Scenario Modelling to Support Monitoring Plans for CO_2 Storage Sites

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Background

- Most jurisdictions require a CO_2 storage site's operator to plan for measurement, monitoring and verification (MMV).

- In Europe, this requirement is specified in EC Directive 2009/31/EC (the 'Storage Directive').

- The UK needs to determine priority technologies and methodologies to enable effective MMV in offshore areas, where CO_2 storage is planned.

- The UK's Energy Technologies Institute (ETI) instigated a project to review UK legislative and technical requirements for MMV, and determine future development priorities.

Aims of Scenario Modelling

- Essential MMV goals are to determine that:
  - the storage system behaves as expected
  - the defined storage complex does not leak CO_2

- Overall project goals included determining:
  - whether each available monitoring technique can identify unexpected abnormal behaviour of stored CO_2
  - under what circumstances

- Scenario modelling aimed to inform evaluations of monitoring techniques by:
  - illustrating hypothetical consequences of abnormal behaviour and CO_2 leakage
  - exploring how quantitative metrics (e.g. amounts of water and free CO_2, pressure etc) might vary in these circumstances

Scenario Development Process

Workshop Attended by Quintessa, BGS, TNO

Agree Scope, Aims

↓

Define illustrative kinds of N. Sea storage site (*generic*)

↓

Define hypothetical leakage scenarios

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Review by ETI & Partners

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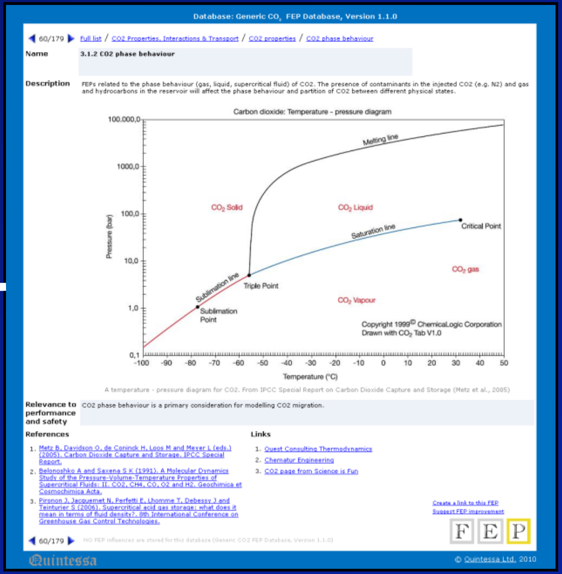
Revise illustrative site descriptions & hypothetical leakage scenarios

↓

Explore hypothetical leakage scenarios using systems models

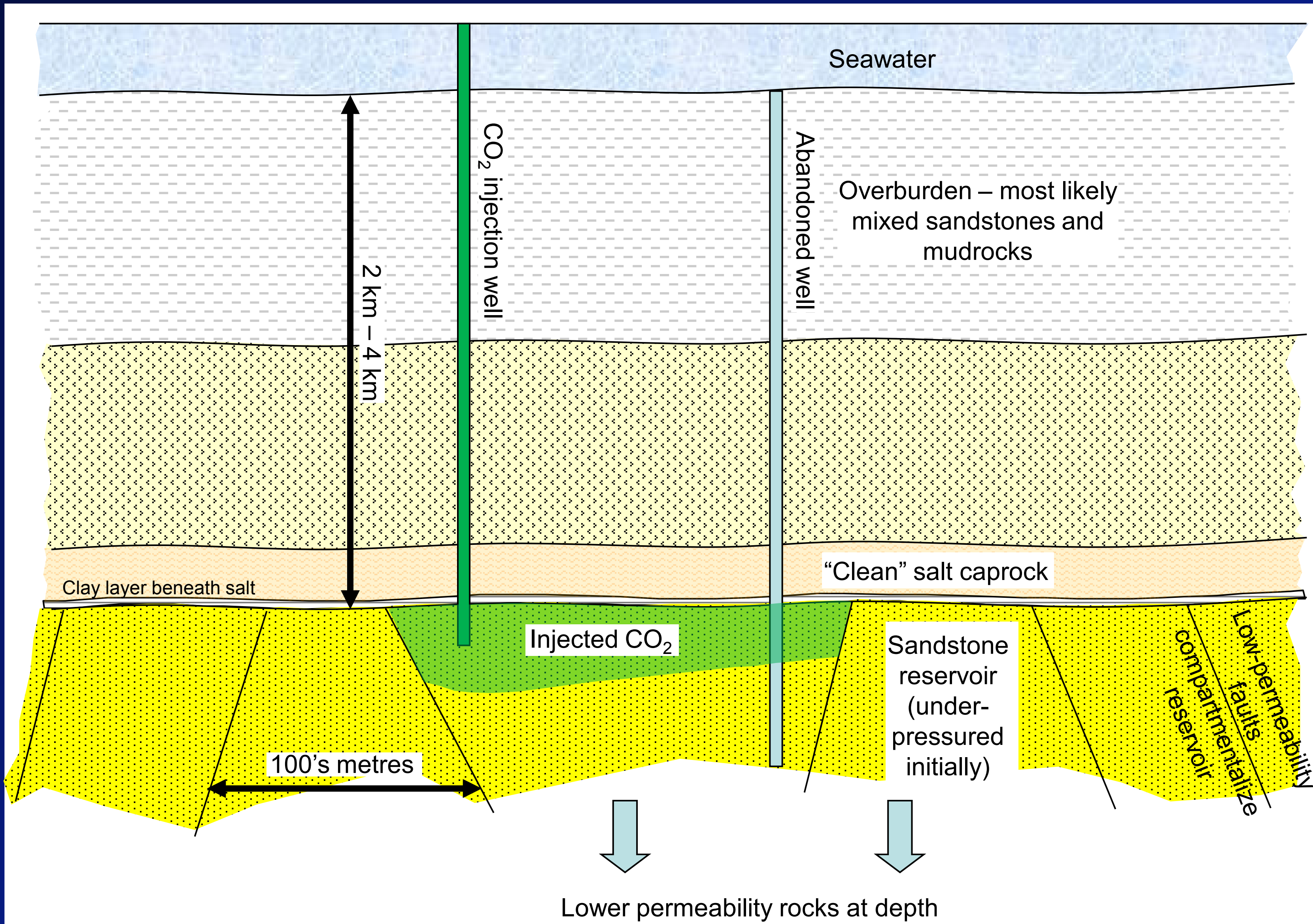
- Audit against Quintessa's Generic Online CO_2 FEP database



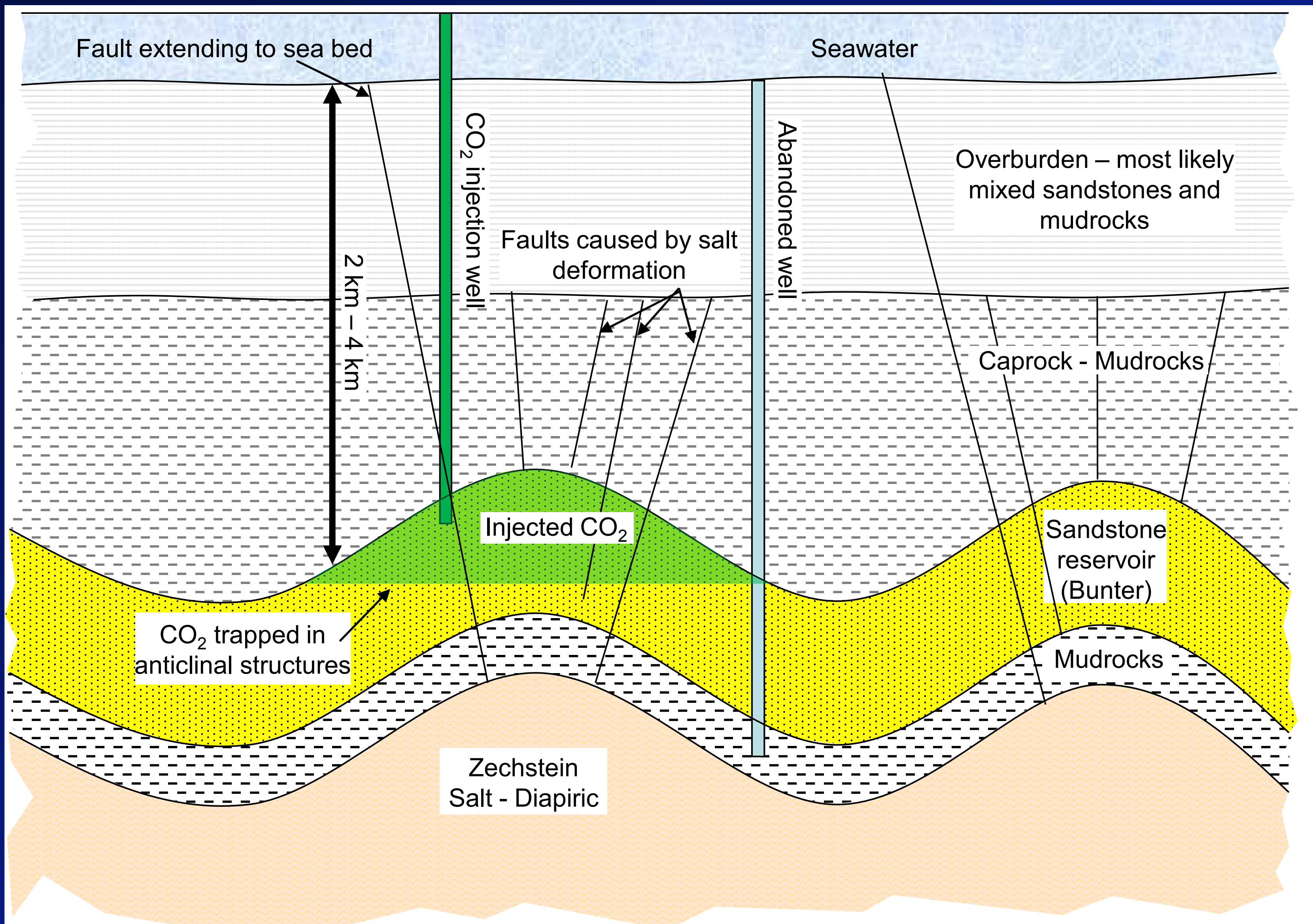
- Standard "check-list"
- Ensure nothing significant missed
- Freely accessible

http://www.quintessa.org/co2fepdb

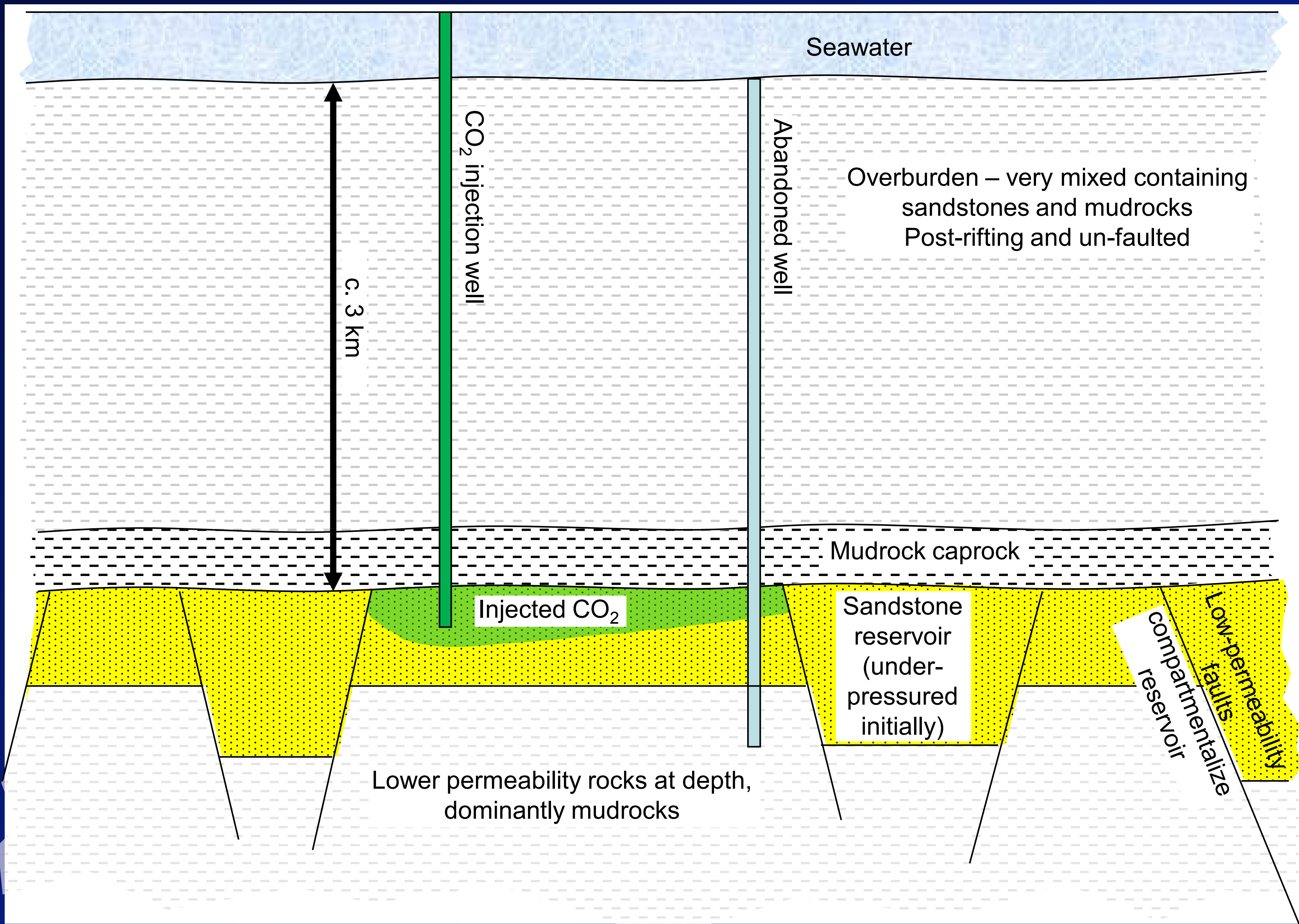
Storage Site Type 1 (S North Sea)



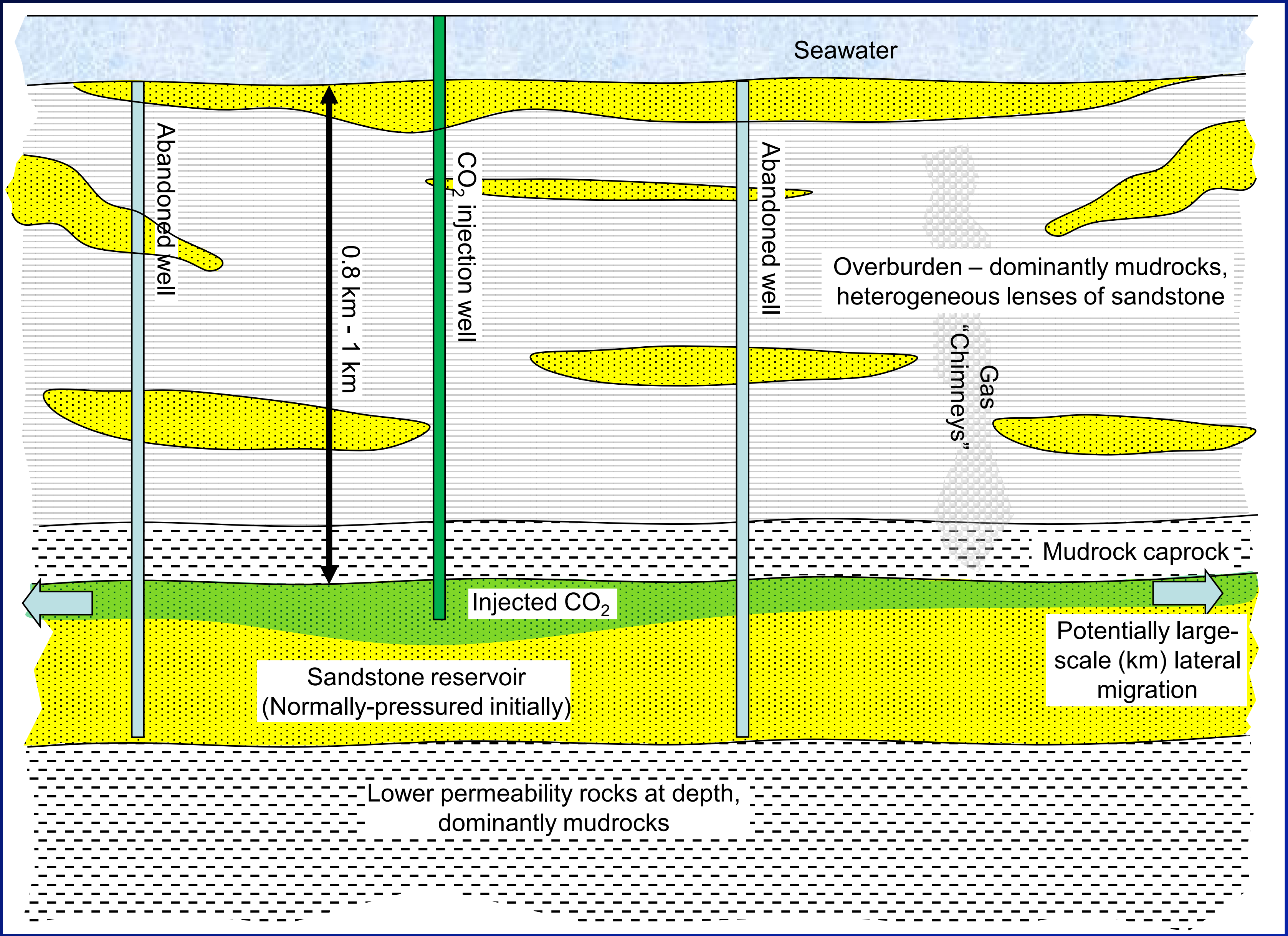
Storage Site Type 2 (S North Sea)



Storage Site Type 3 (Central, Northern N Sea)



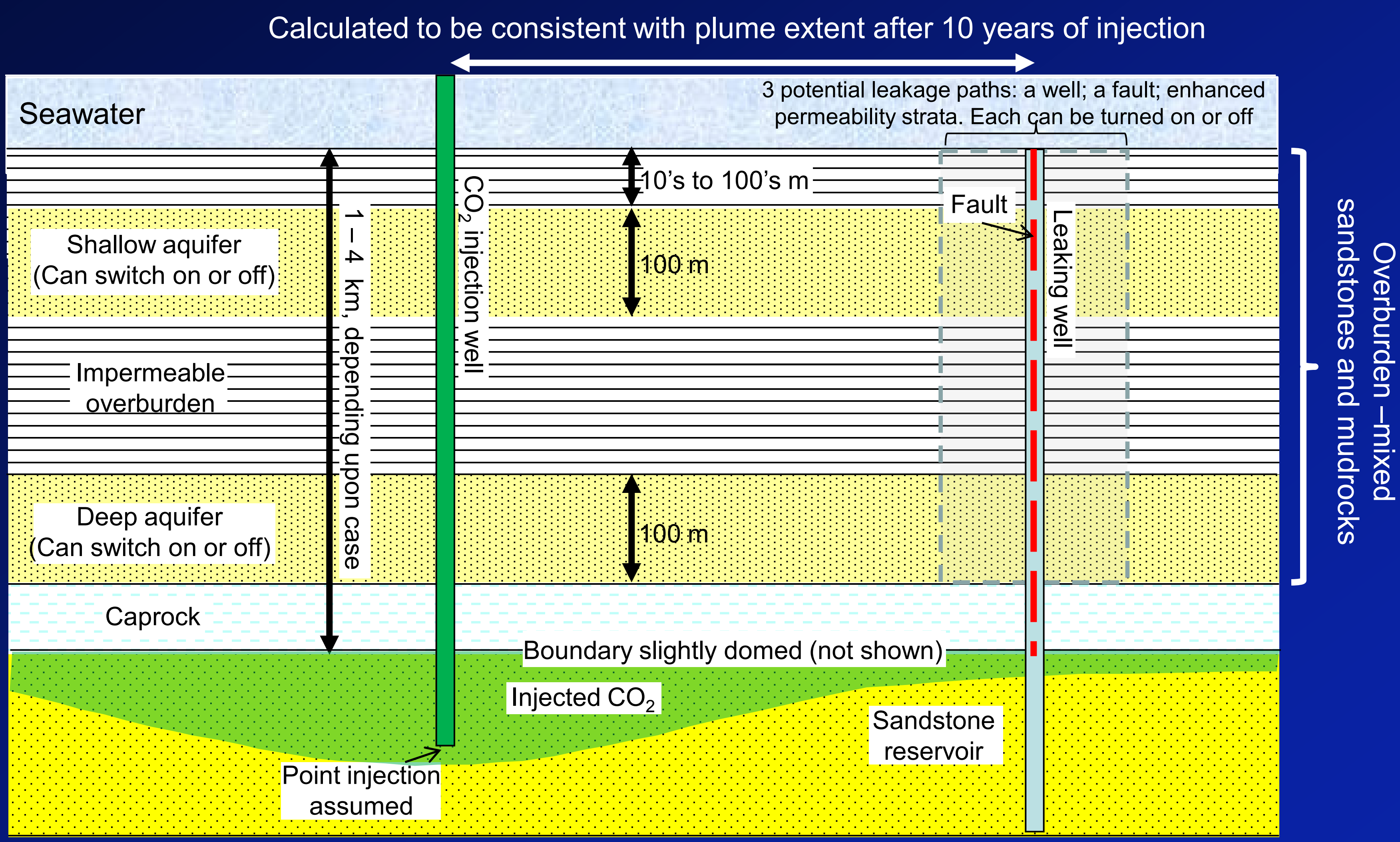
Storage Site Type 4 (Central, Northern N Sea)



Scenarios

- In the hypothetical case that CO_2 can leak upwards, the most likely pathways are:
  - a well (1D path, “well leakage scenario”)
  - a fault (2D path, “fault leakage scenario”)
  - enhanced-permeability rock zone (3D path, “enhanced permeability overburden scenario”) representing
    - heterogeneously distributed interconnected permeable strata within dominantly impermeable overburden
    - or a gas chimney
  - the caprock, over wide area (“leaking caprock scenario”)
- Common features of scenarios:
  - reservoir
  - impermeable caprock
  - impermeable overburden containing a “deep aquifer” and a “shallow aquifer”
  - seawater at the top boundary
  - injection well

Basic Systems Model



Lower permeability rocks at depth – represent by no-flow boundary

For each kind of site, each kind of leakage path placed same distance from injection well

Model Cases

- Case 1 –
  - relatively deep brine-filled reservoir brine
  - initial, pre-injection CO_2 pressure below hydrostatic
  - final reservoir fluid pressure hydrostatic
- Case 2 –
  - relatively shallow saline water-filled reservoir
  - initial, pre- injection CO_2 pressure is hydrostatic pressure
  - end-injection reservoir fluid pressure slightly >hydrostatic
  - decreases rapidly to hydrostatic
- Case 3 –
  - relatively shallow brine-filled reservoir
  - initial pre-injection CO_2 pressure hydrostatic pressure
  - final reservoir fluid pressure just below (85%) of lithostatic

3 pathways considered for each case:

Case 1_Well
Case 1_Fault
Case 1_Cap
etc

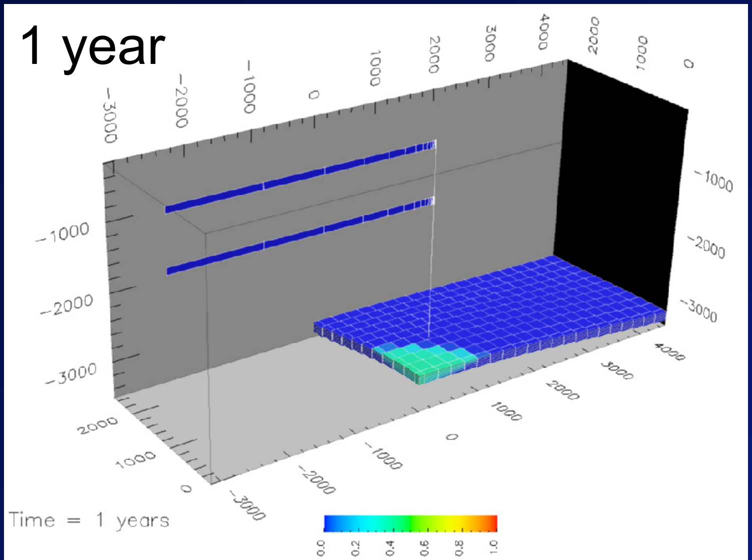
Site / Scenario / Case Correspondence

Simulations with generic systems model				Corresponding Storage Site			
Cases				Southern North Sea Type 1	Southern North Sea Type 2	Central & Northern North Sea Fault Block-type Type 3	Central & Northern North Sea Aquifer Type 4
Case	Initial reservoir pressure	Final reservoir pressure	Injection duration				
Leaking well scenario							
1_Well	Under-pressured	Hydrostatic	50 years	Correspondence	Correspondence	Correspondence	None
2_Well	Hydrostatic	Hydrostatic+	50 years	Weak correspondence	Correspondence	Correspondence	Correspondence
3_Well	Hydrostatic	Sub-lithostatic	50 years	Weak correspondence	Correspondence	Correspondence	Weak Correspondence
Leaking fault scenario							
1_Fault	Under-pressured	Hydrostatic	50 years	None	Correspondence	None	None
2_Fault	Hydrostatic	Hydrostatic+	50 years	None	Correspondence	None	None
3_Fault	Hydrostatic	Sub-lithostatic	50 years	None	Correspondence	None	None
Leaking caprock and enhanced overburden permeability scenario							
1_Cap	Under-pressured	Hydrostatic	50 years	None	Correspondence	None	None
2_Cap	Hydrostatic	Hydrostatic+	50 years	None	Correspondence	None	Correspondence
3_Cap	Hydrostatic	Sub-lithostatic	50 years	None	Correspondence	None	None

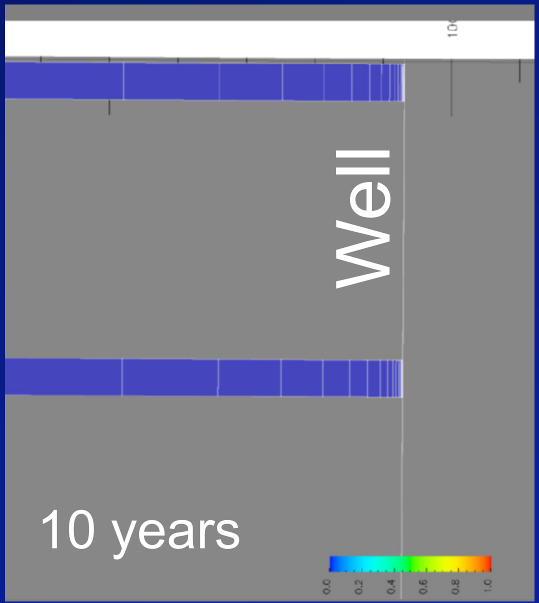
Modelling Software

- Quintessa's QPAC software:
  - General-purpose modelling tool
  - Solves wide-ranging problems, including strongly-coupled, non-linear processes
- Allows modeller to define included processes:
  - Thermal
  - Hydrogeological (Darcy Flow, Multi-Phase Flow etc)
  - Mechanical
  - Reactive Transport
  - Solute Transport
  - a 'systems-level'
  - 'detailed' research-level

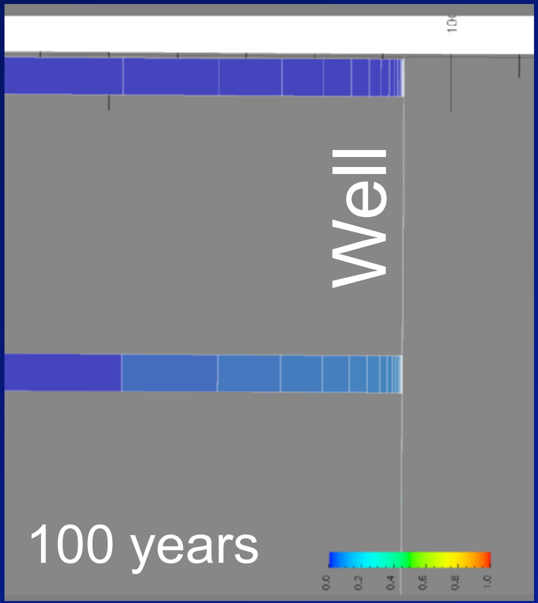
Well Leakage Scenario, Case 1_Well



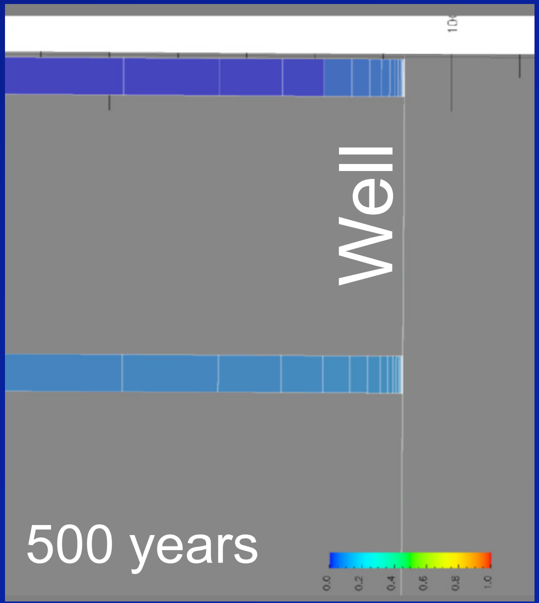
Buoyancy only driving force



CO_2 Saturation

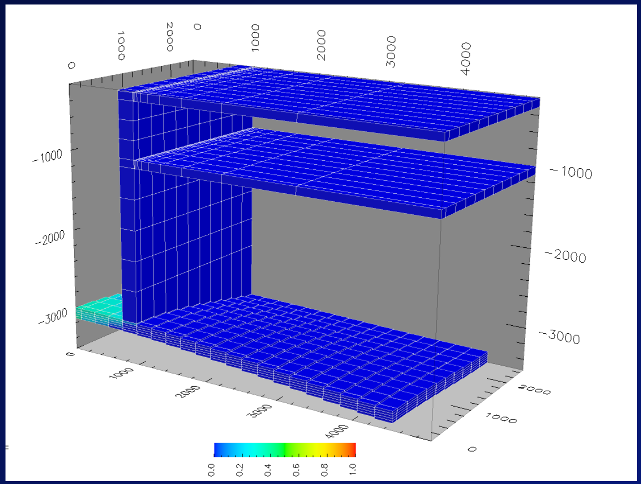


- Significant CO_2 enters aquifers (esp. lower aquifer)
- Explained by large CO_2 surface area per unit volume flowing

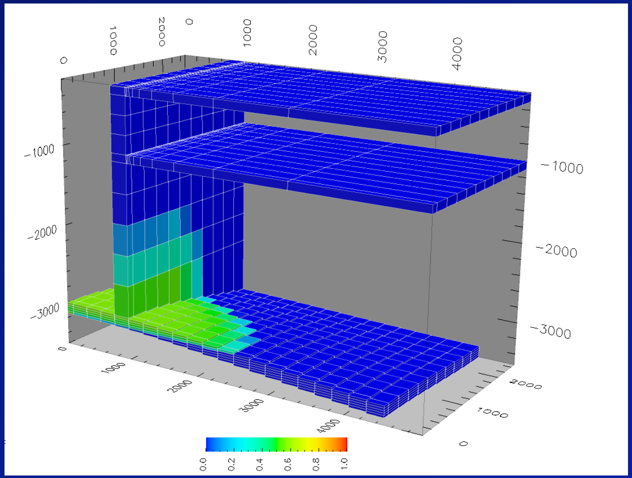


Fault Leakage Scenario, Case 1_Fault

1 year

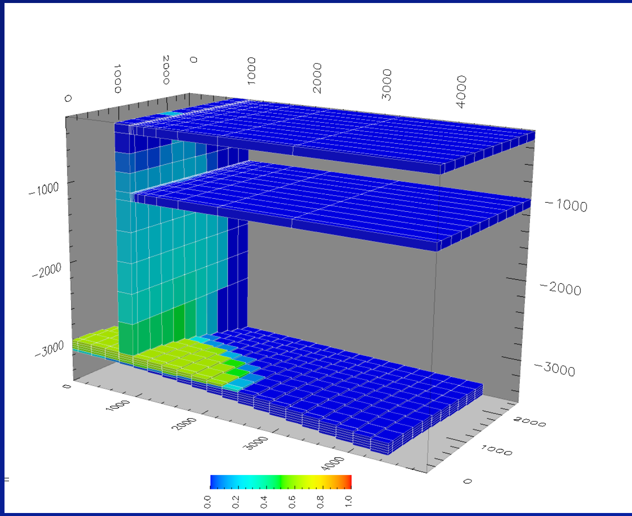


50 years



CO_2 Saturation

400 years

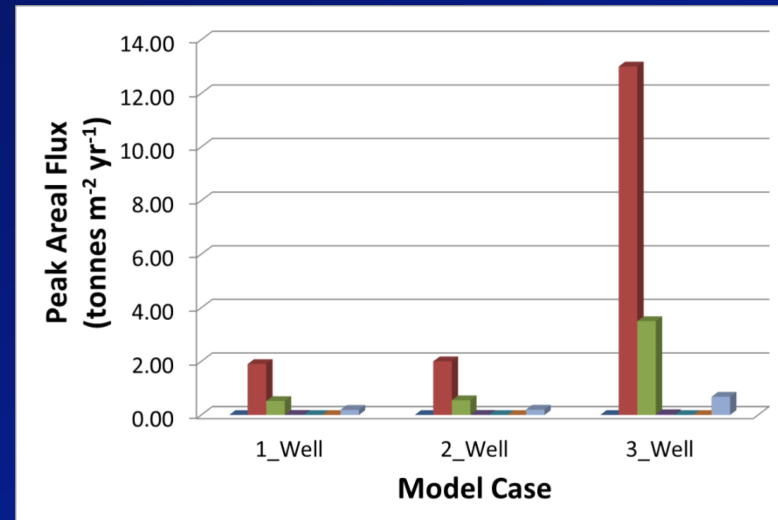


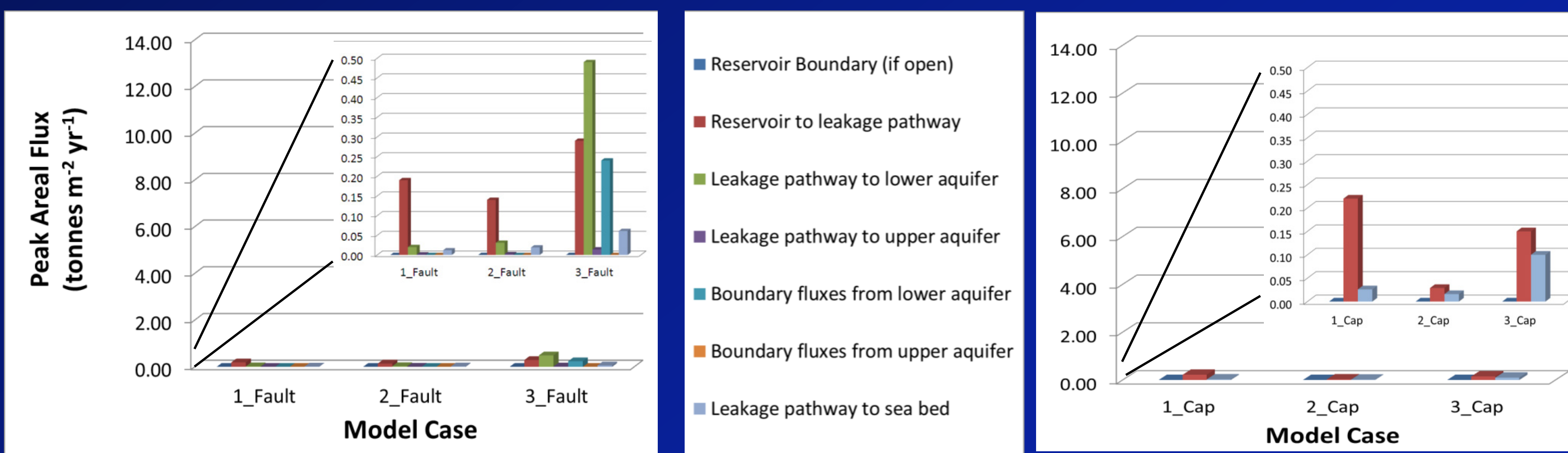
- Negligible CO_2 enters the aquifers
- Owing to relatively small CO_2 surface area per unit volume (c.f. wells)

Free CO_2: Peak Areal Fluxes at Key Locations

- Peak fluxes for well cases
- Highest fluxes for near-lithostatic final pressure condition
- Fluxes reflect area of leakage path intersecting the particular model location

<<Hydrostatic – Hydrostatic | Hydrostatic – >Hydrostatic | Hydrostatic – 85% Lithostatic

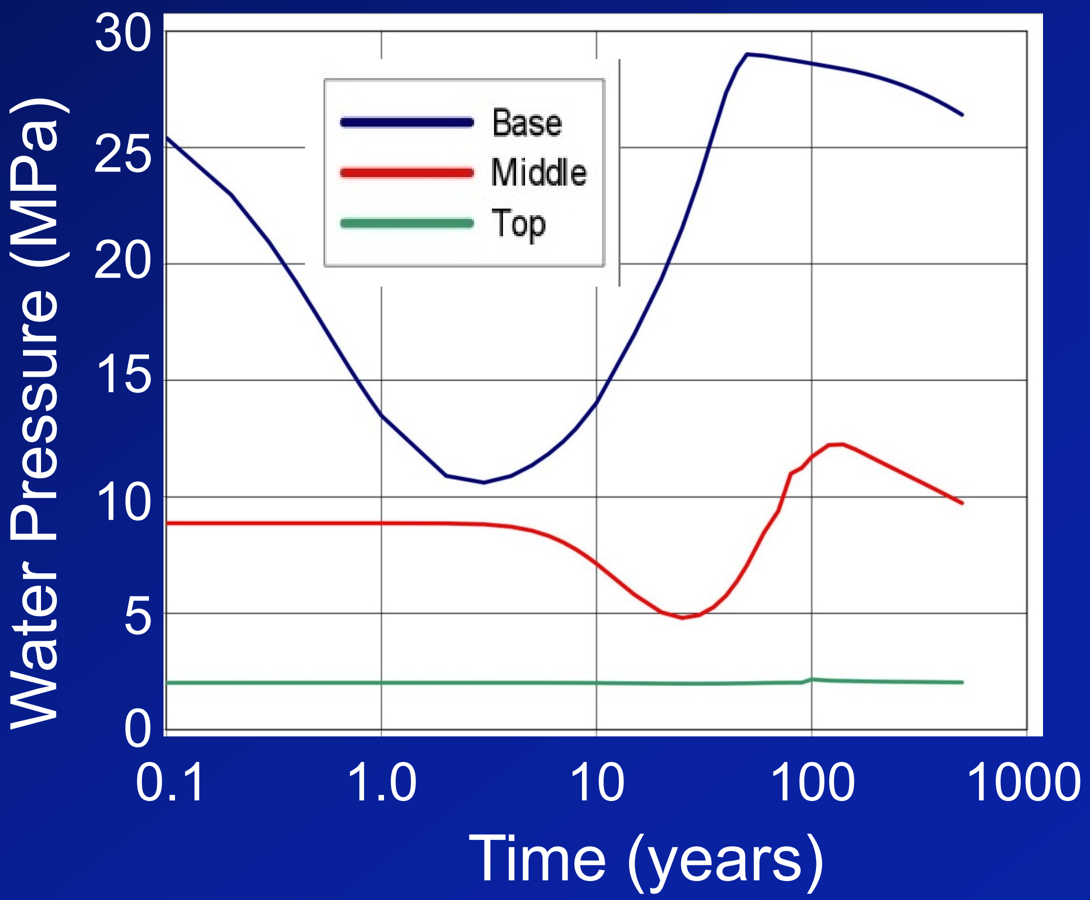




Case 1_Cap, Failed Cap Pressure Response

- Initial pressure below hydrostatic
- Greatest pressure variation among the 3 leak modes
- Impact of low initial reservoir pressure seen
- See effects of subsequent CO_2 injection, and initiation of upwards pressure-driven flow (esp. 2 - 20 years)
- Buoyancy effects tend to dominate by >20 years

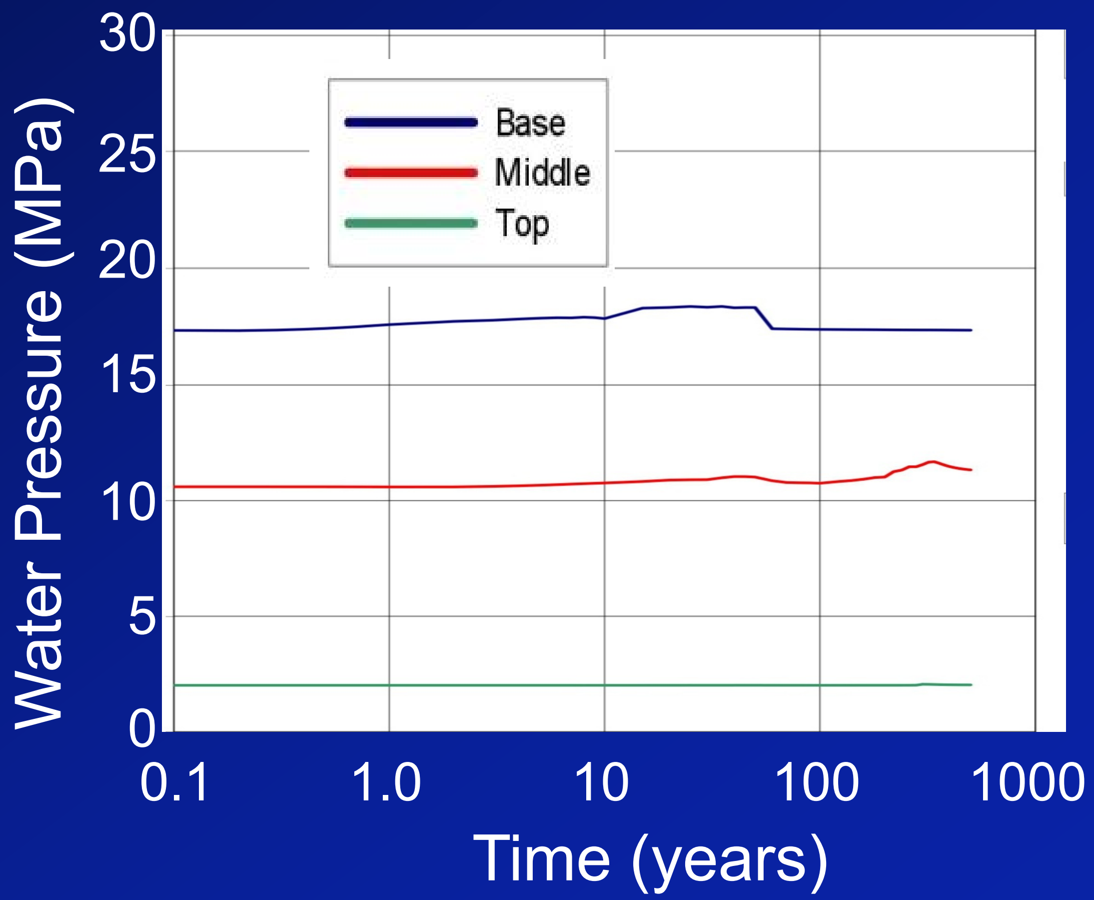
Locations along leakage path



Case 2_Cap, Failed Cap Pressure Response

- Initial pressure hydrostatic
- Much lower pressure variation than in initially underpressured case (Case 1_Cap)
- Minor pressure impacts caused by CO_2 injection
- Subsequent CO_2 migration up the pathway is largely buoyancy driven

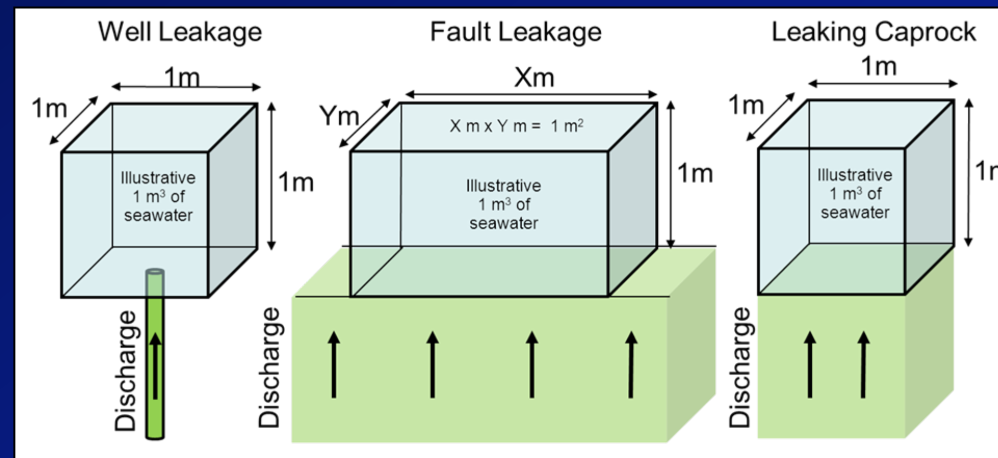
Locations along leakage path



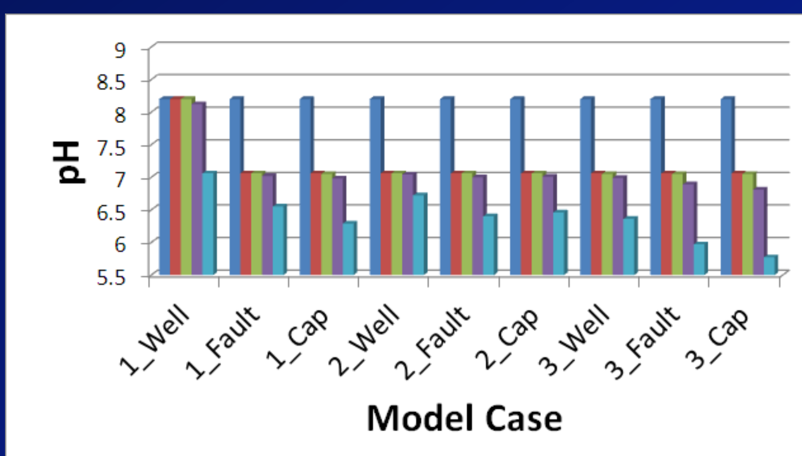
Illustrative Influence on Seawater pH

- Free CO_2 flux causes much greater influence than dissolved CO_2 flux
- Dissolved CO_2 effect only for near-lithostatic pressures in well case

Conceptual Model For Illustrative Calculations



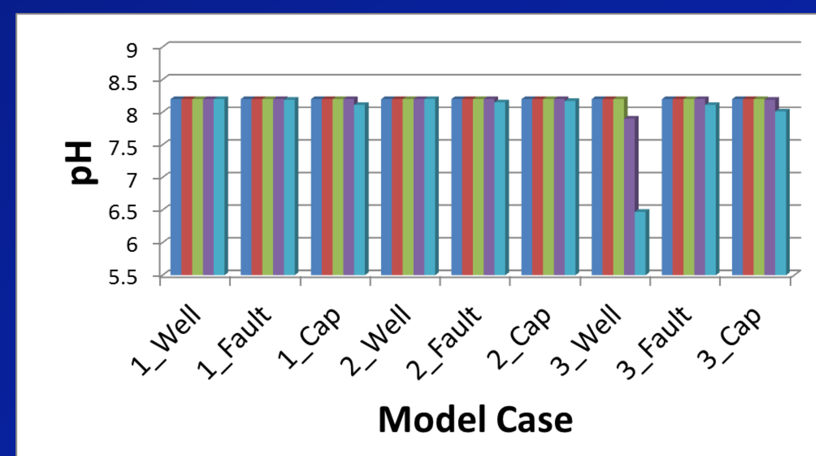
Peak Free CO_2 Flux to Seabed



Seawater Turnover Rate

- Initial
- 1 sec
- 1 min
- 1 hour
- 1 day

Peak Dissolved CO_2 Flux to Seabed



Conclusions

- Scenario modelling aids development and communication of monitoring plans, and is not a prediction tool

- Systems modelling using simplified grids allows rapid exploration of alternative cases (sensitivity studies)

- Reservoir and over-burden characteristics heavily influence the most appropriate monitoring strategies, e.g:

  - Pressure monitoring of initially under-pressured reservoirs before CO_2 injection could help indicate potential leakage paths
  - Monitoring aquifers in overburden likely more useful for demonstrating wells don’t leak than for demonstrating no other kinds of leakage path
  - Monitoring CO_2 remaining in a reservoir less able to identify leaks through borehole leaks than through faults or enhanced-permeability zones
  - Chemical monitoring of a caprock inappropriate because little CO_2 will enter the caprock over relevant timescales

Acknowledgments

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- We thank the ETI for the support of its staff and members in completing this work