An integrated 4D seismic inversion workflow applied to the Catcher fields

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Harbour Energy [2]

Contents

An Integrated Workflow for the Probabilistic Estimation of Pressure and Saturation Changes from 4D Seismic Data: Application to the Catcher Fields, Central North Sea

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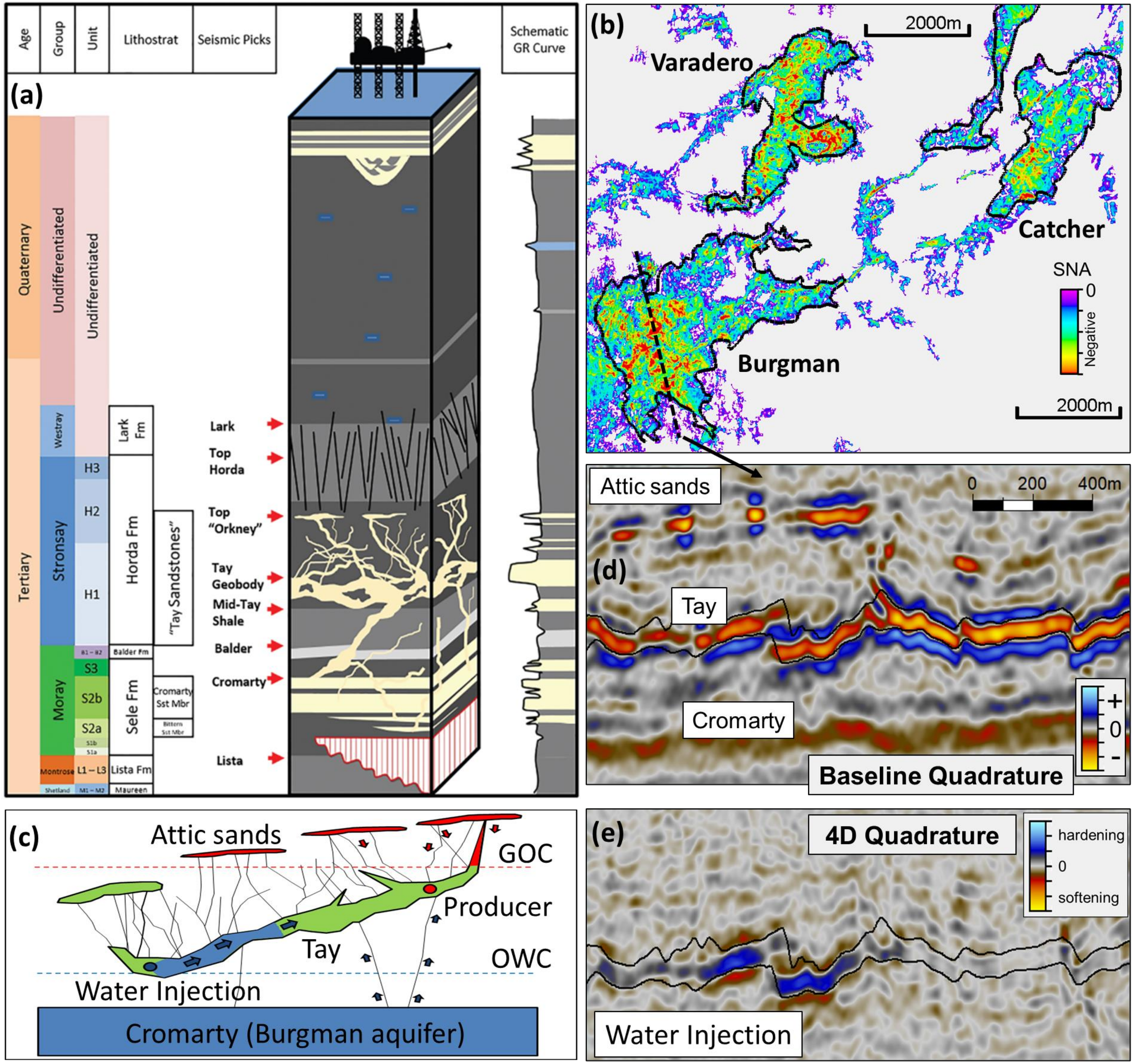
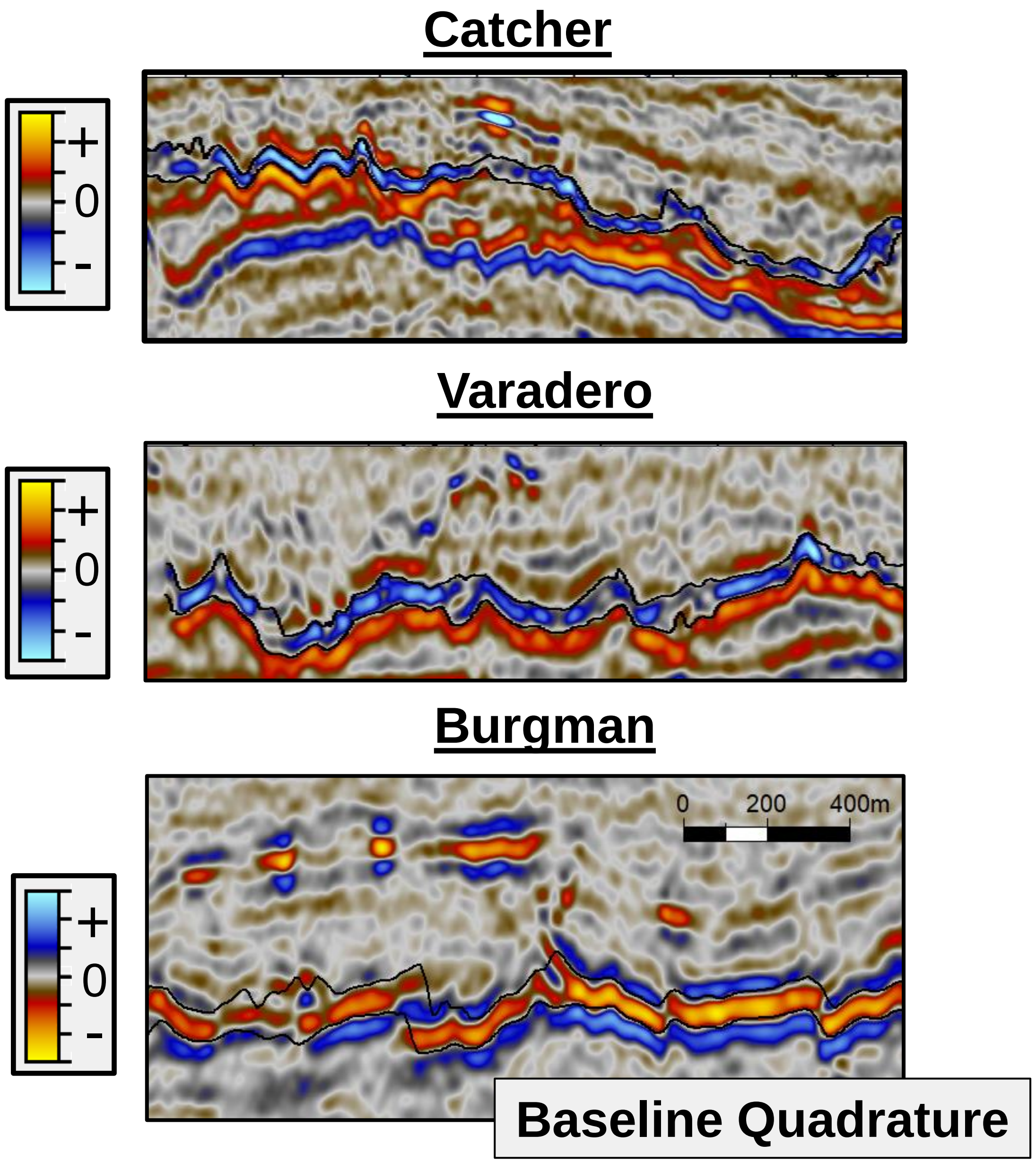
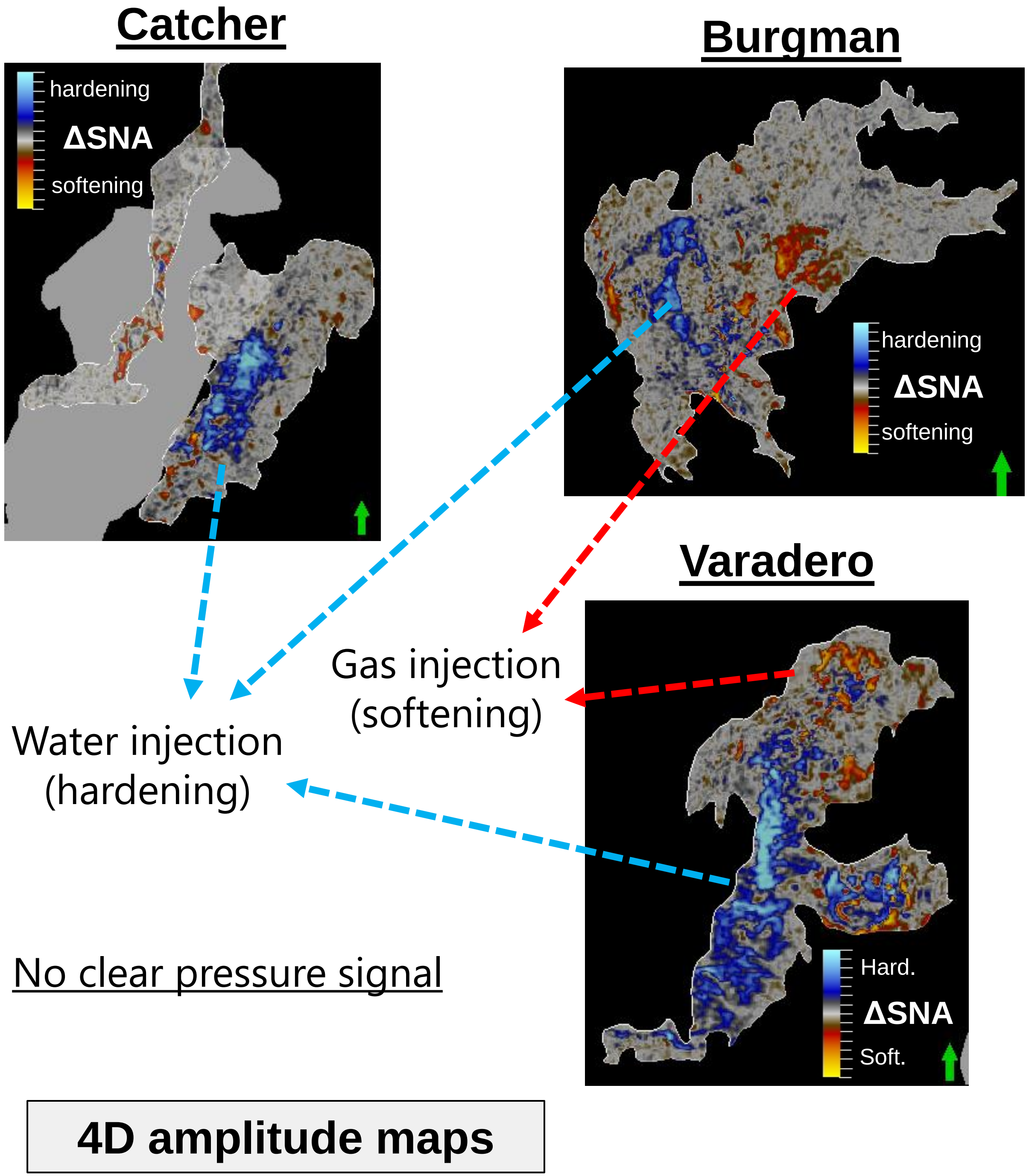
The Catcher area fields

- Clean sandstone injectites
- 35% porosity
- 3 Fields under development
  - Catcher, Varadero & Burgman
- Oil bearing Tay reservoir
  Cromarty aquifer
  Gas bearing attic sands
- Water injection (dedicated injection wells)
- Gas injection (intermittently through producer wells)
- Dedicated 4D seismic
  - ~3.5 years of production
  - High repeatability (NRMS ~11%)



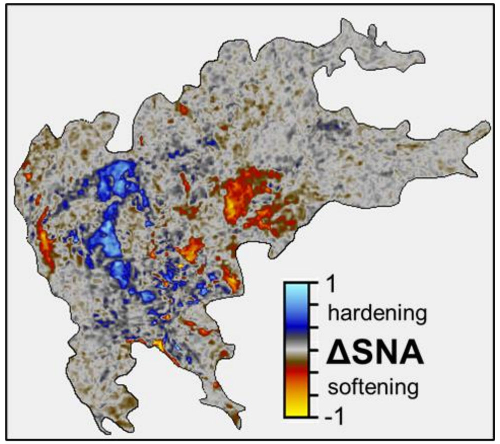
The Catcher area fields



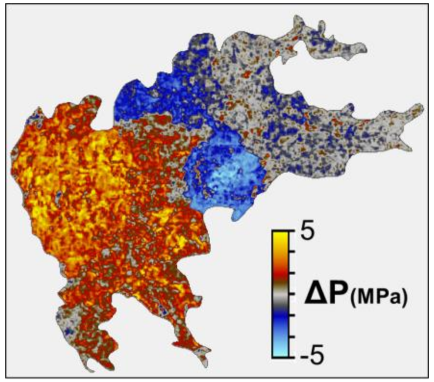


Objective

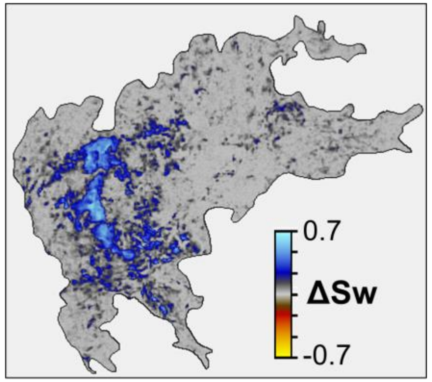
4D seismic amplitudes



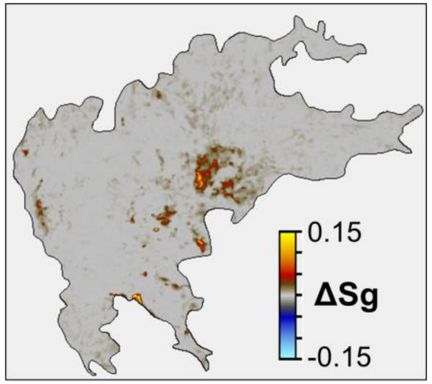
Reservoir property changes



- Pressure



- Water saturation



- Gas saturation

Petro-elastic model calibration

Hamed Amini and Colin MacBeth (2015)
“Calibration of rock stress-sensitivity using 4D seismic data.”
77th EAGE conference & exhibition, Madrid, Spain.

Hamed Amini (2018a)
“Calibration of minerals’ and dry rock elastic moduli in sand-shale mixtures.”
80th EAGE conference & exhibition, Copenhagen, Denmark.

Petro-elastic model (PEM)

Dynamic model calibrated with:

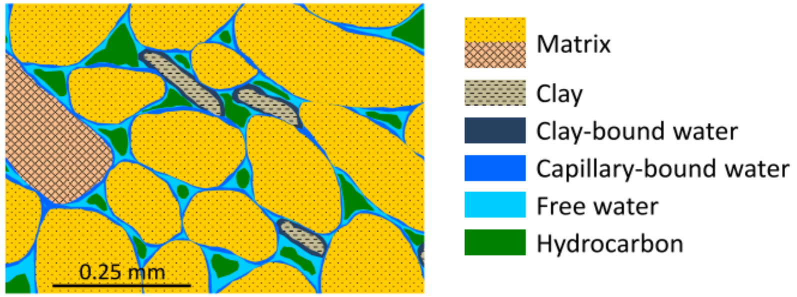
- Lab data (core plugs)
- 4D Time-shift data

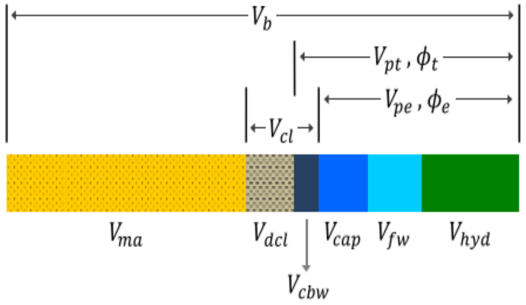
Static model calibrated with:

- well log data

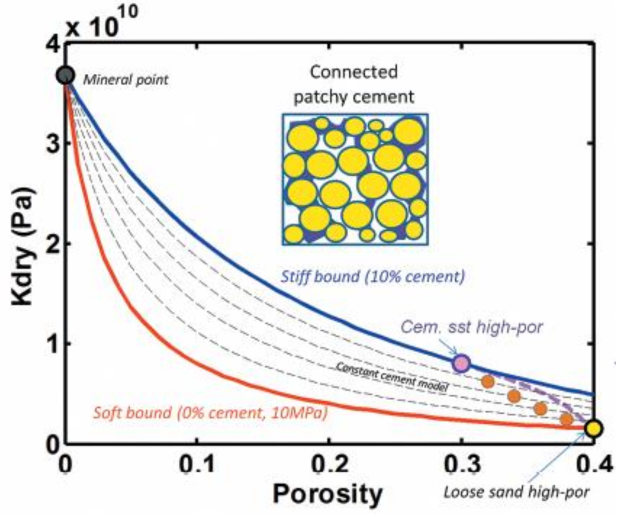
1) Mineral and Fluid elastic properties

2) Mixing laws



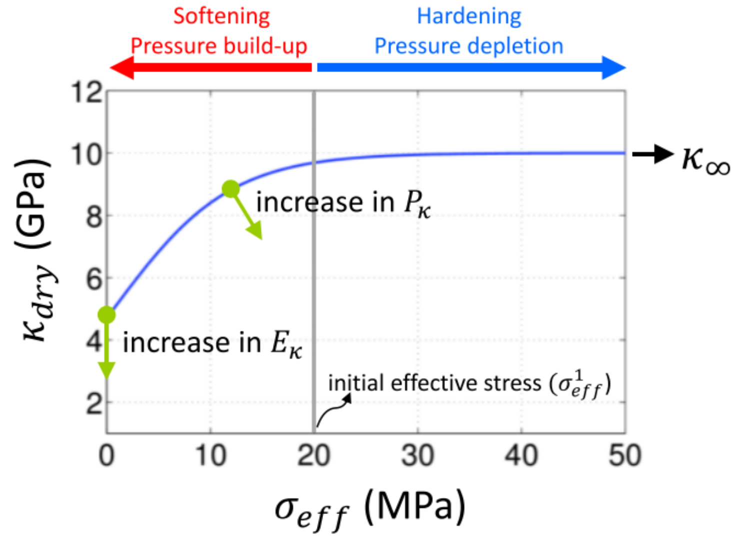


3) Porosity dependence (Dry frame moduli)



- Nur´s Critical Porosity
- Krief
- Cemented sand
- Soft sand
- Xu-White

4) Pressure sensitivity

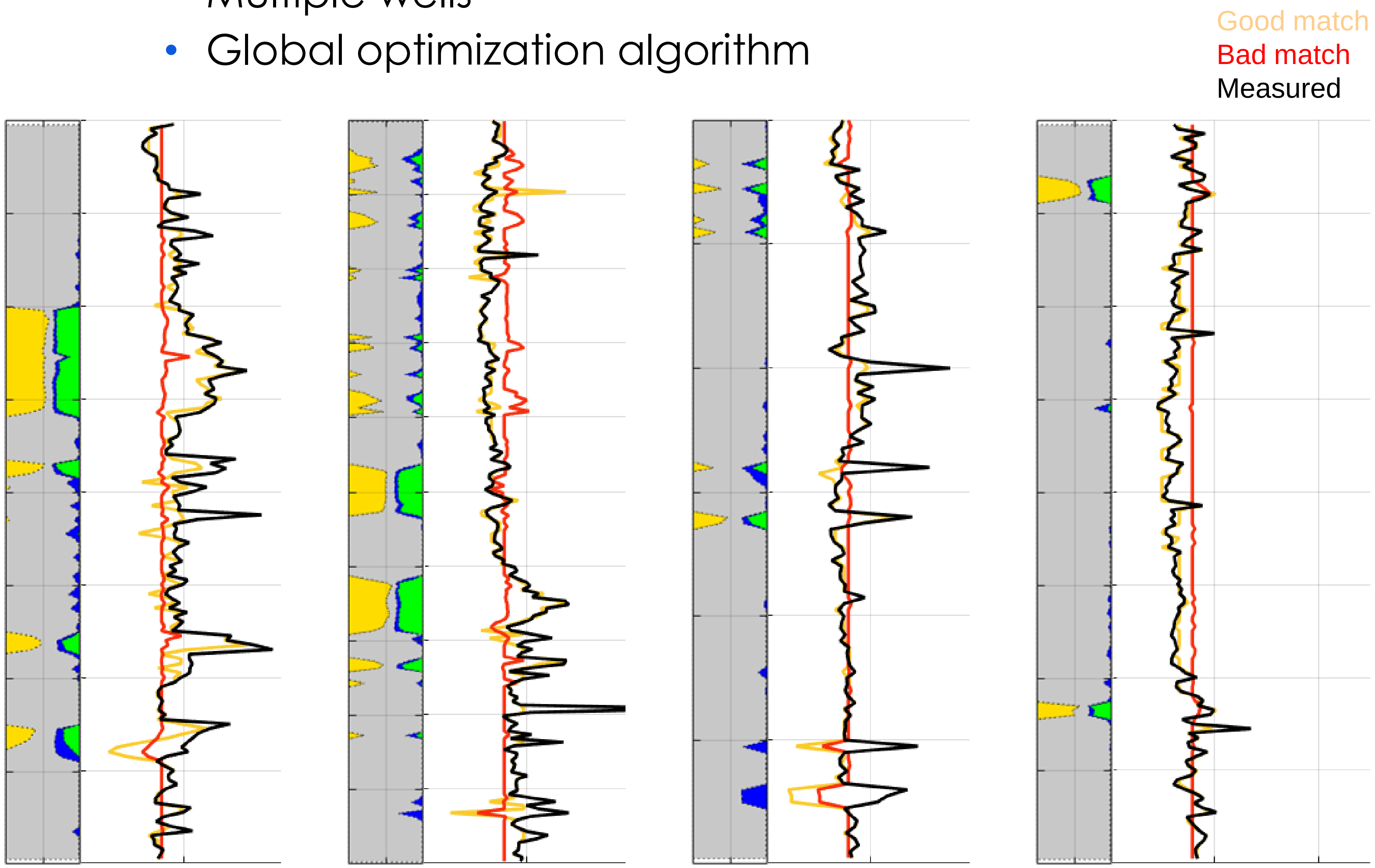


- MacBeth (2004) equations

Static model calibration

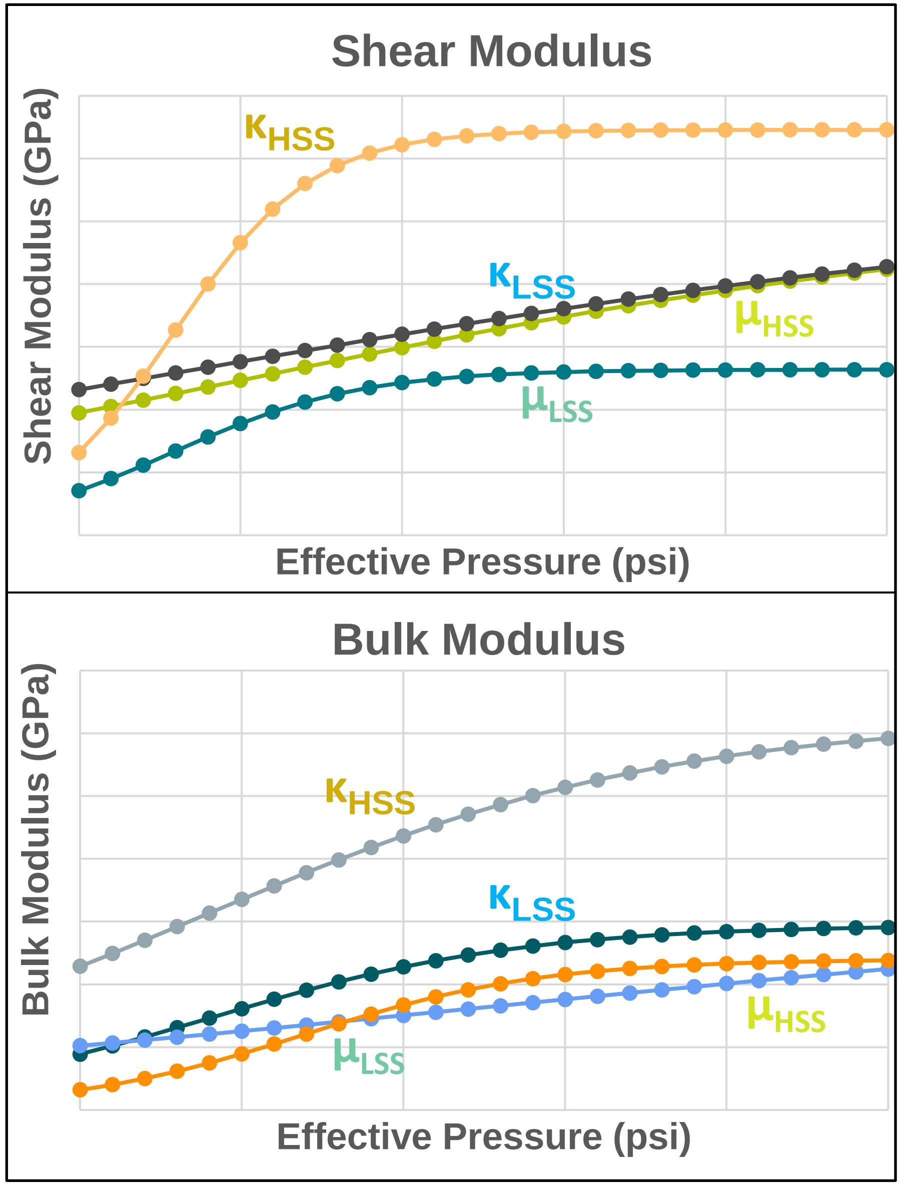
Well log data:

- Density, Vp and Vs
- Multiple wells
- Global optimization algorithm

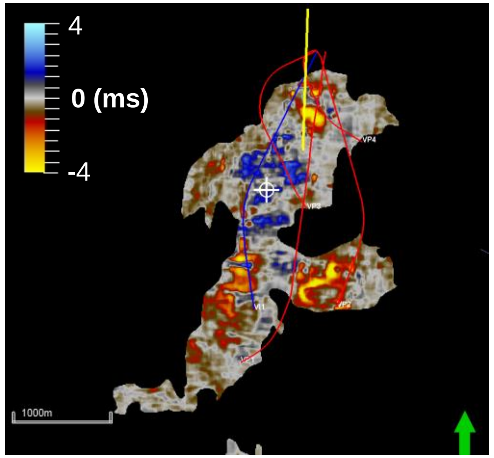


Dynamic model calibration

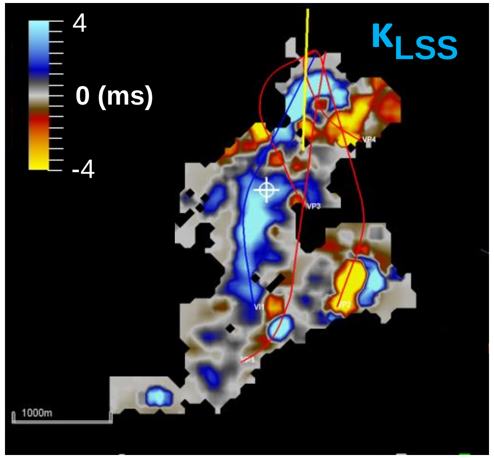
Core plug laboratory data

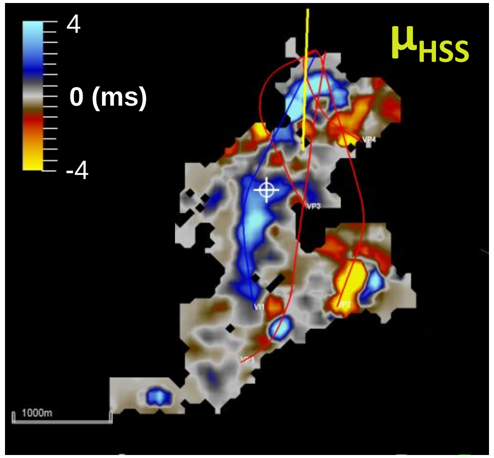


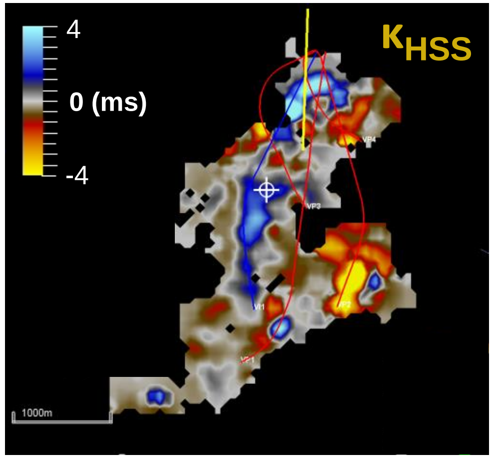
Time-Lapse Time-Shifts



Observed







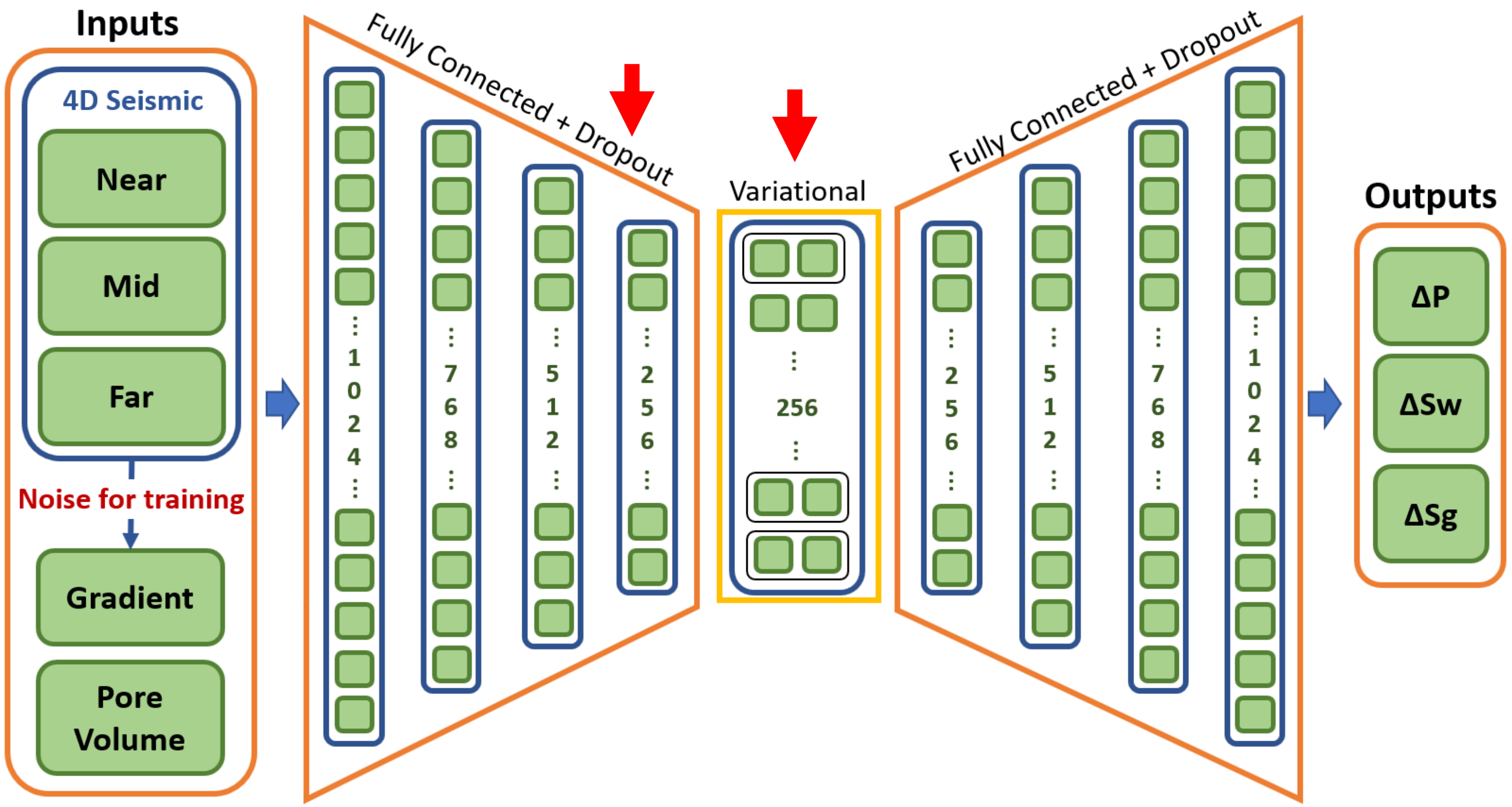
Modelled

Deep Neural Network (DNN) inversion

Gustavo Côrte, Jesper Dramsch, Hamed Amini, and Colin MacBeth (2020),
“Deep neural network application for 4D seismic inversion to changes in pressure and saturation: Optimizing the use of synthetic training datasets”.
Geophysical Prospecting, 68: 2164-2185.

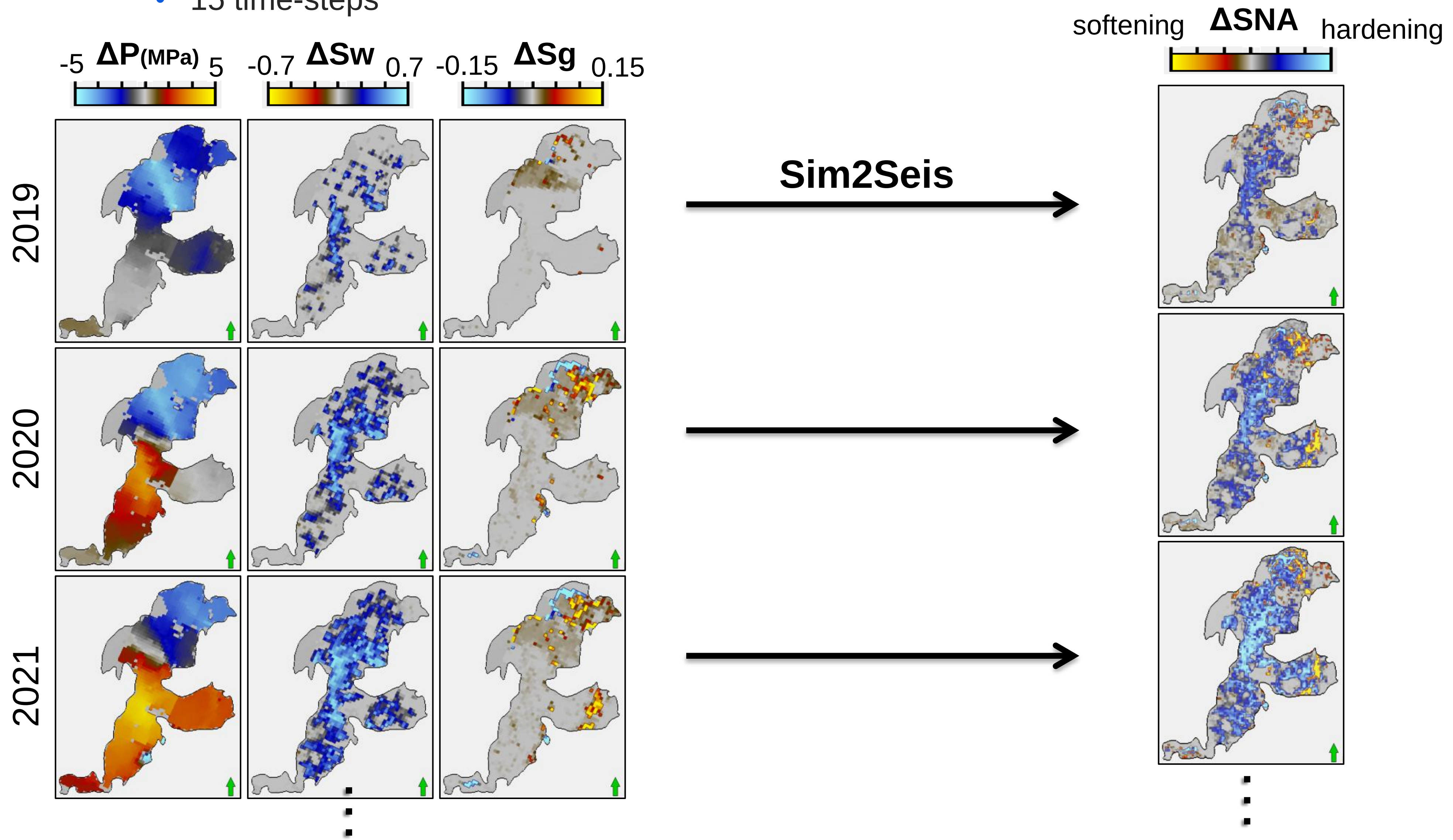
DNN Architecture

- Variational Auto-Encoder
- Pixel by Pixel inversion
  - No lateral correlation constraints
- Regularization
  - Variational central layer
  - Dropout regularization
  - Train with noisy synthetic data



Synthetic training dataset

- Reservoir simulation results
  - 15 time-steps
- Synthetic 4D seismic maps



Synthetic training dataset

- Reservoir simulation results
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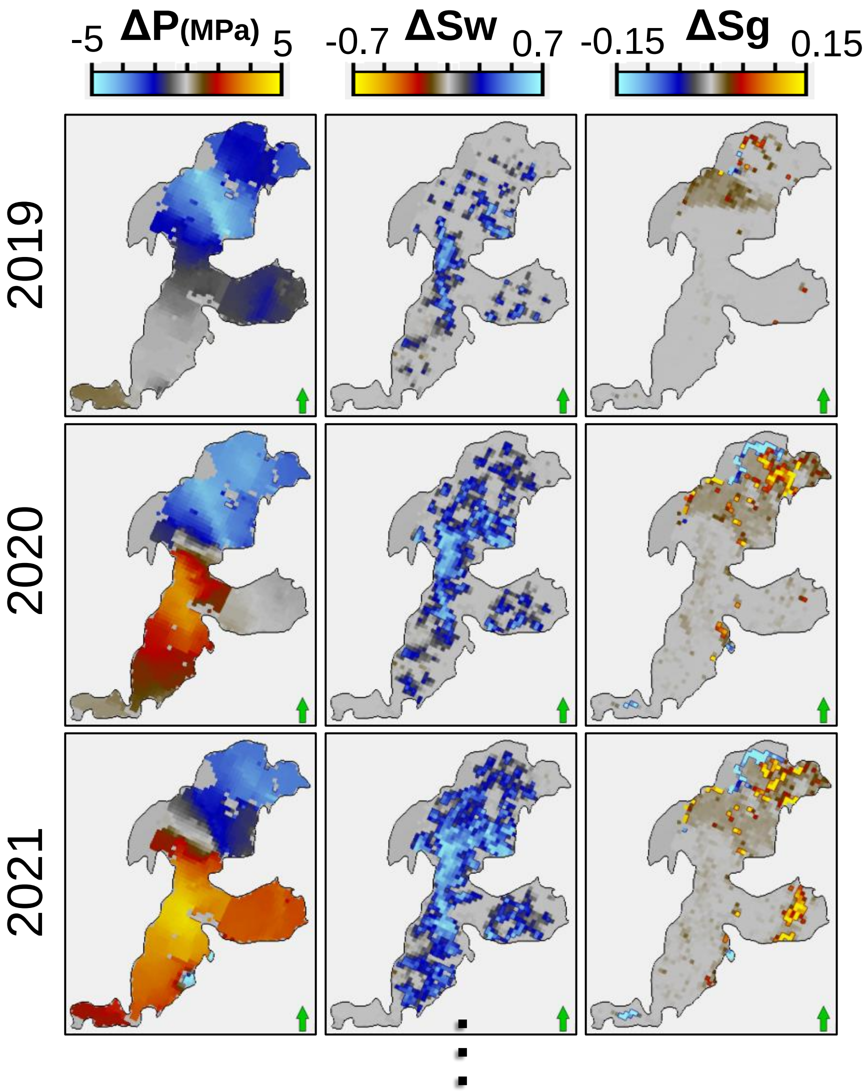
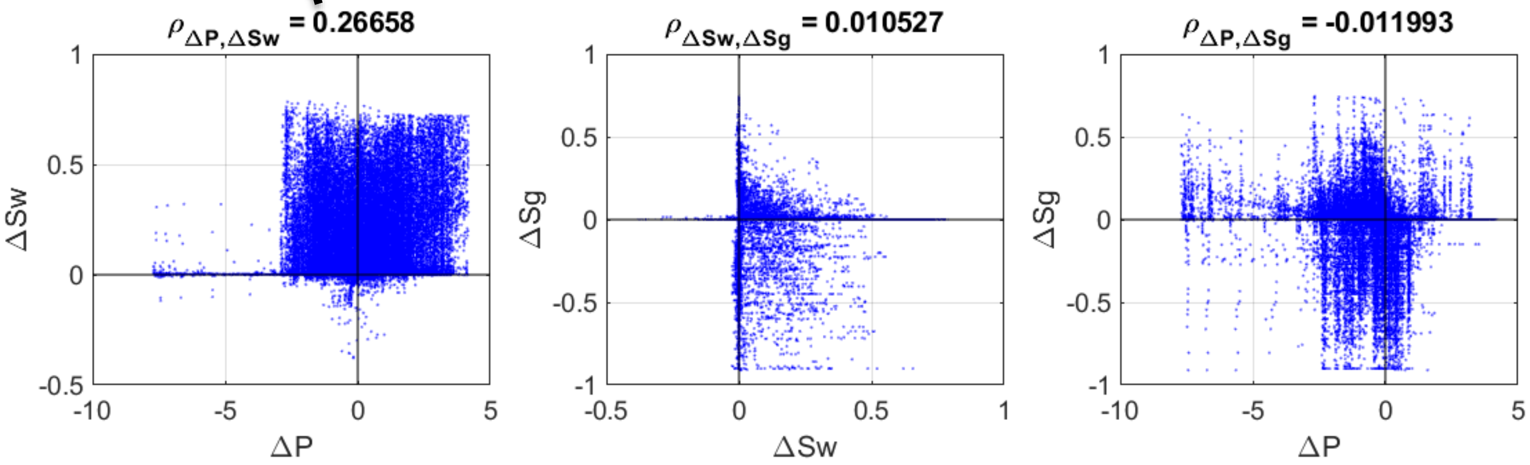


- Pressure increase always related to water injection
- Statistical correlation between:

  Pressure increase ⟷ Water saturation increase



DNN Inversion results

<u>Training data property correlation</u>

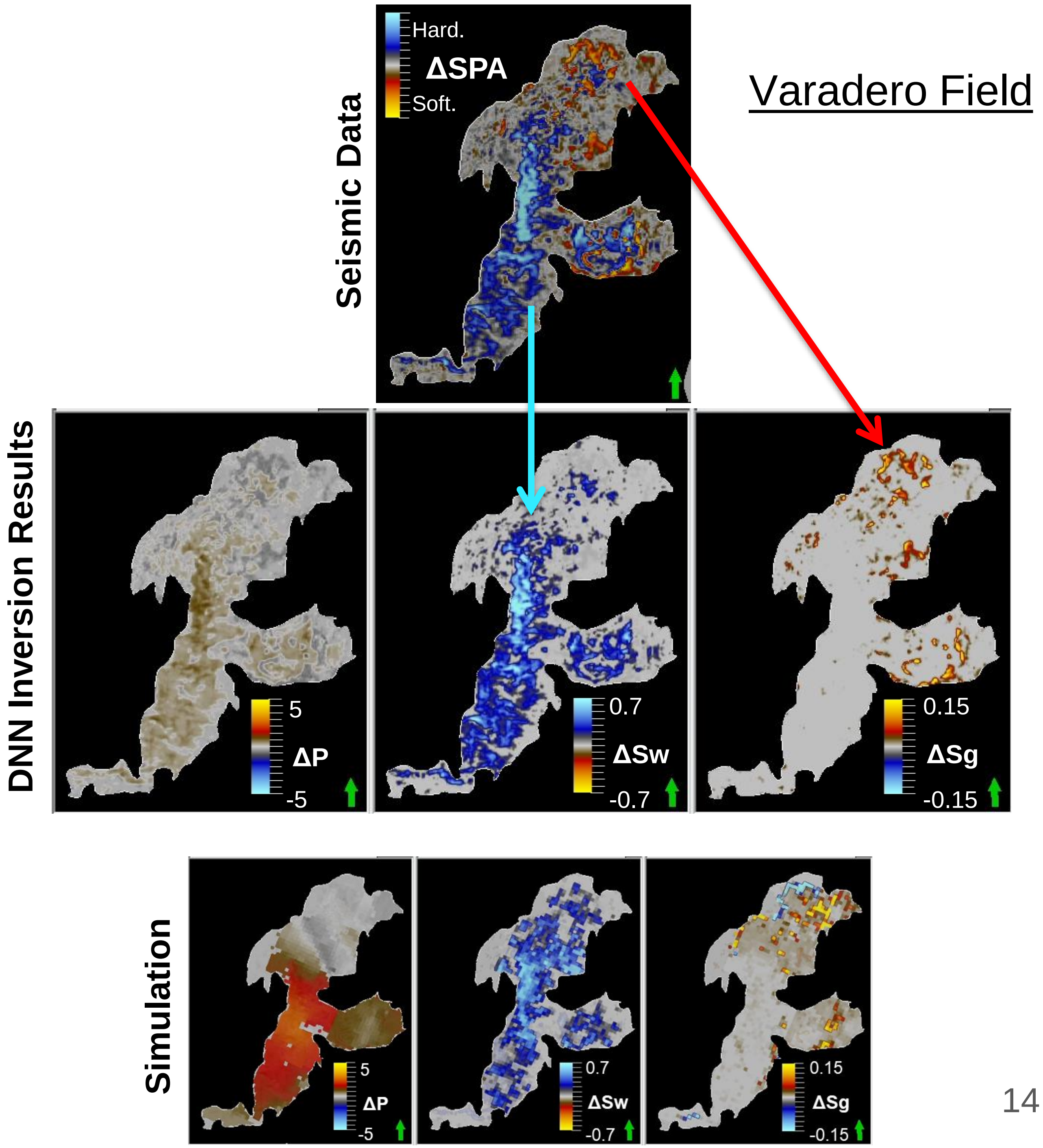
Water injection

↓

Pressure increase

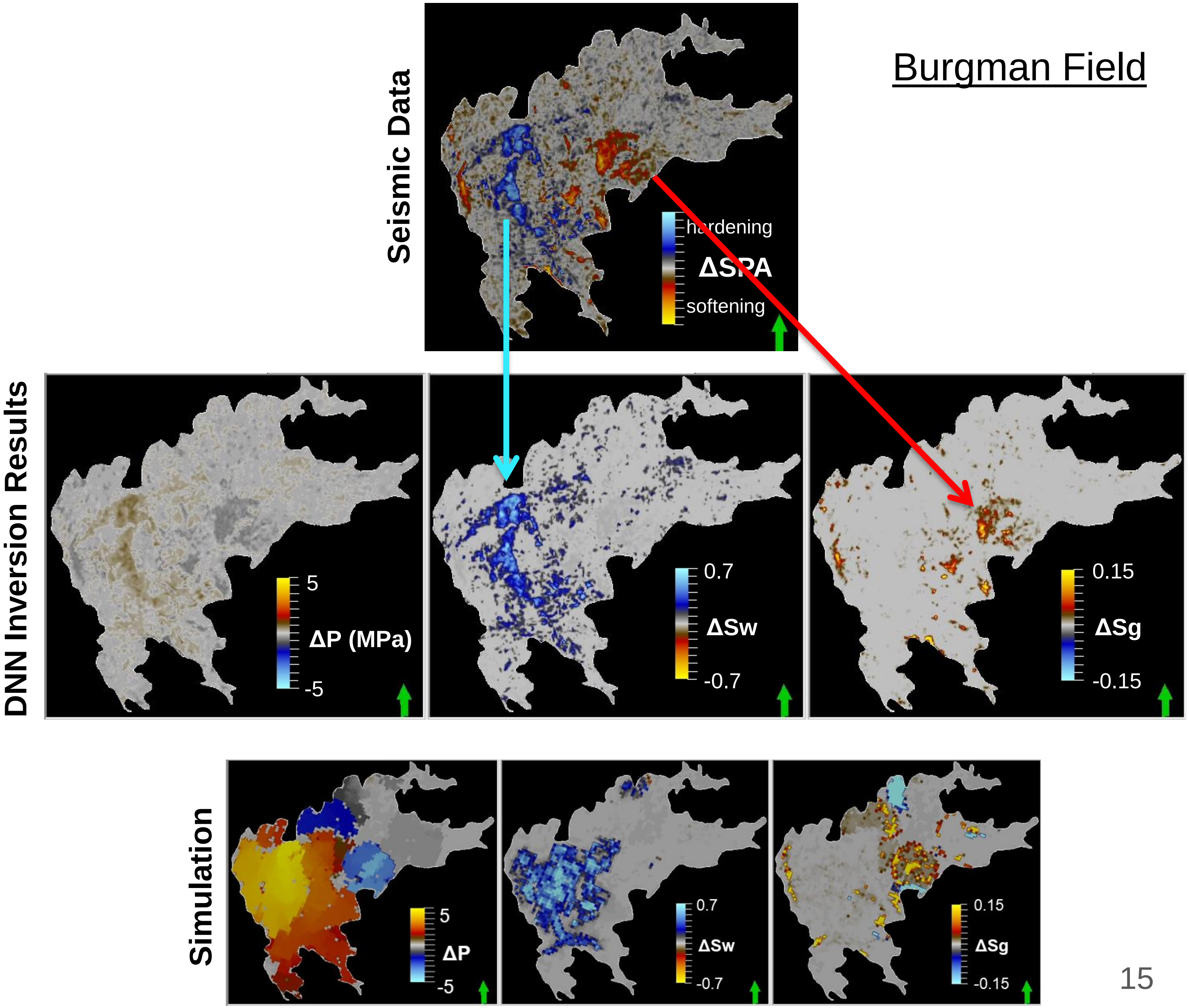
<u>Pressure Results</u>

Pressure increase in hardening signal regions



DNN Inversion results

Burgman Field



Training data property correlation

Water injection

↓

Pressure increase

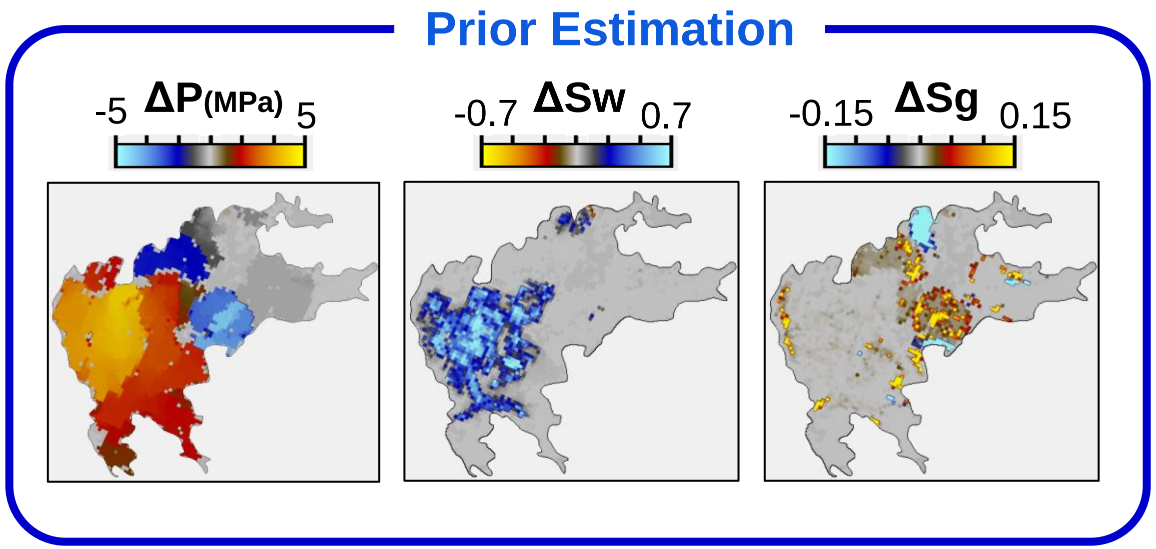
Pressure Results

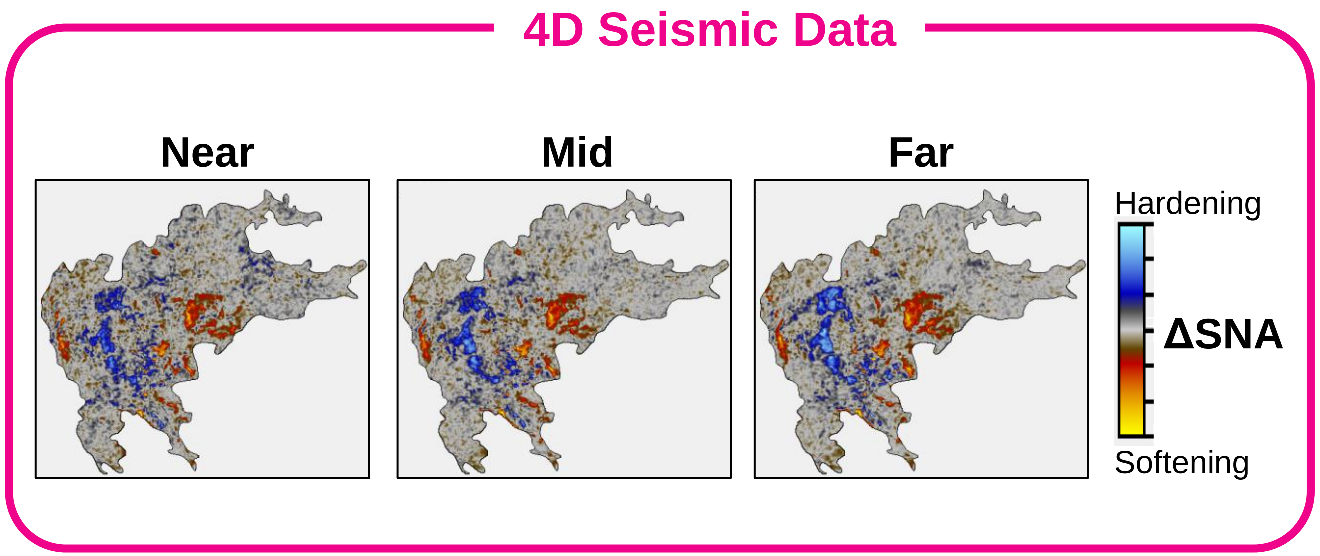
Pressure increase in hardening signal regions

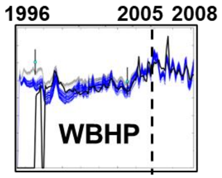
Bayesian Stochastic Inversion

Gustavo Côrte, Hamed Amini, and Colin MacBeth (2023),
“Bayesian inversion of 4D seismic data to pressure and saturation changes: Application to a west of Shetlands field”.
Geophysical Prospecting, 71, 292– 321.

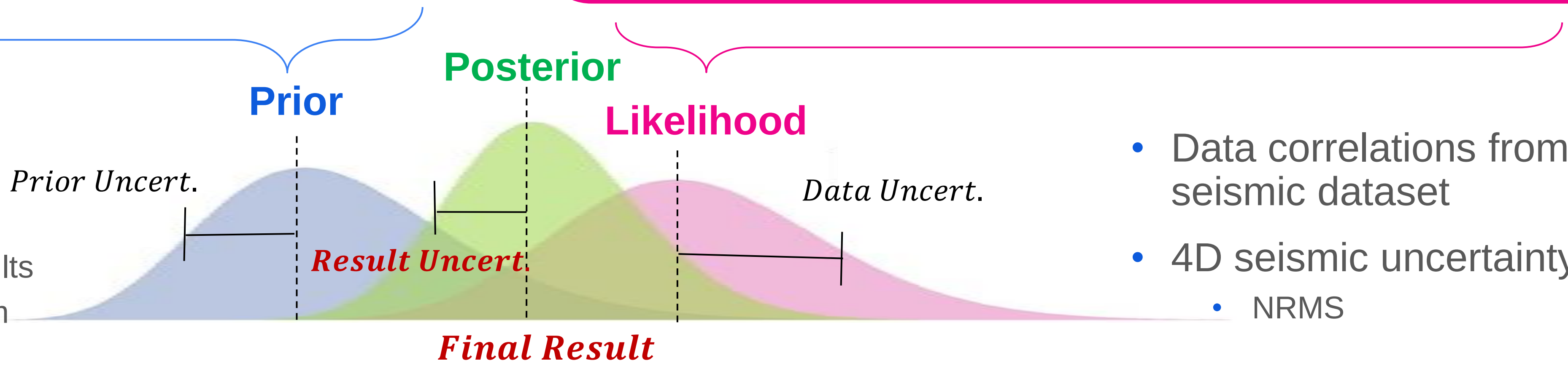
Bayesian Stochastic Inversion







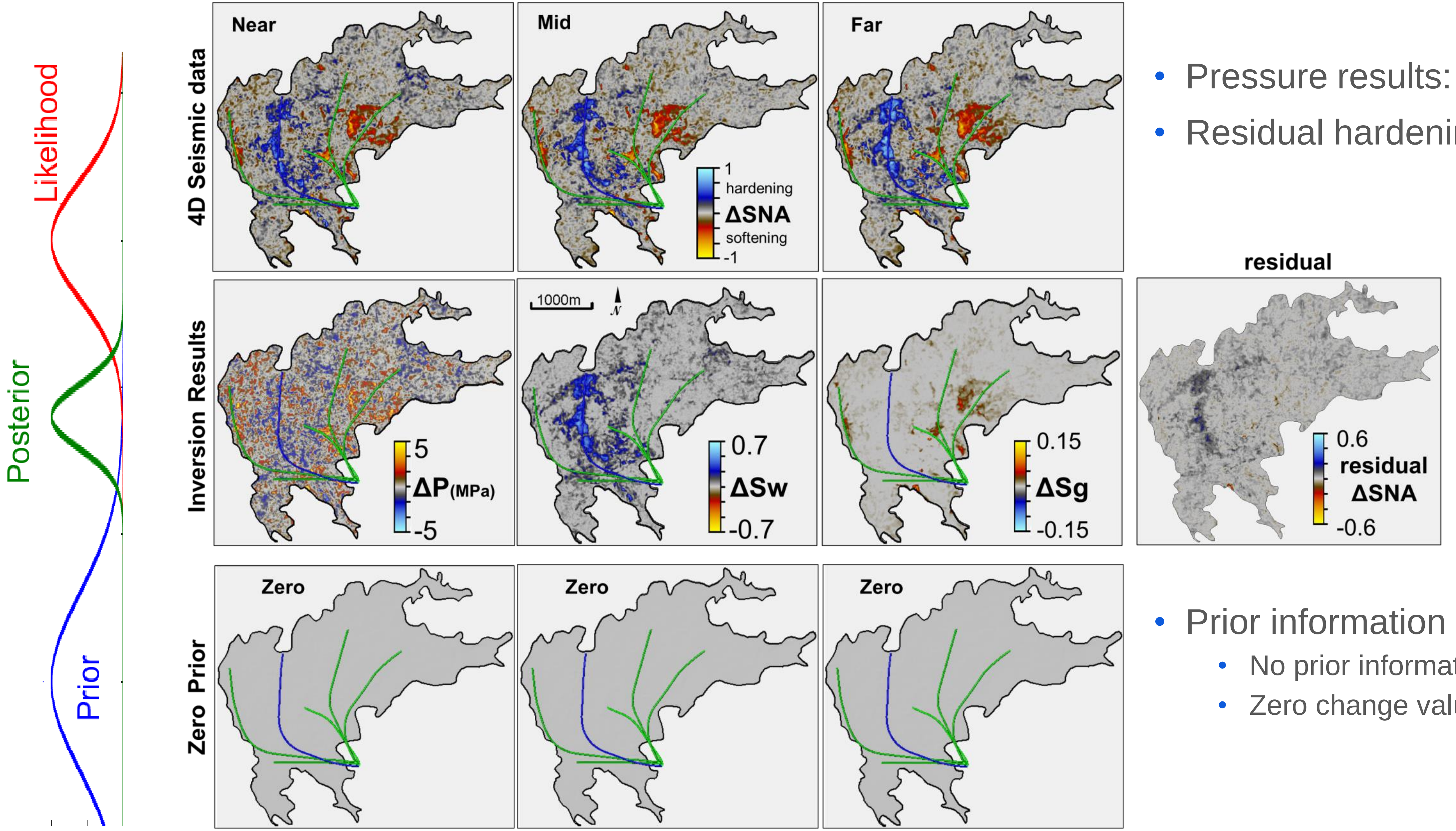
- Prior information
  - Reservoir simulation results
  - Property correlations from training dataset
  - Well pressures (BHP)



- Data correlations from seismic dataset
- 4D seismic uncertainty
  - NRMS

- Stochastic Markov-Chain Monte Carlo

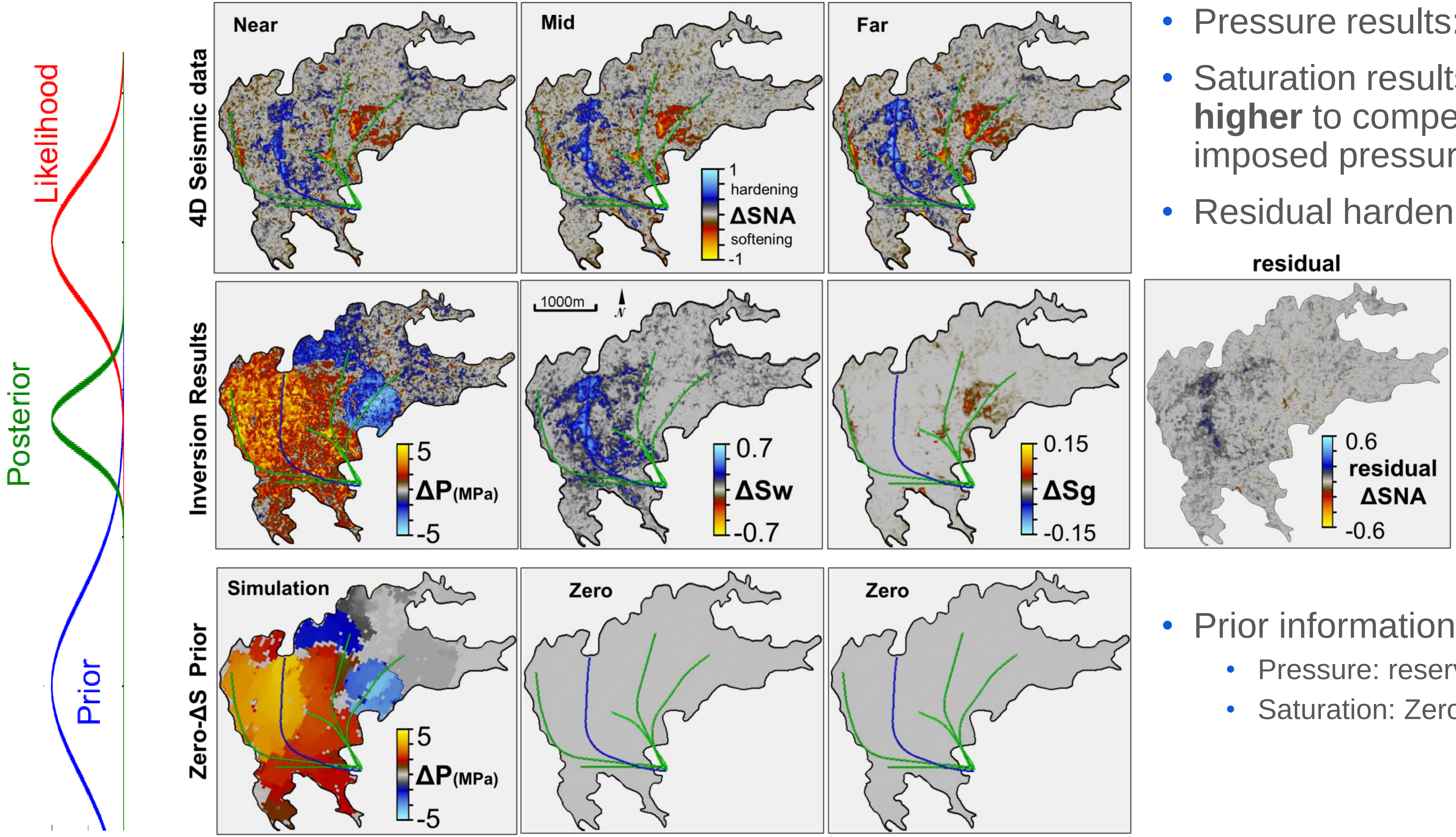
Bayesian Stochastic Inversion



- Pressure results: noise
- Residual hardening

- Prior information
  - No prior information
  - Zero change values everywhere

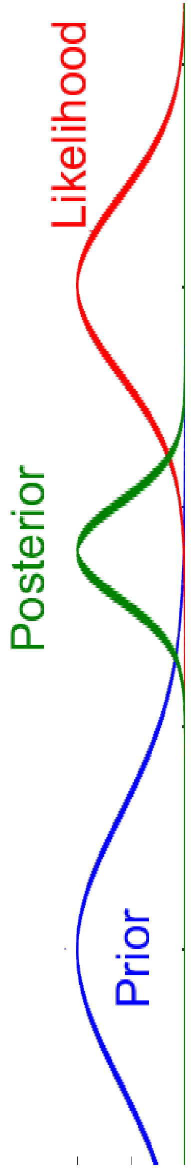
Bayesian Stochastic Inversion

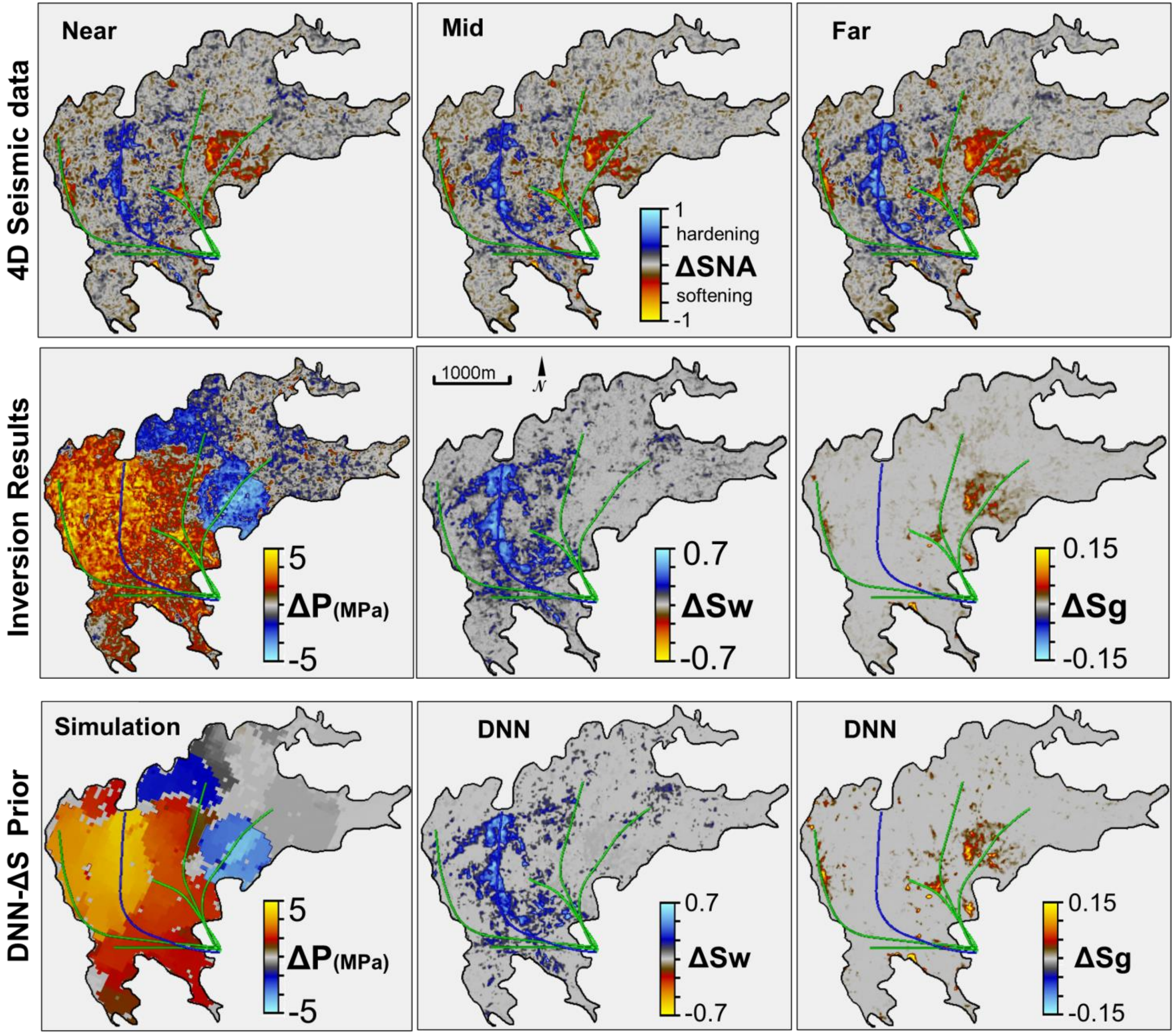


- Pressure results: simulation
- Saturation results: **slightly higher** to compensate for the imposed pressure signal
- Residual hardening

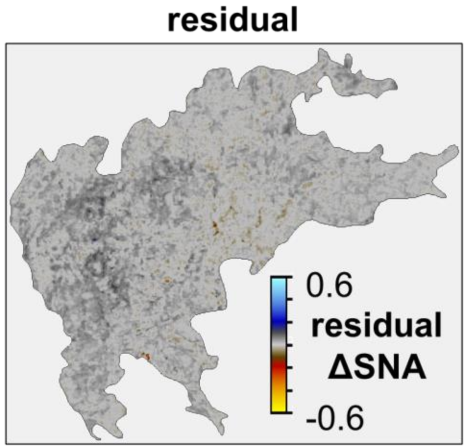
- Prior information
  - Pressure: reservoir simulation
  - Saturation: Zero change values

Bayesian Stochastic Inversion



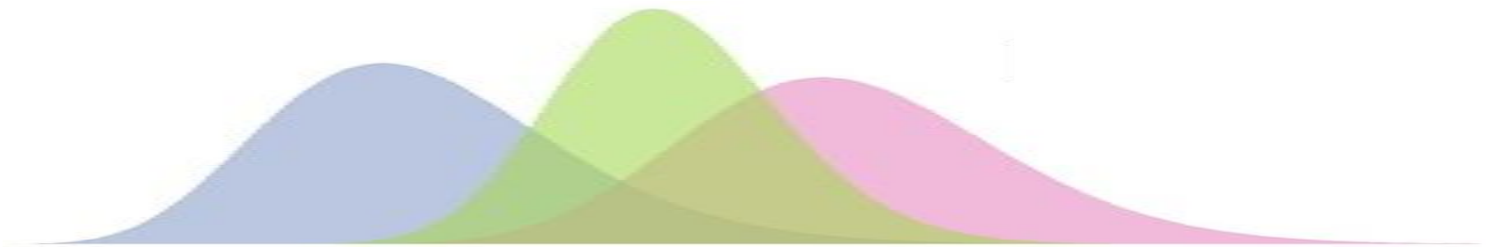


- Pressure results: simulation
- Saturation results: **slightly higher** than previous and also the DNN prior values
- Residual hardening **gone**

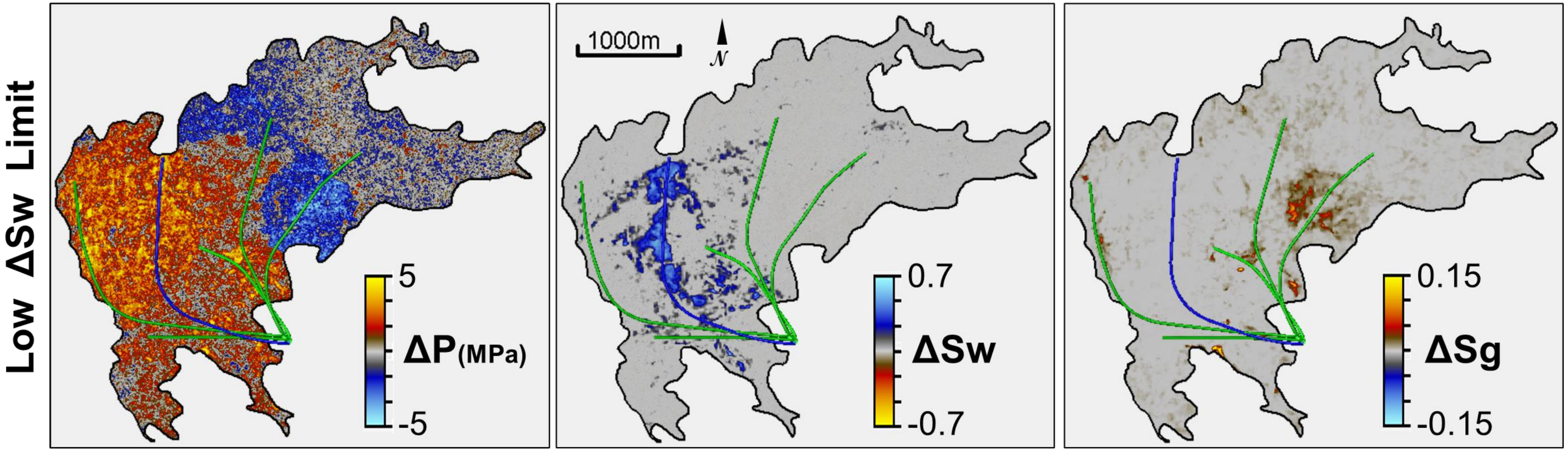


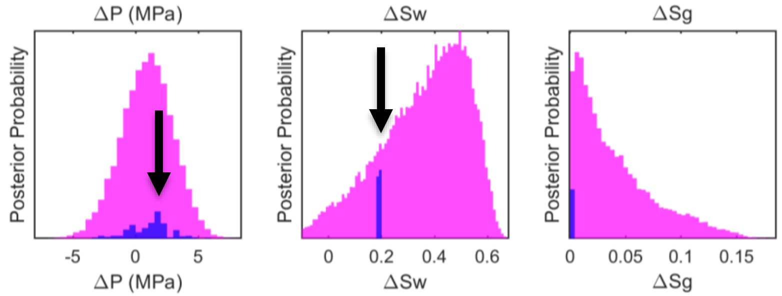
- Prior information
  - Pressure: reservoir simulation
  - Saturation: DNN inversion

Uncertainty quantification



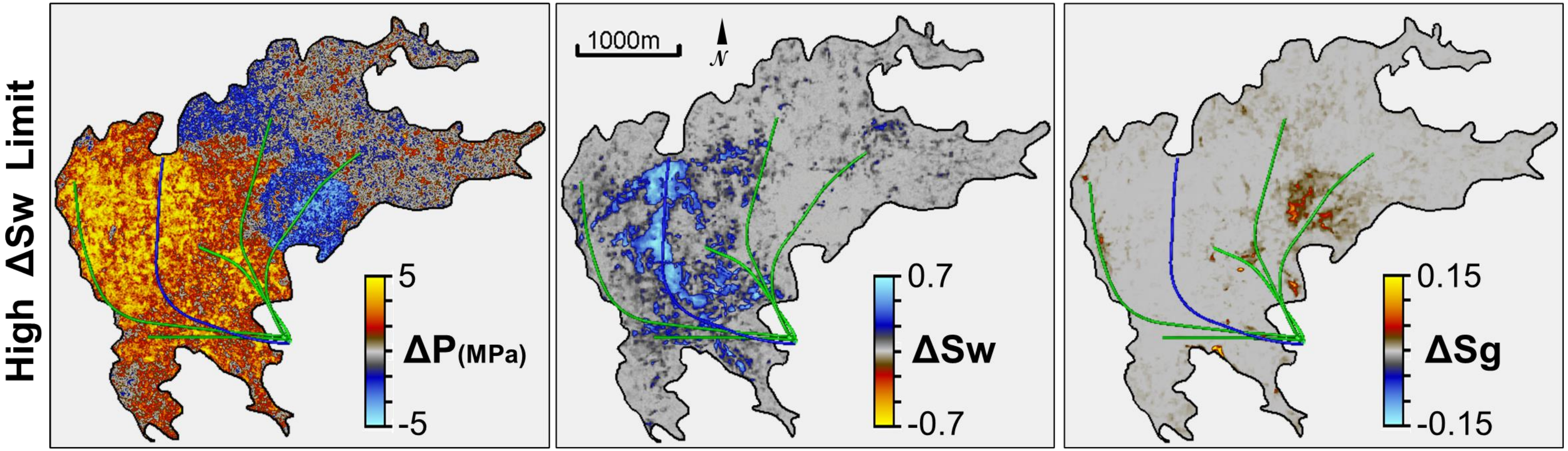
Uncertainty quantification

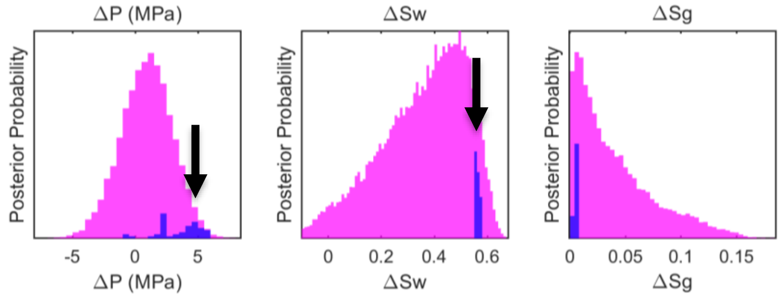




- Low water saturations require pressure increases lower than +2 MPa to match seismic data.

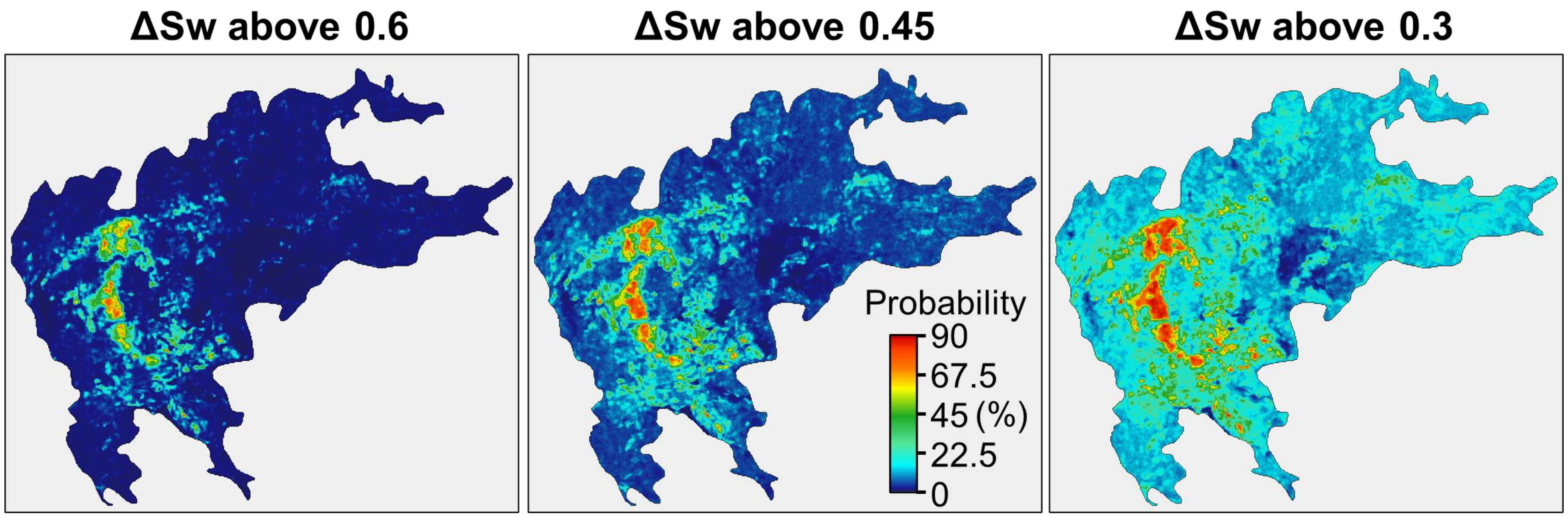
Uncertainty quantification





- High water saturations require pressure increases as high as +5 MPa to match seismic data.

Uncertainty quantification



- Probability of water saturation increase above a certain threshold

Conclusions

- **DNN inversion** provides a quick solution
  - Unbiased by prior information such as a reservoir simulation model
  - Incorporates global prior information: property correlations from fluid flow physics
  - Pressure estimations are reasonable, but inaccurate
  - Lack of uncertainty estimation

- **Bayesian inversion** adds to the information content
  - Reservoir simulation pressure prior
    - Likely more accurate than without, but biased by reservoir simulation results
  - DNN saturation prior
    - Better match to the 4D seismic data
  - Uncertainty quantification
    - Multiple realizations that match the 4D seismic data
    - High and low uncertainty bounds
    - P10 and P90 estimations

Acknowledgements

- Harbour Energy and Catcher JV partners

- Colin MacBeth
  Hamed Amini
  Jesper Dramsch

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