TOWARDS QUANTITATIVE CO_2 MONITORING

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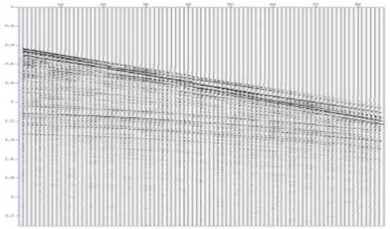
Outline

- Quantitative CO_2 monitoring: combination of geophysical imaging with rock physics inversion
- Uncertainty assessment/quantification
- Value Of Information for CO_2 storage monitoring

Two-step seismic inversion

SEISMIC DATA (macroscale) → **FWI** → SEISMIC IMAGE (macroscale) → **Rock physics inversion** → ROCK PHYSICS PROPERTIES (meso/macroscale)



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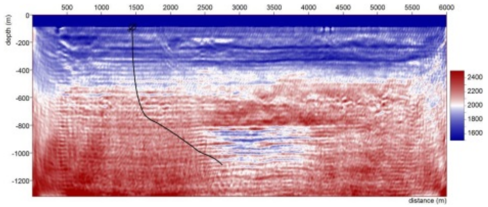

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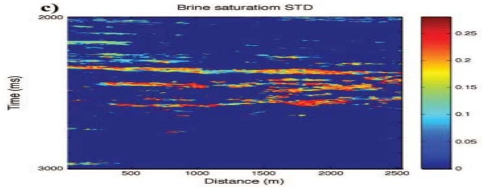
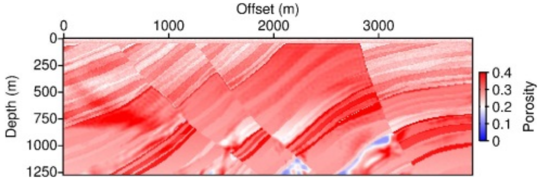


Saturation map (Bachrach, 2006)



Porosity map (Dupuy et al, 2015)

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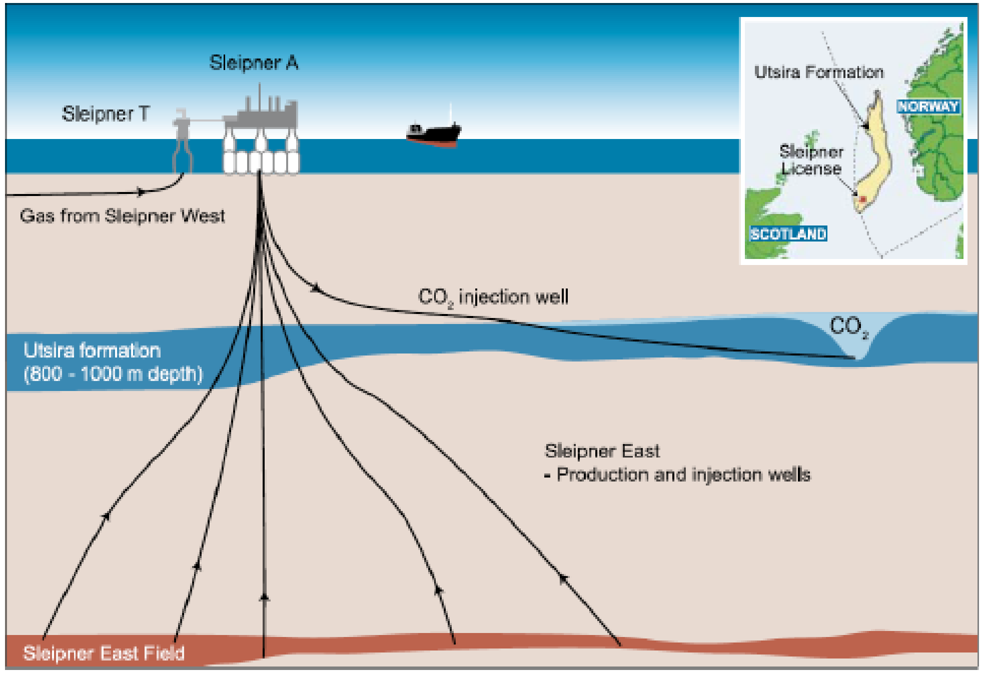
CO_2 injection at Sleipner

- CO_2 separated from the produced gas in the Sleipner Vest gas field.
- CO_2 injection site **since 1996**.
- Approximately 1 Million tonnes per year of injected CO_2.
- Injection into Utsira saline reservoir between 800 -1000 m depth.
- Injection point is about 1010 m below sea level.
- Near critical state at reservoir conditions.
- Storage reservoir: Utsira formation (Upper Miocene to Lower Pliocene).



Location of the Sleipner East field and sketch of injection in Utsira formation (IPCC, 2005).

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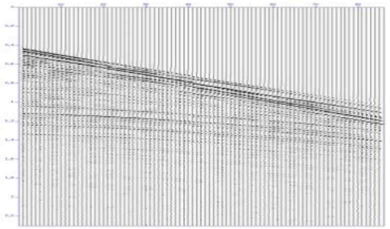

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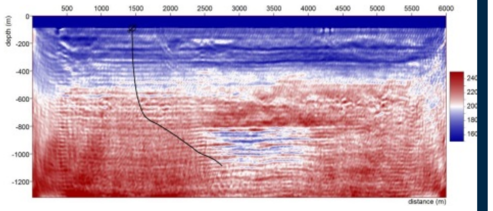

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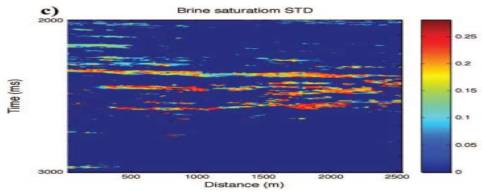

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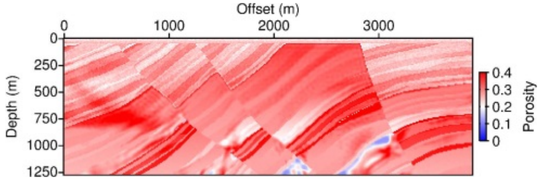
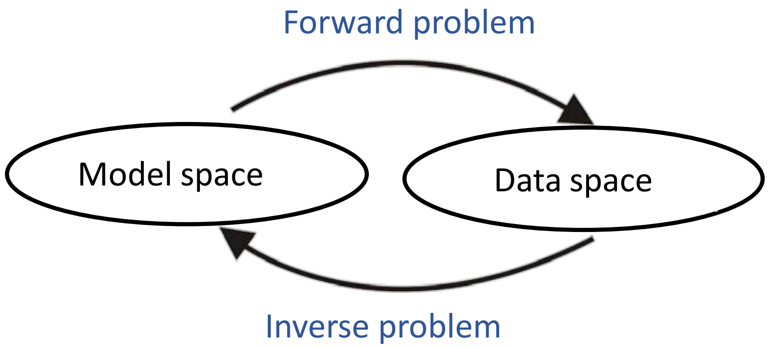
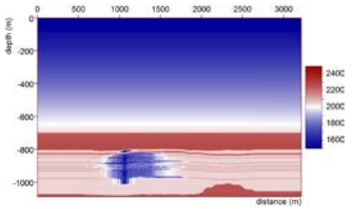


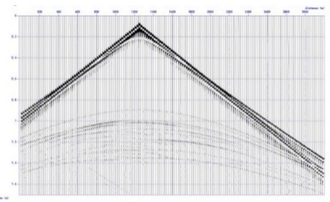
Porosity map (Dupuy et al, 2015)

Methodology
Waveform imaging: FWI

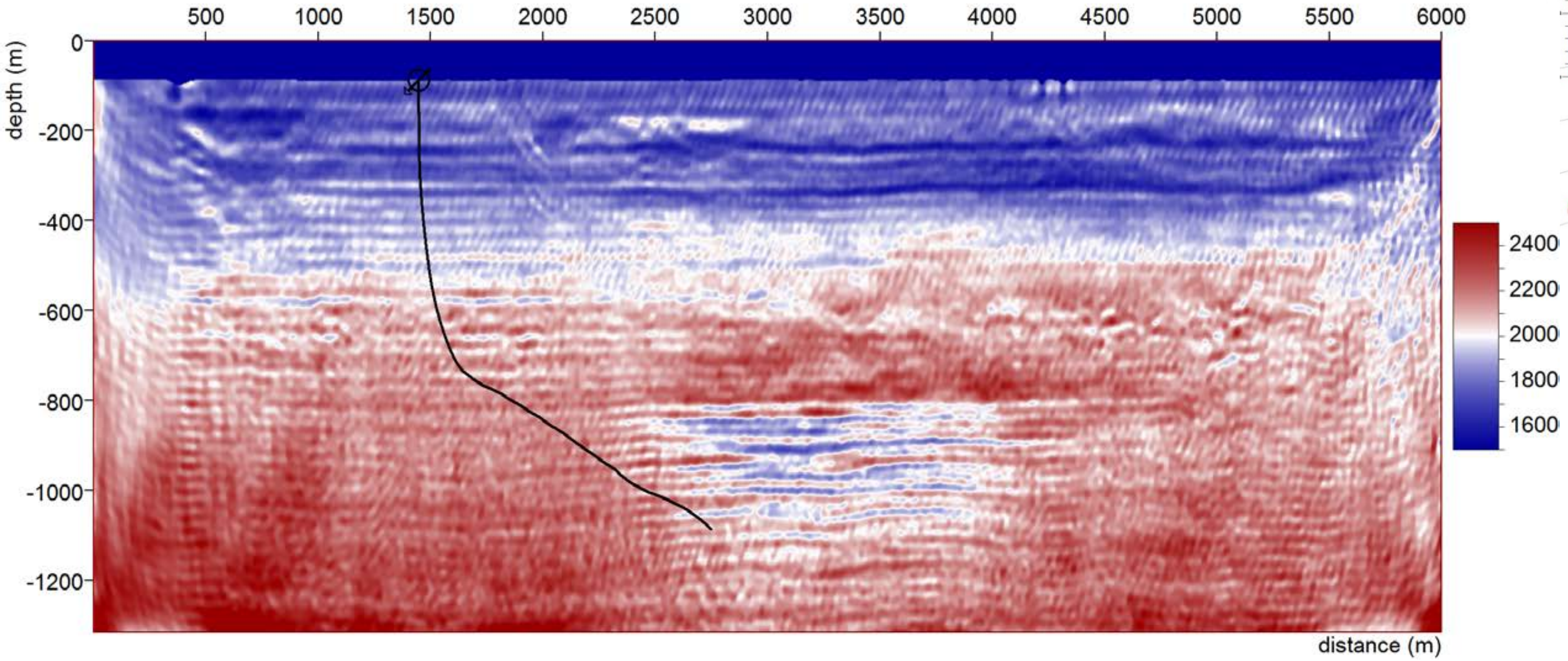
- Waveform based imaging methods
  - Potential to deliver highly resolved geophysical properties
- Finds the “best” model that minimises the misfit between observed and modelled data
- Choice: Frequency-space domain
  - Large memory requirements
  - Can efficiently handle large number of RHS
  - Possibility to perform the inversion from low to high frequencies
    - Very useful to mitigate the non-linearity of the inverse problem
  - Possibility to select few discrete frequencies for the inversion



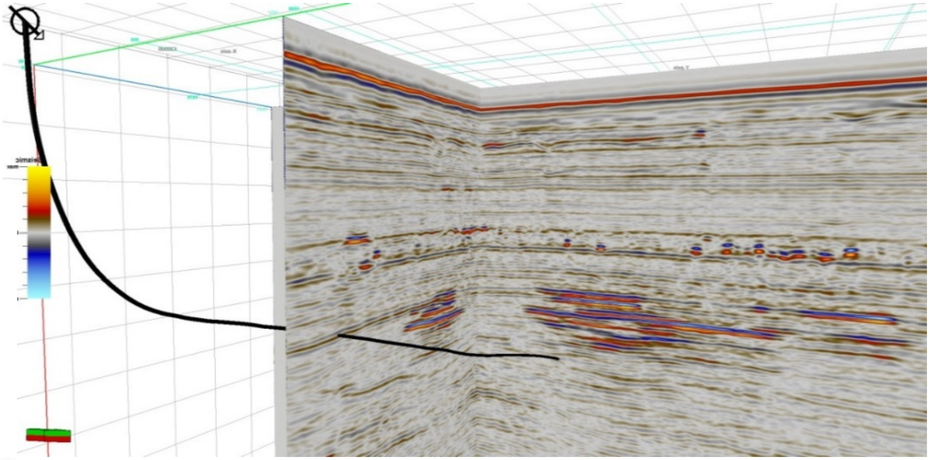

model parameter (for example Vp)


recorded data

FWI for high resolution imaging at Sleipner



P-wave velocity model derived from FWI at Sleipner ; the black line corresponds to the injection well (15/9-A-16) in a projected view into the plan of the seismic section



Example of post-stack time migrated sections from the 2008 vintage

Romdhane and Querendez, 2014

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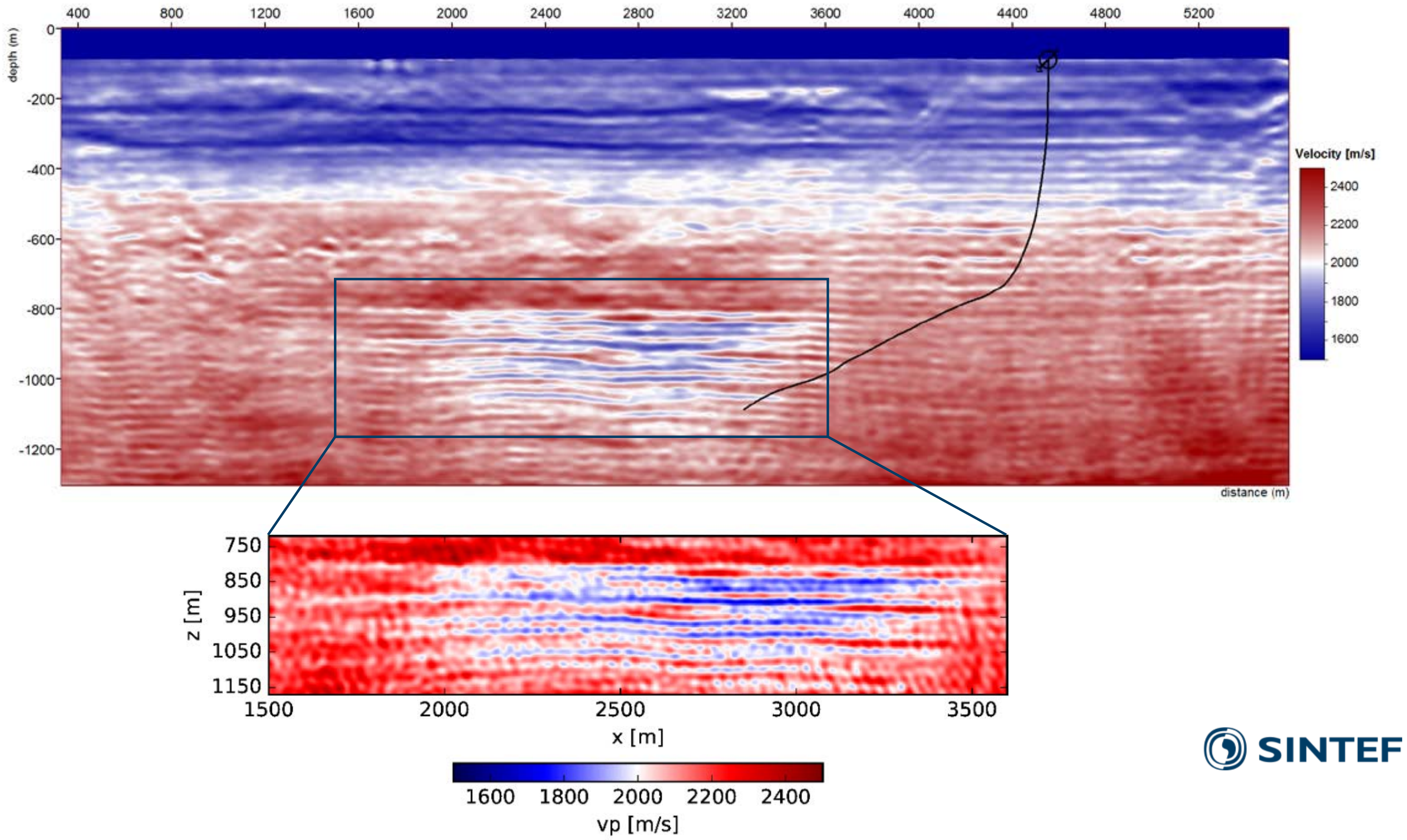
FWI results

- Clear indications of the lateral extent of the low-velocity CO_2 plume and the internal geometry of CO_2 saturated layers
- Low velocity layers observed at the target zone with a thickness varying between 10 m and 20 m

P-wave model derived from FWI; the black line corresponds to the injection well (15/9-A-16) in a projected view into the plan of the seismic section



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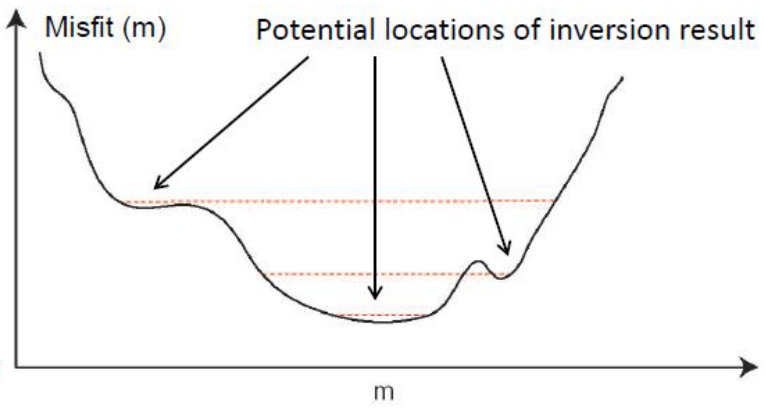
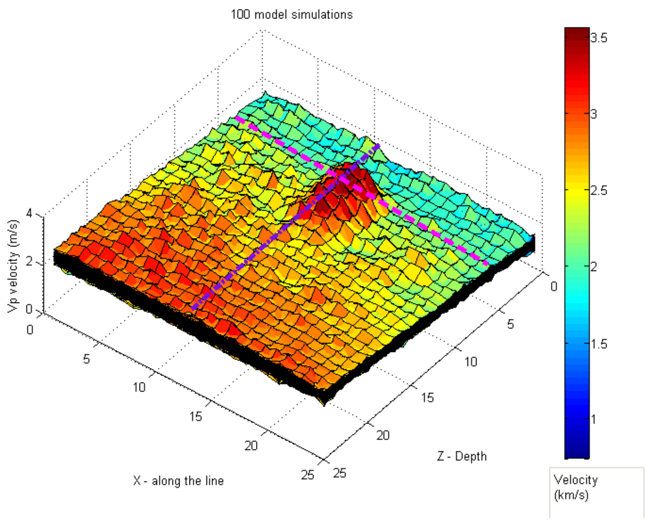
Uncertainty quantification method



- Monitoring methods are based on waveform inversion.
- Inversion means minimization of data misfit (between observed and simulated data) and constraints by iterative subsurface parameter updates.
- Requires calculation of data misfit and its gradient and Hessian with respect to the subsurface parameters.
- Uncertainty quantification based on "posterior covariance analysis". Mathematical tricks ("preconditioned" Hessian and randomized SVD) used for computational efficiency.
- "Equivalent models" (similar misfit) by sampling from posterior covariance.



100 equivalent velocity models

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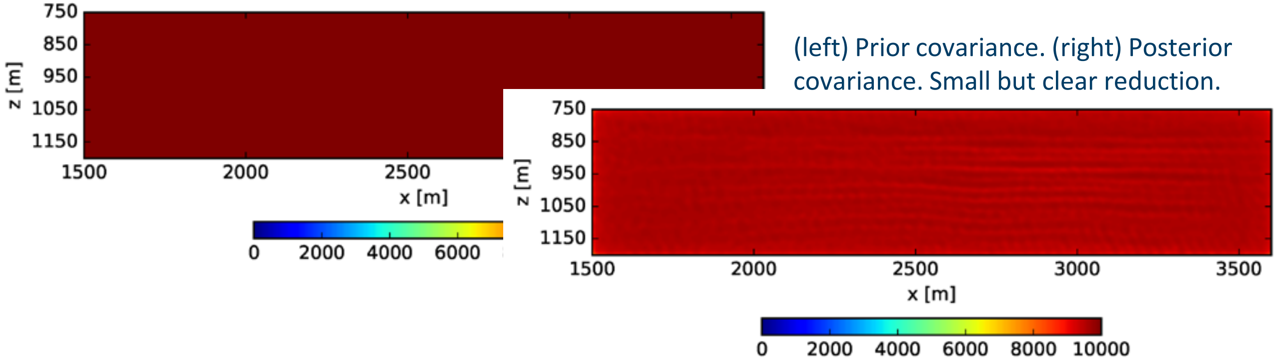
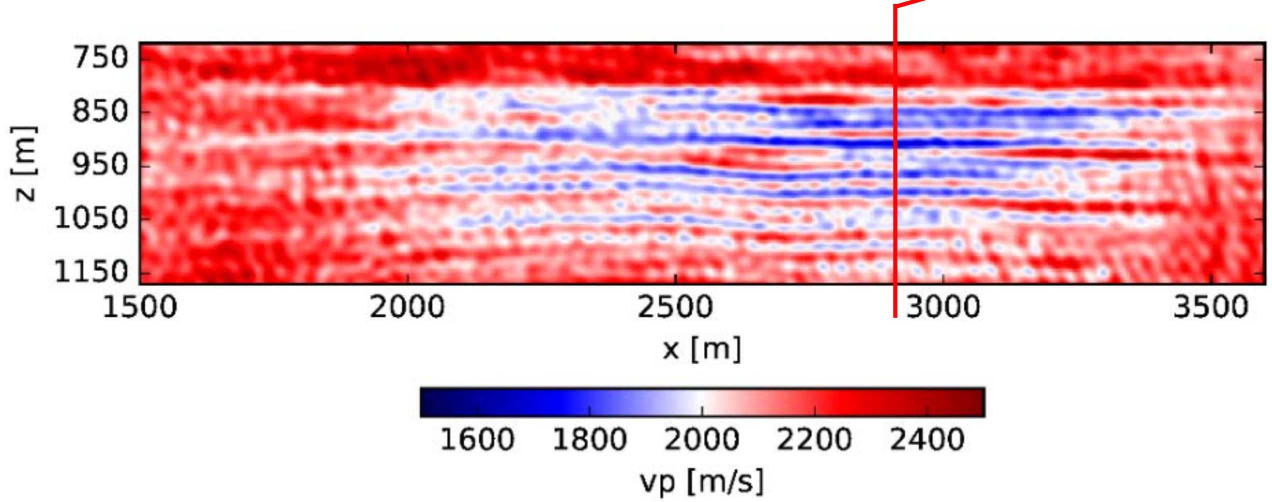
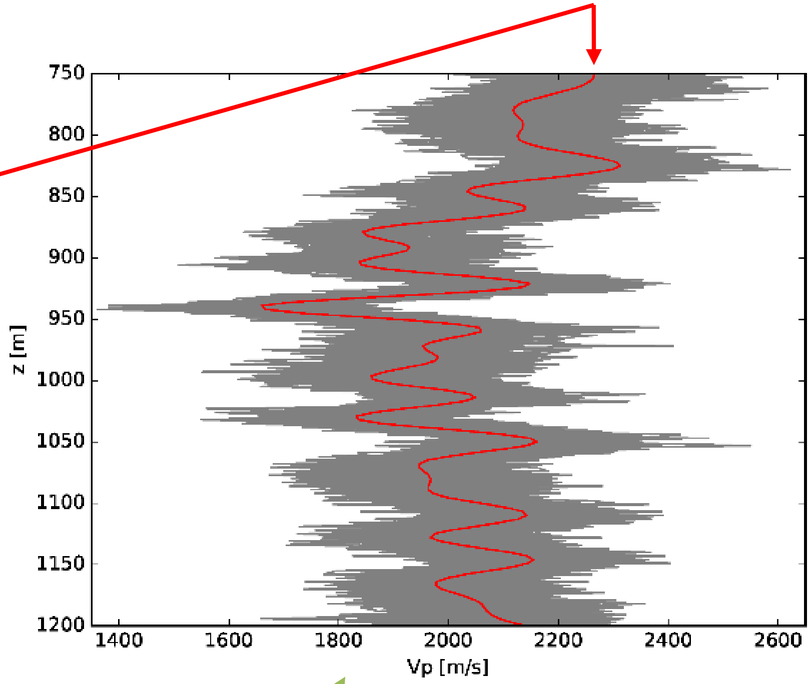
Uncertainty assessment of FWI results



(left) Prior covariance. (right) Posterior covariance. Small but clear reduction.





Eliasson and Romdhane, 2017

Successful uncertainty quantification and generation of equivalent models!

Close-up of plume region. (right) Extracted depth velocity profiles from 100 "equivalent models " at x=2916 m. The red line corresponds to the velocity of the final FWI model.

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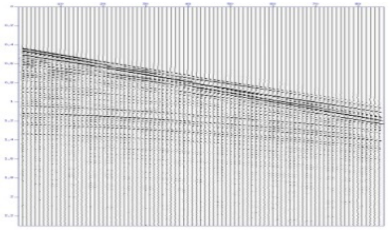

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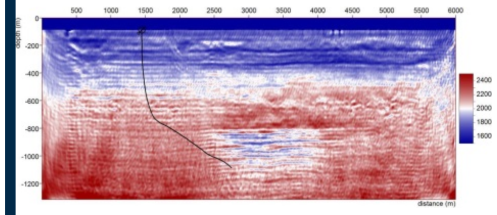

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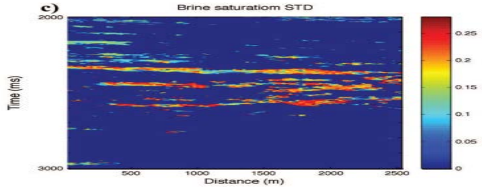

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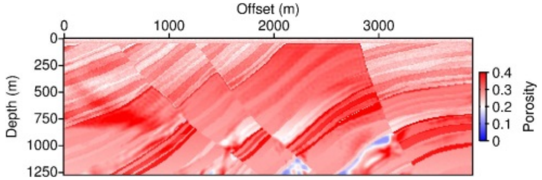


Porosity map (Dupuy et al, 2015)

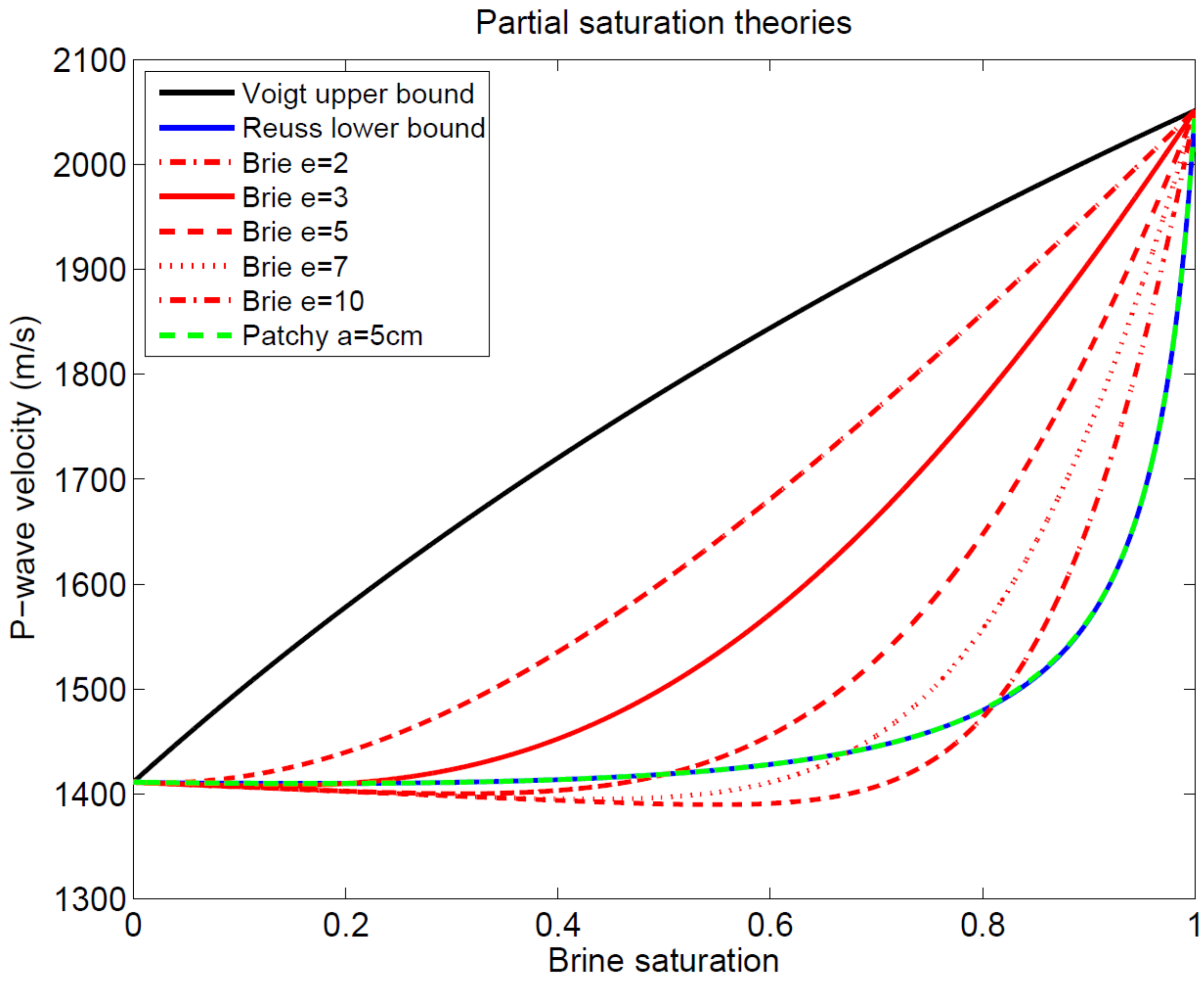
Rock physics models: relation between seismic velocity and CO_2 saturation

- Effective fluid phase plugged into *(Biot-) Gassmann* equations: different ways of calculating **effective fluid bulk modulus**.

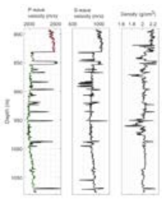
- Brie equation (*Brie et al., 1994*):

$$K_f = (K_w - K_{CO_2})S_w^e + K_{CO_2}$$

- e = 40 ➔ uniform saturation
- e = 1, 3, 5? ➔ patchy-mixing saturation

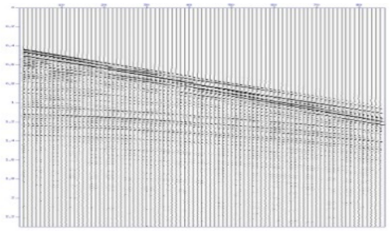


Baseline and monitor strategy



LOG DATA

SEISMIC DATA → (FWI) → SEISMIC IMAGE → (Rock physics inversion) → ROCK PHYSICS PROPERTIES



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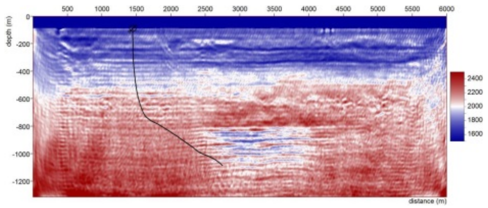

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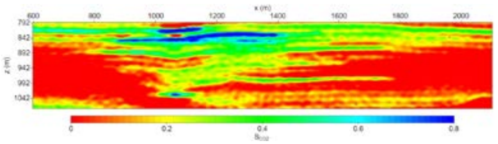

CO_2 saturation map (Yan et al., 2017)

Dupuy et al., 2016, Geophysics

<u>Workflow:</u>

1. **Baseline** data (1994): mapping of porosity + moduli (K_D, G_D)
   - based on **1D log data** and extended to 2D via seismic interpretation.
   - **2D mapping using FWI**.
2. Monitor data (2008): **mapping of CO_2 saturations** using baseline porosity and moduli maps as a priori input

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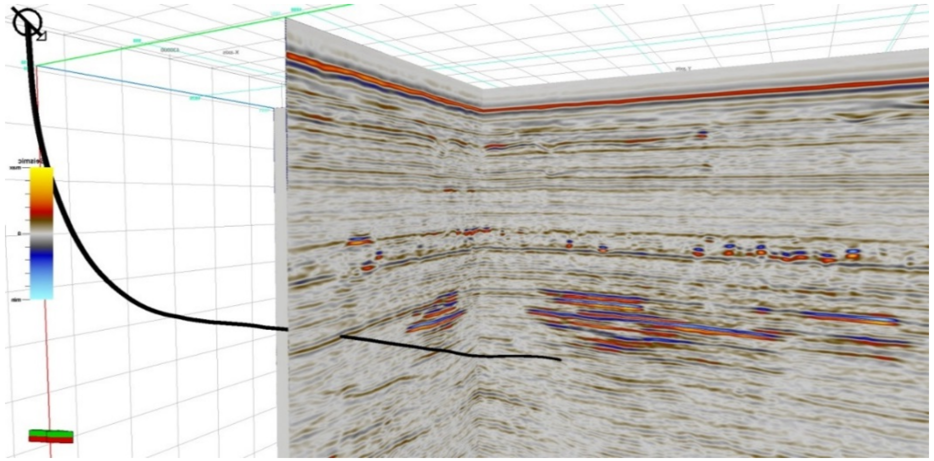
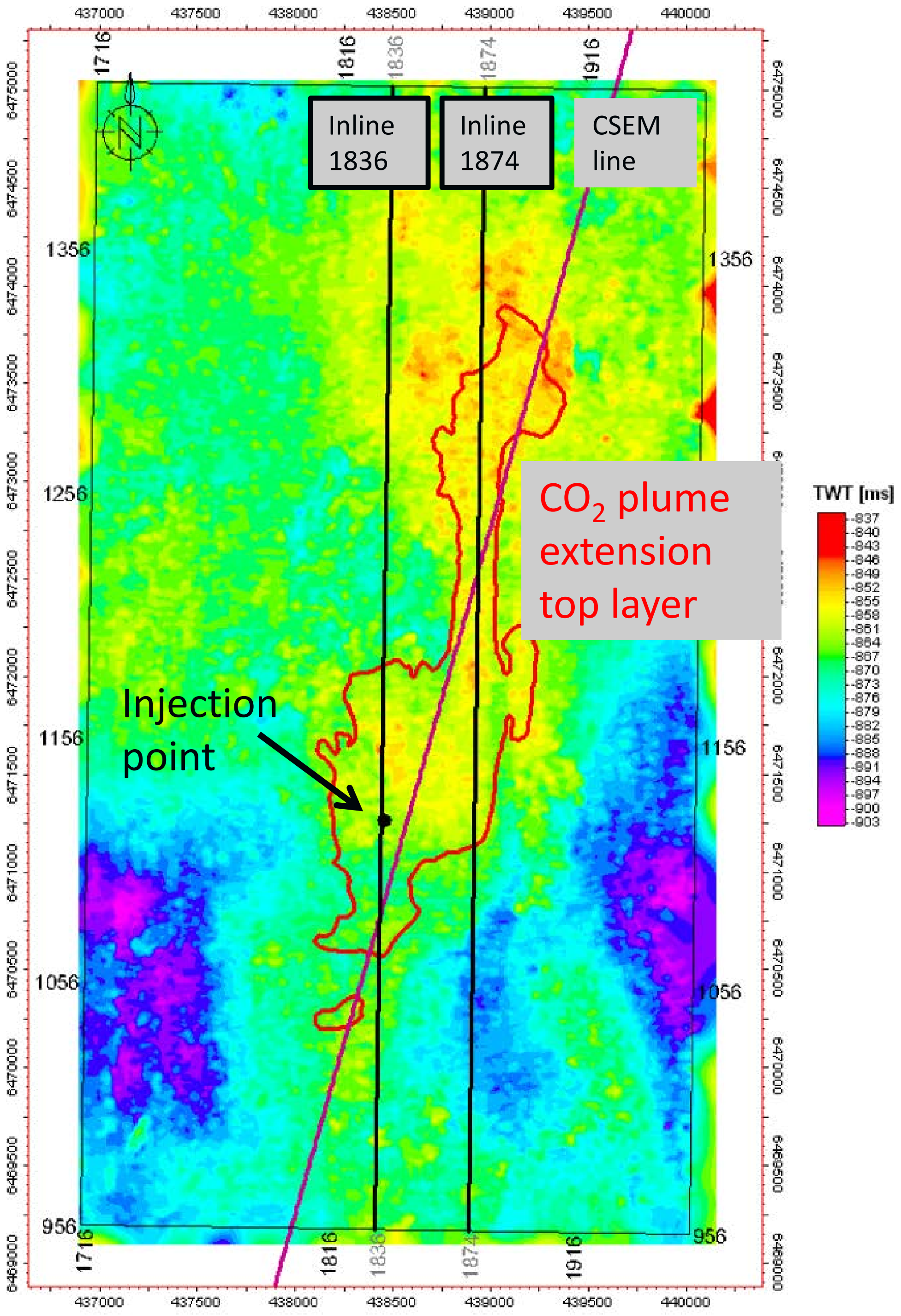
Sleipner data, 2008 vintage



Example of post-stack time migrated sections from the 2008 vintage



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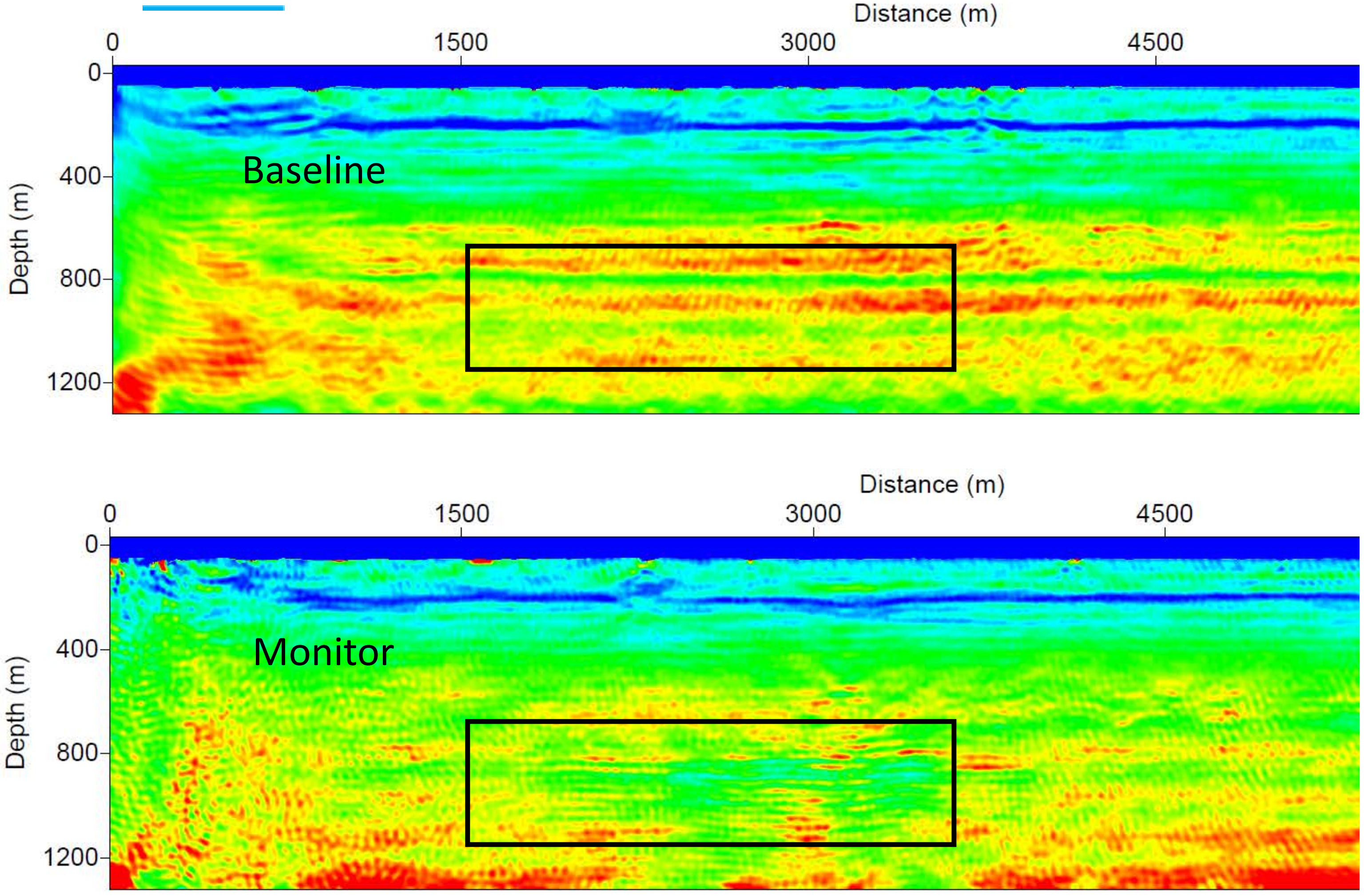
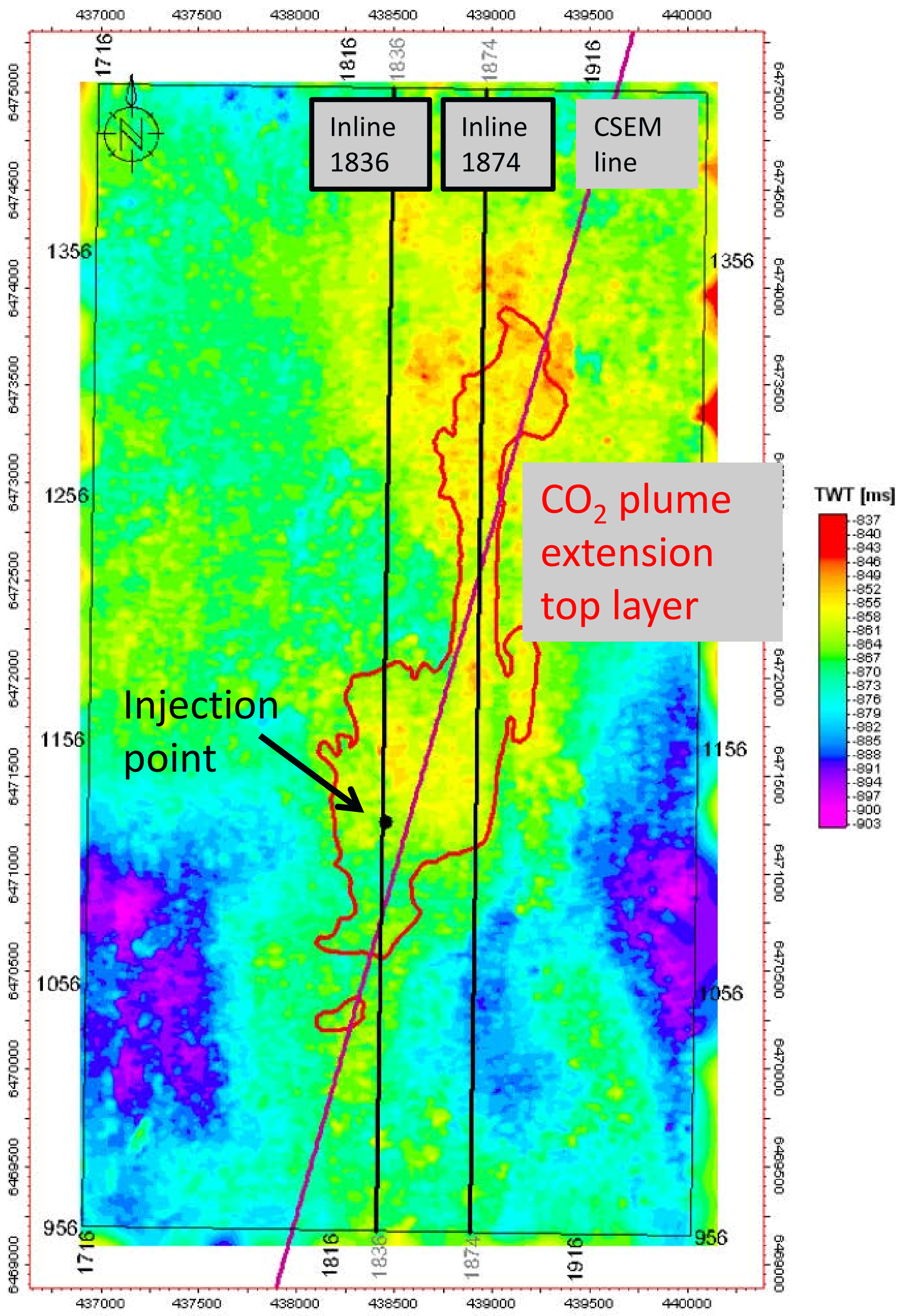
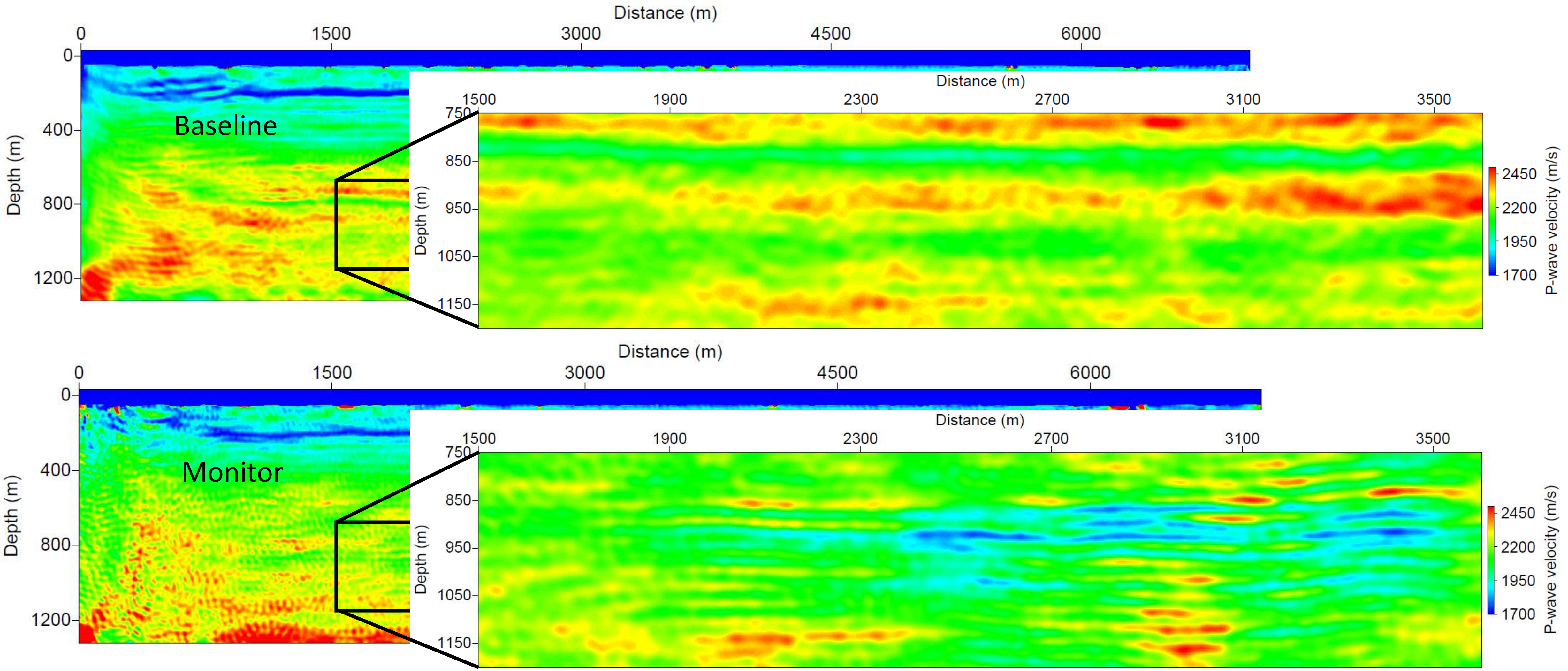
Inline 1836: FWI results

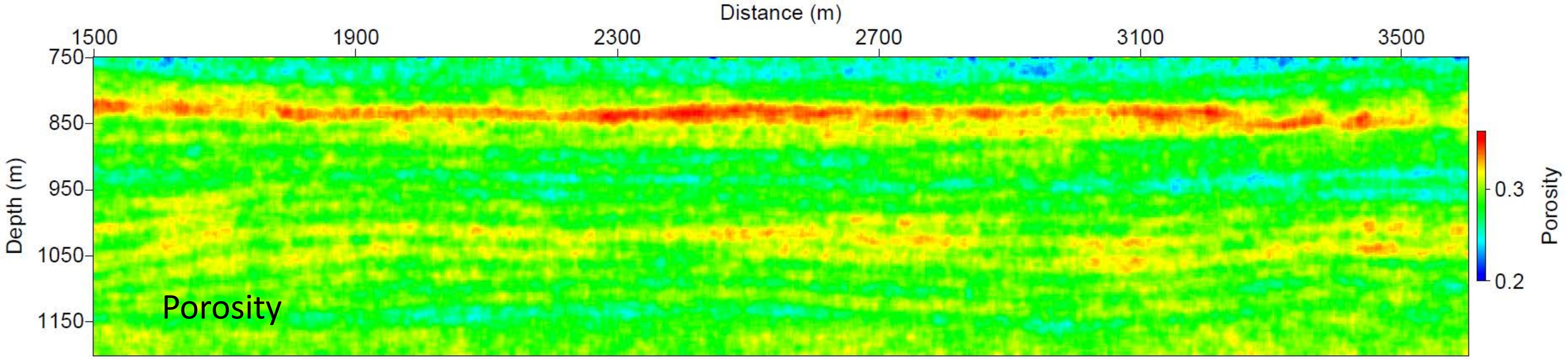


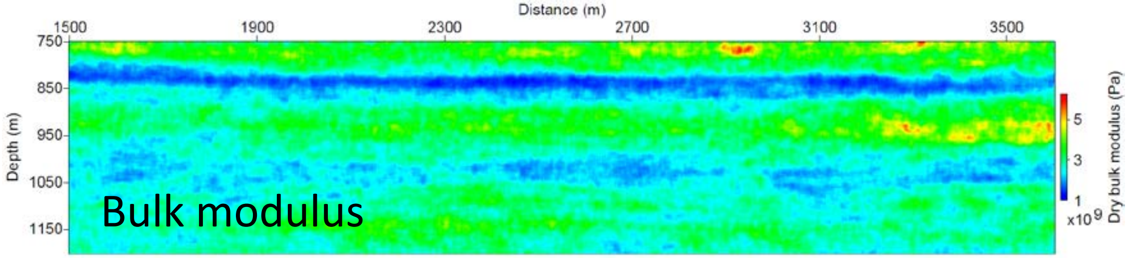


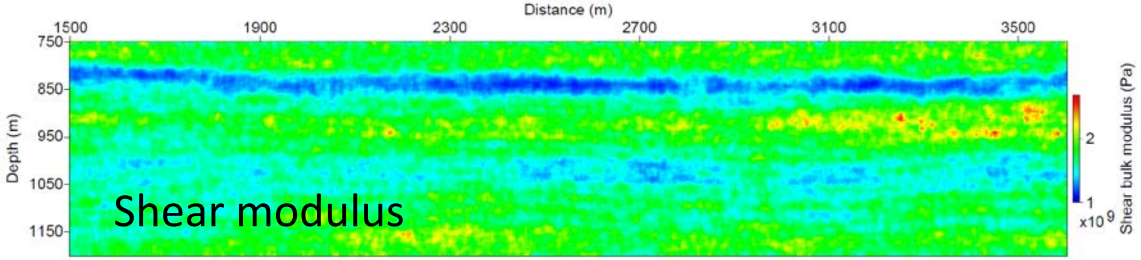
Inline 1836: FWI results, reservoir close-up



Baseline mapping from FWI (1994)







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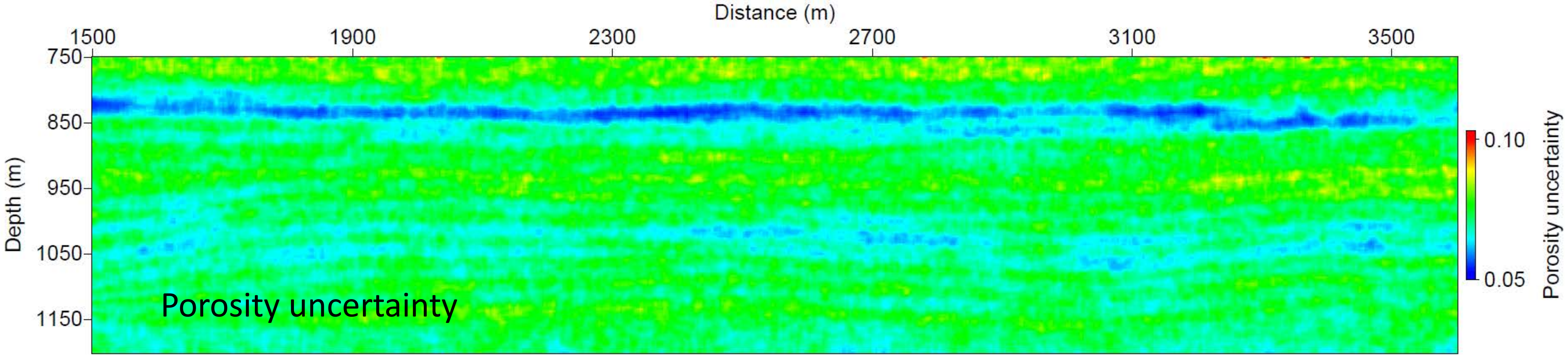
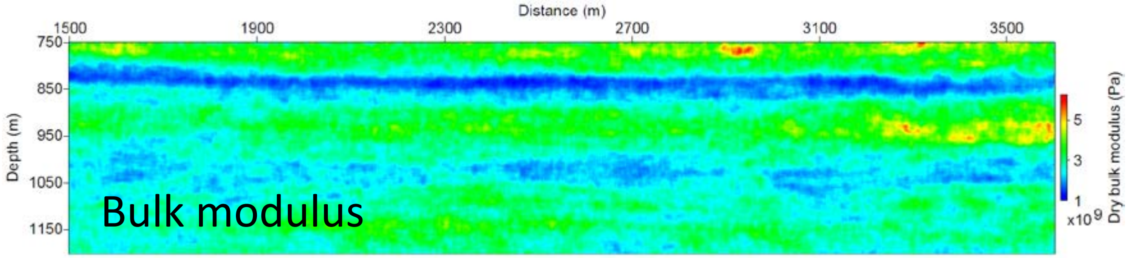
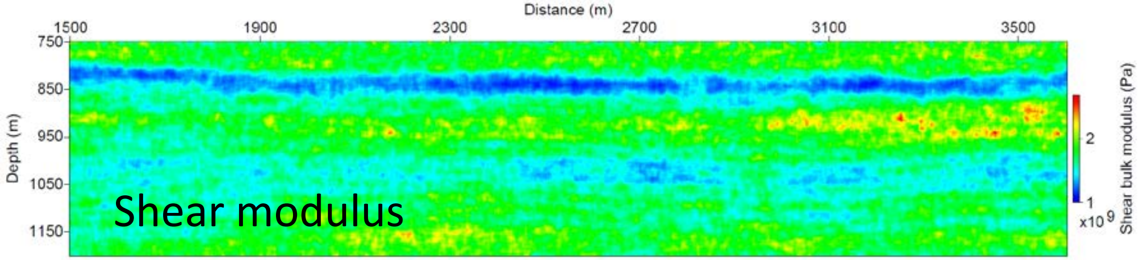
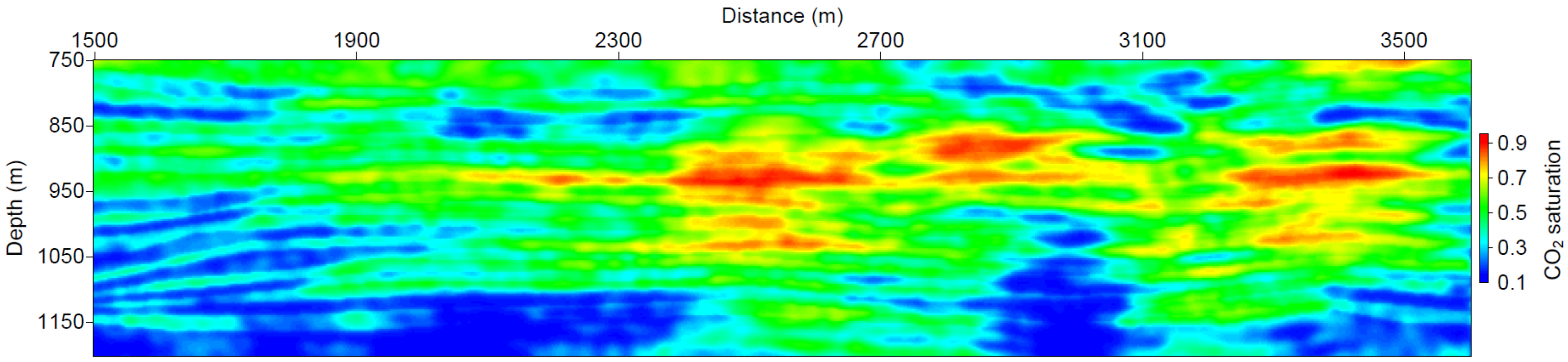


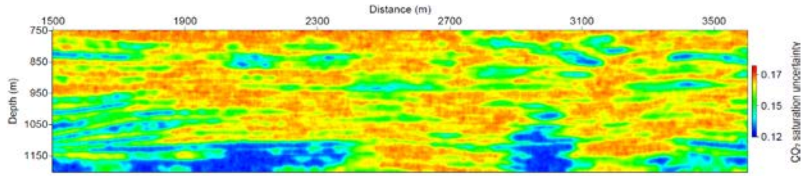


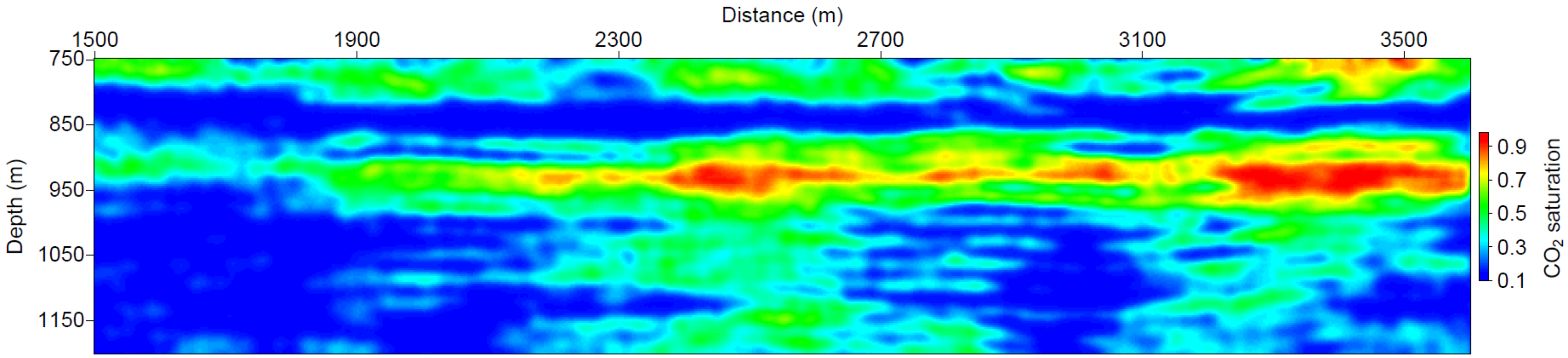


Saturation maps (2008)



2D saturation distribution and associated uncertainty using baseline models from log data





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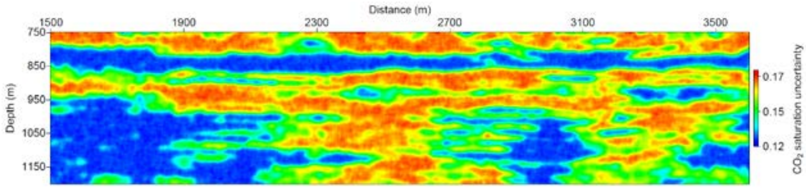
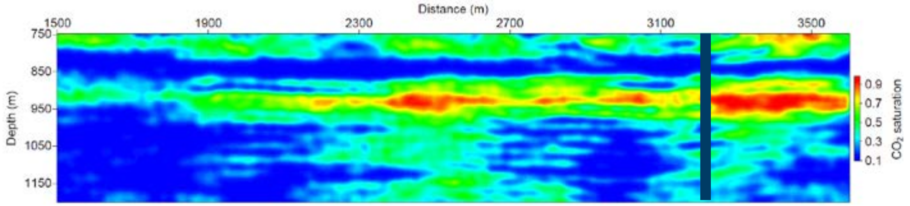
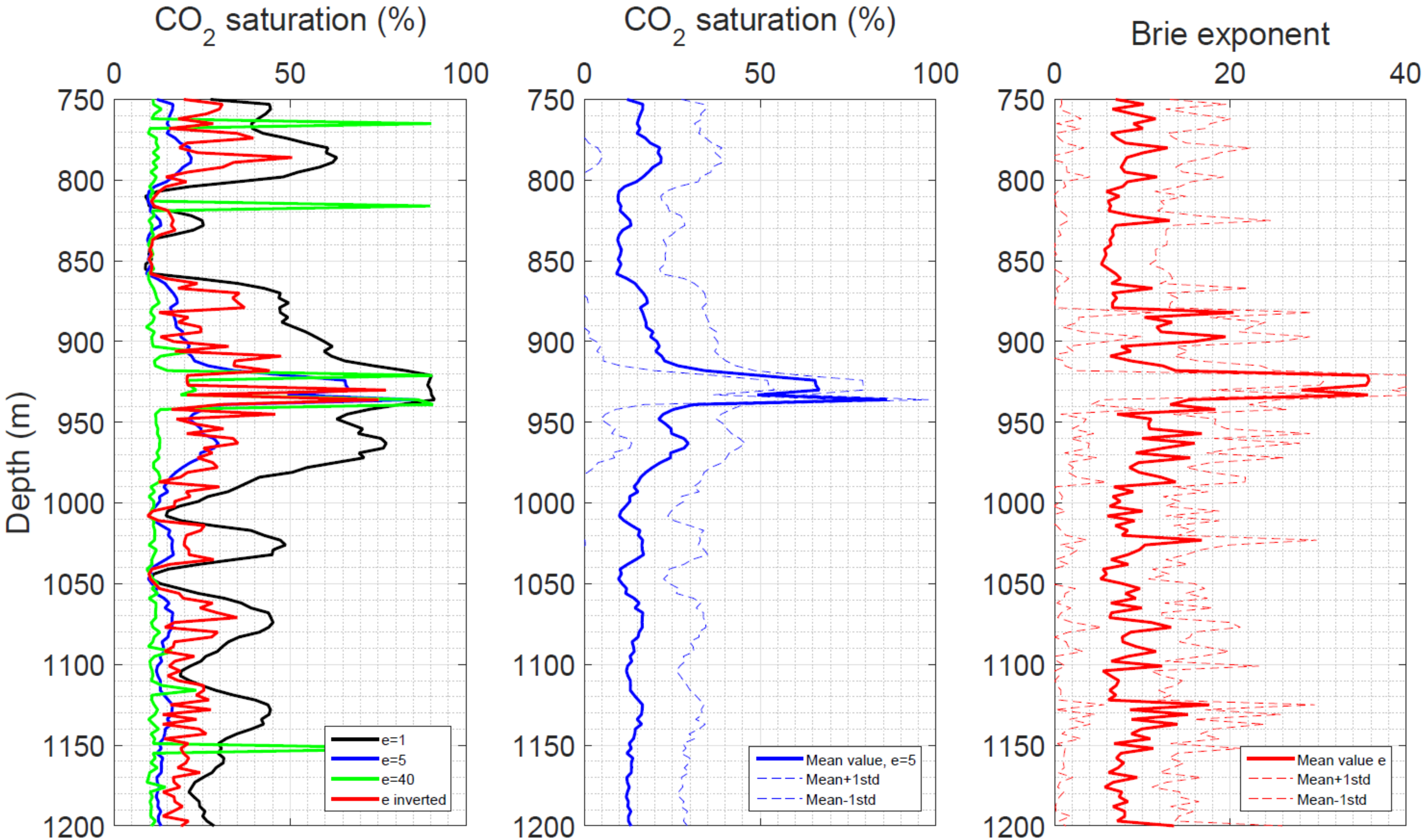


1D comparisons, offset=3240m





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First insights regarding quantification

- 1st inversion step:
  - High resolution estimates of seismic properties with FWI.
  - Assessment/quantification of uncertainty related to FWI step.
- 2nd inversion step for quantitative estimates of CO_2 saturations (and pressure) ➔ proper uncertainty propagation is needed.
- Pressure-saturation discrimination requires additional geophysical data/inversion.
- Proper quantitative estimates require extensive work on baseline models.
- Additional geophysical inputs (gravity, EM) can reduce uncertainties and trade-offs.
- The ability to quantify uncertainty means more reliable risk assessment and can help to optimize geophysical surveys (minimize costs).

➔ Integration using Value of Information concept

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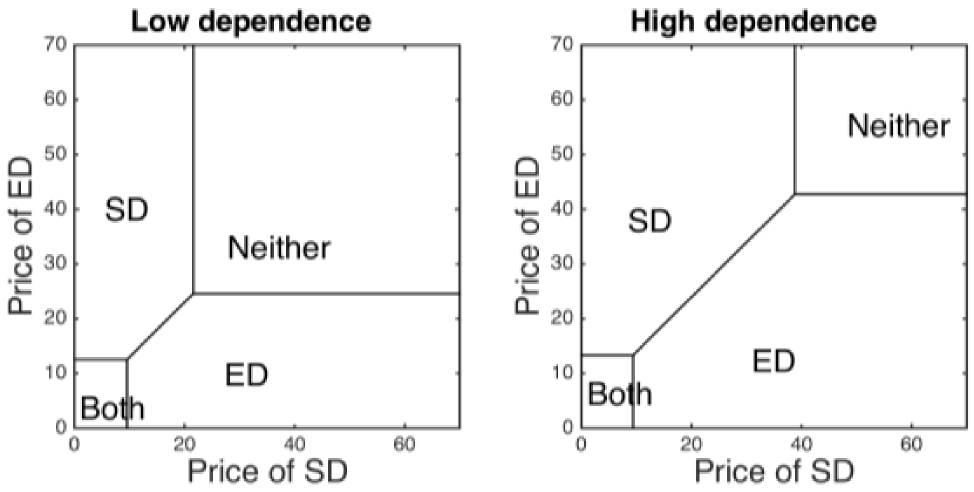
Value of information concepts

- Popular notion in decision making under uncertainty
- Need to investigate how VOI concepts can be used in the context of CO_2 monitoring
- Examples in petroleum exploration and production industry
  - Integration of VOI concepts with rock physics and spatial statistics to make drilling decisions



Decision regions for pre-stack seismic AVO data and EM data for the high flexibility drilling decisions. The left display has small correlation in the profits, while the right display has more spatial correlation (Eidsvik et al, 2015)

VOI for CO_2 monitoring

- Value function has to be defined
  - Considering purshasing selected (addtional) geophysical data
    - Examples: pre-stack seismic, EM data, gravimetry data
  - Including fluid flow
- Maximize the avoidance of intervention costs could be set as a value function
- Analysis examples:
  - Risk assessment approach (Pawar et al., 2016, Bourne et al.,2014)
  - Cost benefit analysis (Ringrose et al., 2013; Dean and Tucker, 2017)
- Benefit from lessons learned from existing/previous storage projects

Dean and Tucker, 2017

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VOI for CO_2 monitoring
Activity

- Investigate which are the most important properties needed from the geophysical monitoring to verify and update the reservoir and geomechanical models.
- Combine with value-of-information concept for efficient updates and optimal monitoring technology/layout.
- Investigate how fast flow modelling can be used to evaluate monitoring strategies.

Acknowledgements

- Part of the presented results have been done in Unicque and NCCS (Task 12, cost-efficient CO2 monitoring) projects.
- The work proposed in PreAct project will be partially done in coordination with NCCS project (Task 12, cost-efficient CO2 monitoring).

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