FORCE:
Making good decisions under subsurface uncertainty:
How difficult can it be?

Estimating leakage risk through legacy wells in a CO_2 storage site

Alejandro Bello Palacios, Malin Torsæter, Jamie Stuart Andrews

7th February 2024

Agenda

Introduction

Motivation

Toolbox for legacy Wells evaluation

- Preliminary analysis
- Simulation workflow

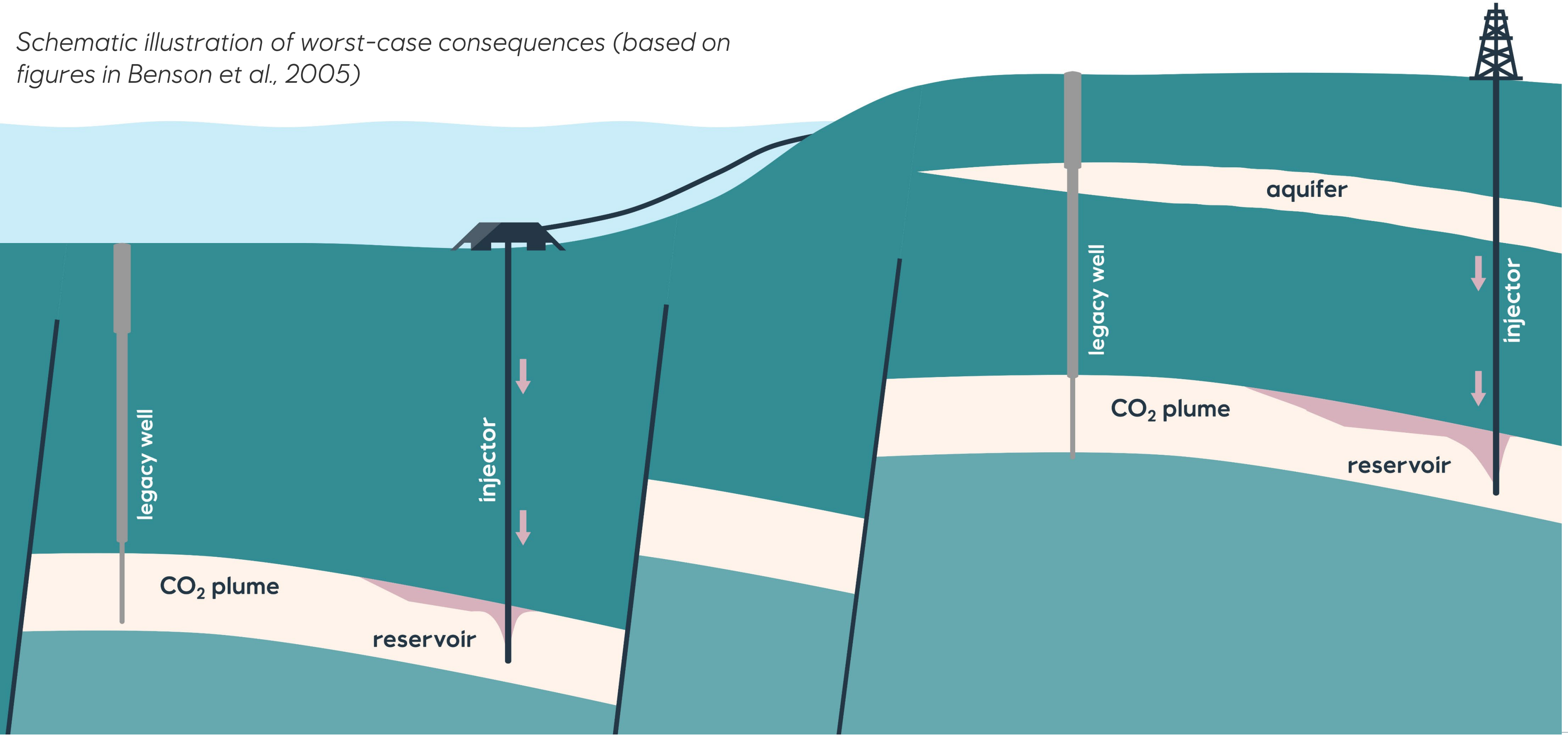
Conclusion

Open

Legacy wells = *any pre-existing well (i.e. exploration, wildcat, appraisal) that is inactive or P&A, and enters the CO_2 storage formation.*

Introduction: Legacy wells

Schematic illustration of worst-case consequences (based on figures in Benson et al., 2005)



Introduction: Legacy wells

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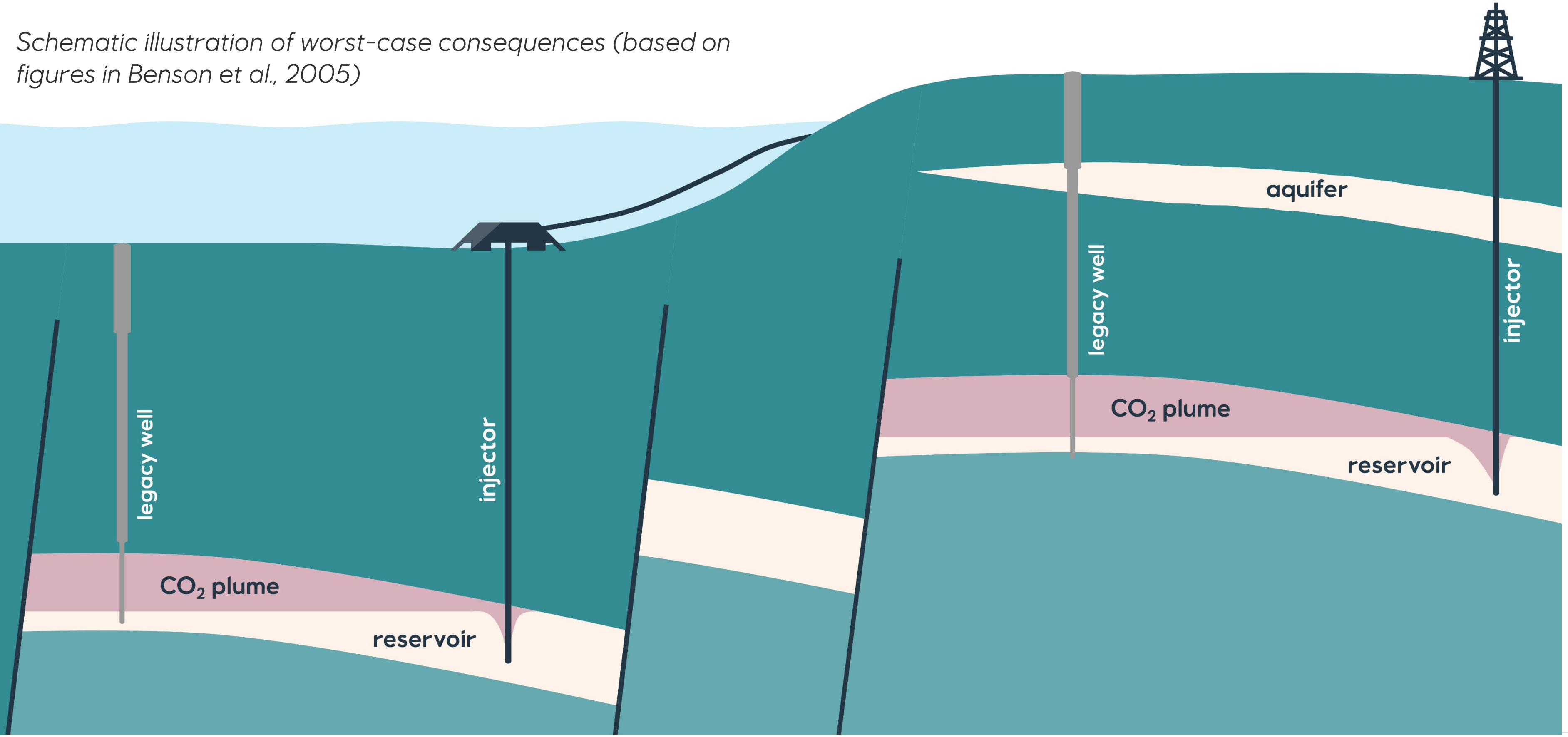


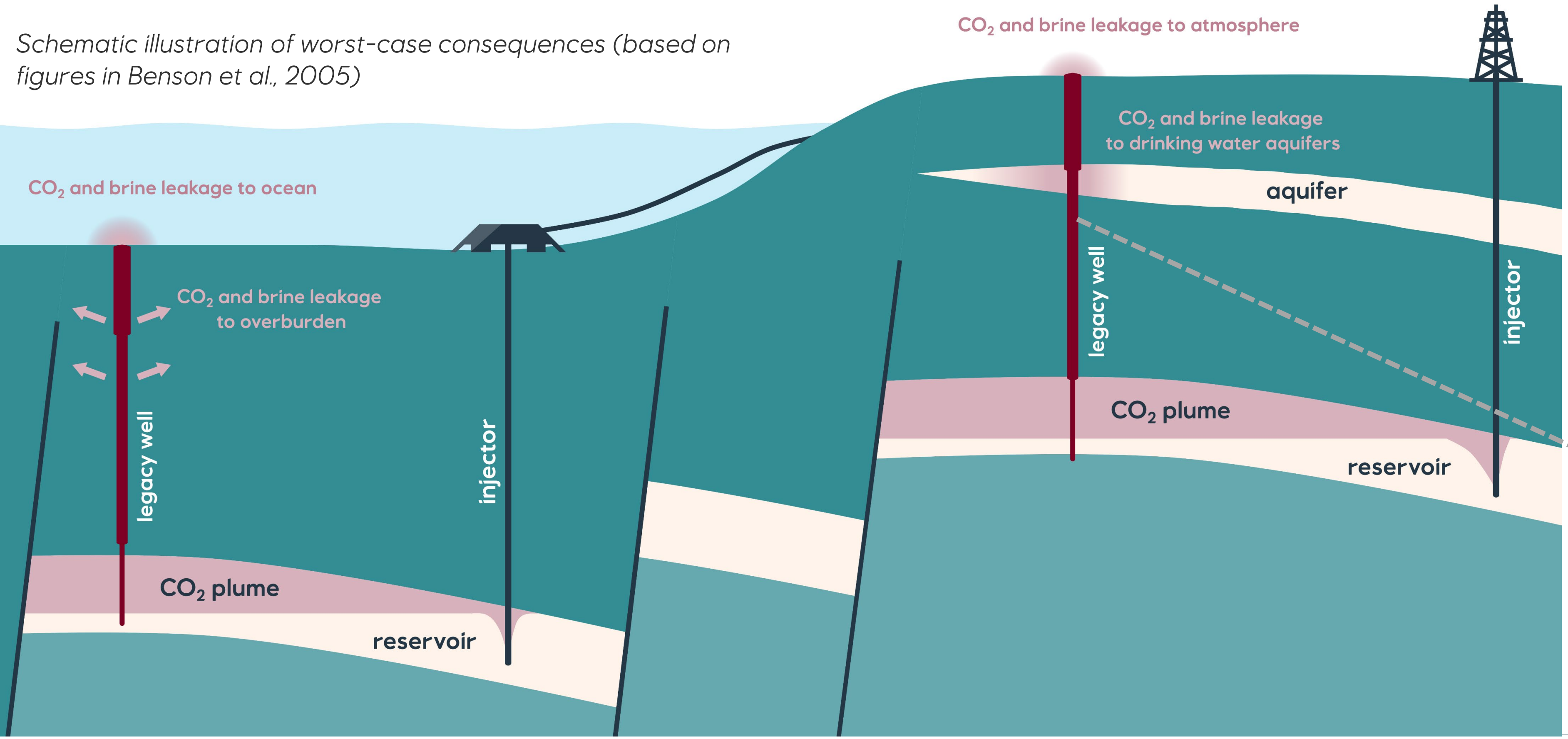
Open

07 February 2024

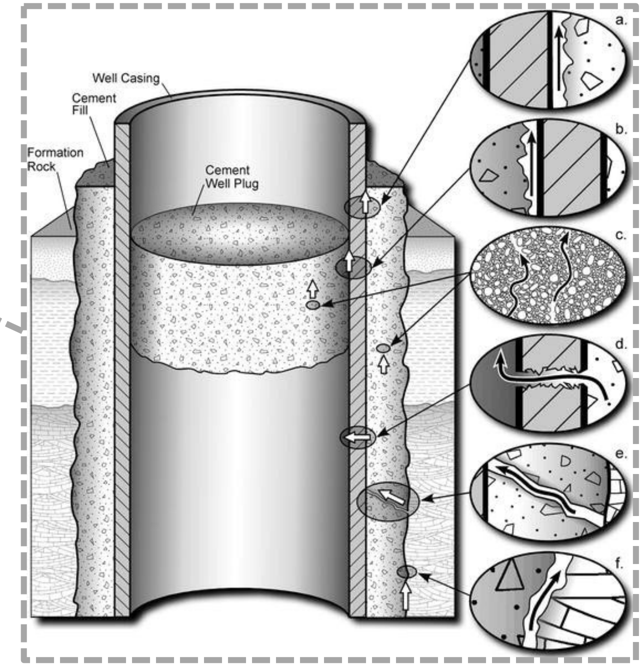
Introduction: Legacy wells

Legacy wells = *any pre-existing well (i.e. exploration, wildcat, appraisal) that is inactive or P&A, and enters the CO_2 storage formation.*
Leakage: *Any CO_2 that has escaped through a legacy well and ended up in the atmosphere, ocean, overburden, drinking water aquifers.*

Schematic illustration of worst-case consequences (based on figures in Benson et al., 2005)



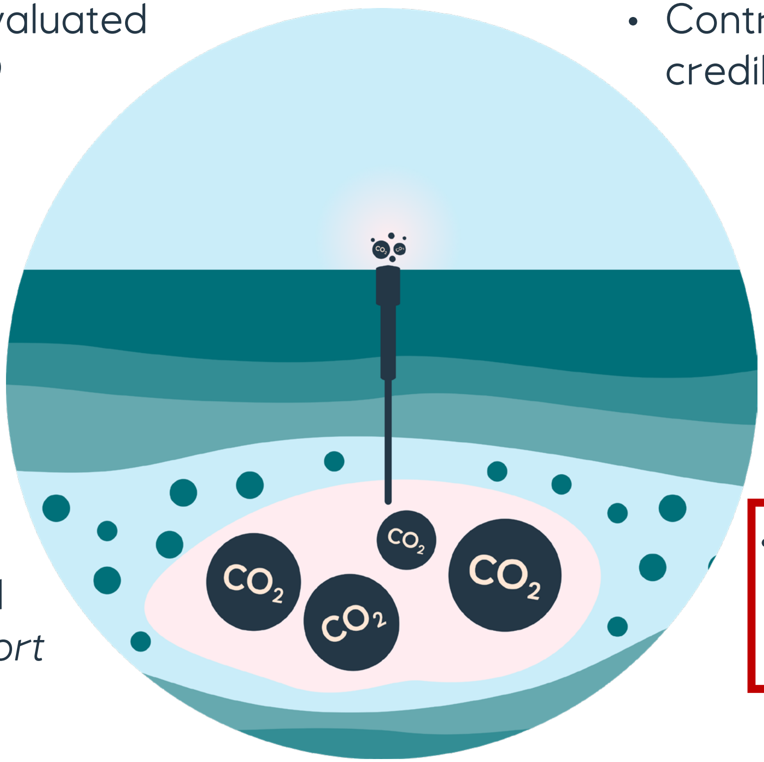
(Gasda et al., 2004)



Introduction: Why are legacy wells relevant for CCS?

External drivers:

- All legacy wells identified […] shall be evaluated […] as potential leakage pathways *(ISO 27914:2017)*.
- Operators shall provide evidence that legacy wells will function within an acceptable level of confidence […] to the effects of CO2 storage. *(DNV-RP-J203)*
- Leakage pathways to be included in all models. *Forskrift om lagring og transport av CO2 på sokkelen (§ 12-1)*



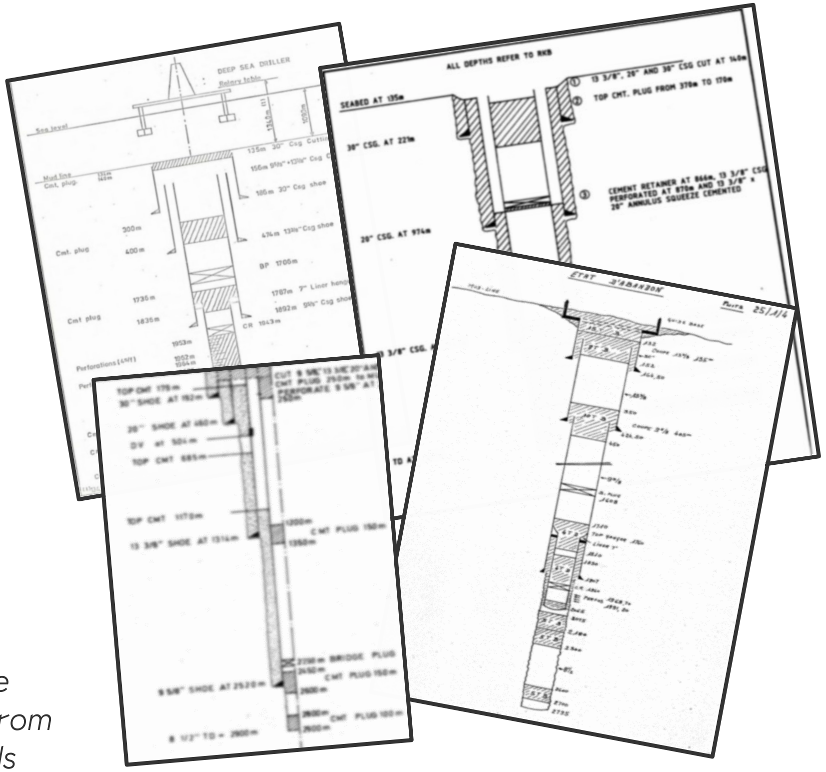
Internal drivers:

- Contributes on building Equinor's credibility as a CCS operator.
- Maximize storage capacity.
- Need for a fit-for-purpose tool for doing leakage risk assessments on legacy wells.

Legacy well → Quantitative eval.

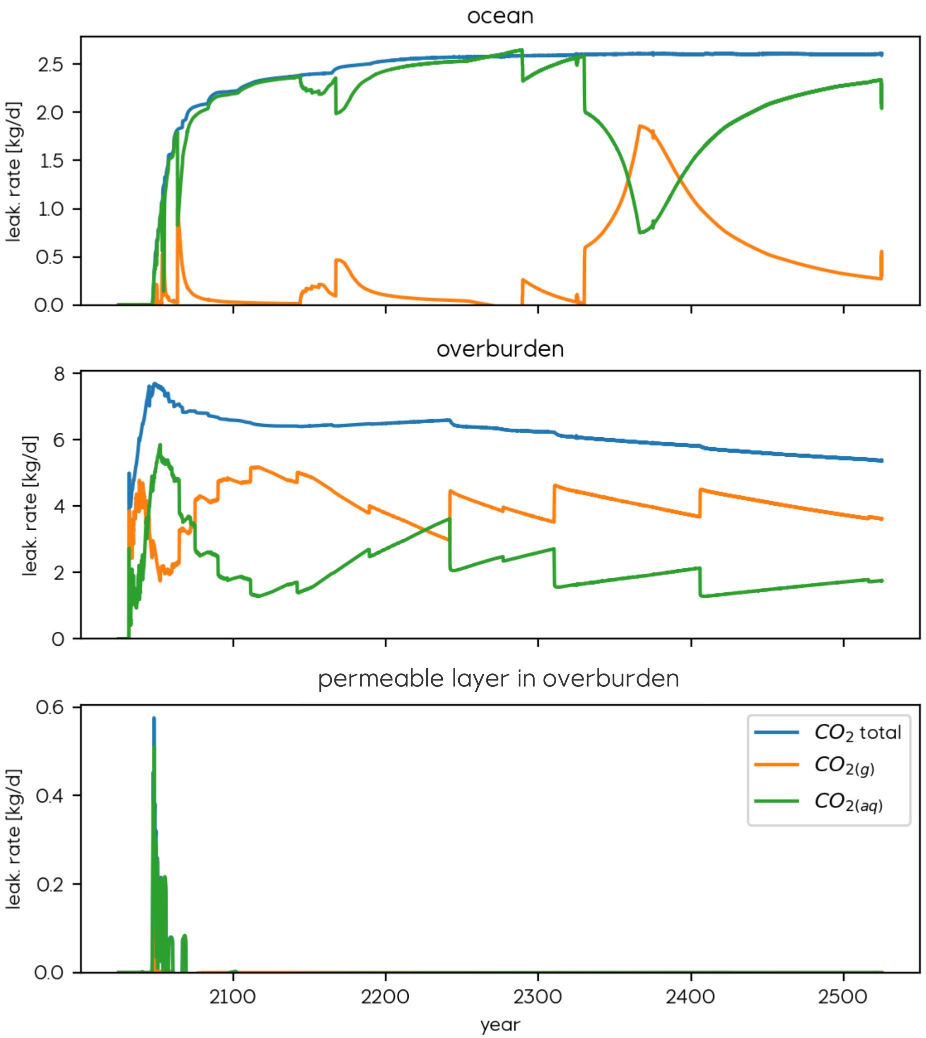
Toolbox: Script-based evaluation of legacy wells in early phase evaluation

- Develop methodology to evaluate legacy wells and estimate the potential amount of CO_2 leakage associated to them.
- Support risk analysis and decision making for the basin and site screening phase



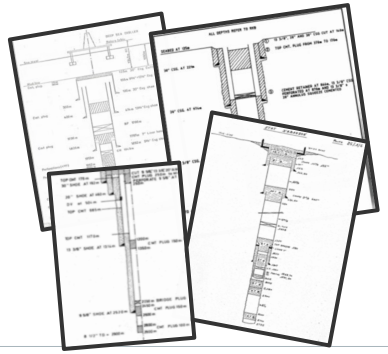
P&A wellbore schematics from different wells

Simulated leakage rates over time.



Input data handling

- Data relevant for legacy wells from multiple sources:
  - Subsurface data
  - **Well engineering details**
- Most of these wells only on archives: Manual data extraction.
- No unified standard data structure



Category	Item	Property	Source
Well	Well header	well name	well reports / database
		well RKB	well reports / database
		well td	well reports / database
		water depth / mudline depth	well reports / database
	Bitsize records	Top and bottom depth (MD RKB), diameter	well reports
		Permeability*	assumed
	Casings	Top and bottom depth (MD RKB), diameter	well reports
		Permeability*	assumed
	Cement bond	Min, max and most likely top and bottom depth	well assesment
		Permeability*	assumed / well assesment
	Barriers/cement plugs	Min, max and most likely top and bottom depth	well assesment
		Permeability*	assumed / well assesment
Subsurface	Geological tops	Top depth (MD RKB)	well reports / database
		Transport properties (porosity, permeability)**	assumed / asset
	Geothermal info	Seafloor temperature	assumed / asset
		Temperature survey (if available)	assumed / asset
		Geothermal gradient	assumed / asset
	Initialization	Reservoir pressure (scenarios)	asset
		Base of CO2 (CO2-water contact depth)	asset

Legacy well → Data processing

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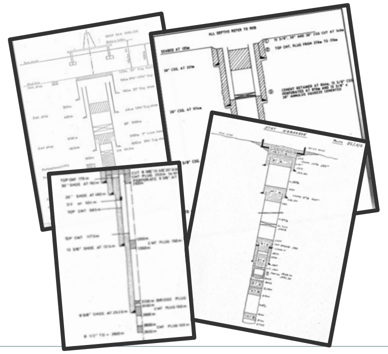

Category	Item		
Well	Well heade		
	Bitsize reco		
	Casings		
	Cement bo		
	Barriers/c	bottom depth	
		Permeability*	
Subsurface	Geological tops	Top depth (MD RKB)	
		Transport properties (porosit permeability)**	
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		Geothermal gradient	
	Initialization	Reservoir pressure (scenarios)	asset
		Base of CO2 (CO2-water contact depth)	asset

spreadsheet / csv

input_data					
well_header					
well_name	Well A				
well_rkb	35	m			
sf_depth_m	108	mTVDMSL			
well_td_rkb	2800	mRKB			
sf_temp	4	degC			
geo_tgrad	40	degC/km			
drilling					
top_rkb	bottom_rl	diameter_in			
143	190	36			
190	449	26			
449	1812	17 1/2			
1812	2800	12 1/4			
casing_cement					
top_rkb	bottom_rl	diameter_	toc_rkb	boc_rkb	shoe
143	158	30	132	158	TRUE
143	439	20	132	439	TRUE
182	1803	13 3/8	450	1803	TRUE
barriers					
barrier_nam	barrier_ty	top_rkb	bottom_rkb		
cplug3	cplug	143	150		
cplug2	cplug	1690	1850		
cplug1	cplug	2050	2300		
geology					

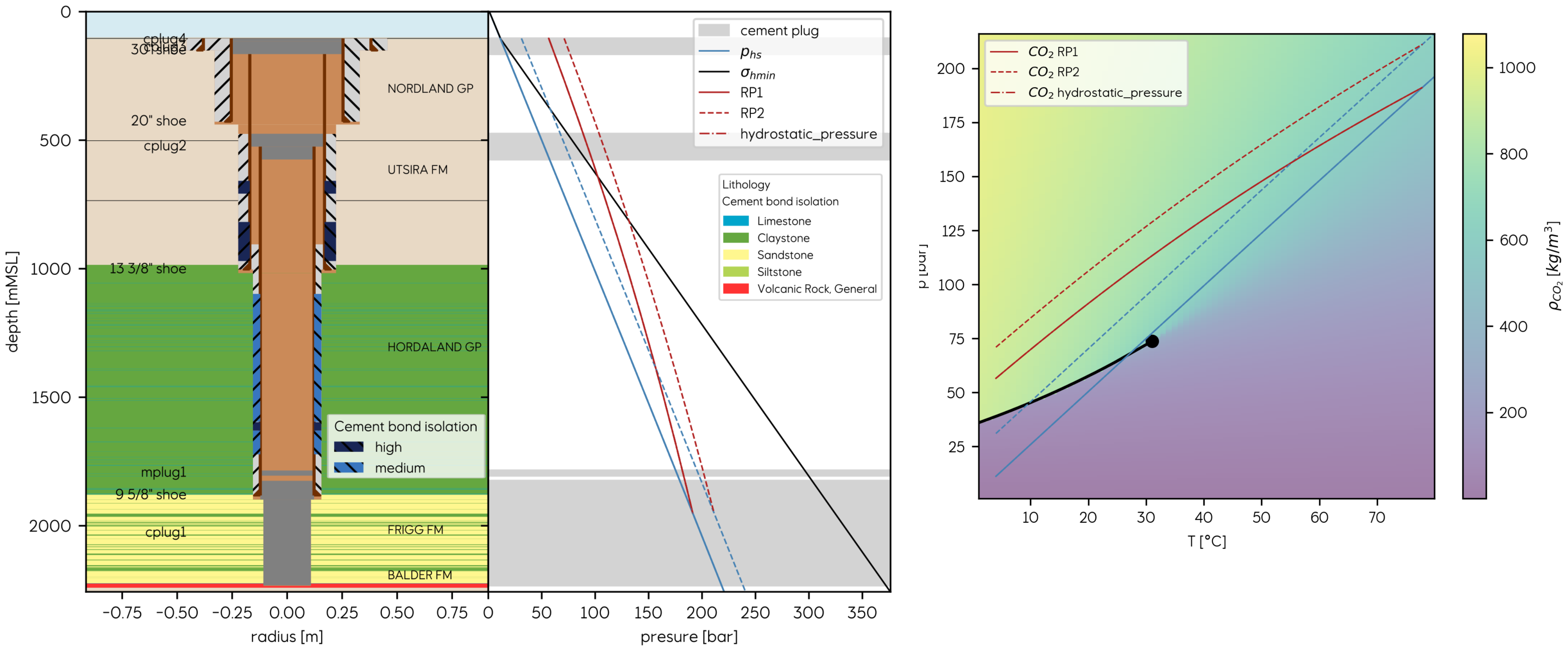
YAML file


```yaml
spec:
  well_header:
    well_name: 'Well A'
    well_rkb: 35
    sf_depth_msl: 108
    well_td_rkb: 2800
    sf_temp: 4
    geo_tgrad: 40
  drilling:
    - top_rkb: 143
      bottom_rkb: 190
      diameter_in: 36
    - top_rkb: 190
      bottom_rkb: 449
      diameter_in: 26
    - top_rkb: 449
      bottom_rkb: 1812
      diameter_in: '17 1/2'
    - top_rkb: 1812
      bottom_rkb: 2800
      diameter_in: '12 1/4'
  casing_cement:
    - top_rkb: 132
      bottom_rkb: 158
      diameter_in: 30
      toc_rkb: 132
```

Legacy well → Data processing → Preliminary analysis

Preliminary analysis

- Generation of well sketch juxtaposed with subsurface data.
- Static pressure analysis for different pressure scenarios.
- P,T diagrams and phases along well.
- Tested the routine in both offshore and onshore sample occurrences of legacy wells.



Legacy well → Data processing → Preliminary analysis → Proxy estimation - - - → Quantitative eval.

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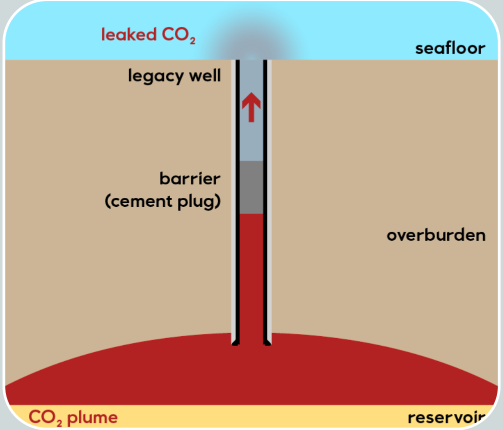
Evaluated parameters

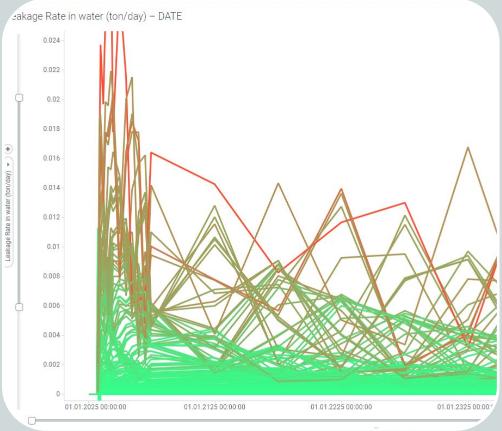
Over pressure in reservoir:	3-20 bar
Reservoir depth:	1300-2500m
Barrier permeability:	0.01 – 10md
Casing diameter (inner)	0.26-0.32 cm
Barrier depth:	500 m – reservoir depth
Barrier thickness:	50-150 m

Leakage proxy: Setup



Simple model setup.

- Dome shape.
- 1 CO_2 source.
- 1 legacy well with 1 barrier.



ERT/FMU (in house ResEng tool.

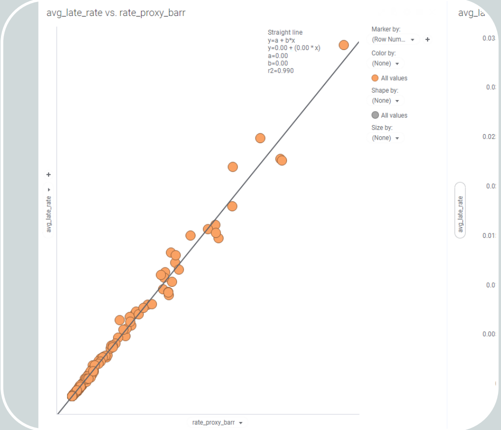
Run multiple simulations (pflotran) with a systematic variation of parameters affecting leakage rate. (200 realizations)

- Extract leakage rate Q from the cases

$$\gamma = \frac{r^2 \cdot K}{L}(L\Delta\rho g + \Delta P)$$

Calculate a simple scalar γ that is a combination of (some of) the input parameters.

- r wellbore radius
- K barrier permeability
- L barrier length
- g gravity acceleration
- $\Delta\rho$ density difference
- ΔP pressure difference along the barrier



Check if the scalar correlates well with the leakage rate

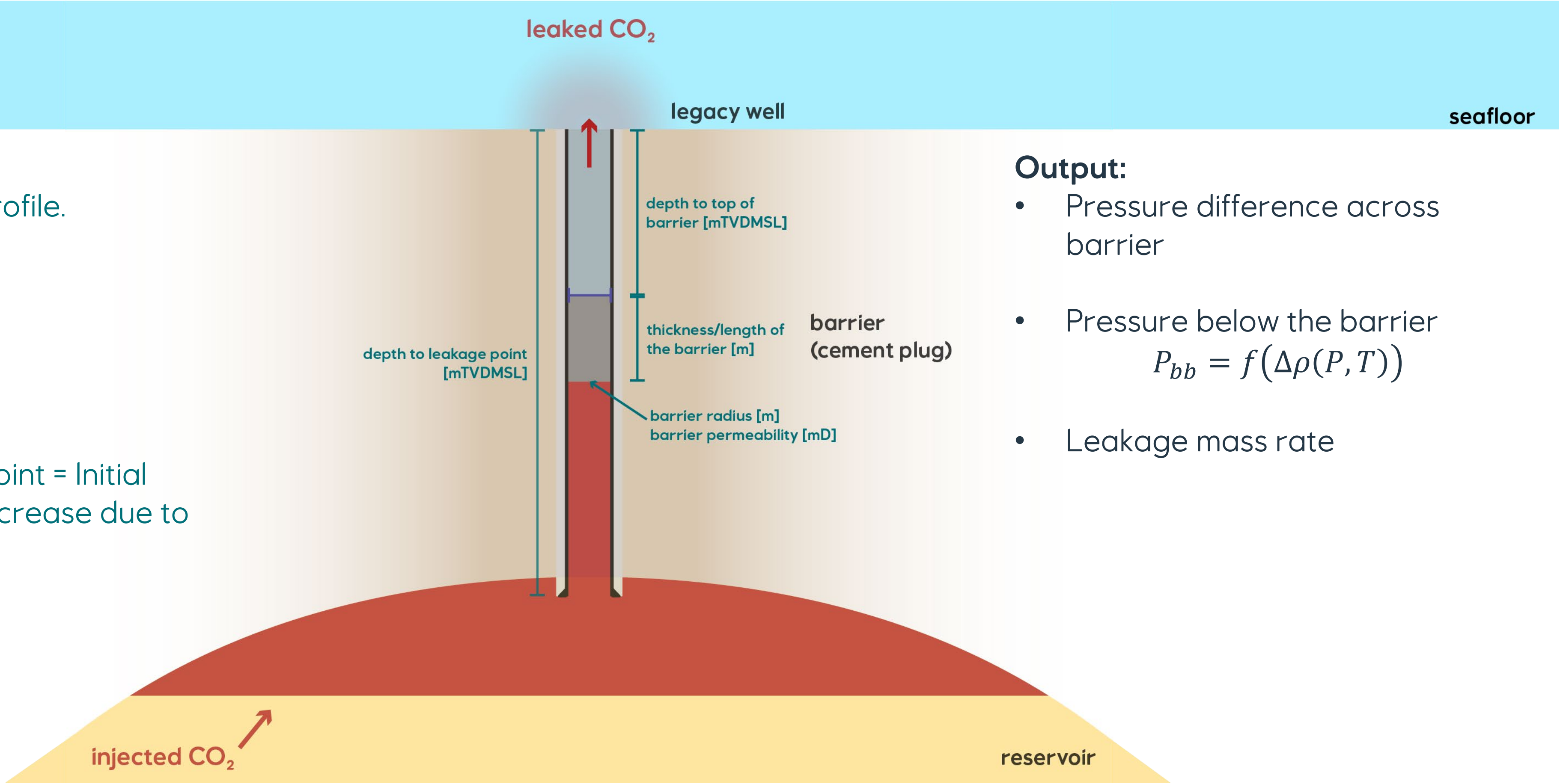
- Make a proxy model to predict the leakage rate Q based on the scalar γ.

$$Q_{proxy} = a + b * \gamma$$

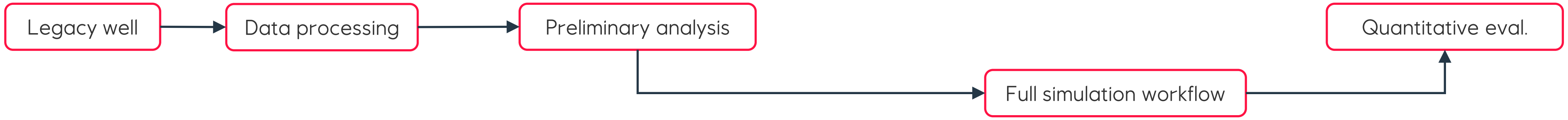
Leakage proxy: Implementation

Assumptions:
- The well bore is completely filled with CO_2 from leakage point up to base of barrier
- The only leakage path is through the cement barrier.

Input parameters:
- Temperature depth profile.
- Barrier details about:
  - Dimensions
  - Location
  - Permeability
- Pressure at leakage point = Initial Pressure + Pressure increase due to CO2 inj.

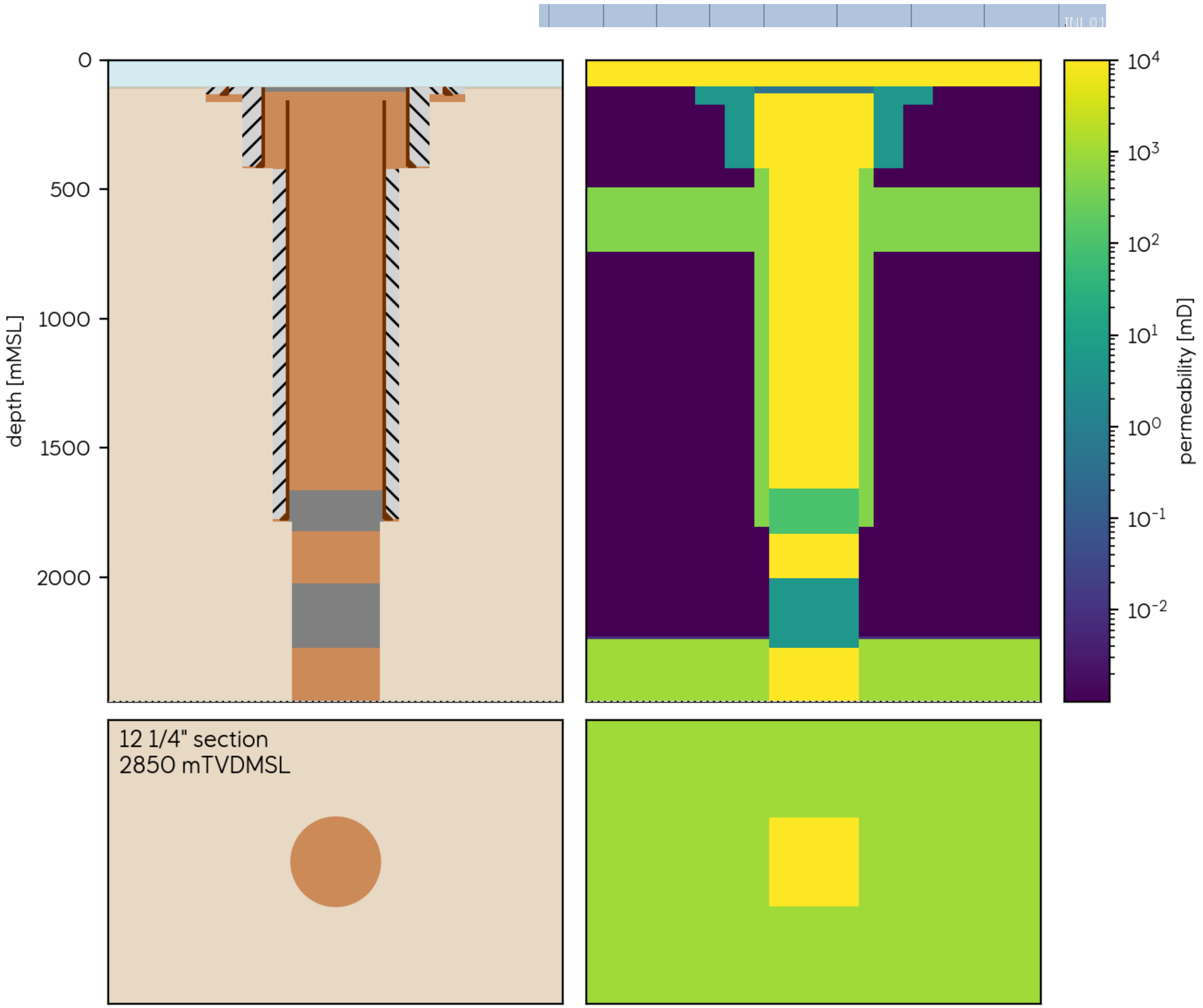


Output:
- Pressure difference across barrier
- Pressure below the barrier
  $$P_{bb} = f\big(\Delta\rho(P,T)\big)$$
- Leakage mass rate

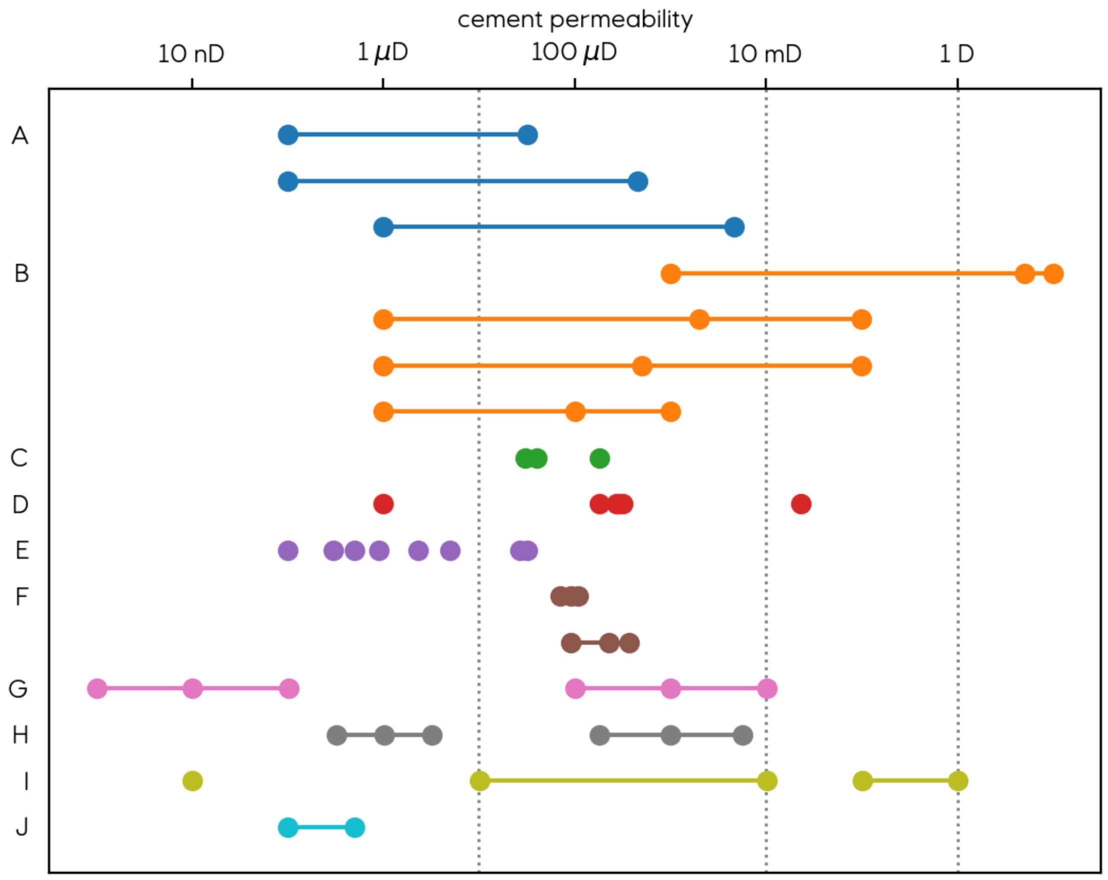


Simulation workflow: Pre-processing

- GAP (Grid-As-Pipe): Workflow driven by scripts that build a numerical simulation model of a legacy well.
- Simulation tool: Pflotran. Other tools considered: REVEAL and T2Well.
- Cartesian approximation of the well construction elements:
    - Borehole/Pipe/Annuli: High permeability elements
    - Cement plugs/bond: Low permeability
    - Casings: Transmissibility restrictions



Simulation workflow: Cement properties



(A) Measured cement permeability (Gasda et al., 2013).

(B) Ranges of permeability for (from top-to-bottom) bad cement to good-to-average cement (internal report., 2018).

(C) Measured permeability at varying confining pressure for aged cement (Beltrán-Jiménez et al., 2022)

(D) Measured permeability for multiple samples of retrieved aged cement (Beltrán-Jiménez et al., 2022)

(E) Measured cement permeability for lab sample and well extracted samples (Crow et al., 2010)

(F) Measured cement permeability for CO2 exposed cement (Carey et al., 2007).

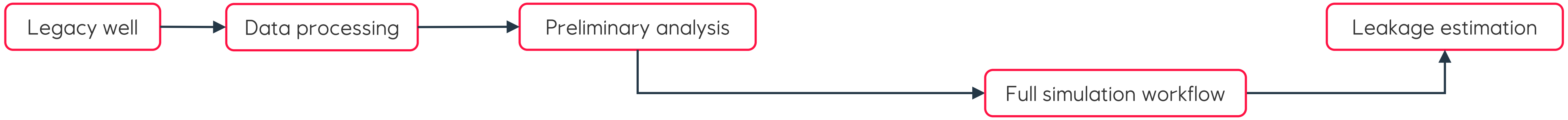
(G) Distribution of permeability from FutureGen project Case 1 (Low)**

(H) Distribution of permeability from FutureGen project Case 4 (High)**

(I) Distribution of permeability from Gulf of Mexico (Bourgoyne et al., 2000, Tao et al., 2010)**

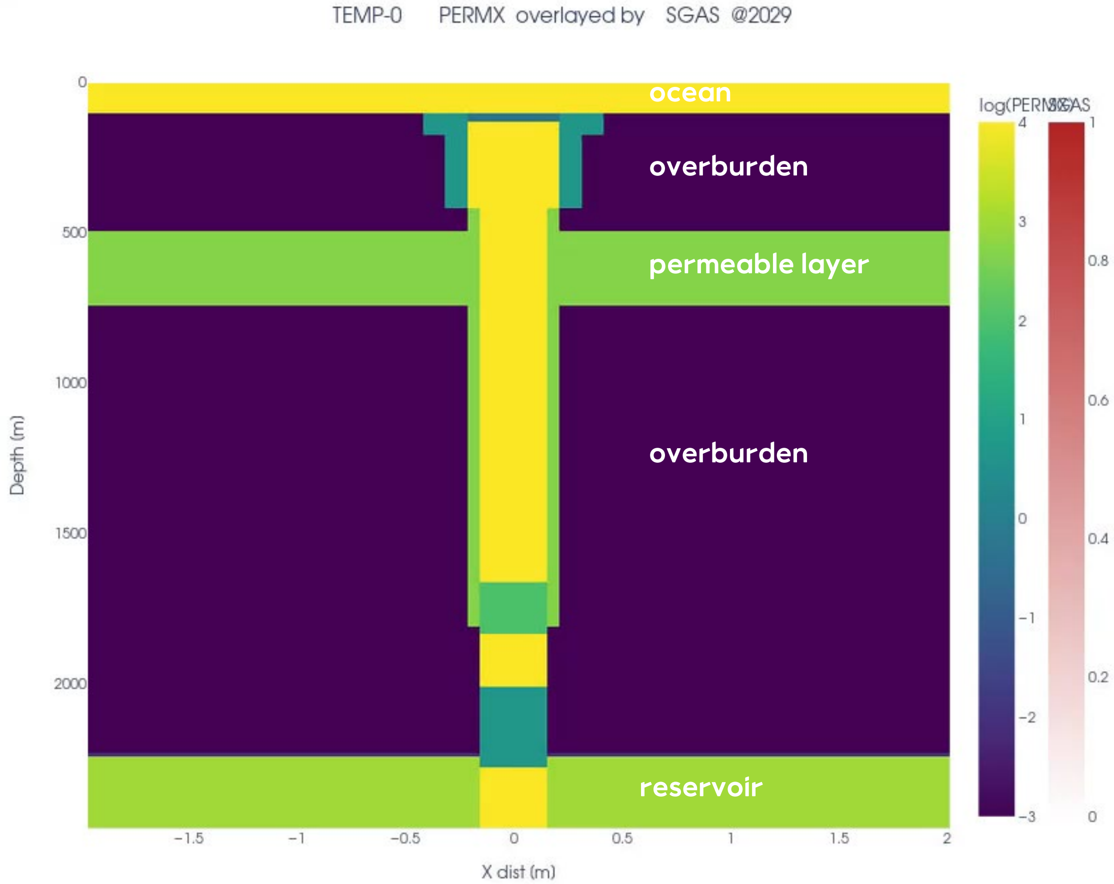
(J) Range of permeability for cement in model (Godoy et al., 2015)

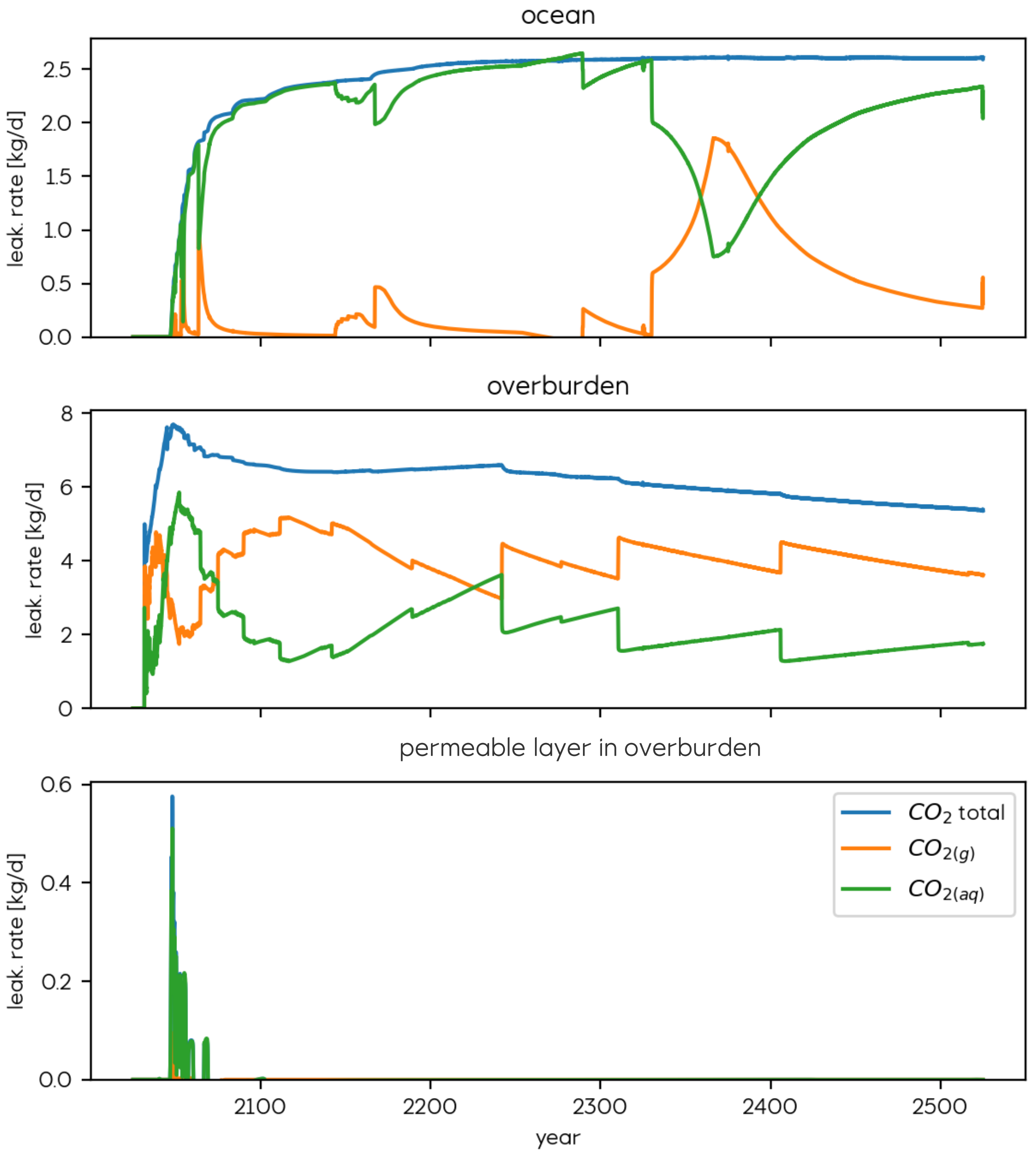
** G, H, and I compiled in NRAP study (Carey, 2018, White et al., 2020)

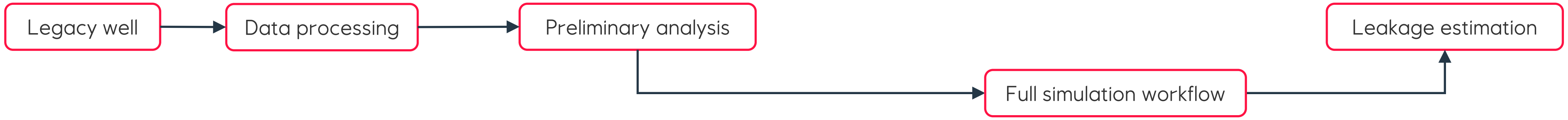


Simulation workflow: Post-processing

Overlay of molar fraction of CO_2 dissolved in water (AMFG) and free CO_2 saturation (SGAS)







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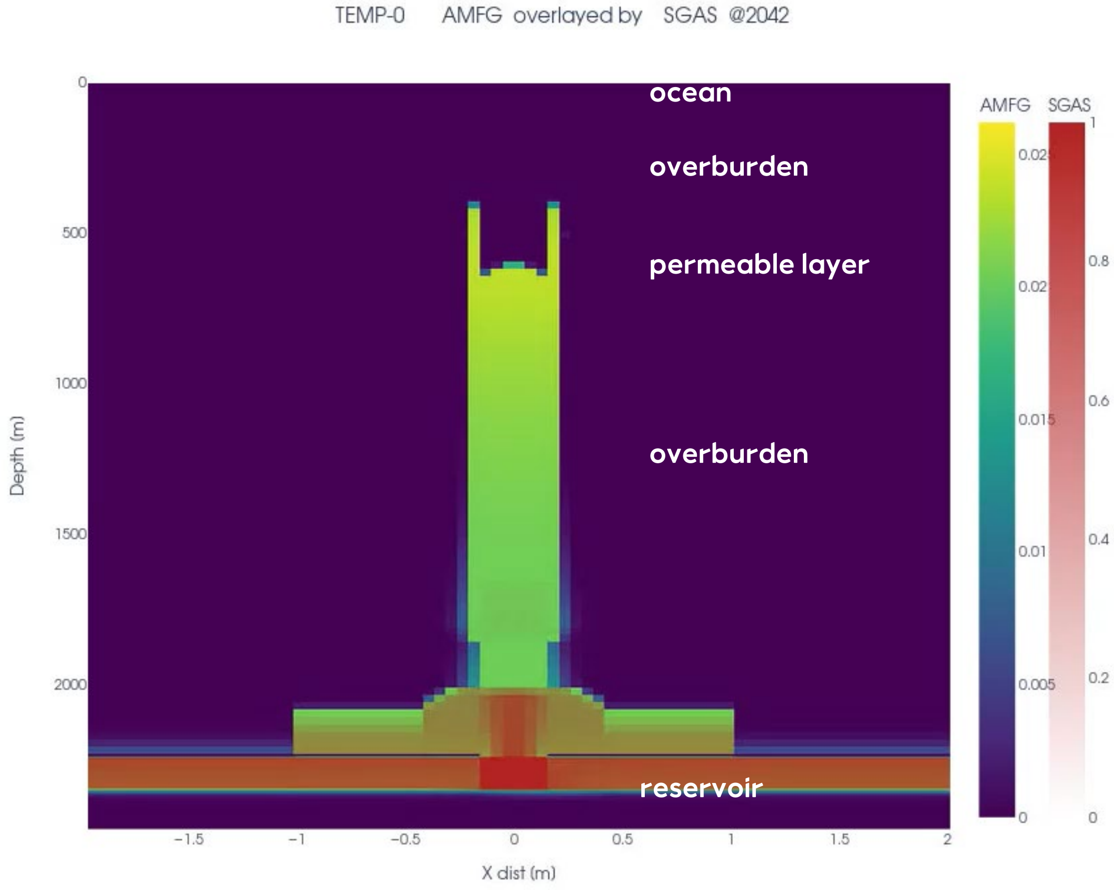

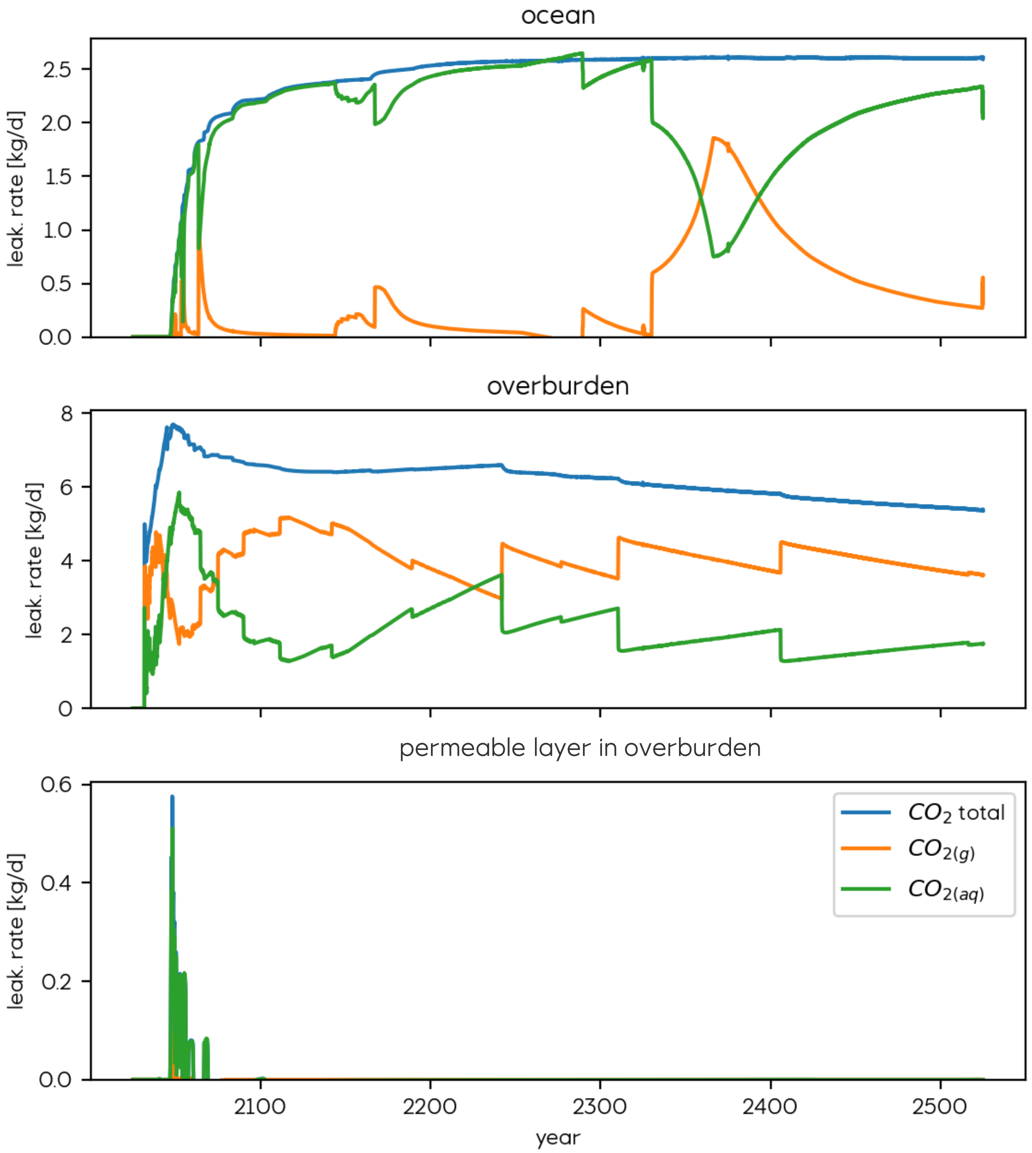

Legacy well → Data processing → Preliminary analysis → Full simulation workflow → Leakage estimation

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Simulation workflow: Post-processing

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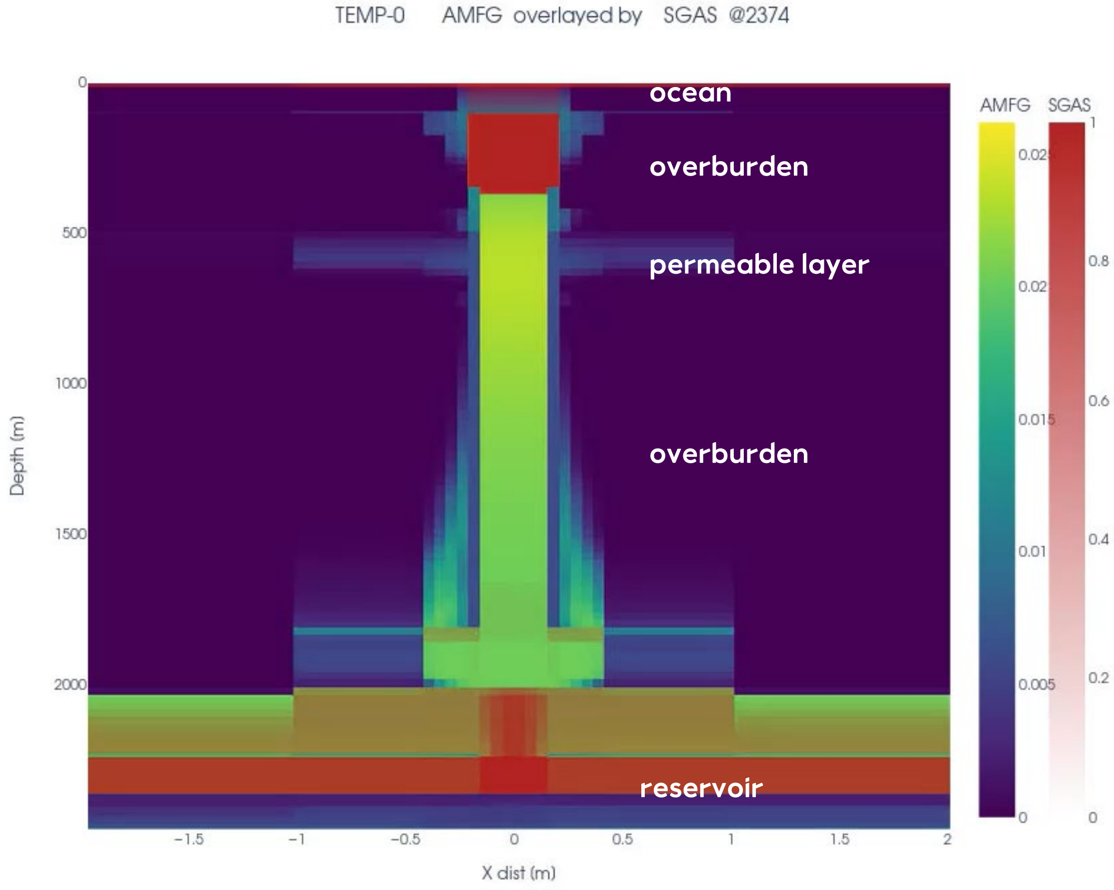

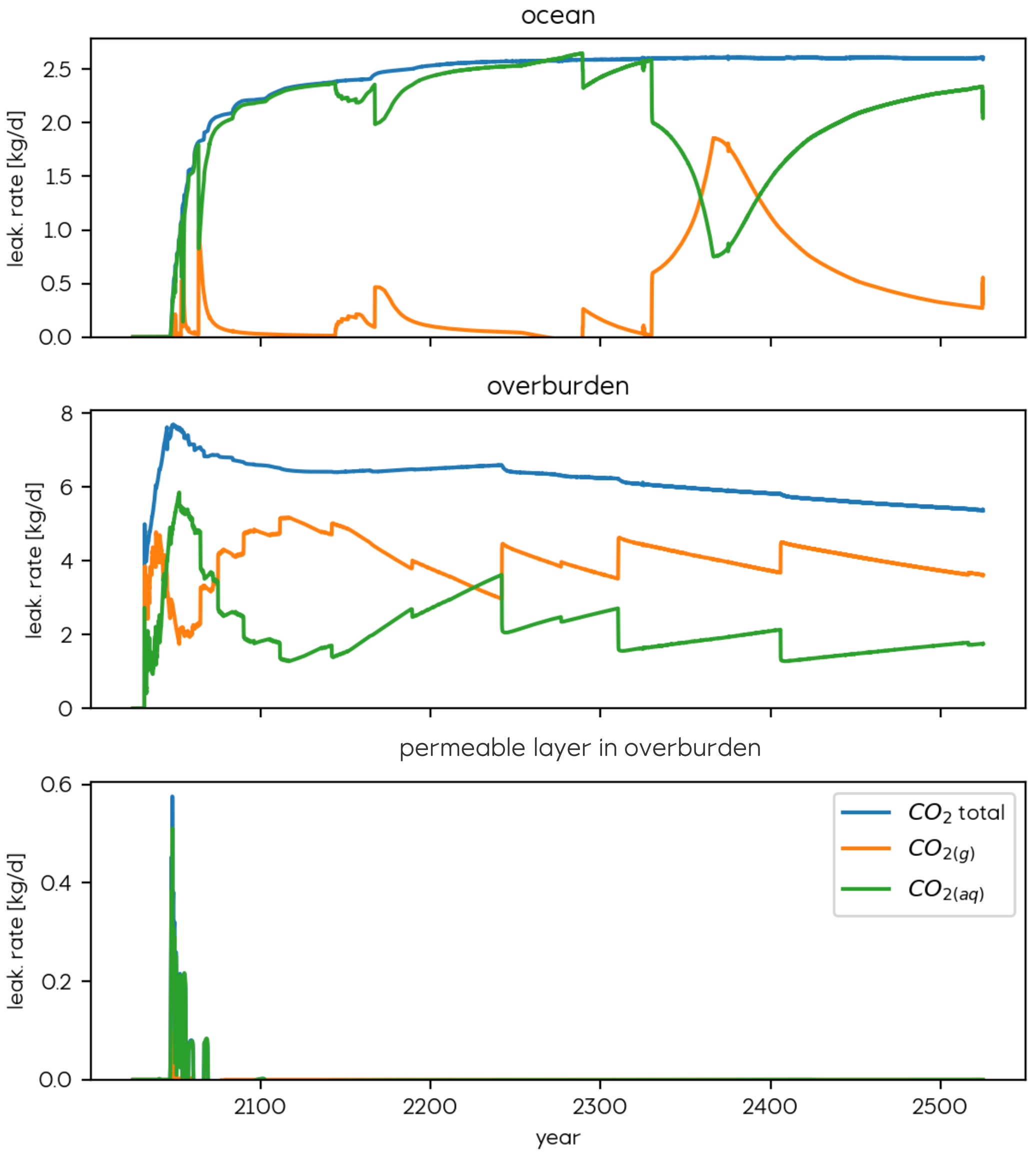

Conclusions and further work

The library of scripts are built to:

- Compile and analyze data relevant to legacy wells in CCS projects.
- Produce simplified visualizations to help assessment.
- Produce a proxy-based estimation of leakage.
- Parameterize the setup of simulation models of the well and its surroundings
- Visualize simulation output.

Identified challenges:

- There is no unique balance between a generic tool and case-specific solutions.
- There are still limitations and constraints on the existing features, and a backlog of new ones to incorporate.
- Understanding of priorities can vary depending on the case study and parts involved (i.e. operator, authorities, specialists).

Thank you!

Estimating leakage risk through legacy wells in a CO2 storage site

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