Critical Trapping Numbers and Capillary Desaturation

Mobilization thresholds in mixed-to-oil-wet carbonates under high-temperature, high-salinity surfactant flooding.

PREPARED BY

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The screening threshold problem

Trapped oil moves only above a threshold force. The threshold in general use was measured on a rock that traps oil by a different mechanism.

Trapped oil moves only above a threshold force, and each rock sets its own

The trapping number is the ratio of mobilizing to capillary forces acting on a trapped oil ganglion.

$$N_c = \frac{v \cdot \mu}{\sigma} = \frac{u \cdot \mu}{\varphi \cdot \sigma}$$

N_c = capillary number · v = interstitial velocity (m/s) · u = Darcy velocity (m/s) · μ_w = displacing aqueous-phase viscosity (Pa·s) · ϕ = porosity (fraction) · σ_{os} = oil–surfactant interfacial tension (N/m)

$$N_t = \sqrt{N_c^{\,2} + N_b^{\,2}}$$

N_t = total trapping number applied at a given condition · N_b = Bond number, the buoyancy contribution · $N_{t,crit}$ = the threshold N_t must exceed · horizontal flow, so the cross term vanishes

- cos θ is set to unity: this is a defined mechanical baseline, not a wettability-corrected criterion.
- Interstitial velocity is used throughout; a Darcy-velocity basis differs by a factor of 4.5 in this rock.
- Buoyancy runs two to three orders of magnitude below the viscous term in the reservoir plugs.

Horizontal flow · dip angle α = 0° · cos θ set to unity
Source: manuscript Eqs. 1–5, p.4; trapping-number formulation after Pope et al. (2000)

The threshold carried in screening workflows was measured on water-wet sandstone

WATER-WET SANDSTONE	UPPER BOUND, +1σ	REFERENCE SET	OUTSIDE THE WATER-WET STATE
1.9×10^{-5}	**2.5×10^{-5}**	**16** cores	**$10^{-4} – 10^{-2}$**
Mean $N_{t,crit}$ across the reference set; standard deviation 0.6×10^{-5}	One standard deviation above that mean	Consolidated, strongly water-wet sandstones	Published $N_{t,crit}$ range for non-water-wet rock

- In strongly water-wet sandstone the residual oil sits as disconnected ganglia in the larger pores.
- It mobilizes over a narrow force interval, which is why a single threshold works in that rock.
- In mixed-to-oil-wet carbonate the oil is held in small pores, microporosity and continuous wetting films.
- Displacement there has to overcome film-drainage resistance, so the water-wet onset does not transfer.

Source: manuscript p.1, p.8; Chatzis and Morrow (1984); Masalmeh (2013); Humphry et al. (2014)

02

How the threshold was determined

Two conditions had to be fixed first: a residual-oil baseline free of end-effect bias, and a chemistry that survives 100 °C at 243,028 ppm TDS.

Centrifuge conditioning, not a waterflood endpoint, set the residual-oil baseline

Three plugs, each aged 21 days in dead crude at 100 °C, then centrifuge-conditioned before tertiary injection. Core RC1 is the manuscript's Core RC; Core RC2 was run after submission.

Core	k_{abs} (mD)	k_w at S_{orw} (mD)	ϕ	S_{wi}	S_{orw}
Core RC1 · reservoir carbonate	10.07	2.24	0.220	0.230	0.400
Core RC2 · reservoir carbonate	8.54	4.86	0.273	0.104	0.170
Core IL · Indiana limestone	97.58	74.93	0.180	0.310	0.165

- A low-rate waterflood endpoint in mixed-wet rock stops at a saturation inflated by the capillary end effect and by very low oil relative permeability.
- Anchoring the desaturation curve on that endpoint biases $N_{t,crit}$ downward and makes a chemical-flood forecast optimistic.
- These S_{orw} values are protocol-dependent reference baselines for curve construction, not universal residual saturations.

Source: manuscript Tables 1–2, p.3, p.4; data package sheet 'Core Properties'. Core RC2 (BB-643-77) is post-submission program data.

The formulation reaches ultra-low interfacial tension at the injection salinity

SF1: sodium Guerbet alkoxy carboxylate at 0.5 wt% active, with internal olefin sulfonate co-surfactants.

OIL-SURFACTANT IFT AT 100 °C

3.07×10^{-3} mN/m

σ_{os} by spinning drop to 90 °C, power-law extrapolation to 100 °C

CHUN-HUH CROSS-CHECK

3.32×10^{-3} mN/m

σ_{Huh}, an independent estimate 8% from the extrapolated σ_{os}

OPTIMAL SALINITY

45,000 ppm TDS

Reached beside the injection brine, not at a formulated-away salinity

AQUEOUS STABILITY LIMIT

70,000 ppm TDS

Homogeneous at least 21 days at 120 °C

$$\sigma_{\mathrm{Hu}h} = \frac{C}{(R^*)^2}$$

C = 0.3 mN/m characteristic scaling constant · R* = optimal solubilization ratio, 9.5 cm^3/cm^3 · returns $\sigma_{Huh} = 3.32 \times 10^{-3}$ mN/m against $\sigma_{os} = 3.07 \times 10^{-3}$ mN/m

- The step from 90 °C to 100 °C is an extrapolation; a ±20% change in σ_{os} moves $N_{t,crit}$ by ±20%.
- Conventional sulfate surfactants hydrolyze in this envelope. Chemistry is not the binding constraint; force is.

Source: manuscript p.5, p.6; data package sheet 'FIG 1 - Phase Behavior & IFT'

An eight-step rate escalation resolves the onset on each plug

1

Condition to baseline

Multispeed centrifuge sets the residual-oil baseline without the end-effect bias of a low-rate waterflood.

S_{orw} = 0.400 · 0.170 · 0.212

2

Seawater pre-flush

Four rates from 0.5 to 8 cm^3/min fix the pressure–rate line and k_w at S_{orw}.

0.5 → 8 cm^3/min

3

SF1 rate escalation

Eight steps from 0.075 to 12 cm^3/min, advanced only when pressure drop and effluent fractional flow both stabilized.

0.075 → 12 cm^3/min

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Read the onset

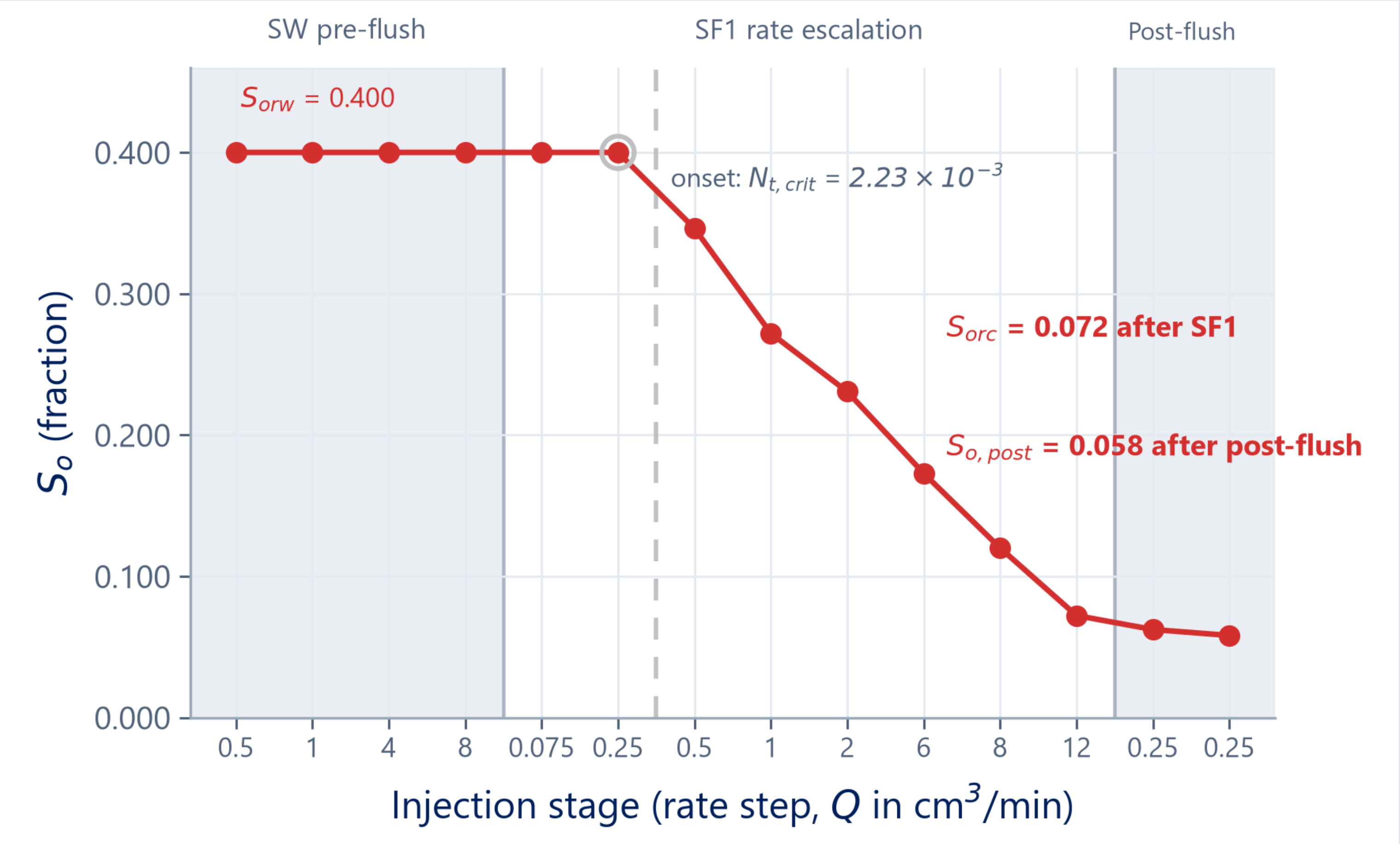
$N_{t,crit}$ is the highest tested trapping number before measurable desaturation, bracketed by the next step that produced oil.

A rate step, not a fit

- One criterion on all three plugs: the highest tested N_t before measurable desaturation, which is the manuscript's own definition of the quantity.
- Core RC1 reads 2.23×10^{-3}, Core RC2 1.72×10^{-3} and Core IL 8.47×10^{-4}, each bracketed above by the next rate step that produced oil.
- Pressure–rate linearity cleared the $R^2 \geq 0.95$ acceptance criterion on Cores RC1 and IL, at 0.960 and 0.981.

Source: manuscript p.4, p.5, p.7; data package sheets 'Coreflood RC1', 'RC2' and 'IL'

Core RC1 holds its baseline, then breaks away



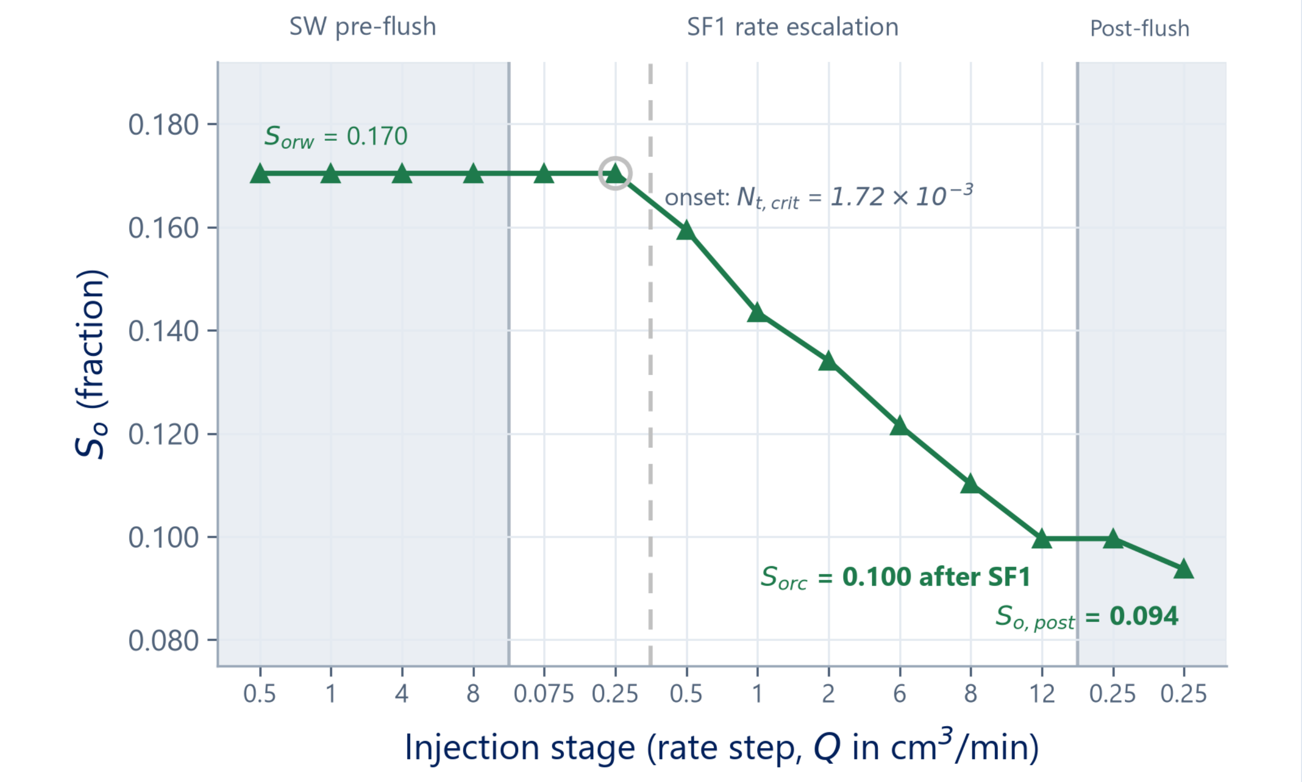
S_o (fraction, 3 decimals) at each of 14 sequential rate steps for Core RC1: seawater pre-flush (Q = 0.5–8 cm^3/min), SF1 rate escalation (Q = 0.075–12 cm^3/min) and post-flush (Q = 0.25 cm^3/min × 2). Ring marks the last no-oil step, which is the onset, $N_{t,crit} = 2.23 \times 10^{-3}$.

WHAT IT SHOWS

Core RC1 holds S_{orw} = 0.400 to $N_{t,crit}$, then desaturates to S_{orc} = 0.072.

- Fourteen sequential rate steps: seawater pre-flush, SF1 escalation, then post-flush.
- The ring marks the last step with no measurable oil; that step is the onset, $N_{t,crit} = 2.23 \times 10^{-3}$, and the next produced oil at 4.47×10^{-3}.
- Endpoints read S_{orc} = 0.072 after SF1 and $S_{o,post}$ = 0.058 after the post-flush.

The second reservoir plug returns an onset 23% below Core RC1 and half the efficiency



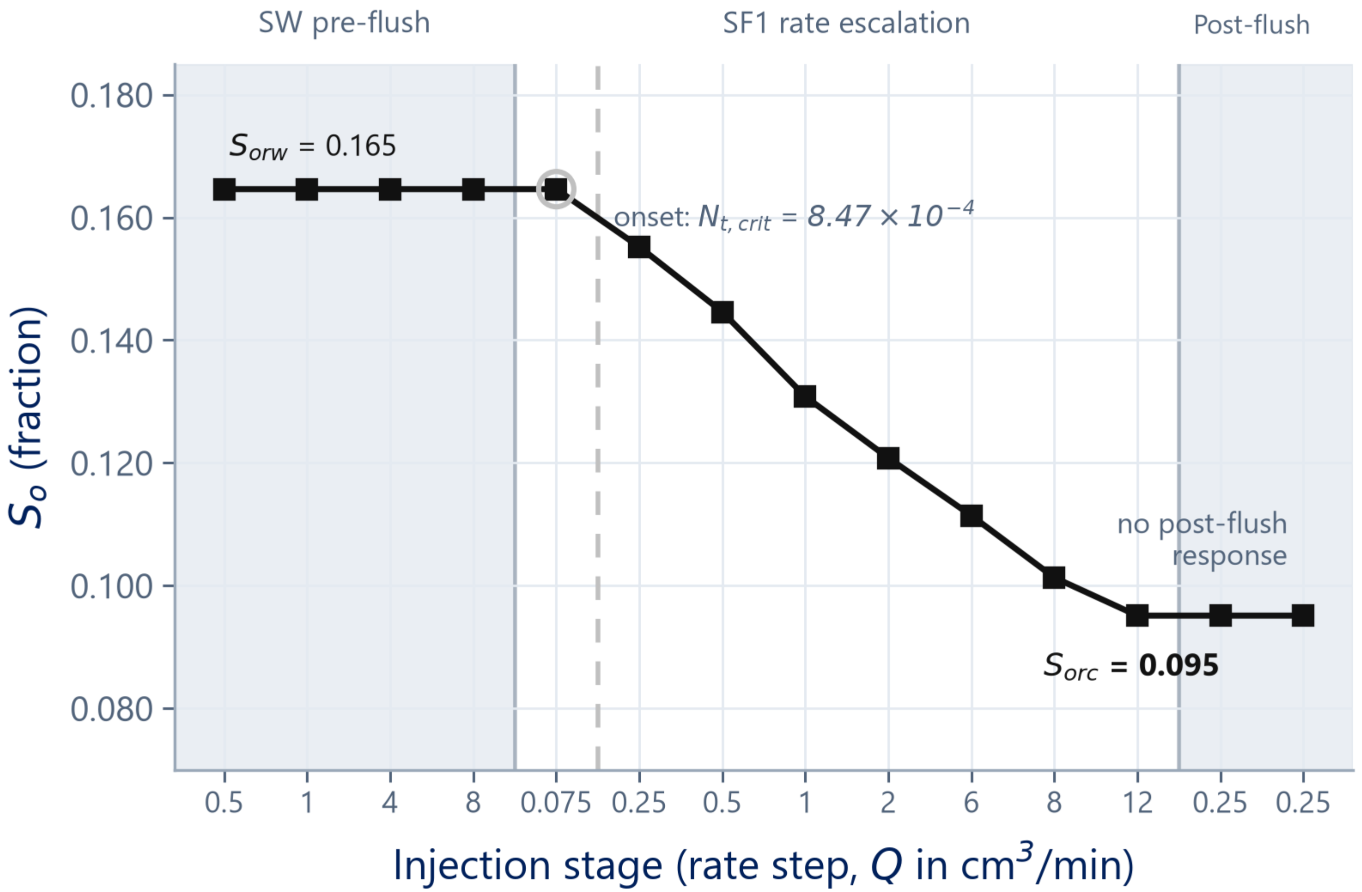
S_o (fraction, 3 decimals) at each of 14 sequential rate steps for Core RC2: seawater pre-flush (Q = 0.5–8 cm^3/min), SF1 rate escalation (Q = 0.075–12 cm^3/min) and post-flush (Q = 0.25 cm^3/min × 2). Ring marks the last no-oil step, which is the onset, $N_{t,crit}$ = 1.72 × 10^{-3}.

WHAT IT SHOWS

Core RC2 holds S_{orw} = 0.170 to $N_{t,crit}$ = 1.72 × 10^{-3}, then desaturates to S_{orc} = 0.100.

- Same protocol as Core RC1: 21 days of aging at 100 °C, centrifuge conditioning, then the same 14 rate steps.
- The onset lands at 1.72 × 10^{-3} against 2.23 × 10^{-3} in Core RC1 — 91× and 117× the water-wet reference.
- Above the onset the response is gradual, not sharp: E_D = 41.5% after SF1 against 82% in Core RC1.
- The post-flush moved S_o from 0.100 to 0.094 — 0.035 normalized, the same increment as Core RC1.

Core IL breaks away earliest, desaturates slowly



S_o (fraction, 3 decimals) at each of 14 sequential rate steps for Core IL: seawater pre-flush, SF1 rate escalation and post-flush. Ring marks the last no-oil step, which is the onset, $N_{t,crit}$ = 8.47 × 10^{-4}. The endpoint reads S_{orc} = 0.095 after SF1, unchanged through post-flush.

WHAT IT SHOWS

Core IL desaturates gradually to S_{orc} = 0.095 and does not respond to the post-flush.

- $N_{t,crit}$ is lowest of the three at 8.47 × 10^{-4}, and the response spreads over more than one order of magnitude in N_t.
- The endpoint reads S_{orc} = 0.095 after SF1, unchanged through the post-flush.
- From S_{orw} = 0.165, the microscopic displacement efficiency is E_D = 42.2% after SF1 — against 82% and 41.5% in Cores RC1 and RC2.

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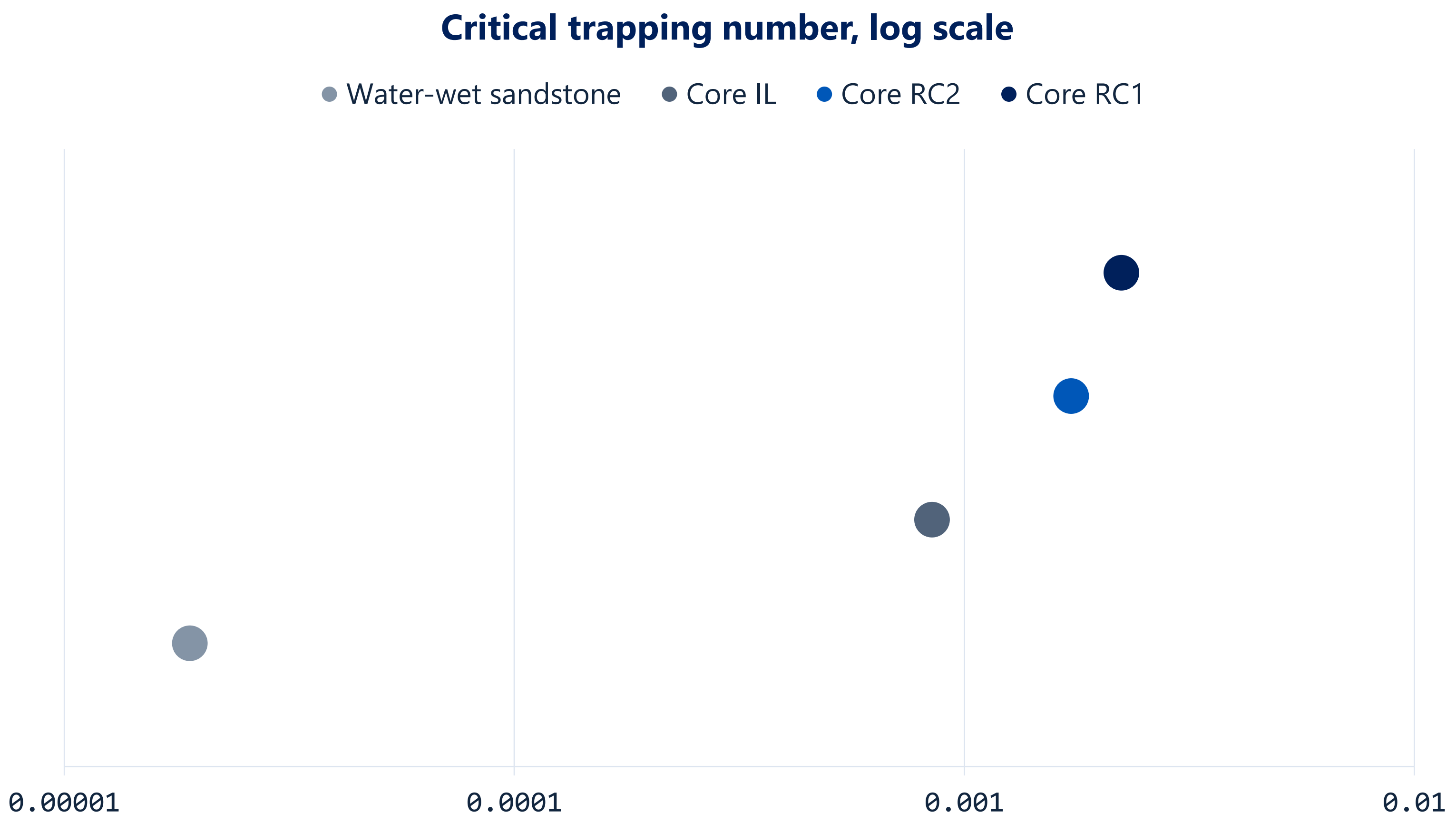
What the measurement returned

Three onsets inside a factor of 2.7, all of them well above the water-wet reference; and desaturation behaviour above the onset that is not the water-wet step function in any of the three.

All three onsets sit far above the reference



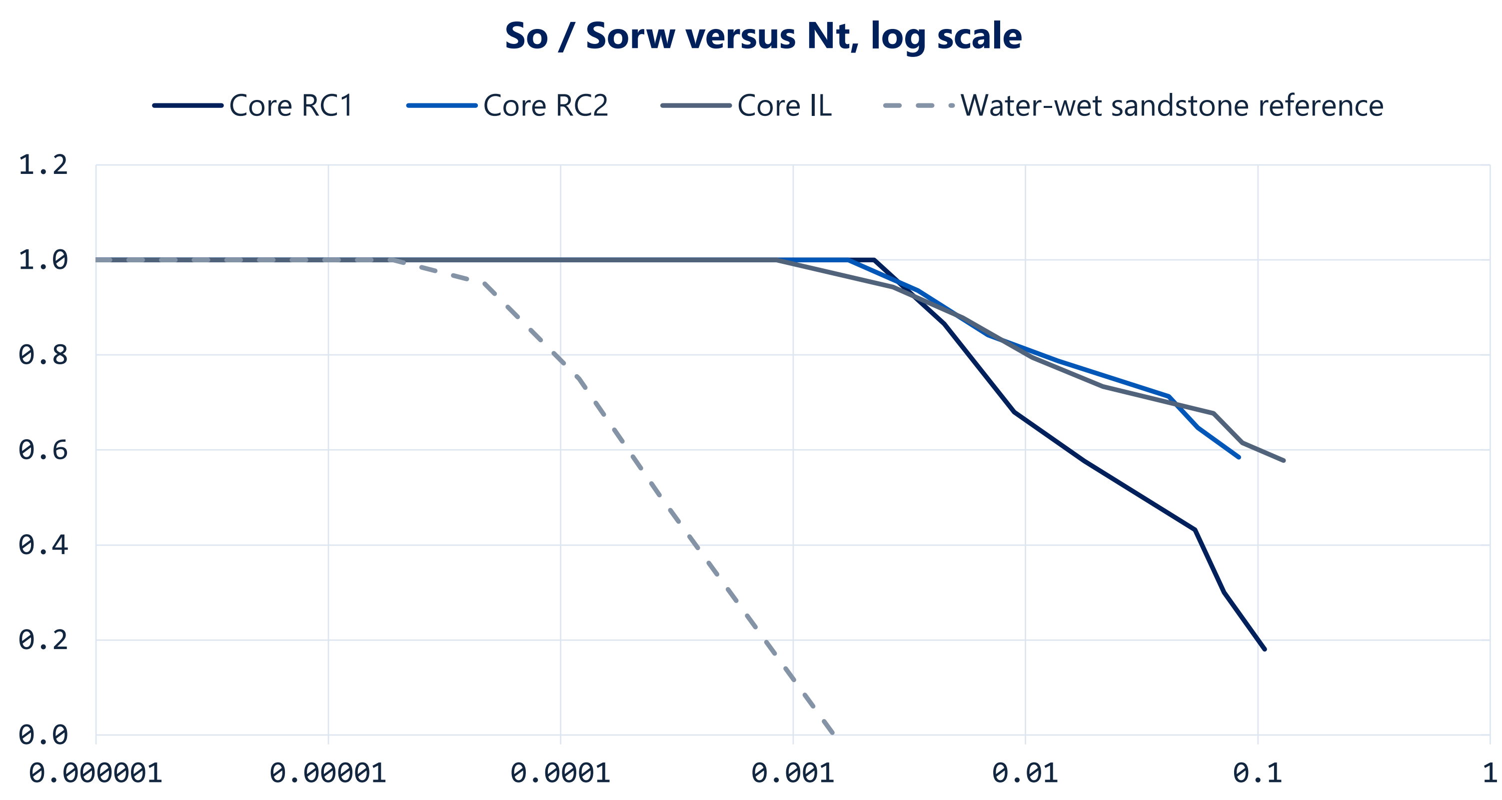
$N_{t,crit}$ for four references on one log axis: water-wet sandstone (1.9 ± 0.6) × 10^{-5} (Chatzis and Morrow 1984, n = 16), Core IL 8.47 × 10^{-4} (45× the sandstone mean), Core RC2 1.72 × 10^{-3} (91×) and Core RC1 2.23 × 10^{-3} (117×).

WHAT IT SHOWS

The three carbonate plugs mobilize at 45 to 117 times the water-wet sandstone onset.

- $N_{t,crit}$ = 2.23 × 10^{-3} (Core RC1), 1.72 × 10^{-3} (RC2) and 8.47 × 10^{-4} (Core IL), against (1.9 ± 0.6) × 10^{-5}.
- All three sit above the reference's own +1σ bound of 2.5 × 10^{-5}, and all three fall inside a factor of 2.7 of each other.
- The two reservoir plugs agree inside a factor of 1.3.
- A workflow carrying $N_{t,crit}$ ≈ 10^{-5} predicts mobilization at 45 to 117 times below what these plugs required.

Three measured curves, one reference, and the whole gap in one image



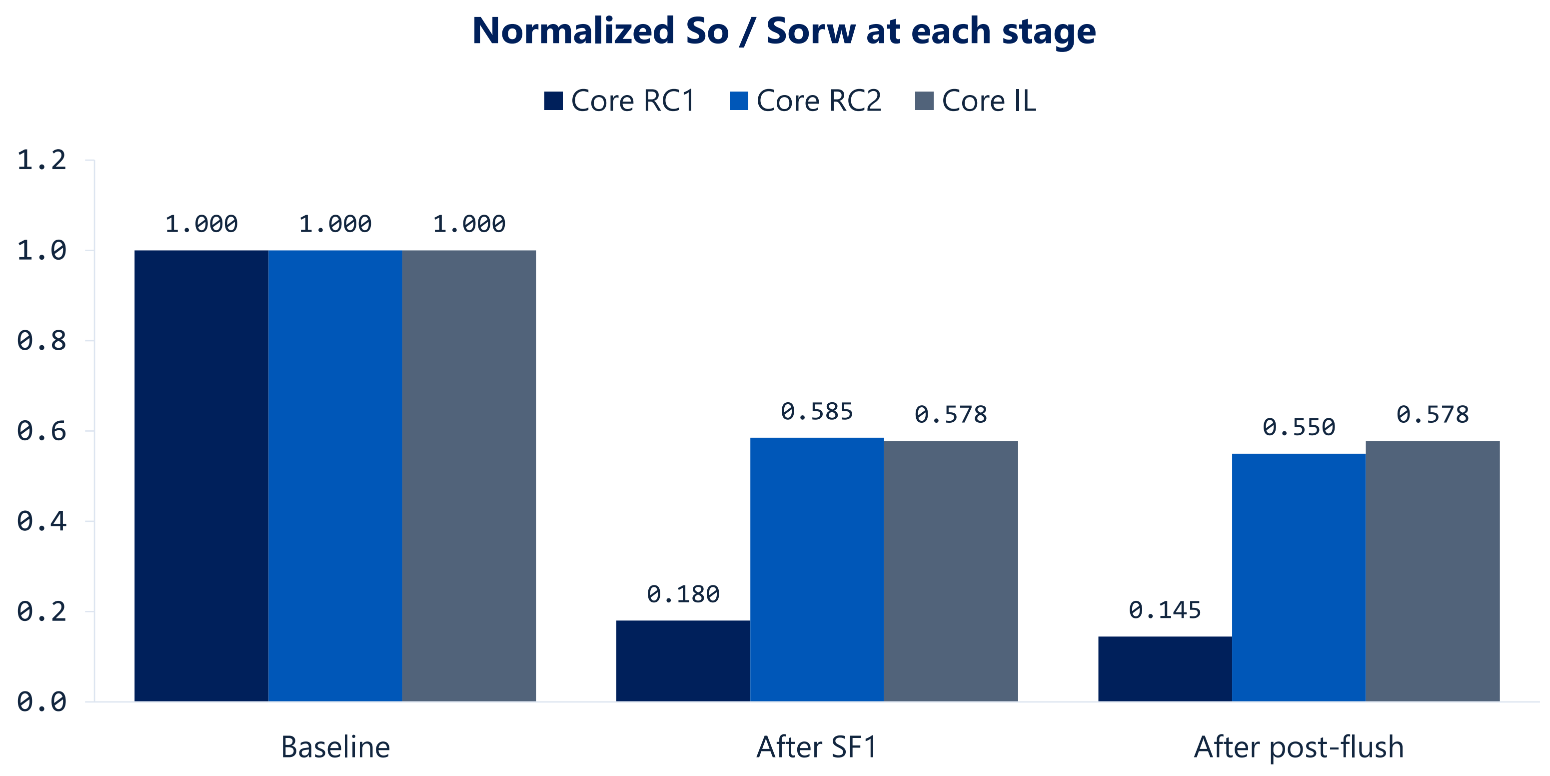
S_o/S_{orw} versus N_t (log scale) for Core RC1, Core RC2 and Core IL, with the Chatzis and Morrow (1984) water-wet sandstone reference (n = 16 cores). Measured $N_{t,crit}$ spans 8.47×10^{-4} to 2.23×10^{-3}, against the sandstone onset at $(1.9 \pm 0.6) \times 10^{-5}$.

WHAT IT SHOWS

Screening thresholds built on water-wet sandstone underpredict these carbonates by 45 to 117 times.

- All three carbonate curves hold a flat plateau, then break away inside half a decade of N_t.
- None reproduces the water-wet step function: Core RC1 transitions sharply, Cores RC2 and IL over more than one order of magnitude.
- The carbonate curves sit 1.6 to 2.1 orders of magnitude to the right of the sandstone reference.
- Left of the reference band nothing has desaturated: that is the regime a low-gradient waterflood endpoint is read in.

SF1 moves most of the oil in one plug and around half in the other two



S_o/S_{orw} normalized to 1.000 at the centrifuge-conditioned baseline, at three stages. Core RC1 (navy): 1.000, 0.180, 0.145. Core RC2 (blue): 1.000, 0.585, 0.550. Core IL (grey): 1.000, 0.578, 0.578 (no post-flush response). E_D is $1 - S_o/S_{orw}$ at the stated stage.

WHAT IT SHOWS

After SF1, E_D is 82% in Core RC1, 42% in Core RC2 and 42% in Core IL.

- Core RC1 S_o/S_{orw}: 1.000, then 0.180 after SF1, then 0.145 after the post-flush.
- Core RC2: 1.000, 0.585, 0.550. Core IL: 1.000, 0.578, unchanged.
- Every efficiency is quoted after SF1; Core RC1 reads 85.5% if taken after the post-flush instead.
- The post-flush ran at 0.25 cm^3/min, below $N_{t,crit}$, so its gain is not a force effect. It is consistent with a shift from near-optimum Winsor III toward under-optimum Winsor I; the data do not identify that mechanism uniquely.

IMPLICATION

A screening threshold taken from water-wet sandstone understates the force these carbonates require by 45 to 117 times.

All four measured $N_{t,crit}$ values sit above the water-wet mean of 1.9×10^{-5} and above its $+1\sigma$ bound of 2.5×10^{-5}, and the three reservoir plugs agree inside a factor of 1.3 across two formations. Following Humphry et al. (2014), the shift is attributed to wettability rather than to the sandstone–carbonate lithology contrast.

CORE RC1 ONSET

2.23×10^{-3}

$N_{t,crit}$, 117× the water-wet mean

CORE RC2 ONSET

1.72×10^{-3}

$N_{t,crit}$, 91× the water-wet mean

CORE IL ONSET

8.47×10^{-4}

$N_{t,crit}$, 45× the water-wet mean

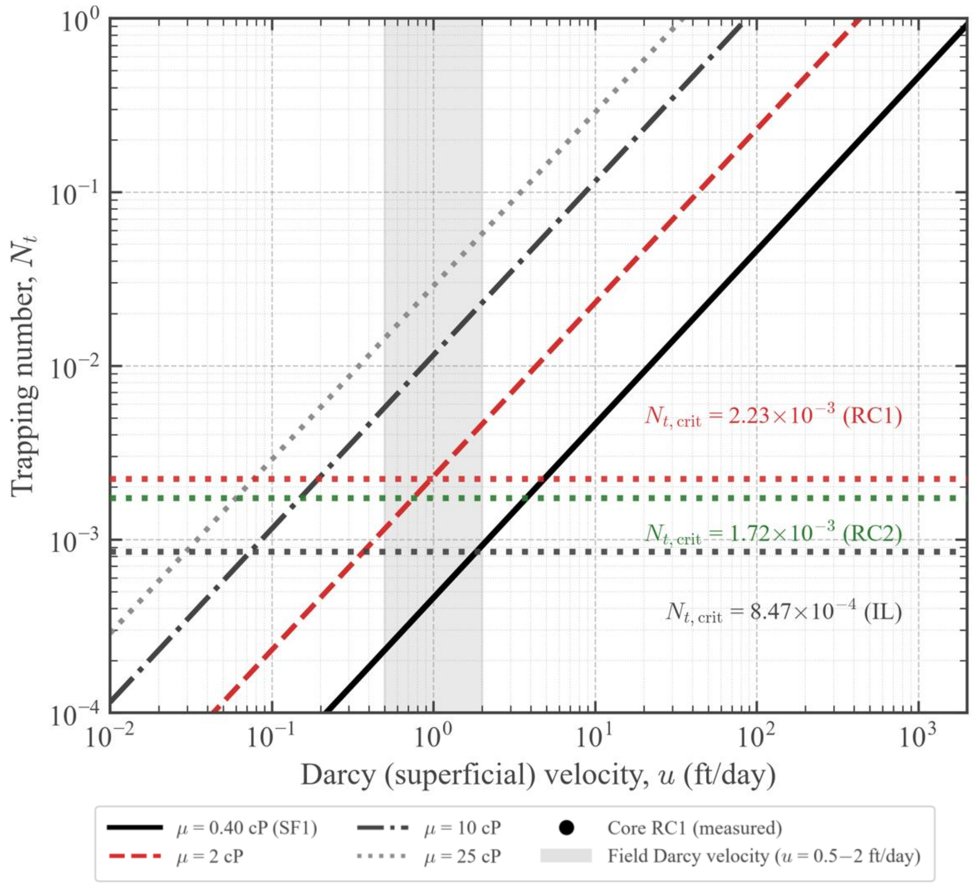
Source: program data package; manuscript p.5, p.8 for Core RC1

04

What it means at field rate

Translating the measured onset to a Darcy velocity of 1 ft/day, and quantifying what would be needed to cross it.

At field rate every reservoir plug lands on its own threshold



N_t (log scale) versus Darcy velocity u (log scale, 0.1–5 ft/day) for Core RC1 at μ_w = 0.40 (measured SF1 baseline), 2, 10 and 25 cP. Grey vertical band marks the 0.5–2 ft/day field-rate range. Four dashed horizontal lines carry the measured $N_{t,crit}$ of each plug, 8.47×10^{-4} (Core IL) to 2.23×10^{-3} (Core RC1).

WHAT IT SHOWS

At u = 1 ft/day, SF1 reaches 0.94 to 1.01 times each reservoir plug's own onset; 2 cP reaches 4.69× in Core RC1.

- Applied N_t at u = 1 ft/day and μ_w = 0.40 cP is 2.09×10^{-3} in Core RC1, against its onset of 2.23×10^{-3} — 6.3% short.
- Computed on each plug's own ϕ and k_w: Core RC1 0.94×, Core RC2 0.98×.
- Both reservoir plugs sit on their own onset at the design rate. Only the outcrop analogue clears it, at 3.06×, and it is 74.93 mD.
- Crossover in Core RC1 at μ_w = 0.40 cP falls at u = 1.07 ft/day, inside the 0.5–2 ft/day band, so rate allocation on the sweep side decides the outcome as much as chemistry does.

Source: manuscript p.7, p.10 · curves and per-plug ratios computed from Eqs. 1 and 5 on each plug's own porosity and effective permeability

Three cases at 1 ft/day: what each requires and what bounds it

Computed from this study's own relation at u = 1 ft/day with $\sigma_{os} = 3.07 \times 10^{-3}$ mN/m, $\phi = 0.220$ and k_w at $S_{orw} = 2.24$ mD. These are calculations on measured inputs, not measurements and not forecasts.

Case at u = 1 ft/day	μ_w (cP)	Applied N_t	Against $N_{t,crit}$	What bounds it
Measured SF1 baseline	0.40	2.09×10^{-3}	0.94× — below	No lever left on σ_{os}; it is already at the measured floor
Crosses the onset	0.43	2.23×10^{-3}	At $N_{t,crit}$	Viscosity only, below the polymer screening band
Deep-desaturation target	1.91	1.00×10^{-2}	Above $N_{t,crit}$	1,500–2,000 ppm active ATBS; propagation at 2.24 mD untested

- Viscosity is the only remaining lever in the calculation: σ_{os} is already at the measured floor and u is set by pattern design.
- Performance of the ATBS chemistry — acrylamido tertiary butyl sulfonate — was not measured here. Viscosity, propagation, degradation, retention and filtration are all open.

Computed from the study's own trapping-number relation (manuscript Eqs. 1 and 5, p.10) at the stated conditions. Not measurements, not predictions.

WHERE THE MARGIN IS

Viscosity is the only remaining lever in the calculation, and the slug it implies was not tested here.

Crossing $N_{t,crit}$ at u = 1 ft/day requires μ_w = 0.43 cP in Core RC1; reaching the $N_t \approx 10^{-2}$ deep-desaturation target requires 1.91 cP, which literature screening maps to 1,500–2,000 ppm active ATBS. At 2.24 mD that slug carries injectivity, mechanical-degradation, face-plugging and fracture-parting exposure, none of which was measured in this study.

TO CROSS THE ONSET

0.43 cP

μ_w at u = 1 ft/day, Core RC1

TO REACH THE TARGET

1.91 cP

≈1,500–2,000 ppm active ATBS

ROCK IT MUST PASS THROUGH

2.24 mD

k_w at S_{orw}, Core RC1

Source: manuscript p.10; polymer concentrations are literature screening targets (Seright et al. 2009)

05

What this changes

Screening inputs, protocol requirements, and the measurements that would close the remaining gap.

Carbonate-specific onsets replace water-wet correlations in screening

Two changes follow directly from the coreflood data. The third is a measurement program, not an analysis.

1

Replace the screening input

Workflows and simulator decks carrying $N_{t,crit}$ near 10^{-5} for mixed-wet carbonate adopt the values these corefloods return.

$8.47 \times 10^{-4} – 2.23 \times 10^{-3}$

2

Make conditioning a requirement

Centrifuge conditioning of S_{orw} becomes a protocol requirement for desaturation work, not a refinement.

Removes the end-effect bias

3

Measure the polymer

Viscosity, propagation, mechanical degradation and retention of an ATBS slug at 100 °C and this salinity.

None measured to date

4

Bound the injection

Injectivity and formation parting pressure at 2.24 mD decide whether the required slug can be placed at all.

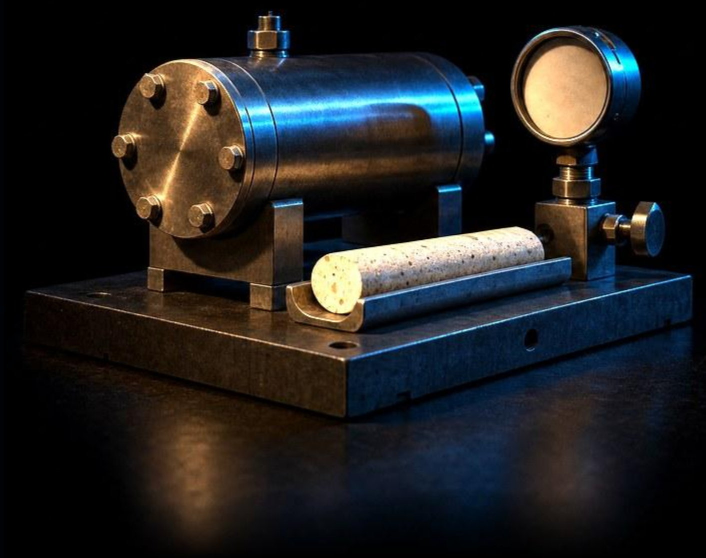
The binding constraint

- Core RC2 is complete and carried on these slides; the manuscript carries Cores RC1 and IL only.
- A 51-core forced-imbibition register is available for selection; 30 plugs meet the residual-oil guidance, and the register's median permeability is 5.46 mD.

Source: manuscript p.10, p.11; program core register and post-submission coreflood records

The onset is resolved. What it would take to cross it is not.

- Polymer viscosity, propagation, degradation and retention measured at 100 °C and 243,028 ppm TDS, not screened from literature.
- Injectivity and formation parting pressure at 2.24 mD, which decide whether the required slug can be placed.
- Surfactant retention in mg/g-rock — the largest chemical cost driver, and absent from this dataset.
- Further reservoir plugs, to turn four onsets into a distribution against permeability and wetting state.



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Thank you

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