Baltic Carbon Forum
Vilnius – 3/4th October

HERIOT WATT UNIVERSITY

ASSESSING THE GEOLOGICAL RISKS OF SUBSURFACE CO2 STORAGE

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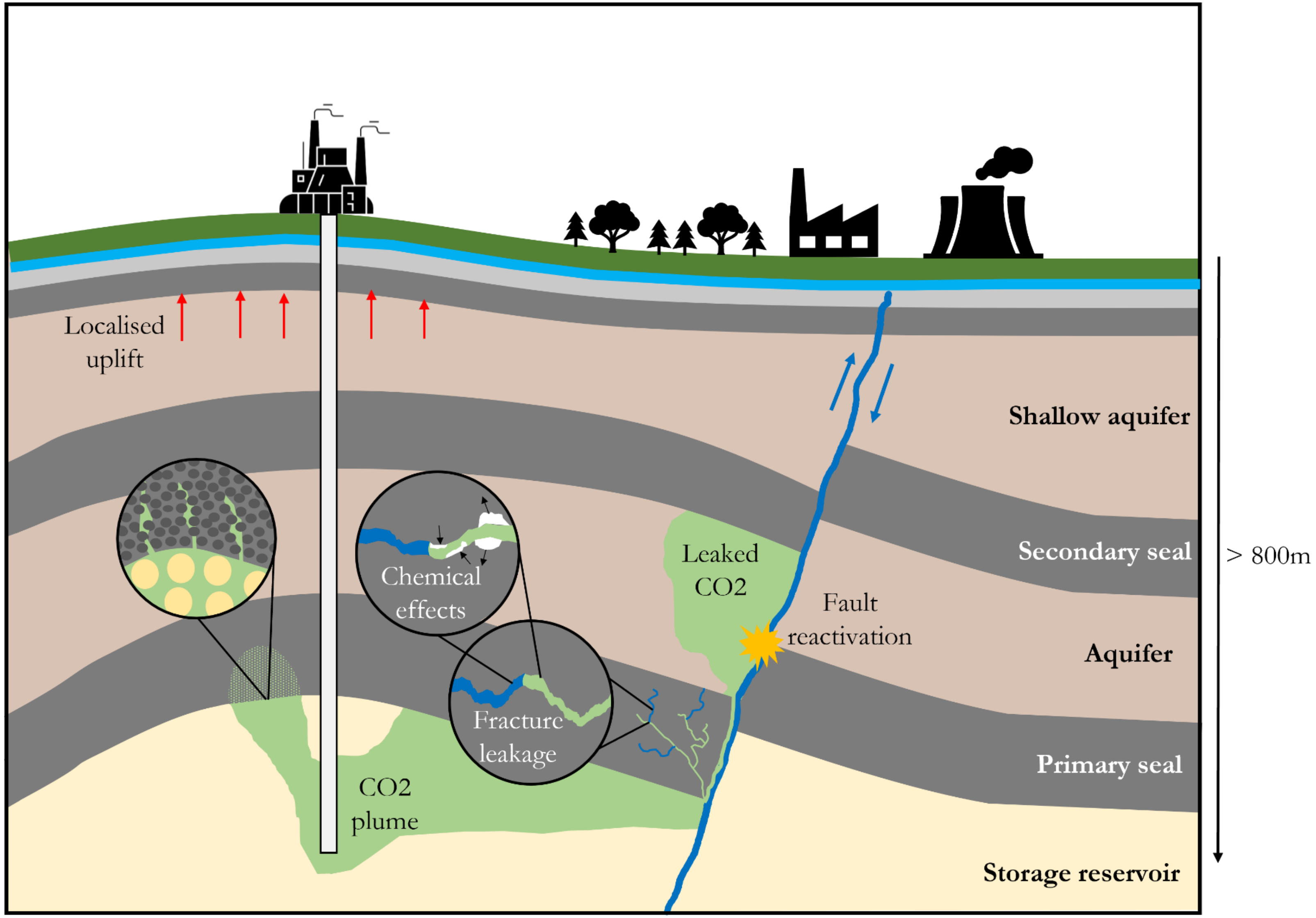
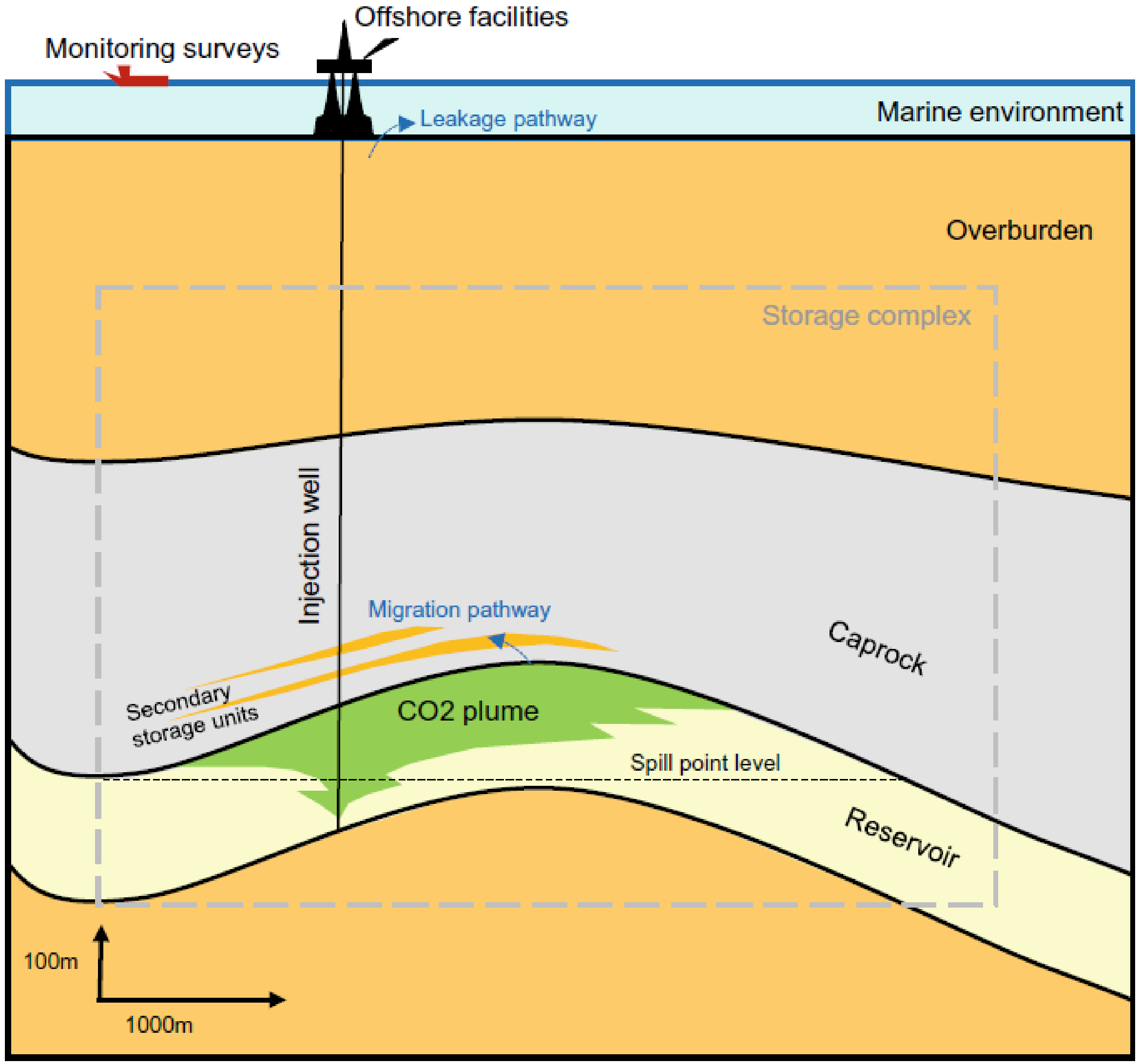
Geological CO2 Leakage



- Define the storage complex
  - Primary/secondary seals
- Wells
  - Injection, Monitoring, Legacy?
- Matrix leakage
  - Slow, likely irrelevant
  - Geochemistry diffusion-controlled, likely irrelevant
- Fault leakage
  - Leakage over relevant time scales?
  - Induced seismicity
  - Temperature effects?

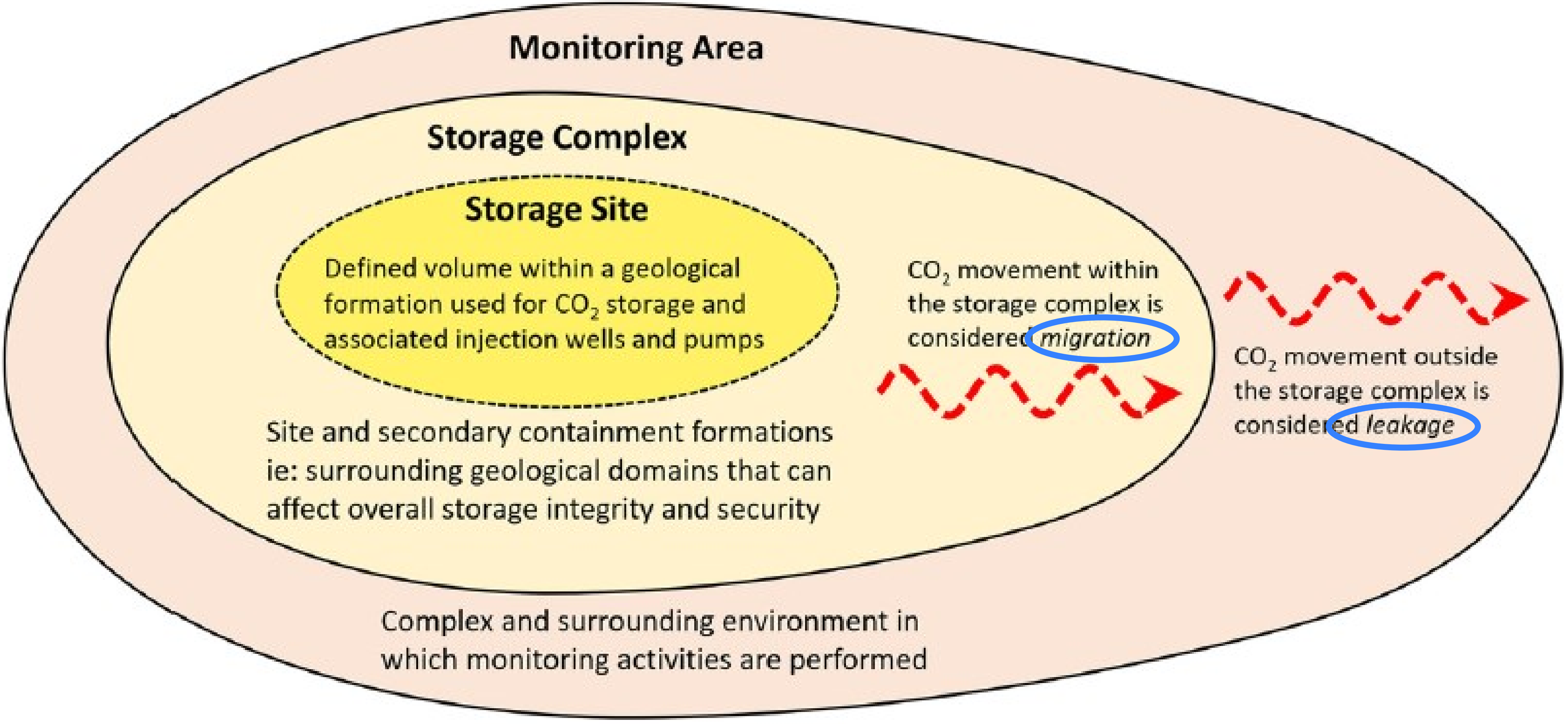
The Storage Complex



- Important to distinguish between *Storage Site* and *Storage Complex*, conceptually and legally
- Storage Complex more difficult to understand in terms of coupled THMC processes

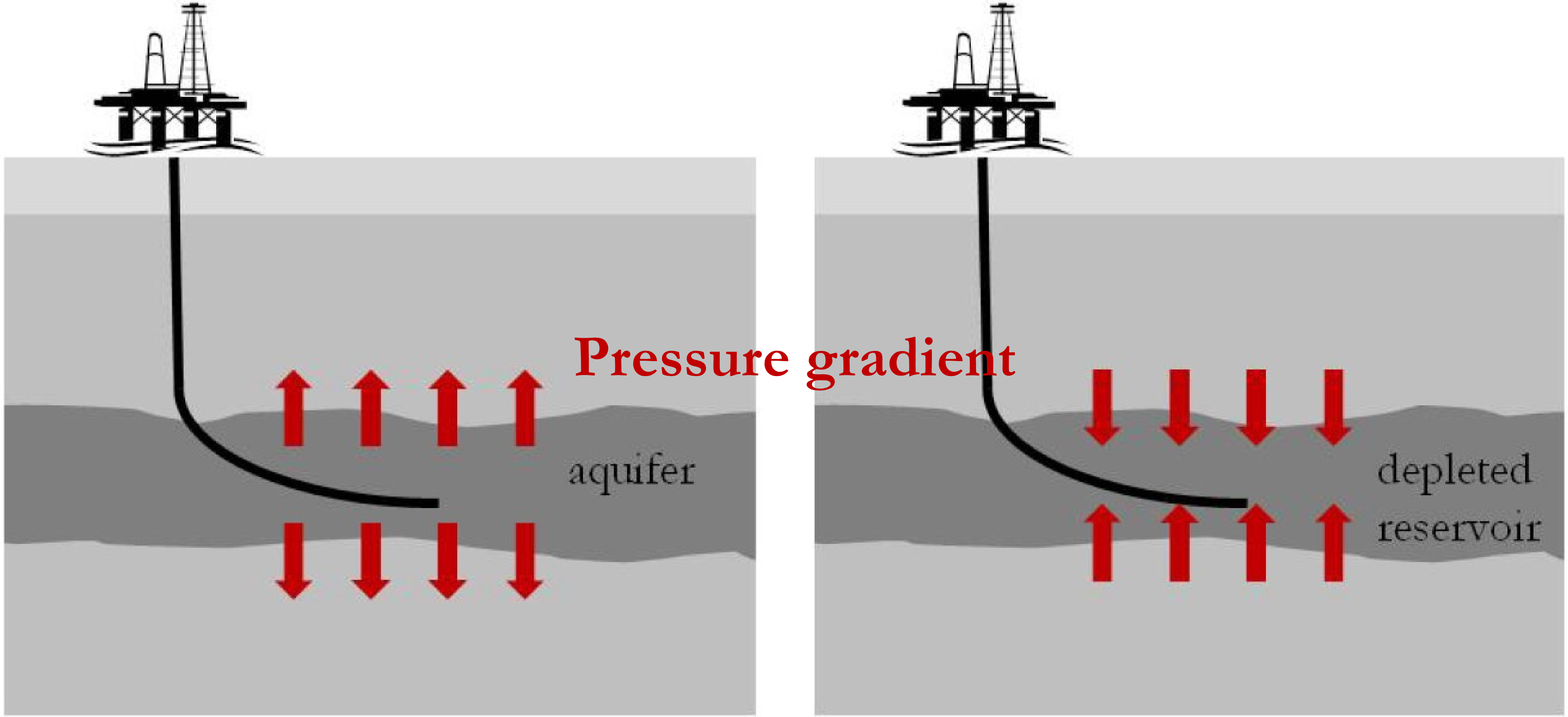
Ringrose - How to Store CO2 Underground: Insights from early-mover CCS Projects, 2020

What matters and what we monitor

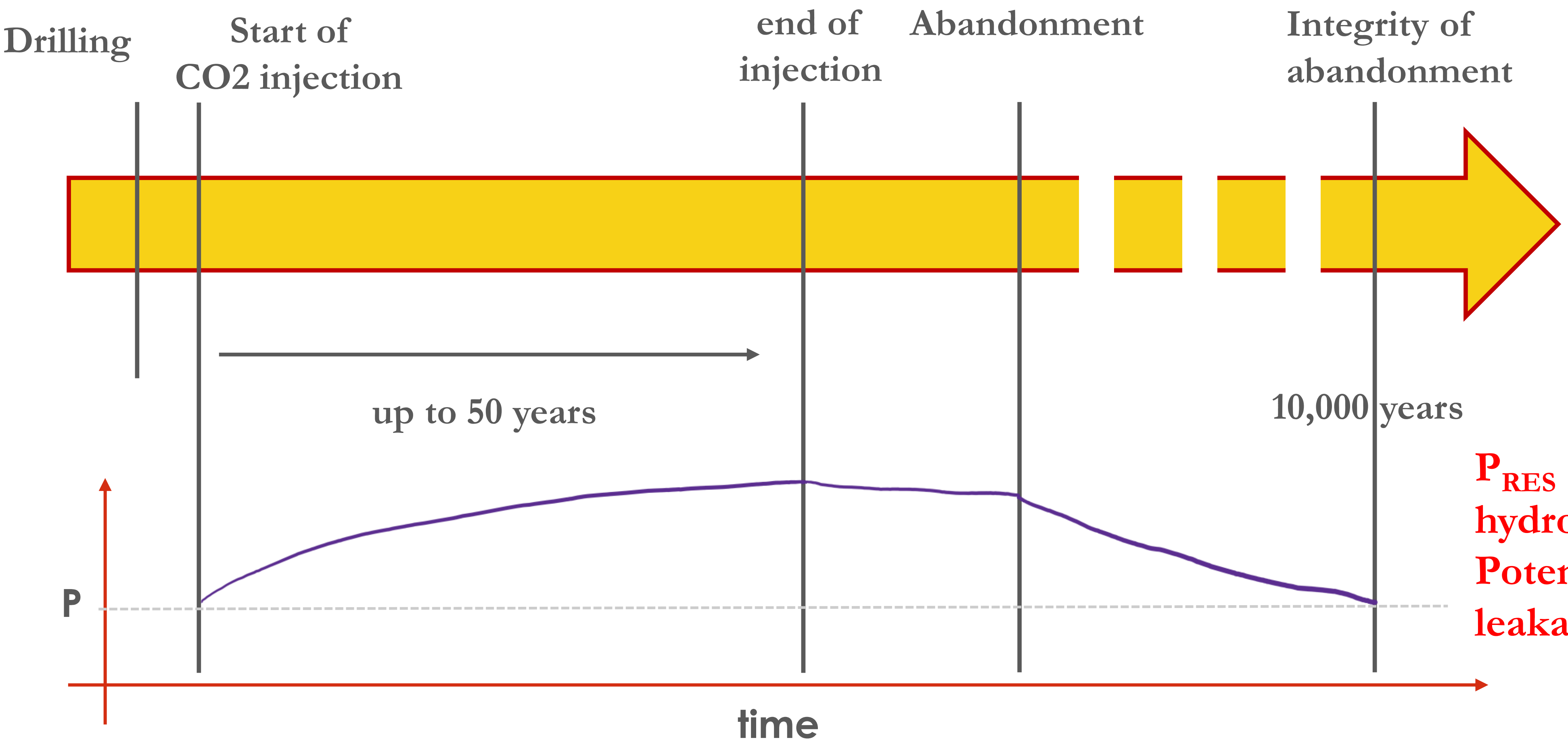


Shoulders and Hodgkinson, Geoenergy, 2024

Saline Aquifer vs Depleted Reservoir



Pressure evolution in saline aquifers

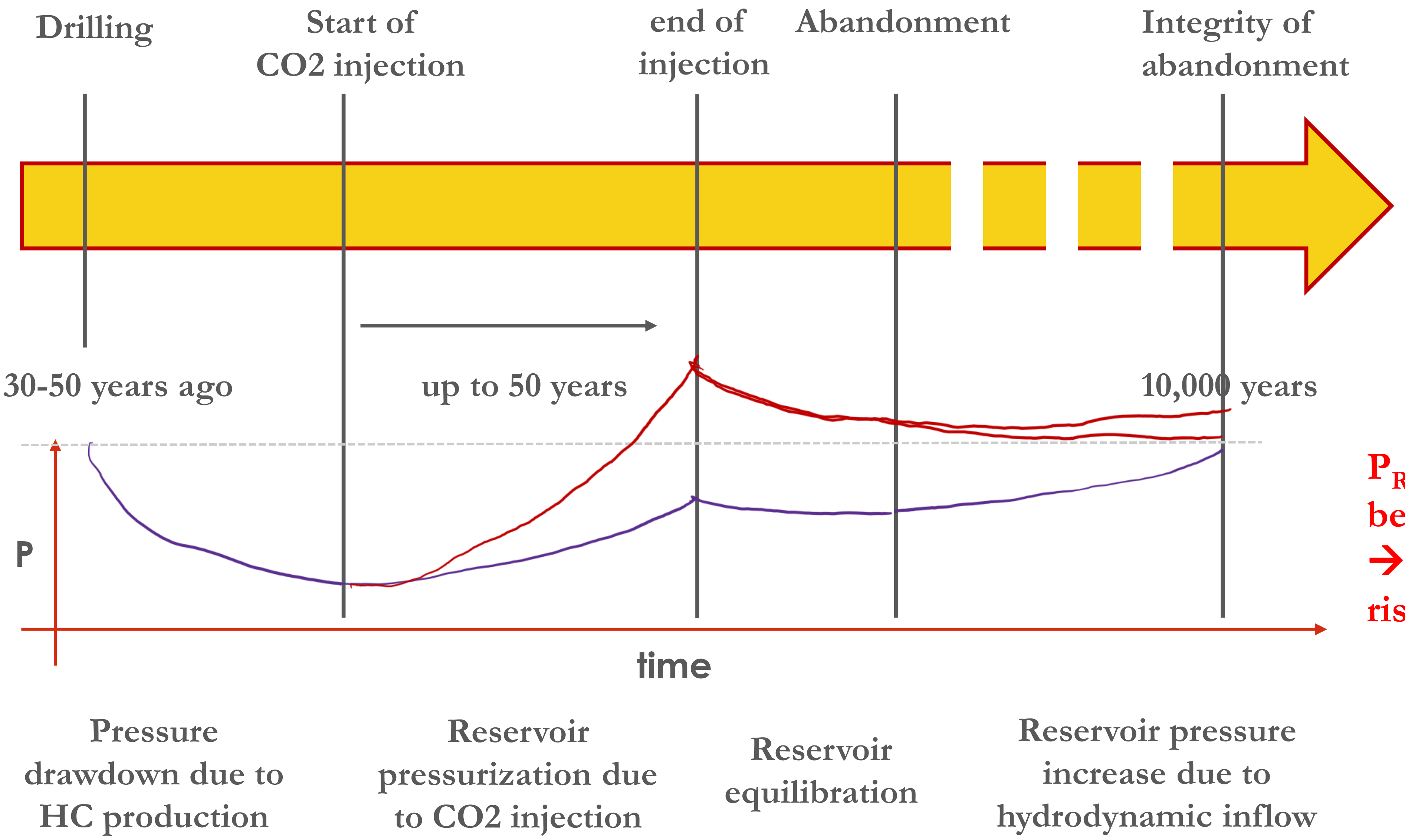


P_{RES} above hydrostatic → Potential risk of leakage

Reservoir pressurization due to CO2 injection

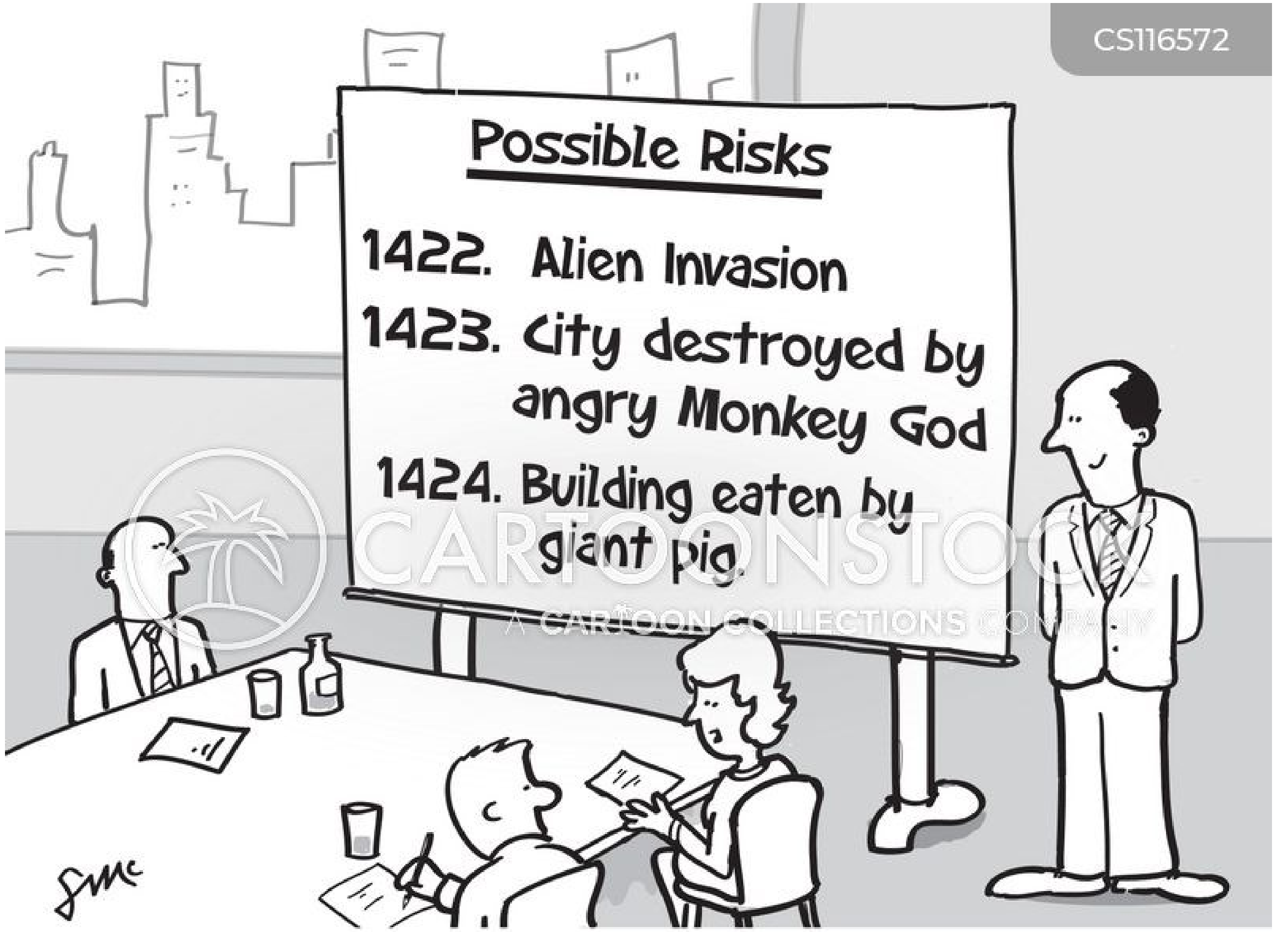
Reservoir equilibration by solubility/mineral trapping

Pressure evolution in depleted reservoirs



P_{RES} generally below hydrostatic → Potential low risk of leakage

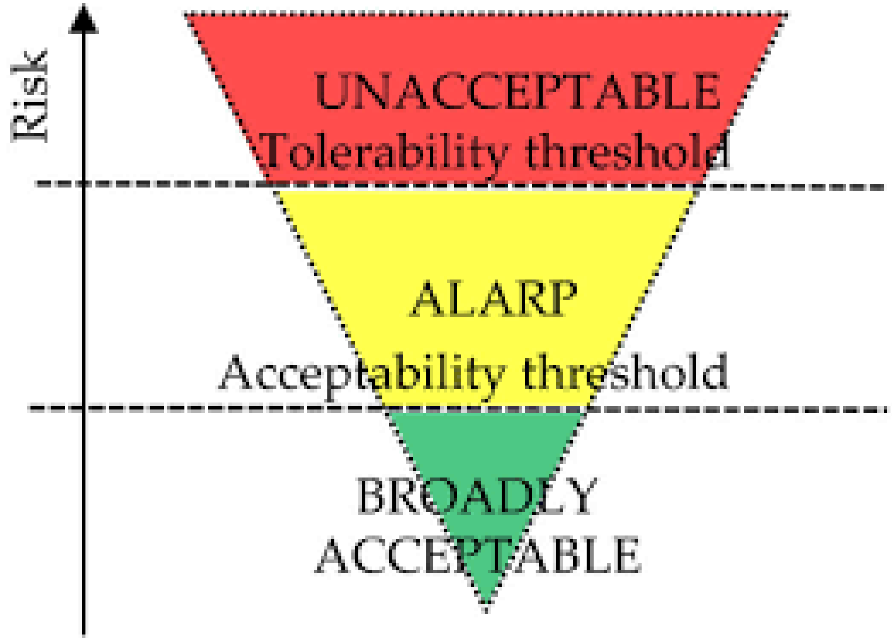
A thorough Risk Assessment is key!

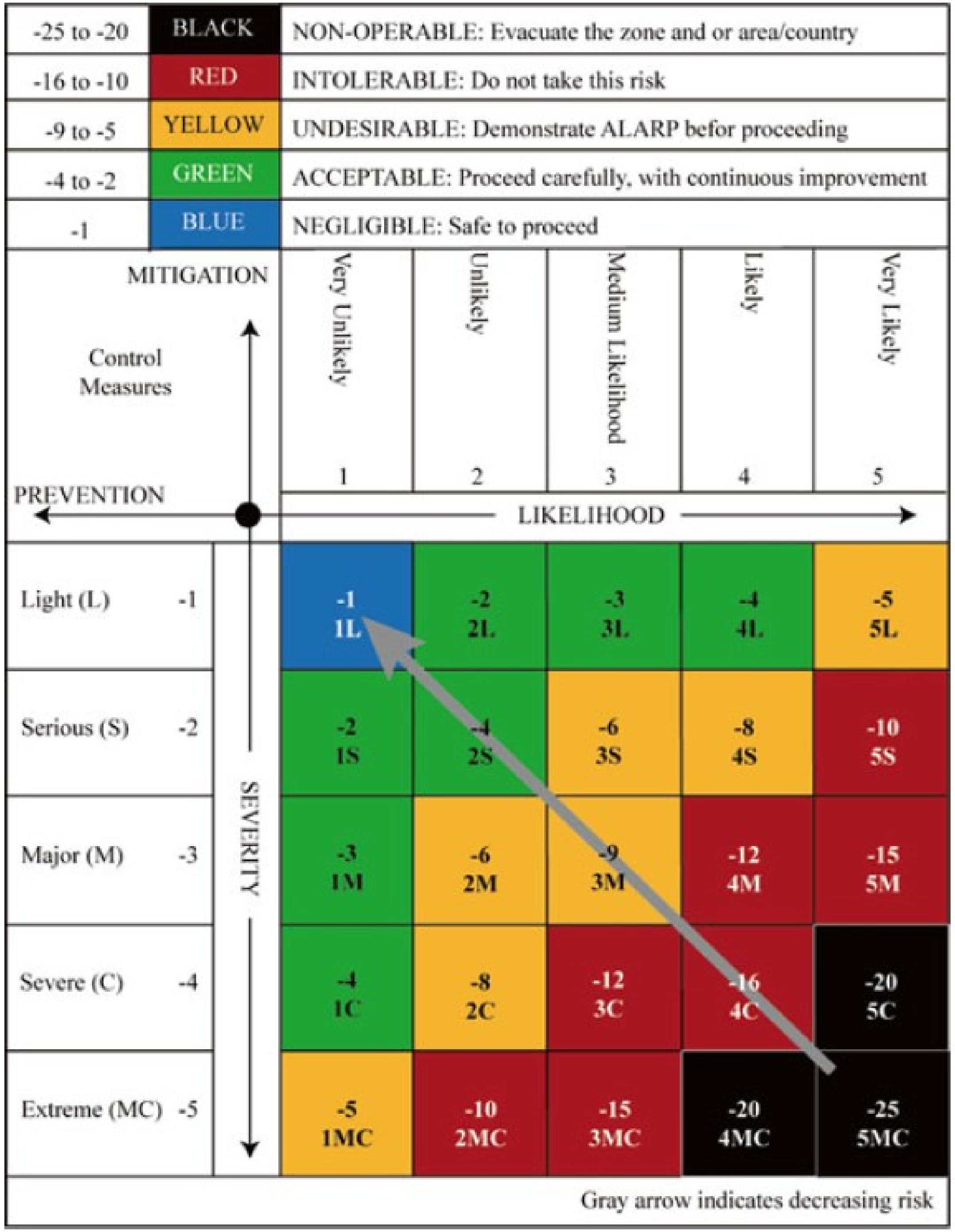


"Well he certainly does a very thorough risk analysis."

ALARP

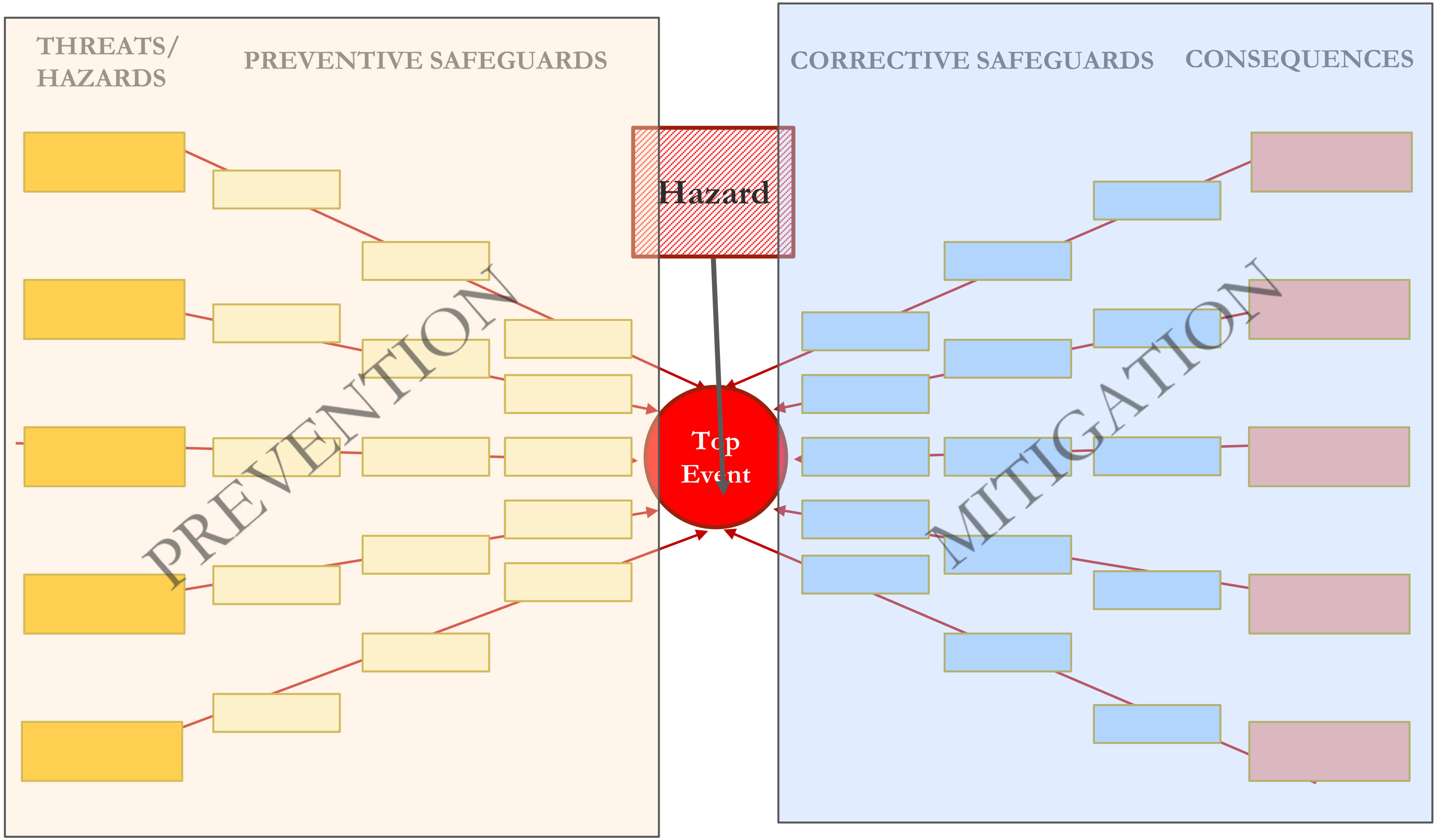
- CO_2 Leakage rates should be ALARP – As Low As Reasonably Practical
- Leakage is legally defined, and rates should be zero
- Realistic? No! What are monitoring detection limits?
- What is a fraction of injected CO_2 that would be tolerable to leak? 0.01%, 0.1%, 1%....?



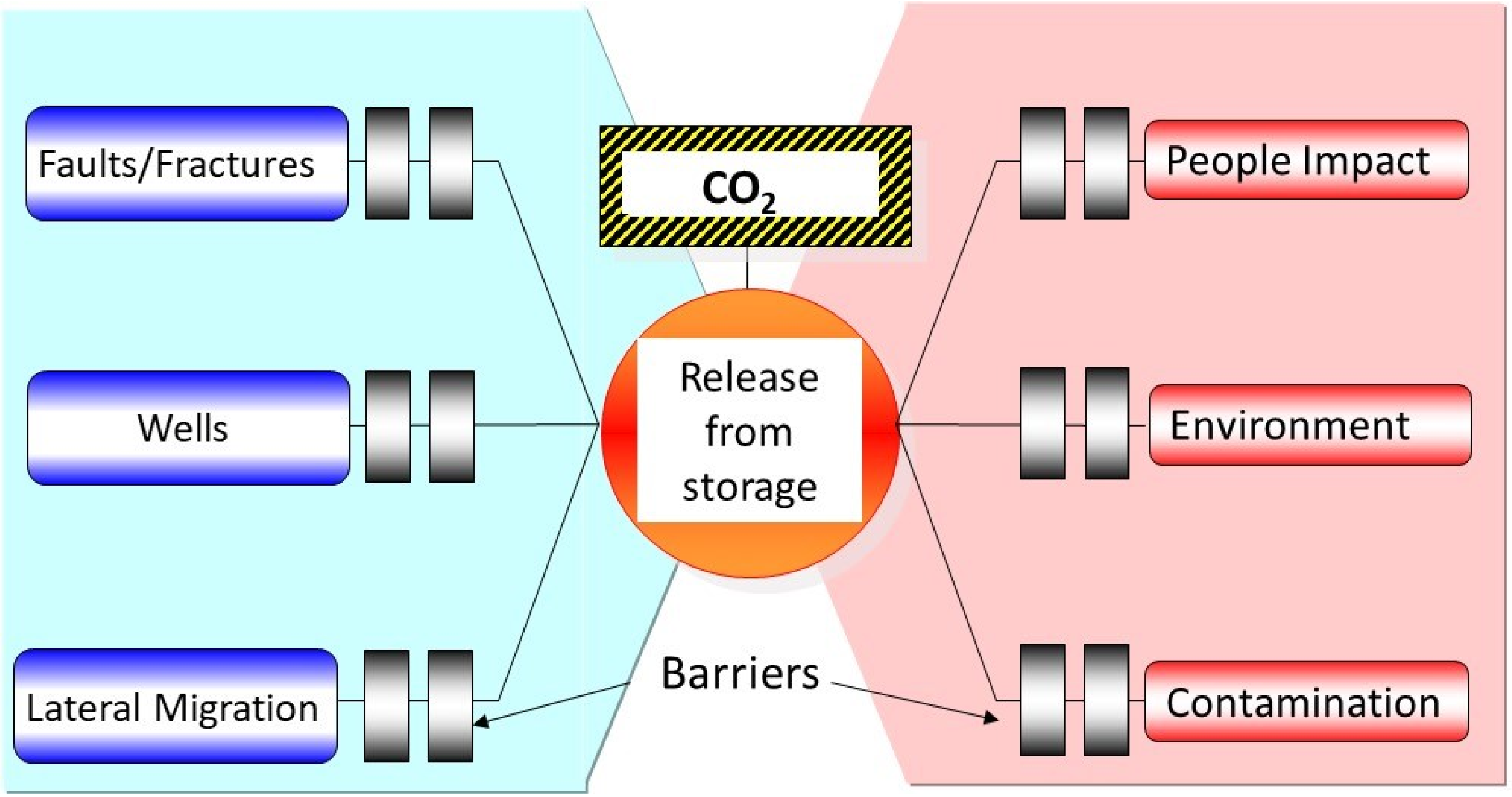


From Li and Liu, 2016 after Schlumberger

Bowtie risk assessment



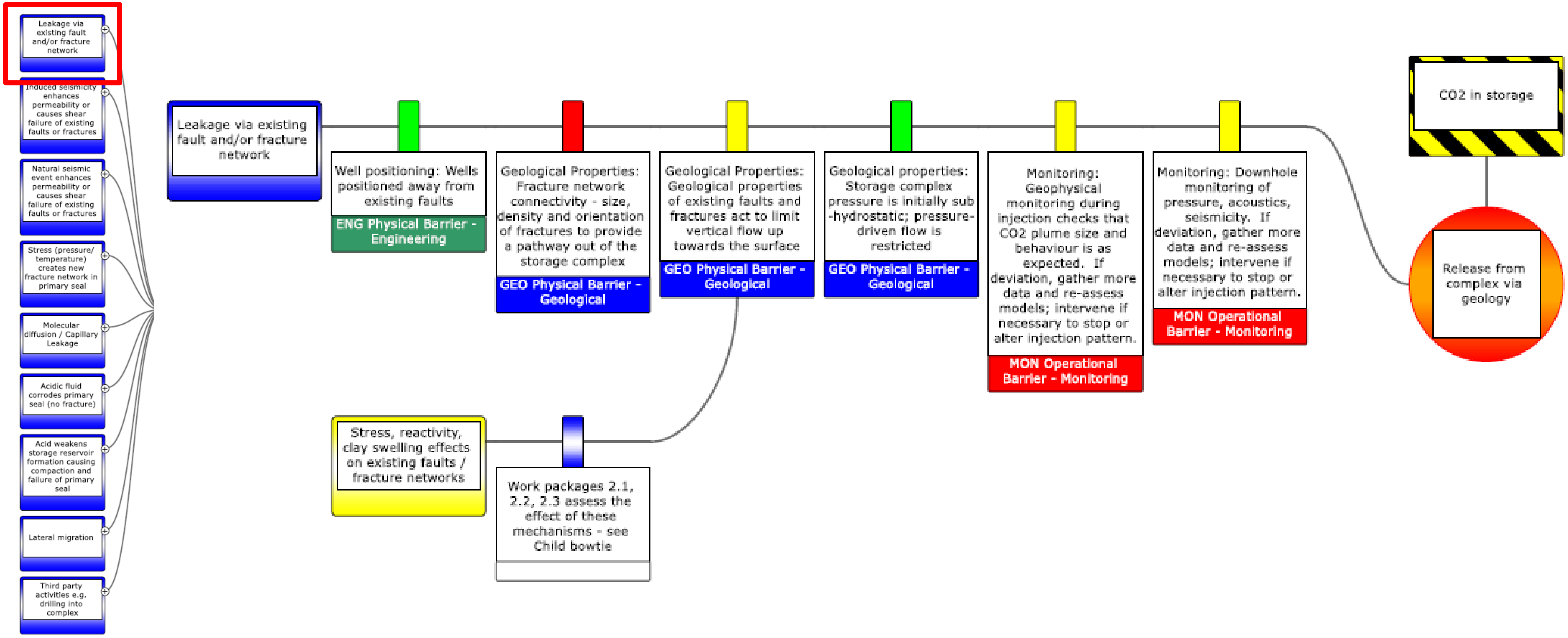
Bowties - Barriers



Barriers

- Inherent / Natural Feature
- Geological Properties
- Operational Strategies
- Engineering (Design, Equipment)
- Monitoring
- Corrective Action
- Public Consultation

Geological leakage



Source: DETECT project

TESLA - Technical Evidence Support Logic Assessment

A) Complete certainty that the Uncertainty Hypothesis is true

B) Complete certainty that the Uncertainty Hypothesis is not true

C) Complete uncertainty – no evidence to support or contradict the uncertainty hypothesis

D) High-levels of uncertainty but some evidence to support the uncertainty hypothesis

E) Significant evidence contradicting the uncertainty hypothesis, but with moderate levels of uncertainty remaining

Shoulders, S., Hodgkinson, J., 2024. Geoenergy 2.

TESLA for Clay Swelling

- Example: Clay swelling in CO2 stores can reactivate faults
- One of the major geological risks for the planned Peterhead CCS project by Shell

Passive safeguards	Argument	Evidence for argument	Evidence against argument	Outcome	TESLA classification
Mineralogy	The quantity of smectite within the storage seal may be insufficient to cause enough swelling.	None	Detailed laboratory studies on caprock samples clearly confirm the presence of significant amount of smectite (57wt-%).	High smectite contents proven, significant swelling strain and stress likely. Uncertainties in subsurface hydration state.	
Geometry	If not compliant with the above, clay swelling only creates a build-up in shear stresses that extends across the entire thickness of the storage seal if there is a significant discontinuity in the storage seal, e.g. a fault, with an offset comparable to the thickness of the storage seal itself.	Faults with throws of up to 33 m have been mapped in parts of this structure: The mapped caprock (U. Valhall/Rødby, lower part of the seal) thickness is greater than the maximum throws of 33 m, except if the reservoir were to extend further than currently mapped in the NE. The integrity of the upper part of the seal (Hidra/Plenus) extending across the whole storage site is good, based on analogue fields, with a total thickness in excess of possible fault offsets.	The lower part of the seal (U. Valhall/Rødby Fms) is thin enough to be offset by mapped possible faults in a limited area at the extreme NE of their possible occurrence; shear failure for this part of the storage seal would therefore be possible. The integrity of the upper part of the seal (Hidra & Plenus) is considered good, but on the basis of analogue fields only.	Threat can be excluded for entire storage seal but a low possibility remains if Rødby/U Valhall shales were the only seal; note that on the basis of hydrocarbon analogue field data the sealing properties of the overlying Hidra & Plenus are considered to be good. Uncertainties are in the North of the reservoir, where the caprock thickness decreases.	
Plasticity	If not compliant with the above, plastic deformation mechanisms in the caprock may relax the induced shear stress to prevent brittle shear type failure within the storage seal.	The higher the smectite content the softer the shale; it is therefore more likely that swelling stress generated can relax into the shale matrix, i.e. more plastic creep.	Analogue data to the Rødby/U Valhall shales are rare/lacking from literature; no direct assessment possible at this point.	This remains a topic of high uncertainty and no consistent or suitable analogue data identified. We recommend performing detailed literature and lab studies.	
Permeability	If not compliant with the above, shear type failure may not develop fault permeability.	A sufficiently large area of a fault needs to undergo shear failure in order to develop permeability along fault; even if permeability would develop, flux rates could be below the detection limits of the monitoring installations.	CO_2 in the reservoir results in a gas column that will always exert a small overpressure (<0.5 MPa) to the caprock following hydrostatic pressure recovery. Therefore, if the fault is permeable it will leak with small but significant flux rates, based on analogue and conceptual data.	This remains a topic of high uncertainty and an R&D effort is needed to solve this issue	
Summary	If not compliant with all of the above, clay swelling will not build up a swelling pressure that is significant enough to cause shear failure of the seal. Further reservoir geometry will not allow fault reactivation and there is no permeability or pressure drive to cause CO_2 to leak.	The geometry of the reservoir (seal thickness versus potential fault offset) does not allow shear failure for the entire seal sequence to occur. Only in the very North of the reservoir a small likelyhood remains that fault offset is comparable to the thickness of the lower part of the seal (U. Valhall/Rødby Fms).	Smectite content could be sufficient to obtain shear failure and if the fault would become permeable, the possibility for a pressure-drive for fault leakage cannot be excluded.	Clay swelling following shear failure and the development of a permeable fault remains uncertain due to many parameters that cannot be quantified. For the Goldeneye reservoir, however, it is found that potential faults are below the thickness of the entire seal and a low risk remains only for the caprock. Loss of containment can therefore be classified as a low geological risk	

Busch et al..2020. Int J Greenhouse Gas Control 94, 102924

Summary and Conclusion

- Geological risks relate to reservoir conformance and seal containment
  - Prediction of CO_2 plume migration in subsurface means understanding reservoir structure and heterogeneity
  - Prediction of leakage risks requires understanding of fault and (legacy) well location, number and condition
- Risk assessment is key in any CO_2 storage project and needs to be conducted at several stages of the project, involving all subsurface disciplines and key experts


THANK YOU!
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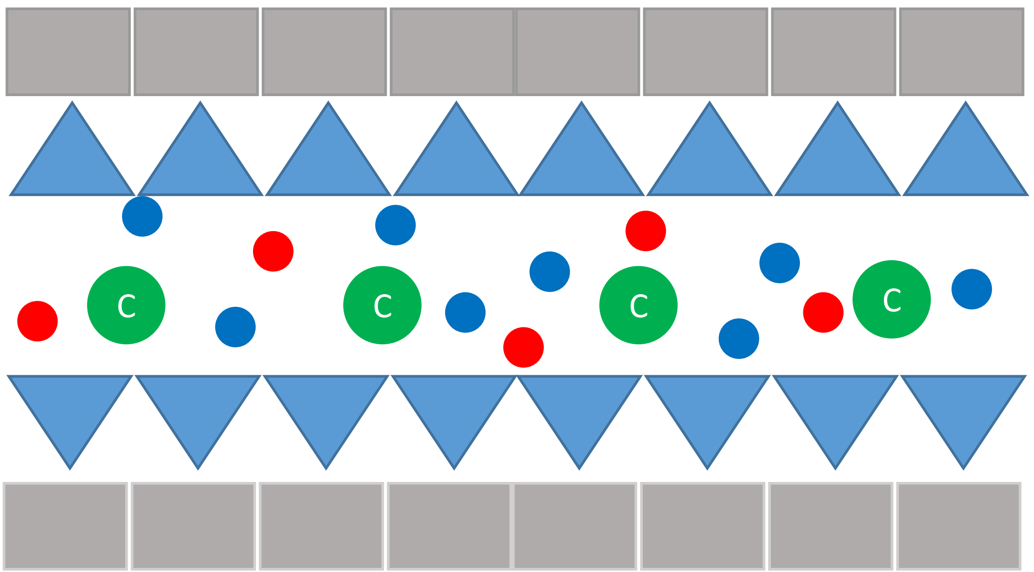
Clay swelling and fault reactivation



- water
- interlayer cation
- CO_2 molecule

Busch et al. 2020, Int J GHGC