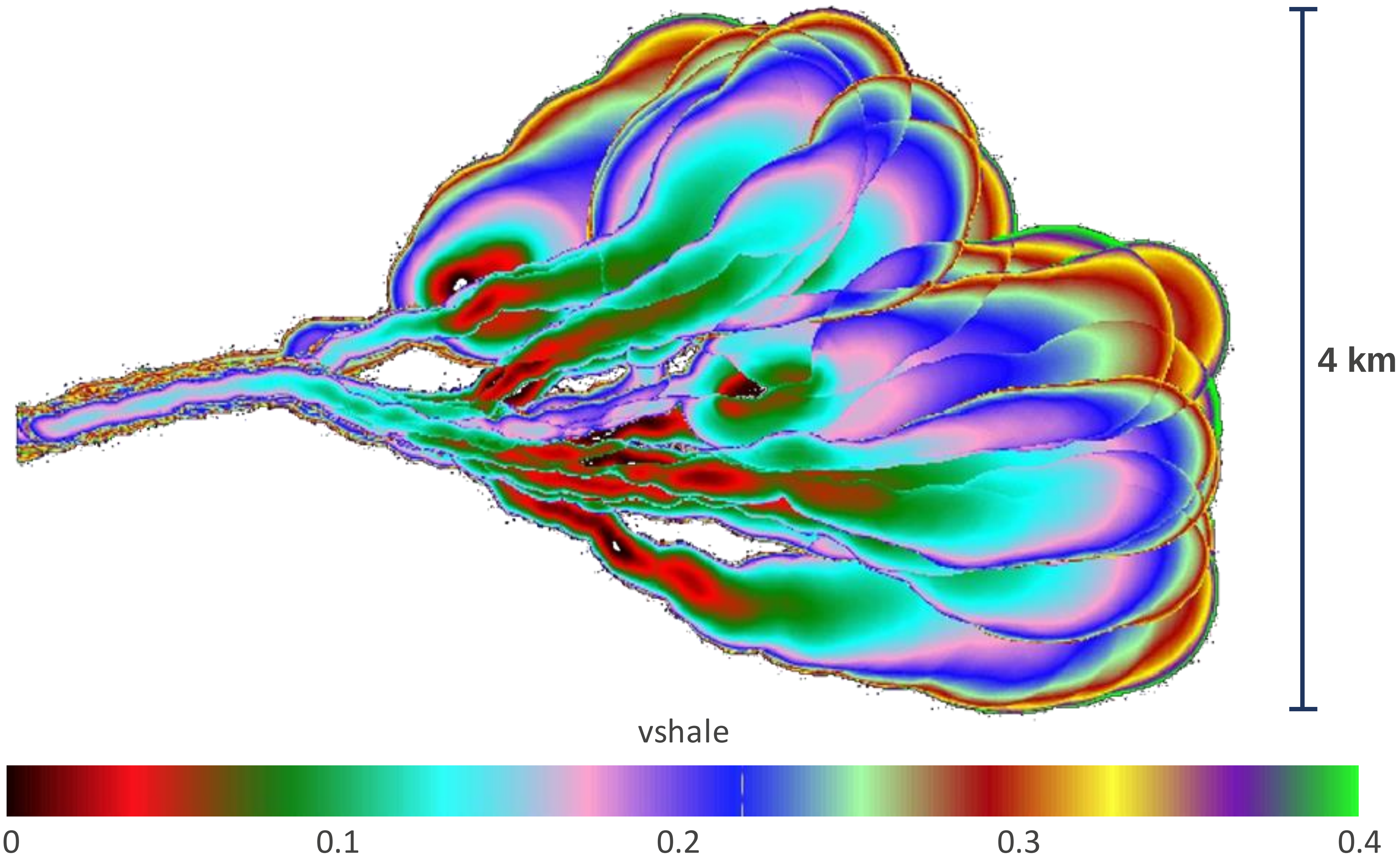
October 21, 2016

Chevron Energy Technology Company



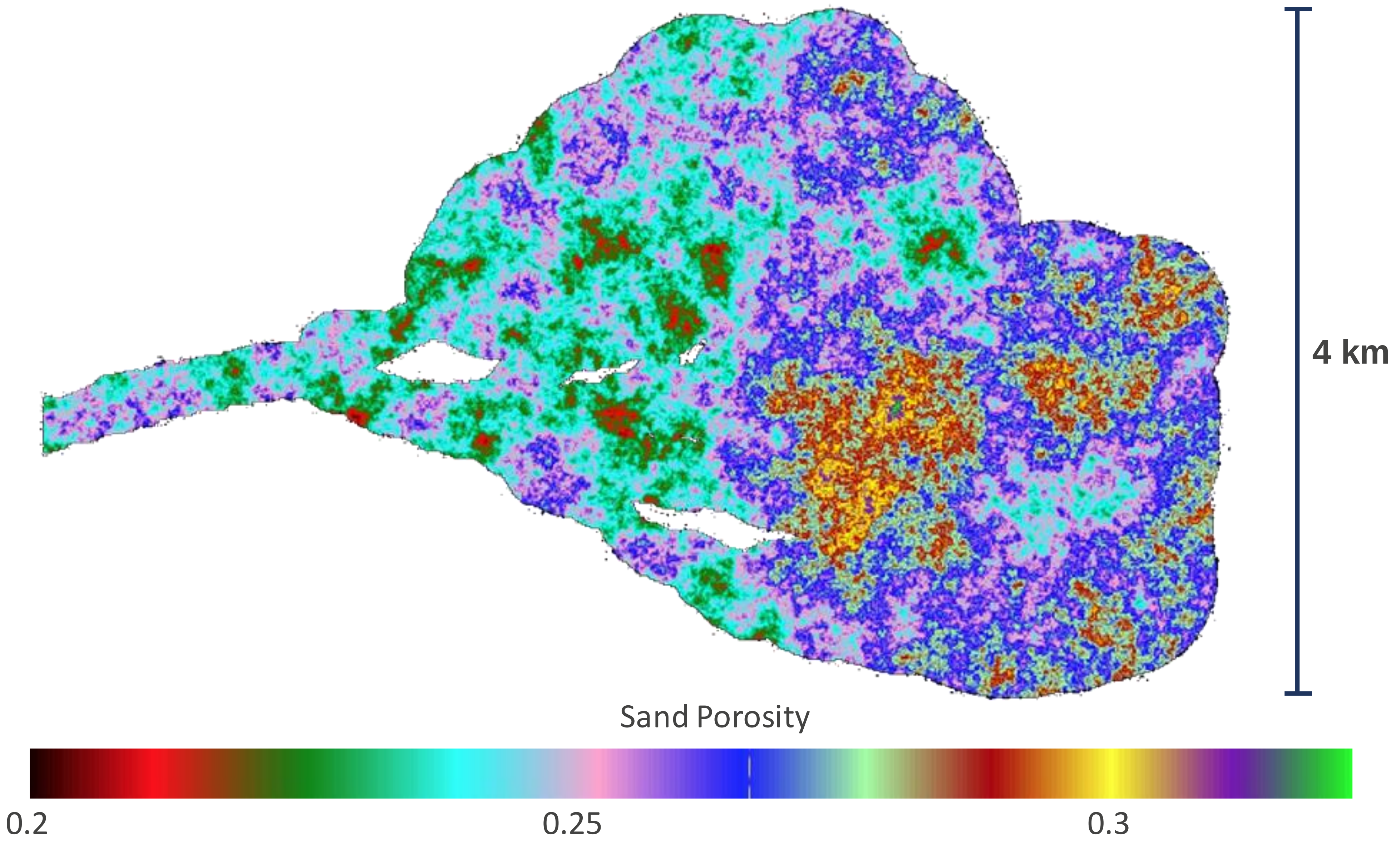
Turbidite reservoir element: Shale volume (vshale)

Sand rich channels spread out into distal shaley lobes: this is one of 80 5-m thick turbidite layers.



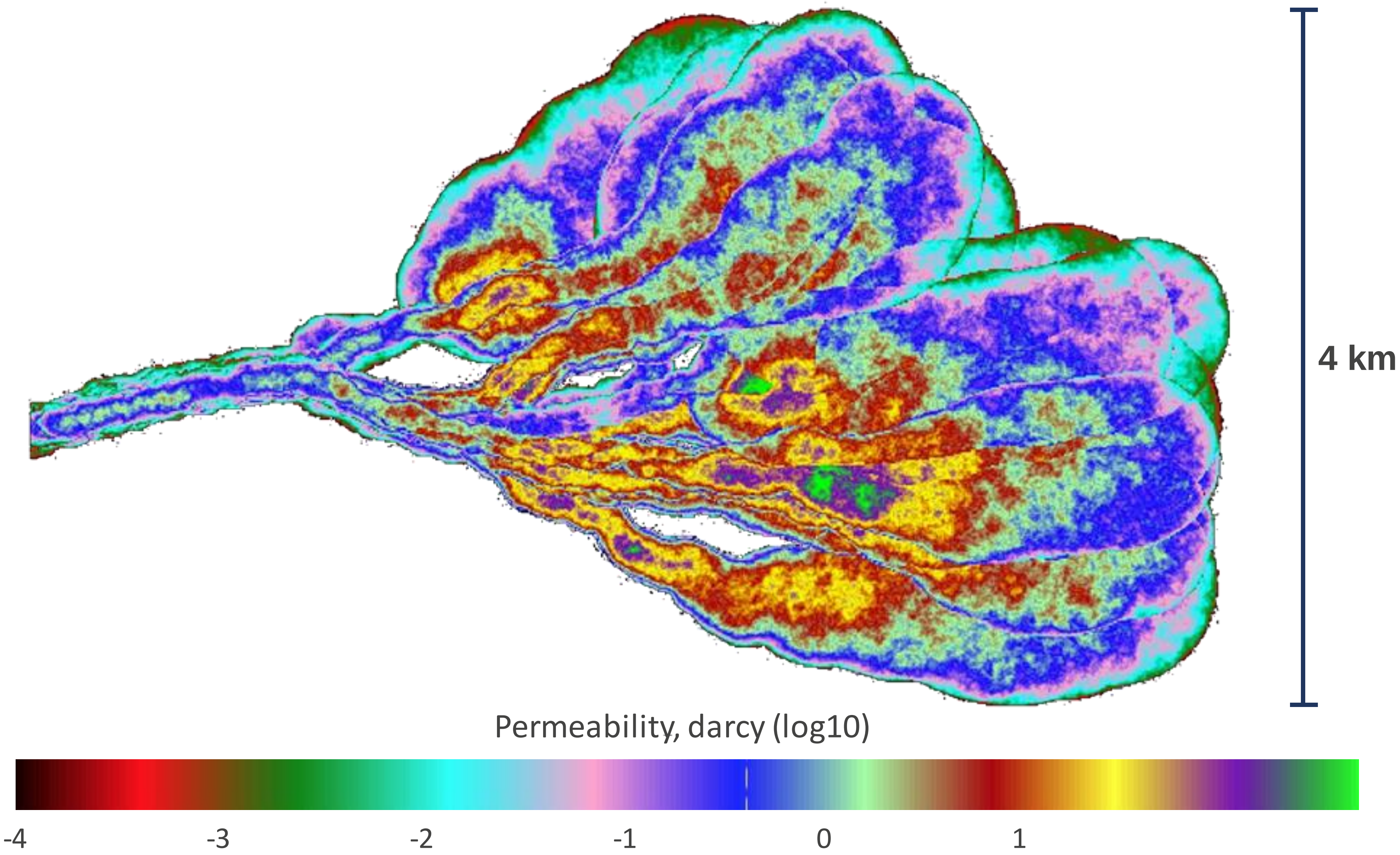
Turbidite reservoir element: Sand porosity

Sand porosity is distinct from shale porosity; it is porosity within the sand fraction only, used in flow simulations.



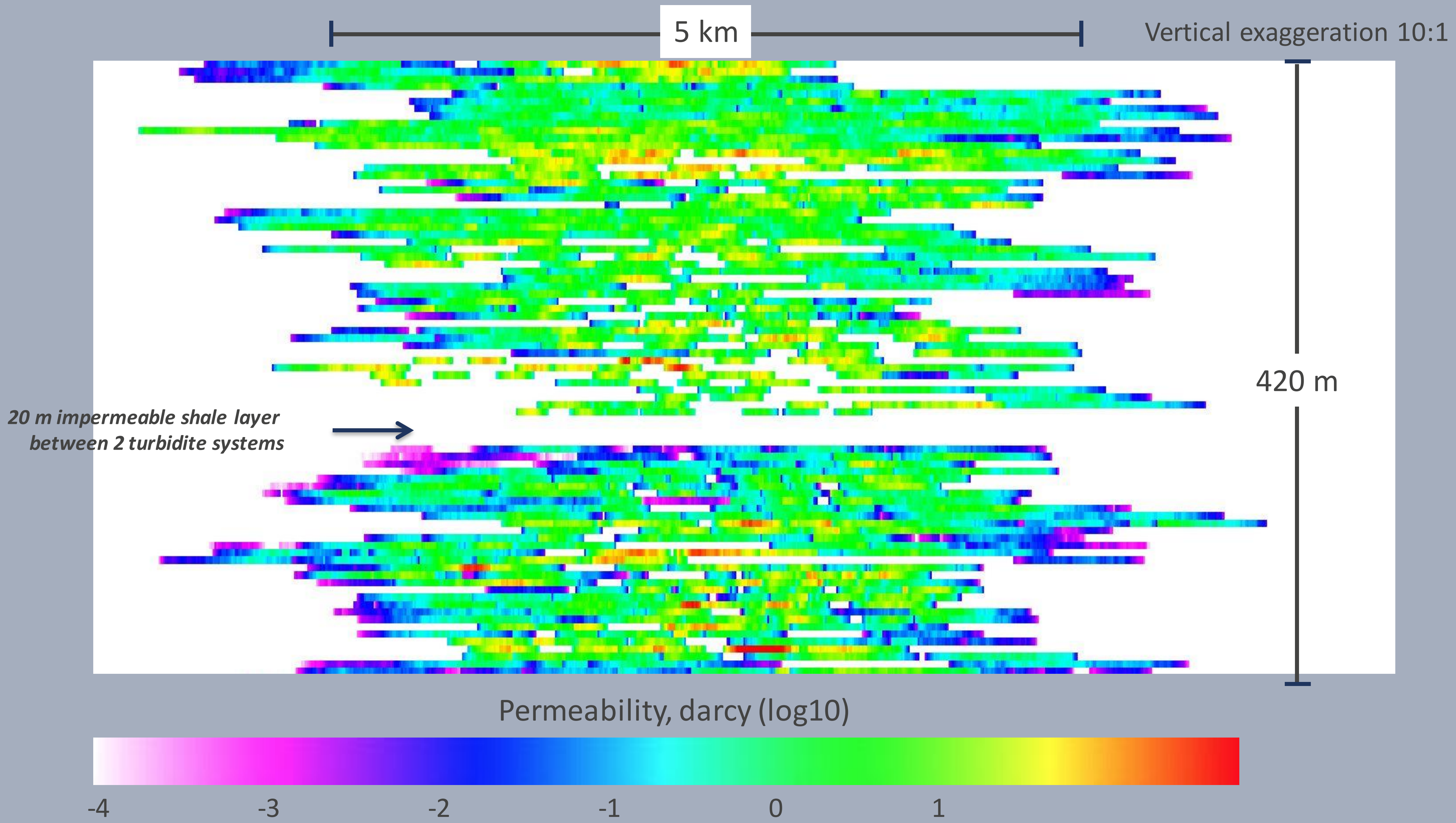
Turbidite reservoir element: Permeability [Darcy], log scale

$$\log_{10}(Perm) \sim -.08 * vshale + 25 * \phi_{sand} - 5.5$$

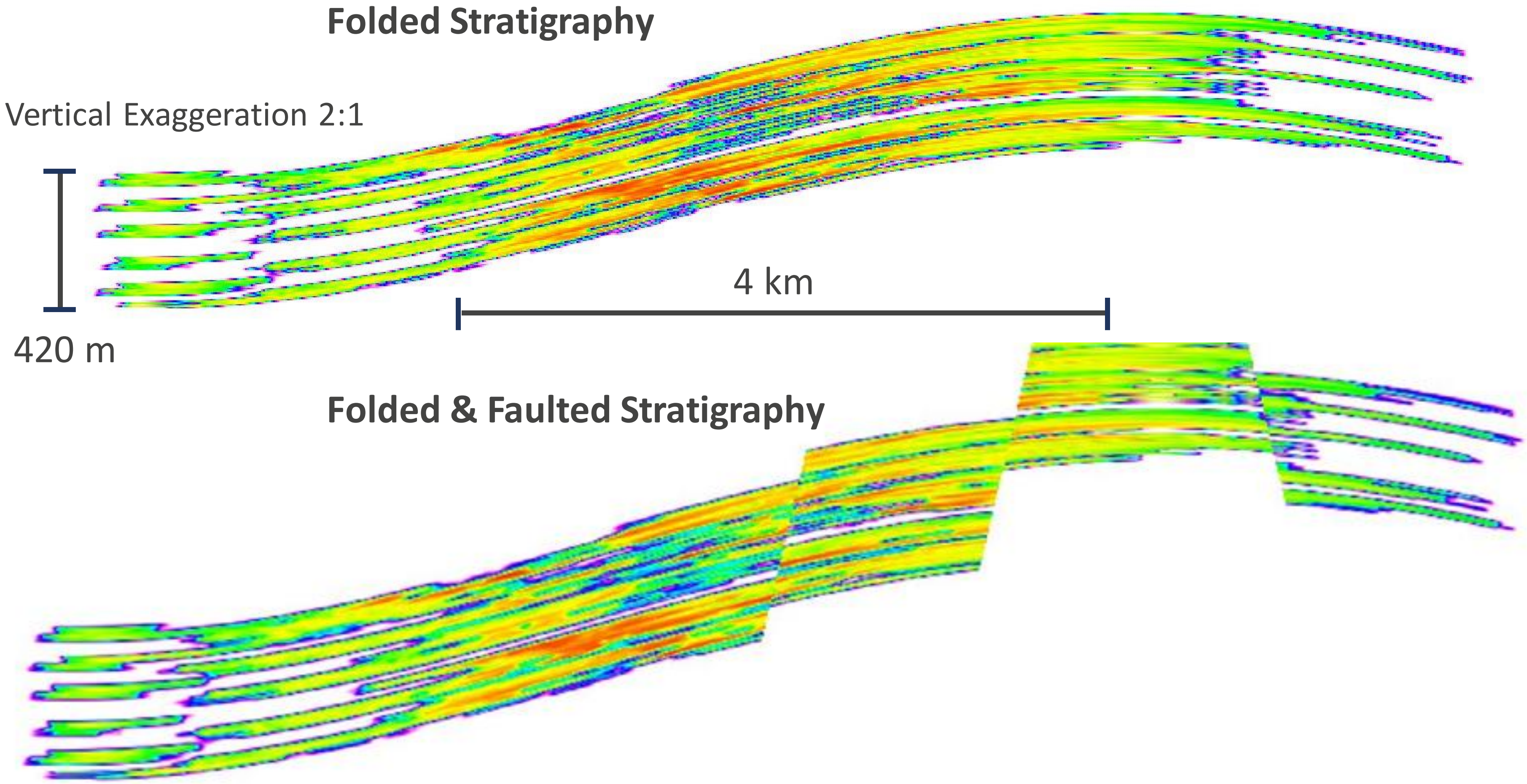


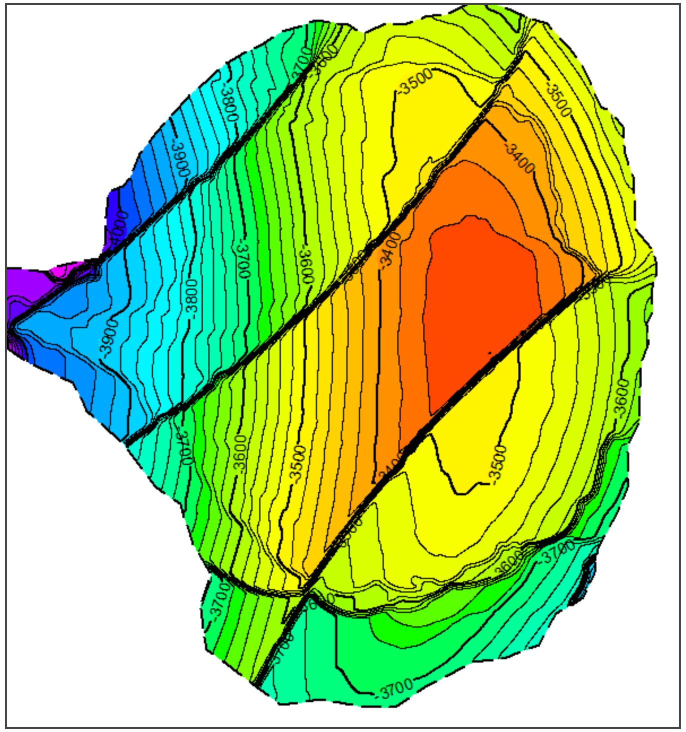
Stacked turbidite reservoir (permeability)

Shale baffles impede direct fluid flow.



Geologic Structure is a faulted anticline





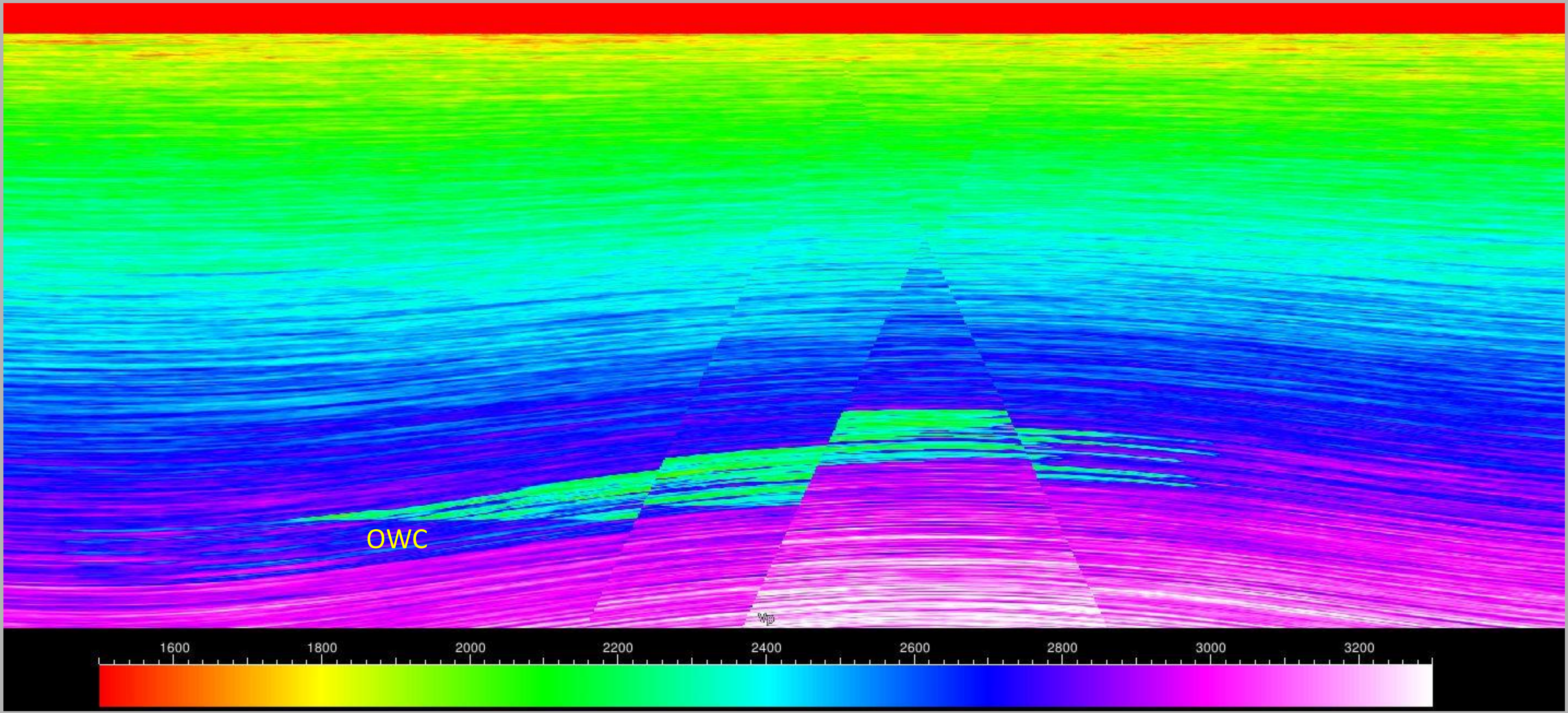
Top Reservoir Structure Map

Model Cross Section in Dip Direction

12.5 km across, 5 km deep

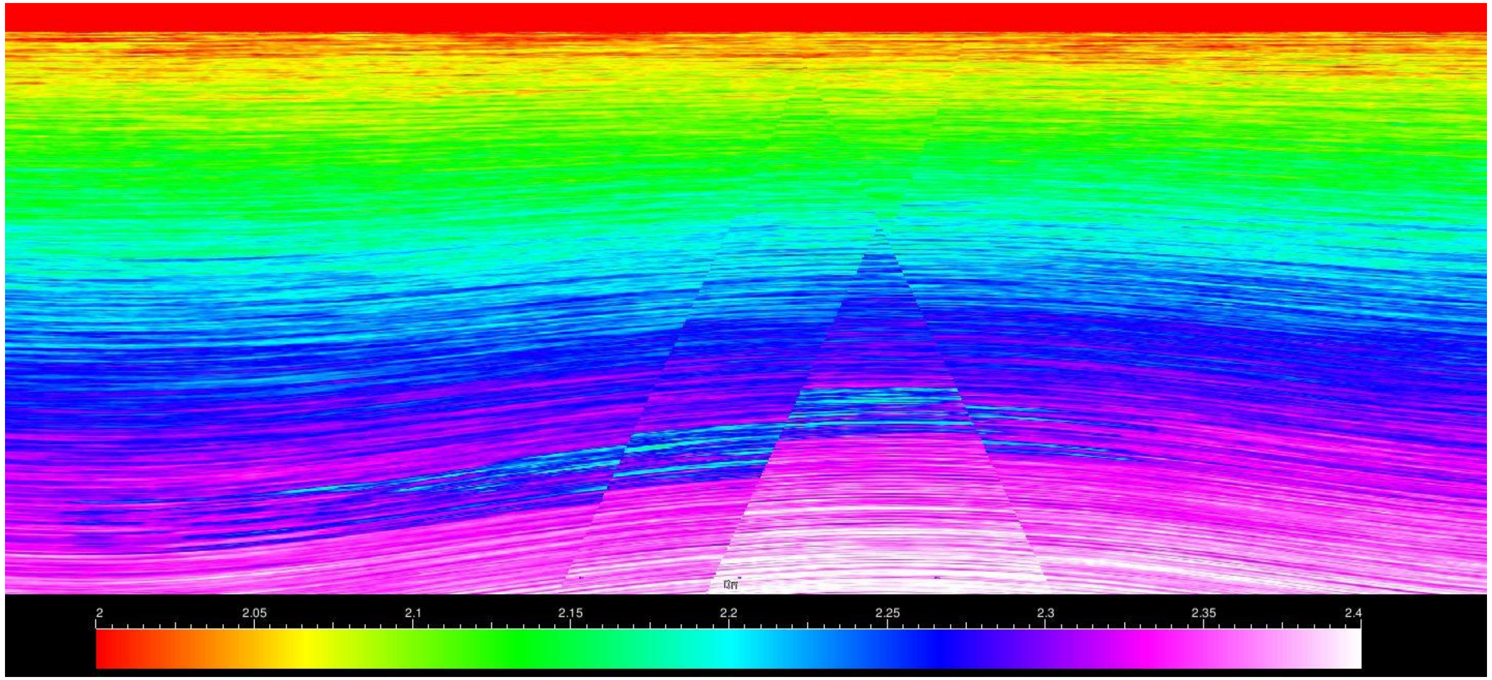
No vertical exaggeration

Vp: 1500–3300 m/s

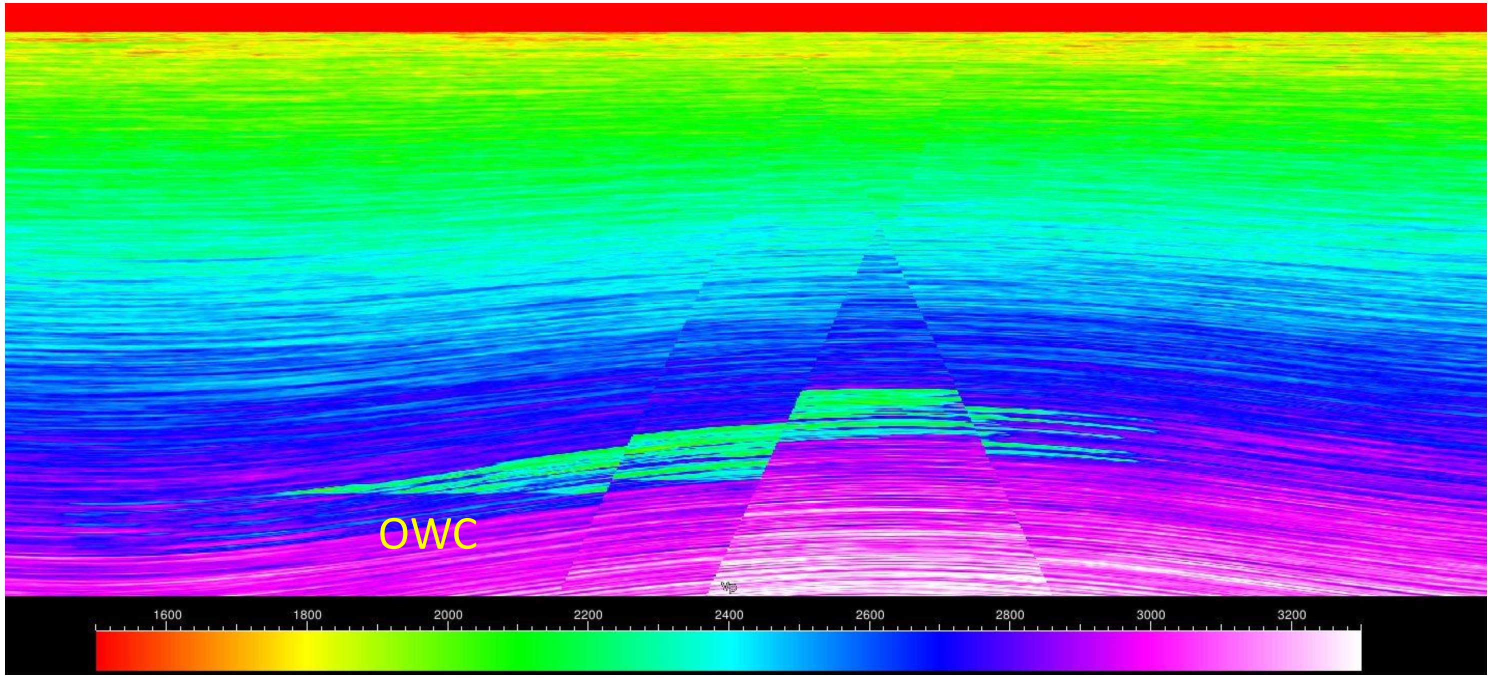


Model Cross Sections in Dip Direction

12.5 km across, 5 km deep
No vertical exaggeration

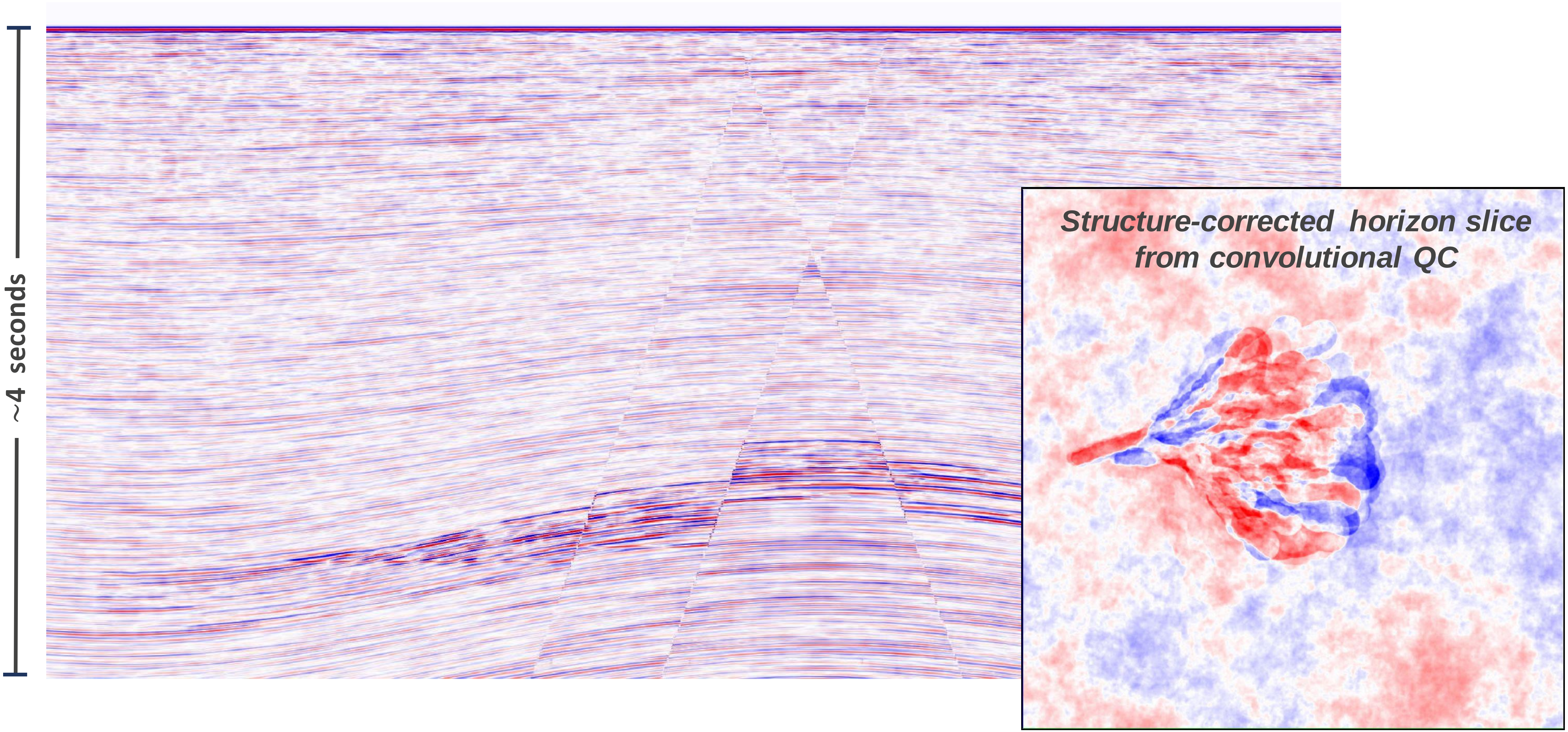


Density: 2.0–2.4 g/cc



Vp: 1500–3300 m/s

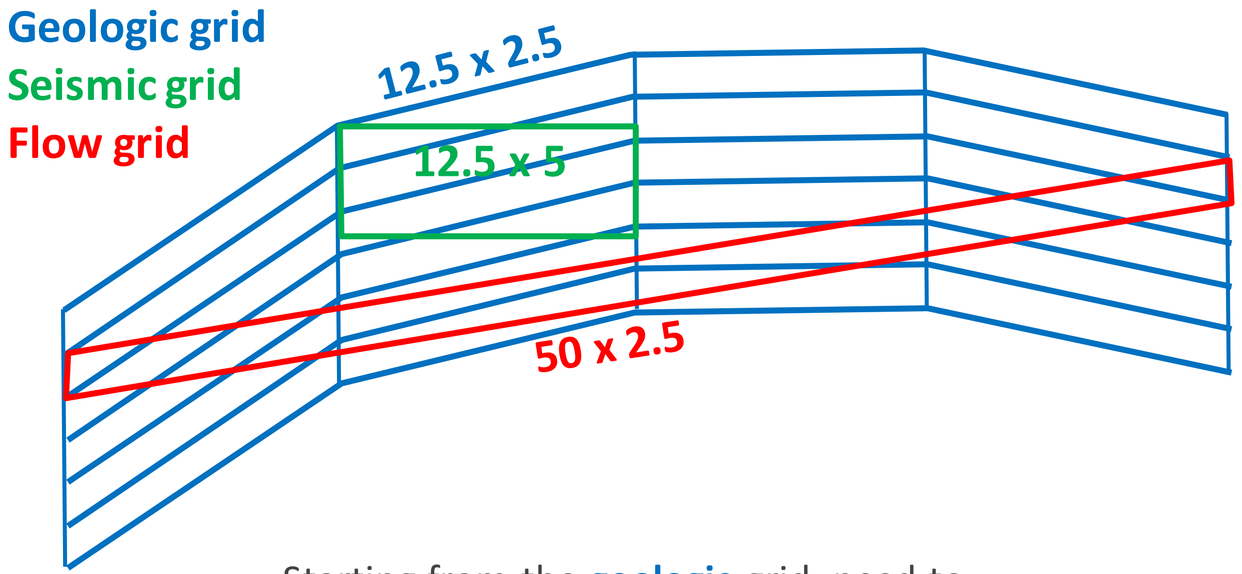
Convolutional Seismic Section ($\lambda = 40$ m)



Cross-Scaling Between Grids

Mesh misalignment occurs when both **seismic** and **flow** simulations are required, and each is separately derived from a **geologic** grid, resulting in up/down scaling errors.

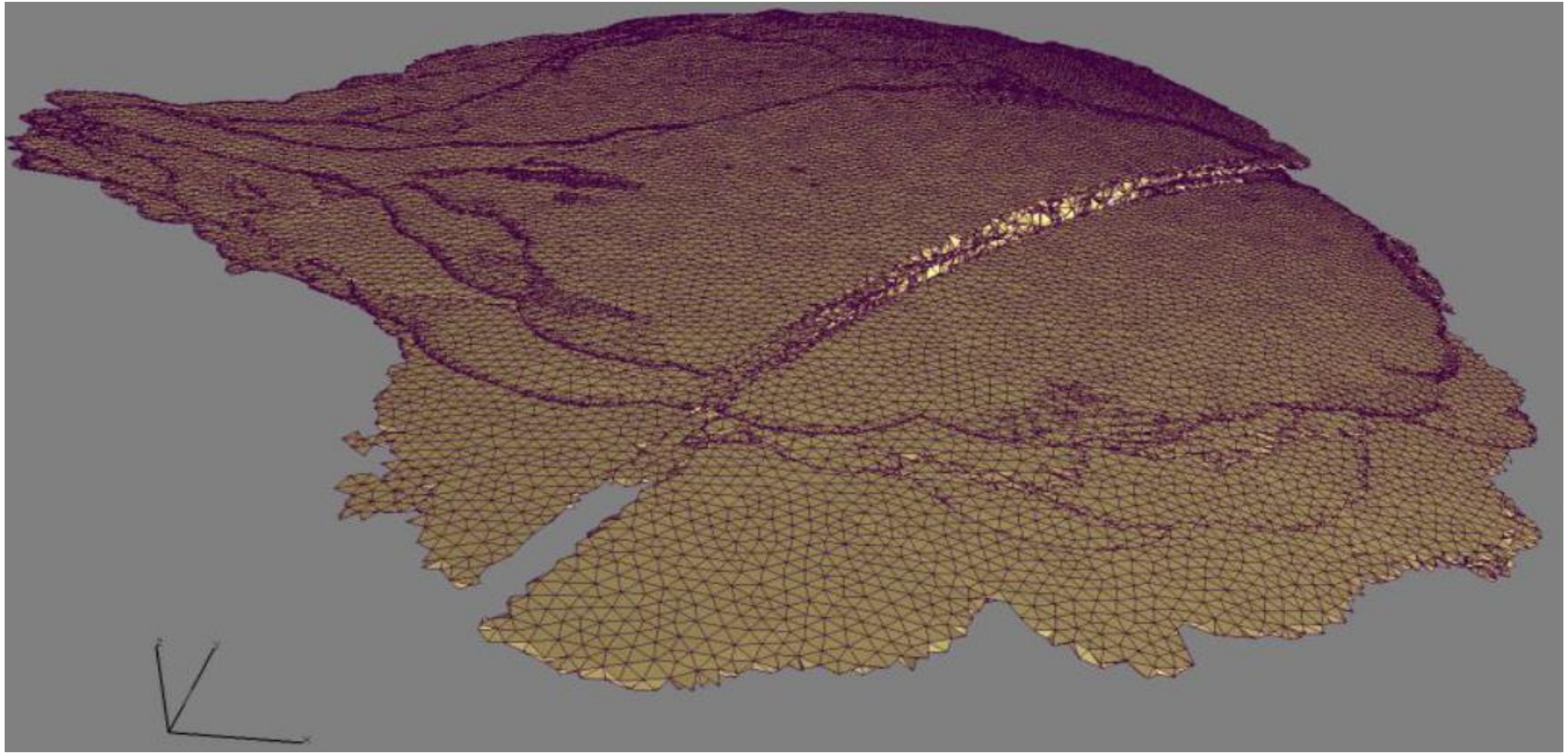
The geologic grids at high resolution were used as the base grids for cross scaling.



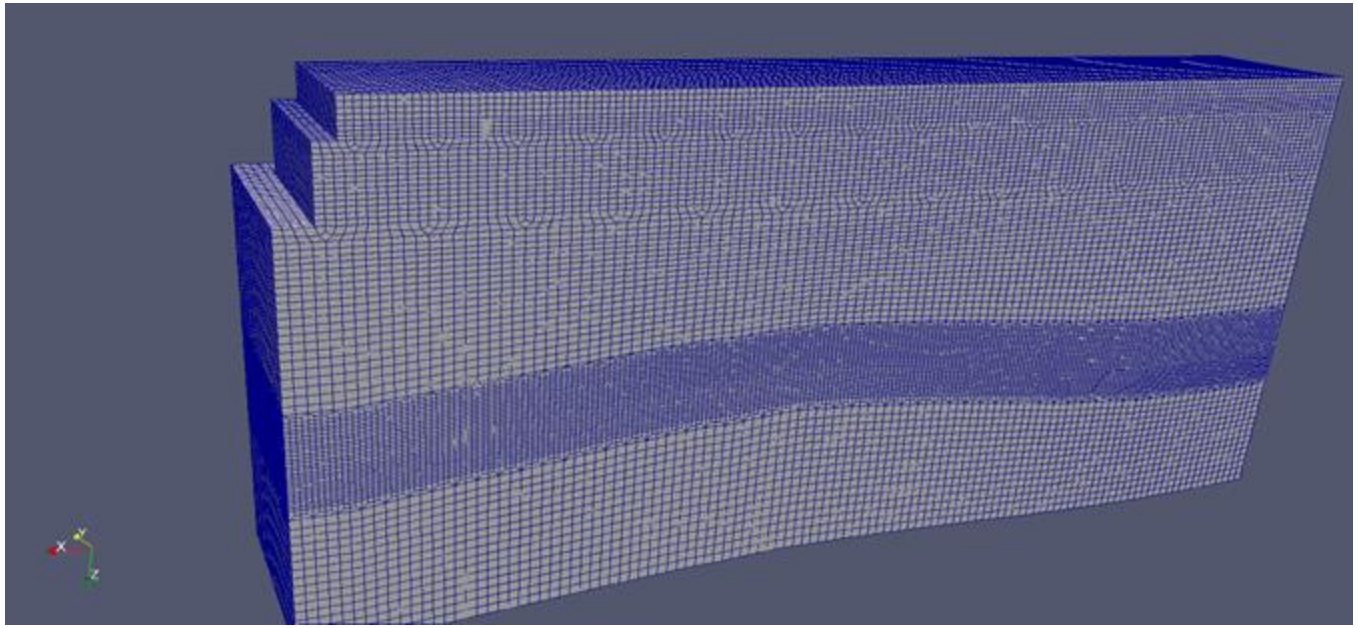
Grid Spacing, m	DX	DY	DZ
Geologic Model	12.5	12.5	2.5
Seismic Simulation	12.5	12.5	5
Flow Simulation	50	50	2.5

Starting from the **geologic** grid, need to:
Upscale in Z and interpolate to get **seismic** grid
Upscale in X and interpolate to get **flow** grid

Finite element grid of turbidite stack for reservoir modeling



- Trace sandstone-shale interface to create water-tight surface mesh of connected turbidite geobody
- Note individual lobes are maintained during surface extraction



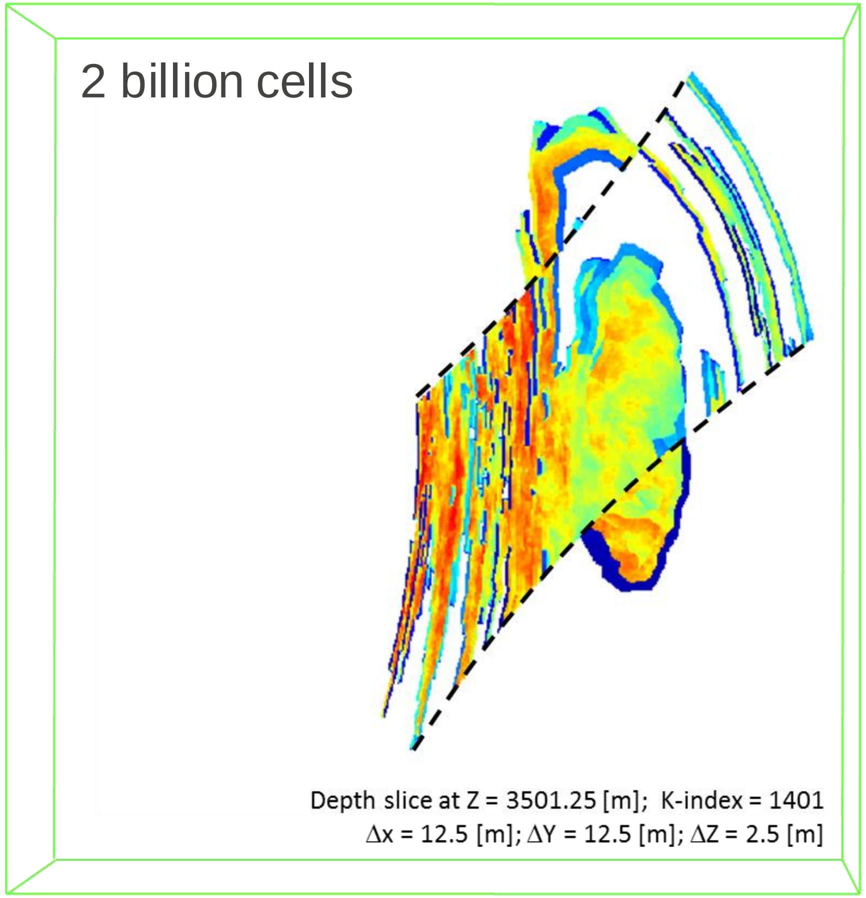
Finite element grid of geologic structure for seismic modeling

Reservoir Simulations: Upscaling

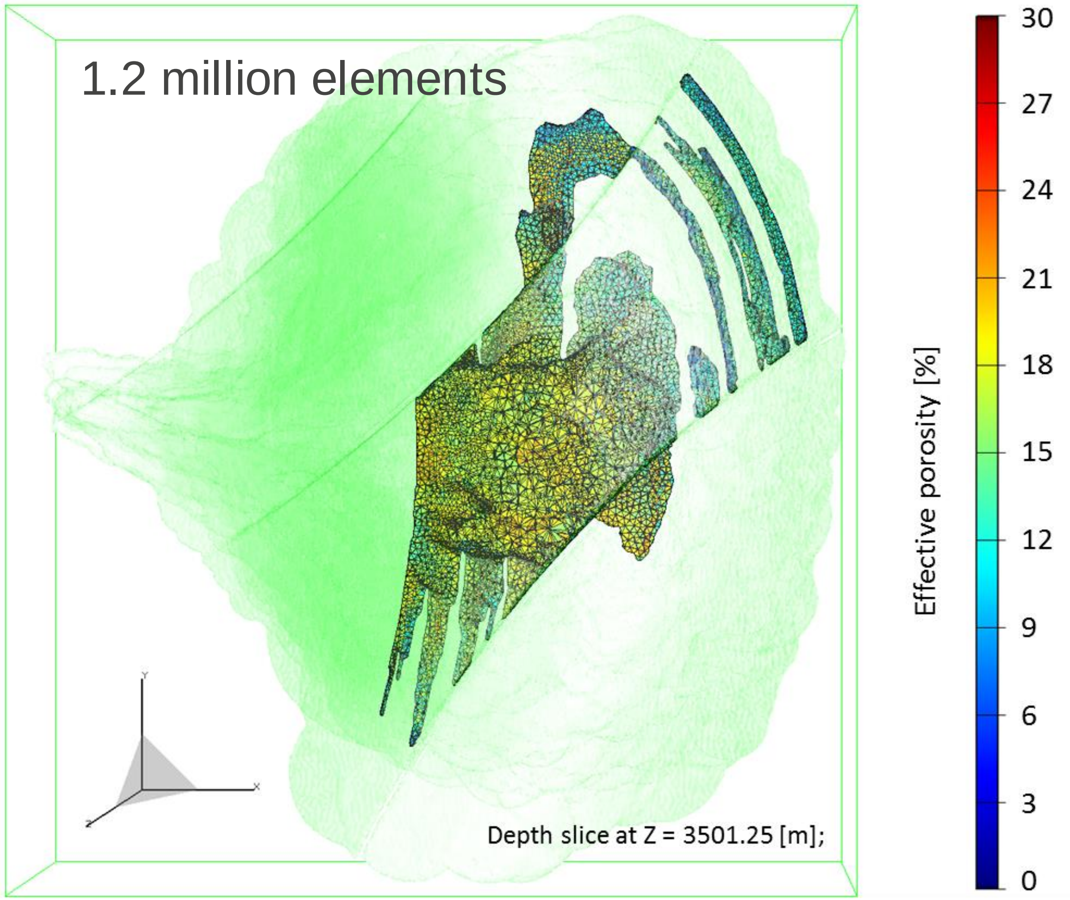
- Upscaling method chosen according to property, e.g.:
  - Phase saturation (S_o, S_w, S_g): volume conserving to preserve local and global fluid volumes
  - Porosity (Φ): volume conserving
  - Permeability (k_h, k_v): Alternating harmonic and arithmetic average
  - Mechanical properties (E, ν, ρ): Sample at several points in element and employ a tri-linear interpolation scheme
- Numerical upscaling/cross-scaling possible, ensuring identical physical behaviour in control volume

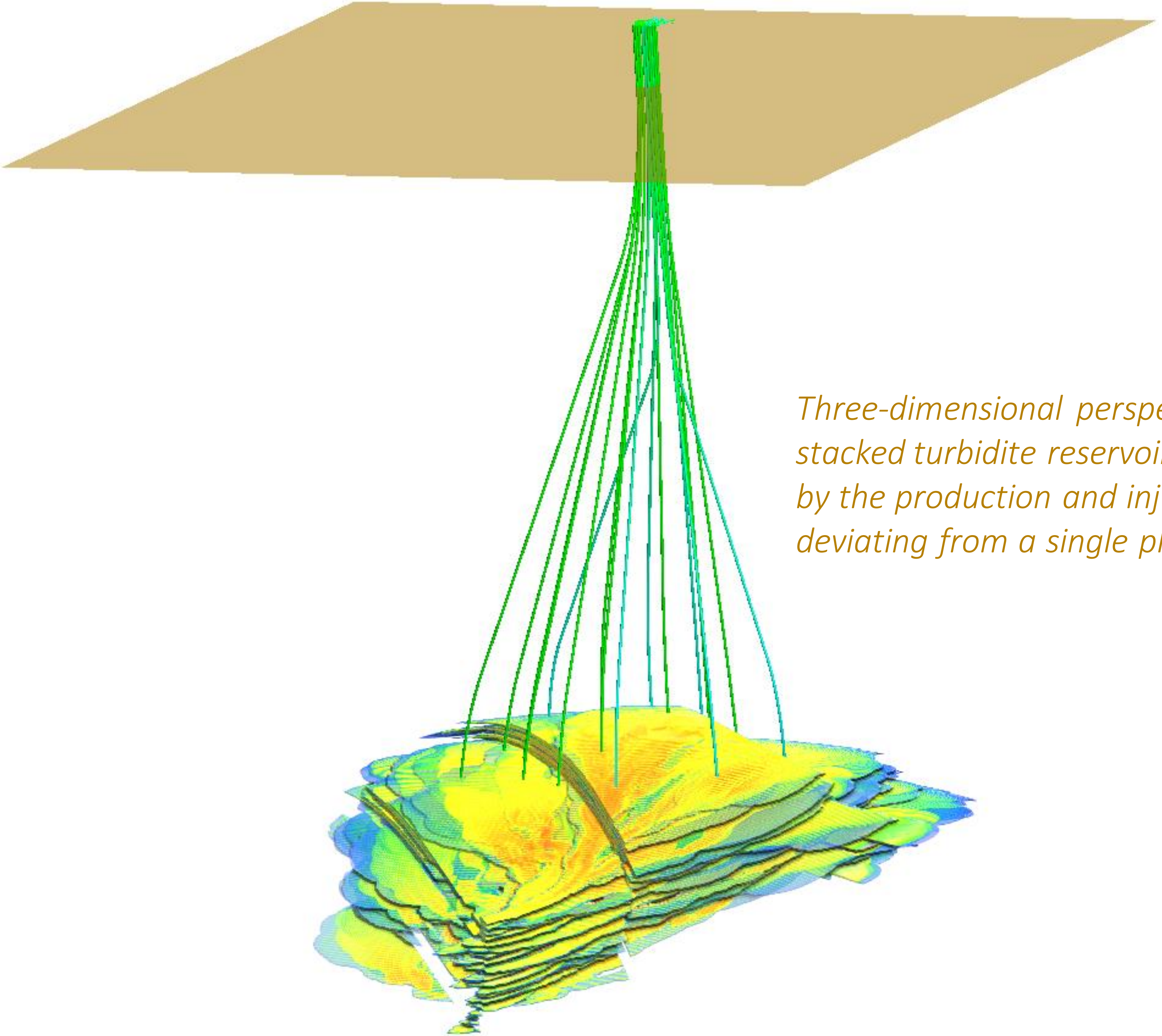
Reservoir Simulations: Upscaling

Geological model
12.5 x 12.5 x 2.5 m regular grid



Finite element model
Variable grid





Three-dimensional perspective of the stacked turbidite reservoir, penetrated by the production and injection wells deviating from a single platform.

Reservoir Production Scenarios for Realistic Time-Lapse Simulations

Shauna Oppert[1] and Vincent Artus[2]
[1] Chevron Energy Technology Company
[2] Kappa Engineering

Goal

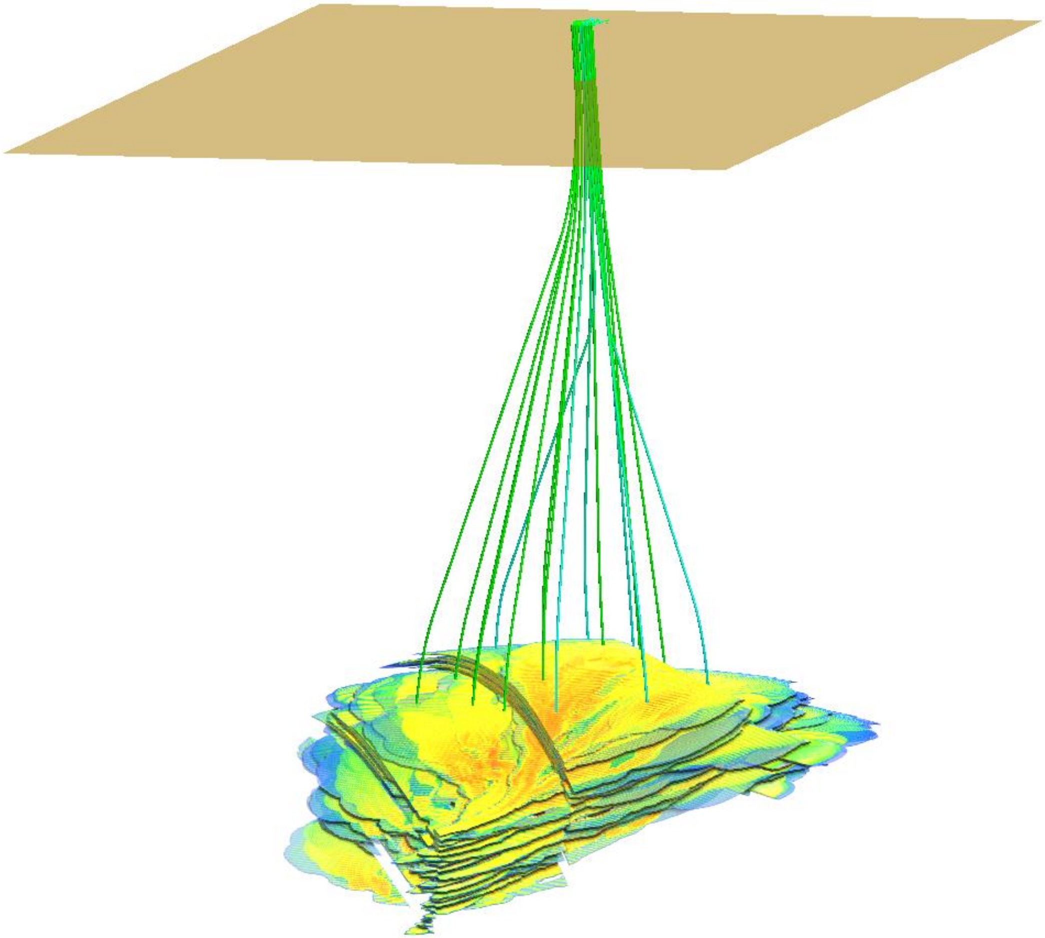
Design the production to realistically create 4D seismic effects of depletion and injection at a repeat survey time of 1-3 years from first oil

Desired 4D effects

Gas exsolution, water replacing oil, gas to oil

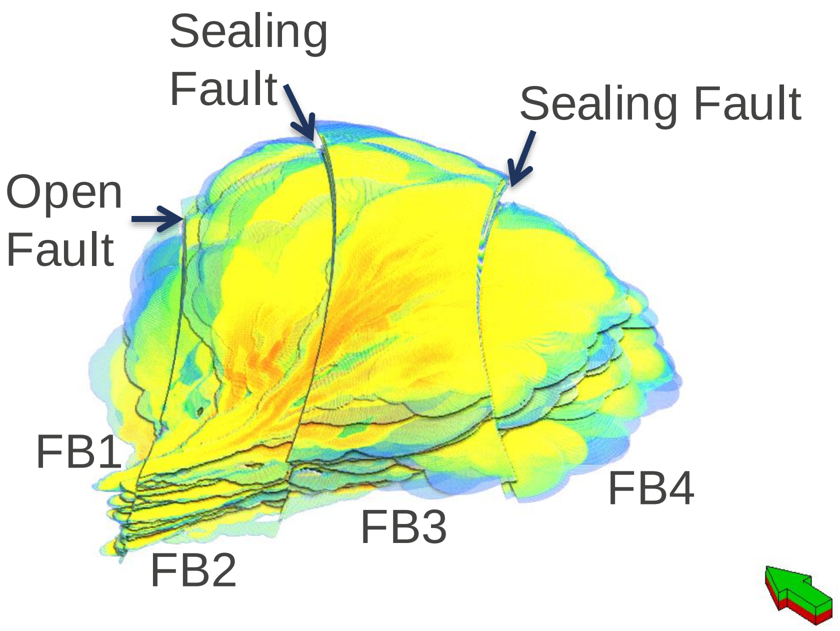
Pressure drop, pressure increase, and maintaining pressure

Geomechnical dilation and compaction responses to depletion and injection

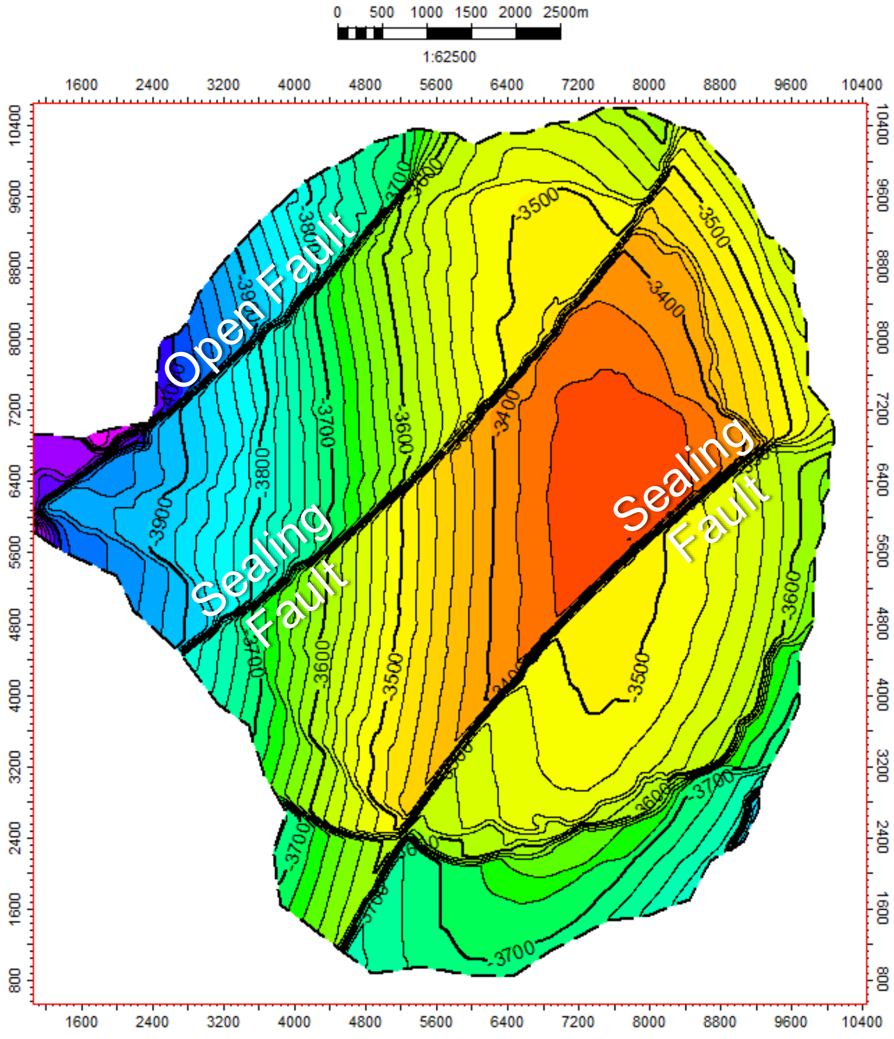


Faulted Compartments

4 Fault Blocks
3 Reservoir Compartments



3D View of Sands (shales transparent)



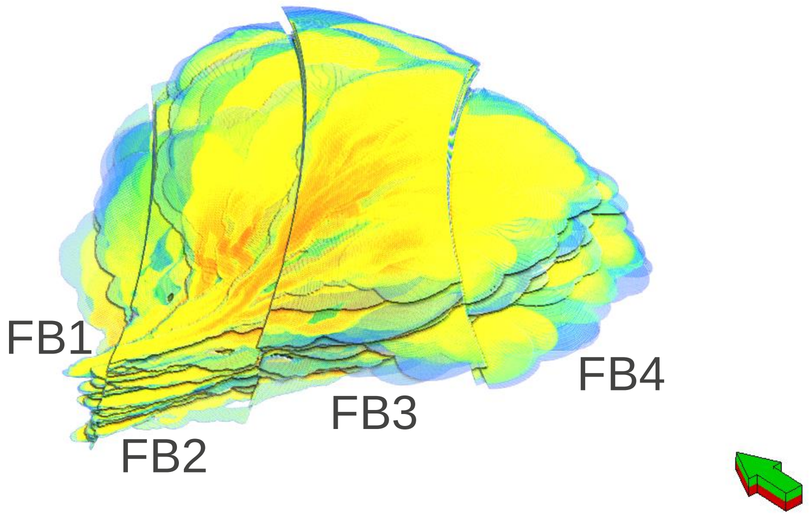
Top Reservoir Structure Map
20m contour interval

Sealed faults allows for testing a different type of production scenario in each reservoir compartment

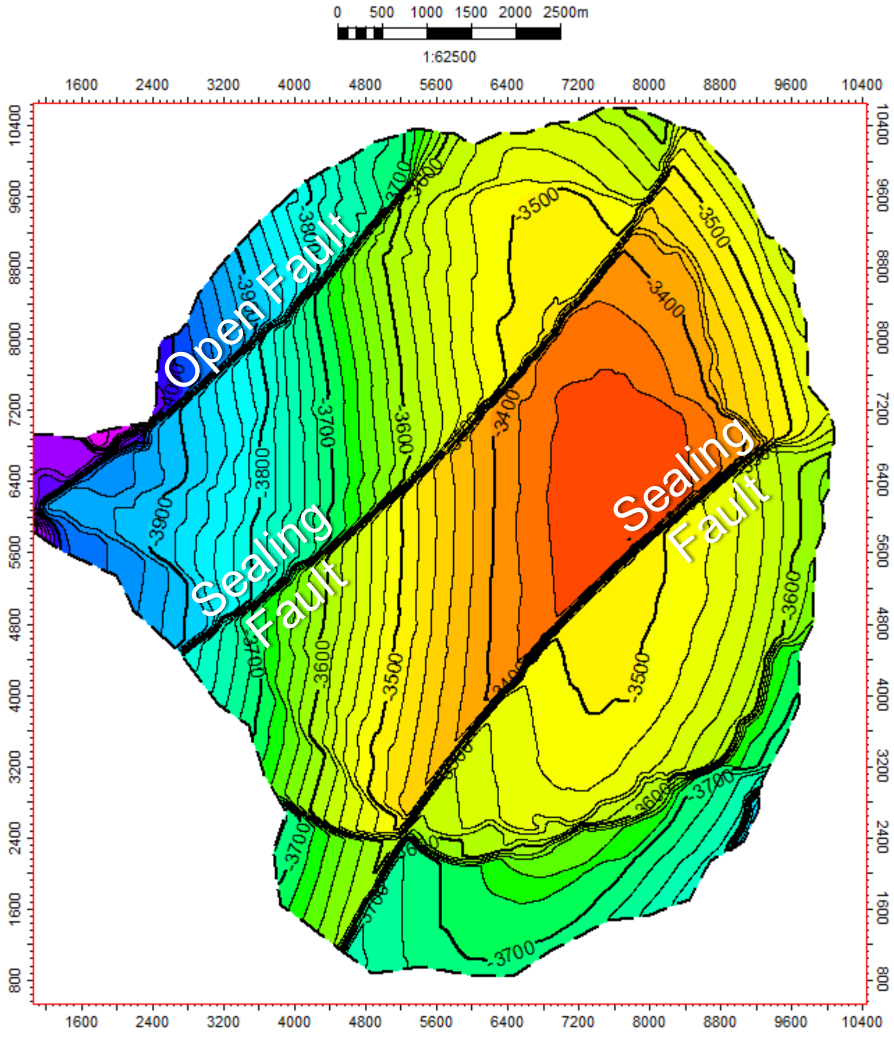
Depletion Plan

<u>Reservoir Compartments:</u>

FB1 & FB2: Depletion Only
FB3: Depletion with Injection
FB4: Over Injection with Depletion



3D View of Sands (shales transparent)



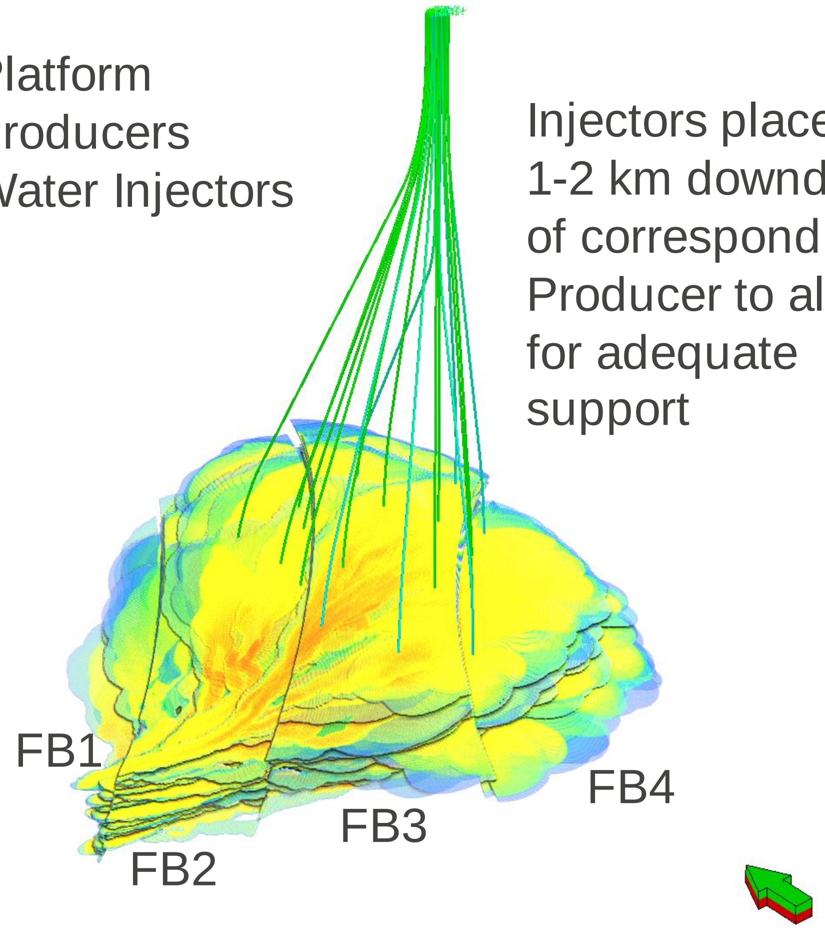
Top Reservoir Structure Map
20m contour interval

Production plan was designed to isolate Geomechanic effects in waterflood and depletion only scenarios.

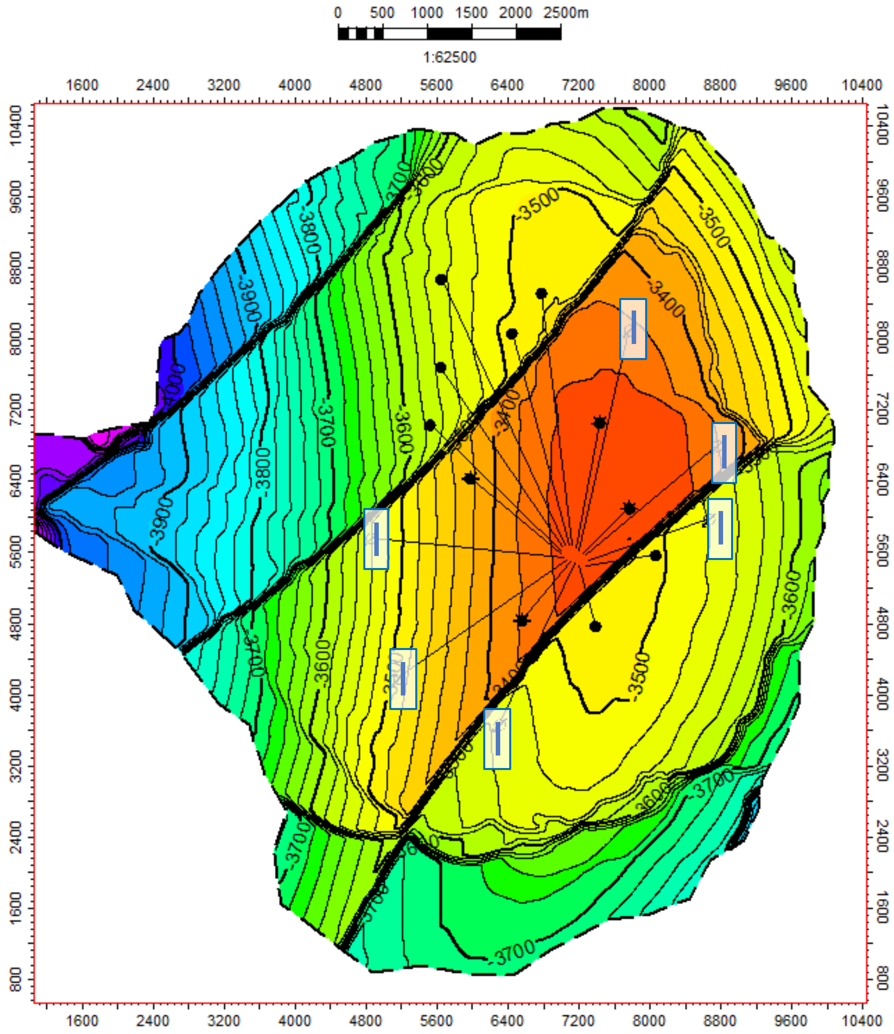
Producer and Injector Wells

1 Platform
11 Producers
6 Water Injectors

Injectors placed 1-2 km downdip of corresponding Producer to allow for adequate support



3D View of Sands (shales transparent)



Top Reservoir Structure Map
20m contour interval

Production Timing:

- All wells were turned on at zero time (Baseline)

- Shut-in was simulated for Hurricane (2 weeks) after 1 year of production and at Monitor time

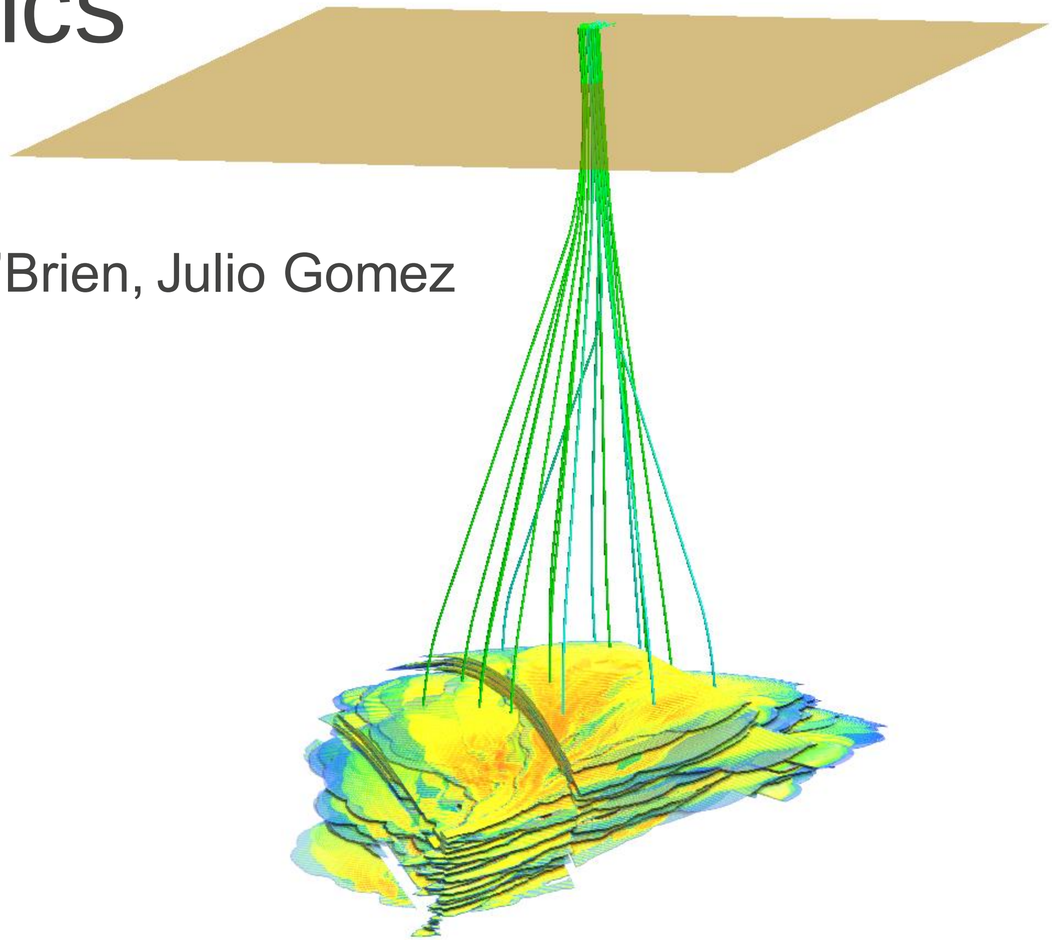
- Monitor Geophysical Surveys simulated after 16 months production

Reservoir Simulations:
Fluid Flow and Geomechanics

Jorg Herwanger, Andy Bottrill, Peter Popov, Paul O’Brien, Julio Gomez

October 21, 2016

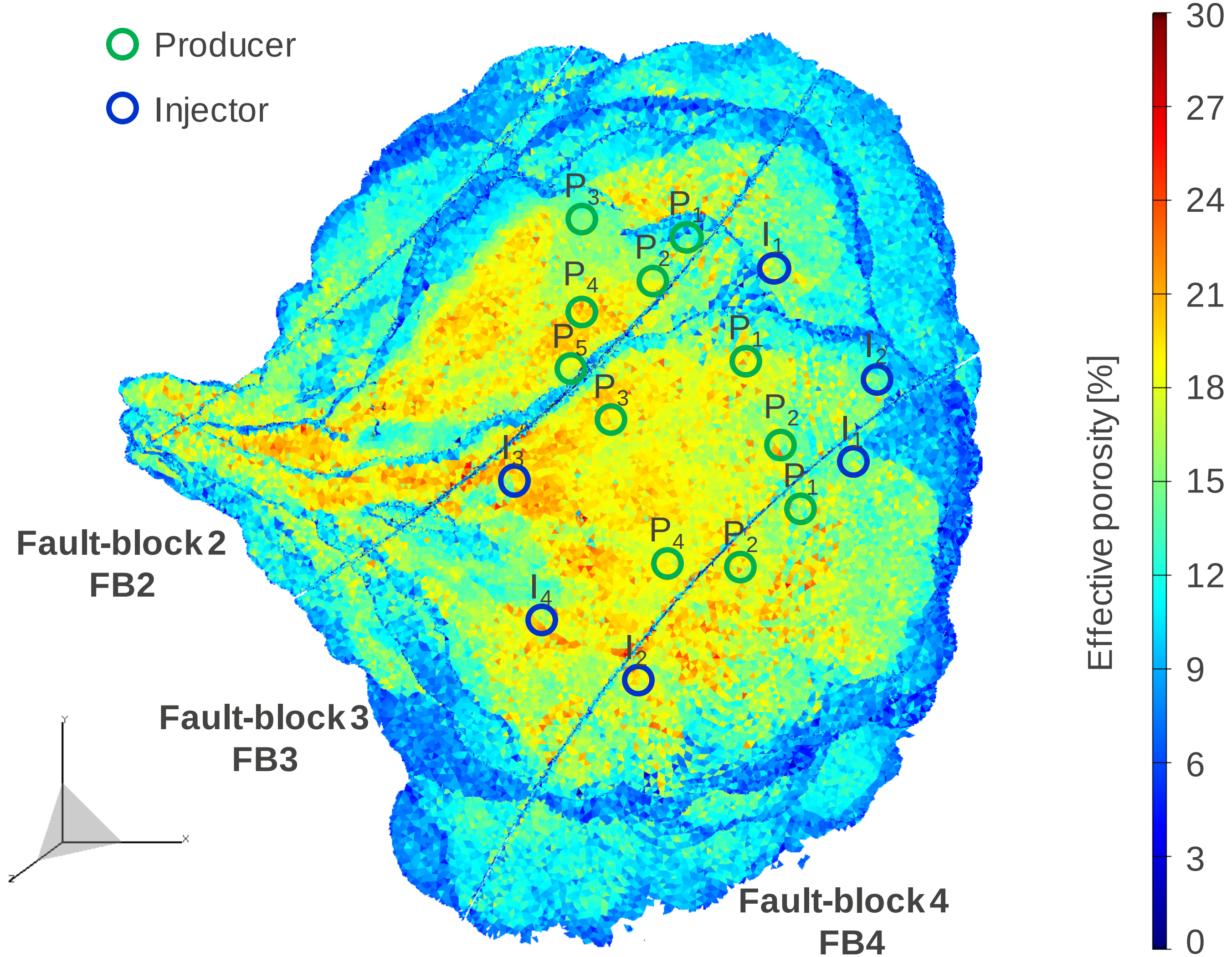
Ikon Science & MPGeomechanics



Reservoir Simulations: Production schedule and well locations

- Constant rate of total fluid production in each well
  - Initial tests with 5000 bbl/d
  - Rates adjusted to avoid “unreasonable” pressure build-up or drop
  - Cumulative production 67500 bbl/d, cumulative injection 32500 bbl/d
- Production from three fault-blocks
  - Fault block 2 (FB2): Primary production from 5 wells
  - Fault block 3 (FB3): Injected volume < produced volume
  - Fault block 4 (FB4): Injected volume > produced volume

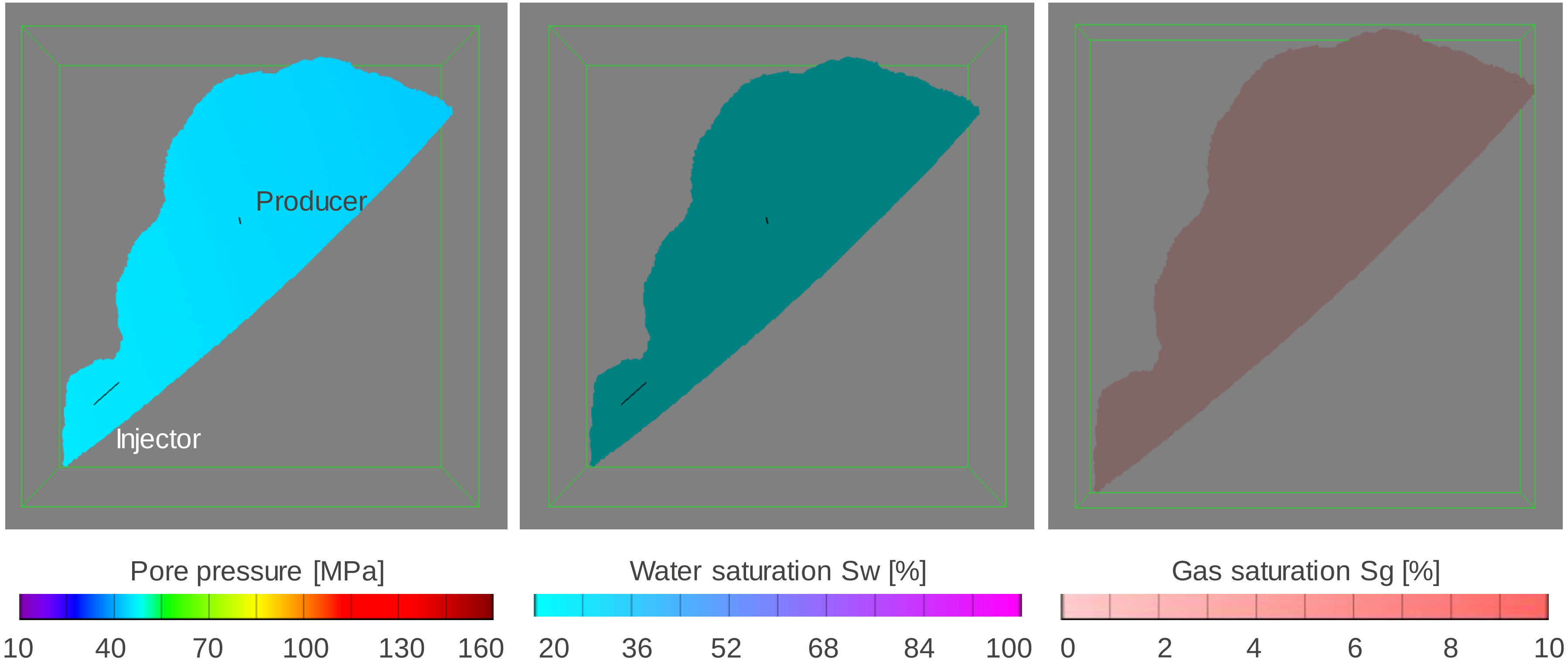
Reservoir Simulations:
Production schedule and well locations



Wellname	Production rate [bbl/d]	Production/injection per fault block
FB2_P1	-5'000	Production (FB2): 25000bbl/day
_P2	-5'000	
_P3	-5'000	
_P4	-5'000	
_P5	-5'000	
FB3_I1	+5'000	Injection (FB3): 22500bbl/day
_I2	+1'500	
_I3	+8'000	
_I4	+8'000	
FB3_P1	-9'000	Production (FB3): 35000bbl/day
_P2	-5'000	
_P3	-12'000	
_P4	-9'000	
FB4_I1	+5'000	Injection (FB4): 10000bbl/day
_I2	+5'000	
FB4_P1	-2'500	Production (FB4): 7500bbl/day
_P2	-5'000	

Reservoir Simulations:
Results Analysis – Multi-Phase Flow

01-Jun.-2016

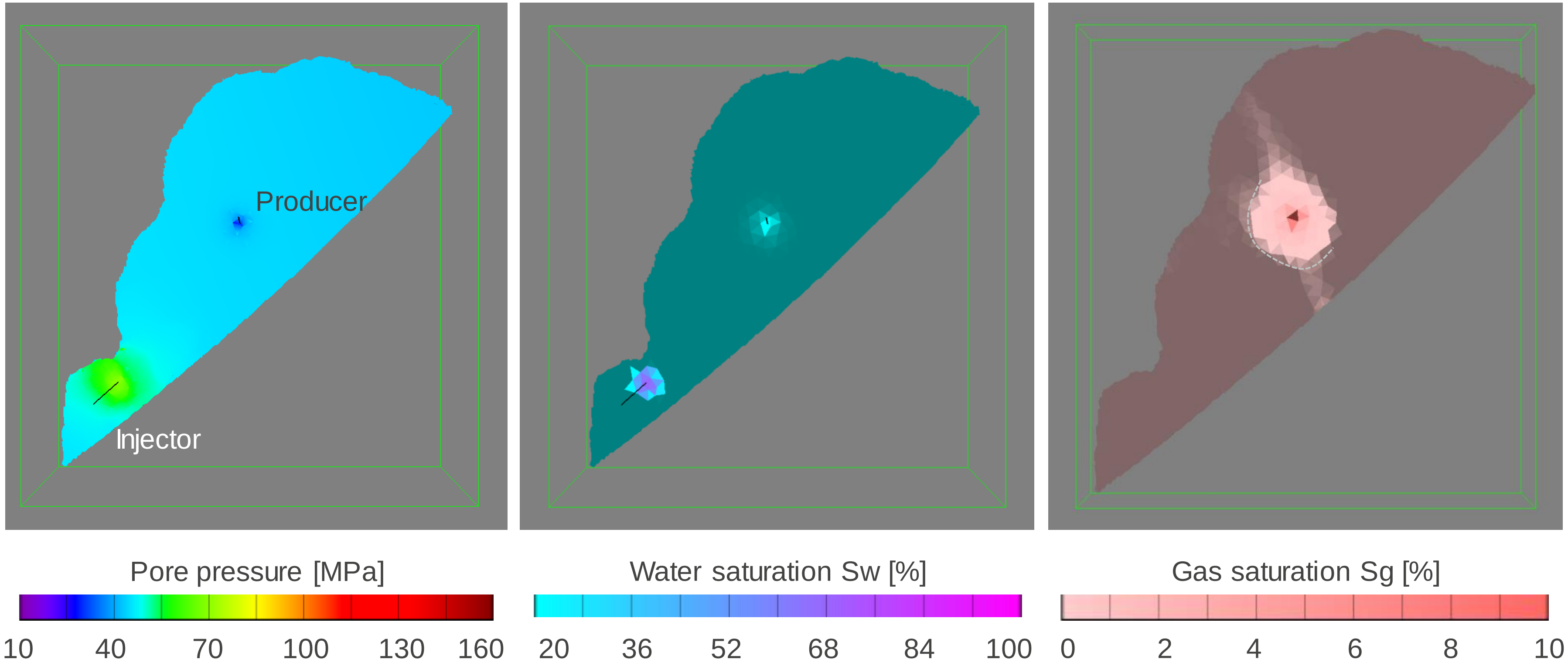


1 MPa ≈ 145 psi

Connate water saturation = 0.2 (20%)

Reservoir Simulations:
Results Analysis – Multi-Phase Flow

01-Jul.-2016; 01 month production

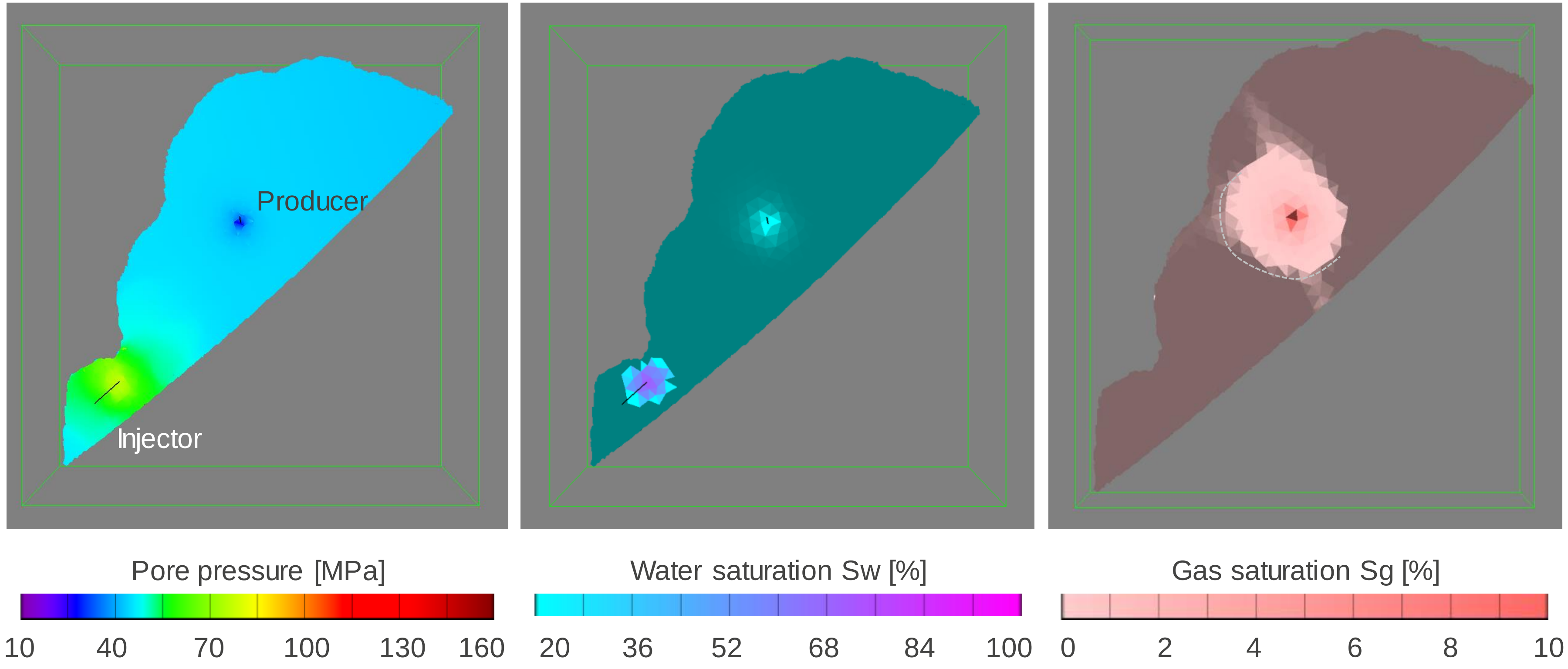


1 MPa ≈ 145 psi

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

Reservoir Simulations: Results Analysis – Multi-Phase Flow

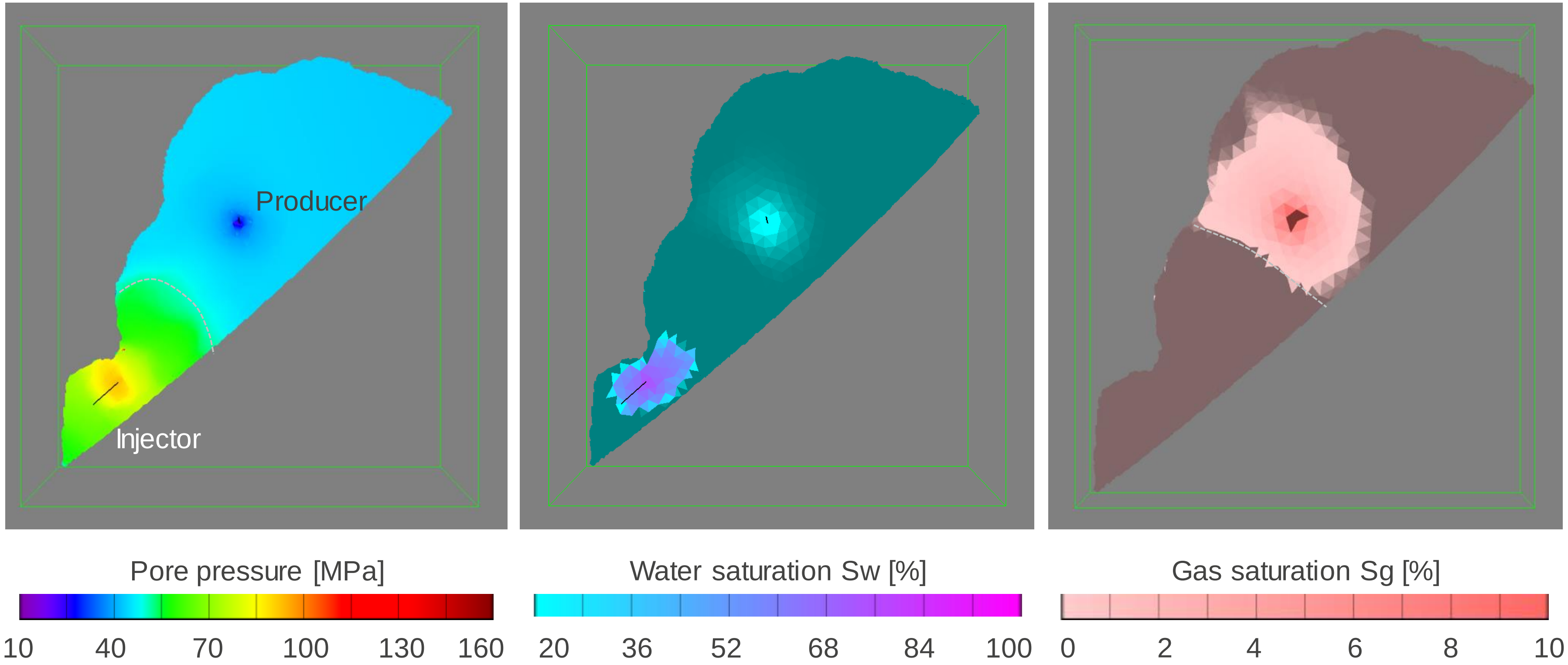
01-Aug.-2016; 02 month production



1 MPa ≈ 145 psi

Reservoir Simulations:
Results Analysis – Multi-Phase Flow

01-Dec.-2016; 06 month production

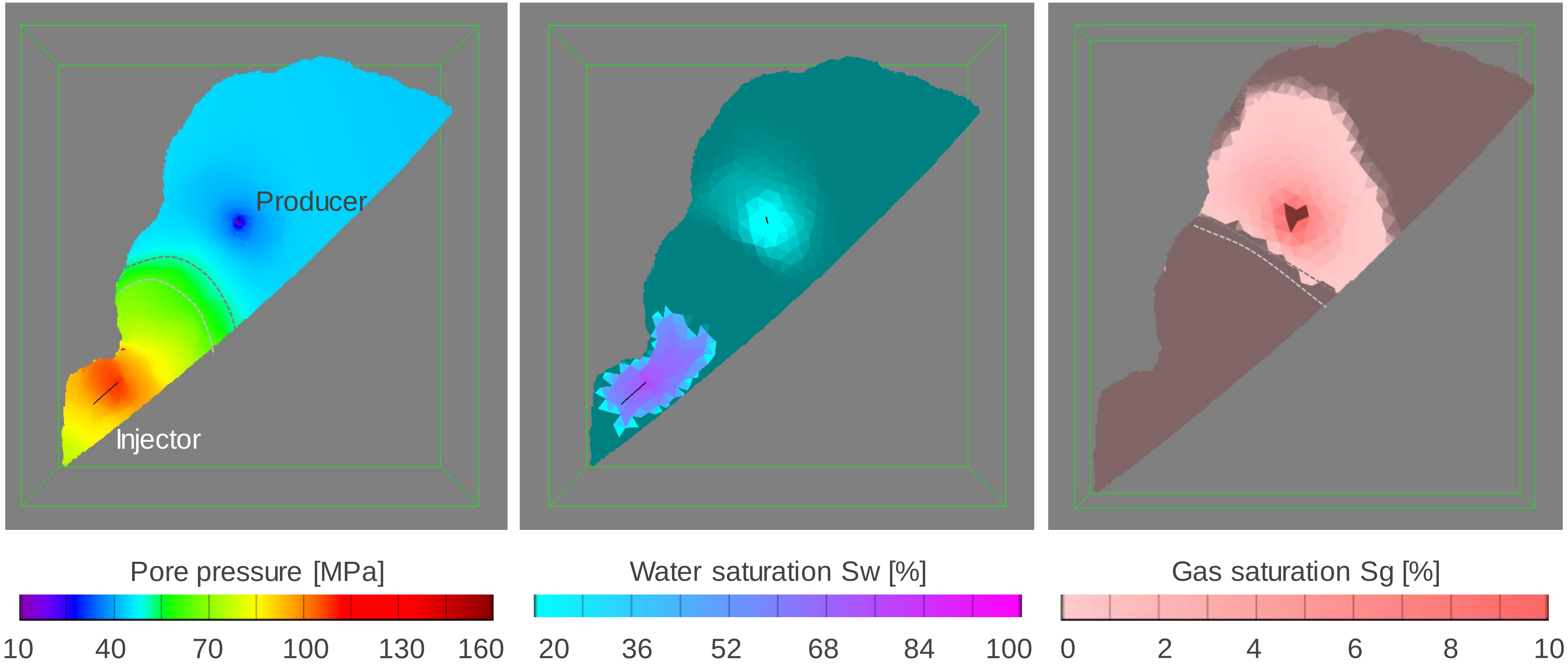


1 MPa ≈ 145 psi

Note: sharp saturation fronts (Sw and Sg), and smooth pressure front

Reservoir Simulations:
Results Analysis – Multi-Phase Flow

01-Jun.-2017; 12 month production

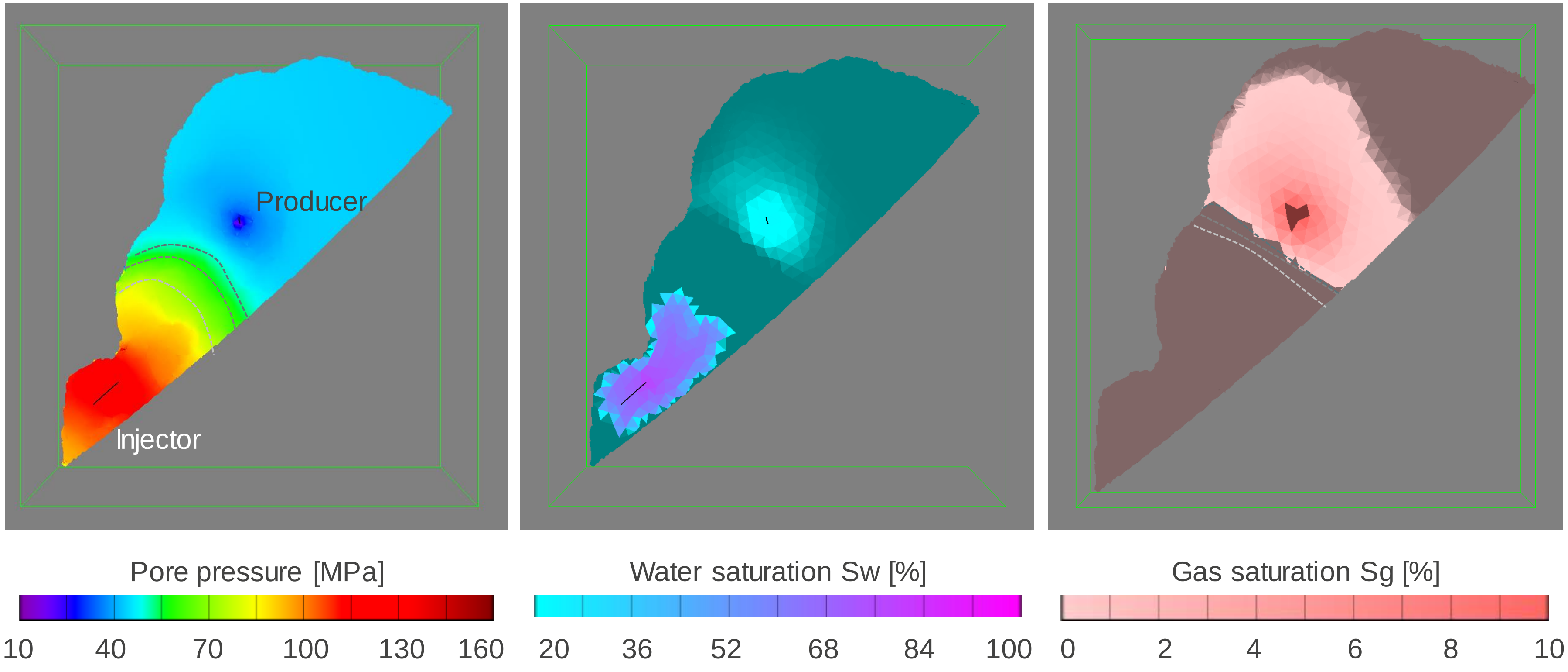


1 MPa ≈ 145 psi

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

Reservoir Simulations:
Results Analysis – Multi-Phase Flow

01-Dec.-2017; 18 month production

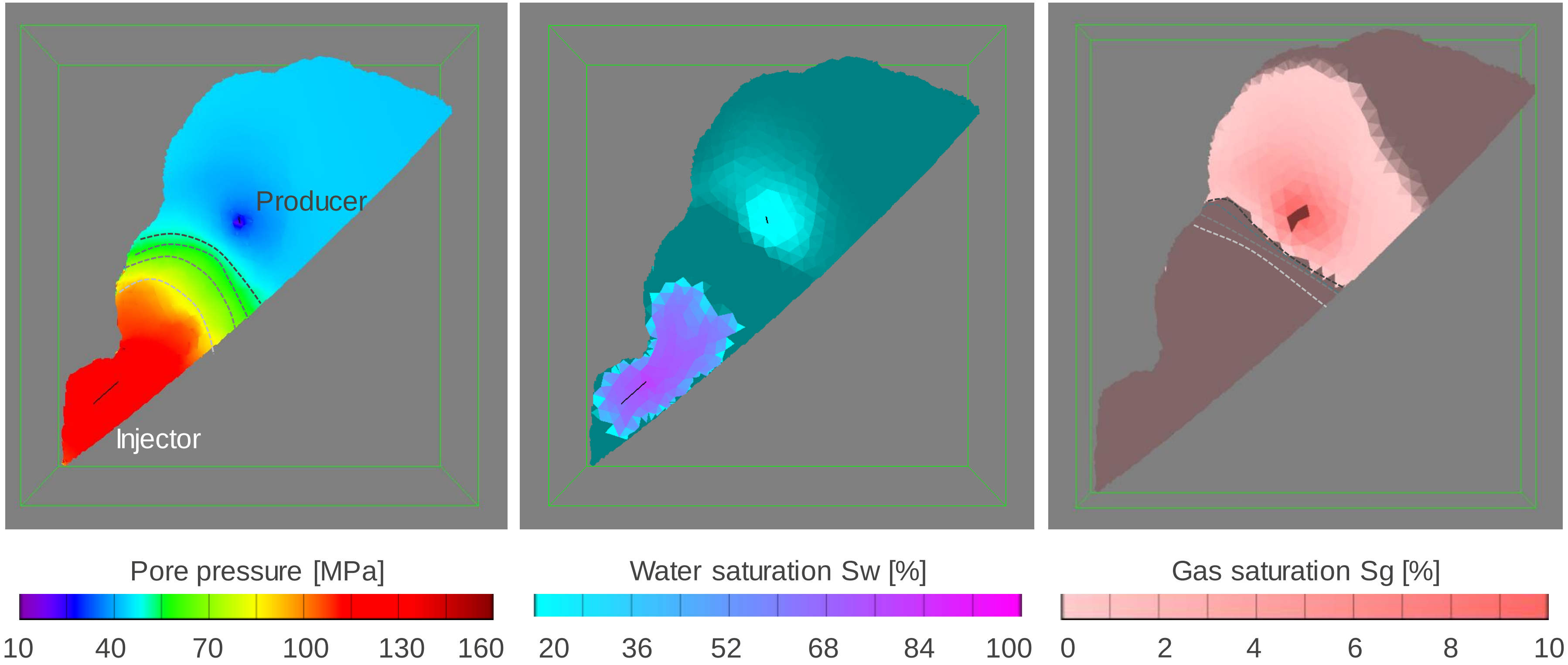


1 MPa ≈ 145 psi

Pressure front continues to force gas back into solution.

Reservoir Simulations: Results Analysis – Multi-Phase Flow

01-Jun.-2018; 24 month production

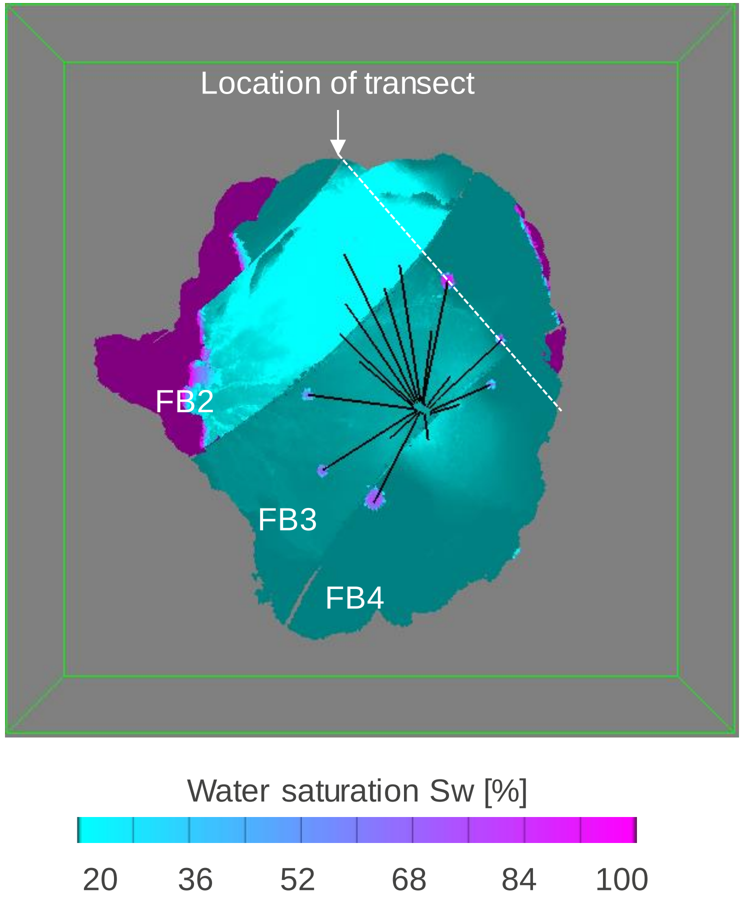


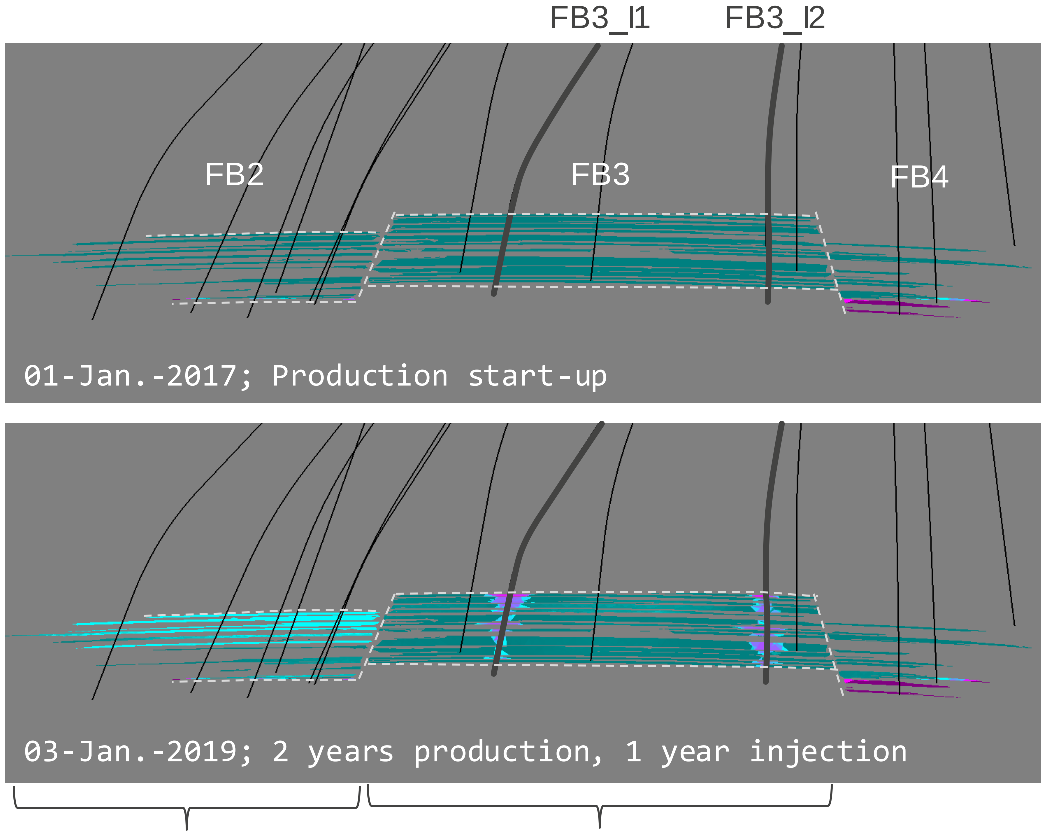
1 MPa ≈ 145 psi

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. less compressible) than oil and gas
- Water takes up a slightly larger percentage of pore space after reduction in porosity

Reservoir Simulations:
Multi-Phase Flow + Geomechanics





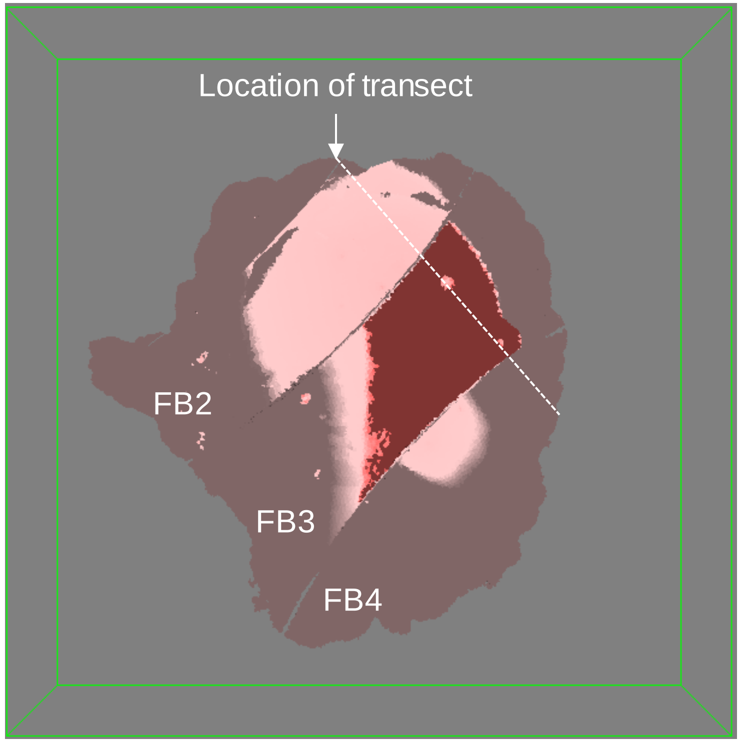
Fault block 2 (FB2):

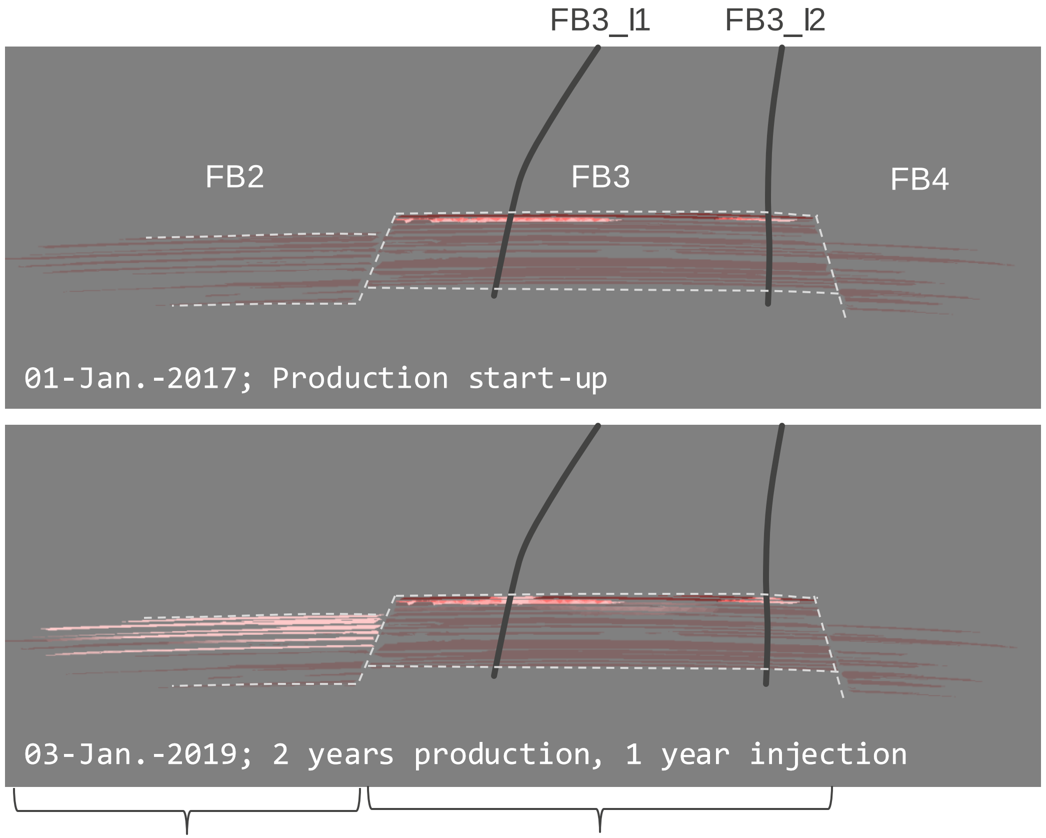
- Primary production
- Pressure drop with gas coming out of solution
- Compaction and subsidence

Fault block 3 (FB3):

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

Reservoir Simulations:
Multi-Phase Flow + Geomechanics





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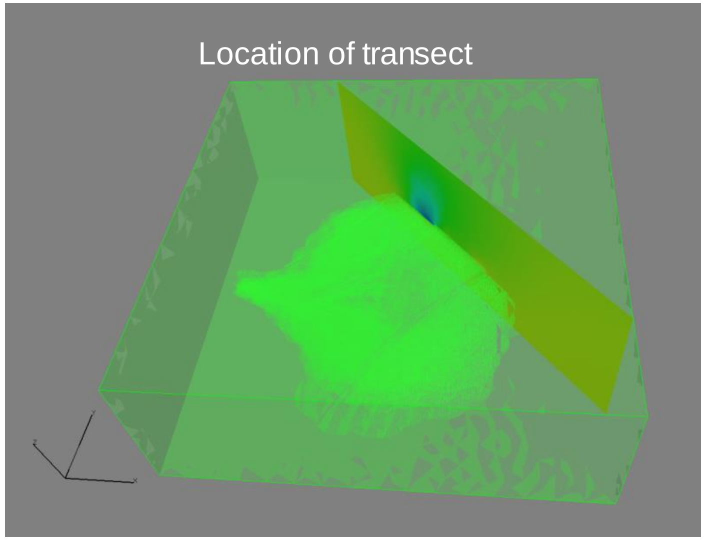
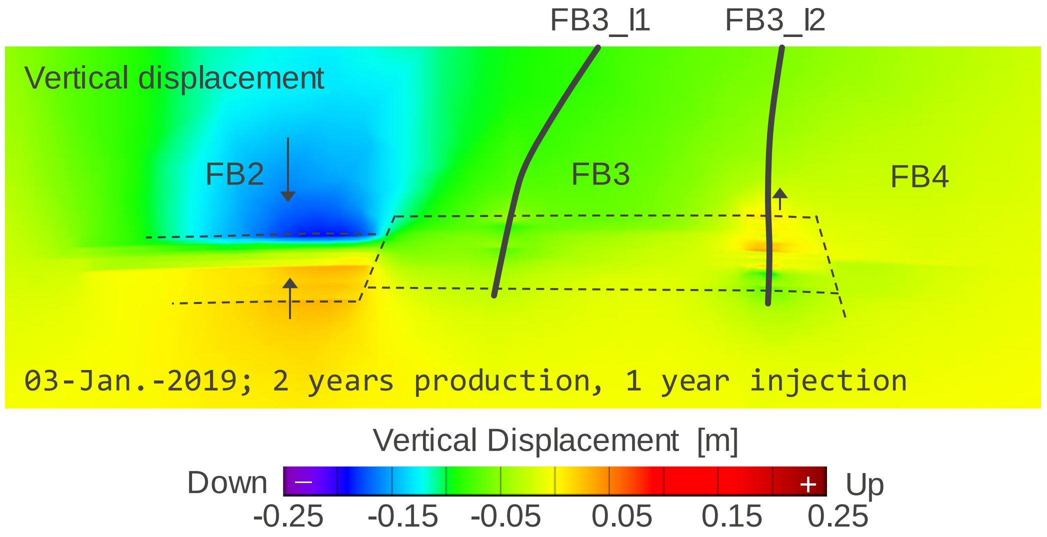
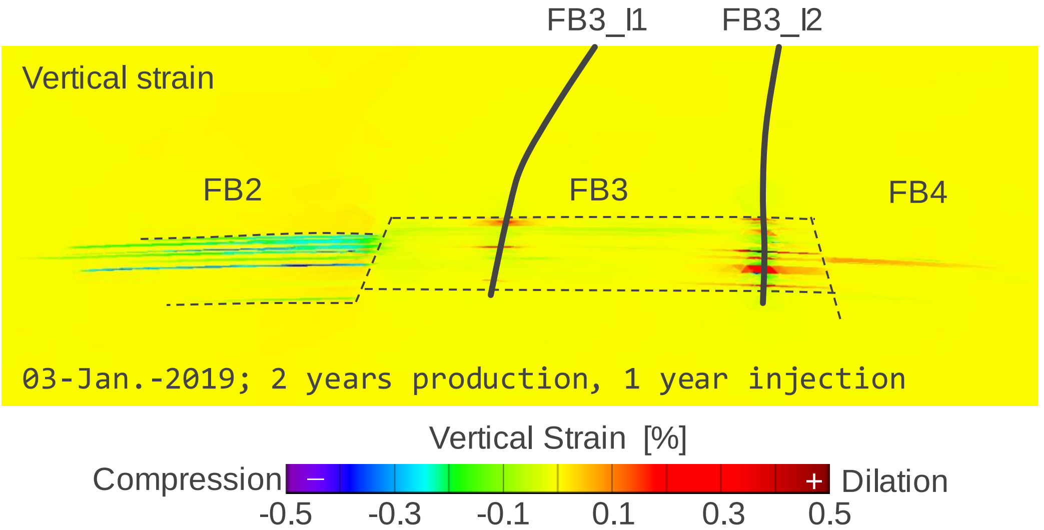
Multi-Phase Flow + Geomechanics







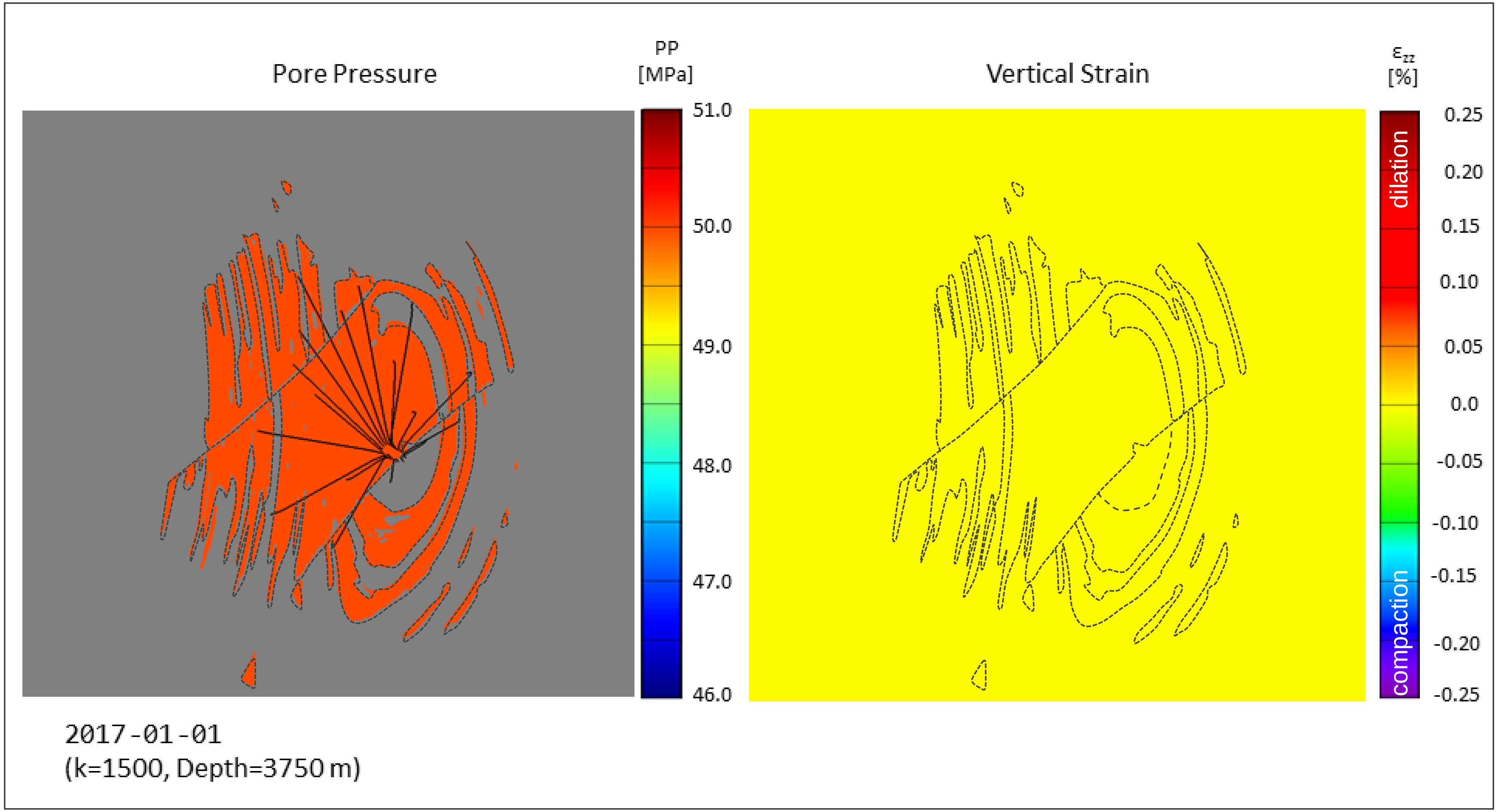
Key message:
→ Maintaining stratigraphy is key
→ Primary production:
- Sands compact, shales dilate

→ Near injection wells
- Sands dilate, shales compact

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 cause pressure increase
- Gas forced back into solution
- Reservoir dilation of sandstones, and compaction of interlayered shales

Reservoir Simulations:
Pore Pressure and Strain

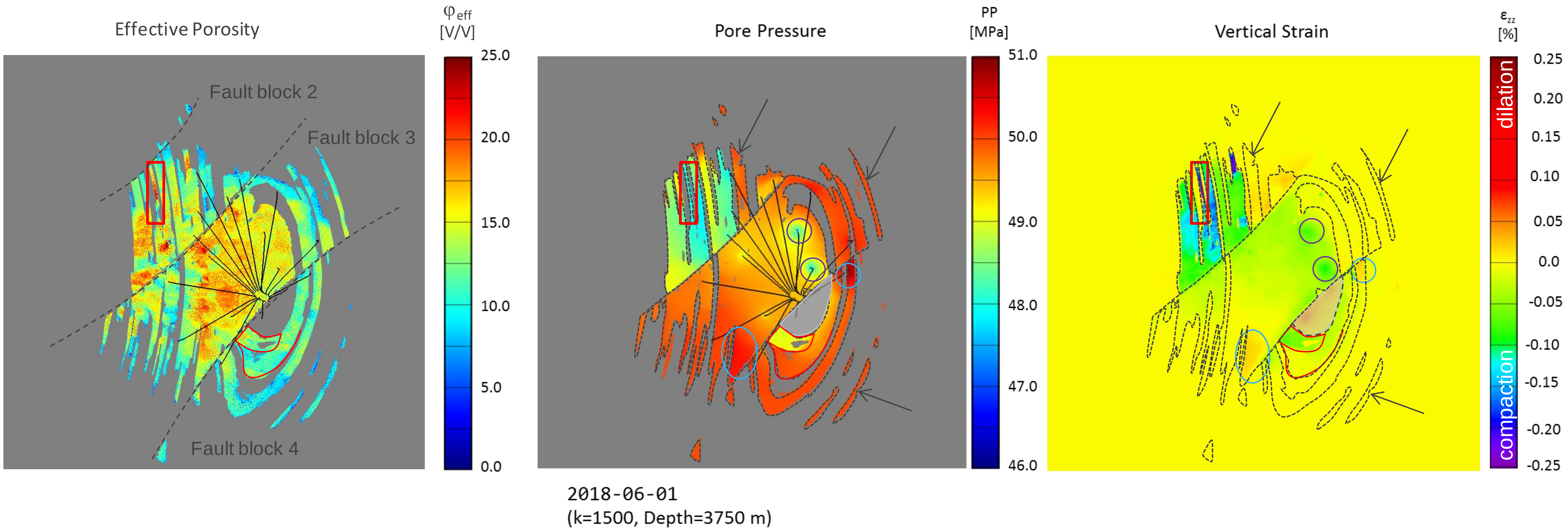


1MPa = 145psi

Movie

Reservoir Simulations:
Porosity model, Pore Pressure and Strain

1 ½ years of field production

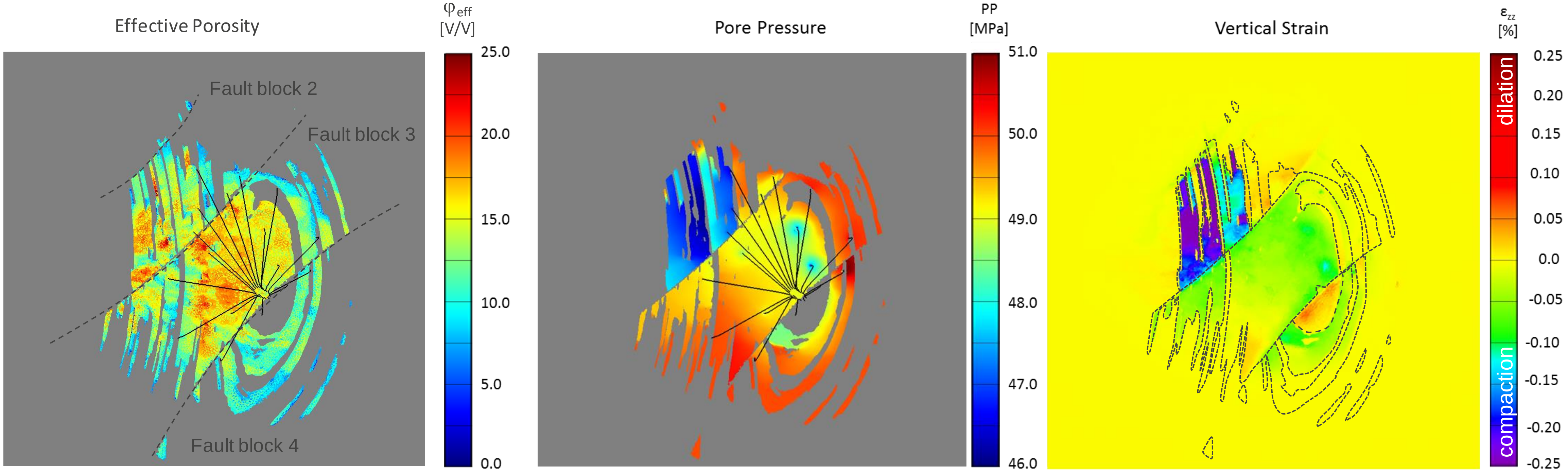


1.) High porosity & well drained → Pressure drop → Compaction
2.) Localized compaction of reservoir around producers
3.) Localized dilation of reservoir around injector
4.) Overburden stretching above producing compartment

5.) Poorly connected, low porosity turbidite fans → marginal pressure drop → marginal compaction

Reservoir Simulations:
Porosity model, Pore Pressure and Strain

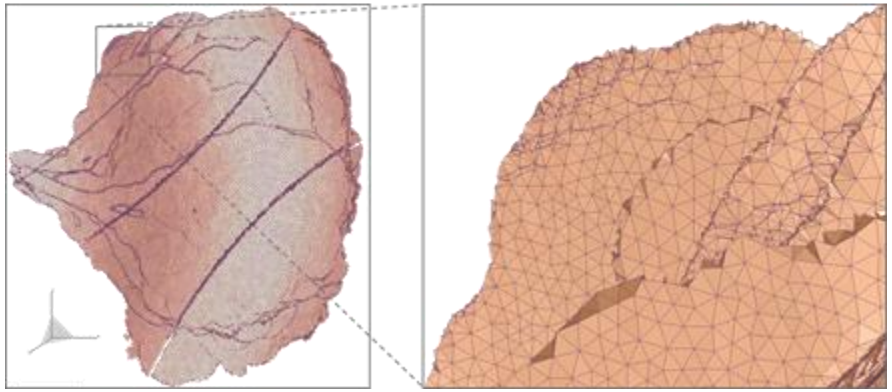
2 ½ years of field production, Time-stamp for time-lapse seismic simulations

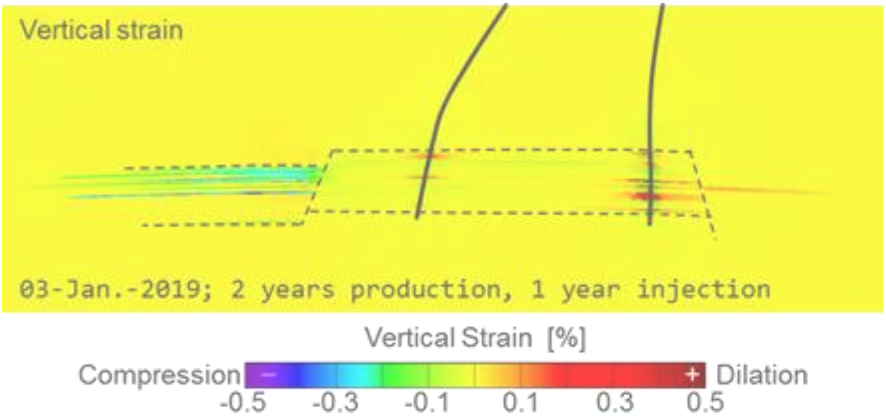


2019-05-08
(k=1500, Depth=3750 m)

Summary and Key Learnings

- Fully coupled simulations of fluid flow and geomechanics
- Tight integration with geological model building
  - Retain facies distribution from simulation model
  - Shrink-wrapping of connected sand bodies
  - Facies distribution determines seismic response, flow response and geomechanical response
  - Rock physics in geological modelling and time-lapse applications needs to be coordinated
- Move towards
  - More complex reservoir geometries (e.g. complex overburden, treatment of faults)
  - Complex material models (e.g. plasticity for stress-strain relationship)
  - Rock-physics during tri-axial stress changes and plastic deformation
  - Integration with field-data observations





SEAM Time Lapse Project
Geophysical simulation datasets

Lijian Tan, Wen-yi Hu, Jianguo Liu

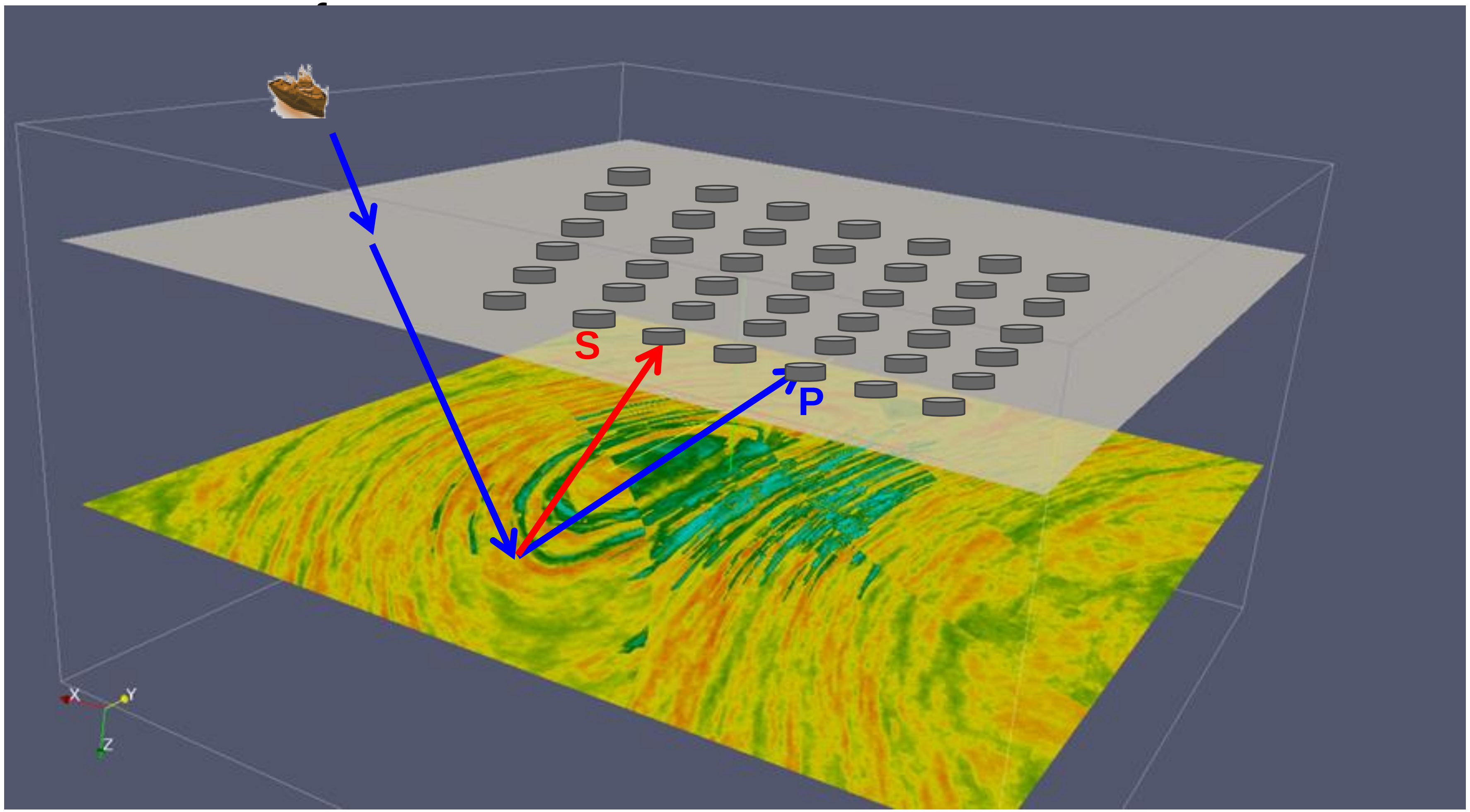
Advanced Geophysical Technology, Inc. (AGT)

1. **Ocean Bottom Node (OBN) marine seismic acquisition (before and after)**
2. **Electromagnetic (EM) surveys**
    a. Marine controlled-source EM (CSEM) acquisition (before and after)
    b. Marine magnetotelluric (MT) acquisition (before and after)
    c. Crosswell EM induction surveys (before and after)
3. **Gravity: absolute and full tensor gradient (FTG) surveys (before and after)**

Seismic acquisition: Ocean Bottom Node (OBN) geometry

– OBN is becoming more widely used because of the capability to acquire multi-component data with full azimuth and full bandwidth.

– Time-lapse measurements with OBN generally have lowest noise among all



Survey Parameters

45 Hz source wavelet

175 m node spacing

3600 nodes (60 × 60, x and y)

25 m shot spacing

Shots everywhere in region [0,12500] × [0,12500]

7 second pressure records (time and budget limited)

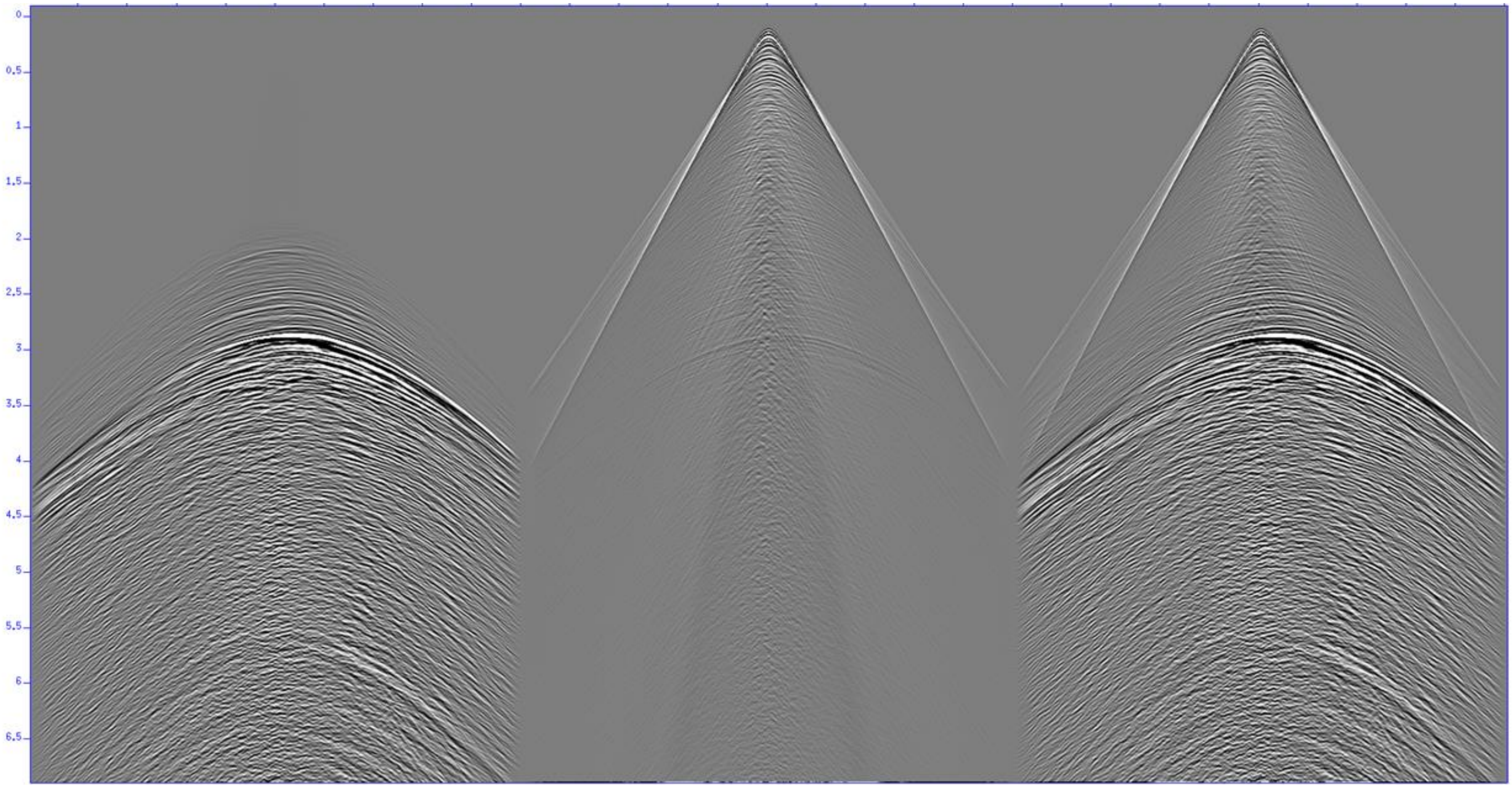
Computational aperture is full model region

Absorbing upper boundary
No surface-multiple ghost

Time Lapse Response
due to material property change only

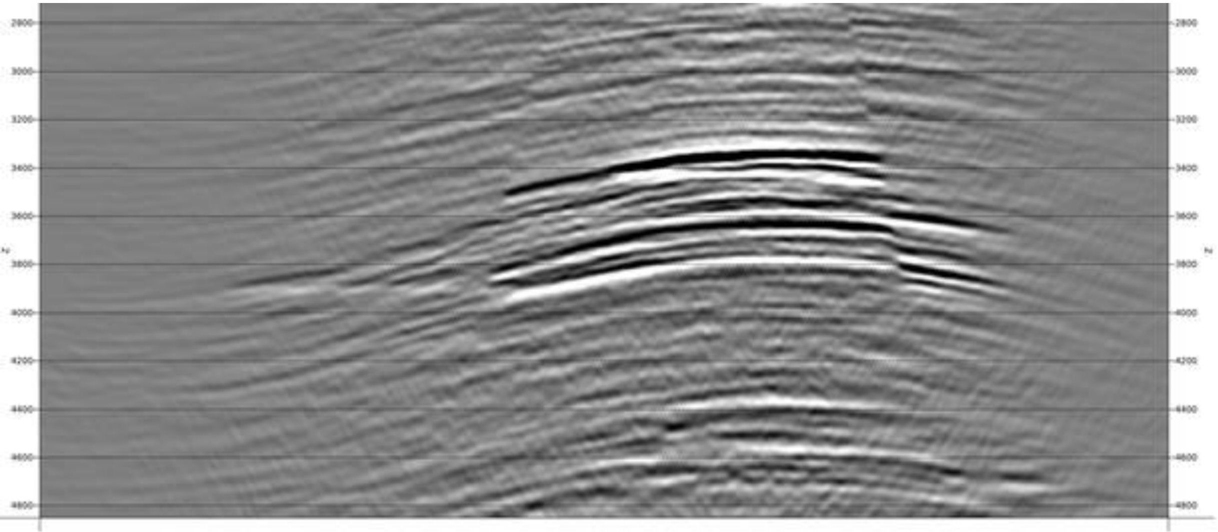
Time Lapse Response
due to geometric shift only

Full Time Lapse Response

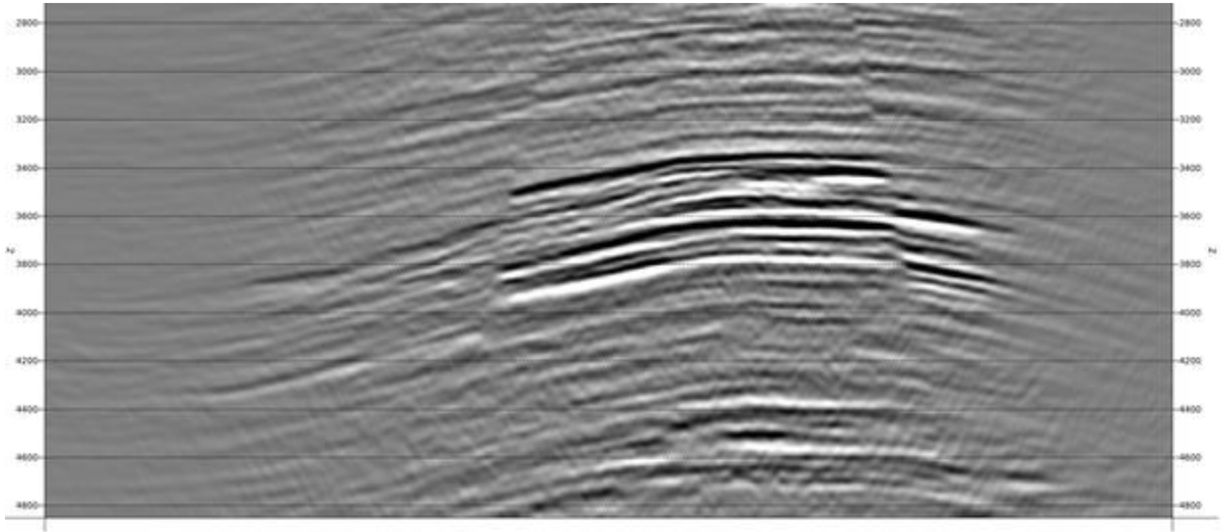


Time Lapse Images Near Reservoir

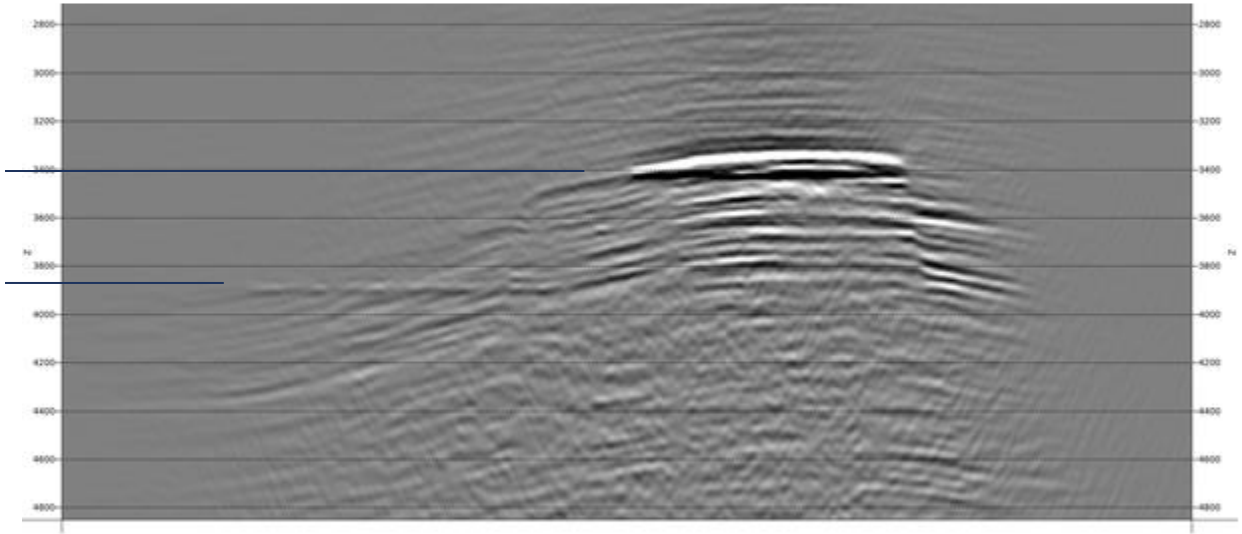
Before production



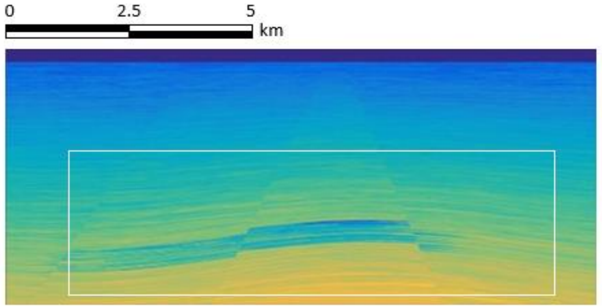
After production



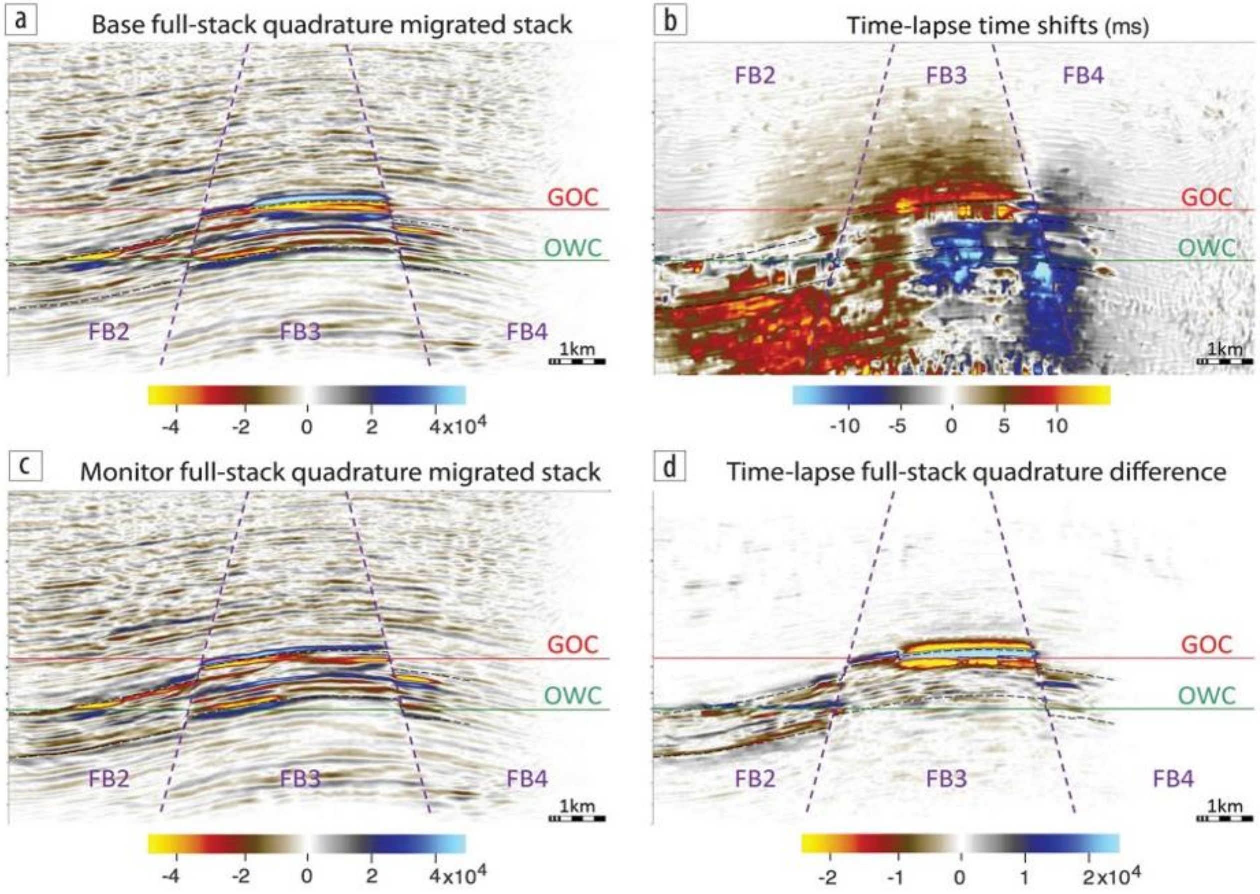
Difference



Sample Time-Lapse Results



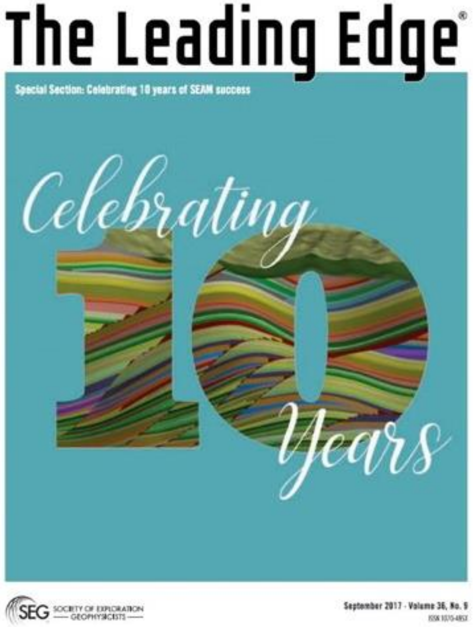
SEAM TIME LAPSE DEEPWATER TURBIDITE MODEL



courtesy Chevron

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.



Virtual time-lapse seismic monitoring using fully coupled flow and geomechanical simulations

Shauna Oppert[1], Joseph Stefani[1], Daniel Eakin[1], Adam Halpert[1], Jorg V. Herwanger[2], Andy Bottrill[2], Peter Popov[2], Lijian Tan[3], Vincent Artus[4], and Michael Oristaglio[5]

[1]Chevron
[2]Ikon/MP Geomechanics
[3]AGT
[4]Kappa Engineering
[5]Yale University/SEAM

750 THE LEADING EDGE September 2017 Special Section: Celebrating 10 years of SEAM success

SEAM Life of Field Clastic Model

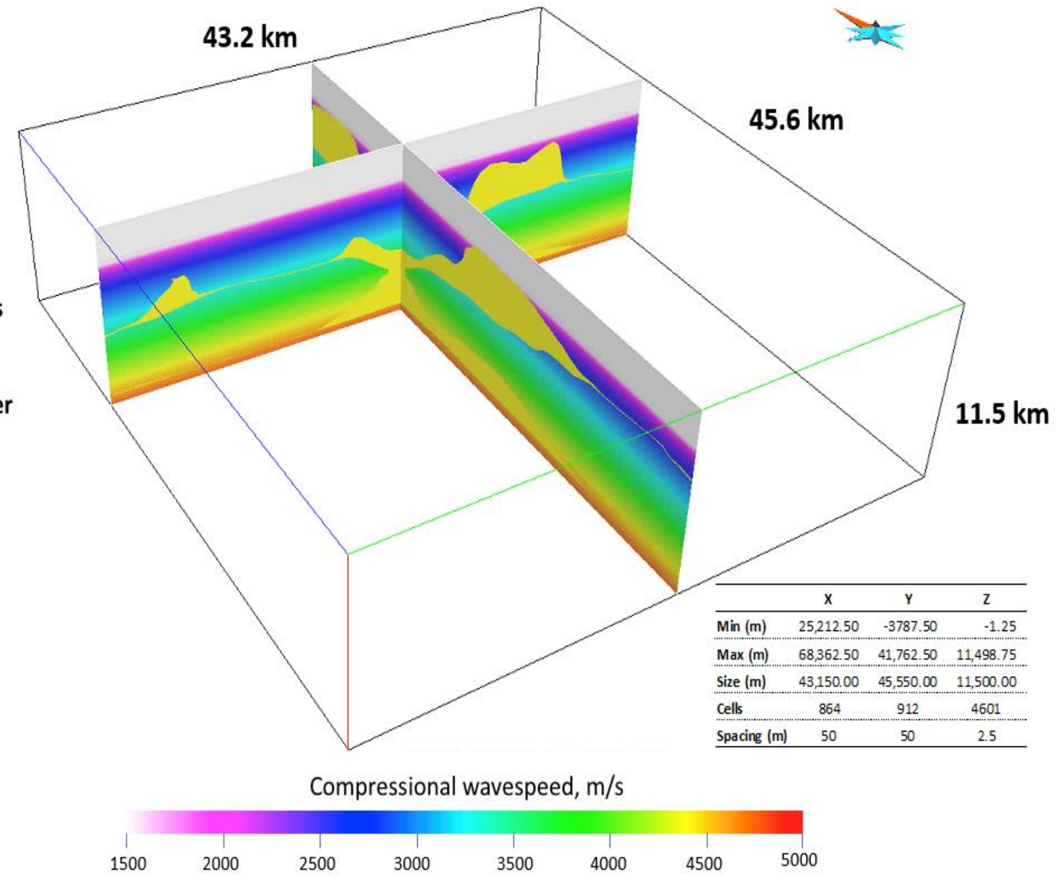
Allochthonous and autochthonous salt bodies

Salt flank and salt-cored deepwater siliciclastic reservoirs

Full 3-phase fluid model

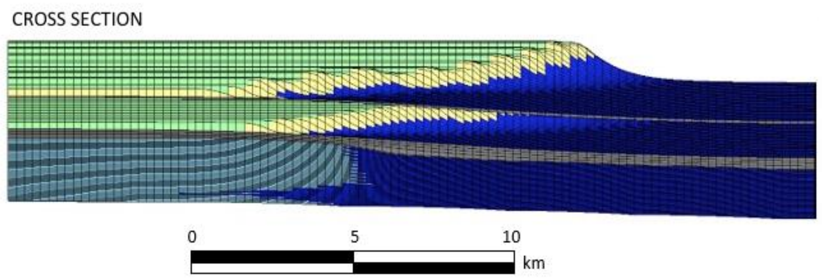
Plastic deformation
Fault reactivation
Brittle fracture

Full seismic anisotropy with anisotropic property updates

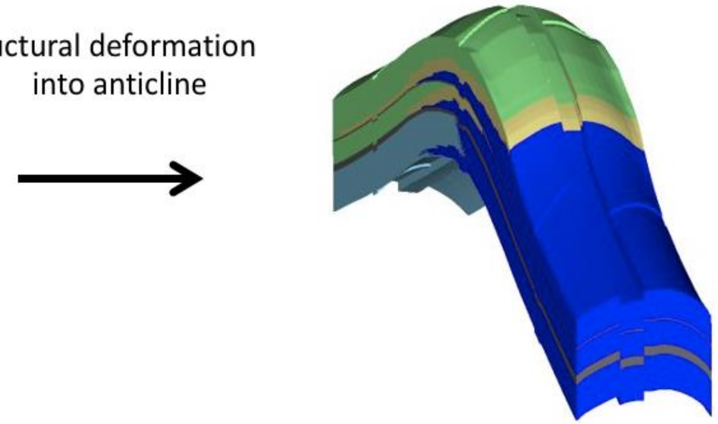


	X	Y	Z
Min (m)	25,212.50	-3787.50	-1.25
Max (m)	68,362.50	41,762.50	11,498.75
Size (m)	43,150.00	45,550.00	11,500.00
Cells	864	912	4601
Spacing (m)	50	50	2.5

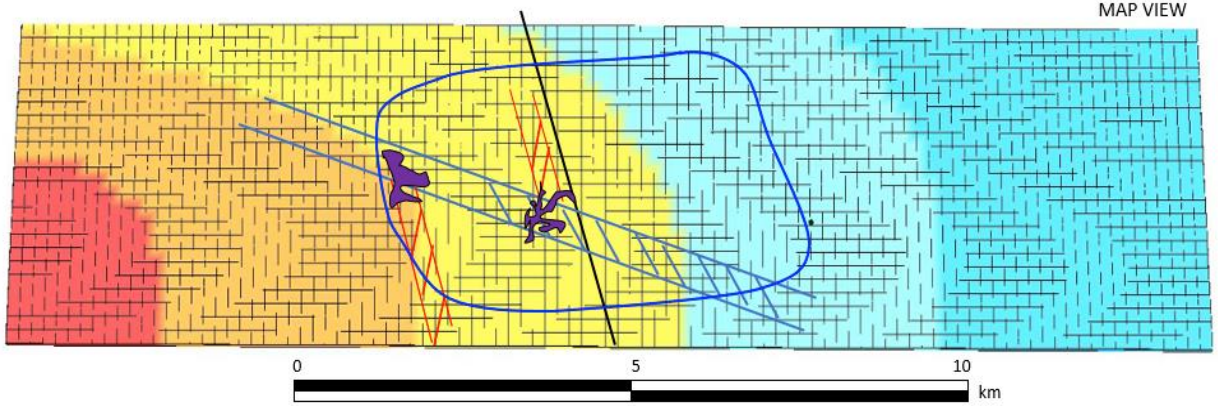
SEAM Life of Field Carbonate Model (Design Elements)



Structural deformation
into anticline



CARBONATE PLATFORM
Prograding features in 3D
Sealing and open faults
Faulted corridors
Karsts at fault intersections



Seismic Survey Design

- OBN surveys simulated in reciprocal mode
  - Approximately 1000 2C nodes at 200 to 600 m spacing over the 2 reservoirs with a dense surface shot array
  - Dense OBN spacing above the oil-water contact
  - Sparse OBN spacing at the perimeter to give long offsets for FWI
  - Broadband wavelet from approximately 0 to 20 Hz
- Reverse VSP simulated with 100 3C shots
- Microseismic simulated with 100 4C shots
- Baseline plus 3 monitor surveys over 10+ years of production
- Anisotropic starting model with anisotropic stress- and fluid-induced updates
- Varying attenuation mechanisms

SEAM Life of Field (LoF) Participants

- Exxon
- Chevron
- Total
- Sinopec
- ENI
- PGS
- Schlumberger
- Fairfield Geotechnologies
- Petrobras

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