

Does CO₂ Storage Work?

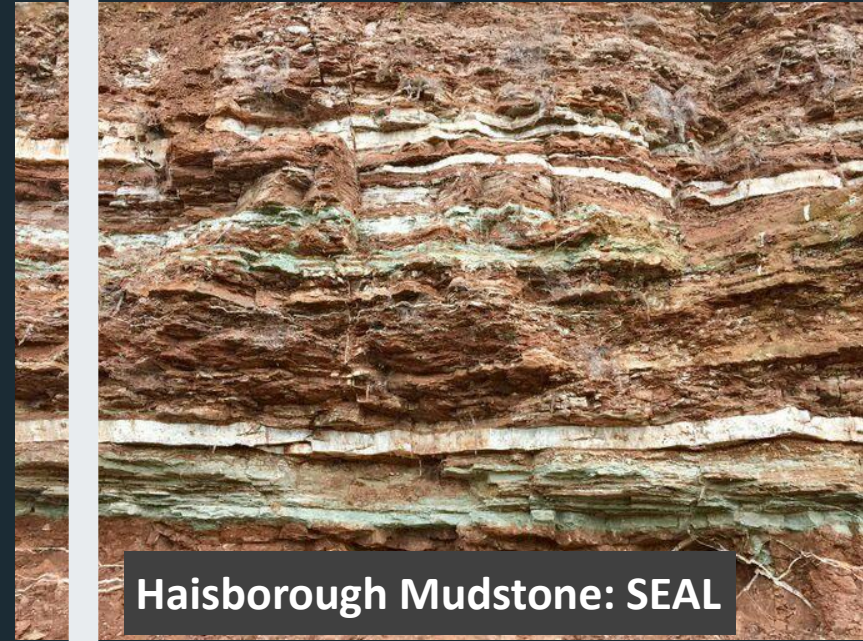
Evidence from Geochemical Modelling of the Southern North Sea

Bunter Sandstone saline aquifer and Haisborough Mudstone caprock

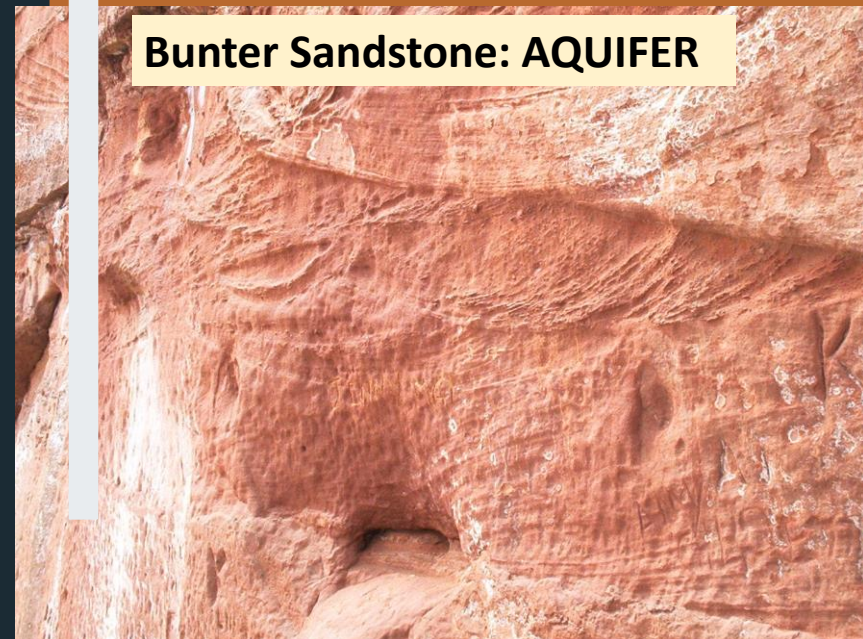
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Based on work commissioned by the North Sea Transition Authority (NSTA)



Haisborough Mudstone: SEAL



Bunter Sandstone: AQUIFER

Two questions every storage project must answer



Injectivity

Will the reservoir keep accepting CO₂ at viable rates?

Do reactions open the pore space, or block it?



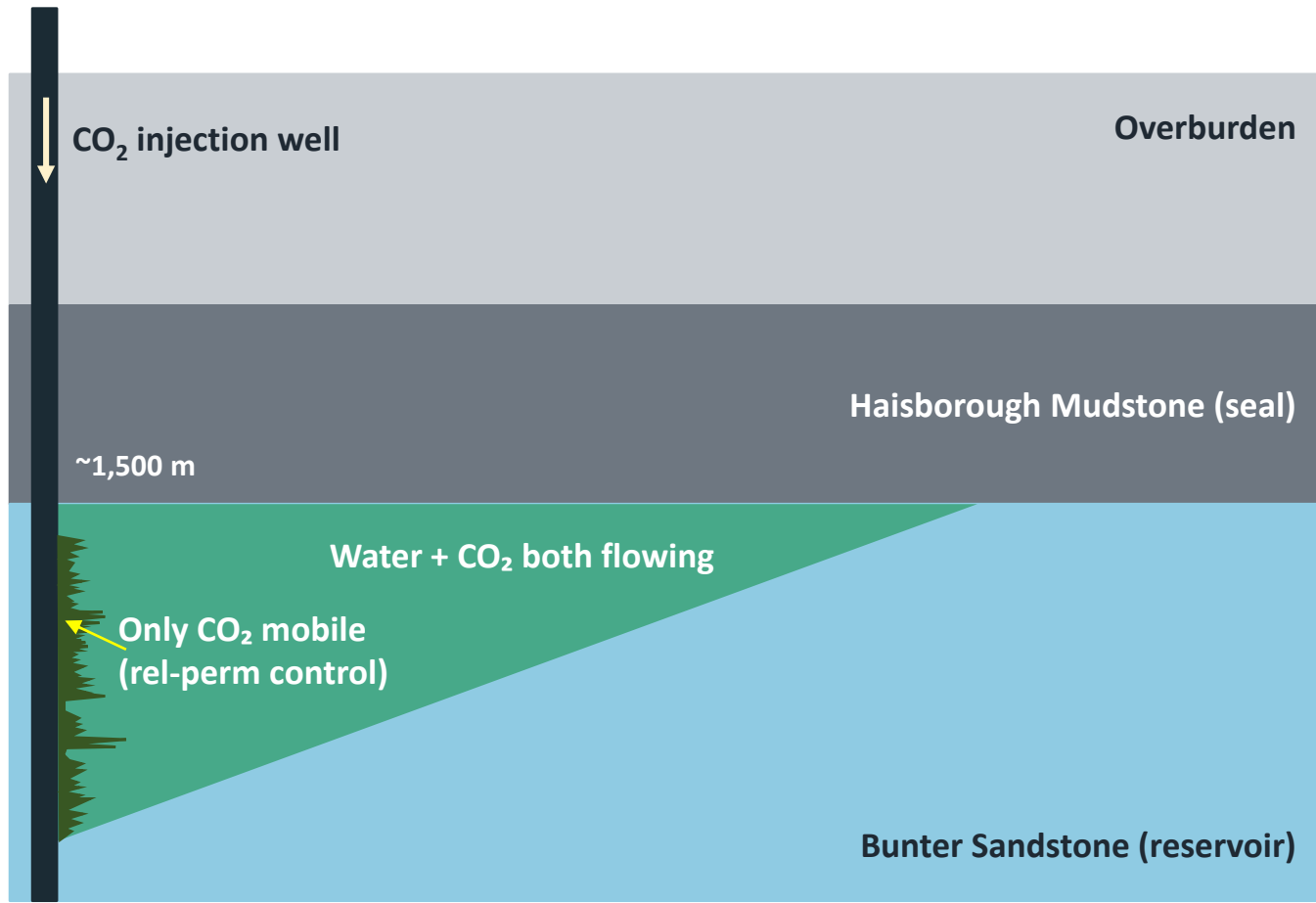
Containment

Will the caprock keep the CO₂ in, for centuries to millennia?

Does CO₂ weaken the seal, or strengthen it?

Both depend on how the rocks' minerals react with CO₂-charged brine, and how fast

The Bunter-Haisborough system: a major UK offshore storage target



Schematic, not to scale

Haisborough Mudstone: caprock

- Tens of metres thick · 10% porosity
- Illite- and dolomite-rich; albite, chlorite
- Very little or no calcite

Bunter Sandstone: reservoir

- ~1,500 m depth · 56 °C · 20% porosity
- ~70% quartz (inert)
- Calcite + dolomite cement; minor albite, chlorite, illite

Data: Endurance well 42/25d-3 (Capture Power Ltd, 2016; BP, 2022) and other sources

Three levels of modelling, each closer to the real subsurface

Increasing realism →

1

Equilibrium

What could react?

Screening only: assumes instant, complete reaction (not realistic).

At 56 °C it wrongly predicts

2

Batch kinetic

How fast does it react?

Rate laws for each mineral in a closed rock–brine box.

Days to millennia.

3

Reactive transport

Where, and how fast?

Kinetics + movement: advection in the reservoir, diffusion in the seal.

Primary basis for conclusions.

All models: PHREEQC (Parkhurst & Appelo, 2013) · mineral rates: Kinec_v3 (Oelkers & Addassi, 2025), equation of state used for CO₂ geochemical reactivity (fugacity)

The PHREEQC geochemical models are anchored to measured formation data



Formation water

Published analyses from Endurance well 42/25d-3 and other Bunter sandstones in the SNS



Mineralogy

XRD data → moles per kg of brine. XRD halite here removed: reported brine is undersaturated, so halite is likely an artefact



Reaction rates

Kinec_v3 kinetic database (new) with alumino-silicate reaction rates modified to be sensitive to CO₂ concentration



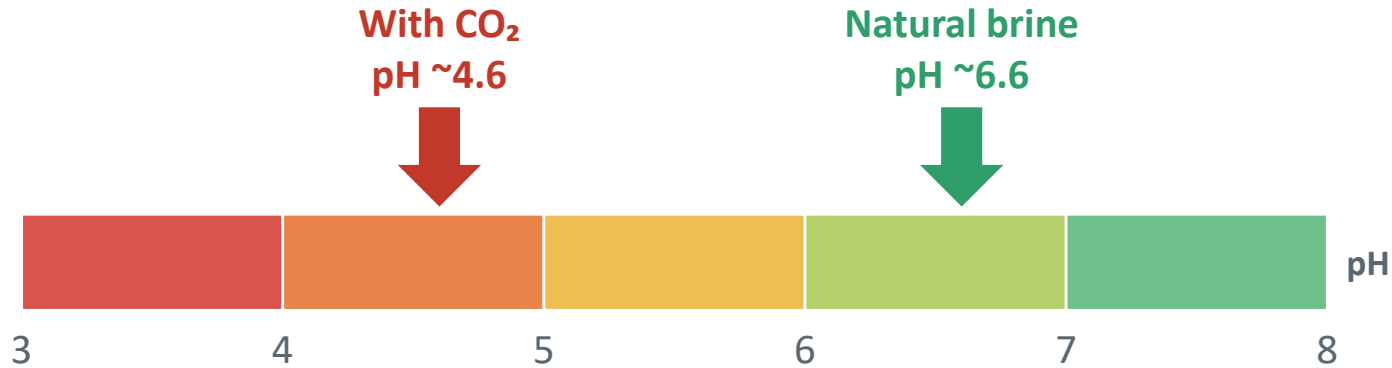
Conditions

56 °C · 125 atm CO₂ (supercritical at reservoir depth) · EOS used to derive CO₂ solubility and pH

Outputs derived

- Mineral volumes through time and space
- Porosity from mineral volumes through time and space
- Permeability from published porosity–permeability relationship (e.g. Gluyas & Bagudu, 2020)
- Fate of CO₂: free phase, dissolved, mineralised

CO₂ acidifies the brine mildly, and carbonate cements buffer it



Acidic enough to dissolve carbonate cement, but not a strong mineral acid.



Kinetics (rate) of carbonate reactions is several orders of magnitude faster than alumino-silicate reactions

~70%

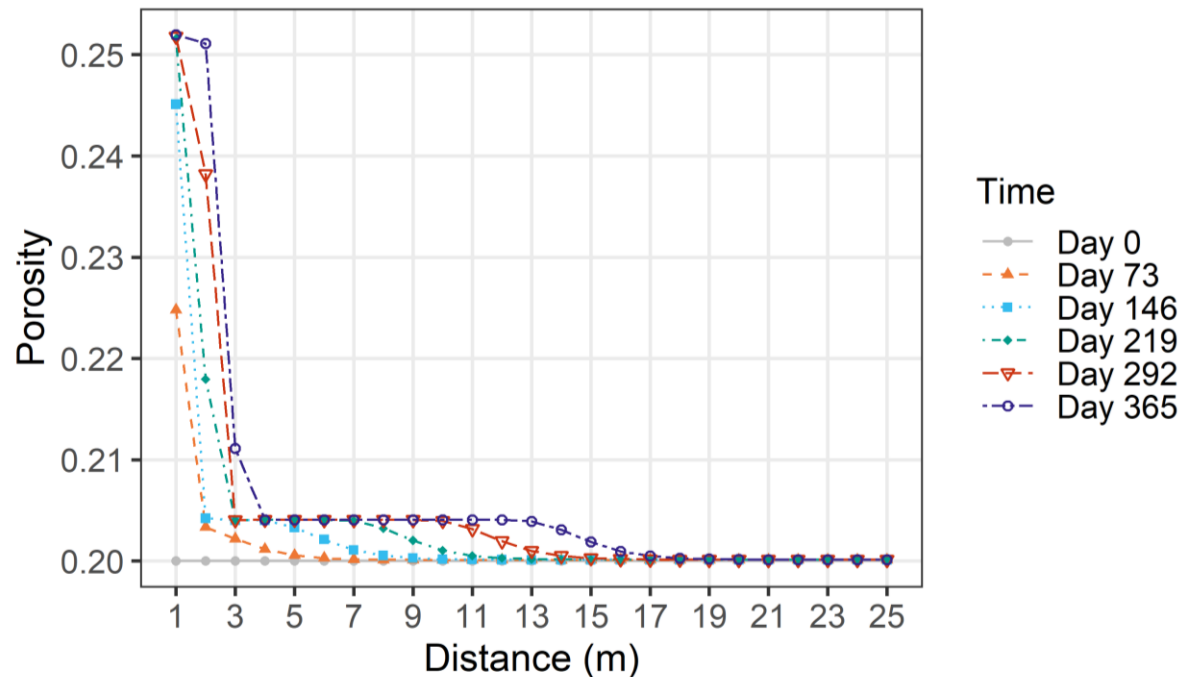
of the rock is quartz, which is essentially inert at 56 °C

Potentially reactive minority minerals

- Calcite, dolomite (buffer the acid)
- Albite → Na, Al for dawsonite
- Chlorite → Fe, Mg for siderite, dolomite
- Illite

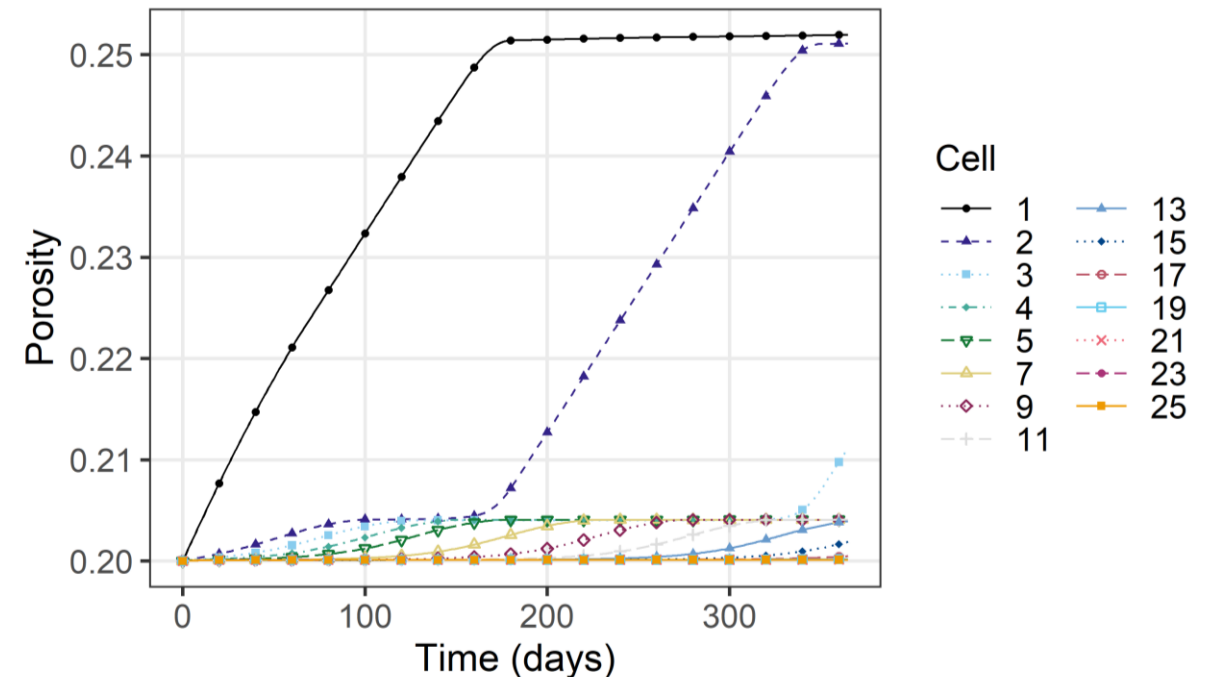
Near the well, porosity rises ~5 percentage points in one year

20% → ~25% in the first 1–2 m of sandstone



Porosity fraction vs distance at Days 0–365 (1 m cells)

Beyond ~17 m: no change after 1 year of injection

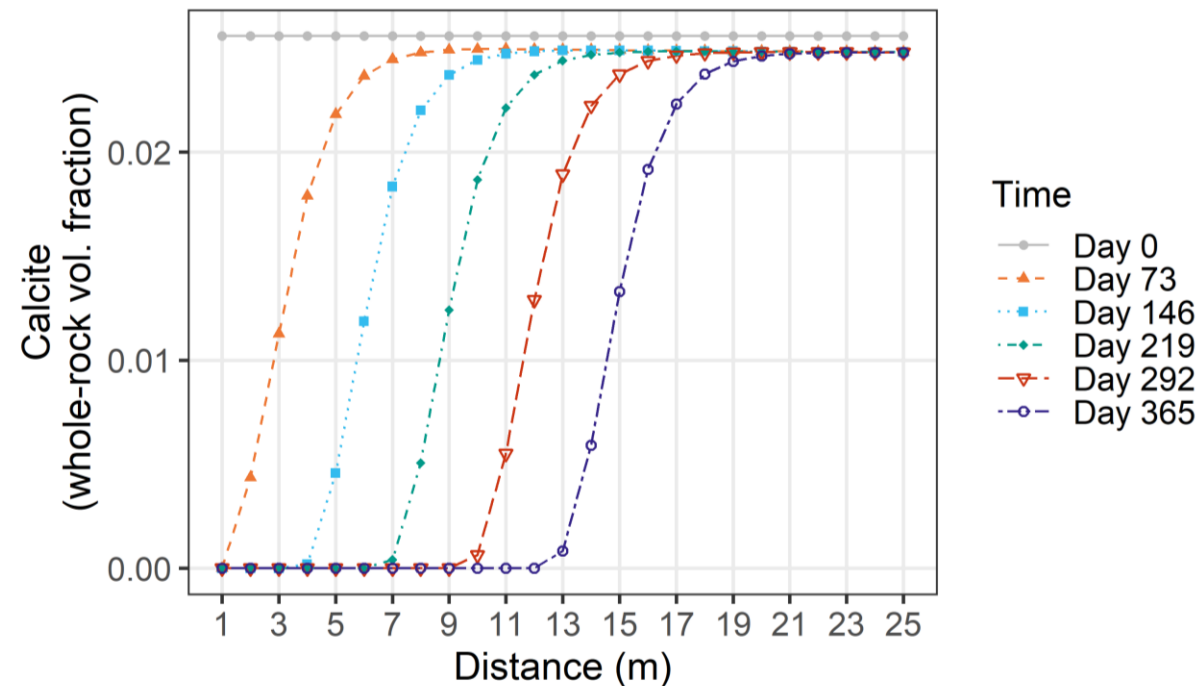


Porosity fraction vs time for each 1 m cell; cells 1 & 2 respond first

Bunter advective reactive-transport model, base case: 125 atm CO₂, 56 °C

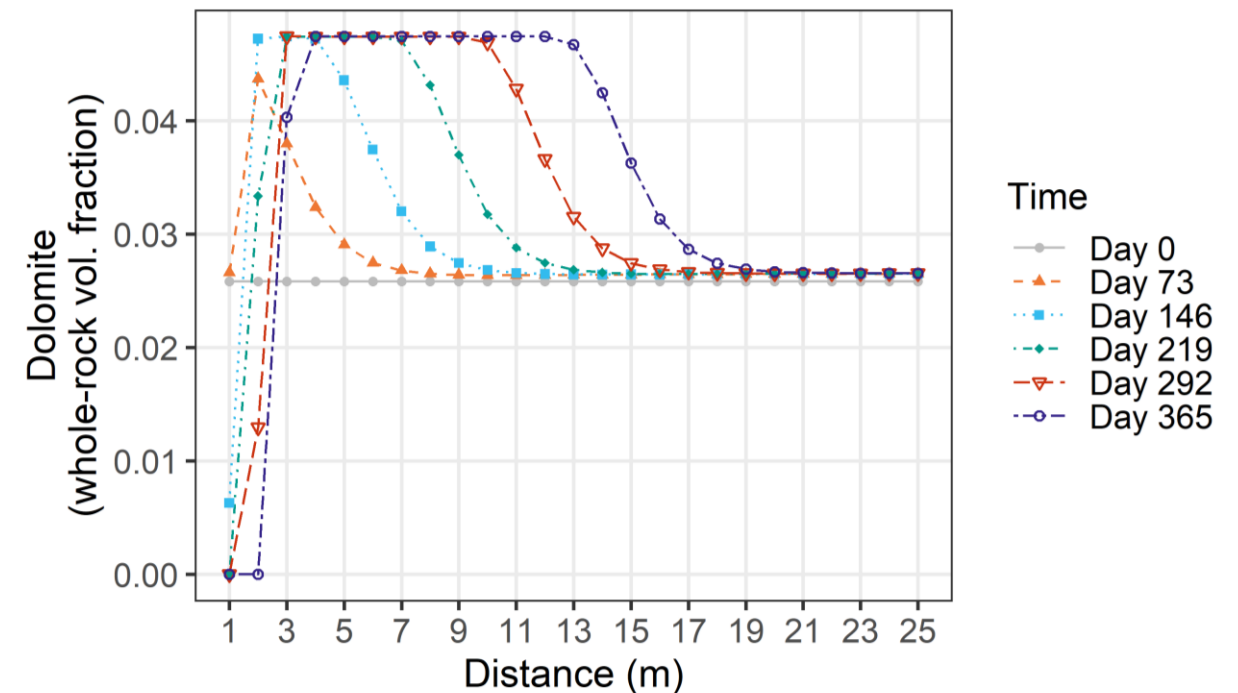
The acid front self-limits and redistributes carbonate cement

Calcite is removed progressively as the reaction front advances



Calcite volume vs distance, Days 0–365

Dolomite dissolves near the well, but locally grows in place of calcite ahead of the front



Dolomite volume vs distance, Days 0–365

Self-limiting: each cell's carbonate holds pH near 4.6 until it is used up, so the acid cannot run ahead.

Operationally: near-well permeability more than doubles

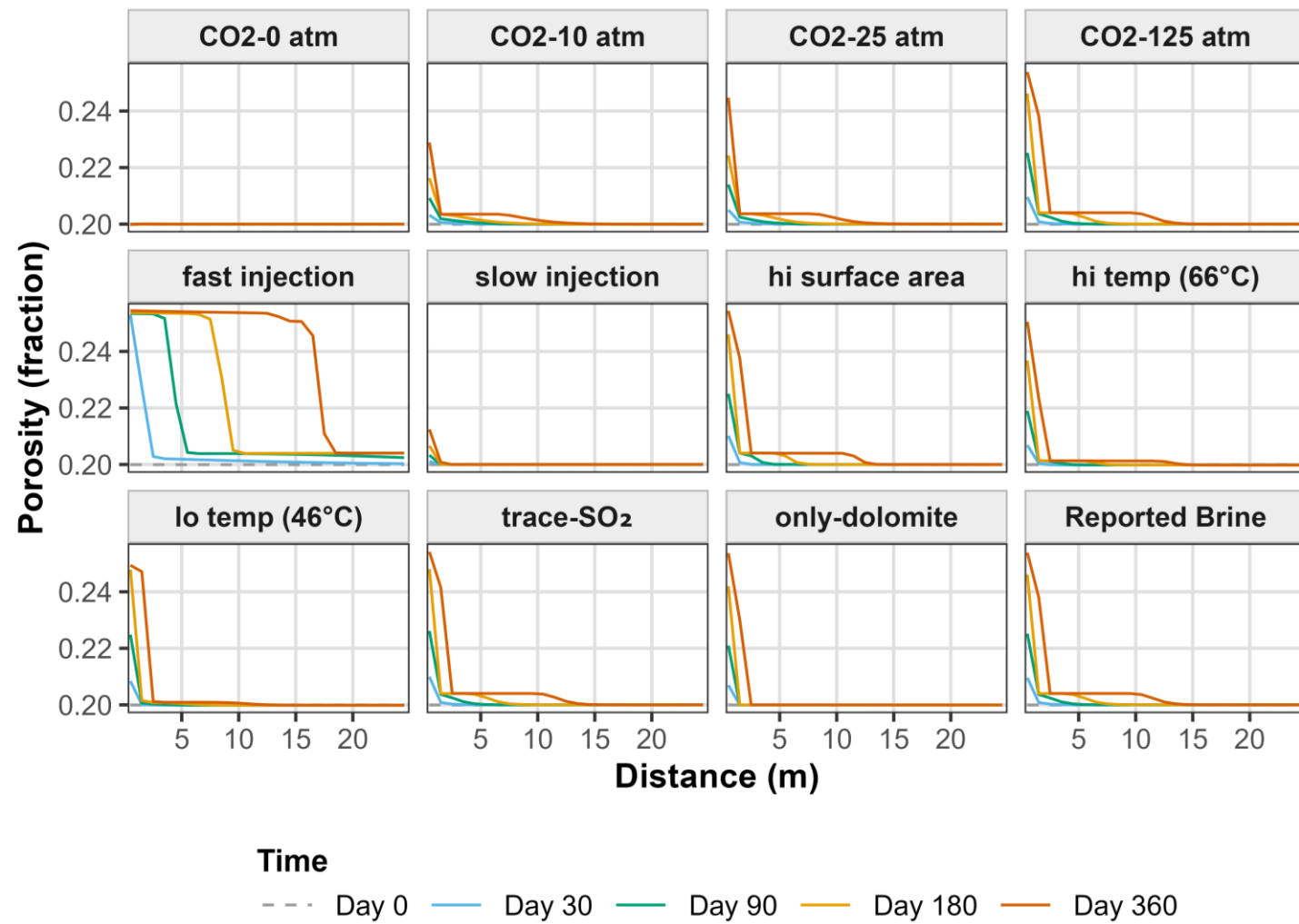
Near-well permeability

~271 → ~639 mD

Porosity 20% → 25.2%, via the Endurance ϕ - k relationship (Gluyas & Bagudu, 2020) and Kozeny-Carmen modelling. Higher permeability should help injectivity.

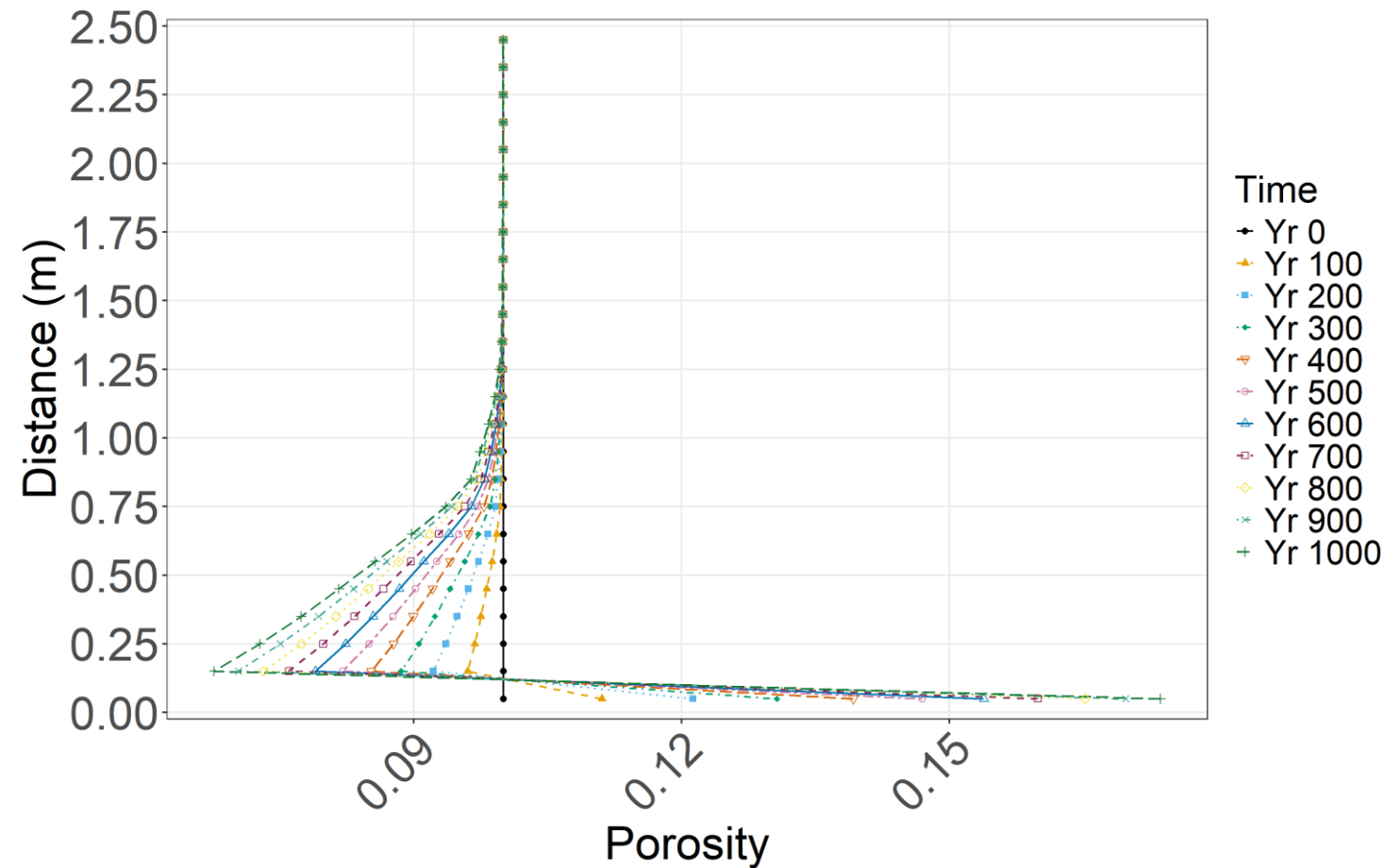
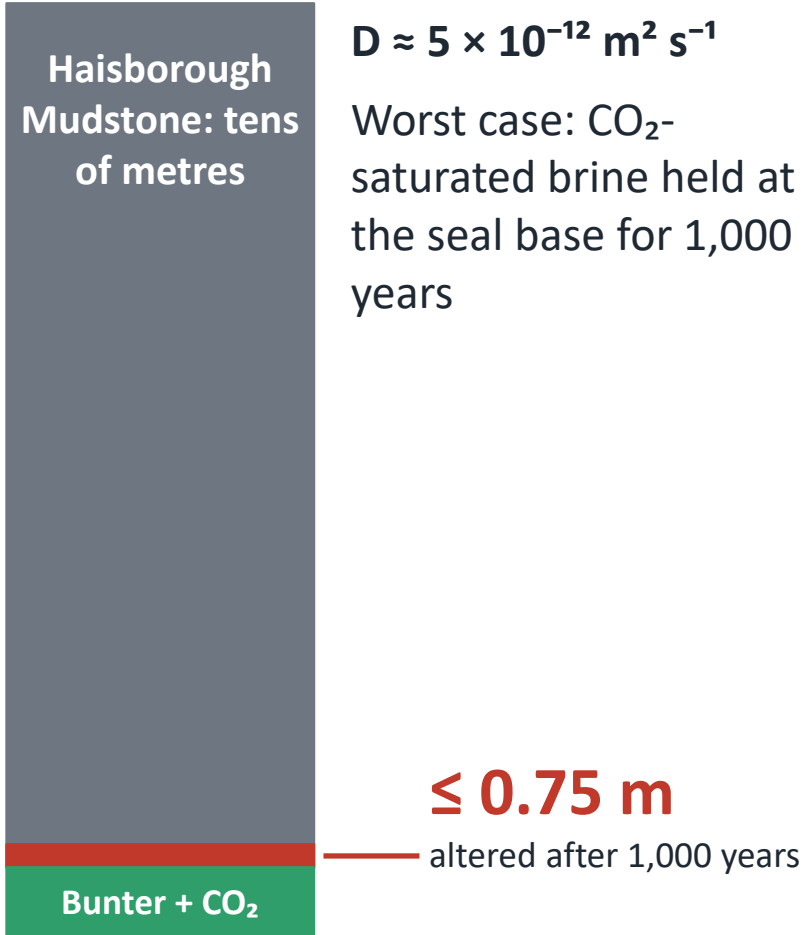
What controls the size of the change?

CO ₂ partial pressure	<i>dominant</i>
Injection rate	<i>strong</i>
Temperature, surface area	<i>moderate</i>
100 ppm SO ₂	<i>negligible</i>



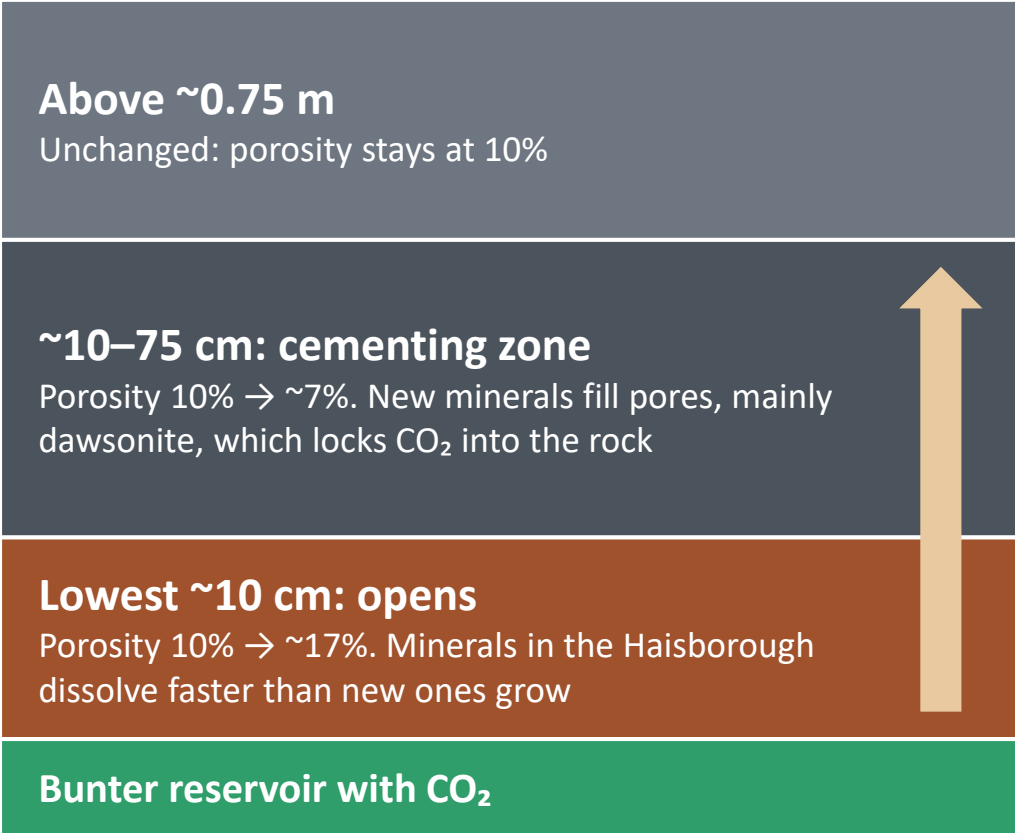
Sensitivity: porosity vs distance for each scenario (panels), Days 0–360

In the intact, water-saturated seal model, dissolved CO₂ transport is diffusion-dominated and is slow

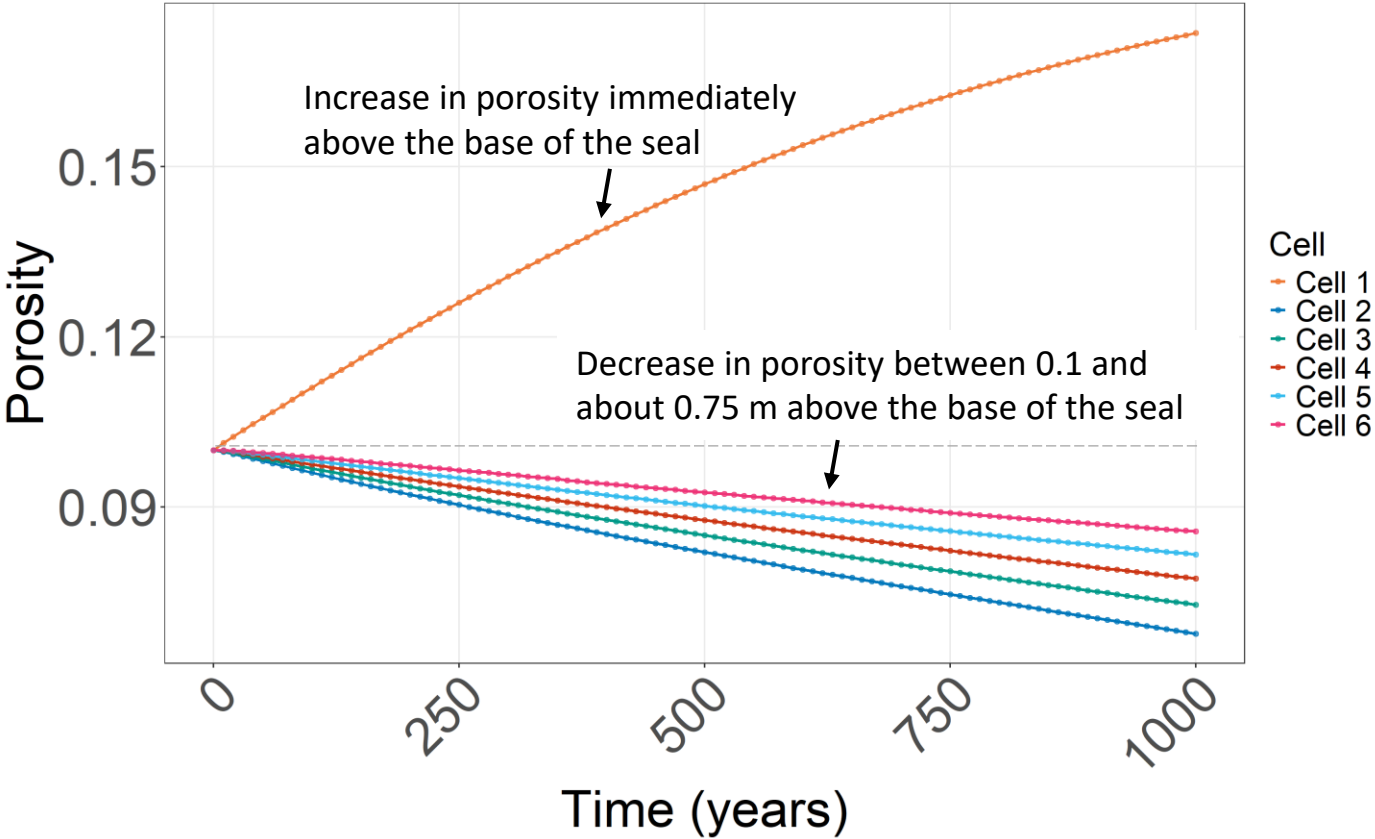


Porosity vs height above the reservoir contact, Years 0–1,000 (10 cm cells). Haisborough diffusion–reaction model, base case.

The seal base reacts in two layers, and the net effect is sealing

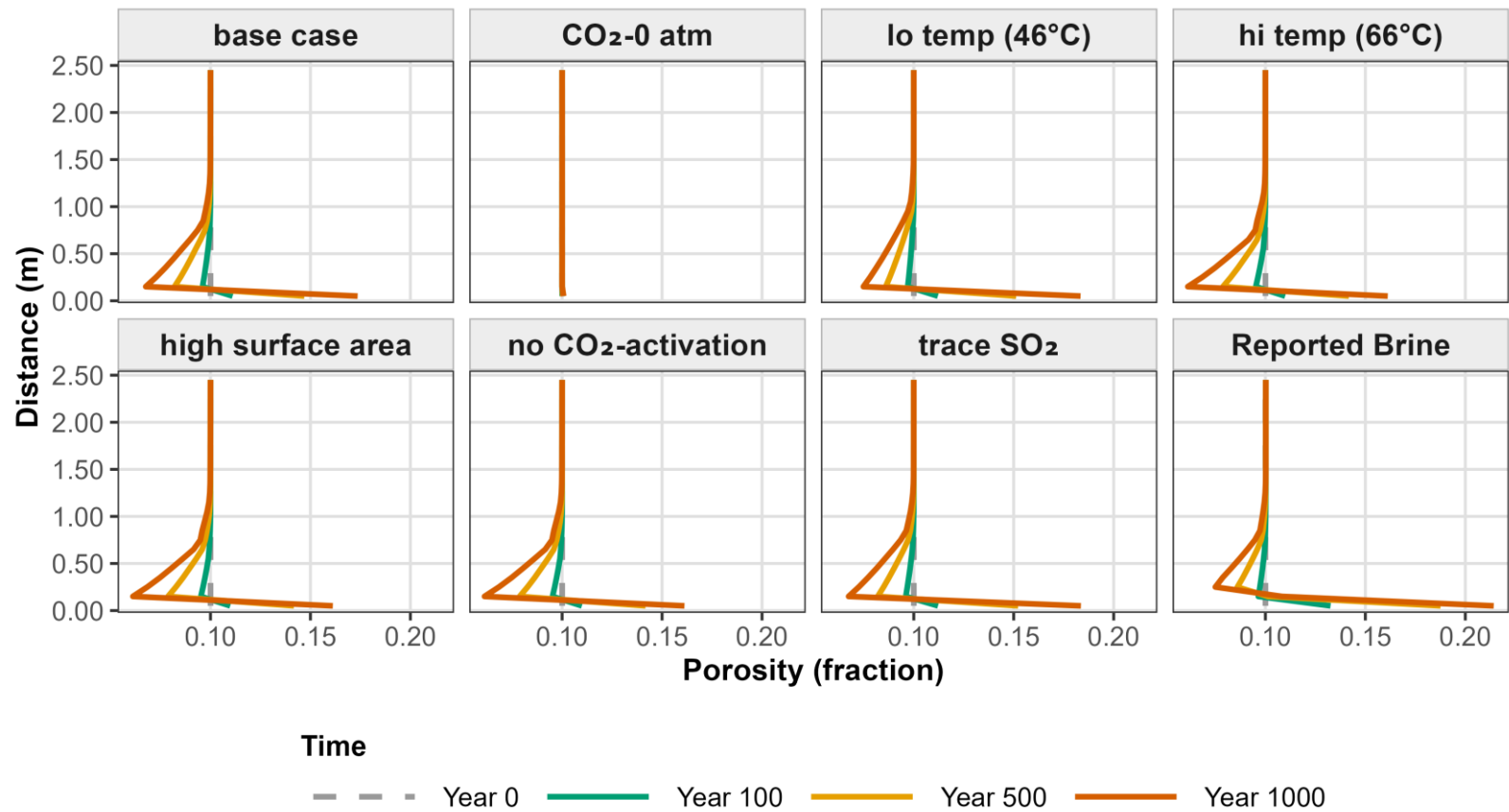


Dissolved Ca, Mg, CO₂ diffuse upward and reprecipitate



Porosity vs time for the lowest six 10 cm layers. Cell 1 (orange) opens; cells 2–6 tighten.

Self-sealing holds in every scenario, and is seen in nature



Porosity vs height above the reservoir contact at Years 0, 100, 500, 1,000 for each scenario

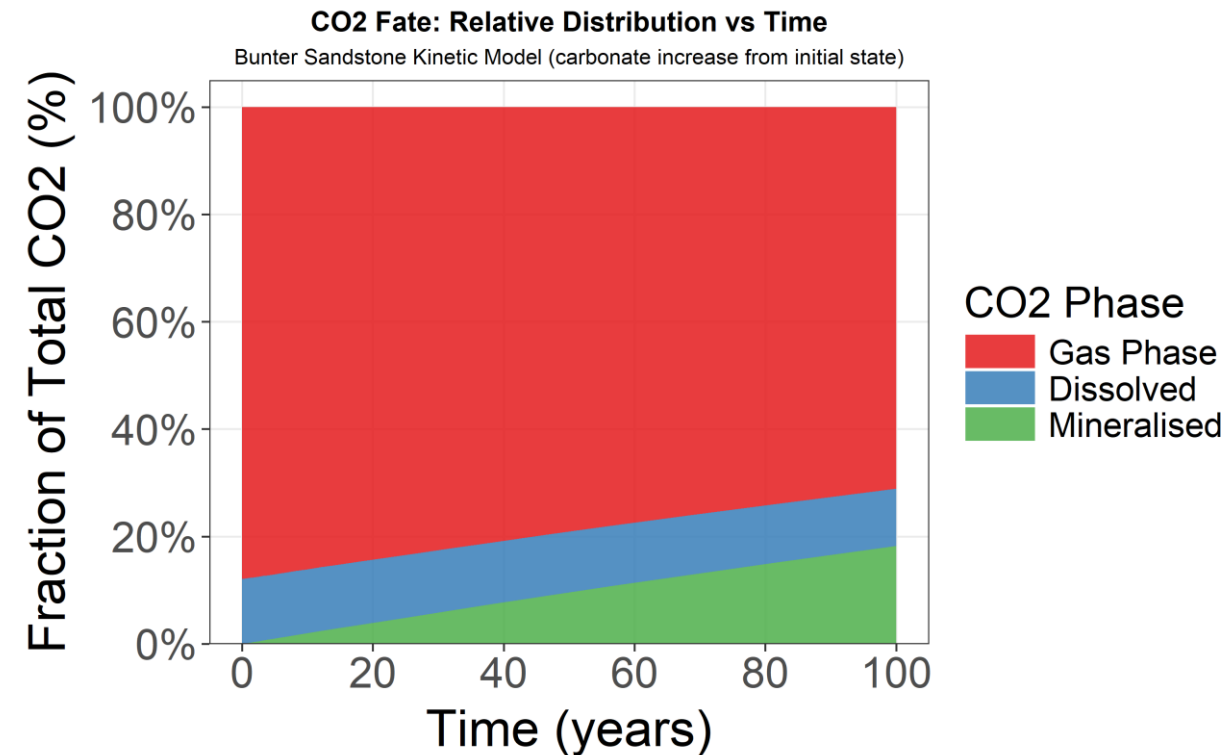
- ✓ Same two-layer pattern in every CO₂ scenario
- Never beyond ~75–80 cm
- CO₂ pressure, temperature and surface area change the size (~1.5×), not the pattern
- No CO₂ means no change

Field evidence: selective mineralisation strengthening mudstone seals over natural CO₂ (Zhang et al., 2026, Energy & Fuels)

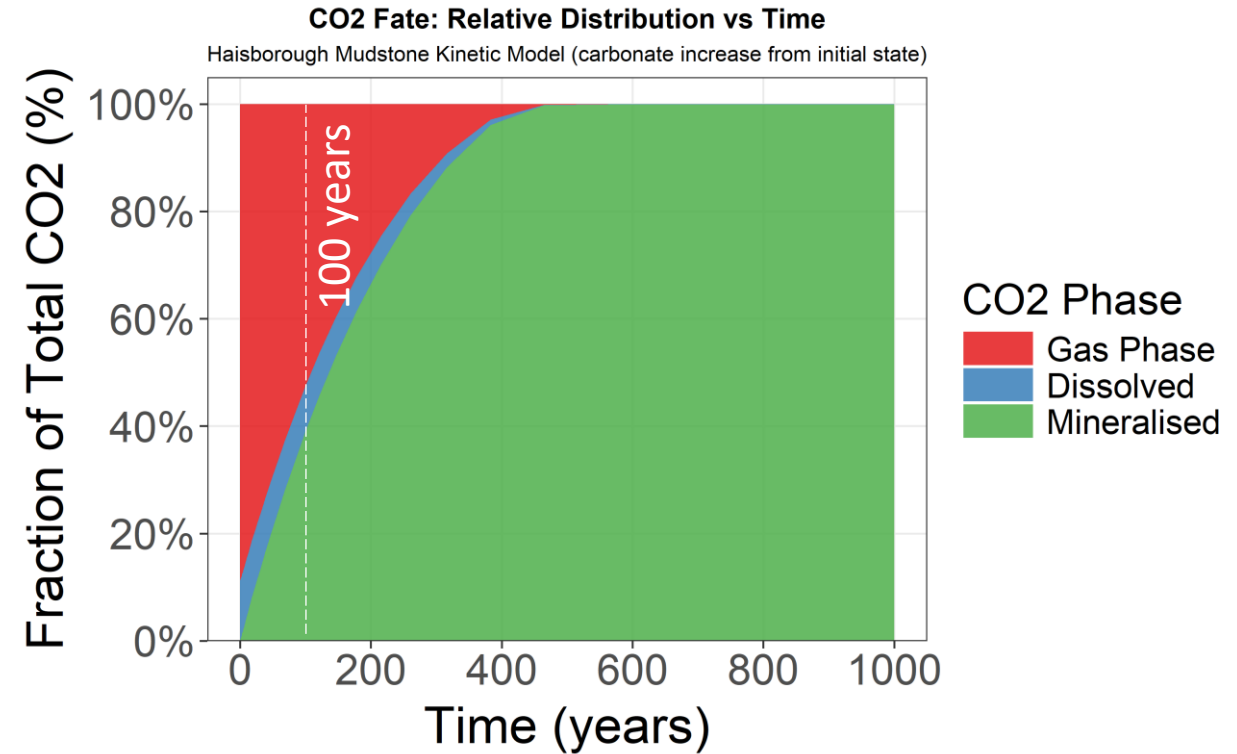
Where does the CO₂ end up? It depends on the rock

Bunter, 100 years (batch, closed system)

~70% free phase · ~11% dissolved · ~19% mineral (dolomite, dawsonite, siderite, but loss of calcite)



Haisborough, 1,000 years (batch, closed system) ≈100% mineral by ~400–1,000 yr (dawsonite, siderite, magnesite)



Batch kinetic (closed-system) models: they show what the rock can do given time, not what happens during injection.

What these PHREEQC models cannot tell you, and what comes next



Near-well halite

Dry-out salt can clog pores (e.g. Quest). Code needs multiphase simulation with capillary back-flow.



Multiphase flow

PHREEQC is single-phase only. Next step: couple with a simulator such as TOUGHREACT.



Geomechanics

Could cement loss cause compaction, or weakening and fracturing?



1-D and pseudo 3D geometry

No lateral heterogeneity, 3-D plume shape or high-permeability laminae.



Wormholes

Channelled dissolution seen in lab experiments (Seyyedi et al., 2020) cannot be excluded.



Reactive surface area

Largest uncertainty after CO₂ pressure. Base case at the low end, so rates are conservative.

Does CO₂ storage work? Geochemically, yes.



Injectivity



- Near-well porosity +5 percentage points in year 1 (20% → ~25%)
- Permeability ~271 → ~639 mD near the wellbore
- Self-limiting acid front; far field unchanged
- No geochemical clogging in any scenario tested



Containment



- CO₂ reaches ≤ 0.75 m into the seal in 1,000 years
- A cemented, self-sealing layer grows above the seal's base
- Dawsonite (mineral) traps CO₂ in the seal
- Same result in every sensitivity case

The Bunter is reactive but not fragile. The Haisborough reacts to CO₂ in a way that strengthens its seal.

Thank you. Questions?

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Key references

Foote et al. (2025) Reservoir characterization of the Triassic Bunter Sandstone in the 43/28-NEPBH1 borehole: implications for CO₂ storage in the neighbouring Endurance structure, Southern North Sea, UK: *Geoenergy*, v. 3

Gluyas & Bagudu (2020) The Endurance CO₂ storage site. *Geol. Soc. Memoir* 52, 163–171

Oelkers & Addassi (2025) Kinec_v3. *Chemical Geology* 695, 123041

Parkhurst & Appelo (2013) PHREEQC v3. USGS Techniques & Methods 6-A43

Rushton et al. (2025) Diagenetic evolution of the Bunter Sandstone Formation and its controls on reservoir quality: implications for CO₂ injectivity and storage *Geoenergy*, v. 3

Seyyedi et al. (2020) Pore structure changes occur during CO₂ injection into carbonate reservoirs: *Scientific Reports*, v. 10.

Smith et al. (2022) Quest CCS facility: halite damage. *IJGGC* 119, 103718

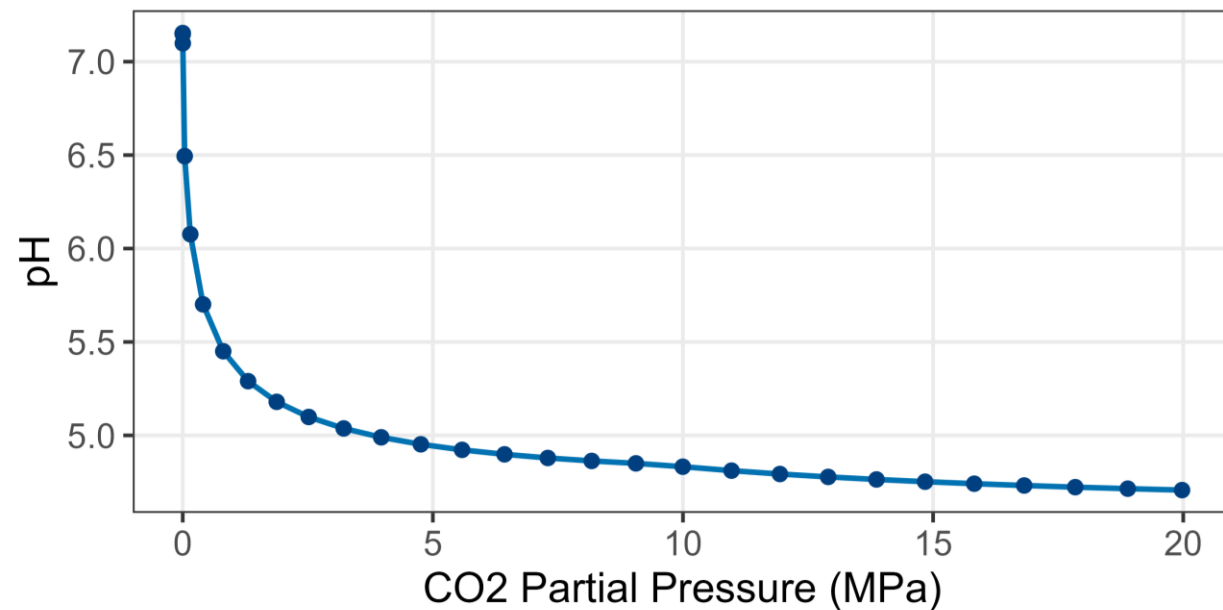
Warren and Smalley (1994) North Sea formation water atlas, London, UK, Geological Society, Geological Society of London Memoir, 208 p.

Zhang et al. (2026) Slow CO₂ leakage and selective mineralization strengthening of mudstone seals. *Energy & Fuels* 40, 7538–7551

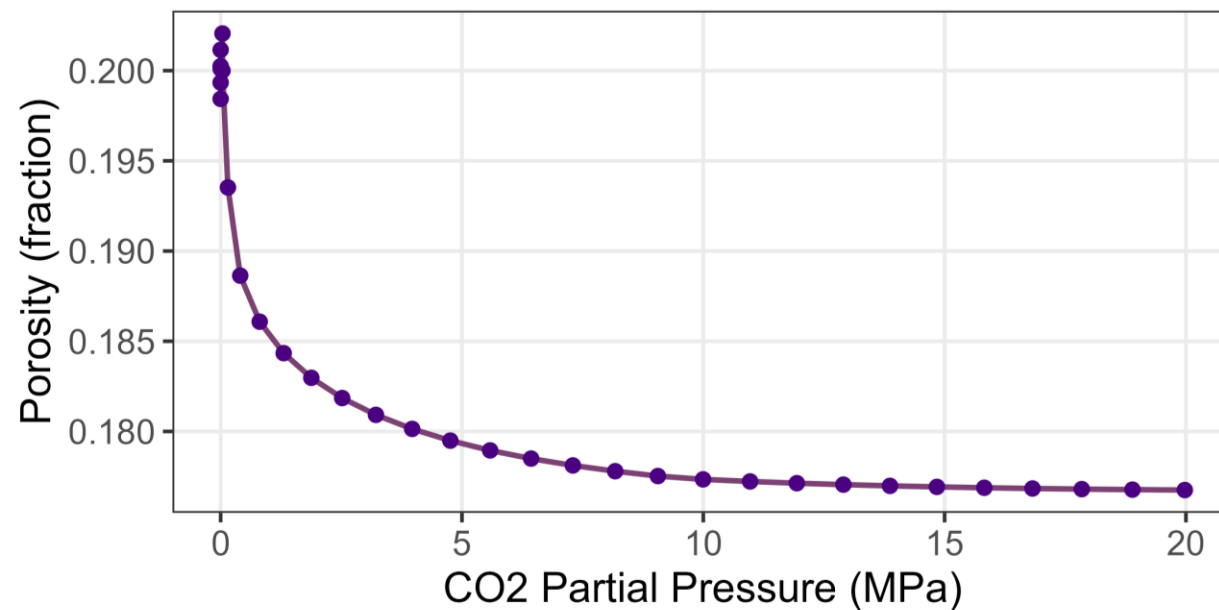
Backup slides

For questions only

Bunter equilibrium models show what could react, not what will

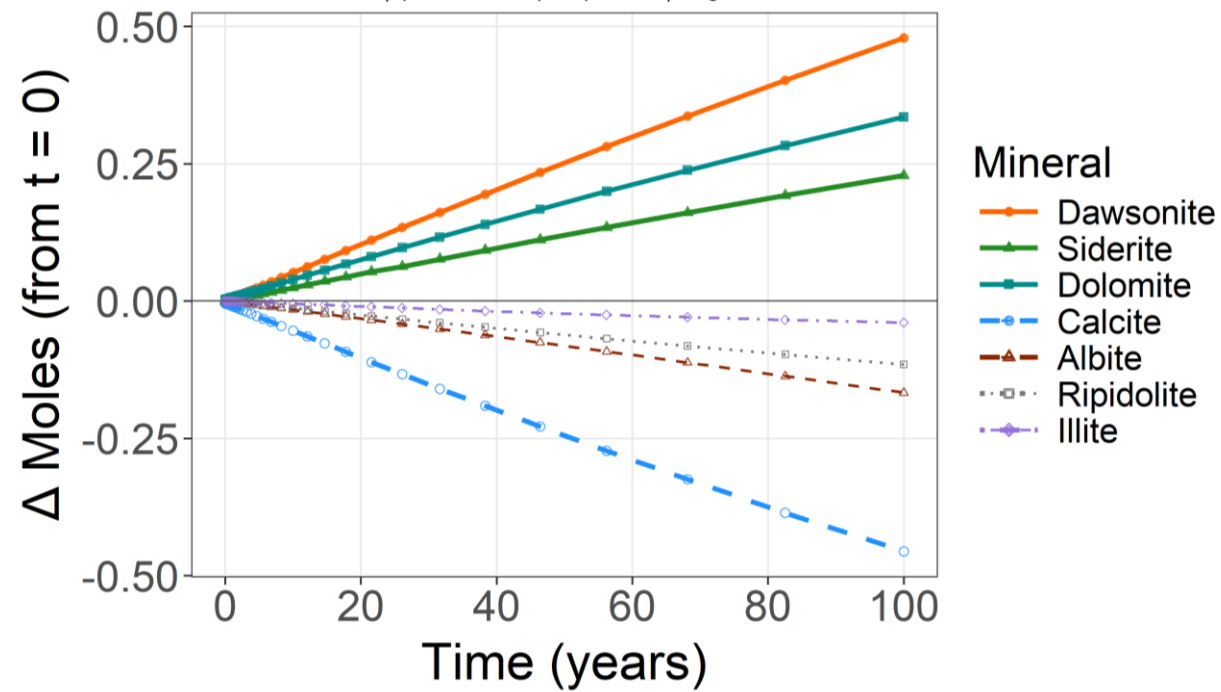


Bunter: pH vs CO₂ partial pressure (equilibrium)

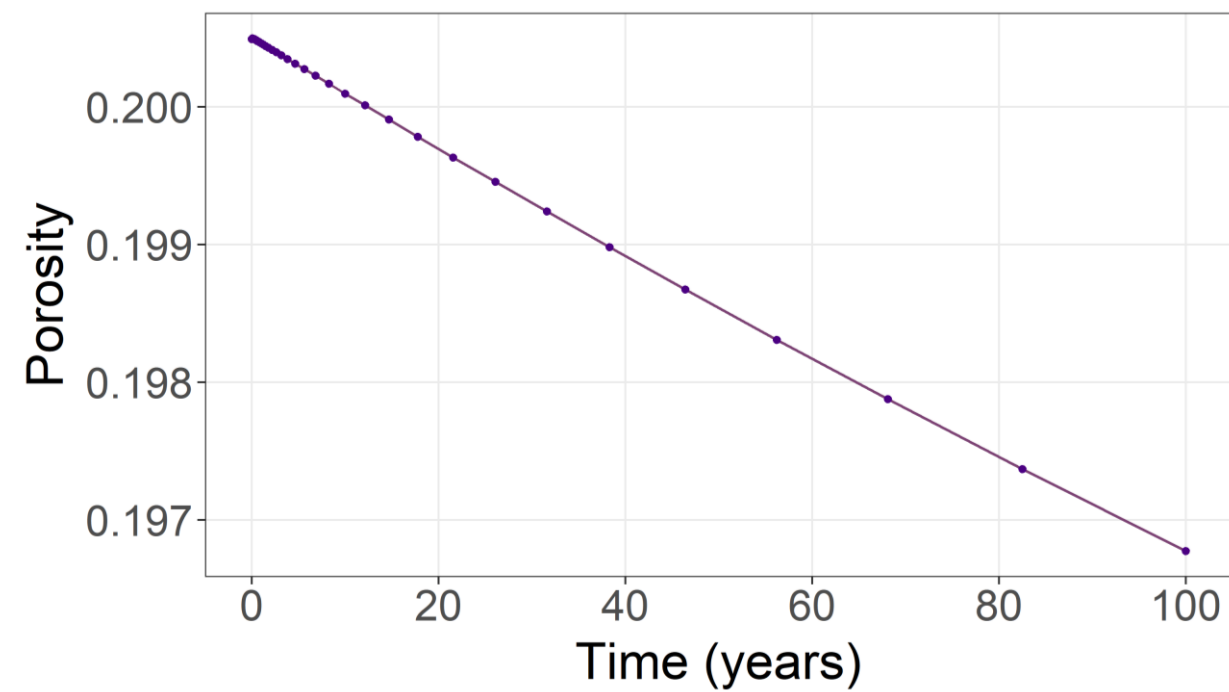


Bunter: porosity vs CO₂ partial pressure (equilibrium)

Bunter batch kinetics: small, steady porosity decline in a closed system

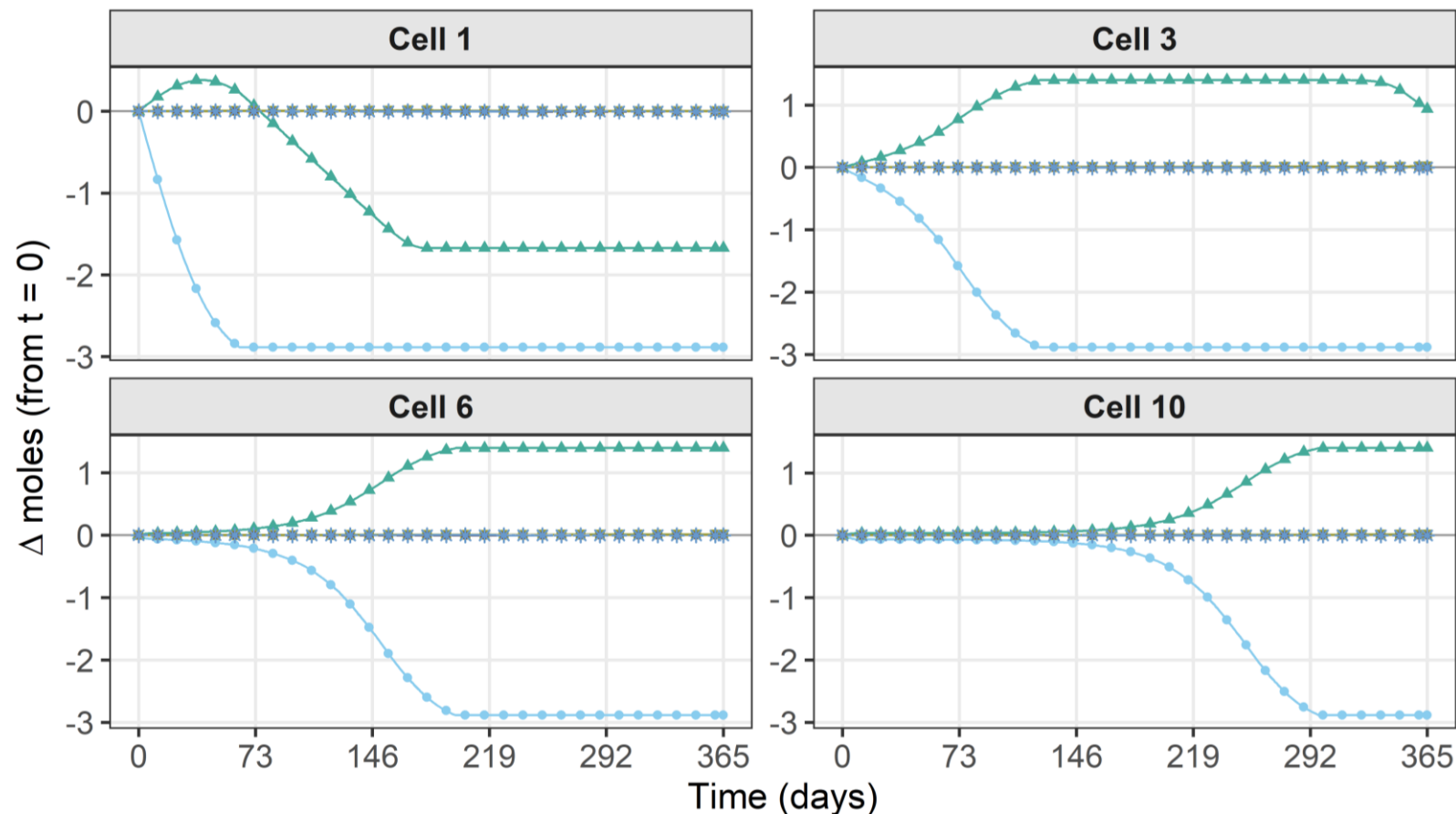


Relative change in mineral moles over 100 years



Porosity over 100 years: 20.04% → 19.66%

Bunter reactive transport: mineral changes by cell



Mineral

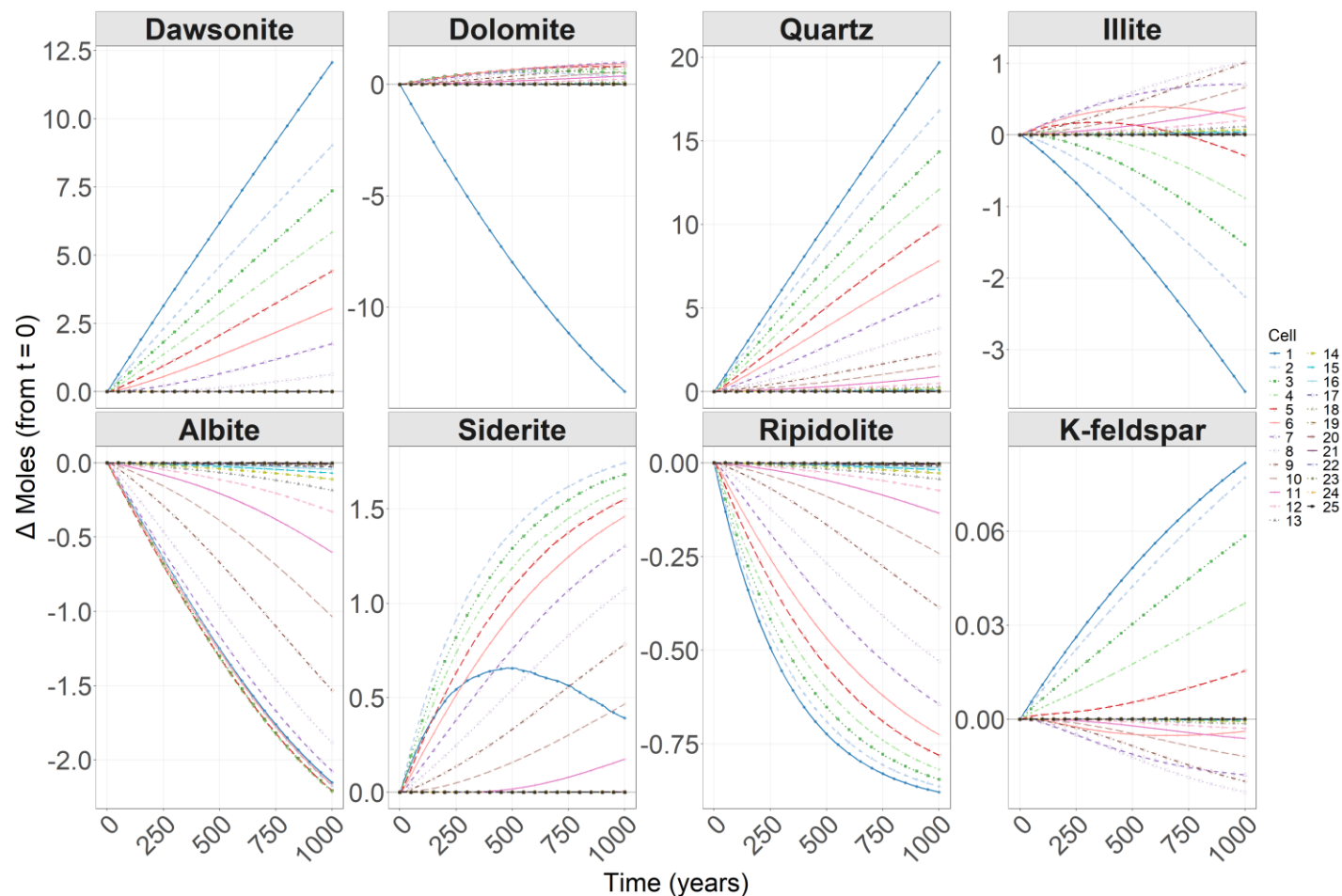
—●— Calcite —▲— Dolomite —■— Dawsonite —◆— Albite —+— Ripidolite —*— Illite

Minerals with no visible change across these cells are omitted.

Cells 1, 3, 6 and 10 (1 m each), base case

- Calcite (blue) is removed cell by cell as the front arrives
- Dolomite (orange) grows first, then dissolves once calcite is gone
- Silicates barely change within one year

Haisborough: mineral changes by layer over 1,000 years

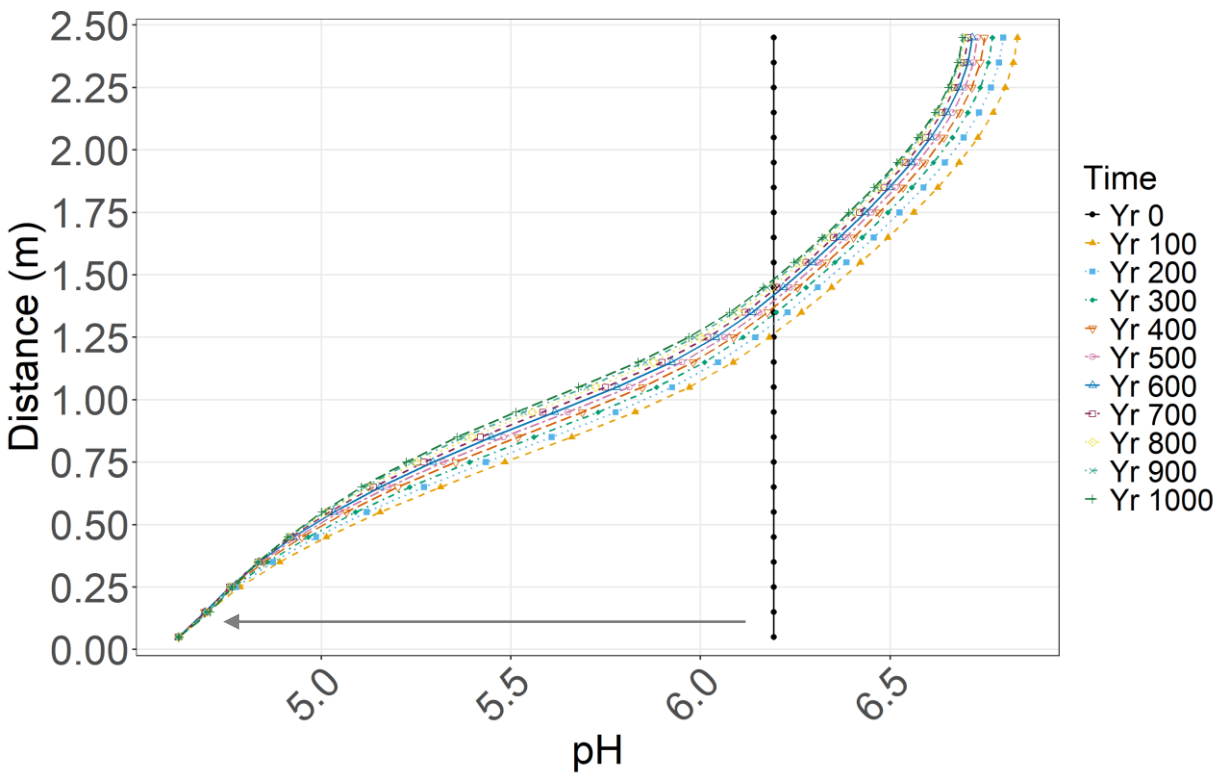


Δ moles from $t = 0$ per 10 cm cell

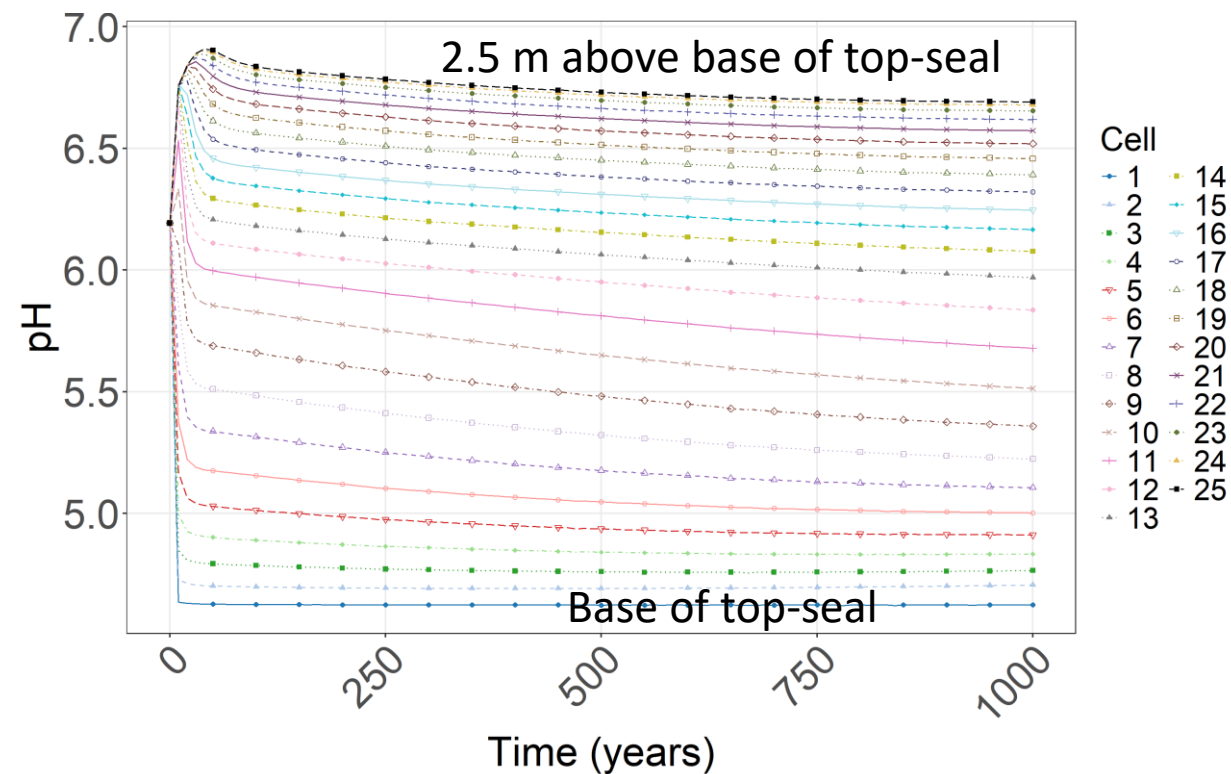
- Dawsonite is the dominant new mineral
- Dolomite dissolves in the lowest layer
- Albite, chlorite and illite are consumed
- Siderite and quartz grow

Not shown – zero throughout: Calcite, Magnesite, Kaolinite, Beidellite-K. Not shown – negligible change: Pyrite (max $\Delta < 0.007$ mol). Not shown – artefact-dominated: Anhydrite (spurious step-changes at $t=100$ yr cell 3, $t=340$ yr cell 13).

Haisborough: CO₂ drops pH at the seal base; minerals buffer it

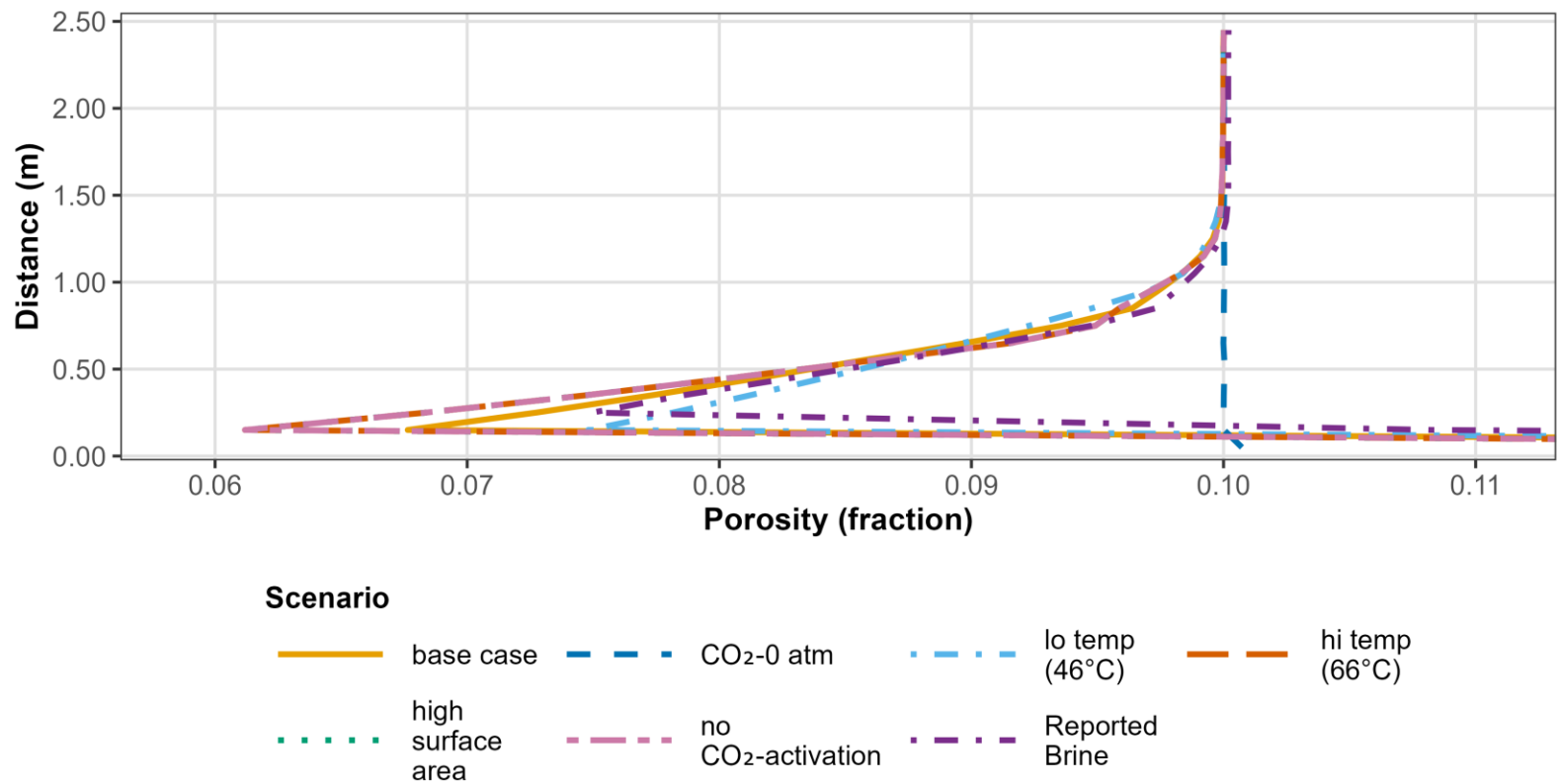


pH vs distance above the reservoir contact, Years 0–1,000



pH vs time for each 10 cm cell

Self-sealing holds in every scenario, and is seen in nature



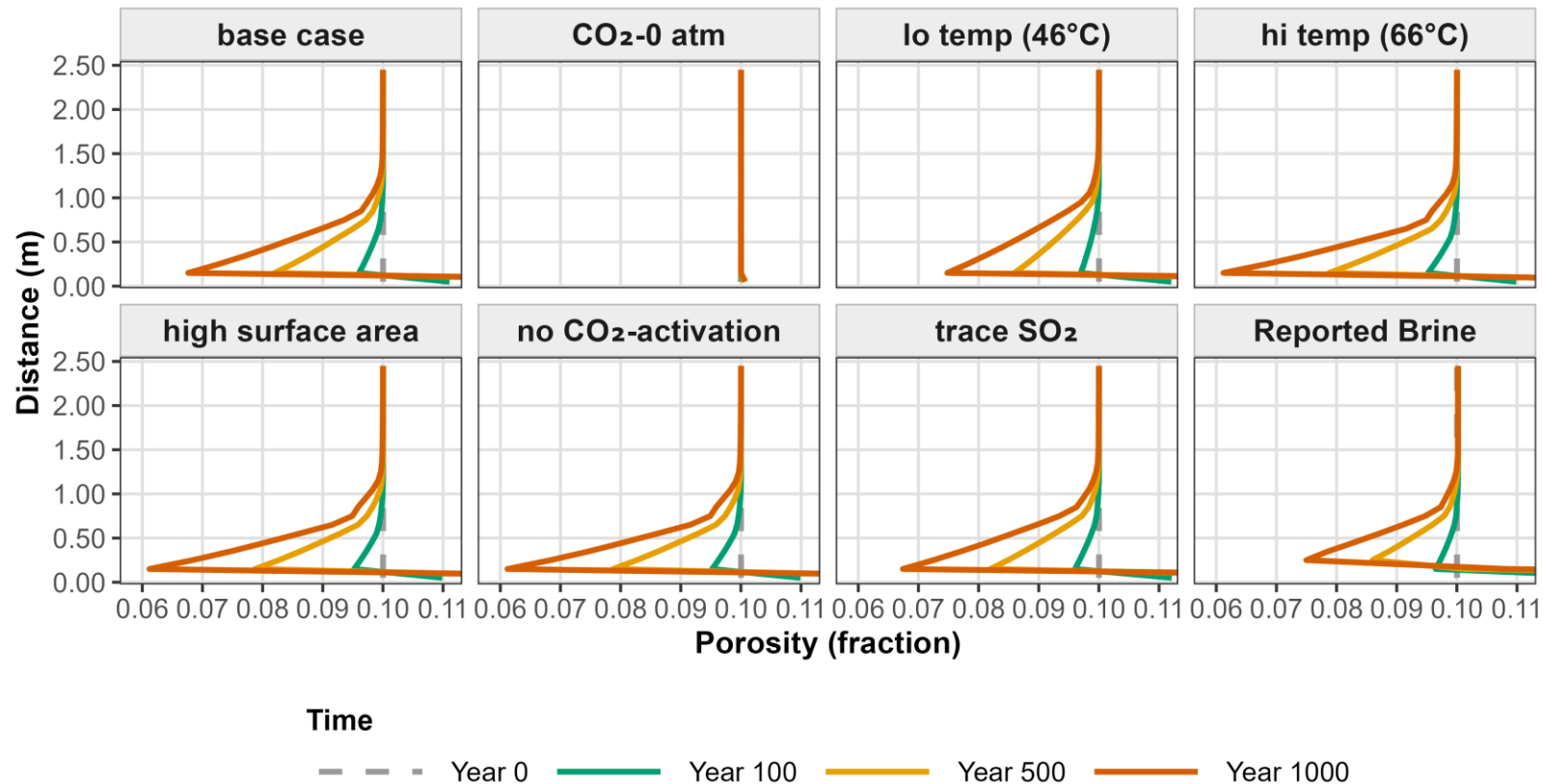
Not shown – indistinguishable from the base case at this scale: trace SO₂
Value axis zoomed on distances ≥ 0.1 m; values in the cell nearest the boundary run off the scale.

Porosity vs height above the reservoir contact at Year 1,000 for various scenarios

- ✓ Same two-layer pattern in every CO₂ scenario
- Never beyond ~75–80 cm
- CO₂ pressure, temperature and surface area change the size (~1.5×), not the pattern
- No CO₂ means no change

Field evidence: selective mineralisation strengthening mudstone seals over natural CO₂ (Zhang et al., 2026, Energy & Fuels)

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