Deep Learning Framework for History Matching CO_2 Storage with 4D Seismic and Monitoring Well Data

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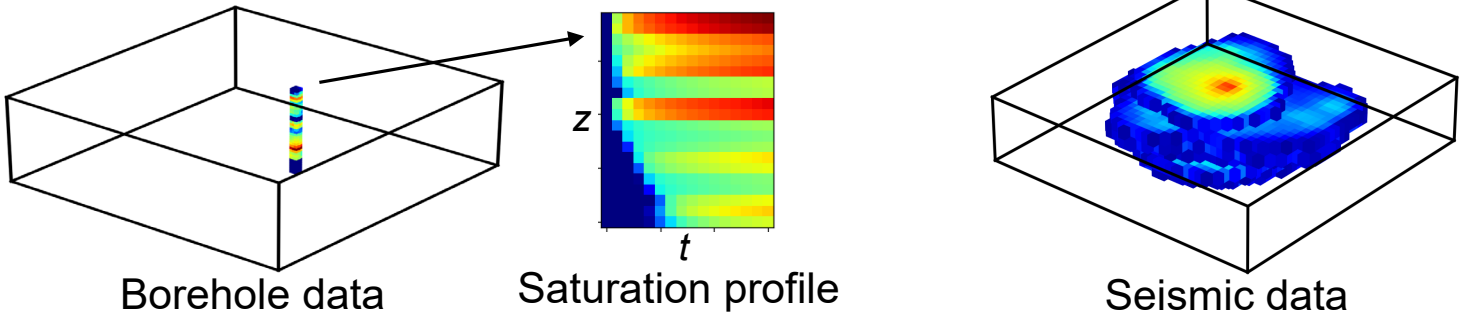
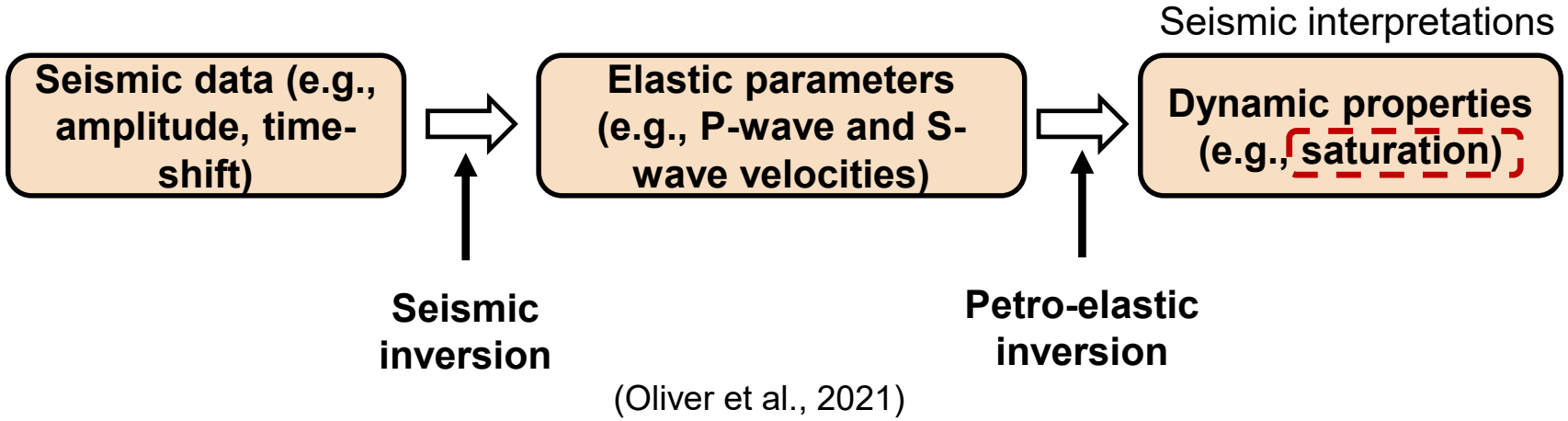
General Motivation

- Monitoring wells in CO_2 storage operations provide data at particular areal locations that are highly resolved in the vertical direction
- 4D seismic data can provide global estimates of saturation at one or more time steps, though these data are of limited spatial resolution
- Deep learning surrogates have been shown to accelerate history matching computations
- Constructing two separate surrogates may be simpler than one all-purpose approach



Time-Lapse (4D) Seismic Data

- In practice, seismic interpretations obtained through geophysical inversion
- Time-lapse seismic data considered here are in the form of estimated CO_2 saturation fields (i.e., seismic interpretations)

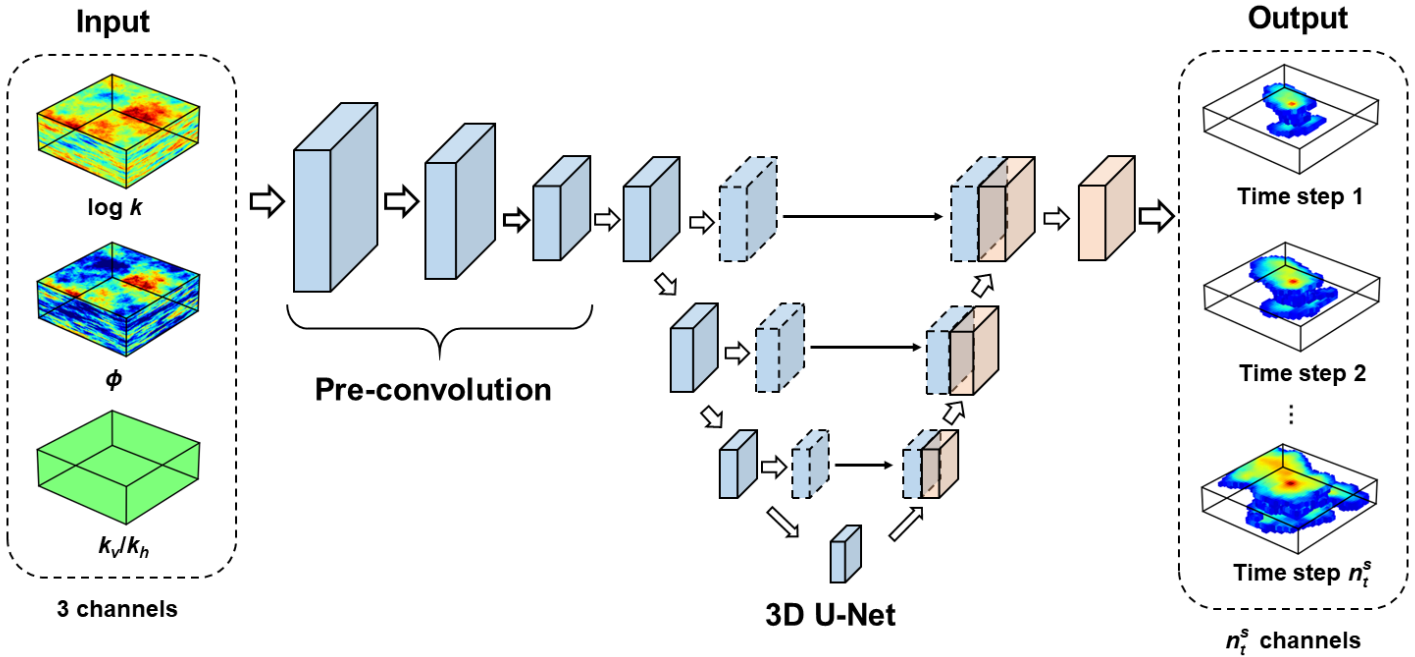


(Oliver et al., 2021)

3D U-Net Surrogate Model for Interpreted Seismic Data

Input: **full high-resolution** geomodel properties

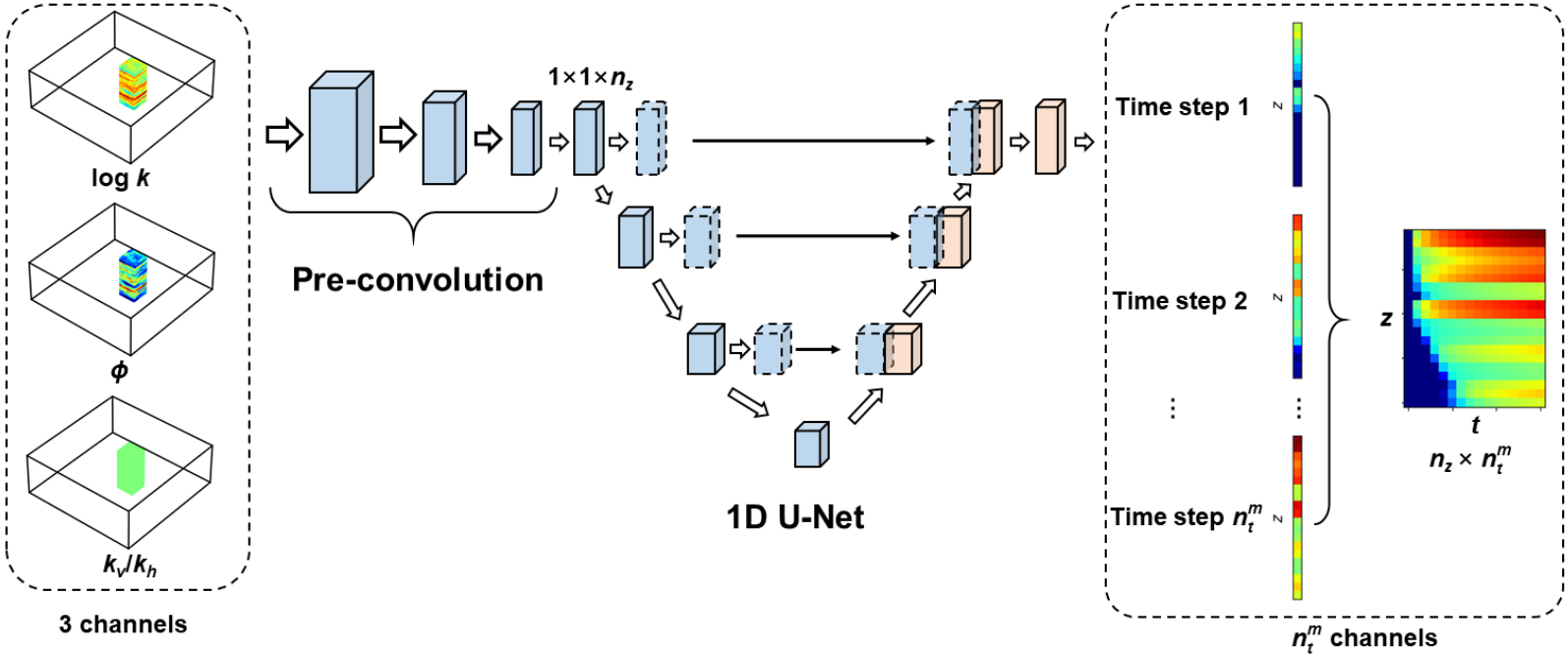
Output: **seismic resolution** saturation field



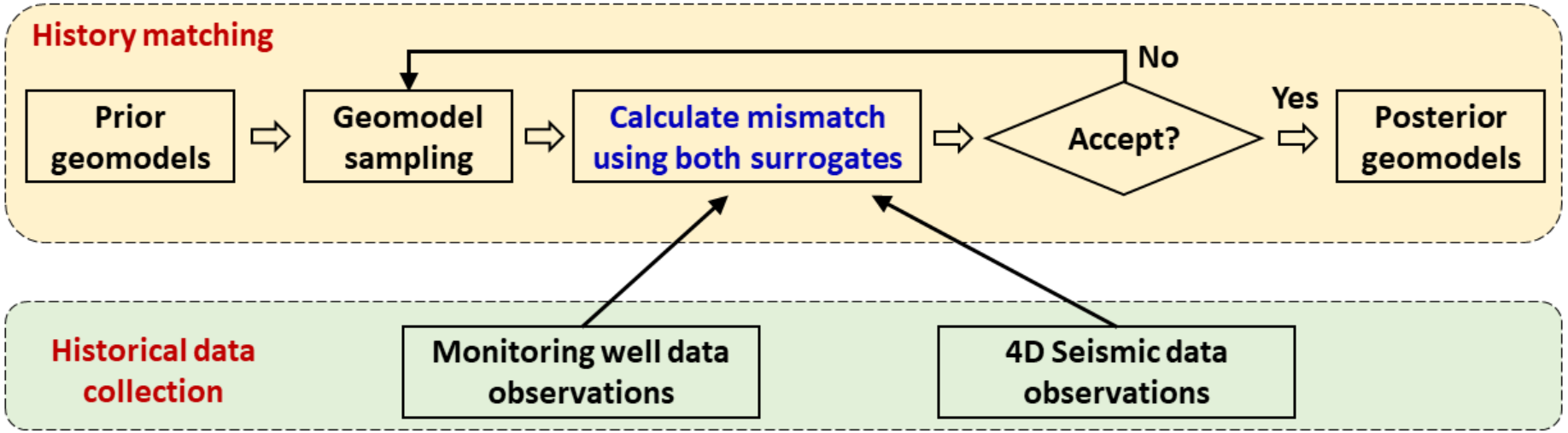
1D U-Net Surrogate Model for Borehole Data

Input: **near-well high-resolution** geomodel properties

Output: vectors of monitoring data at **high vertical resolution**



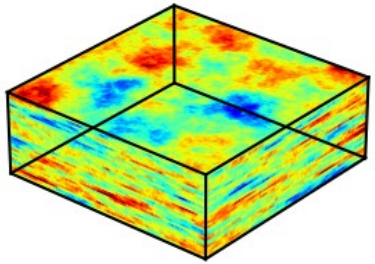
History Matching Framework



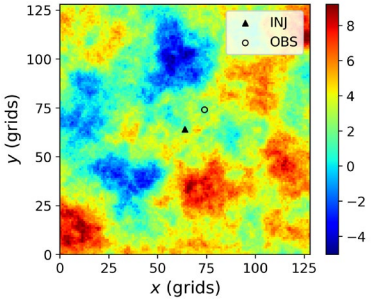
Problem Setup

- Injection rate: 0.5 Mt/year
- Time frame: 1 year
- 1 monitoring well, 100 m from injector

3D geomodel



Top layer with well locations

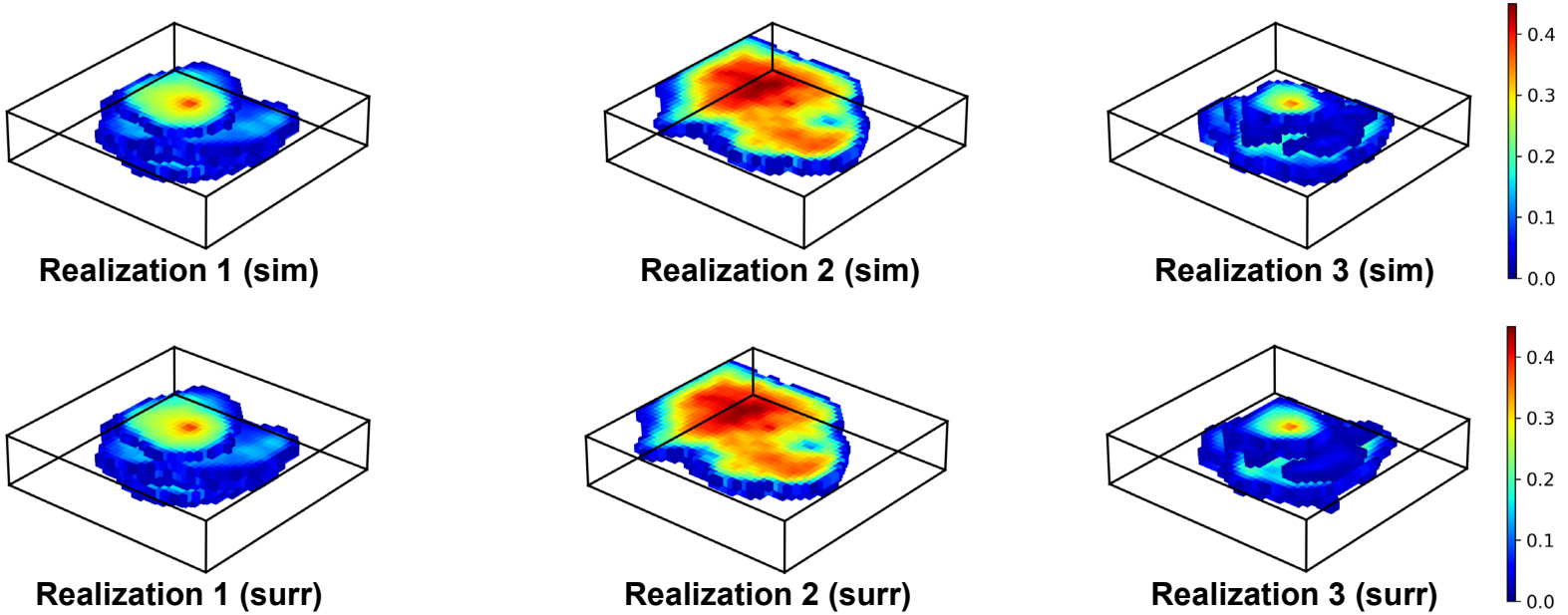


3D geomodel parameters

nx, ny, nz	128, 128, 35
$\Delta x, \Delta y, \Delta z$	**7 m, 7 m, 2 m**
Horizontal correlation length: l_h	40 $(0.31L_x)$
Vertical correlation length: l_v	3.5 $(0.1L_z)$
Mean of log k: $\mu_{\log k}$	U [2 , 6]
Standard deviation of log k: $\sigma_{\log k}$	U [1.0 , 2.5]
Permeability anisotropy ratio: $\log_{10}(k_v/k_h)$	U [-2, 0]
Parameter d (in $\phi = d \cdot \log k + e$)	U [0.02, 0.05]
Parameter e (in $\phi = d \cdot \log k + e$)	U [0.05, 0.12]

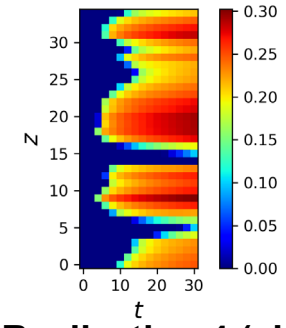
Seismic Surrogate Model Performance

- Datasets: training – 3500 realizations; testing – 500 realizations

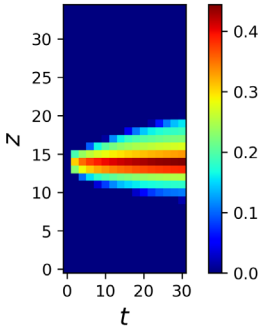


Monitoring Well Surrogate Performance

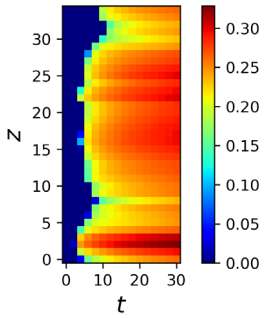
- Datasets: training – 3500 realizations; testing – 500 realizations



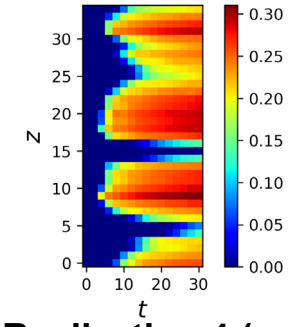
Realization 4 (sim)



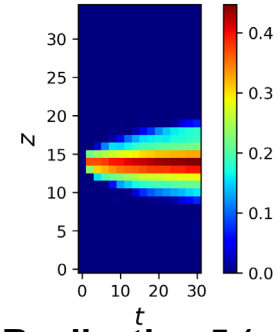
Realization 5 (sim)



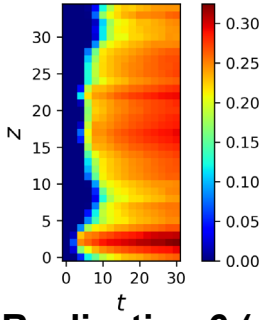
Realization 6 (sim)



Realization 4 (surr)



Realization 5 (surr)



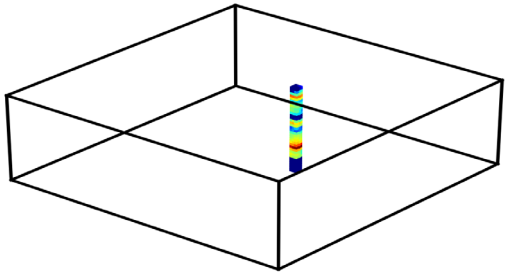
Realization 6 (surr)

History Matching Setup

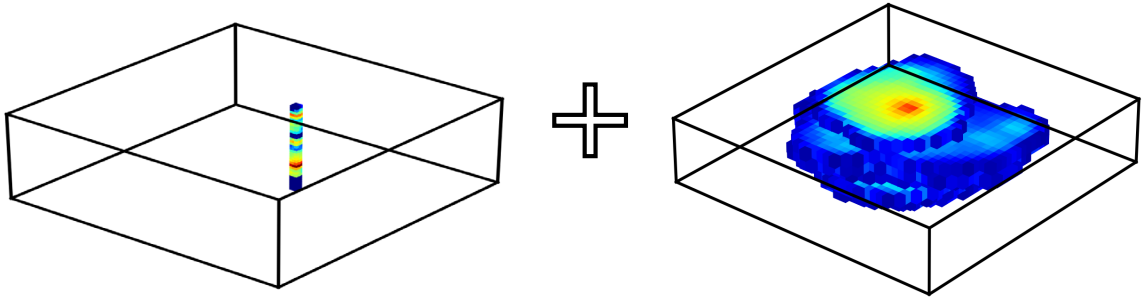
- Synthetic true model: randomly sampled metaparameters and random realization, simulated with GEOS
- Measurements:
  - Monitoring well data: saturation from 12 to 120 days (10 time steps, all 35 layers)
  - Interpreted seismic data: interpreted saturation at 60 days and 120 days
  - Saturation monitoring error std dev: 5% of $S_{mon\text{-}max}$
  - Seismic error std dev: 10% of $S_{seis\text{-}max}$
- Method: Hierarchical Markov Chain Monte Carlo (MCMC) (from Yifu Han)

History Matching Setup

- Scenario 1: Just use borehole data at first 10 time steps



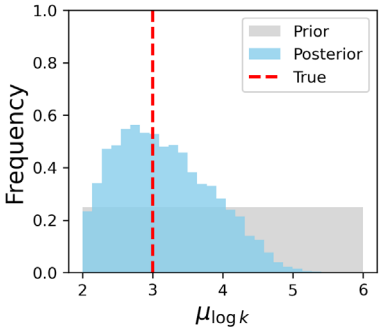
- Scenario 2: Borehole data at 10 time steps + seismic data at 2 time steps

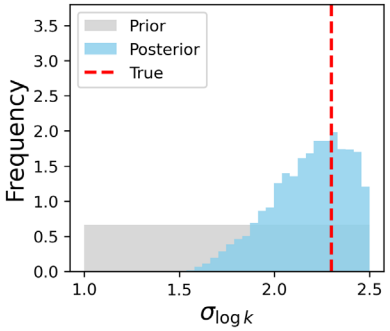


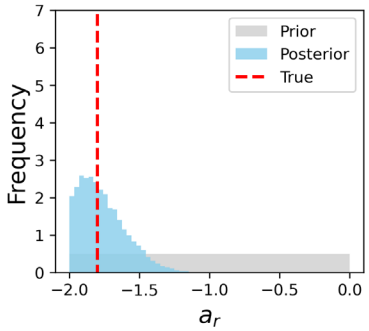
History Matching Results

Mean log perm | **Std dev log perm** | **$\log_{10}(k_v/k_h)$**

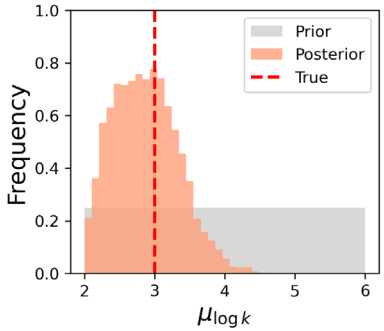
Without seismic

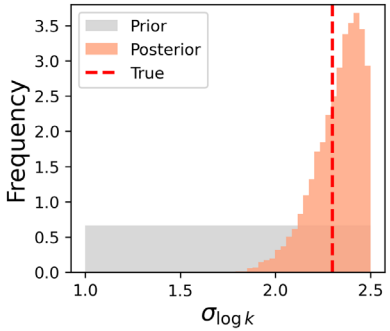


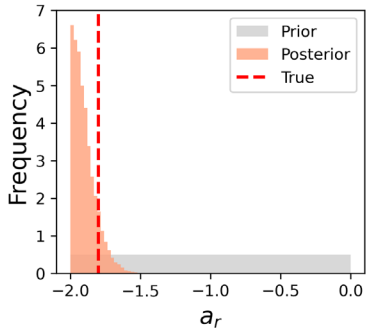




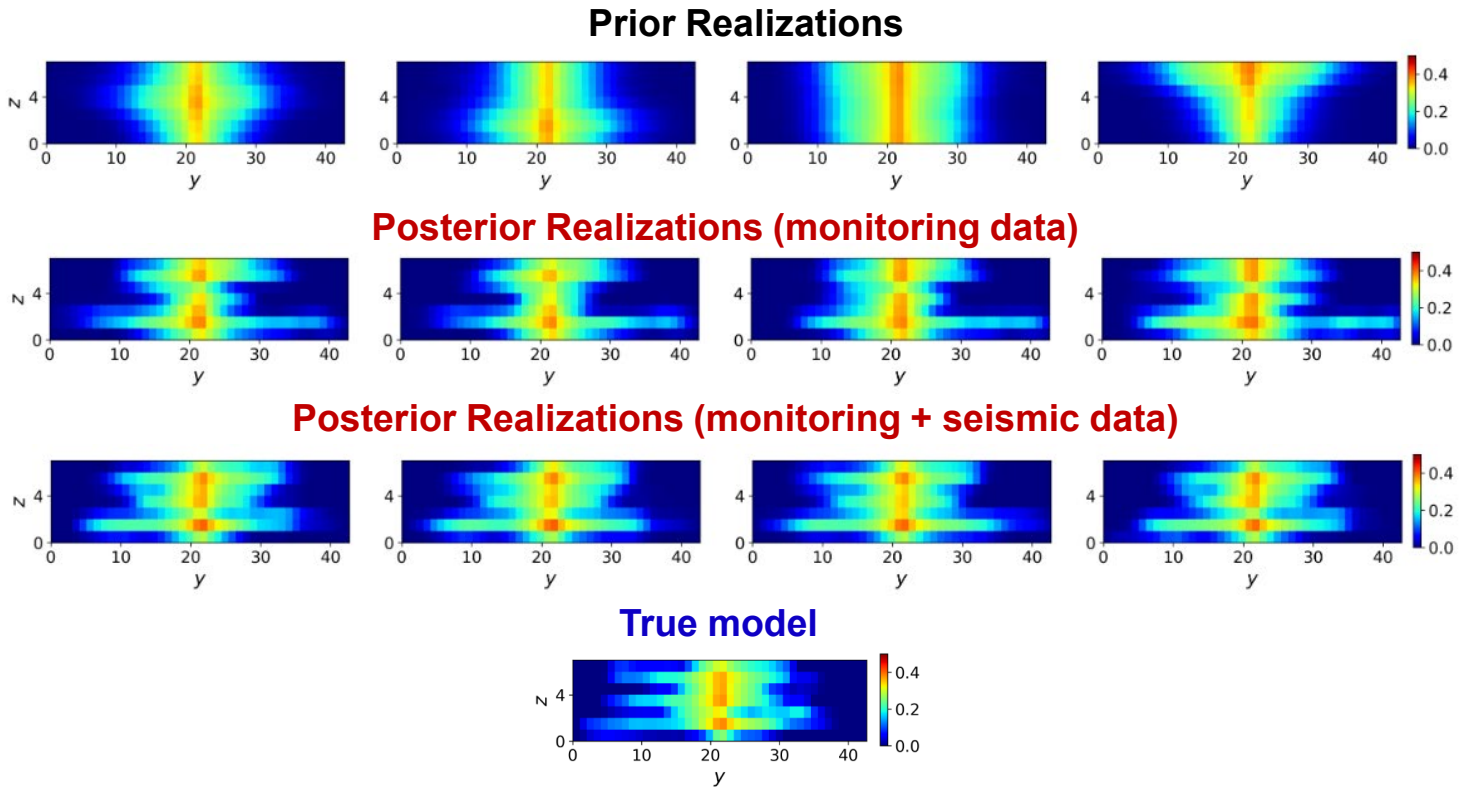
With seismic





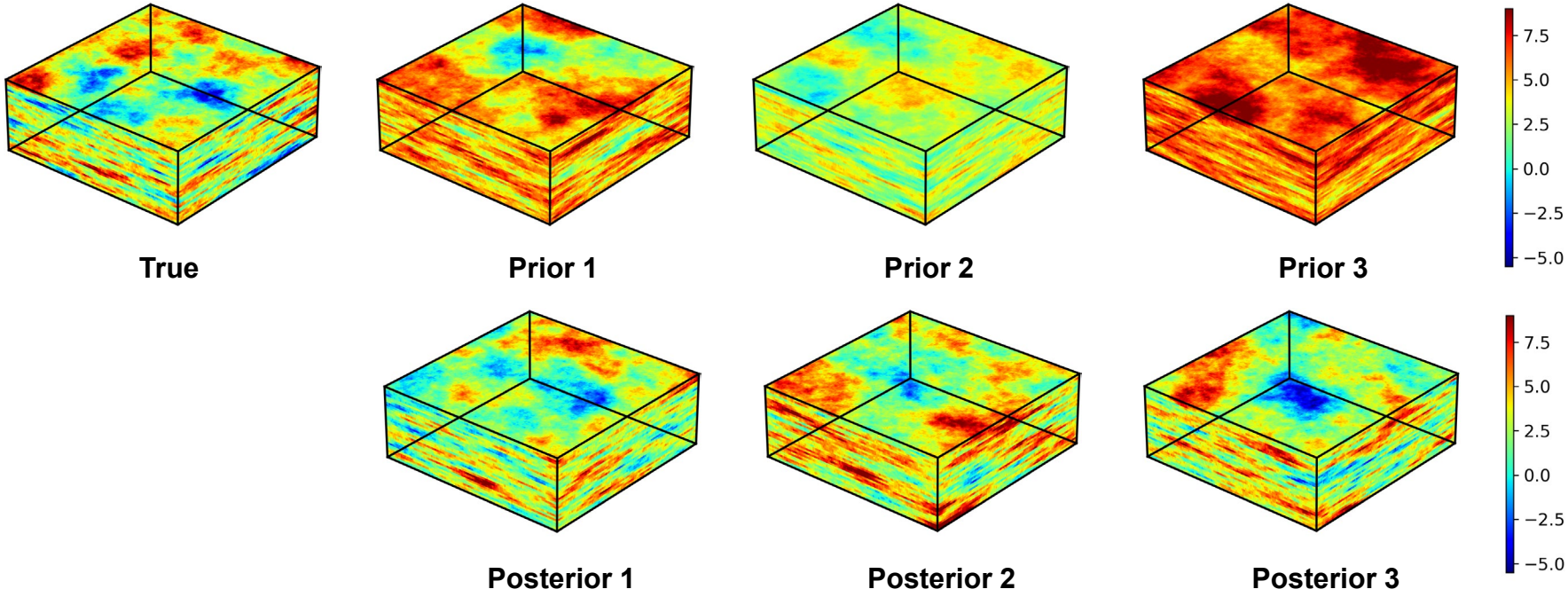


Representative Realizations with Seismic (y-z cross-sections)



Posterior Geomodel Realizations

- **High-resolution** geomodel realizations are obtained during history matching



Summary and Future Work

- Constructed a 3D U-Net surrogate model to predict seismic scale saturation
- Constructed a 1D U-Net surrogate model to predict high-resolution saturation monitoring well data
- Applied an MCMC-based history matching procedure using both surrogate models and both data types
- Better estimates of geological metaparameters and larger uncertainty reduction achieved using both seismic and monitoring well data
- Currently, applying history matching workflow to GeoCquest Field Validation (GFV) project, and considering data-weighting strategies

Acknowledgements

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