Distributed Strain Sensing based Reservoir Monitoring for Carbon Sequestration Reservoirs

Presenter: Dr. Ge Jin, Colorado School of Mines

Coauthors: Yanrui Daisy Ning & Peiyao Li, Colorado School of Mines

Richard Hammack, National Energy Technology Laboratory

Kan Wu, Texas A&M

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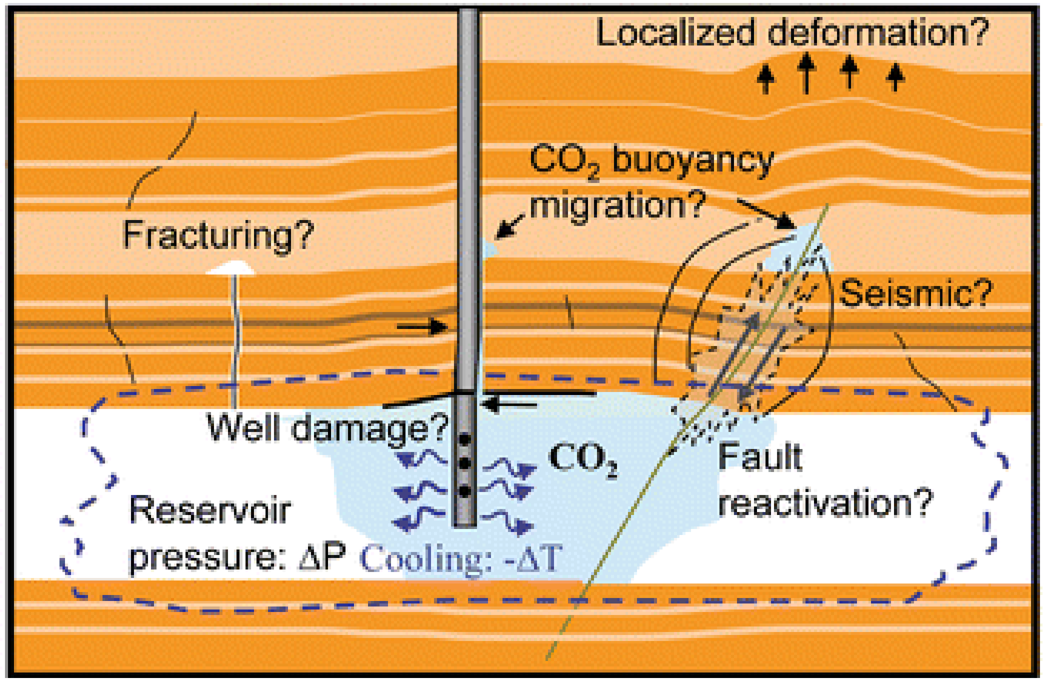
Outline

- Introduction
- Aseismic Deformation and Distributed Strain Sensing
- Geomechanical Inversion and Uncertainty
- Discussion and Future Works
- Conclusion

Risk of Cap Rock Integrity and Induced Seismicity for CCS Projects

Unwanted mechanical changes

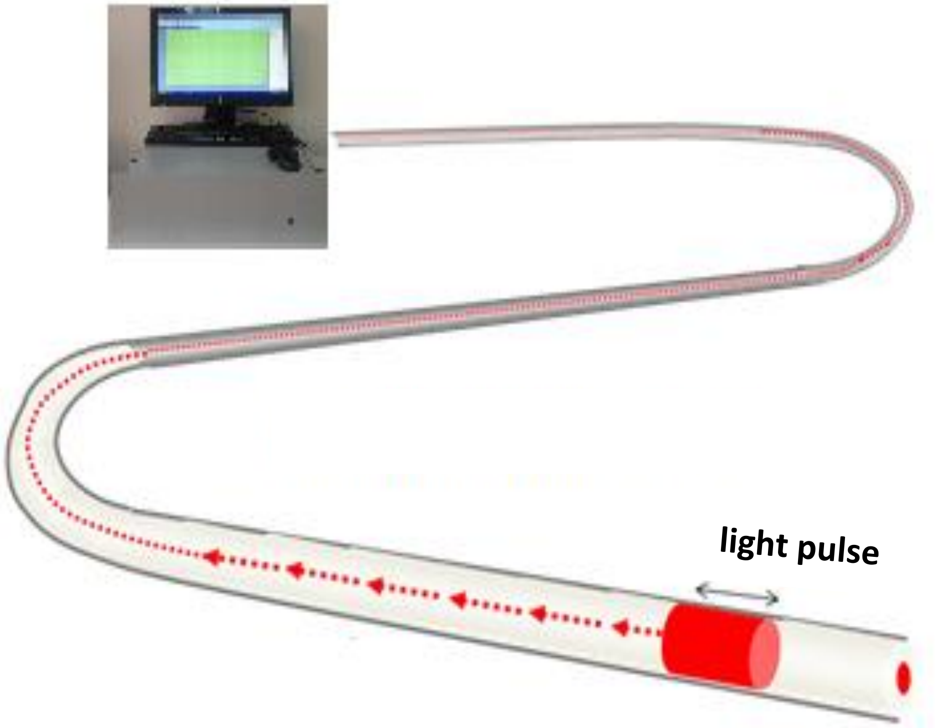


Rutqvist, 2012

- Cap rocks are typically low-permeability shales.
- Deformation in shale formations can occur without causing seismic activity due to the presence of ductile rocks.
- Monitoring for microseismic activity may not be effective for assessing the integrity of caprocks in CO_2 storage (CSS) reservoirs.
- Overburden pressure and chemical monitoring can only detect CO_2 leakage after it has already occurred.

Is there a monitoring method to detect cap rock and reservoir fracture deformation before overburden leakage?

Distributed Fiber-Optic Sensing



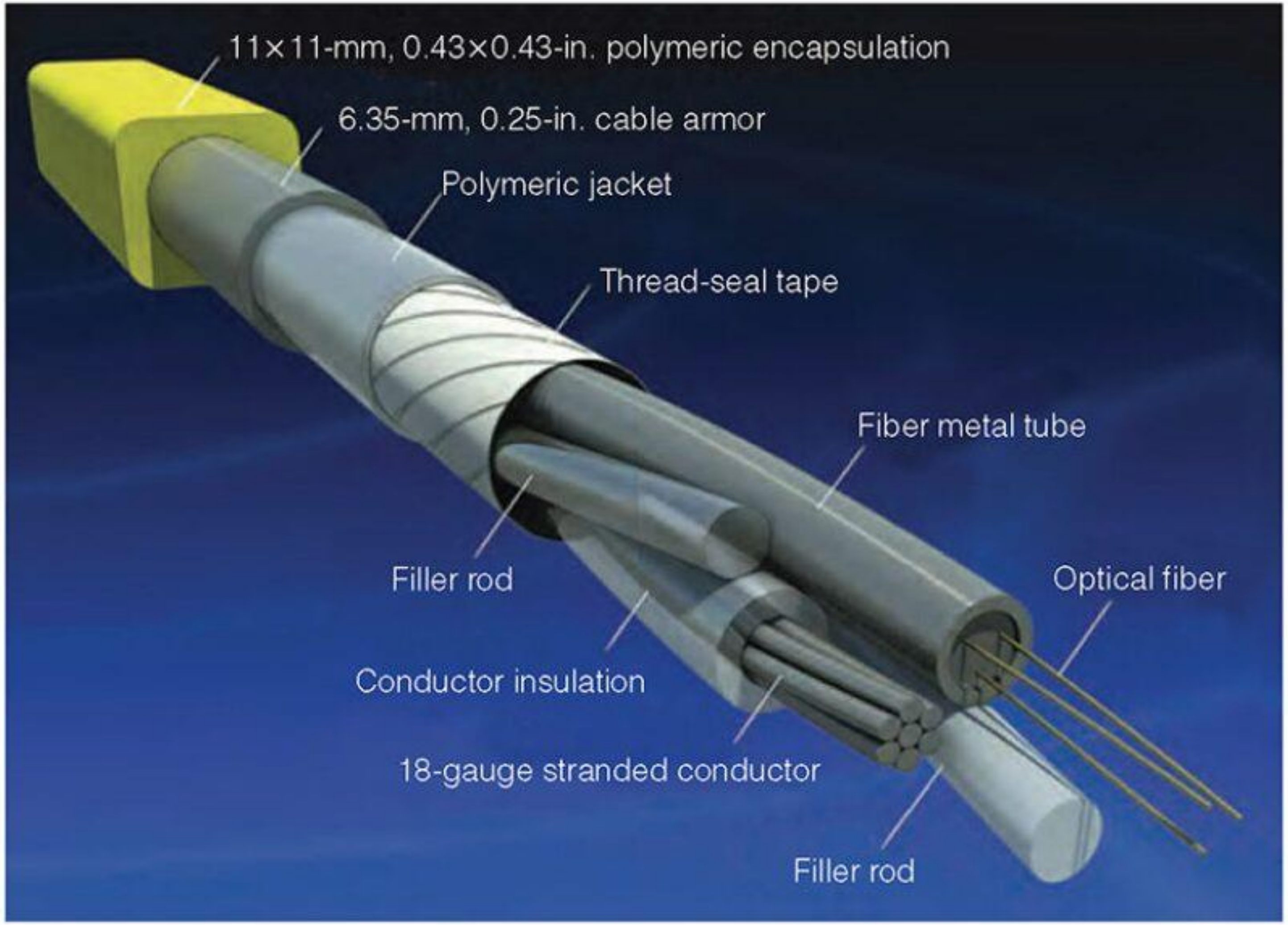
Distributed Temperature Sensing (DTS)

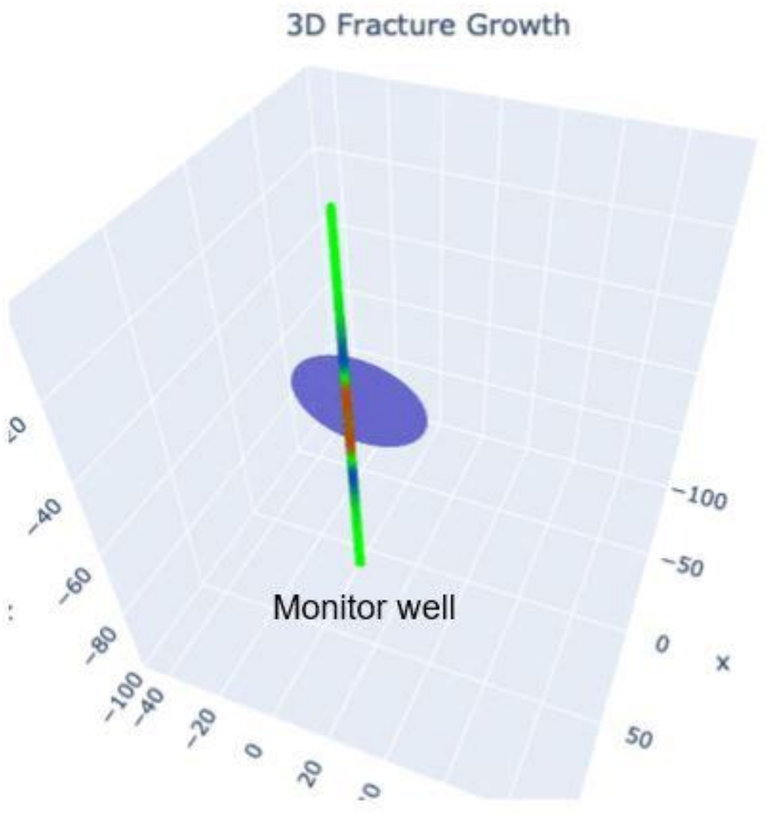
Distributed Acoustic Sensing (DAS)

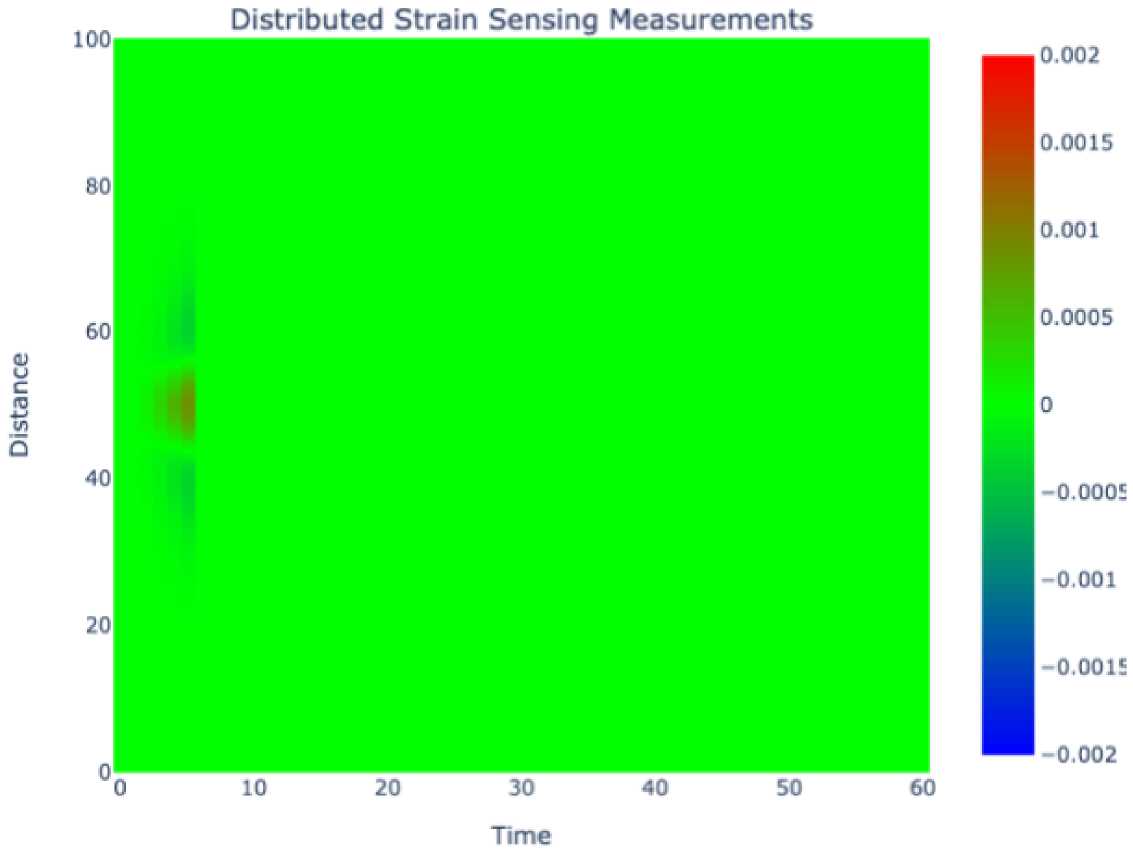
Distributed Strain Sensing (DSS)

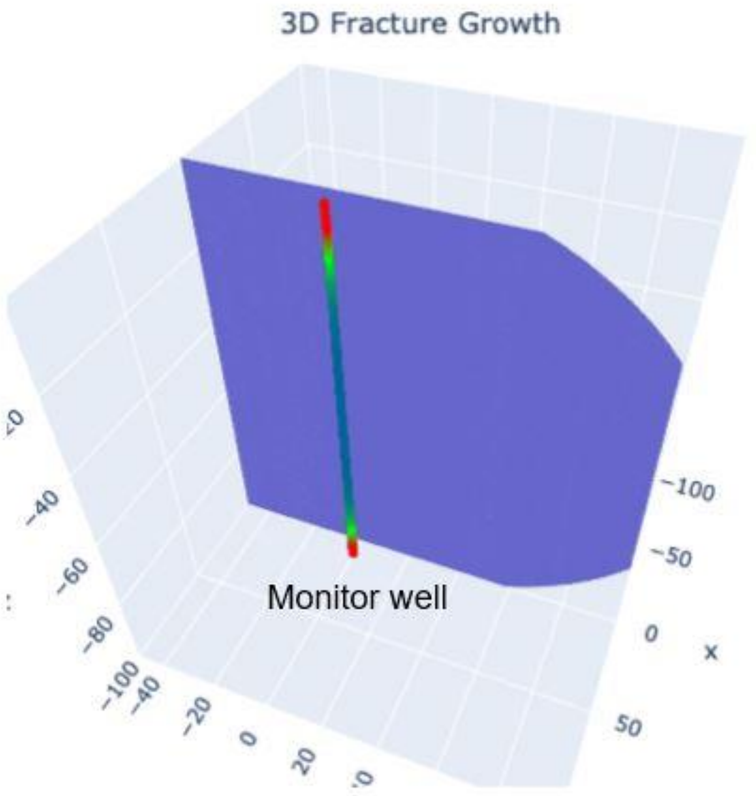
- Distance: up to 8 km
- Spatial resolution: 0.2 m
- Sampling interval: 30 s
- Sensitivity: 0.1 $\mu\varepsilon$

Borehole Cable Deployment




3D Fracture Growth
Monitor well
−100
−50
0
x
50
−40
−60
−80
−100
−40
−20
0
20


Distributed Strain Sensing Measurements
Distance
Time
0
20
40
60
80
100
0
10
20
30
40
50
60
0.002
0.0015
0.001
0.0005
0
−0.001
−0.002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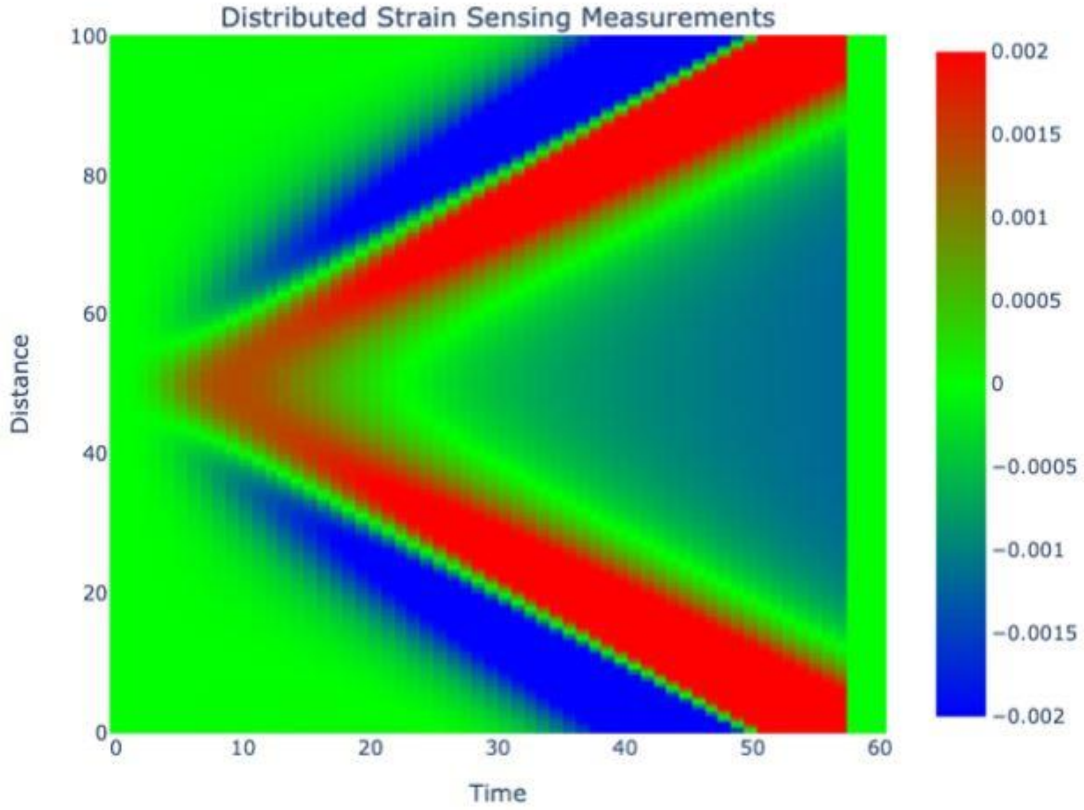
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−0.001
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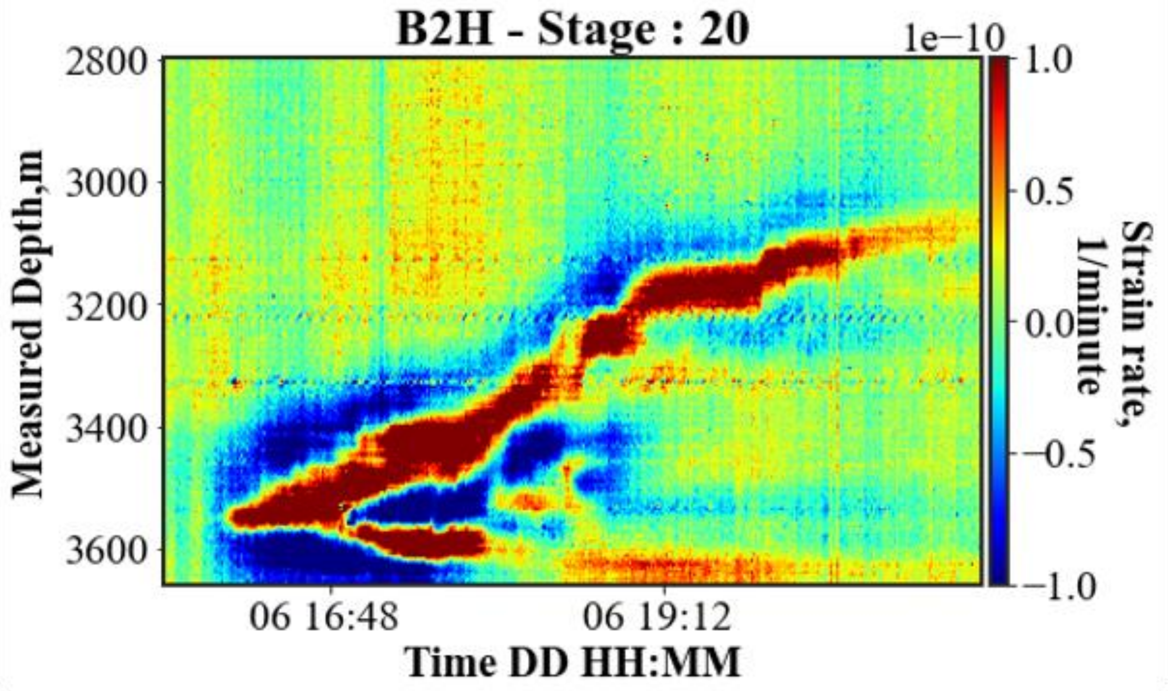
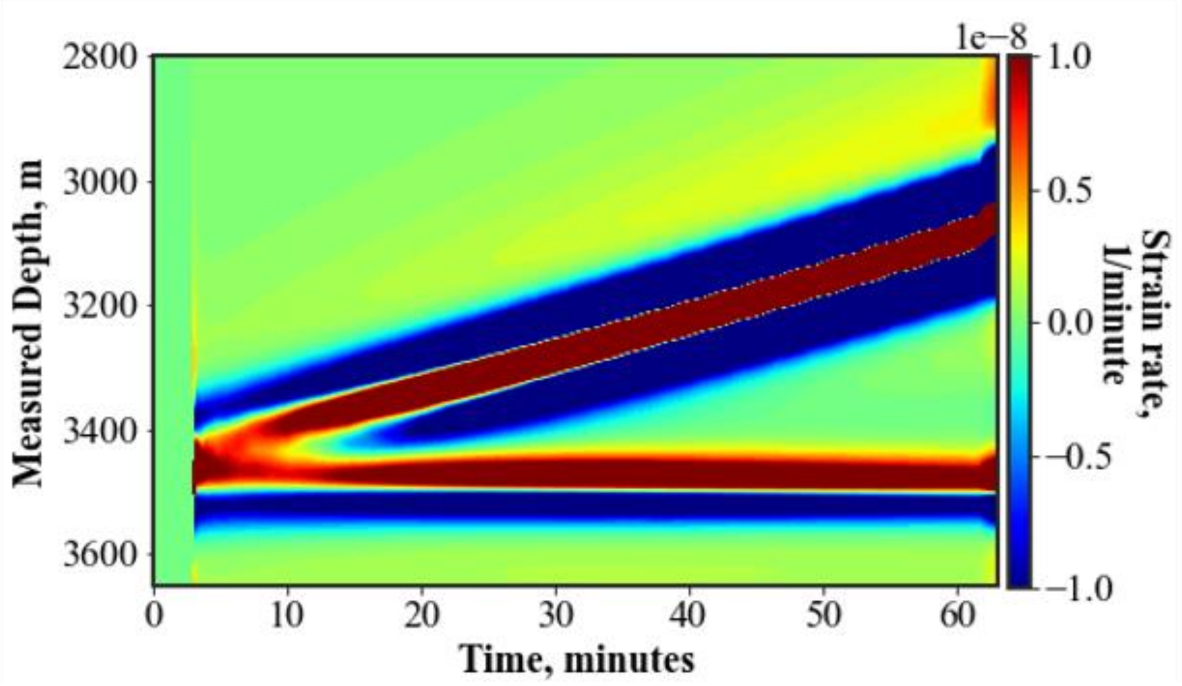
Vertical Well DSS Signal vs. Simulation

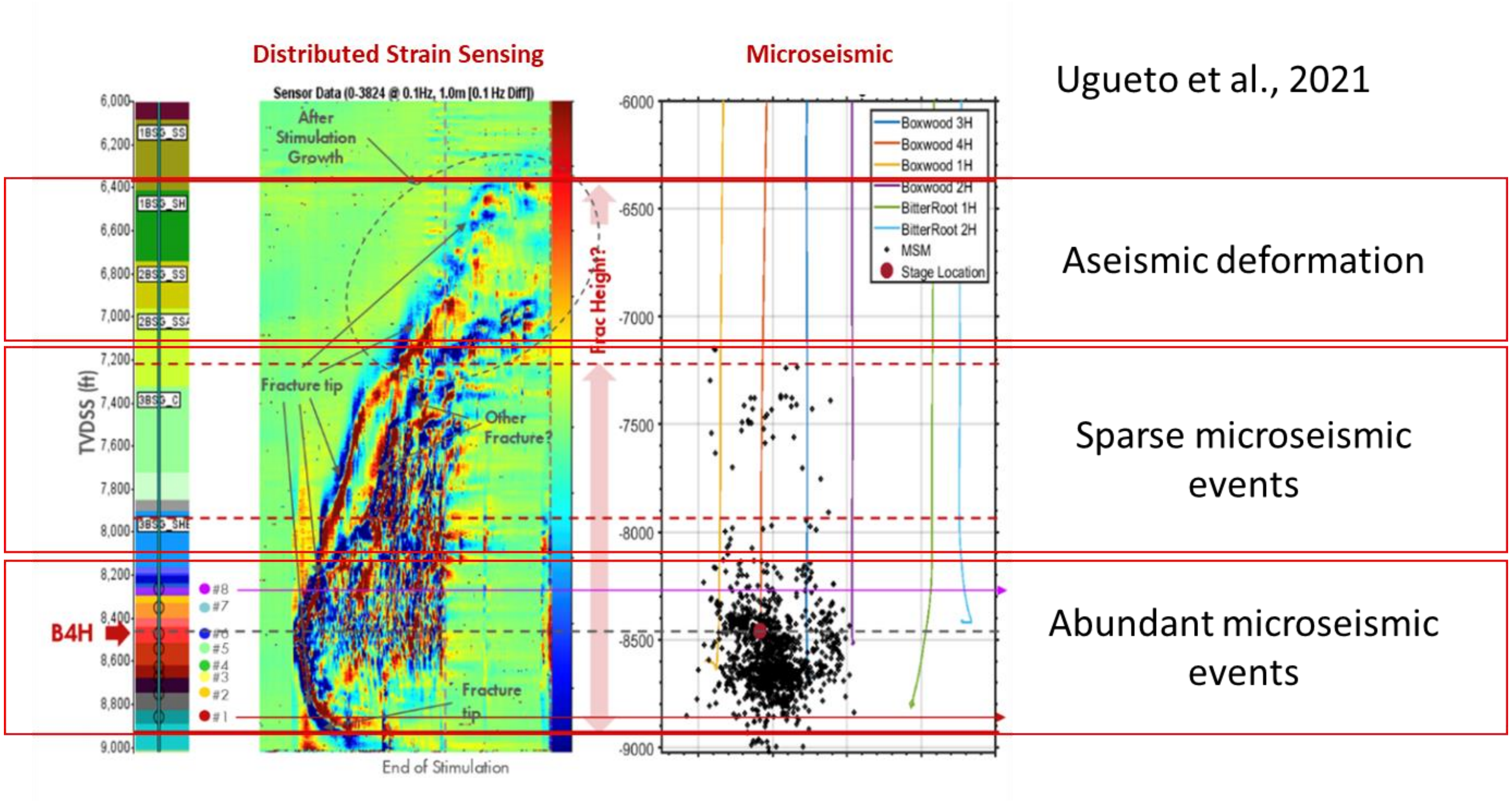




Srinivasan et al., SPE-214690-PA

- Single fracture
- Fracture upper tip location grows continuously

Aseismic Deformation Observed in Shale

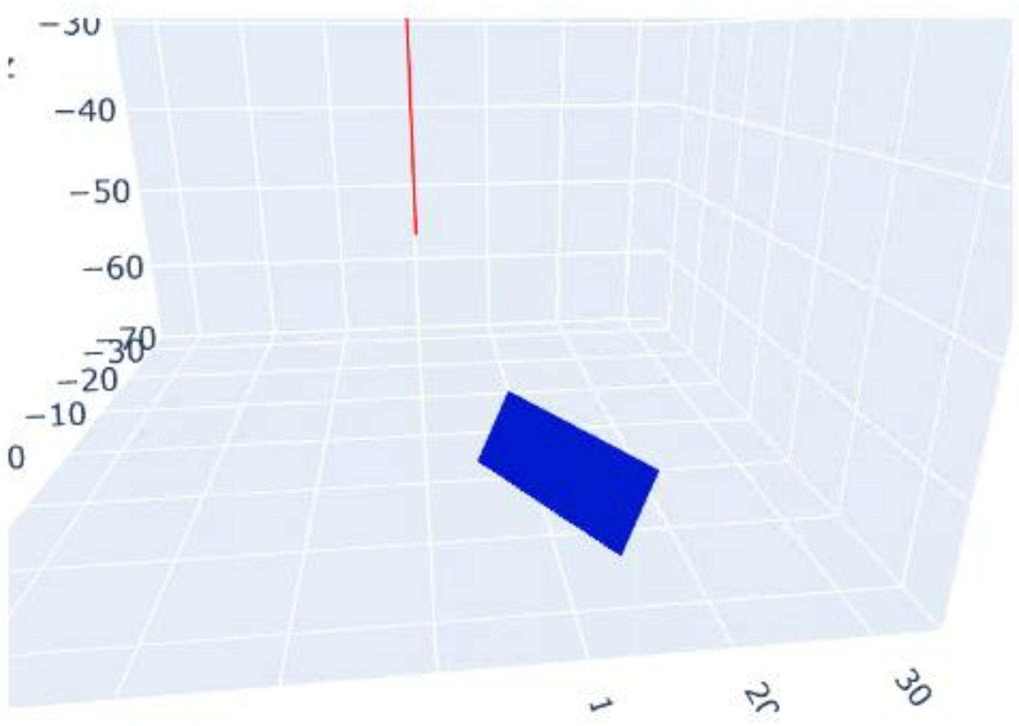


Ugueto et al., 2021

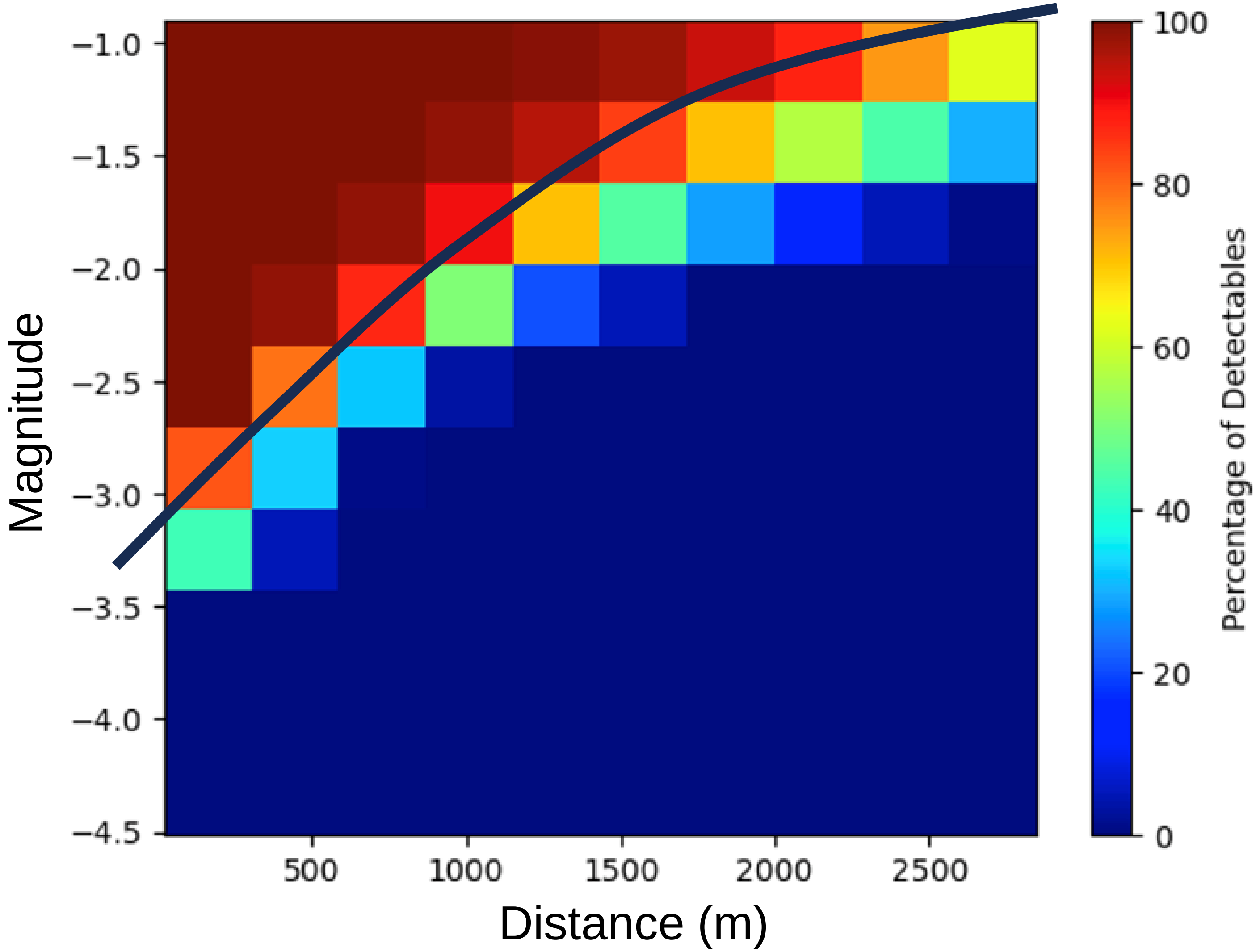
Deformation in shale formation can be aseismic due to ductile rocks → Microseismic monitoring may be inefficient for caprock integrity monitoring for CSS reservoirs!

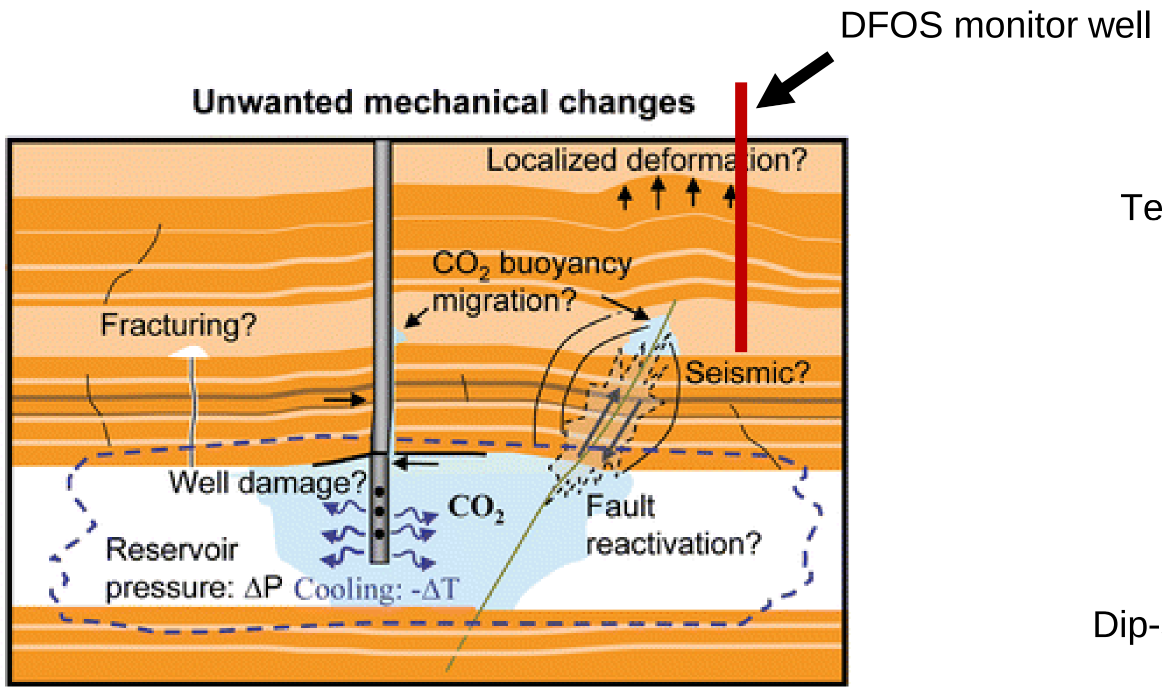
Problem Statement

- Can we observe aseismic deformation induced strain change using DSS?
- Using strain change observed along monitor well(s), how well can we constrain the fracture location, geometry, and deformation?
- 10 degrees of freedom:
  - Location: x, y, z
  - Geometry: L, H, Strike, Dip
  - Deformation: W, S1, S2

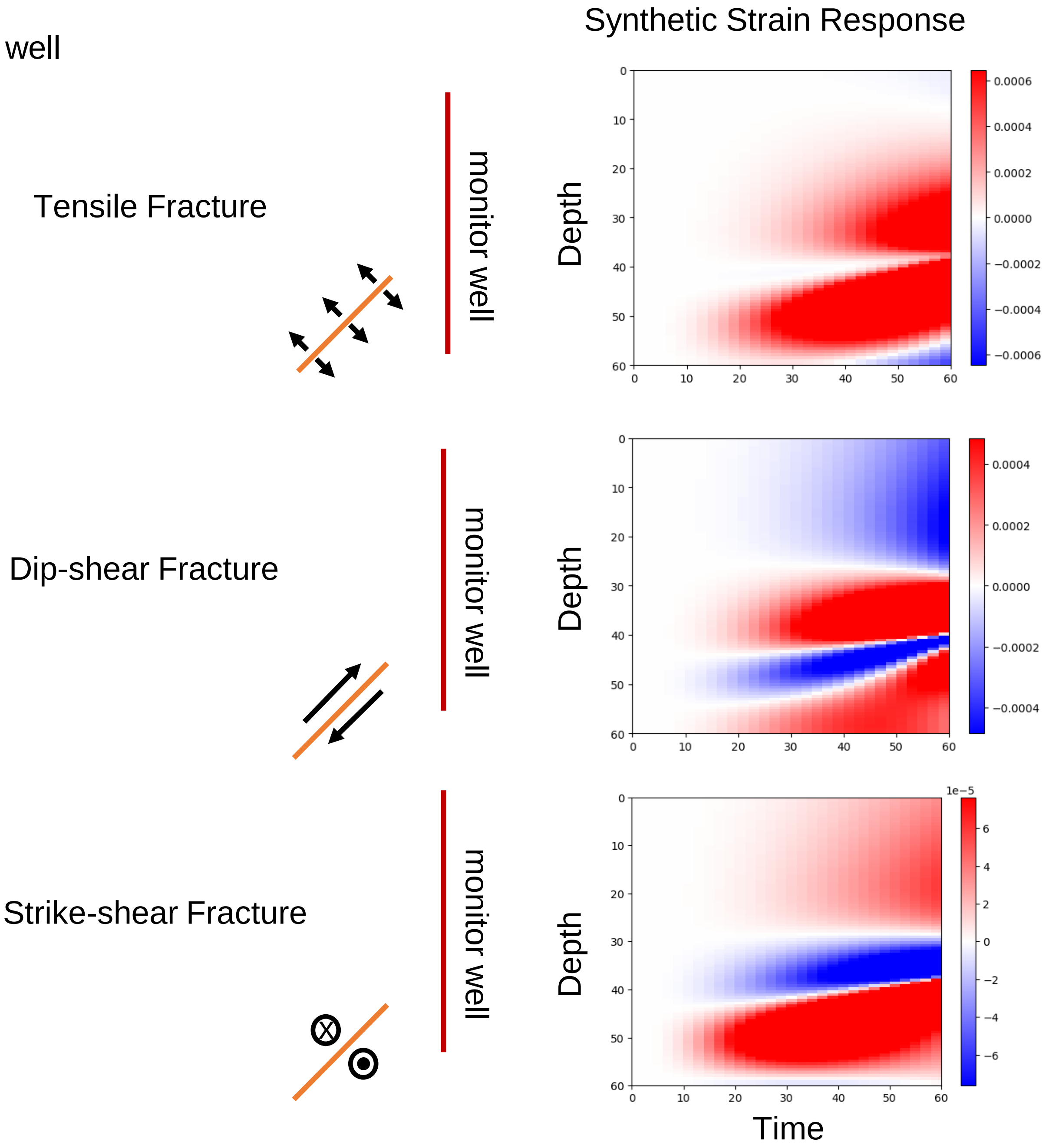


DSS Detection Threshold (0.1 $\mu\varepsilon$ sensitivity)





Rutqvist, 2012

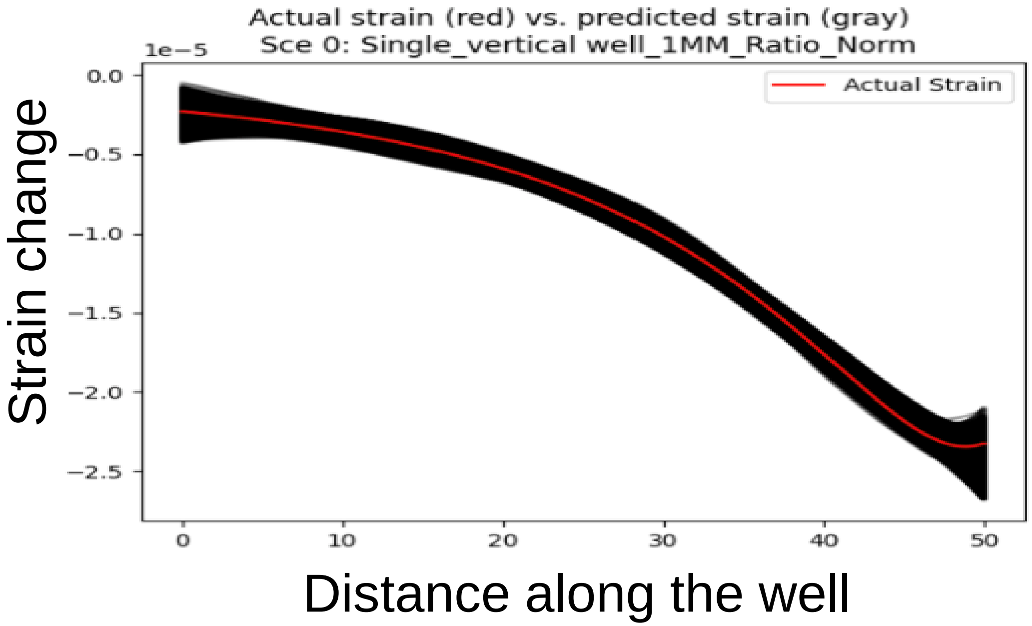


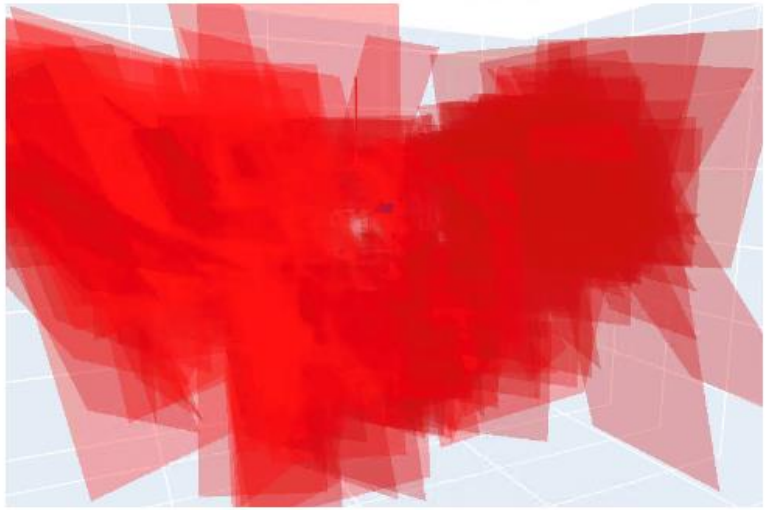
Monitor well in the overburden can detect fracture aseismic deformation in caprocks, allowing early warnings and mitigations.
An inversion algorithm is required to interpret the strain measurements.

Non-linear and Non-uniqueness Inversion Problem: Single Vertical Well

Generated 1 million random initial models, followed by gradient decent inversion.
52,116 final models with errors smaller than 5% were found using 1050 CPU hours.
Non-uniqueness due to the following trade-offs:

- Single component measurements (azimuth)
- Distance/fracture size/deformation value

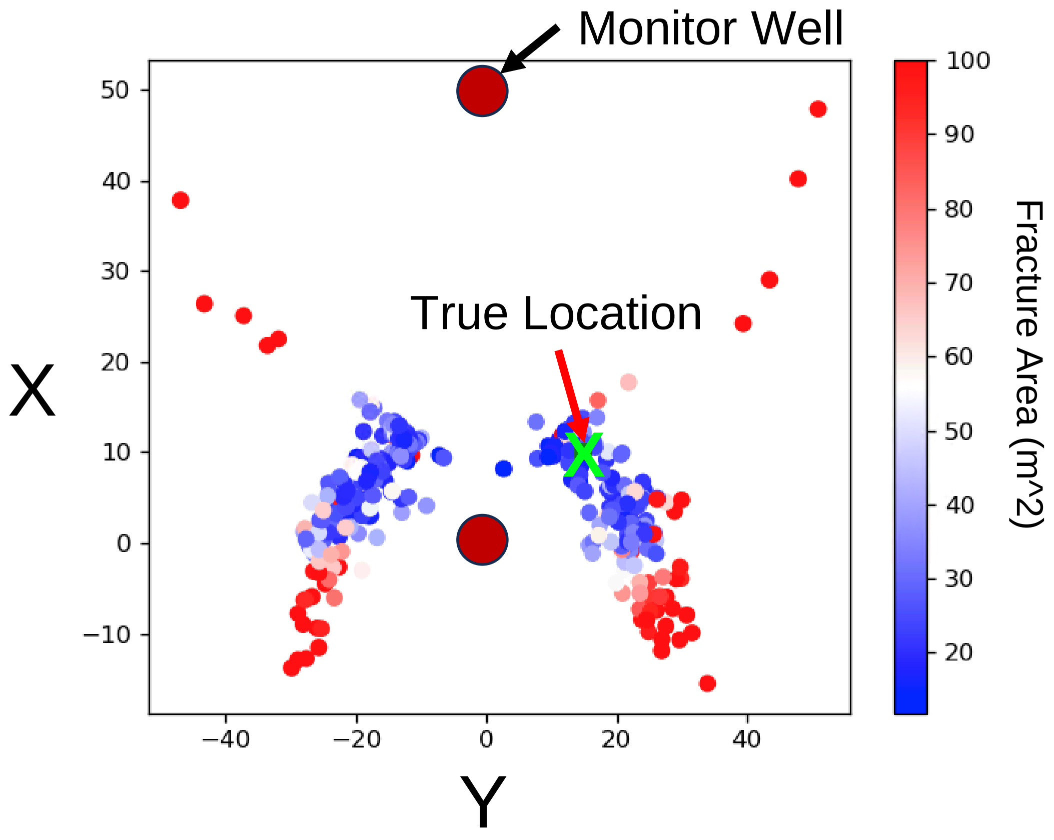


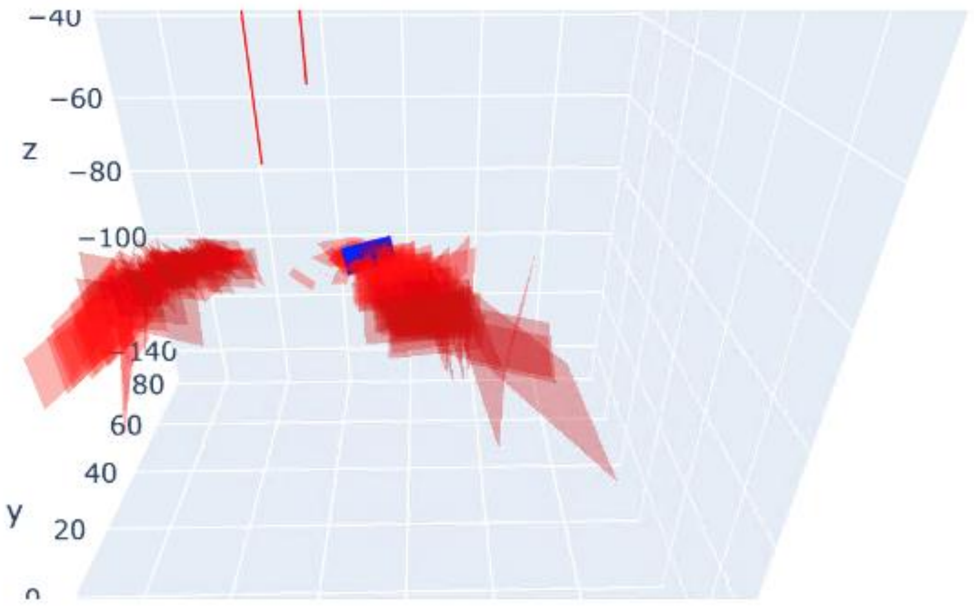


Error < 5%
- 52,116 fractures

Two Vertical Wells

Uncertainty of azimuth is improved.
Trade-off between distance and fracture size still exists.

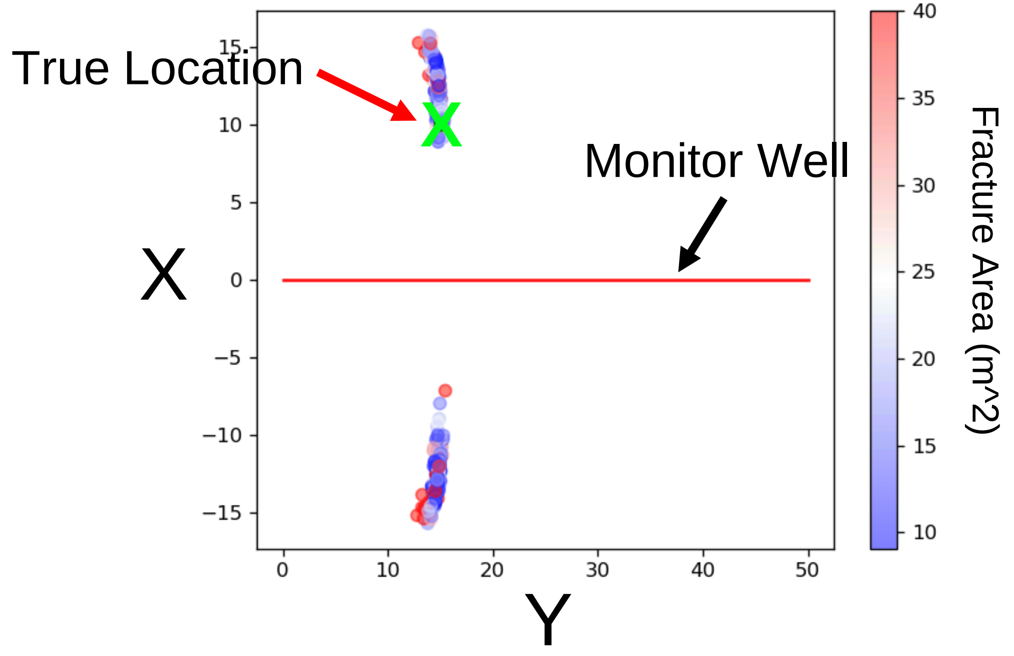


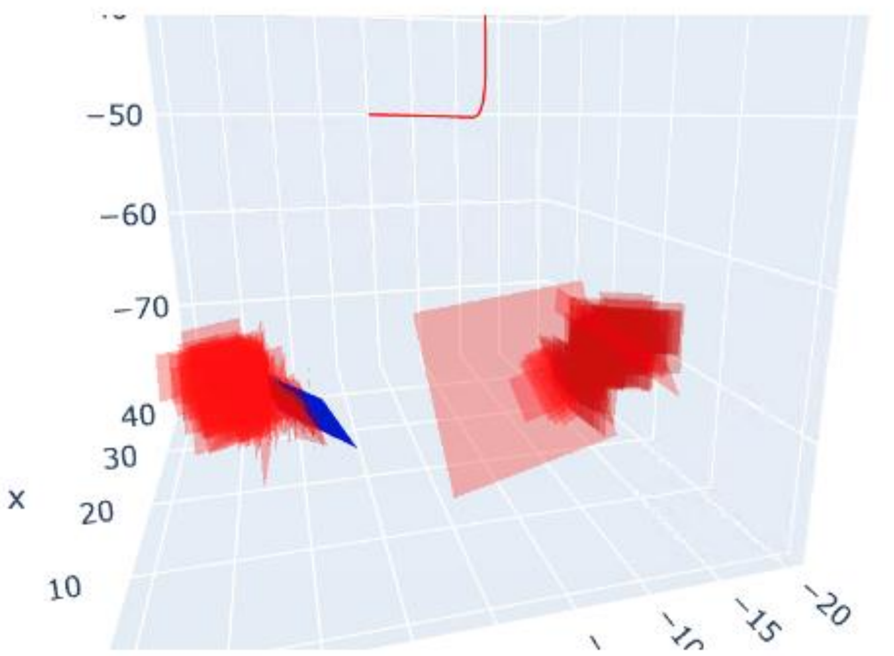


Error < 5%
- 367 fractures

L-shape Monitor well

- Azimuth uncertainty is reduced.
- Symmetric distribution on both sides of the monitor well.
- Distance/fracture size trade-off.





Error < 5%
- 541 fractures

L-shape + Vertical wells:

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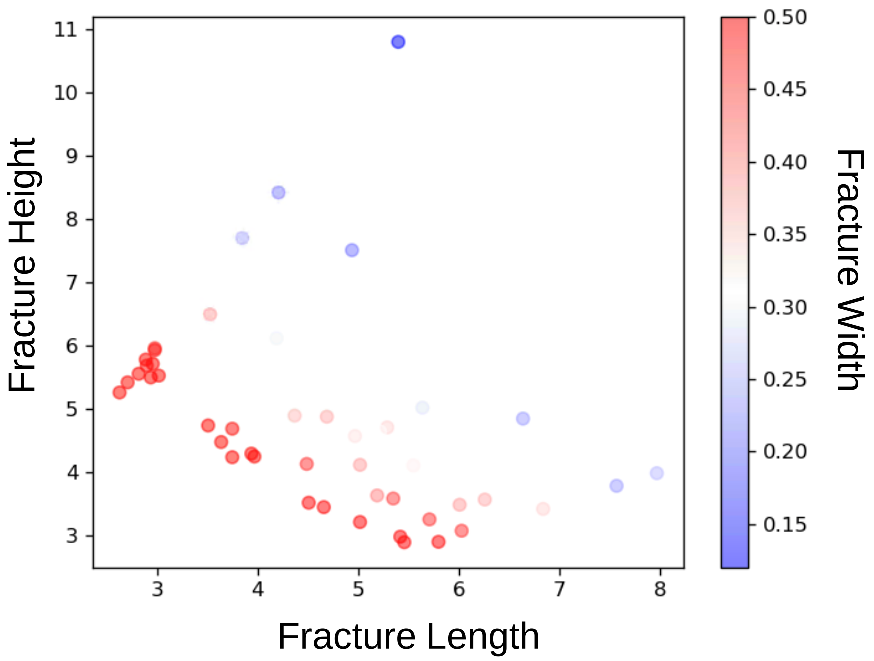
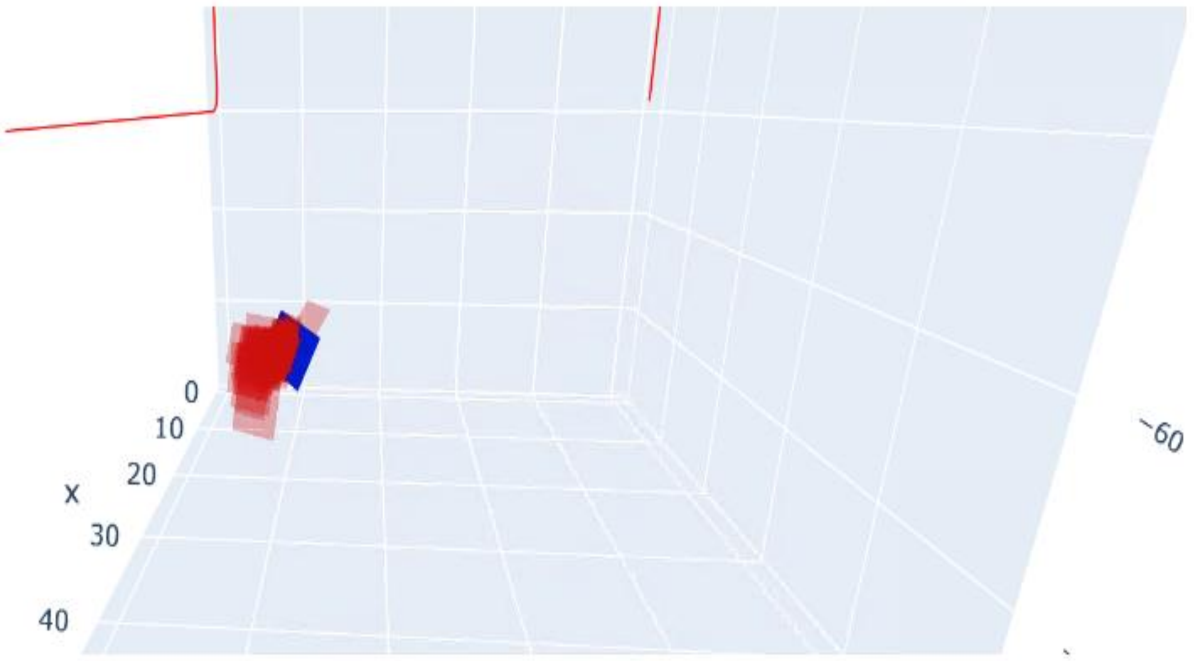
- Fracture location can be accurately estimated.
- Trade-off between slippage value and fracture size.

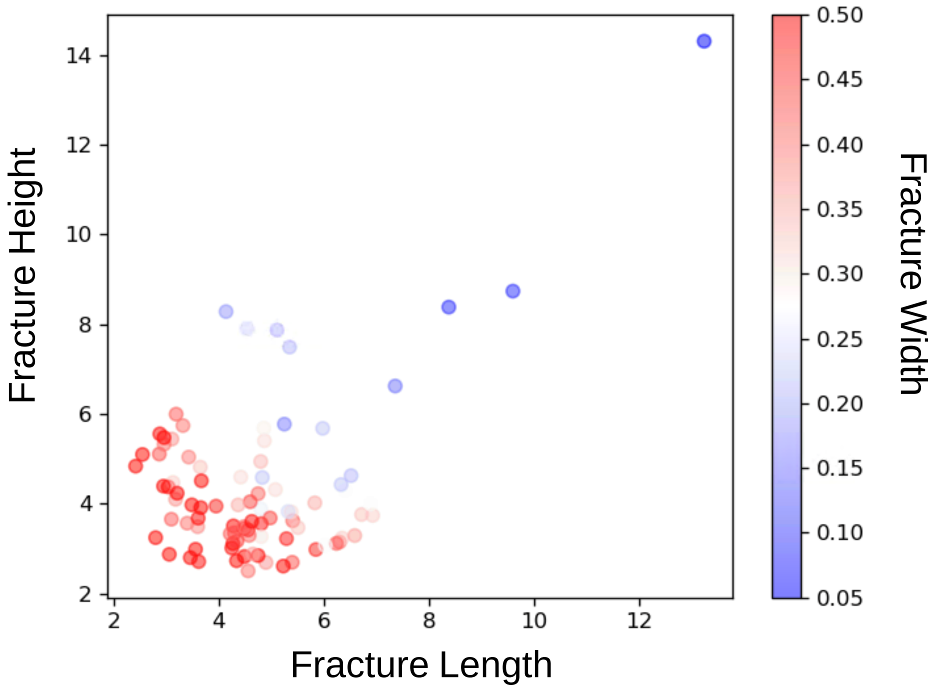


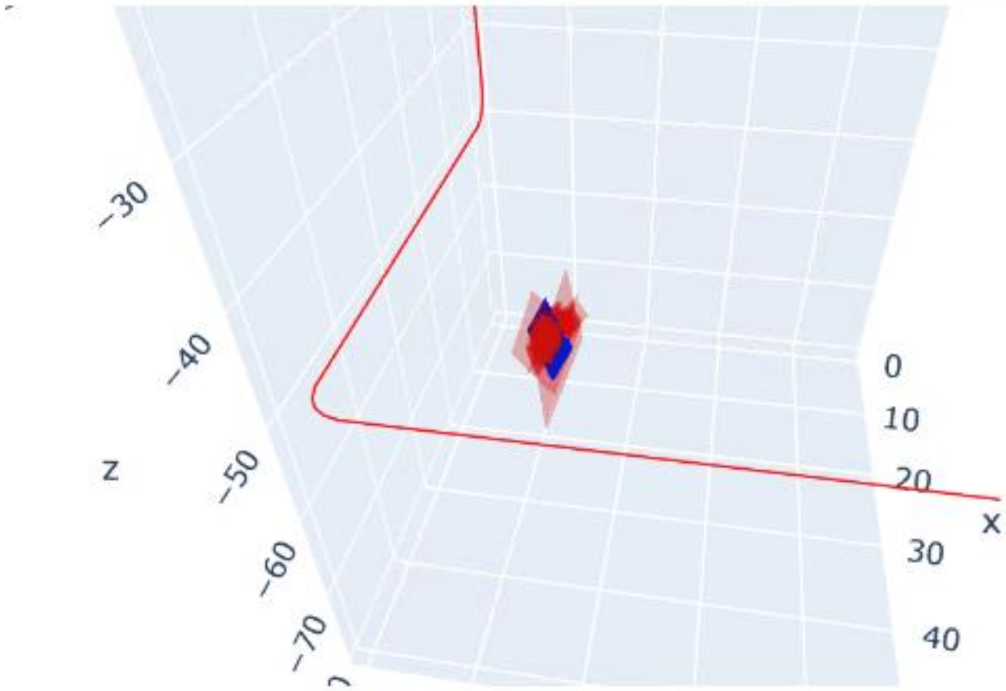


Error < 5%
~ 47 fractures

Monitor well with complex geometry

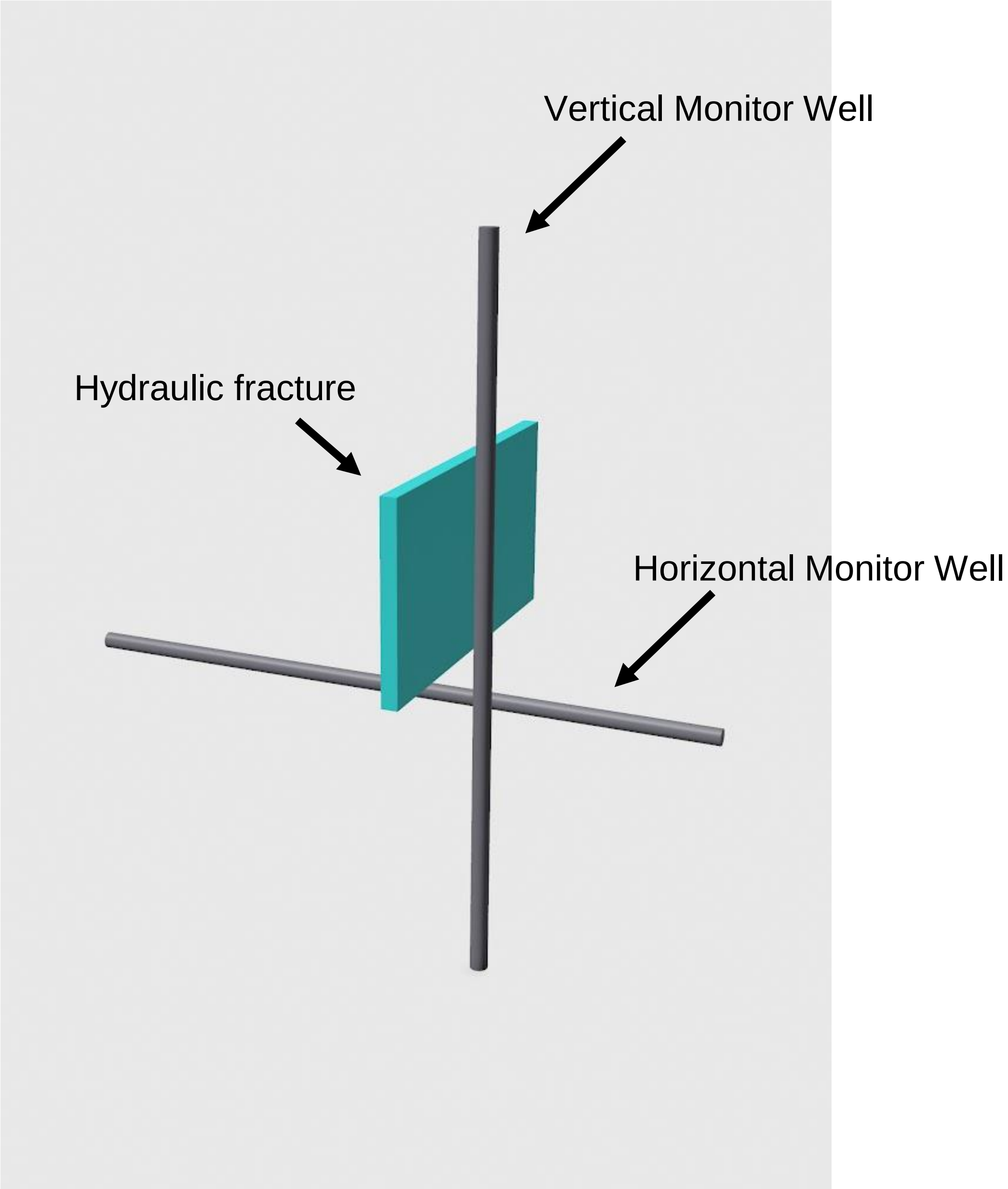
- Similar results as two monitor wells.
- It can be more cost-effective for monitoring purposes.

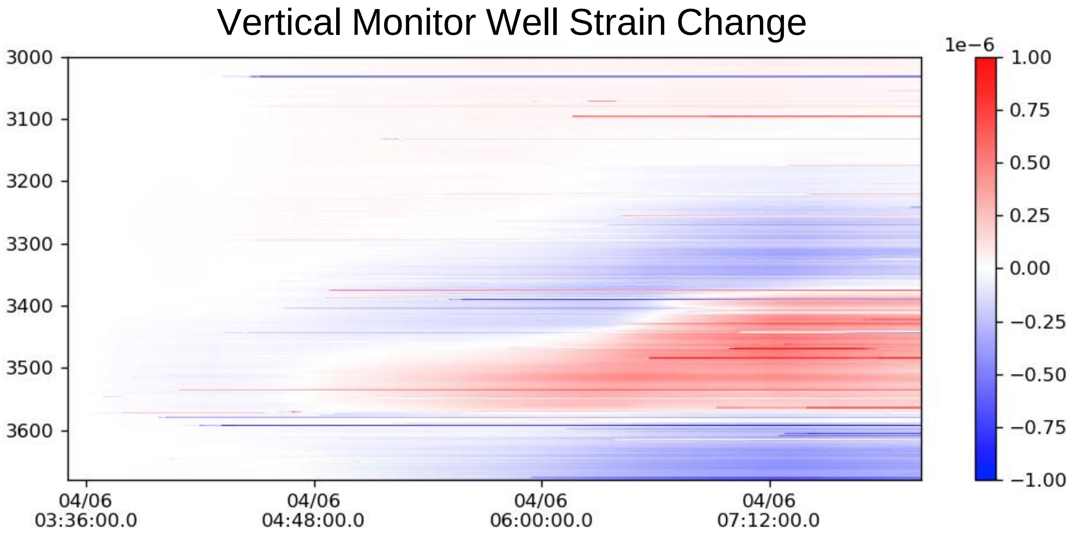


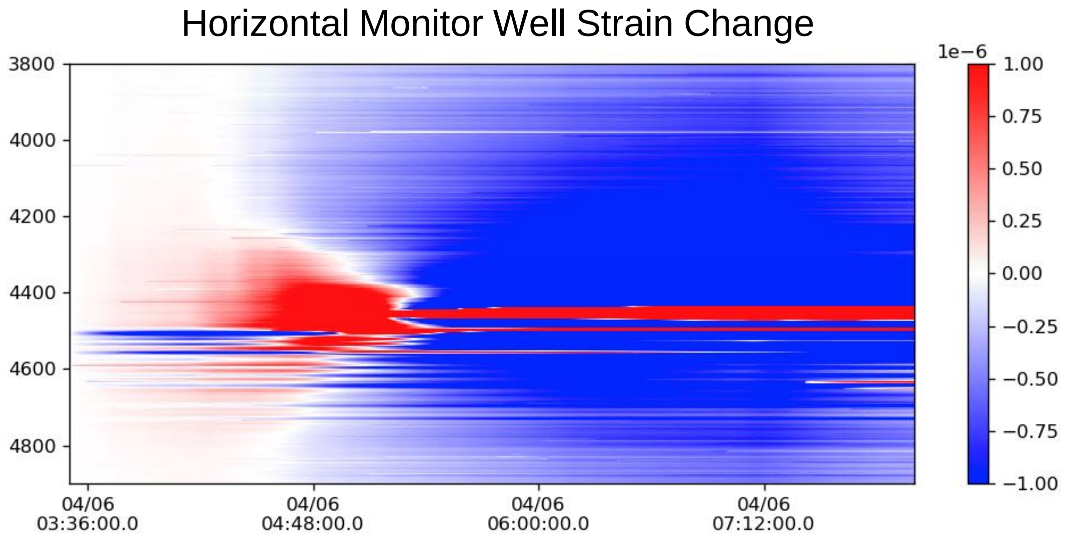


Error < 5%
~ 89 fractures

Field Data Example: HFTS2







Future Works

- Improving calculation efficiency for the inversion algorithm.
- Adding geological constraints to improve accuracy.
- Apply the inversion algorithm for the field measurements.
- Optimize monitor well designs for maximum detectability on fractures in cap rocks and CCS reservoirs.

Conclusion

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- CO_2 injection can cause natural fractures and faults to deform, compromising the integrity of the cap rock in CCS reservoirs, leading to overburden leakage and increasing the risk of induced seismicity.
- Cap rocks are typically composed of shale, which can undergo aseismic deformation that is not easily detectable using seismic methods.
- By deploying fiber-optic-based distributed strain sensing in monitor wells, it is possible to characterize aseismic and seismic deformation before CO_2 leaks into overlying formations, offering earlier warning opportunities compared to other monitoring methods.
- Optimal positioning and design of monitor wells can enhance detection accuracy.