A machine learning based monitoring framework for CO2 storage

EGU-2020

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70 years 1950-2020

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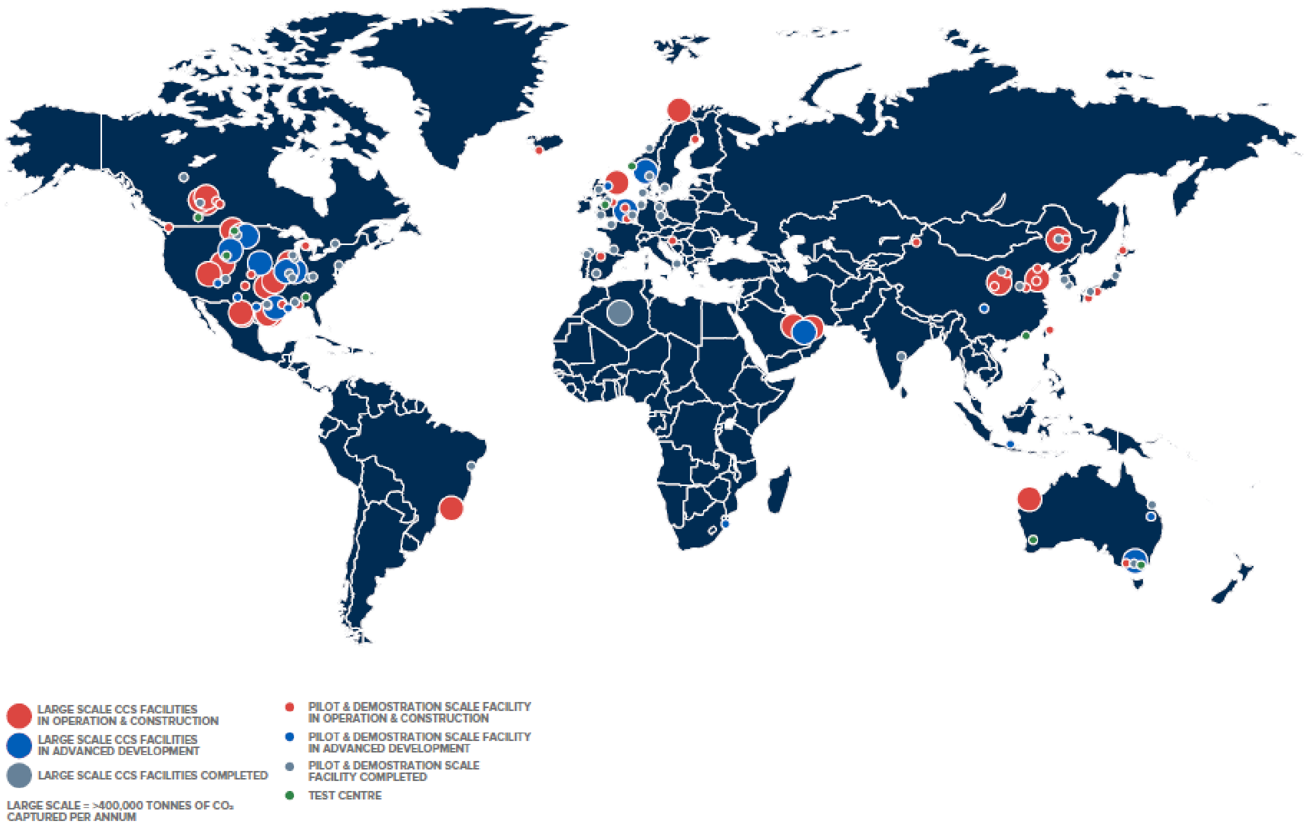
Background

- 19 operating large-scale facilities
  - 2 in Norway
  - More than 25 Mtons stored in 2019
- CCS (carbon capture and storage) is gathering pace, but the rates are still insufficient to make a significant impact on green house gas emissions
- There is a lot at stake. CCS requires high investments



CCS facilities around the world.
(source: global status of ccs, http://www.globalccsinstitute.com)

→ Cost efficiency, including in monitoring is a must

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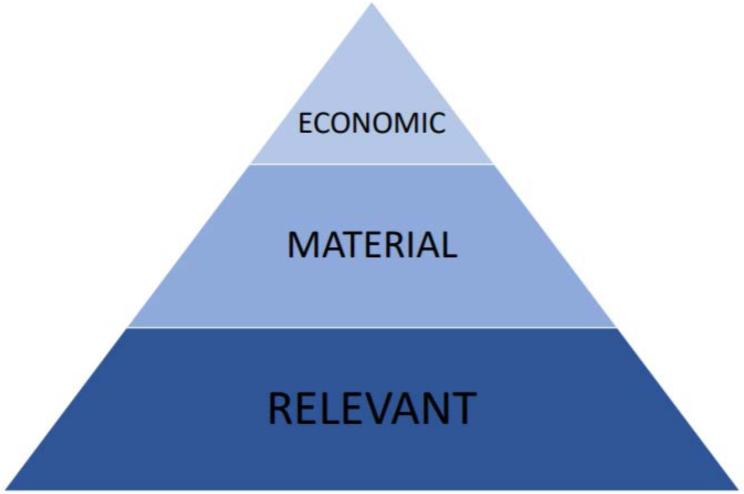
Background
Geophysical monitoring

- Important for conformance and containment verification
  - conformance: CO_2 behaviour in the storage site is consistent with model-based forecasts
  - containment: demonstrate security of CO_2 storage
- Geophysical monitoring is very valuable but can be costly.
  - Example: Time lapse 3D seismic
- Acquire data if *the value* is larger than the acquisition cost, need for:
  - Dealing with uncertainties
  - The right kind of information
  - The right amount of information



Criteria for information to be valuable

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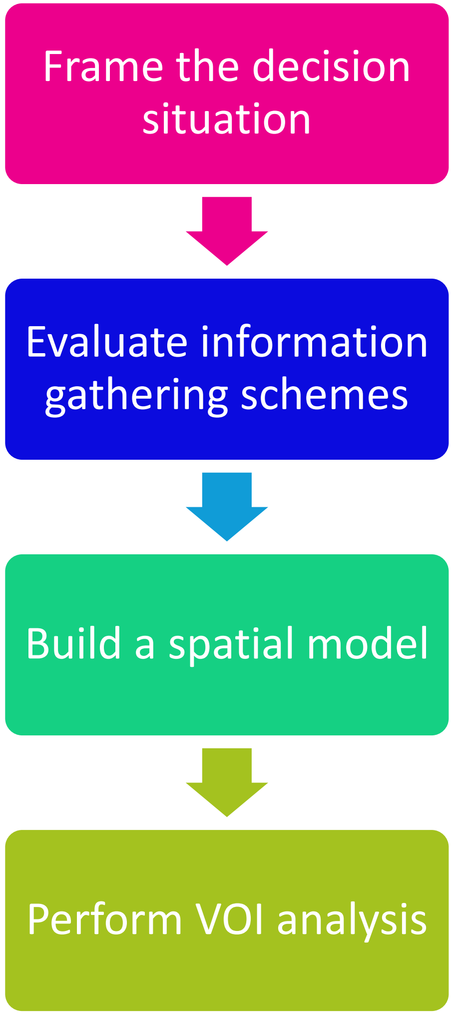
Value of information (VOI)

Why VOI analysis?

- VOI has the potential to support decision making around information gathering
- It allows the decision maker to perform a reasonable evaluation before the information is purchased and therefore revealed
- If the decision maker can model value using monetary units, then VOI is also in monetary units
- Can incorporate the spatial dependence of subsurface uncertainties, the gathered information, and the decision situation

Robust and general framework to support decision making



Framework for VOI analysis (Eidsvik et al., 2015)

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Value of information

- We need to define:
  - Alternatives: $a \in A$
  - Uncertainty/Scenario class: $x \in \Omega$
  - Time (if the VOI analysis is time dependent): t
  - Value derived from the decision situation: $v_t(x, a)$
  - Purchased data (at time t): $\boldsymbol{y}_t$
- The VOI is defined by the difference between posterior (PoV_t) and the prior value (PV_t).

$$\begin{aligned} \mathrm{VOI}_t &= \mathrm{PoV}_t - \mathrm{PV}_t \\ &= \int \max_a \{E[v_t(x,a)|y_t]\}\, p(y_t) dy_t - \max_a \{E(v_t(x,a))\} \end{aligned}$$

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Value of information

- The posterior value can be hard to calculate with imperfect information
- Monte Carlo sampling and approximate conditional probabilities $\hat{P}(X = x|yt)$ can be used to approximate PoV_t and calculate the VOI

$$\begin{aligned}
\mathrm{PoV}_t &= \int_{\boldsymbol{y}_t} \max_{a \in A} \left\{ \mathrm{E}[v_t(x,a)|\boldsymbol{y}_t] \right\} p(\boldsymbol{y}_t) d\boldsymbol{y}_t \\
&\approx \frac{1}{B_{test}} \sum_{b=1}^{B_{test}} \max_{a \in A} \left\{ \mathrm{E}[v_t(x,a)|\boldsymbol{y}_t^b] \right\}, \\
\mathrm{E}[v_t(x,a)|\boldsymbol{y}_t^b] &= \sum_x v(x,a_t) P(X = x|\boldsymbol{y}_t^b) \approx \sum_x v(x,a_t) \hat{P}(X = x|\boldsymbol{y}_t^b).
\end{aligned}$$

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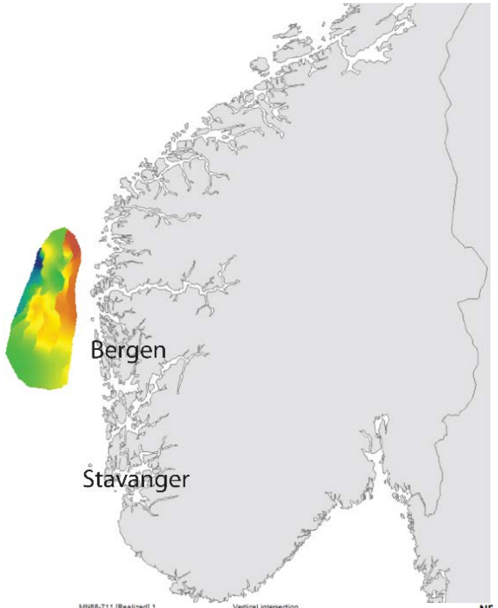
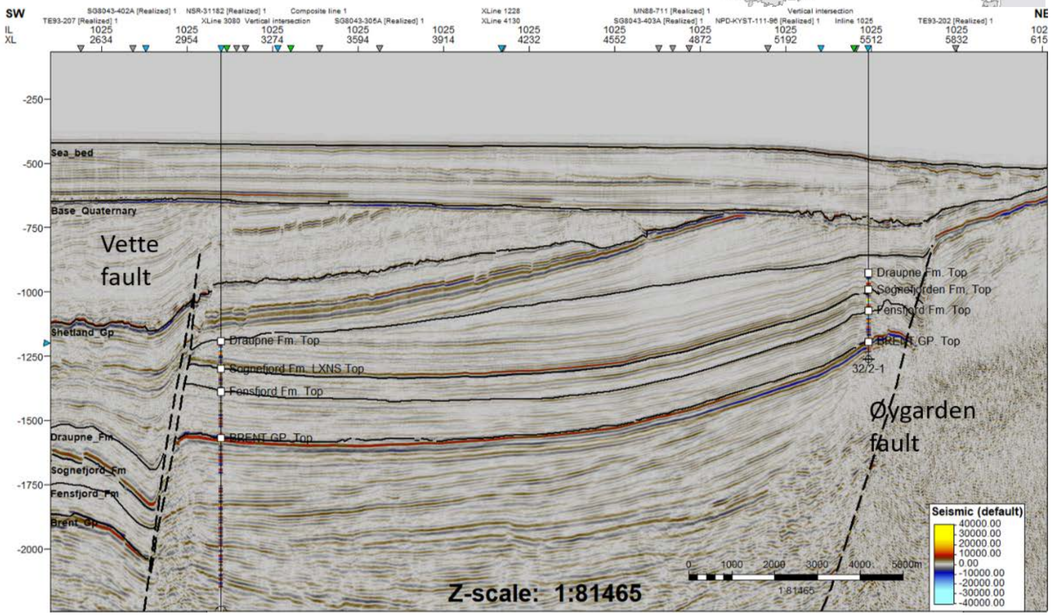
Case study Smeaheia

- Possible storage candidate for the Norwegian full-scale CCS project
- Possible injection @ 1200-1500m deep in Sognefjord, Fensfjord or Krossfjord formations under Draupne shale overburden.
- Uncertainties related to:
  - Reservoir and caprock properties
  - Fault properties

Location of Smeaheia area. The top of the Fensfjord (reservoir) formation is displayed





Example of a 2D extracted seismic section from the Smeaheia area. The main faults, inter-preted horizons, and well locations are indicated.

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Case study
Decision problem

- An operator wants to inject CO_2 for a period of 25 years.
- It is uncertain whether the site will leak or not
- During this injection period, the operator has the possibility to do one seismic survey and decide whether to continue or stop the injection.
- When should the survey be done?

→ Time dependent VOI analysis of seismic data related to leakage detection.

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Case study
Decision problem

- Alternatives: $a \in A = \{0,1\}$, to continue ($a = 1$) or to stop the injection ($a = 0$) at time t
- Uncertainty/Scenario class: $x \in \Omega = \{0,1\}$, whether CO_2 will leak ($x = 1$) or not ($x = 0$)
- Time (if the VOI analysis is time dependent): $t \in (0,25)$
- Value derived from the decision situation: $v_t(x,a)$
- Purchased data (at time t): $\boldsymbol{y}_t$ seismic data

- 25 years injection time
- One unit injected per year
- Fixed cost if injection is done: 5
- Cost of injecting per unit CO_2 : 0.2
- Fixed cost if leakage: 2
- Fine if leakage per unit of injected CO_2 : 1.2
- Cost of not injecting per unit CO_2 : 0.8

Many assumptions and simplifications

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Case study
Decision problem

- Alternatives: $a \in A = \{0,1\}$, to continue ($a = 1$) or to stop the injection ($a = 0$) at time t
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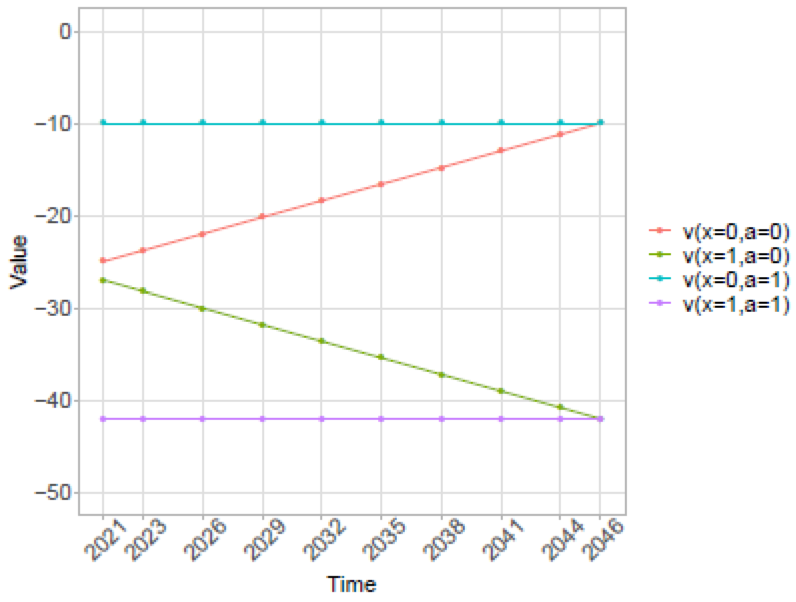
Values before any monitoring data is purchased

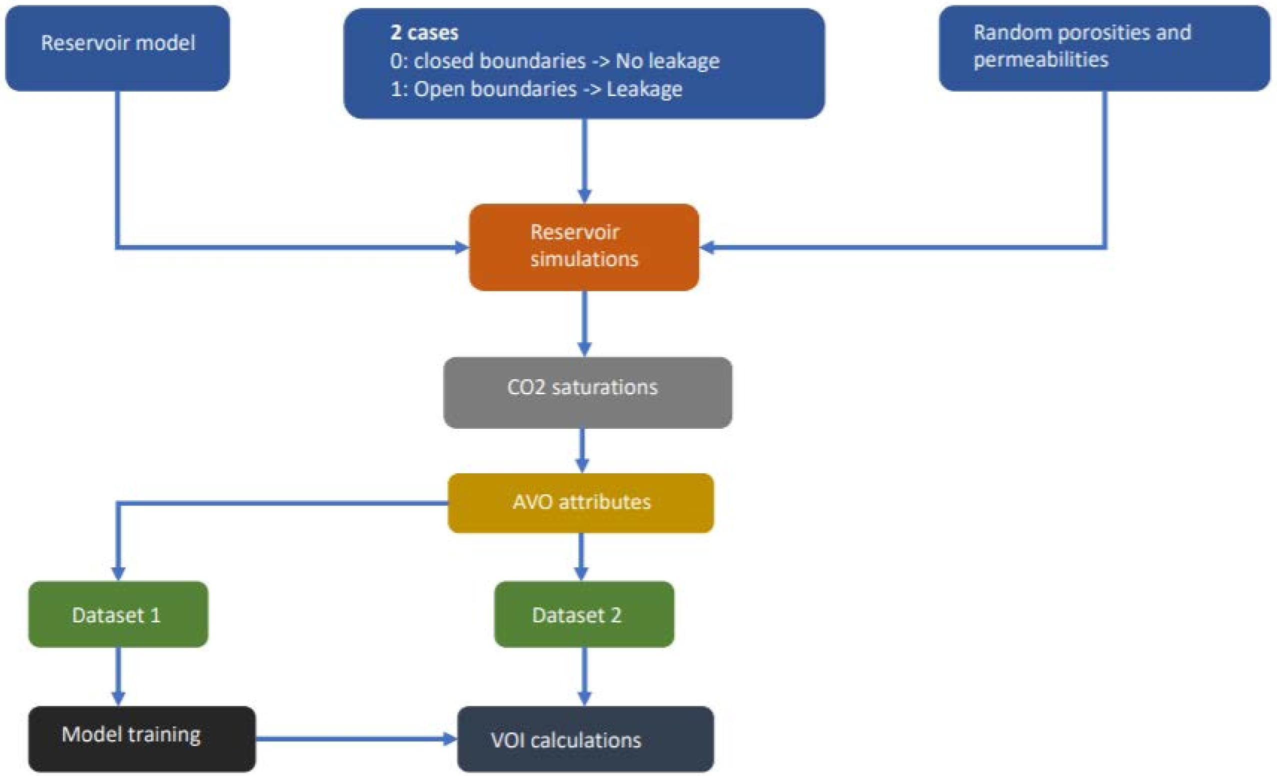
- $v_t(x = 0, a = 0) = -5 - 0.2\mathrm{t} - 0.8(25 - \mathrm{t}) = -25 + 0.6\mathrm{t}$
- $v_t(x = 1, a = 0) = -5 - 0.2\mathrm{t} - 0.8(25 - \mathrm{t}) - 2 - 1.2\mathrm{t} = -27 - 0.6\mathrm{t}$
- $v_t(x = 0, a = 1) = -5 - 0.2 * 25 = -10$
- $v_t(x = 1, a = 1) = -5 - 0.2 * 25 - 2 - 1.25 * 25 = -42$



Objective: compare the expected values with monitoring data to the one without monitoring data

Case study
Workflow

1. Reservoir simulation
2. AVO attributes
3. ML
4. VOI analysis



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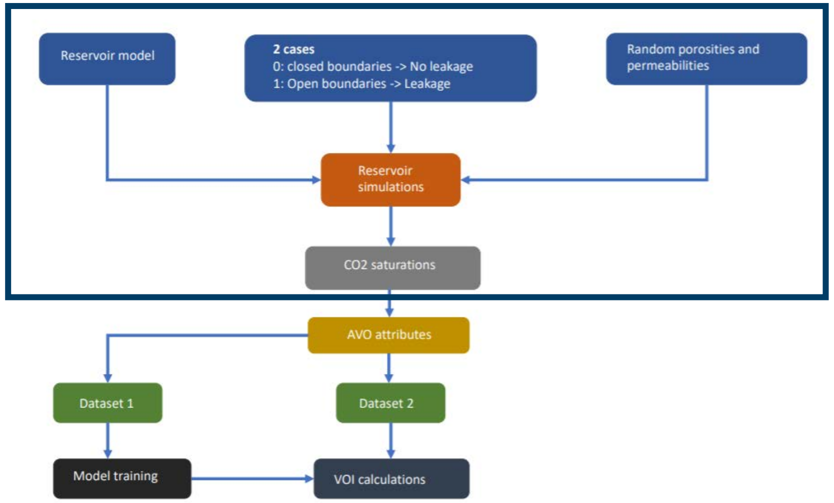
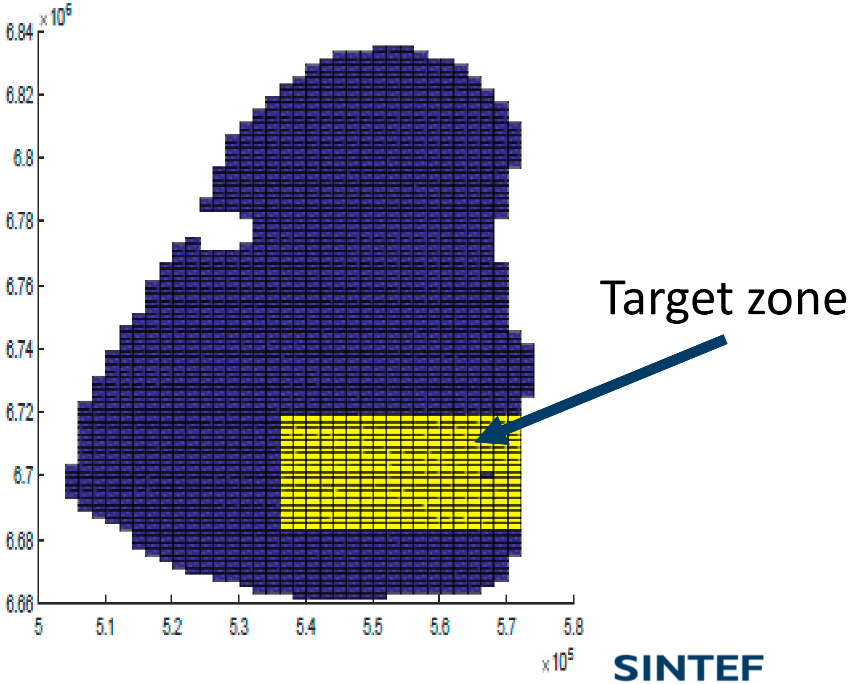
Workflow
Reservoir simulation

- MRST: MATLAB Reservoir Simulation Toolbox
  - Sognefjord formation
  - Vertical equilibrium model
  - 1000 realisations:
    - Reservoir boundaries set to open (leaking fault) or closed (sealing fault)
    - Uncertain porosity and permeability variables
      - Mean and variance estimated from log data.
      - Spatial correlation introduced





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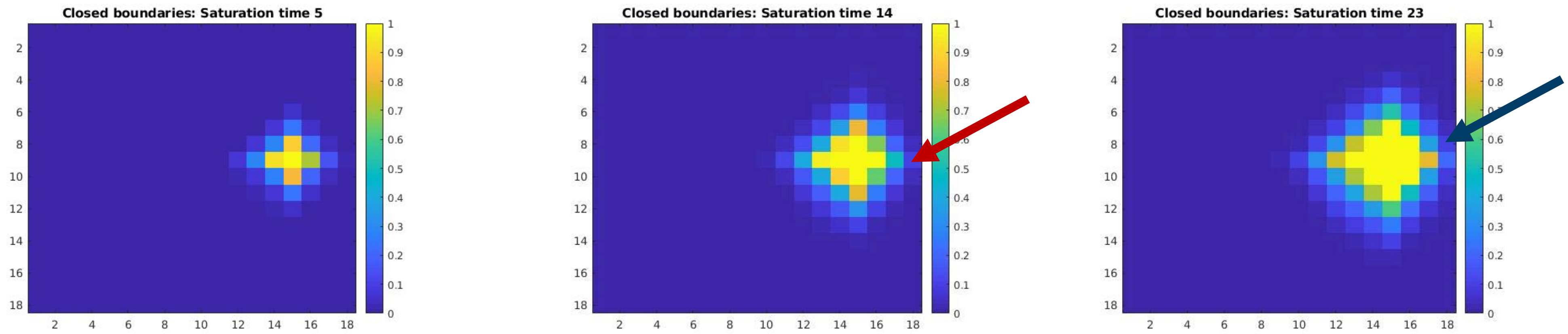
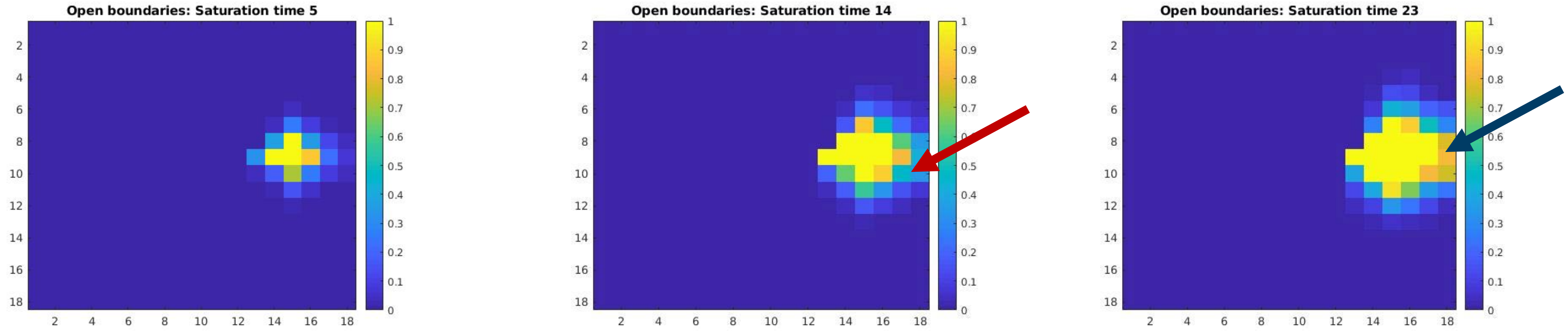
Workflow: Saturation maps – examples



Closed boundaries



Open boundaries

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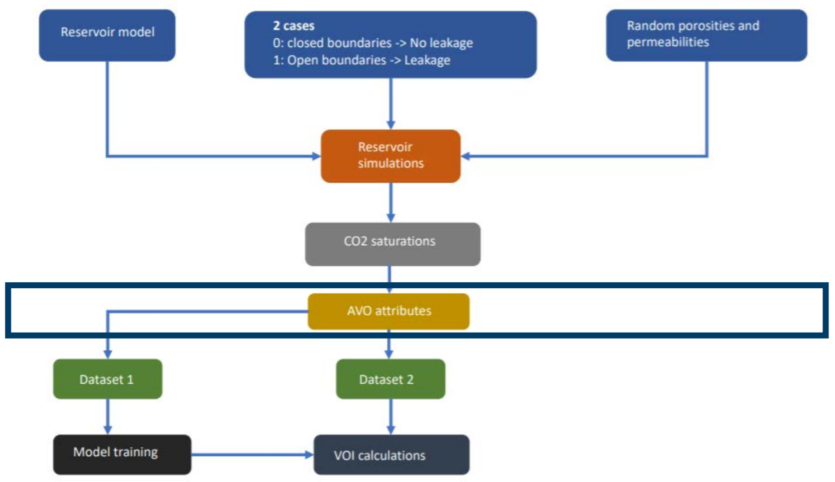
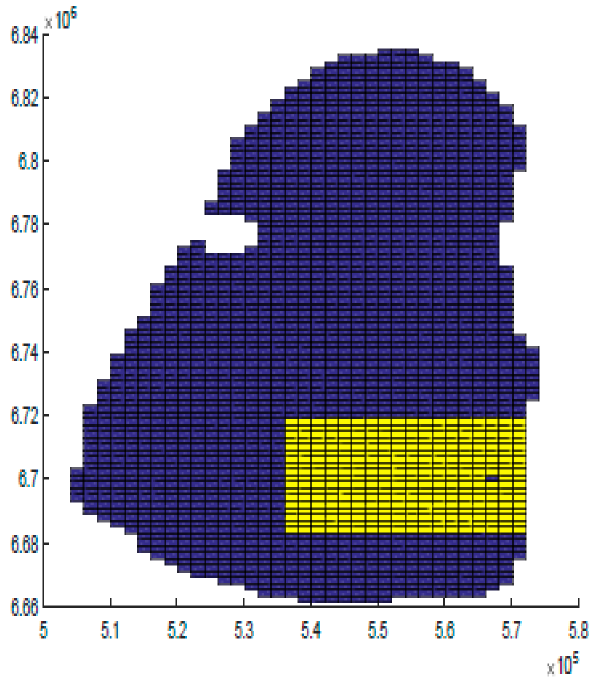
Workflow
AVO attributes

- AVO attributes generated along the top reservoir zone
  - Gassmann fluid substitution (from saturations to elastic properties)
  - Noise (variance) added for both attributes
- Two different datasets:
  - R_0 (zero offset reflectivity) attribute
  - R_0 and G (AVO gradient) attributes (two attributes per cell)

$$R_0 = \frac{1}{2}\left(\frac{\Delta V_p}{V_{pm}} + \frac{\Delta \rho}{\rho_m}\right),$$

$$G = \frac{1}{2}\frac{\Delta V_p}{V_{pm}} - 2\left(\frac{V_s}{V_p}\right)^2\left(2\frac{\Delta V_s}{V_{sm}} + \frac{\Delta \rho}{\rho_m}\right)$$





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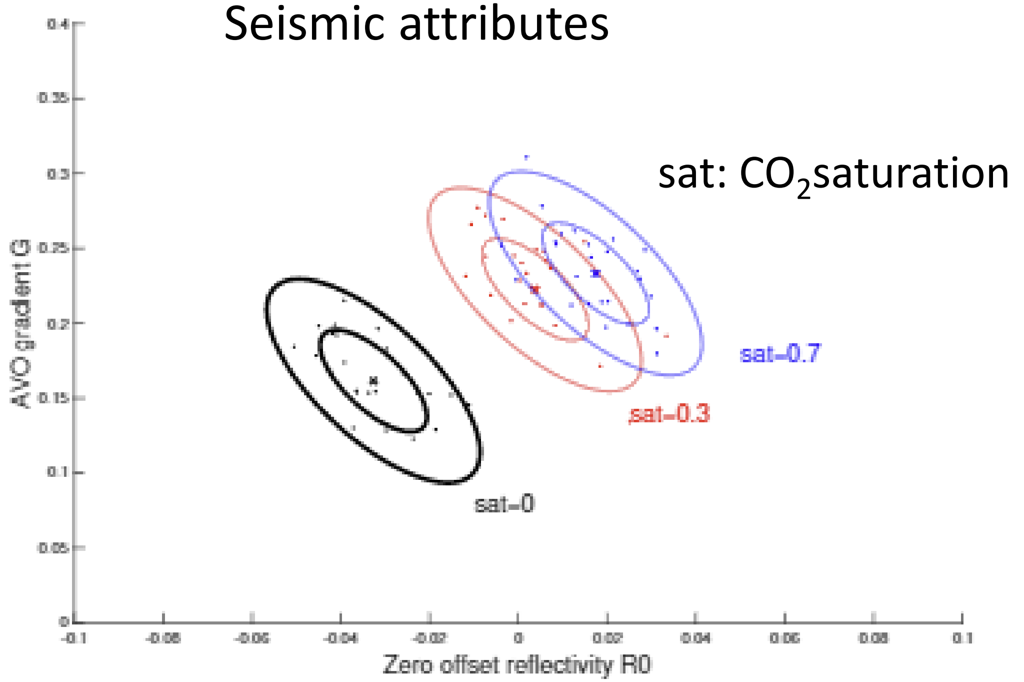
Workflow
AVO attributes

Seismic attributes



Not straightforward to differentiate CO_2 saturation levels with AVO attributes

Expected seismic AVO response (dots) for different levels of CO_2 saturation along with 50 % and 80 % uncertainty contours in the seismic AVO observation model.

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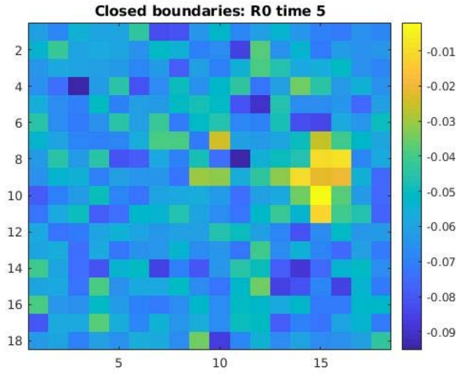
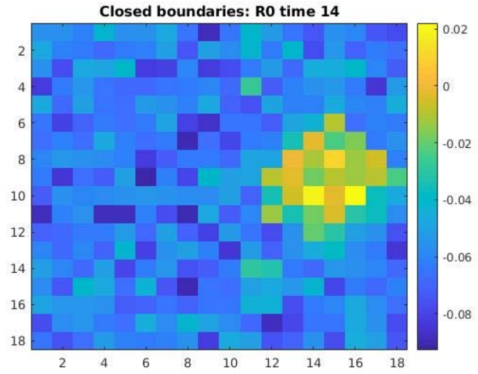
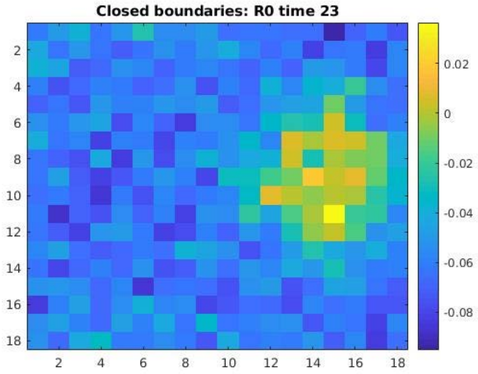
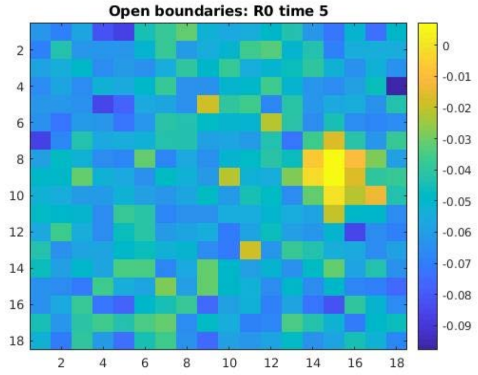
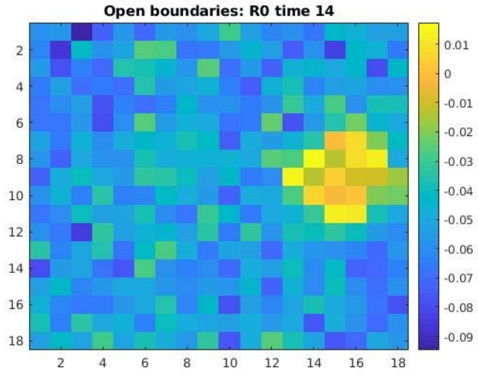
Workflow: R0 maps– examples

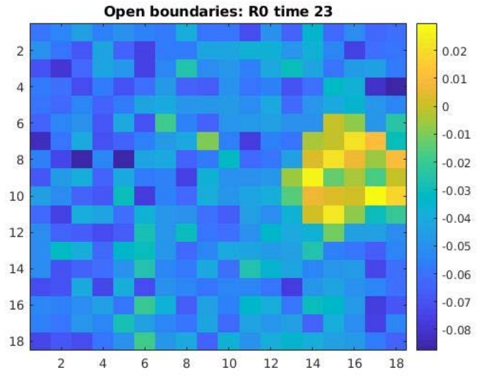












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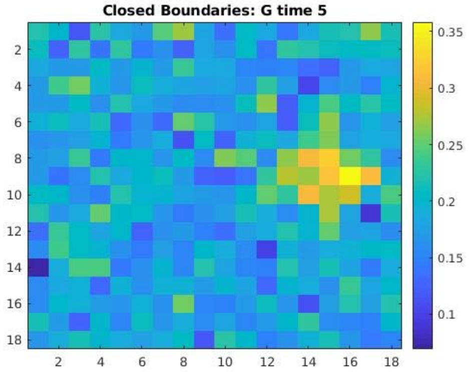
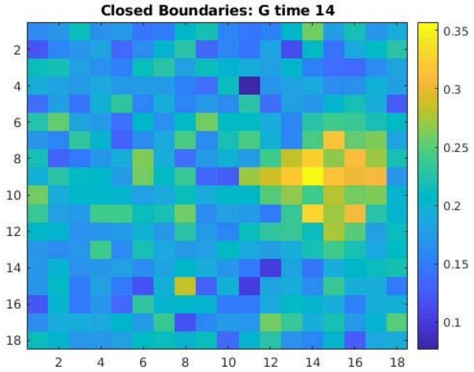
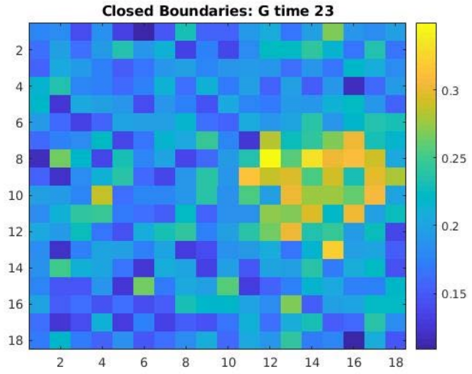
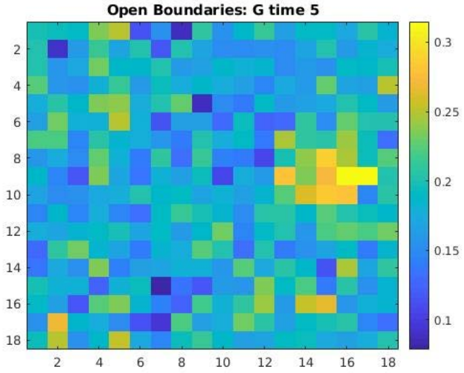
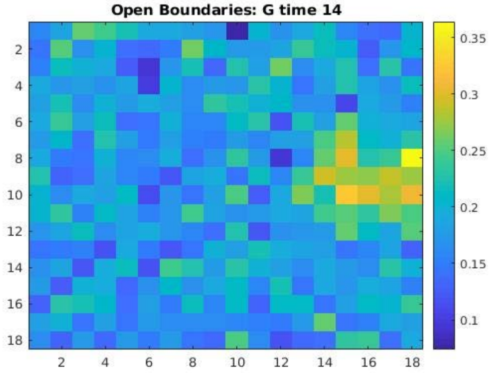
Workflow: G maps– examples

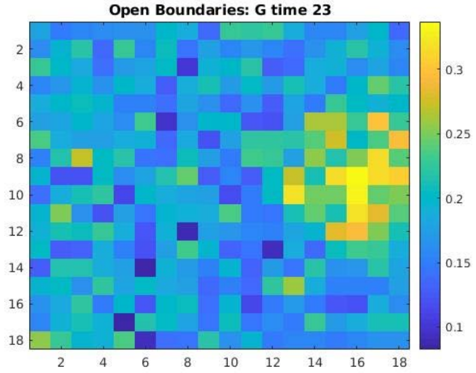












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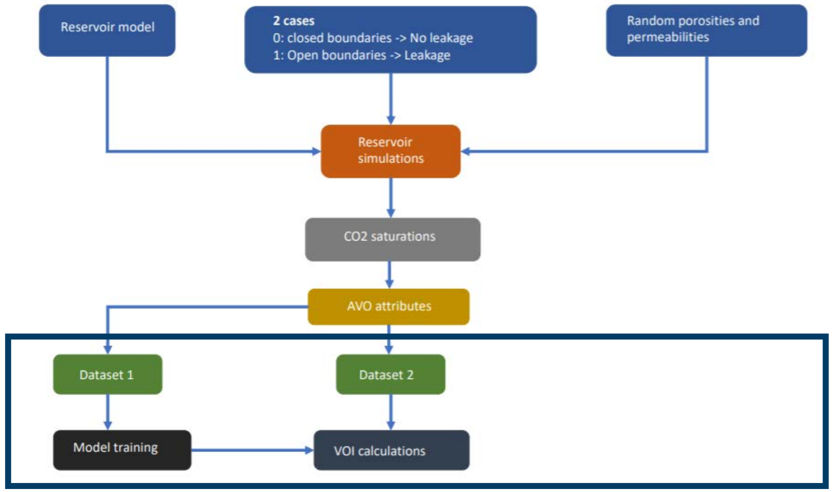
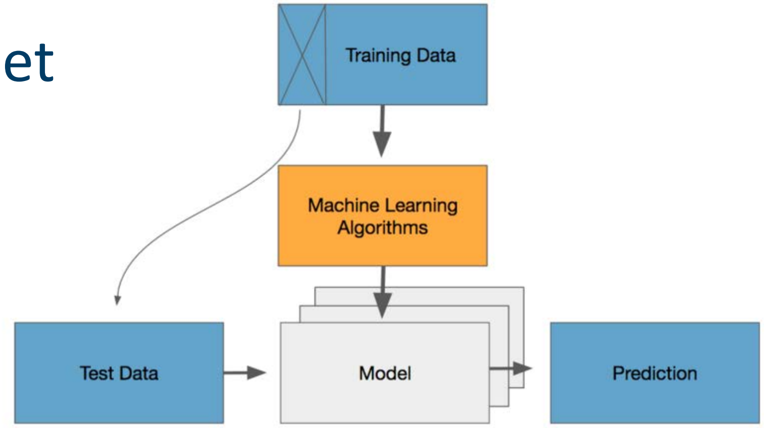
Workflow
Machine learning



- Objective: classify probabilities of seal and leak scenario ($\hat{P}(X = x|y_t)$, $x \in \{0,1\}$) needed for the PoV calculation
- We split the data generated through reservoir simulation

and AVO modelling into training (80%) and testing (20%) dataset

  - Training can be performed using different ML algorithms



- Input data: AVO attribute(s) in each grid of the top of the reservoir
- Output: seal or leak class by comparing $\hat{P}(X = 1|y_t^b)$ and $\hat{P}(X = 0|y_t^b)$

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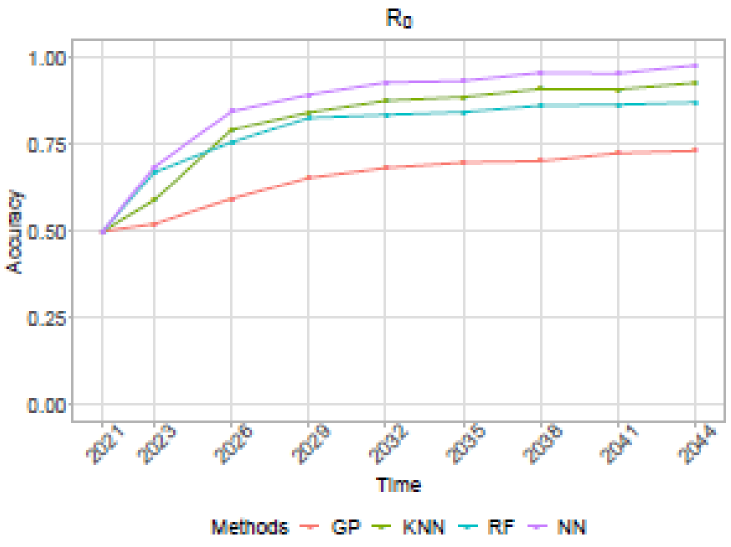
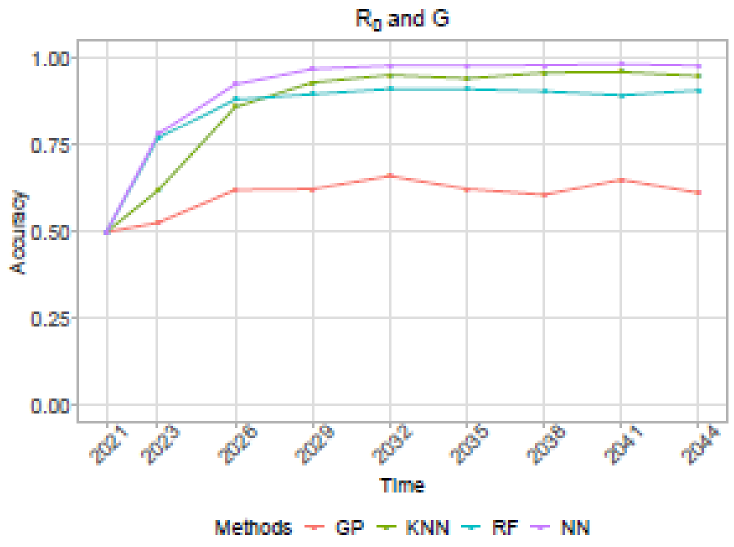
Workflow
Machine learning

- Accuracy score (ACC) to evaluate the performance of the prediction

$$ACC = \frac{TP + TN}{TP + TN + FP + FN}$$

- Methods tested:
  - Gaussian process (GP)
  - K-Nearest neighbours (kNN)
  - Random forest (RF)
  - Neural network (NN)





The accuracy values plotted as a function of the year of monitoring

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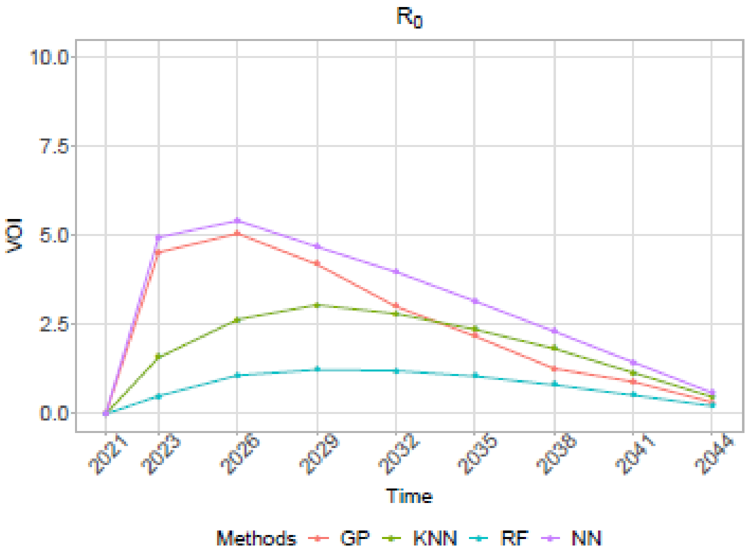
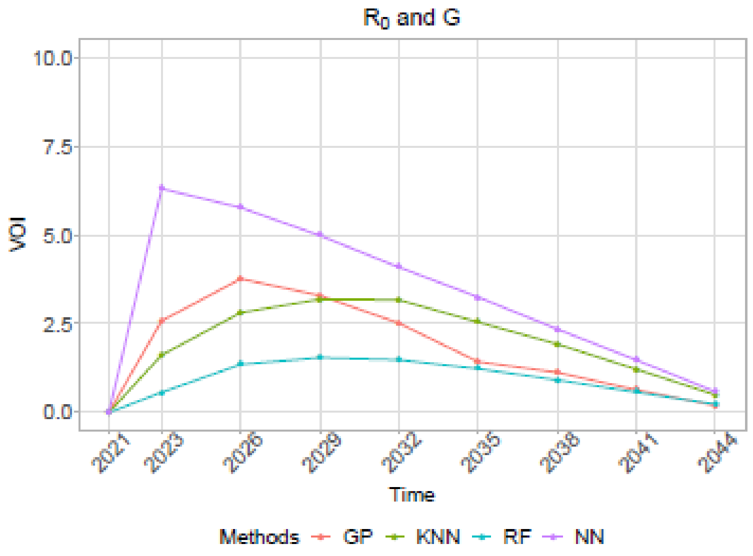
Results
VOI for the different models

- Increase and decrease in all models
- Optimum time around year 2026-2029
- Largest value provided by the NN
- With both seismic attributes, the optimal monitoring time is shifted towards earlier times → possible to detect leakage earlier with more info



(a) VOI of zero-offset seismic AVO attribute.



(b) VOI of zero-offset and AVO gradient.

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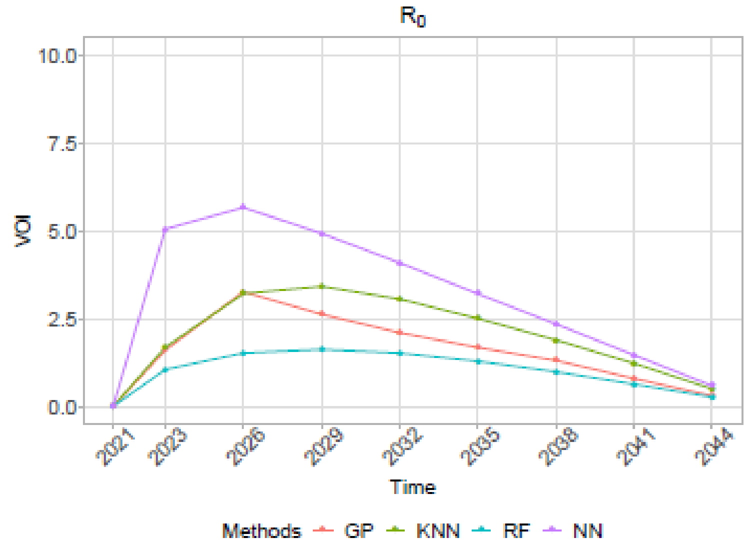
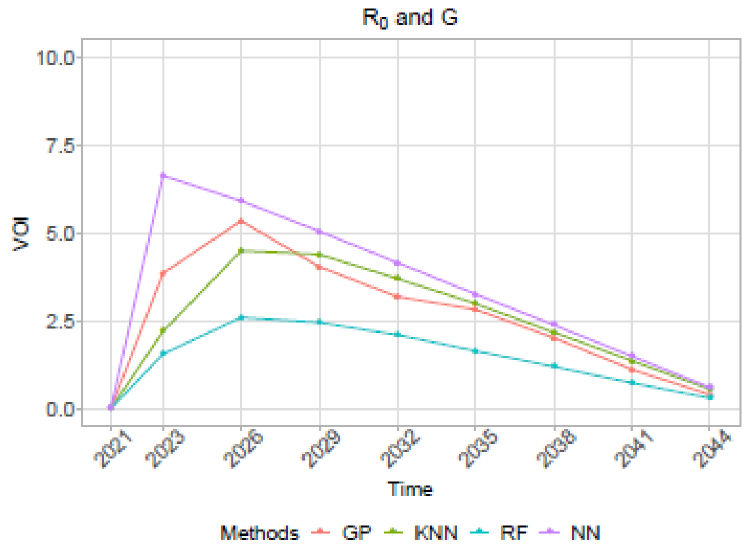
Results-VOI for the different models- higher signal to noise ratio (SNR)

- Higher VOI with less noise
- Shift towards earlier times for GP, KNN, and NN
- Little changes with NN indicating possible overfitting



(a) VOI of zero-offset seismic AVO attribute.



(b) VOI of zero-offset and AVO gradient

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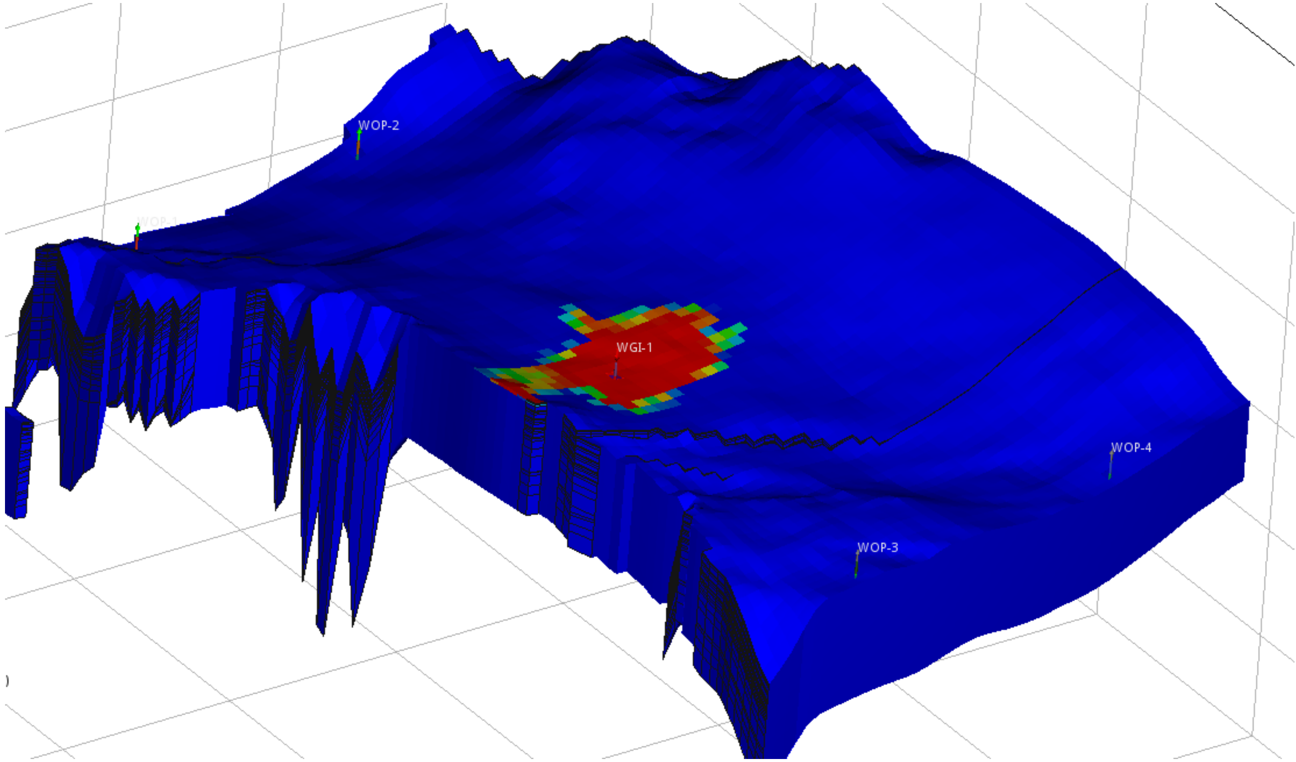
Discussions/perspectives

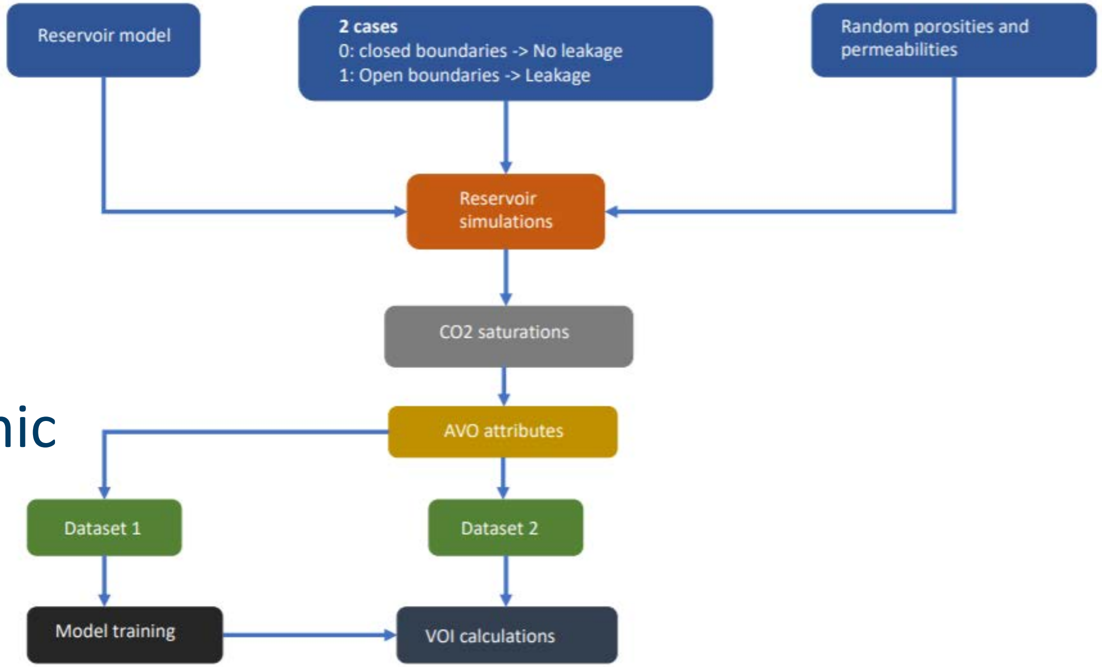
- More realistic model:
  - Grid size relatively large
  - Include a more detailed reservoir topography
  - Smaller blocks would likely lead to higher detail in the PDE solver and better separation (and hence classification) between open/close boundary realizations.



→ To be analysed against the computational burden to generate enough realizations

Summary

- Proposed workflow for CO_2 storage includes reservoir modelling, geophysical and rock physics analysis, VOI with elements of ML
- Simplified case study at Smeaheia with seismic data
  - MRST for reservoir modelling
  - Random porosity/permeability perturbations
  - Leaking/non leaking scenarios
- Various ML techniques tested



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Discussions/perspectives

- More realistic model
  - Possibility to study
    - Sensitivity to compartmentalization
    - 3D connections of volumes
- Beyond binary leak or seal input
  - Could be generalized to partial leakage near the fault
- More complex decision problem, including options to:
  - Increase/decrease injection rate
  - Produce water
  - Study sensitivity to the decision framing parameters

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