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QUANTITATIVE MONITORING AND MULTIPHYSICS INVERSION

Bastien Dupuy, Anouar Romdhane, Peder Eliasson (SINTEF)

Joonsang Park (NGI)

+ colleagues

Outline

- Why quantitative monitoring for CO_2 storage?
- Methodology
  - Two-step inversion
  - Bayesian workflow
  - Time-lapse strategy
- Why multiphysics/joint inversions?
  - Trade-offs between saturation, pressure and fluid mixing/distribution
- Conclusions

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Why quantitative monitoring?

- Legal requirements for **safe** CO_2 storage:
  - Containment monitoring: plume migration, potential leakages…
  - Conformance monitoring: **consistency between models and observed site behaviour**. Requires quantitative properties: pressure, saturation, stress changes…
- How can geophysical monitoring provide **quantification** of relevant rock physics properties?
- What is the **uncertainty** related to these estimates?
  - Link to operational decision making.
- Can we do this in a **cost-efficient** way during and after the injection?

Dean and Tucker, 2017

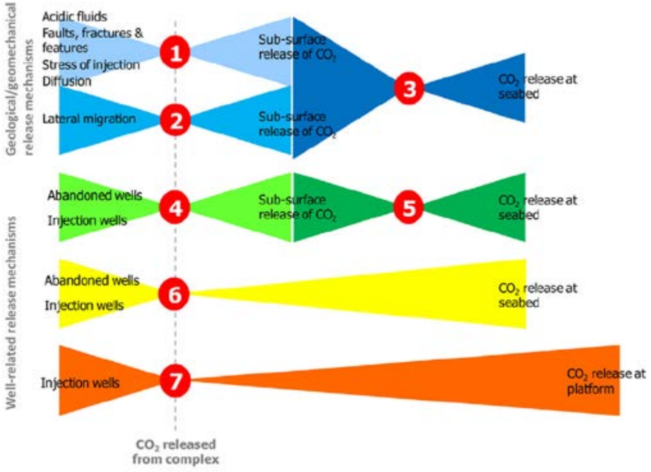

Fig. 6. The Goldeneye bowtie risk assessment required the use of multiple bowties.

Fig. 7. Ranking of monitoring technology options according to expected benefits and costs. Blue oval = in base MMV plan, green oval = pending on further assessment, yellow oval = not in base MMV plan. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Two-step geophysical inversion

SEISMIC + EM DATA

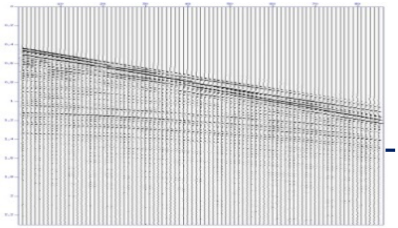
Geophysical inversion

GEOPHYSICAL PROPERTIES

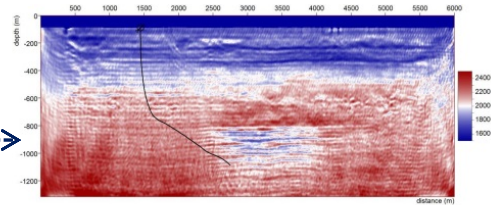
Rock physics inversion

ROCK PHYSICS PROPERTIES

Seismic data

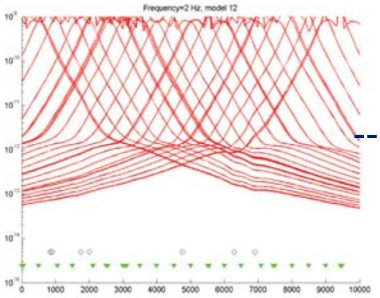


Seismic inversion (FWI)

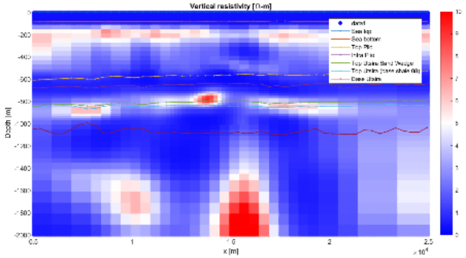


P-wave velocity map

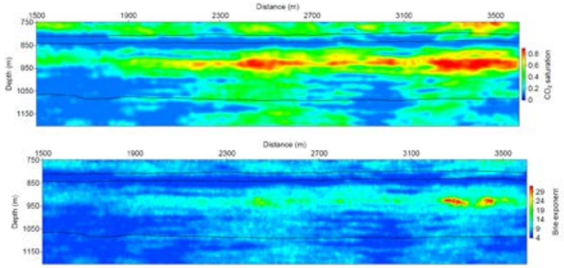
CSEM data



CSEM inversion



Resistivity map



Saturation and fluid mixing maps

Figures from Romdhane and Querendez (2014), Park et al. (2013), Bøe et al. (2017), Dupuy et al. (2017), Yan et al. (2018)

Two-step geophysical inversion

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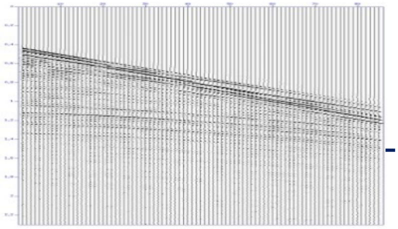
Seismic data



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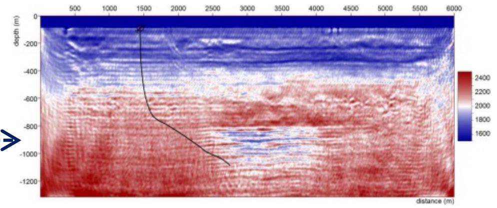

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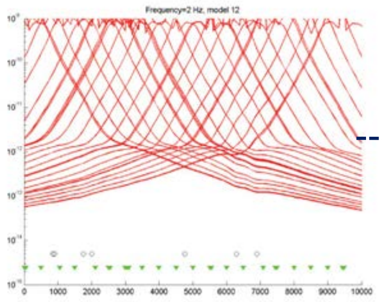
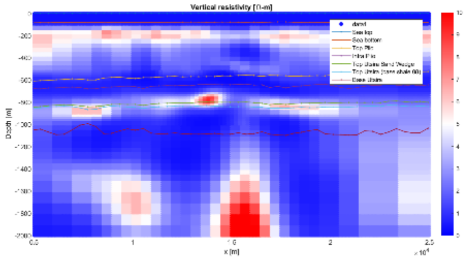
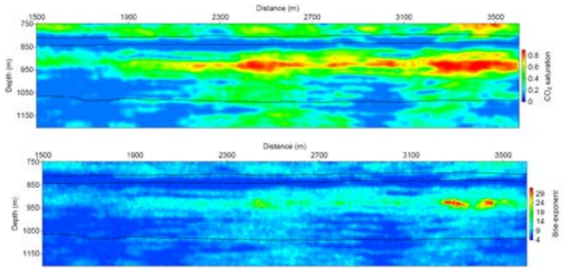
CSEM data



CSEM inversion



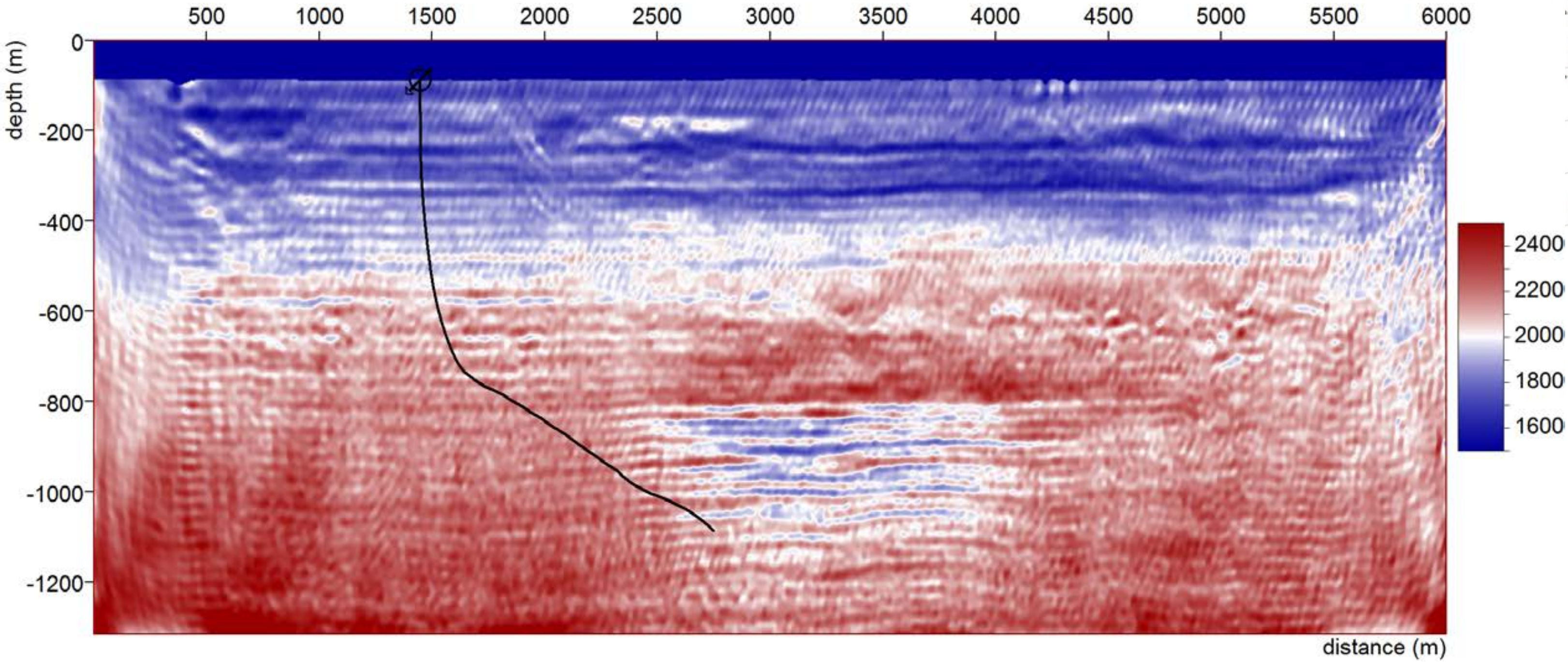
Resistivity map



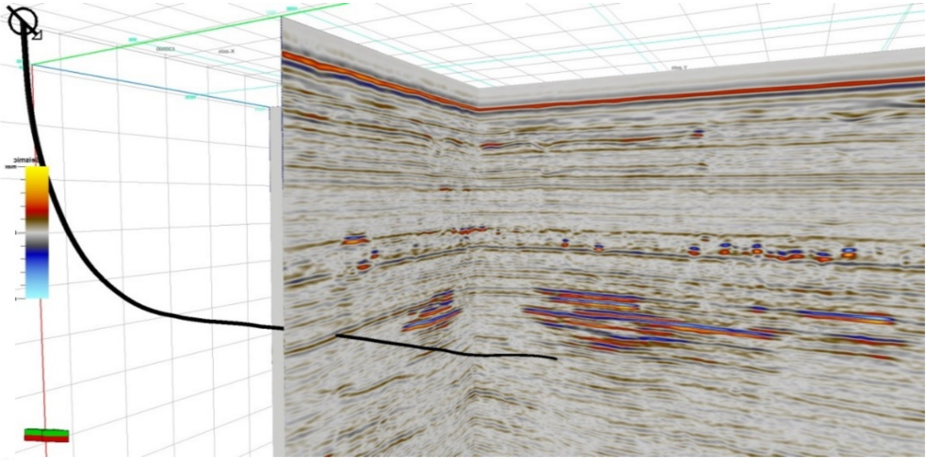
Saturation and fluid mixing maps

Figures from Romdhane and Querendez (2014), Park et al. (2013), Bøe et al. (2017), Dupuy et al. (2017), Yan et al. (2018)

Geophysical inversion
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 plane of the seismic section



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

Romdhane and Querendez, 2014

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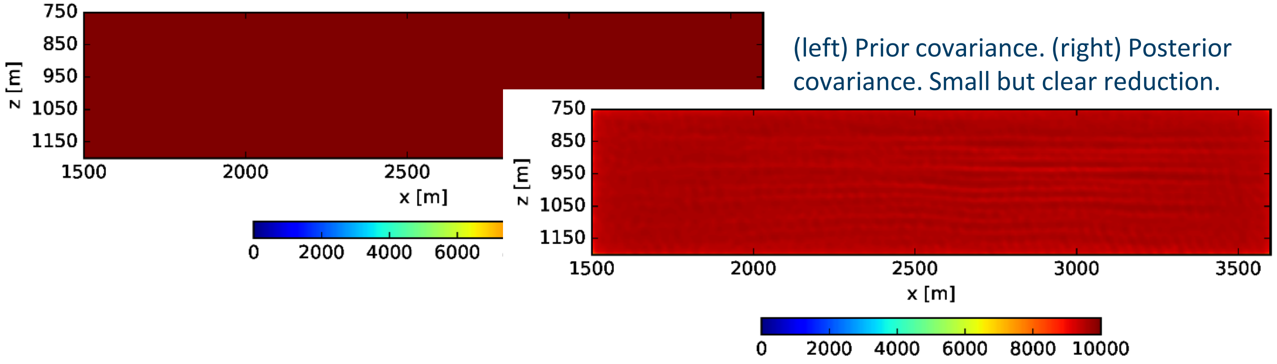
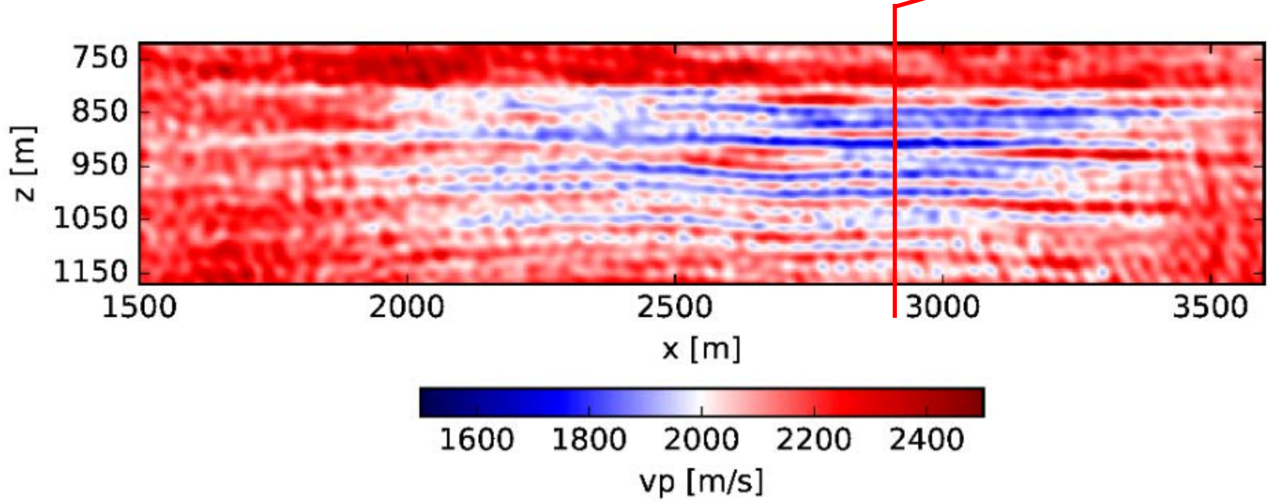
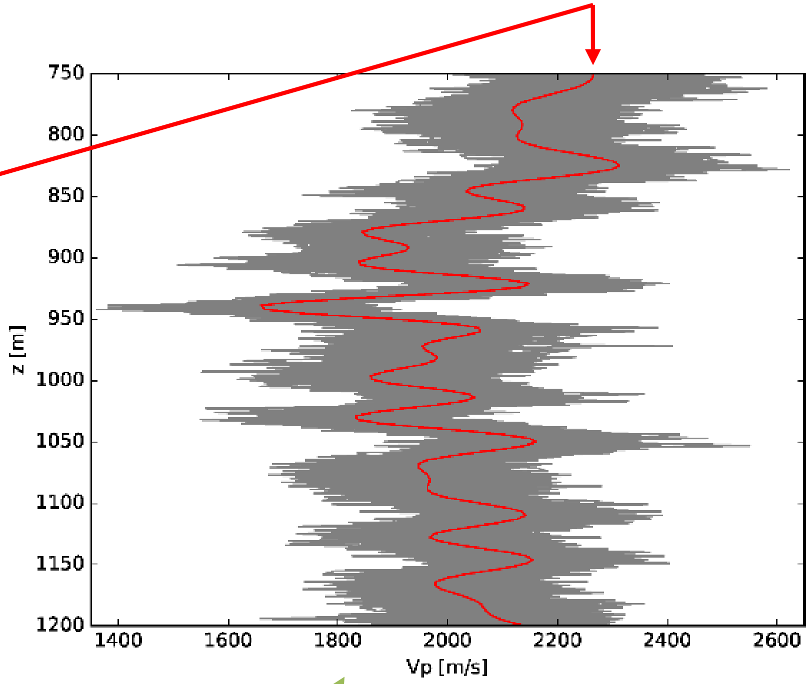
Geophysical inversion
Uncertainty assessment

The inverse of the Hessian of the misfit function being minimized can be interpreted as the posterior covariance matrix C_{post}^{FWI} in a local probabilistic sense (Tarantola, 2005; Zhu et al., 2016)



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



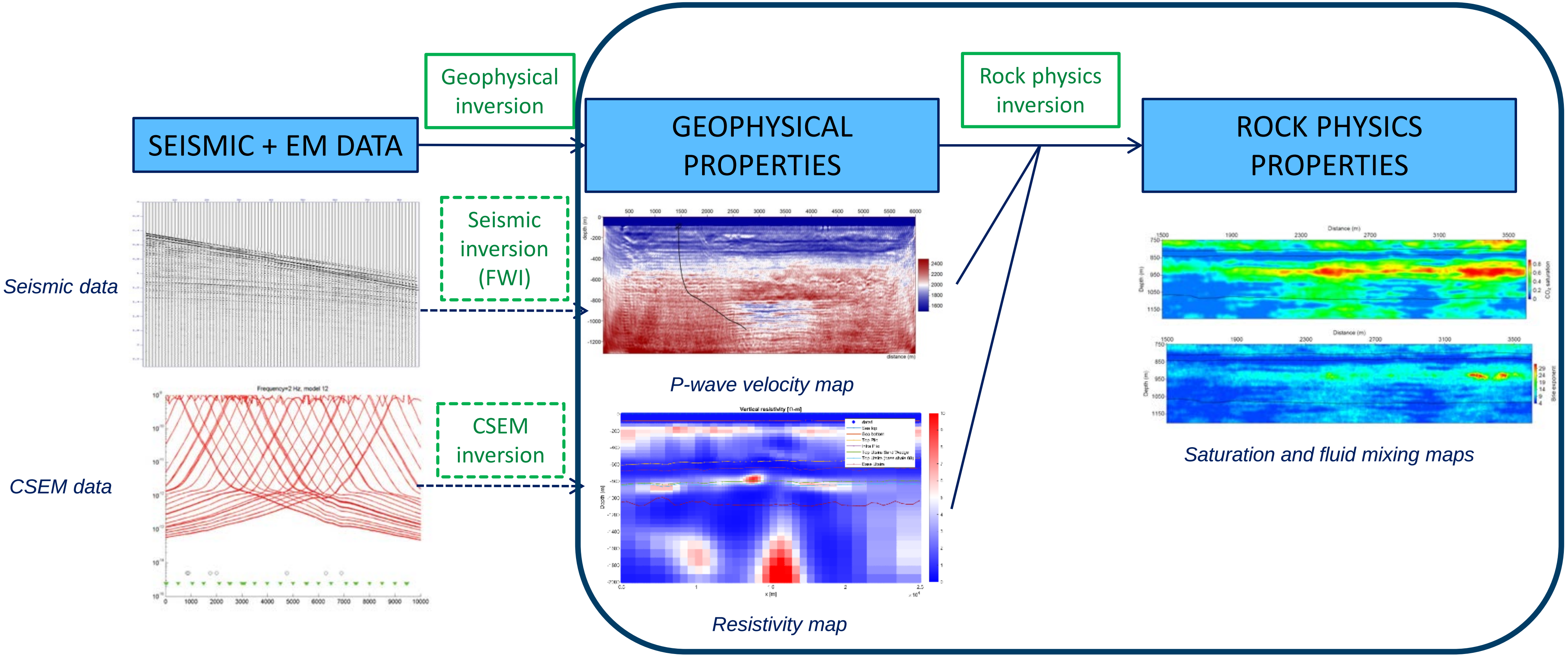


Eliasson and Romdhane, 2017

(top) 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.

Successful uncertainty quantification and generation of equivalent models

Two-step geophysical inversion



SEISMIC + EM DATA

Geophysical inversion

GEOPHYSICAL PROPERTIES

Rock physics inversion

ROCK PHYSICS PROPERTIES

Seismic data

Seismic inversion (FWI)

CSEM data

CSEM inversion

P-wave velocity map

Resistivity map

Saturation and fluid mixing maps

Figures from Romdhane and Querendez (2014), Park et al. (2013), Bøe et al. (2017), Dupuy et al. (2017), Yan et al. (2018)

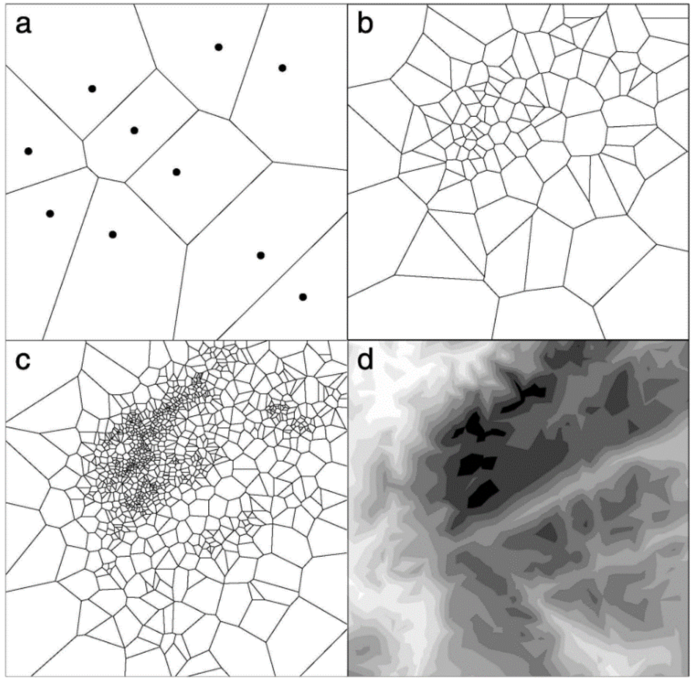
Bayesian rock physics inversion
Global optimization

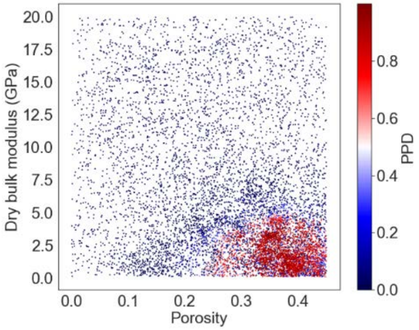
- **Inverse problem difficult** because under-determined, non-linear and non-unique solutions.
- Two stages to get statistically meaningful information:
  - Global optimization: search ensemble of models with associated likelihood (MC, SA, NA…)
  - Importance sampling: calculate Bayesian integrals (PPD, marginal distributions, covariance…)
  - Fast and analytic forward problem ➔ **global exploration using Neighbourhood algorithm** (NA, *Sambridge, 1999*):
    - Mix of good exploration of model space and "tendency" to look for the most likely models.
    - **Give an ensemble of models representing "all information".**

Forward problem: $\boldsymbol{d} = g(\boldsymbol{m})$

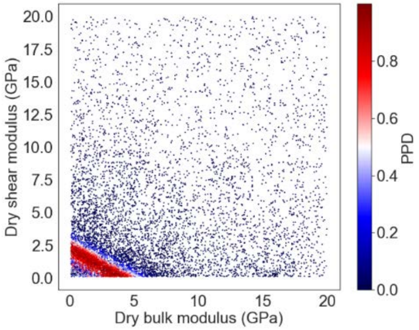
Data likelihood function: $L(\boldsymbol{d}|\boldsymbol{m}) = k \exp\left(-\frac{1}{2}\left(\boldsymbol{d} - g(\boldsymbol{m})\right)^T \boldsymbol{C}_D^{-1}\left(\boldsymbol{d} - g(\boldsymbol{m})\right)\right)$

Data covariance matrix: $\boldsymbol{C}_D = \boldsymbol{C}_{post}^{FWI}$





Search step: 2D slices of 3D model space, models with likelihood



True model:
$\phi = 0.36$
$K_D = 2.56$ GPa
$G_D = 0.75$ GPa

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Bayesian rock physics inversion
Importance sampling


Geophys. J. Int. (1999) **138,** 727–746

Geophysical inversion with a neighbourhood algorithm—II. Appraising the ensemble

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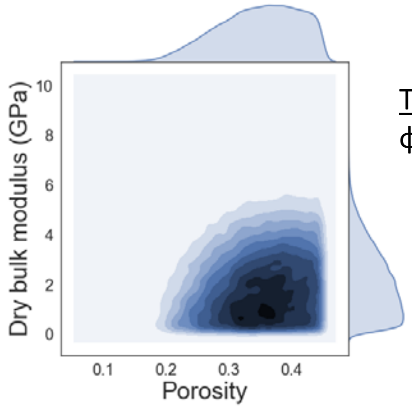
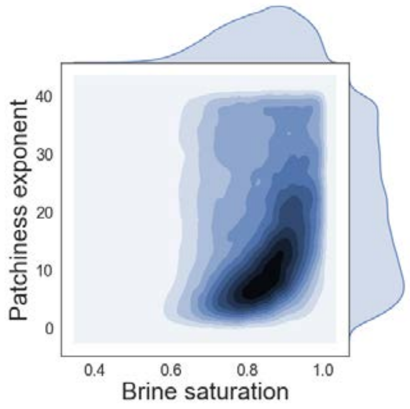
- Bayesian inference framework: $\sigma_{post}(\boldsymbol{m}|\boldsymbol{d}) = c\ \rho_{prior}(\boldsymbol{m})\ L(\boldsymbol{d}|\boldsymbol{m})$
- Need to infer statistically meaningful information from the ensemble of models: **importance sampling**.
- NA: adapted to different search methods (SA, MC, GA, NA…).
- Calculate **approximated PPD** everywhere in model space which is then used for evaluation of **Bayesian integrals**.
    - Use Voronoï cells for multi-dimensional interpolant, then use Gibbs sampler in neighbour cells (random walks).
- We can then calculate Bayesian integrals: posterior mean model, posterior model covariance matrix, resolution matrix and **marginal distributions**.
- **Appraisal step implemented in Python and Go**: soon available open source (github).

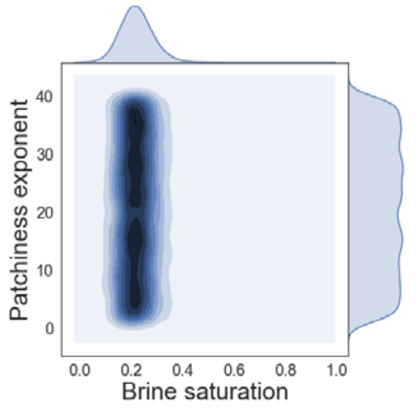


<u>True model</u>:
$\phi = 0.36$, $K_D = 2.56$ GPa

<u>Appraisal step</u>:
1D and 2D marginal probability densities (KDE)



<u>True model:</u>
$S_{CO_2} = 20\%$, e = 5



<u>True model:</u>
$S_{CO_2} = 80\%$, e = 5

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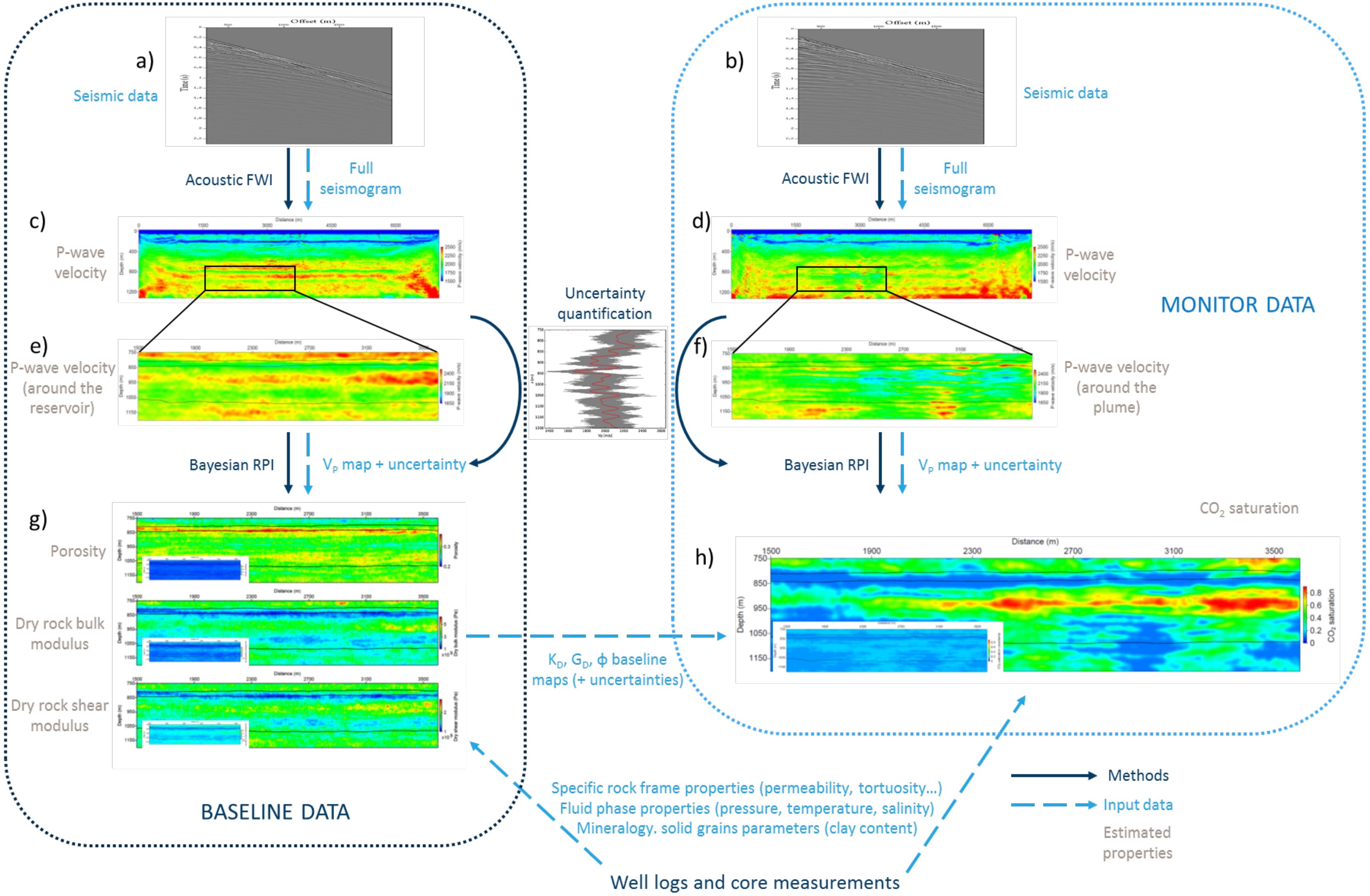
Time-lapse strategy



Workflow:

1. FWI + uncertainty analysis provides observed data $\mathbf{d_{obs}}$ and associated uncertainty $\mathbf{C_D}$ for second inversion and
2. Baseline data (1994): mapping of porosity + moduli (K_D, G_D)
3. Monitor data (2008): mapping of CO$_2$ saturations using baseline porosity and moduli maps as a priori input $\rho_{prior}(\boldsymbol{m})$

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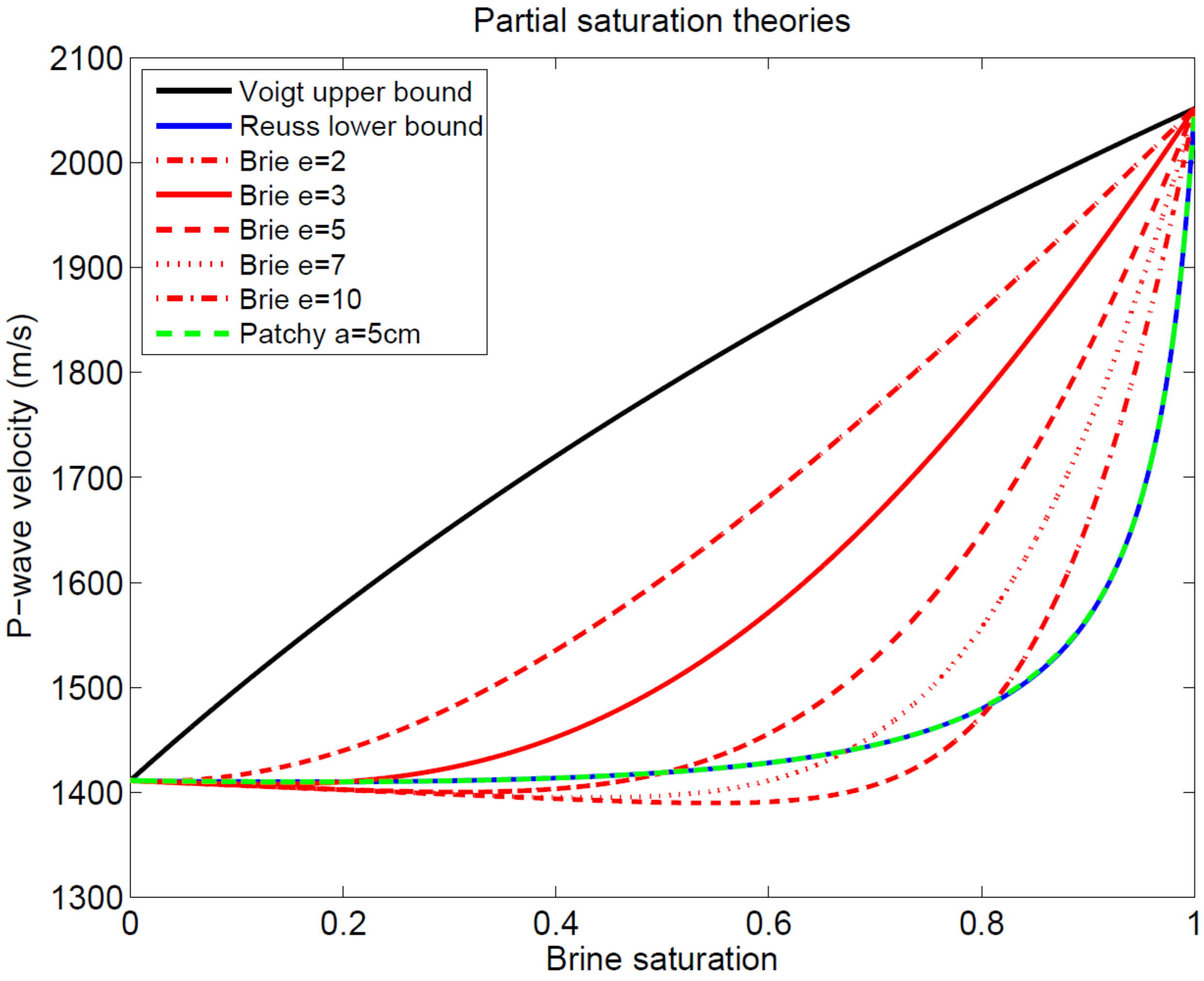
CO_2 partial saturation rock physics models

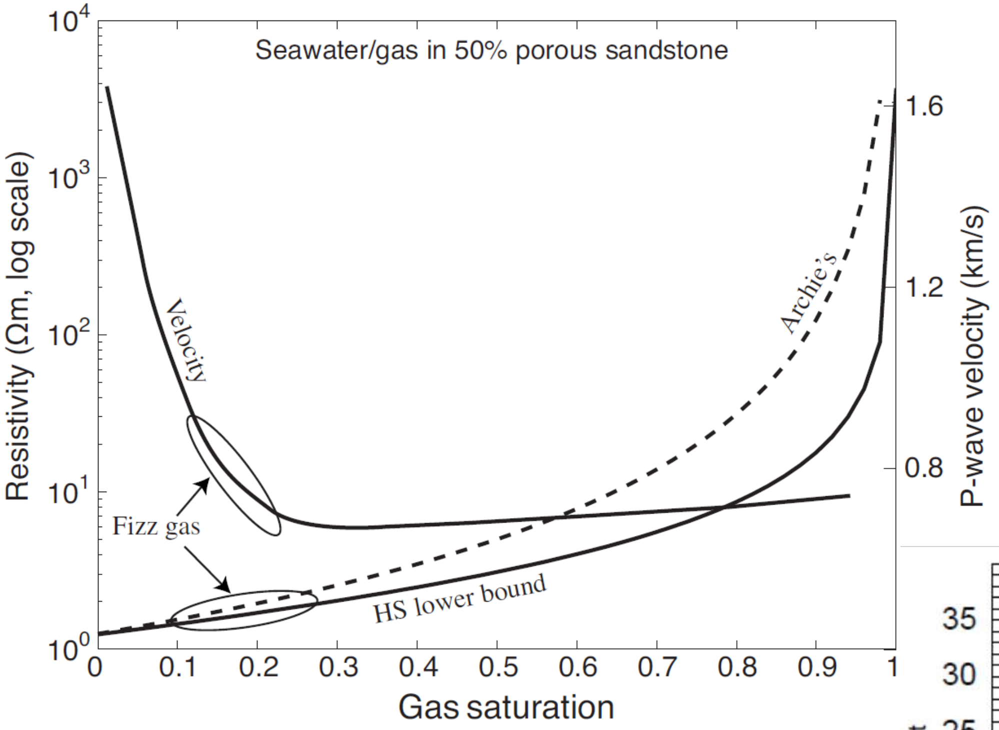
- Effective fluid phase plugged into *(Biot-) Gassmann* equations: different ways of calculating **effective fluid bulk modulus**.
- Brie equation (*Brie et al., 1994*):

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

- Patchiness/Brie exponent e:
  - e = 40 ➔ uniform mixing
  - e = 1, 3, 5? ➔ patchy mixing

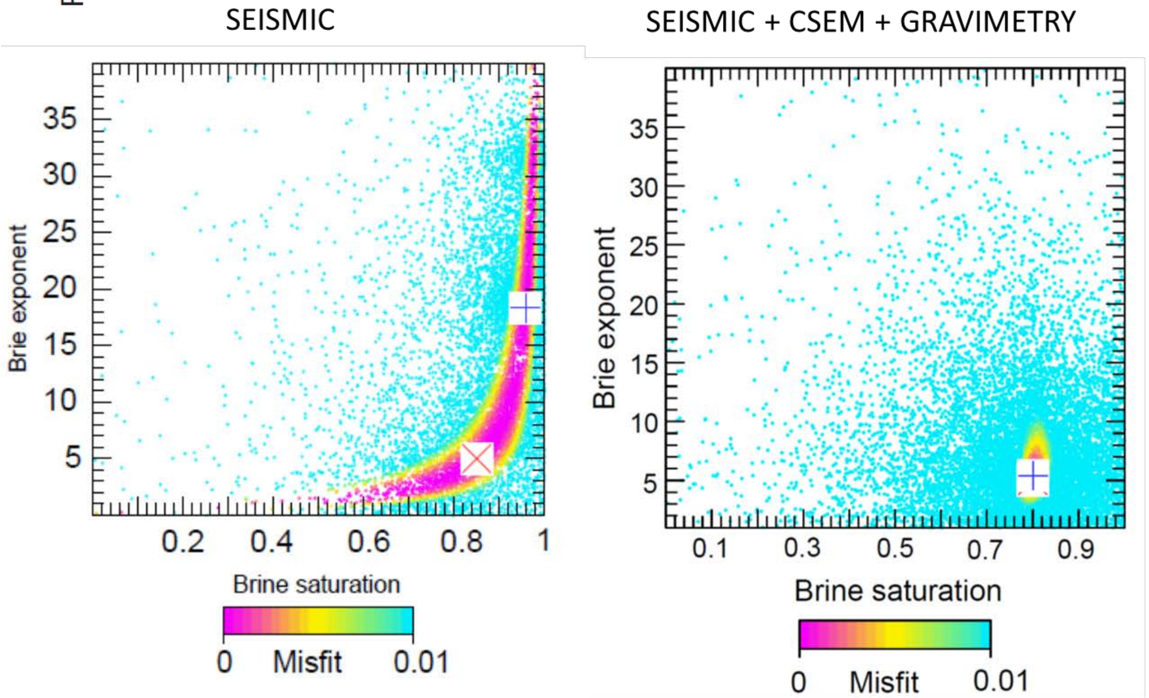


CO$_2$ partial saturation rock physics models



Constable (2010)

Archie law: $R_t = \frac{R_w}{\phi^m S_w^n}$



Dupuy et al., 2018

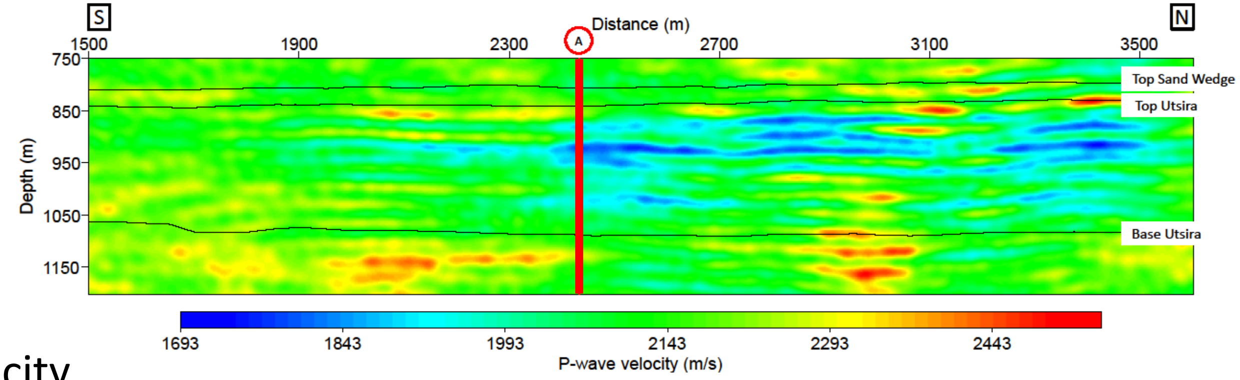
S_{CO2} = 20 %

X True model

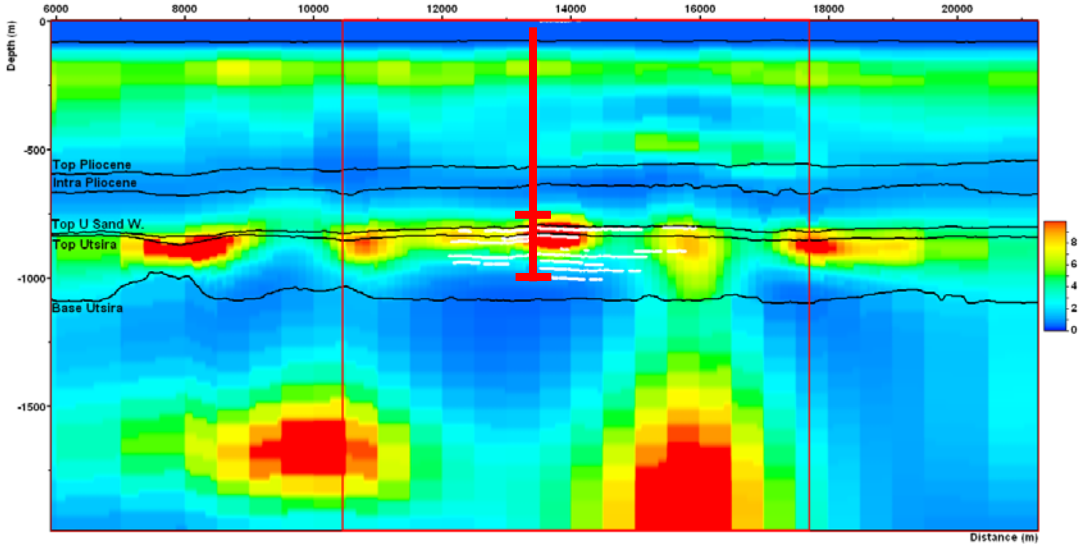
\+ Lowest misfit model

Inversion of saturation and Brie exponent

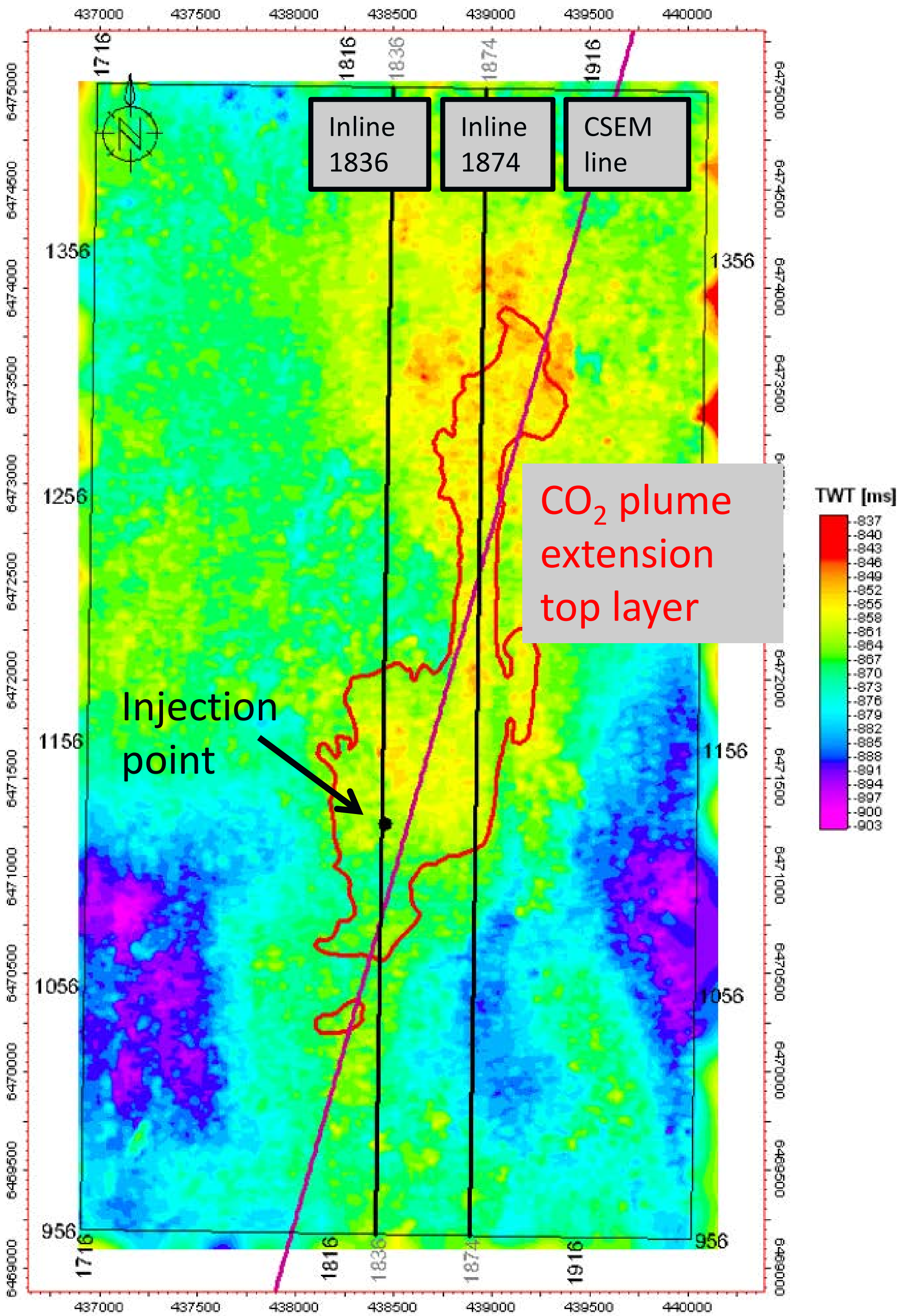
Sleipner real data case
Results of CSEM and seismic inversions



P-wave velocity model, inline 1836



Resistivity model along CSEM line (from Joonsang Park, NGI)



Inline 1836

Inline 1874

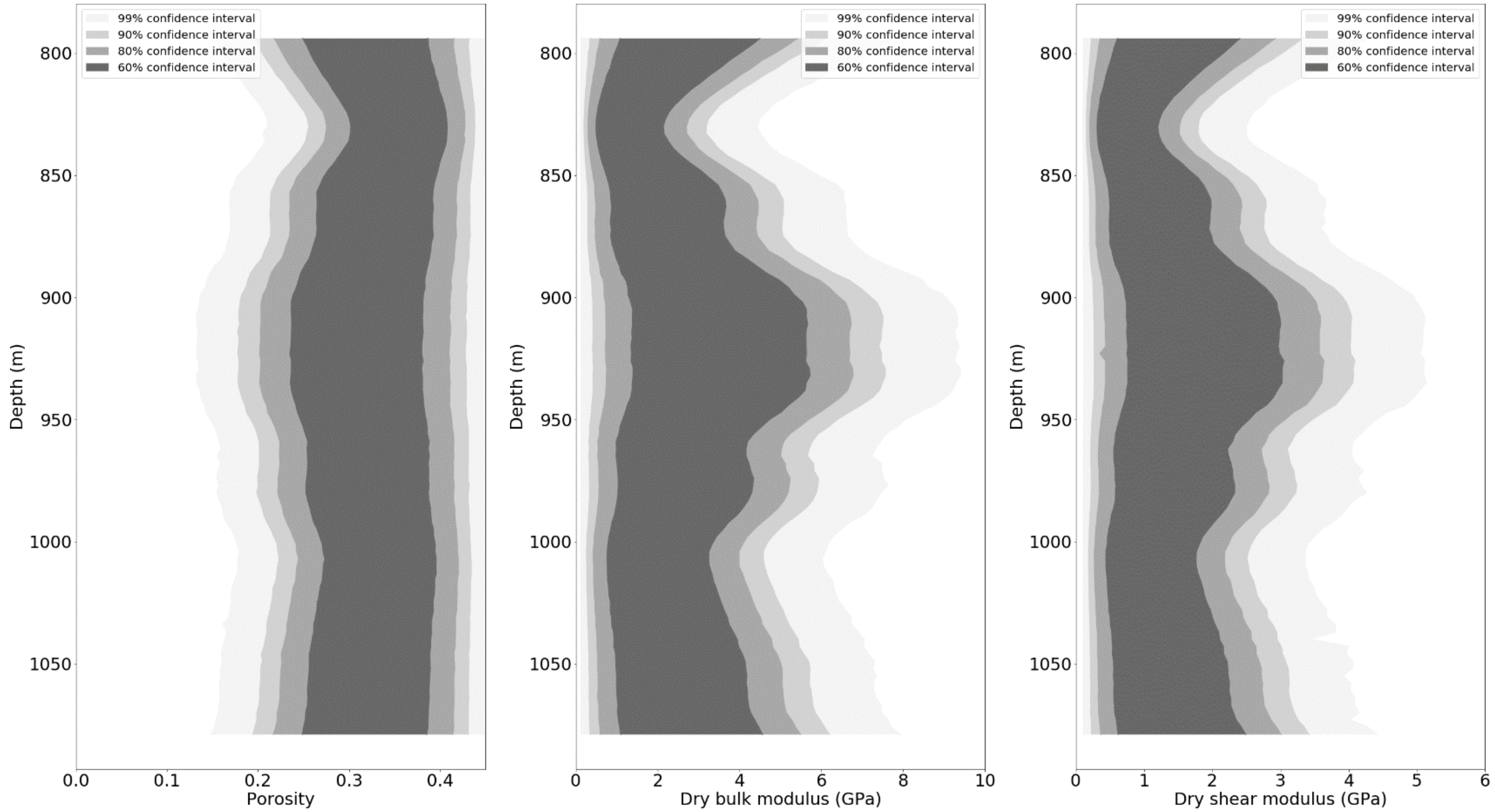
CSEM line

CO_2 plume extension top layer

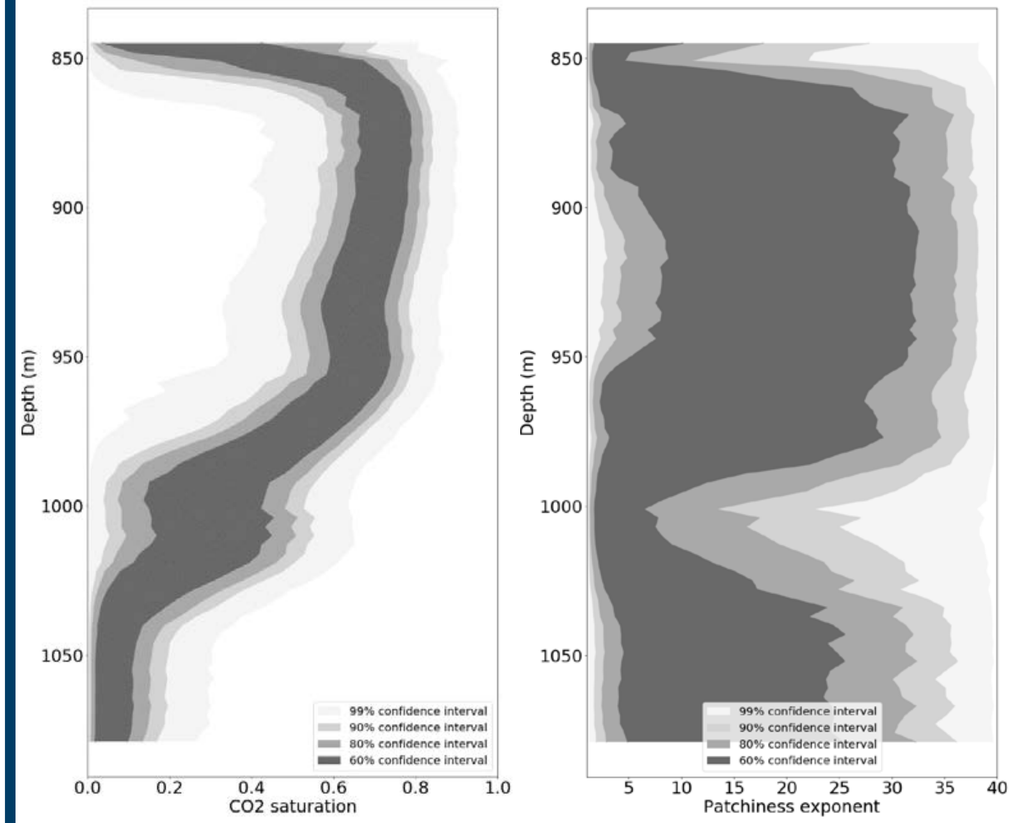
Injection point

Sleipner real data case
Results of rock physics inversion after appraisal

99% confidence interval
90% confidence interval
80% confidence interval
60% confidence interval



Baseline results: porosity, dry bulk and shear moduli

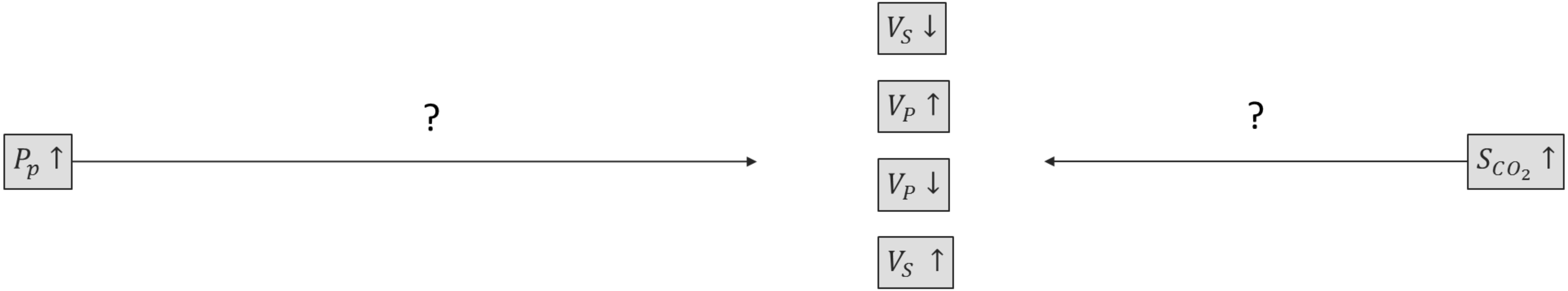


Monitor results: CO_2 saturation and patchiness exponent

Pressure effects

P_p = pore pressure

S_{CO_2} = CO_2 saturation



$P_p \uparrow$

?

$V_S \downarrow$

$V_P \uparrow$

$V_P \downarrow$

$V_S \uparrow$

?

$S_{CO_2} \uparrow$

V_P = P-wave velocity
V_S = S-wave velocity
ρ = bulk density

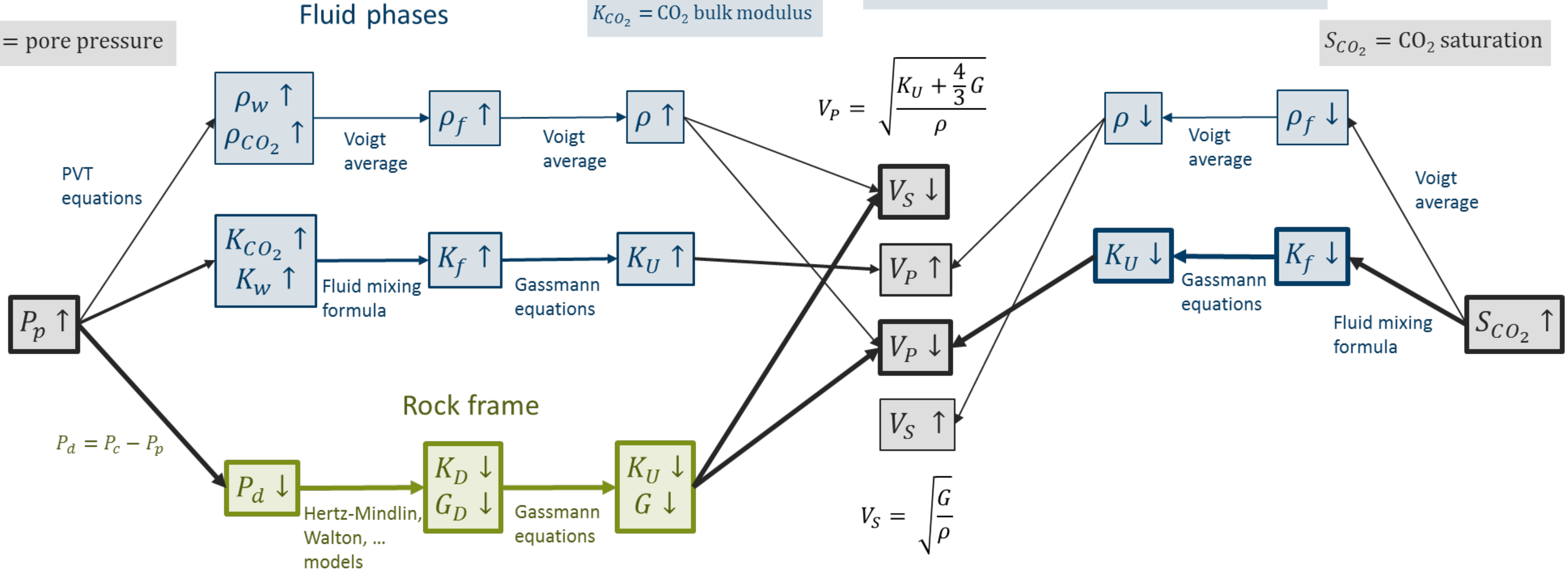
Pressure effects

P_p = pore pressure

ρ_w = brine density
ρ_{CO_2} = CO₂ density
K_w = brine bulk modulus
K_{CO_2} = CO₂ bulk modulus

ρ = bulk density
K_U = saturated rock (undrained) rock bulk modulus

S_{CO_2} = CO₂ saturation



Fluid phases

$P_p \uparrow$

PVT equations

$\rho_w \uparrow$ $\rho_{CO_2} \uparrow$

Voigt average

$\rho_f \uparrow$

Voigt average

$\rho \uparrow$

$K_{CO_2} \uparrow$ $K_w \uparrow$

Fluid mixing formula

$K_f \uparrow$

Gassmann equations

$K_U \uparrow$

Rock frame

$P_d = P_c - P_p$

$P_d \downarrow$

Hertz-Mindlin, Walton, … models

$K_D \downarrow$ $G_D \downarrow$

Gassmann equations

$K_U \downarrow$ $G \downarrow$

$$V_P = \sqrt{\frac{K_U + \frac{4}{3}G}{\rho}}$$

$V_S \downarrow$

$V_P \uparrow$

$V_P \downarrow$

$V_S \uparrow$

$$V_S = \sqrt{\frac{G}{\rho}}$$

$\rho \downarrow$

Voigt average

$\rho_f \downarrow$

Voigt average

$K_U \downarrow$

Gassmann equations

$K_f \downarrow$

Fluid mixing formula

$S_{CO_2} \uparrow$

P_c = confinement pressure
P_d = differential pressure

K_D = dry rock bulk modulus
G_D = dry rock shear modulus
K_U = saturated rock (undrained) rock bulk modulus
G = saturated rock shear modulus

V_P = P-wave velocity
V_S = S-wave velocity
ρ = bulk density

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Conclusions

- Quantitative inversion carried out in two steps with uncertainty propagation.
- Bayesian formulation is crucial for uncertainty assessment/quantification in CO_2 storage monitoring to verify conformance.
- Time-lapse strategy is crucial for definition of prior models.
- Proper CO_2 saturation estimation requires joint inversion of seismic and EM data.
- Final uncertainty range in CO_2 saturation for real data is quite narrow.
- Pressure-saturation discrimination should be taken into account when pressure effects are not negligible.

Acknowledgments

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