MULTIPHASE FLOW MODELLING OF CALCITE DISSOLUTION PATTERNS FROM CORE SCALE TO RESERVOIR SCALE

Presentation for UKCCSRC Specialist Meeting on Flow and Transport for CO2 Storage

Imperial College London,

30th October 2015

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Resources: Our use of the term "resources" in this presentation includes quantities of oil and gas not yet classified as SEC proved oil and gas reserves. Resources are consistent with the Society of Petroleum Engineers 2P and 2C definitions.

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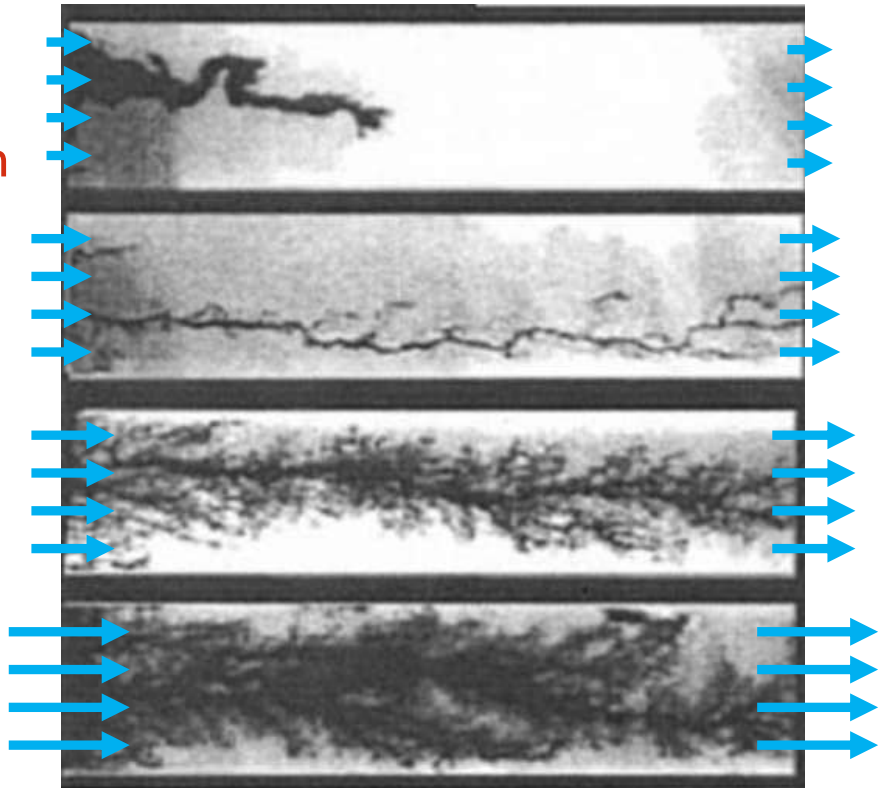
INTRO: CALCITE DISSOLUTION DURING CO2 INJECTION

- Context: CO_2 storage/EOR
- CO_2 injection → acidification → carbonate dissolution
- Experiments show 'wormholing' for CO_2 -saturated brine injection
  - Similar to patterns in extensive acid stimulation literature
- Very limited experimental work done with gas/SC CO_2 injection

⇨ Model investigation

  - Impact of gas phase
  - Upscaling to field scale



Fred and Fogler (1999), SPE 56995

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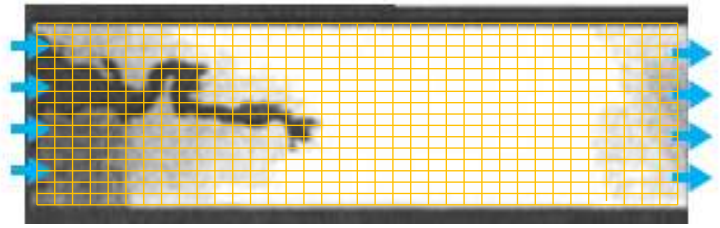
MODELLING APPROACH

Using in-house dynamic multiphase reservoir flow simulator (MoReS) coupled to open-source geochemical package (PHREEQC v3)



Detailed model (core scale)

- Explicit representation of WH patterns
  - Grid resolution << WH diameter
- Chemistry including kinetics (phreeqc.dat, Palandri & Kharaka)
- 2-phase flow description including capillary effects and diffusion
  - Permeability, capillary pressure, relperms modified during dissolution
  - Continuum scale (Darcy) model → flow within WH approximate

Effective model (core scale to well/reservoir scale) [2nd part of presentation]

- Implicit representation of WH patterns
  - Generalised to 2-phase case with CO_2
  - Parameters tuned to detailed model and experiments

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DETAILED MODEL

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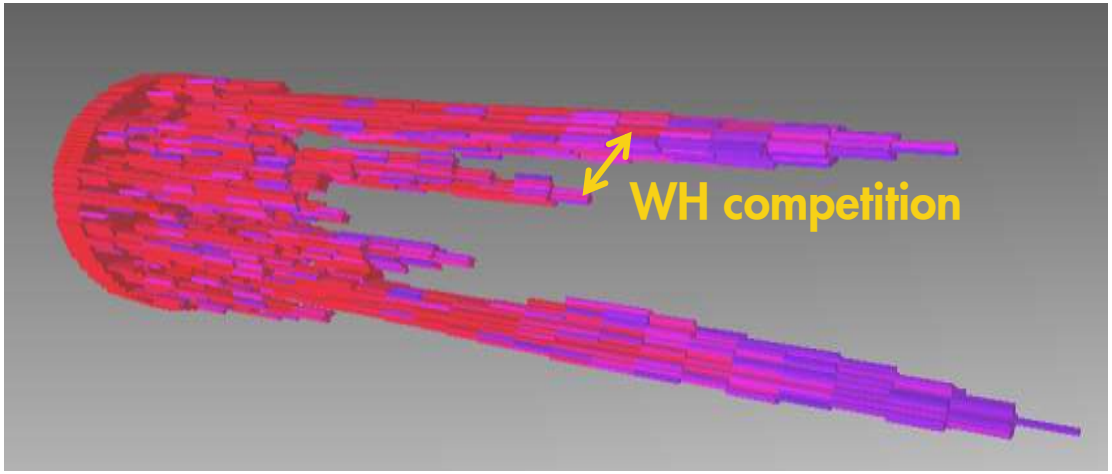
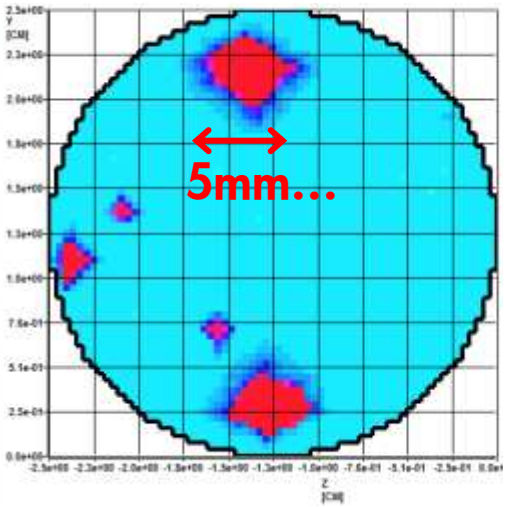
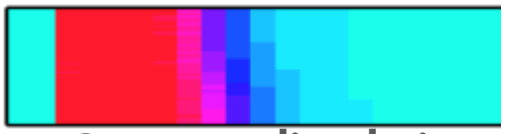
SOME MODEL RESULTS (SINGLE PHASE)

- 3D

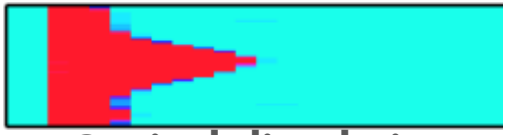




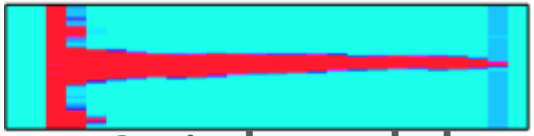
- 2D



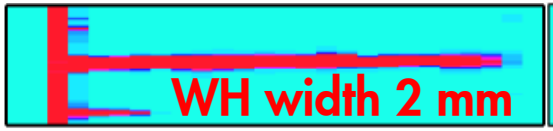
Compact dissolution



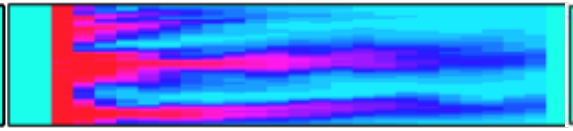
Conical dissolution



Conical wormhole



Dominant wormhole



Ramified wormholes

Homogeneous dissol.

- Most of fine-scale simulations done in 2D

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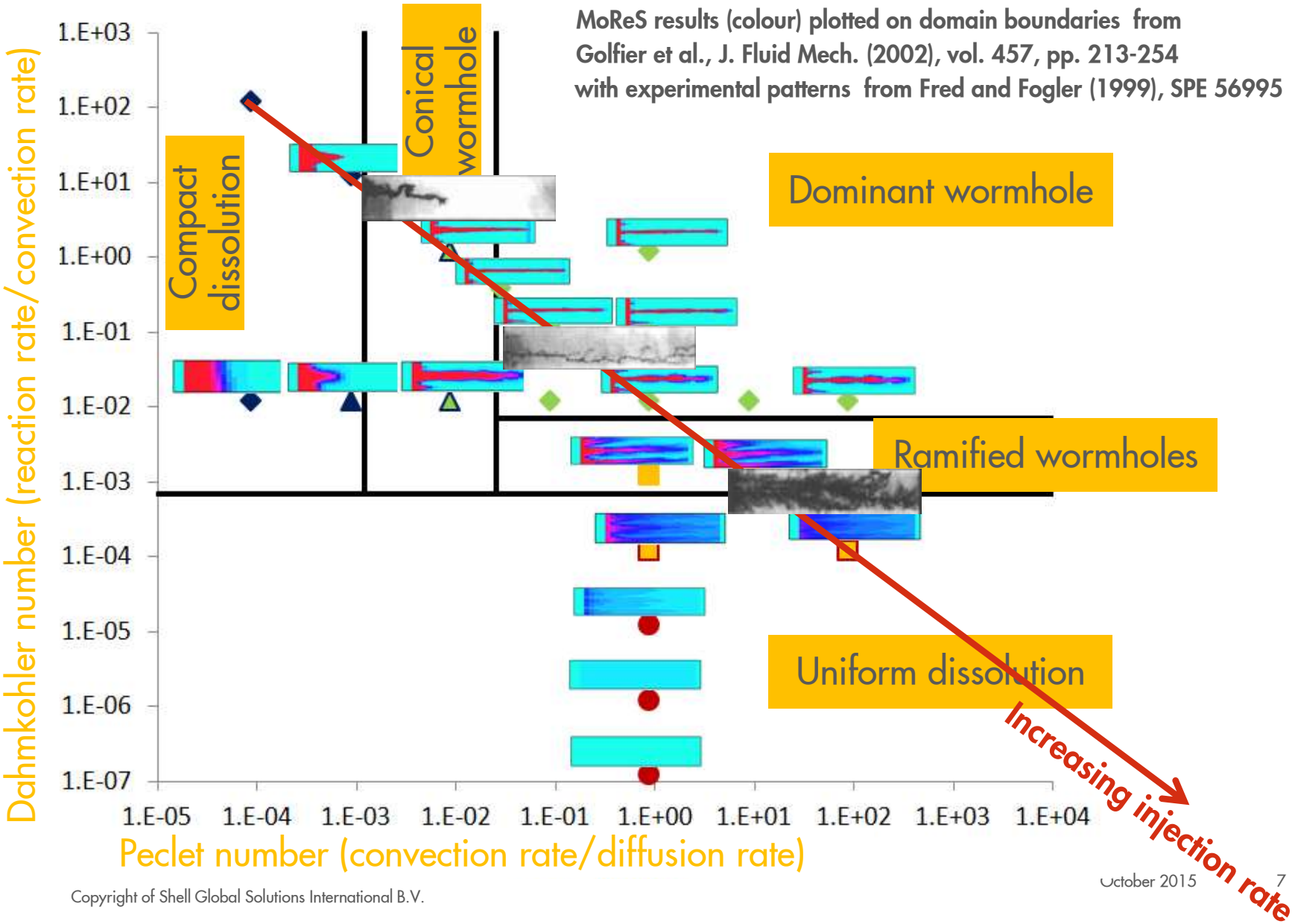
MODEL VALIDATION (SINGLE PHASE)



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TWO-PHASE EXPERIMENT/MODEL RATIONALE

Experiment

- Two experiments were done at Shell with CO_2 + brine co-injection
- This is ~representative for the conditions somewhat behind the CO_2 plume front in CCS
- Pure CO_2 injection WH experiment would be more challenging
  - longer core to resolve profiles (gas saturation, calcite dissolution)
  - high CT signal:noise to resolve subtle calcite dissolution patterns

Model:

- Model experiment with CO_2 + brine co-injection and compare results
- Derive upscaled (effective) model description
- Apply effective model to pure CO_2 injection (larger model dimensions)

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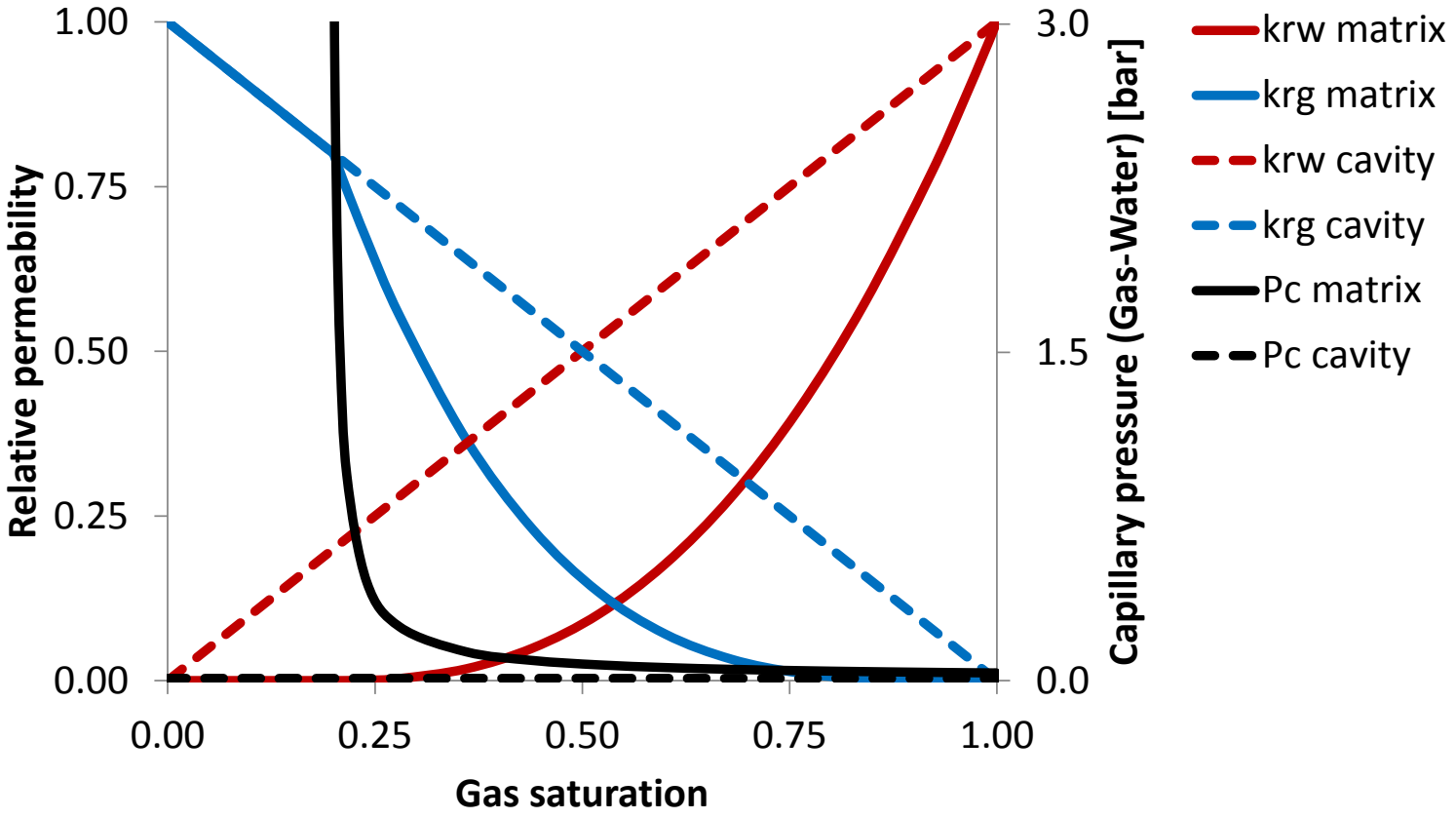
2-PHASE RELPERM AND CAPILLARY PRESSURE



During dissolution

- Interpolation between curves (linear in porosity)
- Power law scaling of permeability with porosity

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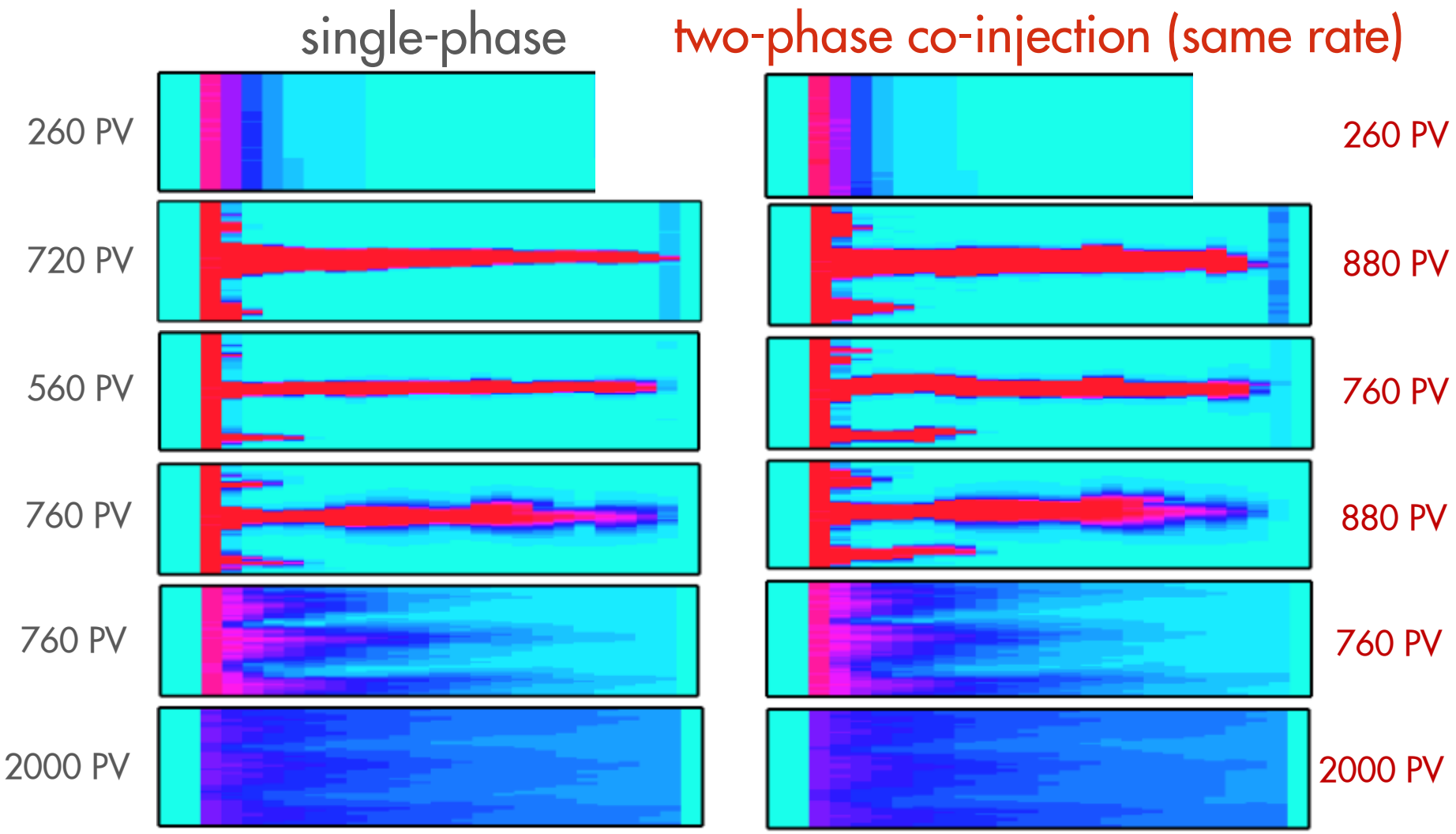
TWO-PHASE MODEL RESULTS (CO-INJECTION)



The gas phase slightly suppresses WH velocity

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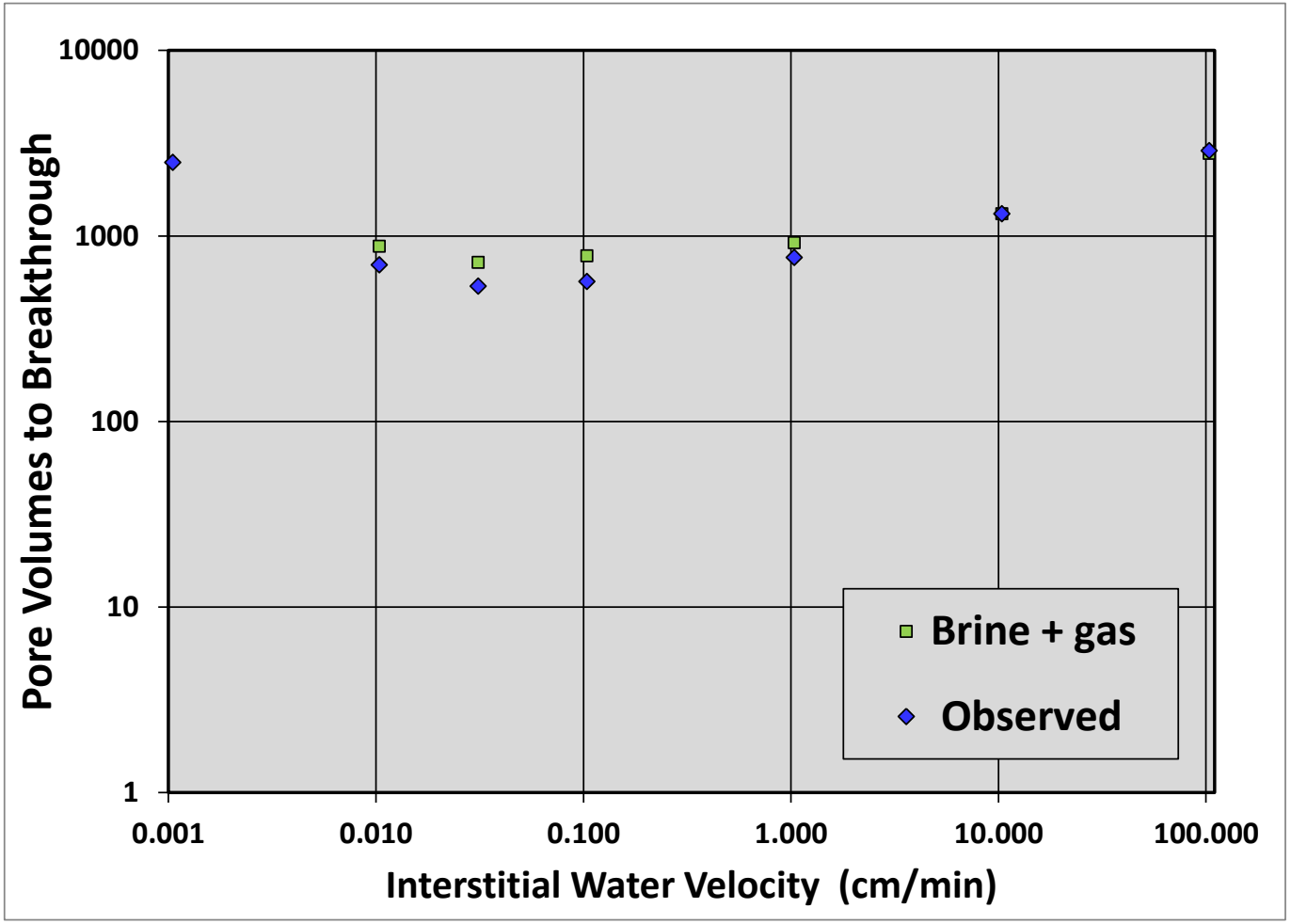
TWO-PHASE MODEL RESULTS (CO-INJECTION)



Most suppression around optimal flow rates (~dominant WH regime)

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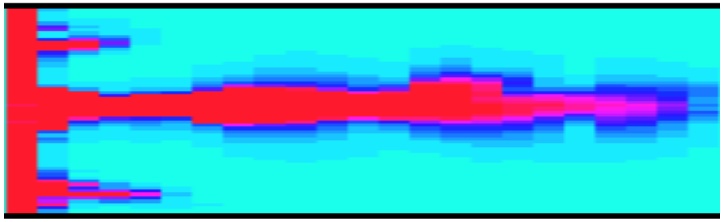
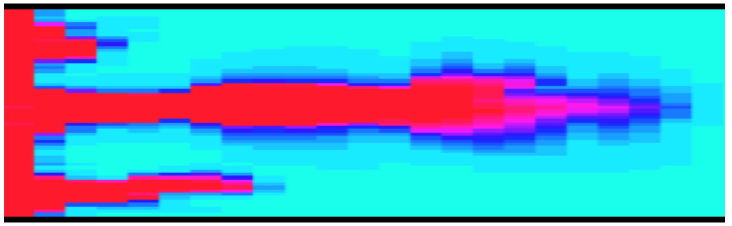
TWO-PHASE MODEL RESULTS: ANALYSIS/COMPARISON

1-phase, 1ml/min **760 PV**

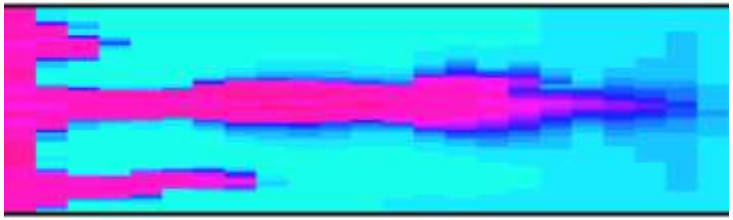
2-phase, 1+1 ml/min co-inj. **880 PV**

Porosity

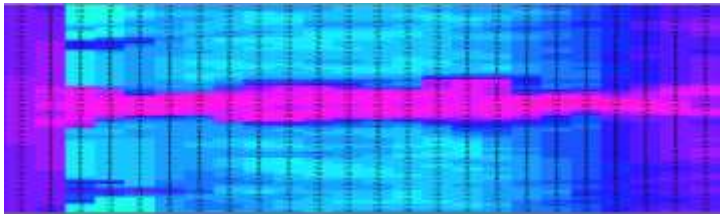


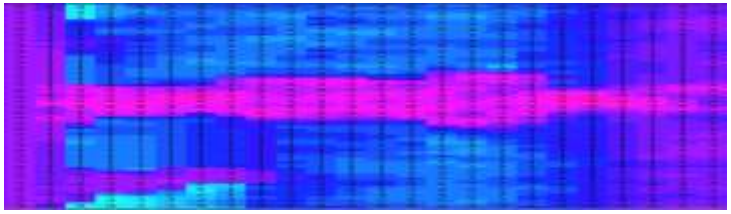


Gas saturation



Water flux (log scale)





Experiment (Shell) (Porosity)

Ott et al. (2013) SCA2013-029

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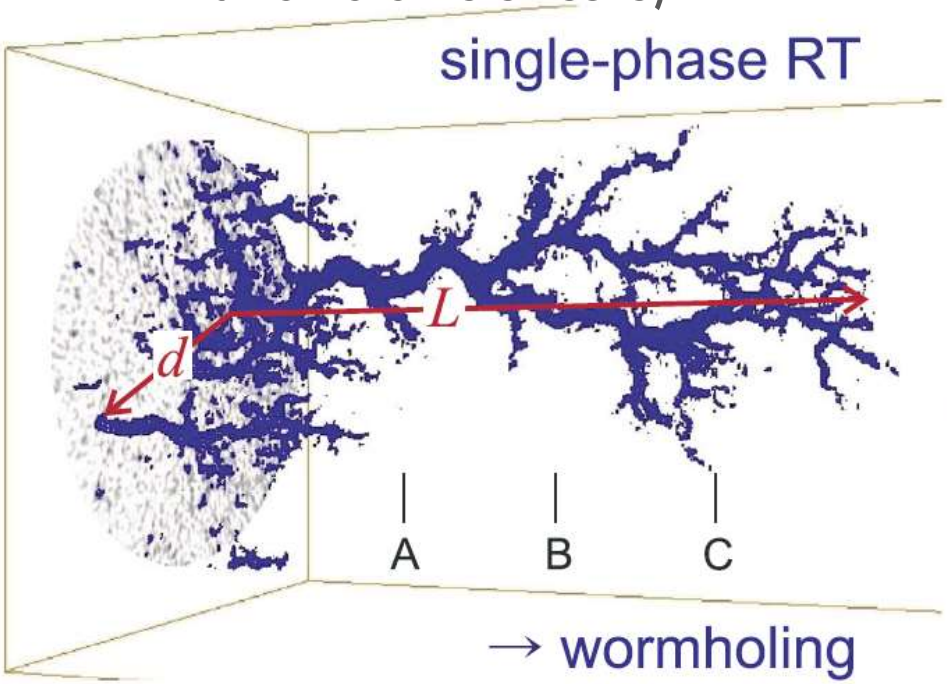
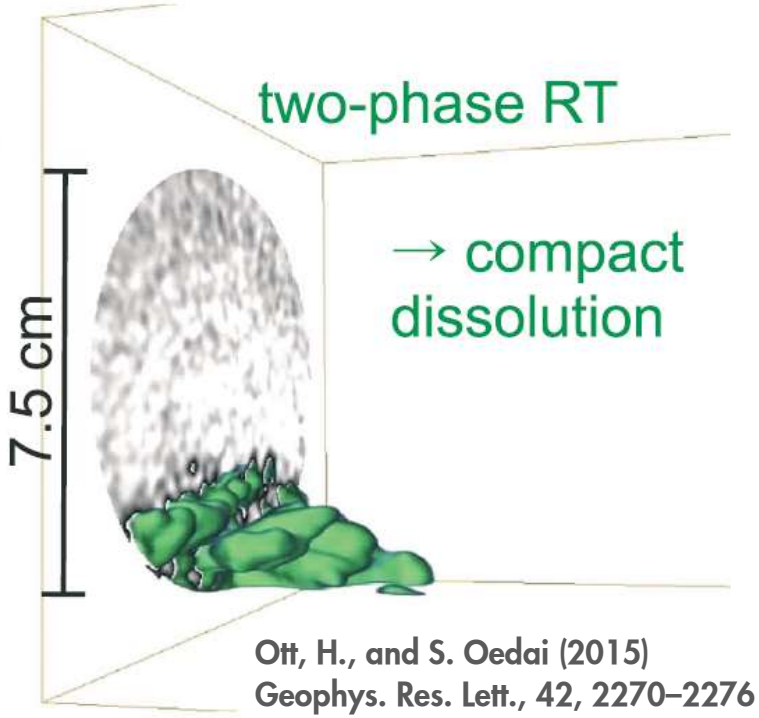
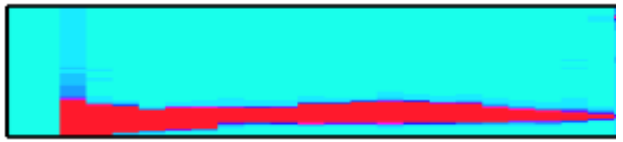
2ND SHELL EXPERIMENT: WH SUPPRESSION

- In this experiment gas co-injection seems to trigger transition from dominant WH into conical WH/compact dissolution
- Slumping reproduced in model runs with gravity (only investigated on small diameter core)





Ott, H., and S. Oedai (2015)
Geophys. Res. Lett., 42, 2270–2276
doi:10.1002/2015GL063582



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EFFECTIVE MODEL APPROACH

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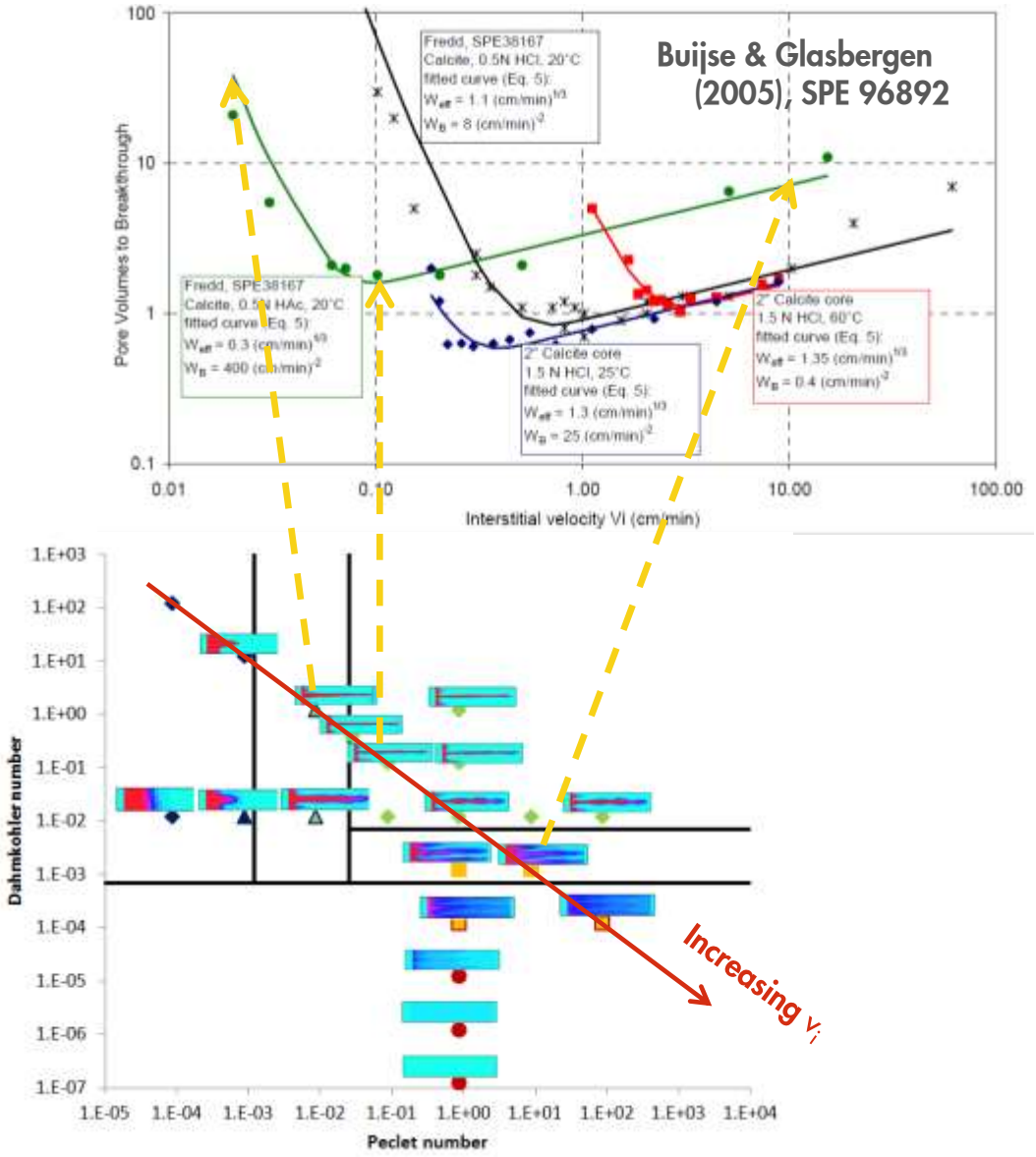
LEARNINGS FROM ACID STIMULATION LITERATURE

- Acid stimulation literature (single phase): Universally shaped curve #PV_{BT} vs v_i (or v_{WH} vs v_i)
- Location of curve depends on phi, perm, aspect ratio, HCl strength, …
- 'Global Wormholing Model' (GWM), *Talbot&Gdanski (2008), SPE 113042*, offers ~universal parameterisation

  ⇨~predictive v_{WH} vs v_i for given phi, perm, HCl strength, etc.



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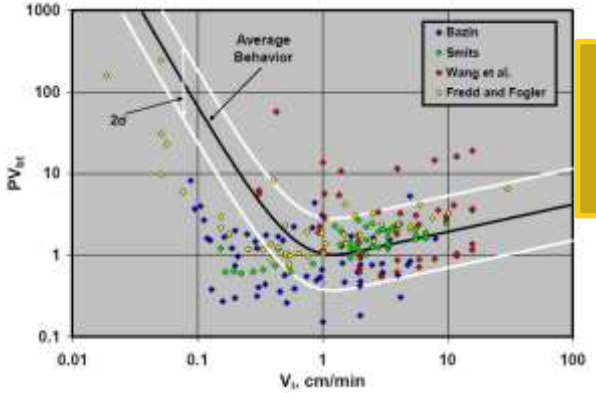
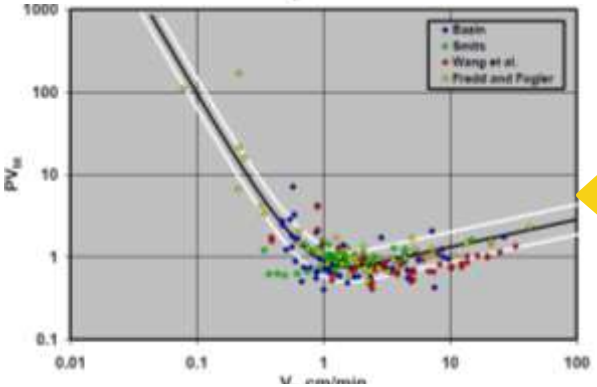
GWM CHARACTERISTICS





$$V_i = 4\frac{q}{\pi d^2 \cdot \phi}$$

$$\frac{V_i}{\quad wh}$$

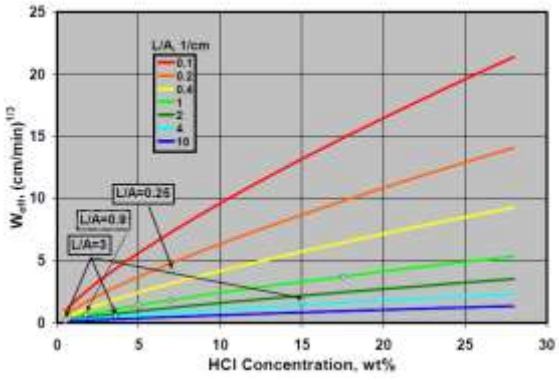
$$W_{eff} = b_1 \cdot C^{b_2} \cdot b_3\left(\frac{L}{A}\right)$$

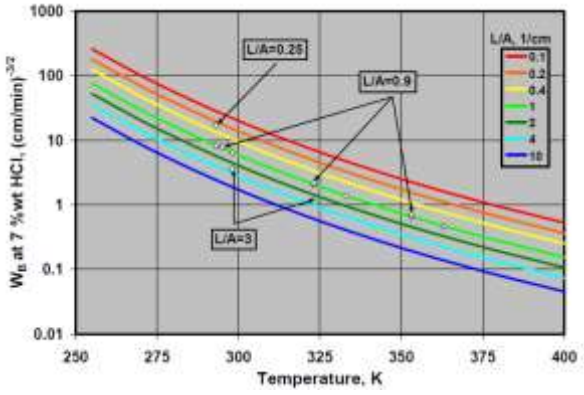
$$b_1 \cdot 0.07^{b_2} \cdot d_1 \exp\left(\frac{d_2}{T}\right.$$

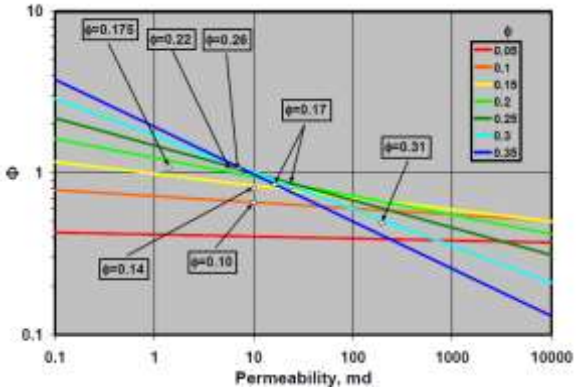
$$W_B =$$

$$\delta = a_3 \cdot \phi^{a_4}$$

Talbot&Gdanski (2008), SPE 113042







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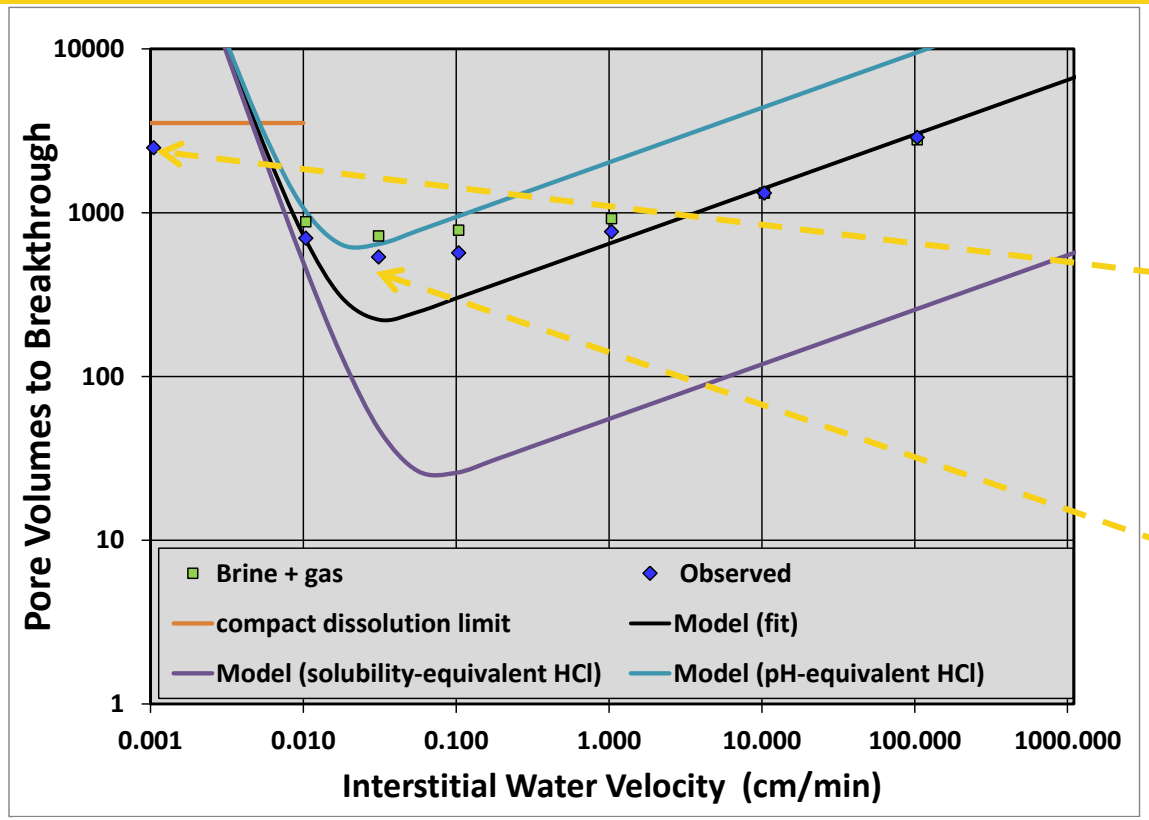
GWM APPLICATION TO CO_2-BRINE

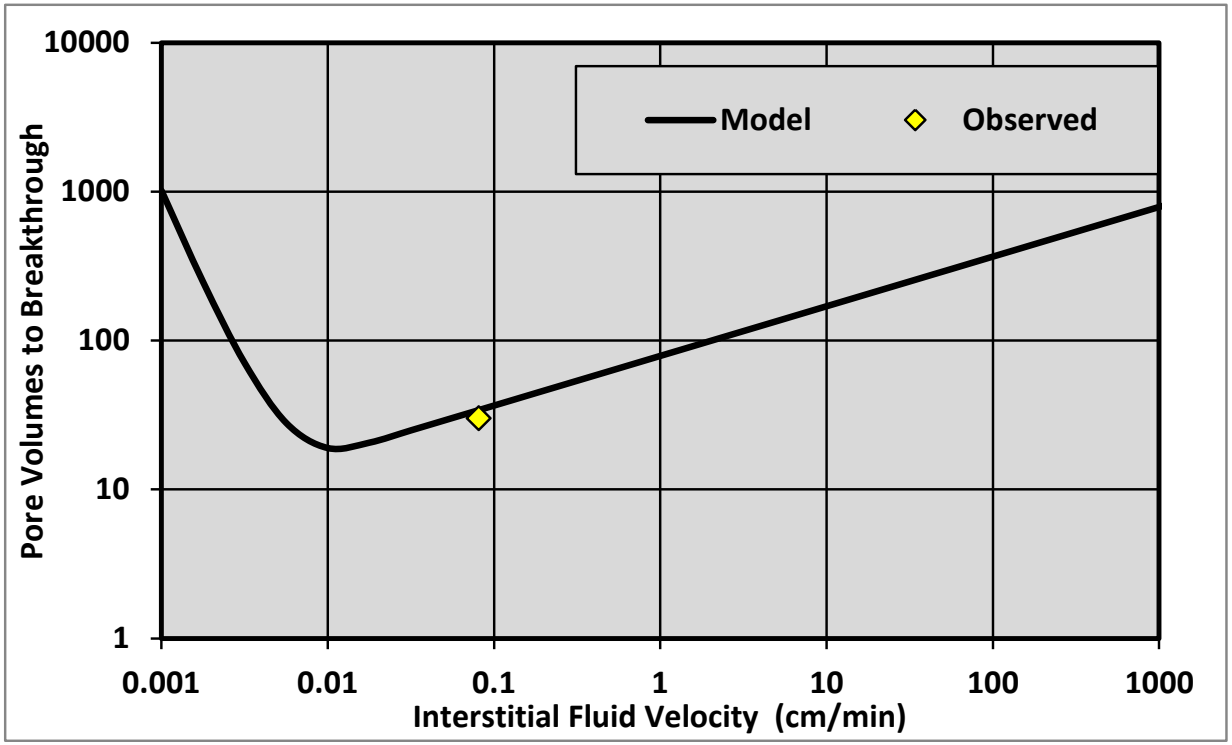


Model was run in 2D, for which GWM model is overshooting in face dissolution regime

Deviation in single WH regime because Poiseuille flow profile in model poorly resolved or grid resolution too coarse

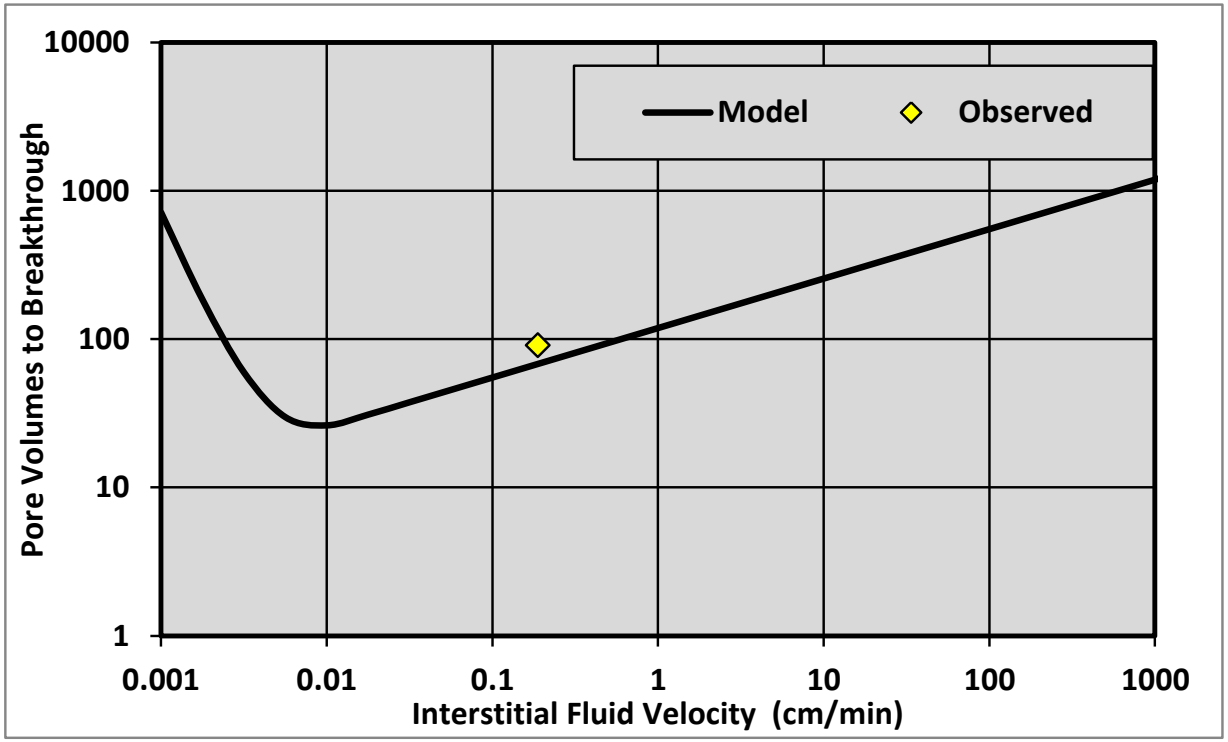
- GWM model fitted by tuning HCl strength
- Resulting GWM model also fits available experimental data well (next slides)
- GWM model applied to dynamic flow simulations by locally accounting for calcite saturation index through HCl strength parameter
- For 2-phase use same GWM parameters – use the <u>water</u> v_i as input velocity

FITTED MODEL COMPARISON TO EXPERIMENTS OTT ET AL. (SHELL) 2013 – SCA 2013-029



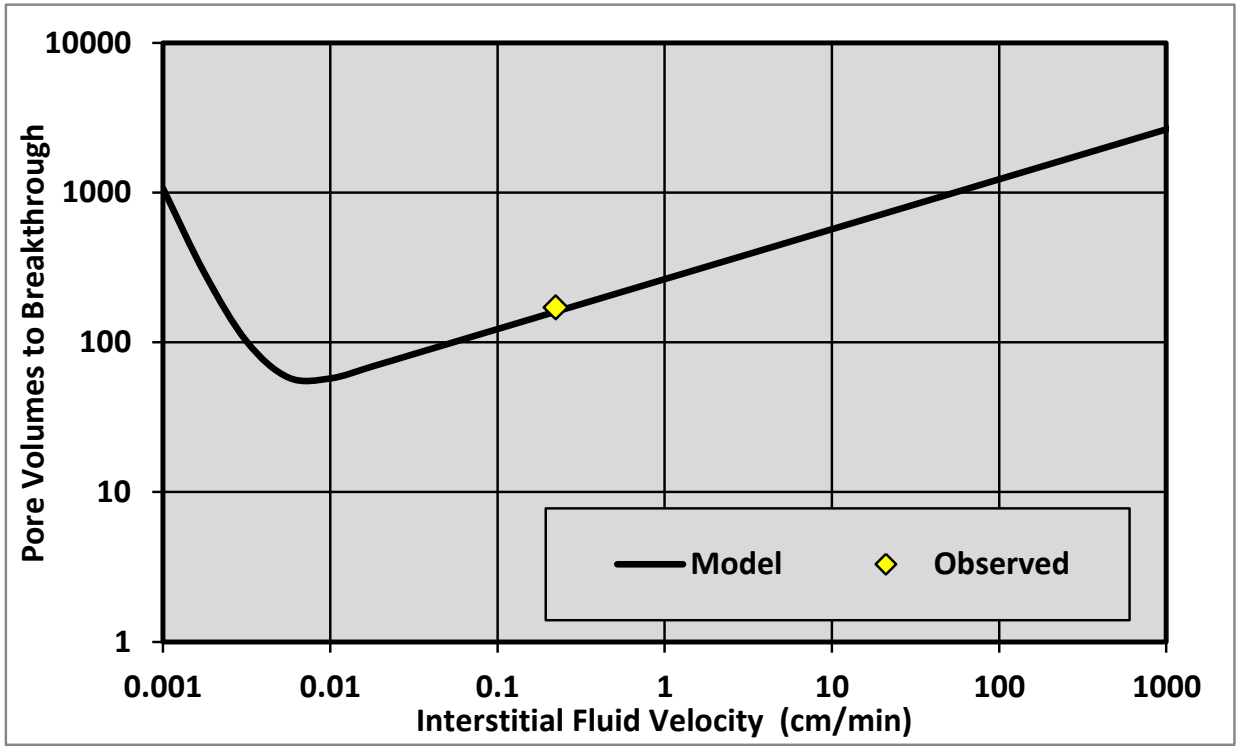
- L=5.91", d=2.95"
- q=1 mL/min
- Estaillades limestone
- φ=0.278, k=270 mD
- T=50 °C, p=100 bar

FITTED MODEL COMPARISON TO EXPERIMENTS CAROLL ET AL. (LLNL) 2013 - IJGHGC 16S (2013) S185–S193



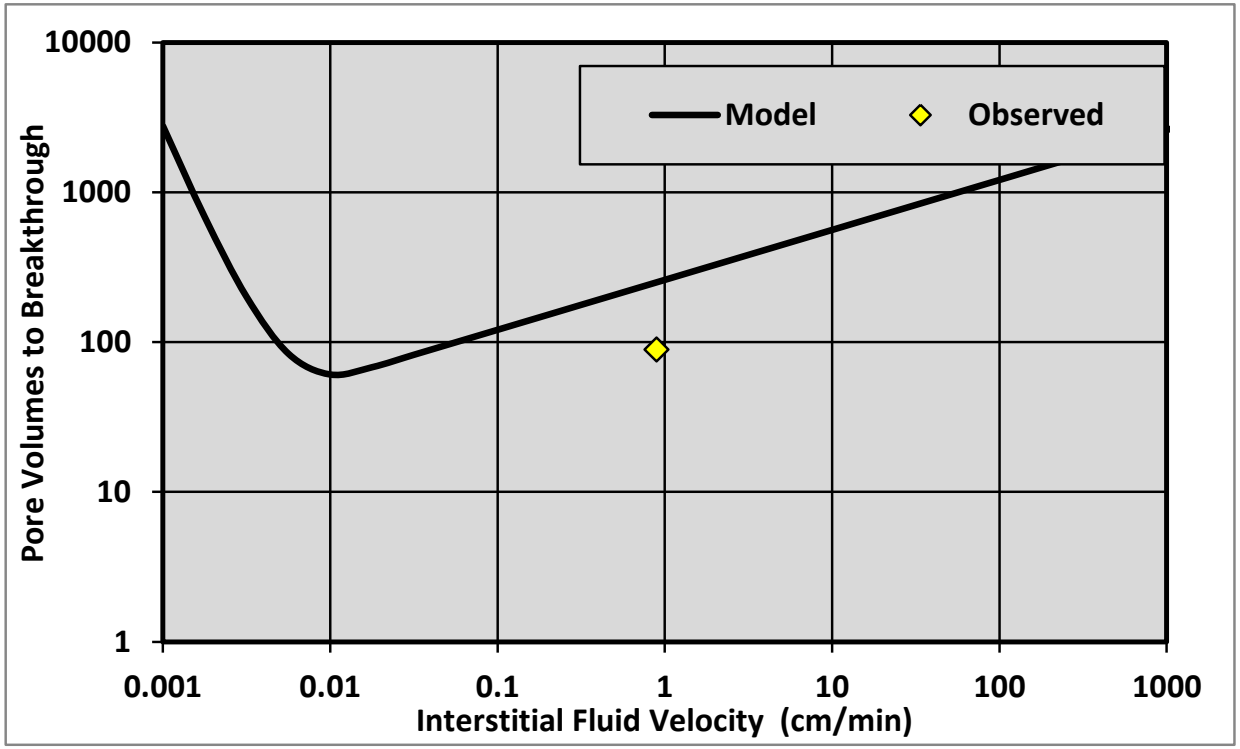
- L=1.18", d=0.59"
- q=0.05 mL/min
- Weyburn limestone (59% calcite)
- φ=0.15, k=0.032 mD
- T=60 °C, p=248 bar, p_CO_2 = 30 bar
- Calculated HCl equivalent based on undersaturated CO_2 molality

FITTED MODEL COMPARISON TO EXPERIMENTS
VIALLE ET AL. 2014 - J. GEOPHYS. RES. SOLID EARTH, 119, 2828–2847



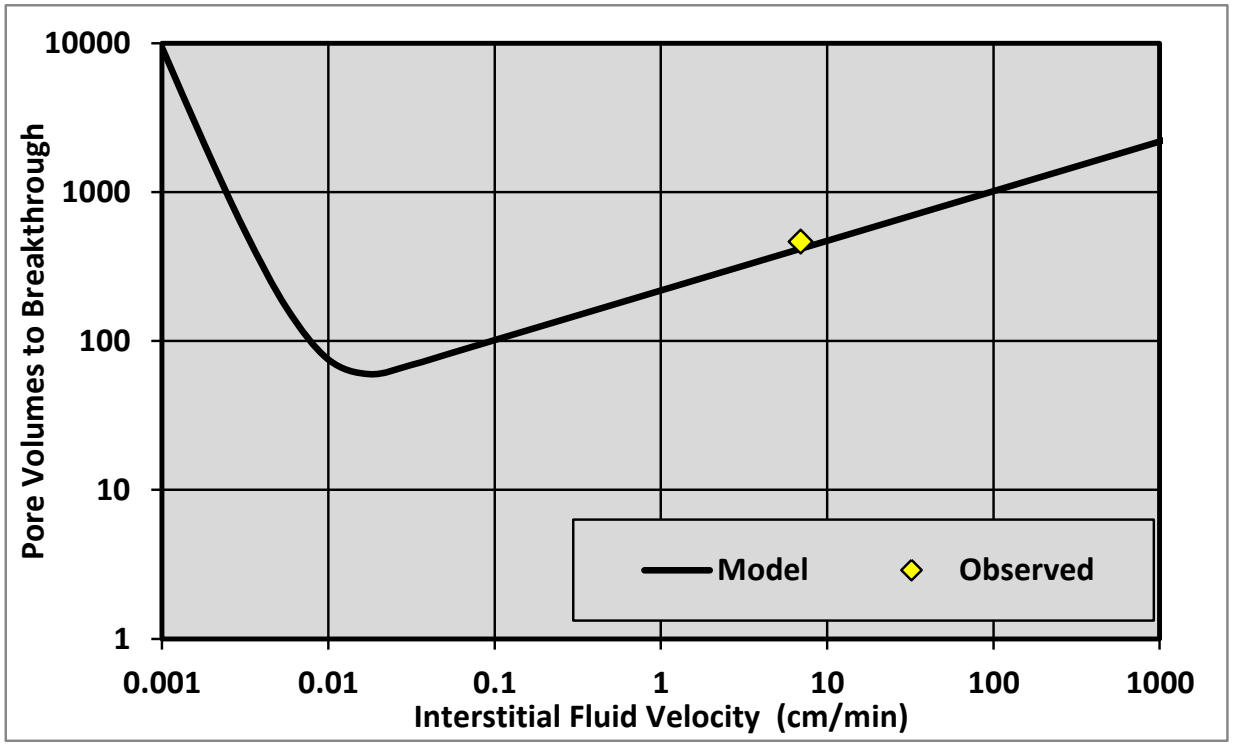
- L=0.13.8″, d=3.94″
- Estaillades limestone
- q=5 mL/min
- φ=0.286, k=120 mD
- Salinity = 25000 ppm
- T=20 °C, p_CO_2 = 1 bar
- Calculated HCl equivalent based on undersaturated CO_2 molality

FITTED MODEL COMPARISON TO EXPERIMENTS
LUQUOT ET AL. 2011 - TRANSP POROUS MED (2014) 101:507–532



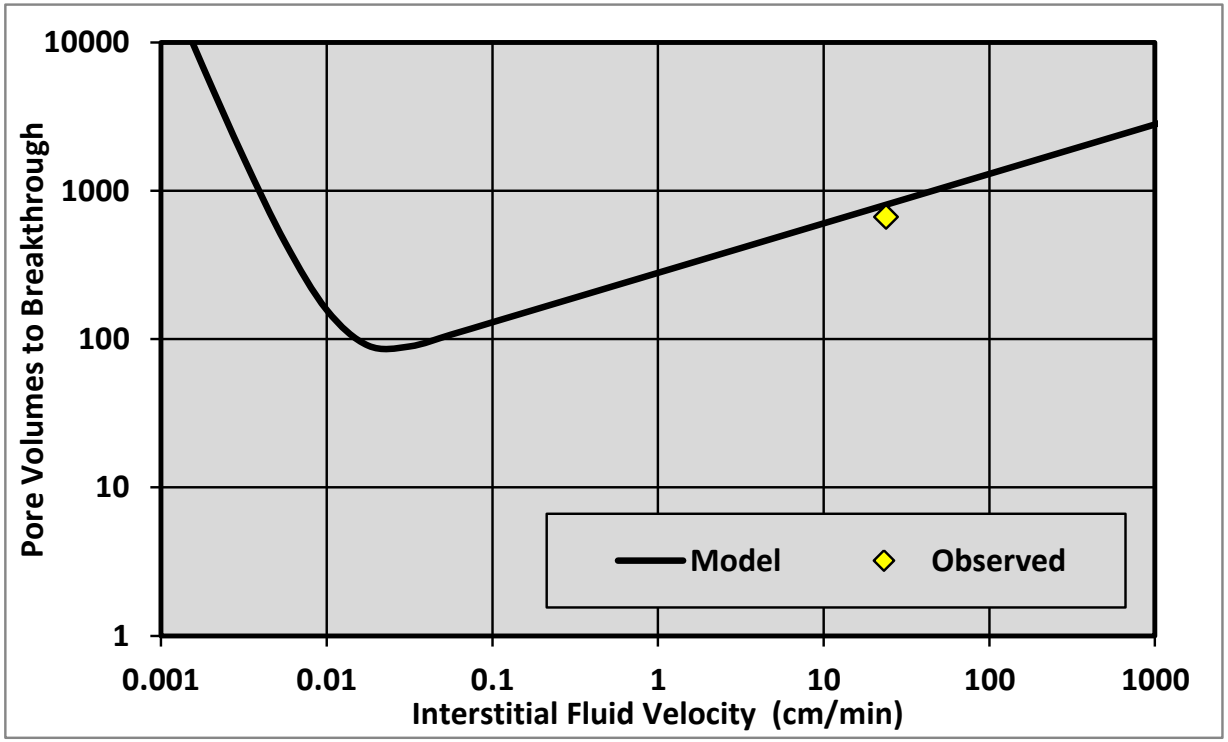
- L=0.71″, d=0.35″
- q=0.08 mL/min
- Alcobaa limestone
- φ=0.15, k=0.24 mD
- T=100 °C, p=120 bar, p_CO_2 = 34 bar
- Calculated HCl equivalent based on undersaturated CO_2 molality

FITTED MODEL COMPARISON TO EXPERIMENTS SVEC & GRIGG 2001 - SPE 71496



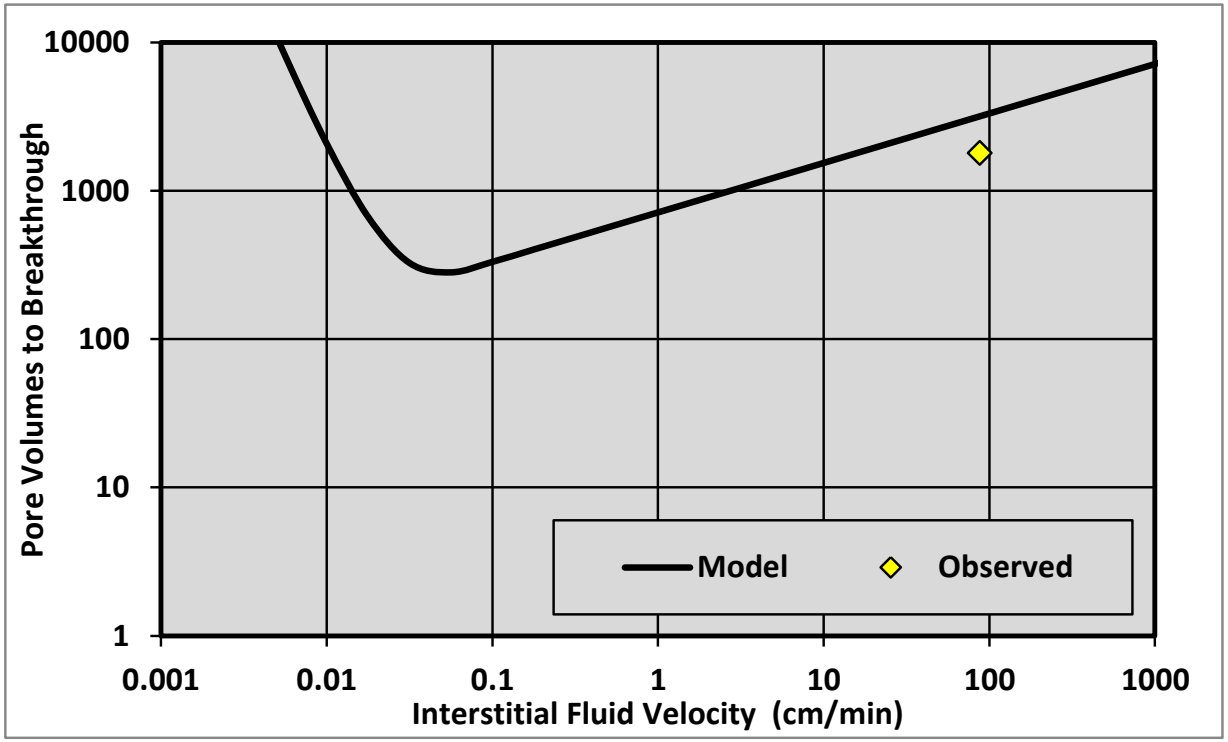
- L=20.3", d=1.98"
- q=17 mL/min
- Indiana limestone
- φ=0.123, k=35.7 mD
- T=38 °C, p=138 bar
- Salinity=86950 ppm

FITTED MODEL COMPARISON TO EXPERIMENTS
LUQUOT & GOUZE 2009 - CHEMICAL GEOLOGY 265 (2009) 148–159



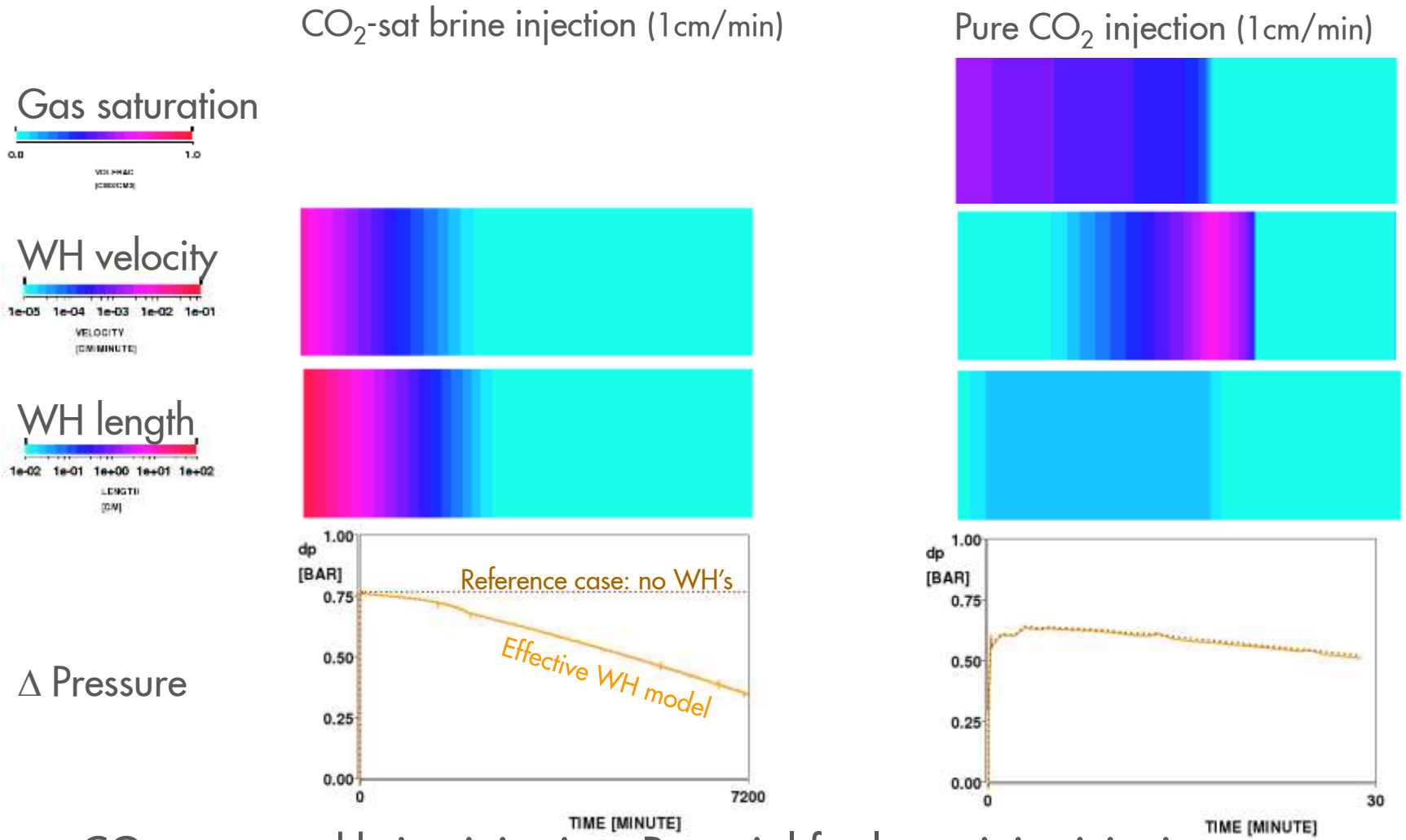
- L=0.71″, d=0.35″
- q=1.14 mL/min
- Mondeville limestone
- φ=0.075, k=35.7 mD
- T=100 °C, p=120 bar, p_CO_2 = 100 bar

FITTED MODEL COMPARISON TO EXPERIMENTS MENKE 2015 - IMPERIAL COLLEGE LONDON – PRIVATE COMM



- L=0.47", d=0.16"
- q=0.5 mL/min
- Salinity = 60000 ppm
- Portland limestone
- φ=0.045, k=0.096 mD
- T=50 °C, p=100 bar

EFFECTIVE MODEL RESULTS (LINEAR MODEL, 1METER)



- CO_2-saturated brine injection: Potential for large injectivity increase
- Pure CO_2 injection: Short/no wormholes. Negligible impact on injectivity

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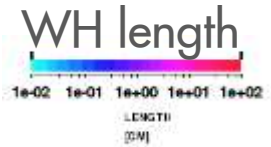
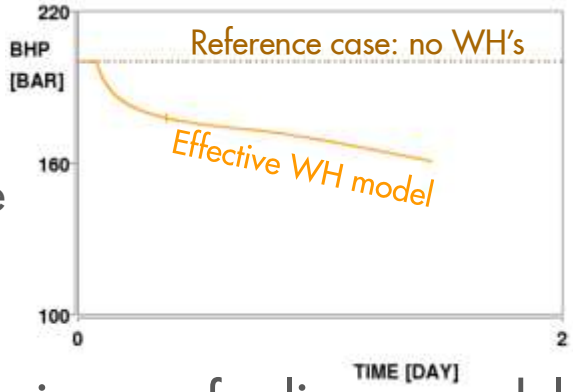
EFFECTIVE MODEL RESULTS (RADIAL MODEL, R=50 METER)

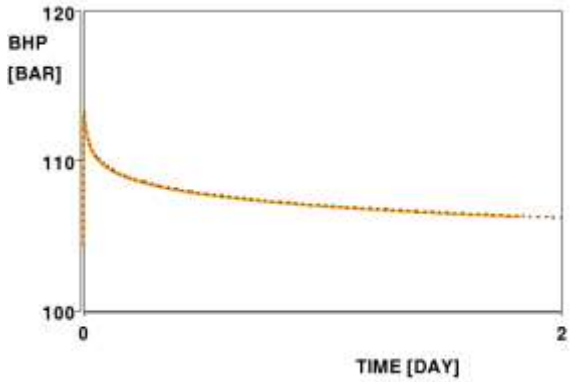
CO_2-sat brine injection (0.5 MT/year)

Pure CO_2 injection (0.5 MT/year)



Injection pressure





- Same conclusions as for linear model
  - Note for pure CO_2 injection: WH length decreases with distance (cf. linear: ~constant)

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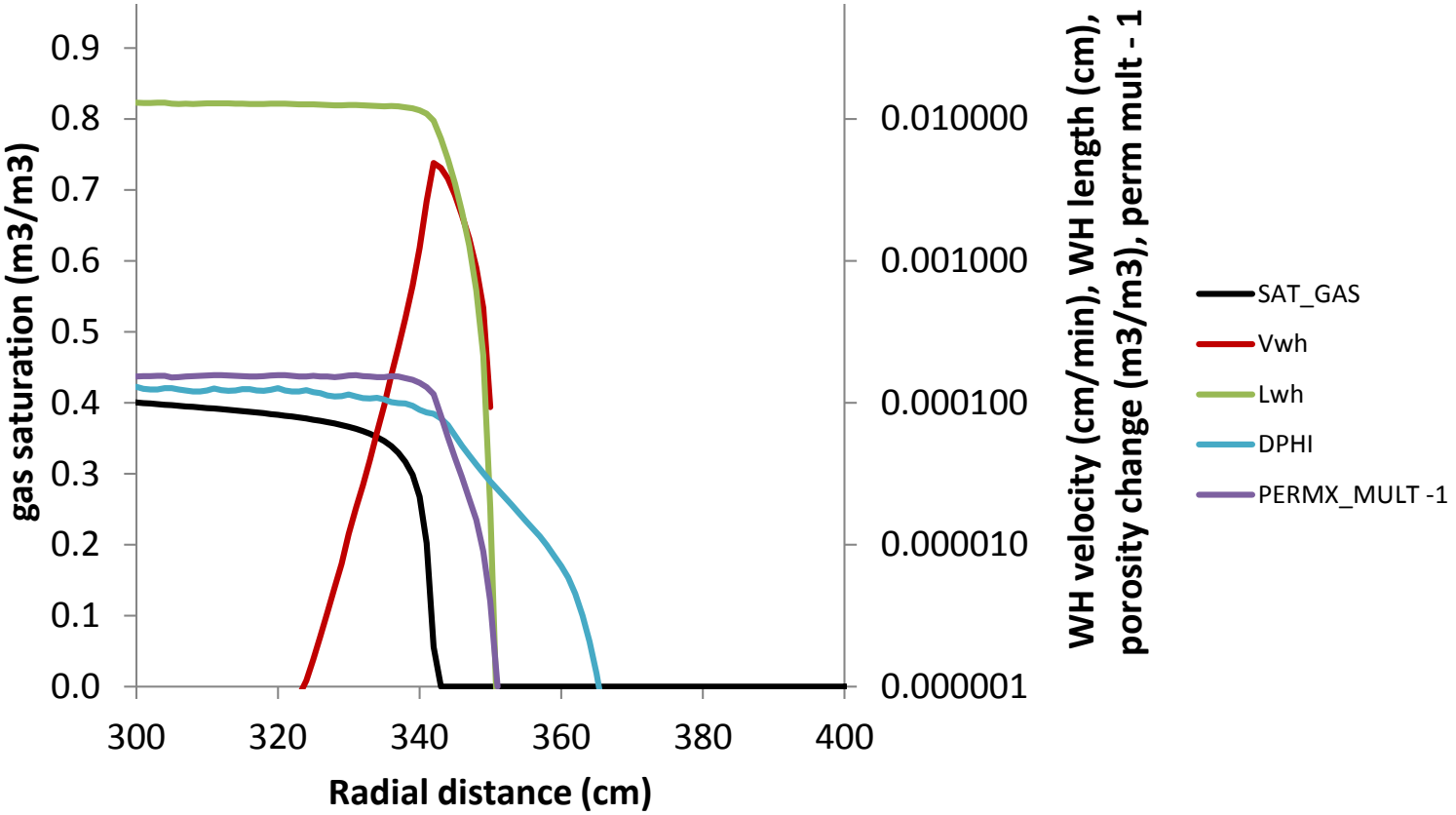
ANALYSIS OF RESULTS (RADIAL MODEL)



- Only thin region in which conditions are favourable for WH growth
- Far ahead of gas front gradual increase in acidity → always close to calcite equillibrium → outside WH regime (too low Da#)
- Note: calcite solubility in CO_2-saturated brine controls final porosity change

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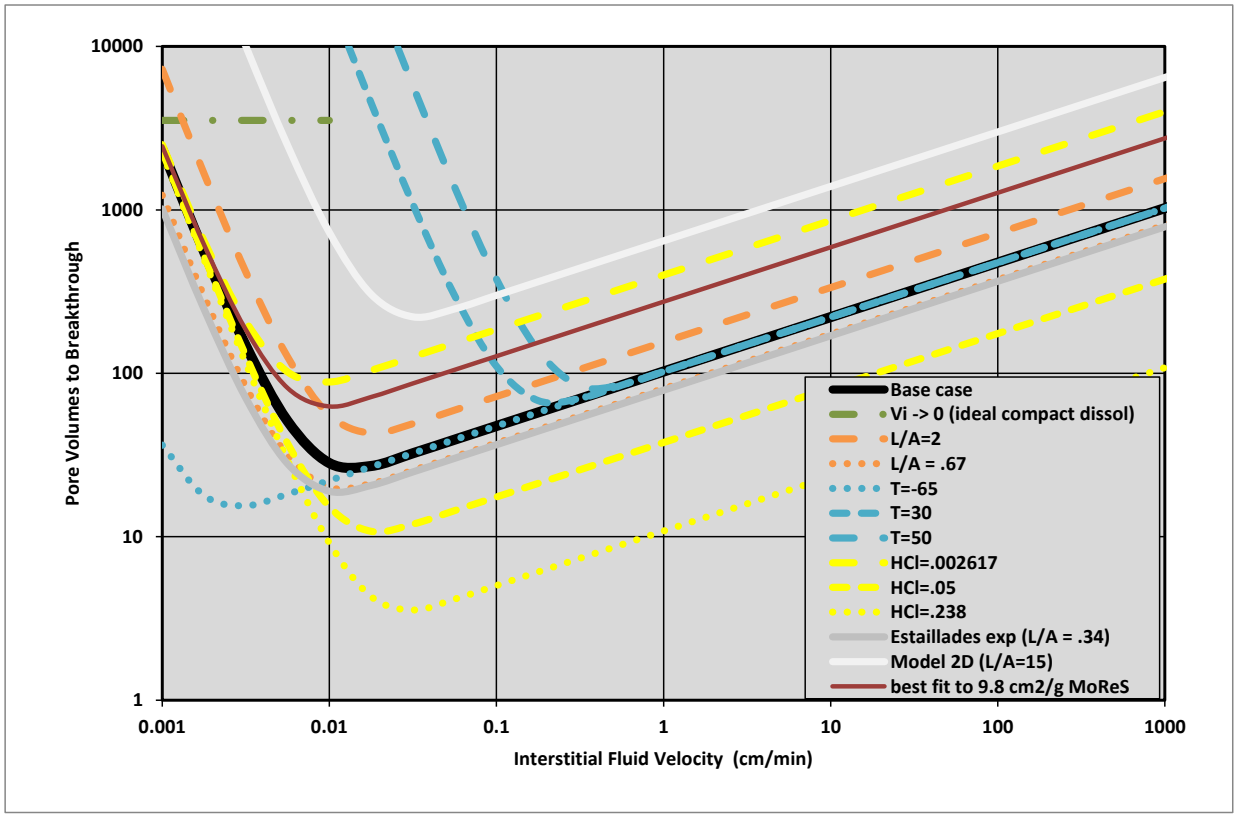
SENSITIVITY TO GWM PARAMETER UNCERTAINTY RANGE



- Parameter ranges based on (wide) envelope around experimental and model results
- For radial application, base case L/A $\approx 1 cm^{-1}$ based on acid stimulation radial corefloods and field application experience

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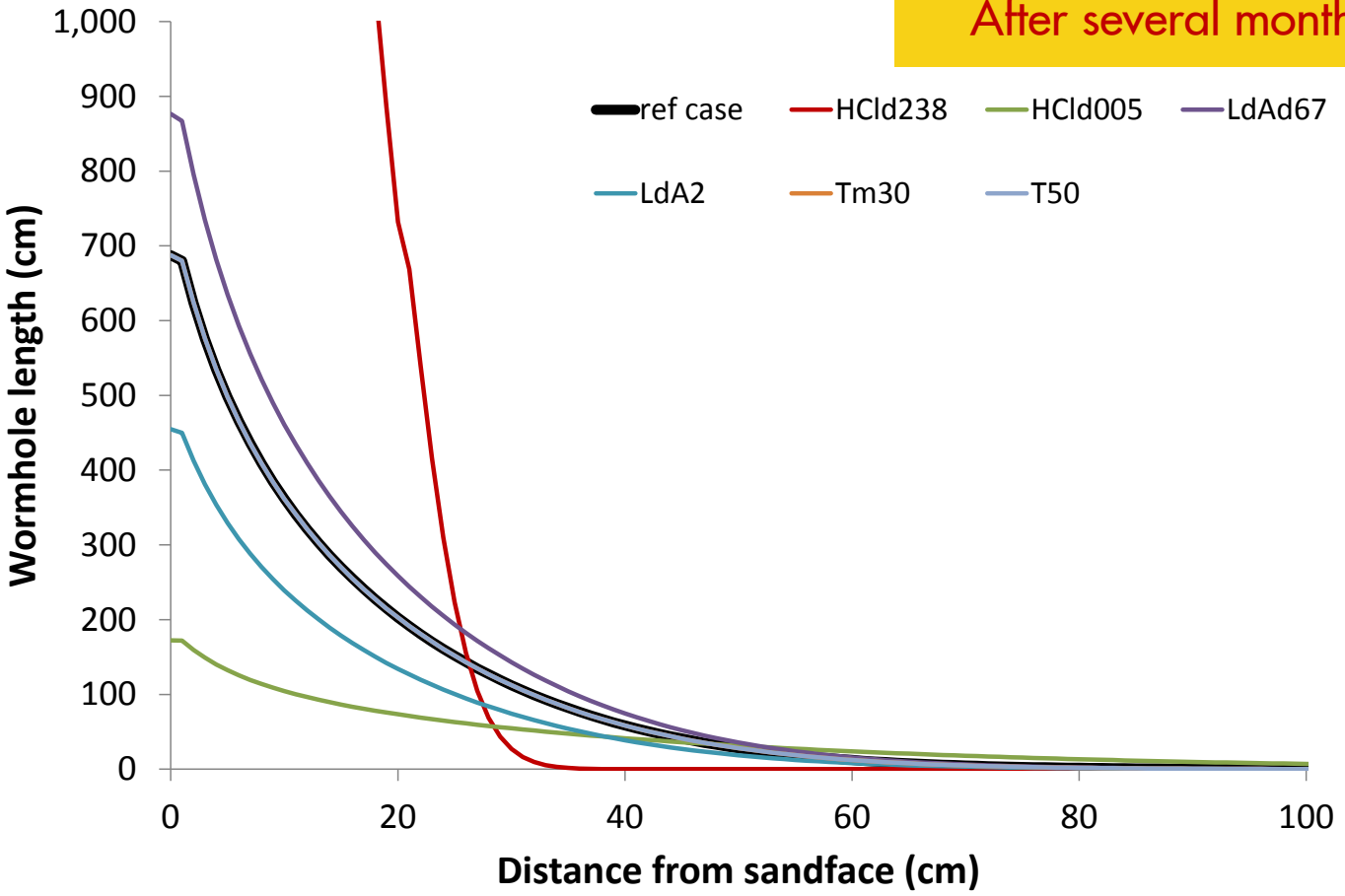
SENSITIVITY RESULTS: IMPACT ON WH LENGTH (1-PHASE)

After several months of injection



- Strong sensitivity, especially to acid strength parameter
- In all cases strong wormhole growth initiating at sandface
  - Hypothetical WH's initiating ahead of sandface overtaken (shock front)

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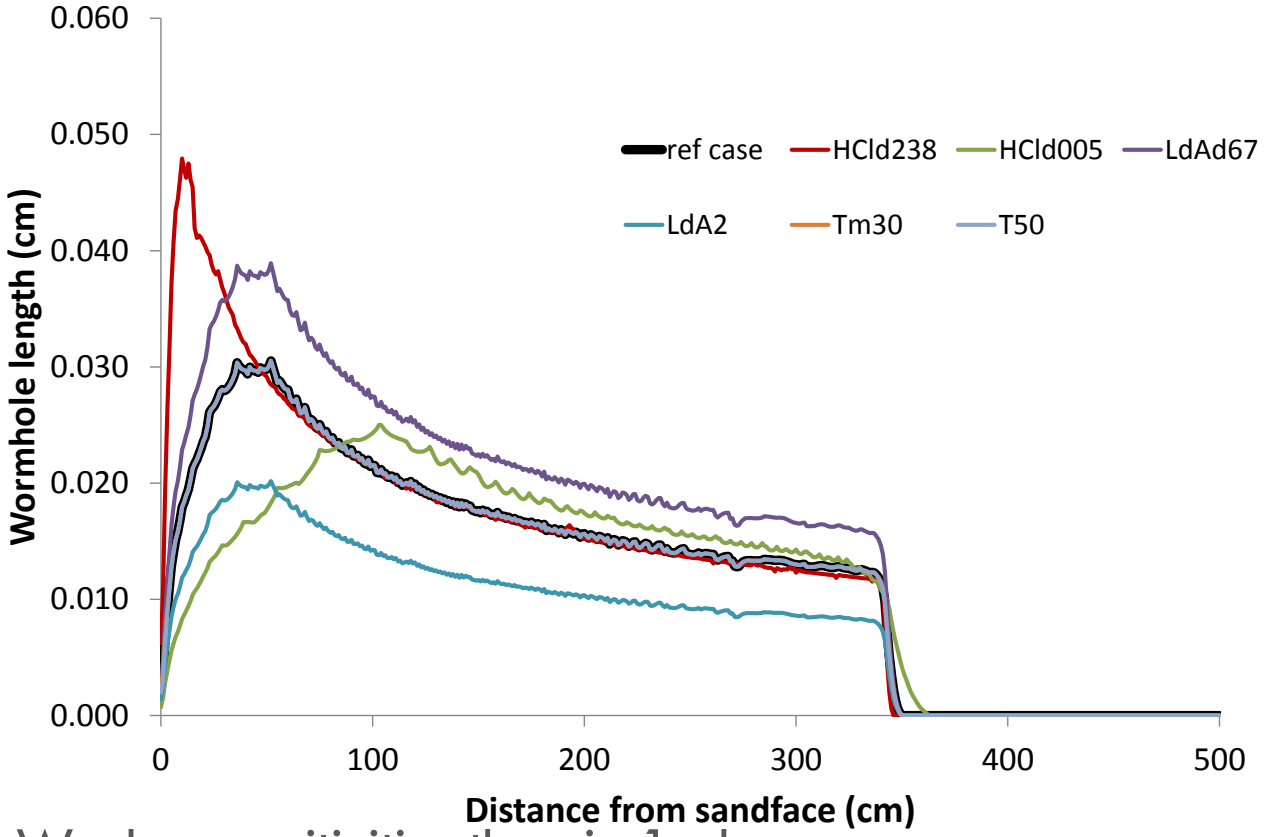
SENSITIVITY RESULTS: IMPACT ON WH LENGTH (2-PHASE)



- Weaker sensitivities than in 1-phase case
- Conclusions from reference case run appear robust, i.e.: short/no wormholes (L_{WH} < 0.05 cm)
- perm multiplier < 1.01 for L_{WH} < 5cm (2D) or 2cm (3D) [next slides]

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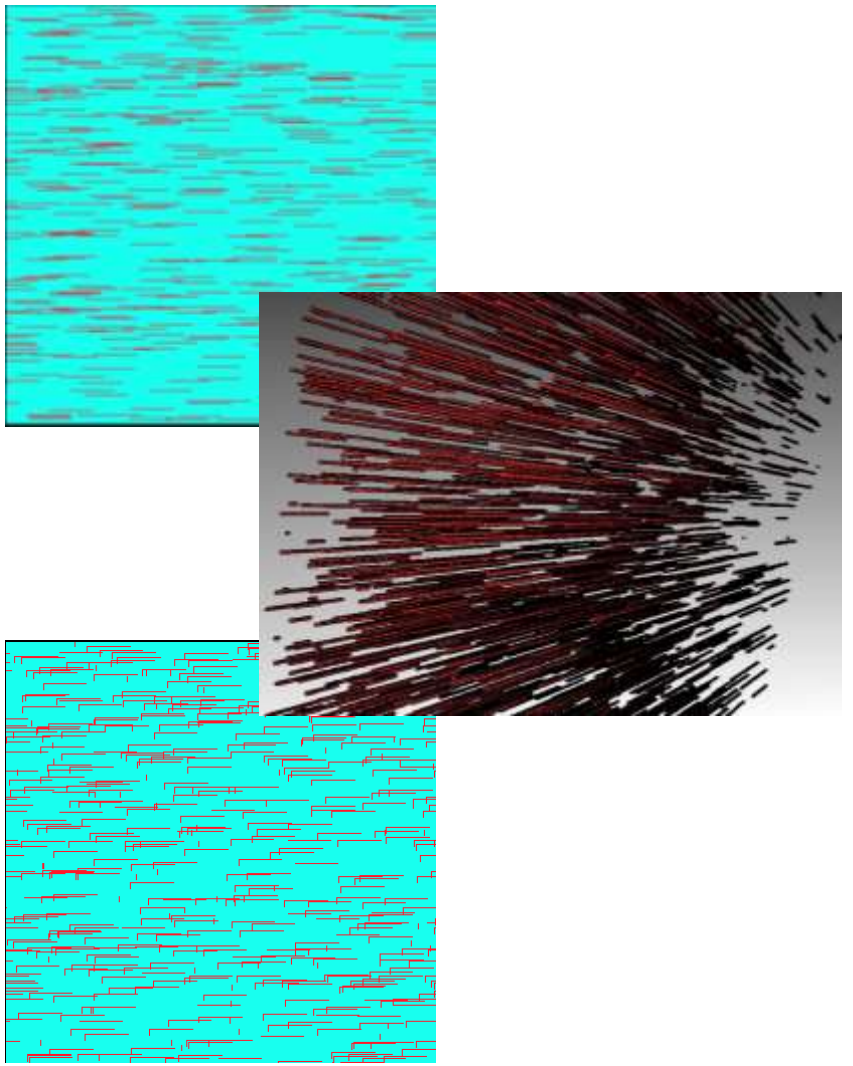
REMARK ON EFFECTIVE PERMEABILITY MULTIPLIER

In pure CO_2 injection case WH's would initiate away from sandface

Q: how assign effective perm?

- Matrix background and high perm WH channels
- Assume random WH initiation pattern
- Assume idealised dominant WH's
  - Straight channel WH ∅ = 2mm
  - From Poiseuille flow, $k_{WH} \approx 10^5$ D
- Control parameters $\Delta\varphi$ and L_{WH}
- Considered both 2D and 3D
- Considered enhanced connectivity case (~ WH angle distribution/bifurcations)



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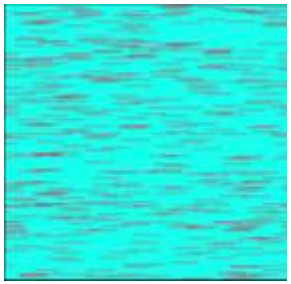
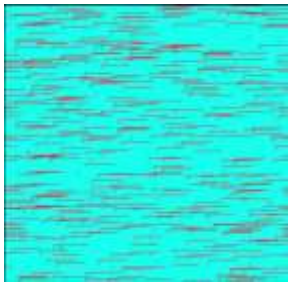
REMARK ON EFFECTIVE PERMEABILITY MULTIPLIER

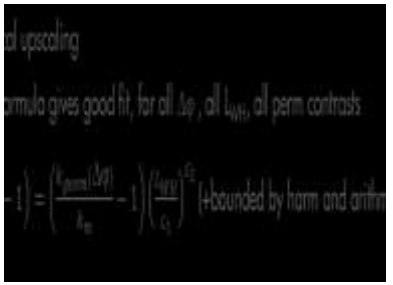
- Numerical upscaling
- Simple formula gives good fit, for all $\Delta\varphi$, all L_{WH}, all perm contrasts

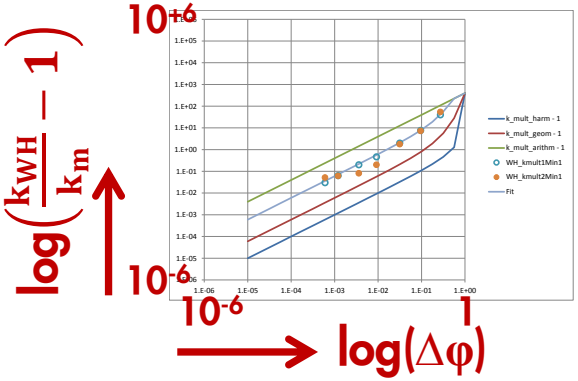
$$\left(\frac{k_{eff}}{k_m} - 1\right) = \left(\frac{k_{geom}(\Delta\varphi)}{k_m} - 1\right)\left(\frac{L_{WH}}{c_1}\right)^{c_2}$$ (+bounded by harm and arithm)

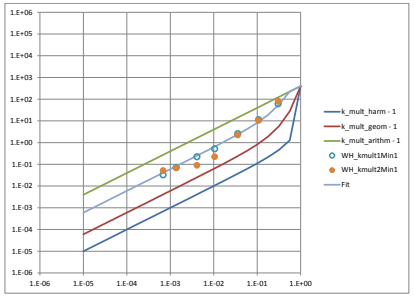
- Example - perm contrast $\frac{k_{WH}}{k_m} = 400$, L_{WH} =100mm

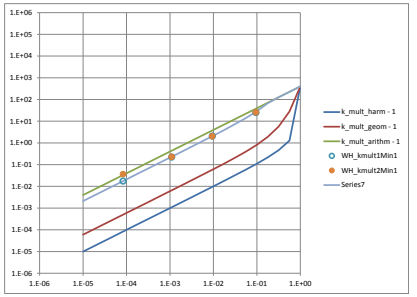












Note: for pure CO2 injection: $\Delta\varphi \approx 10^{-4}$

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CONCLUSIONS

- At fixed brine rate, gas co-injection causes some suppression of calcite dissolution patterns.
  - Modelling indicates limited suppression for any flow rate
  - Experiment: limited to strong suppression in dominant/conical WH regime
- Successfully applied effective GWM model (from acid stimulation literature) to CO_2-brine system (matches fine-scale model and experiments)
- Effective model predicts WH can be significant in carbonate reservoirs on operational timescale (days-years) for CO_2 & water co-injection
  - Good for injectivity
  - Potentially problematic for well/rock stability (depending on WH pattern)
- Effective model predicts negligible wormhole formation for pure CO_2 injection (at any scale from core scale to reservoir scale)

  ⇨WH formation irrelevant for pure CO_2 injection projects ('standard' CCS)

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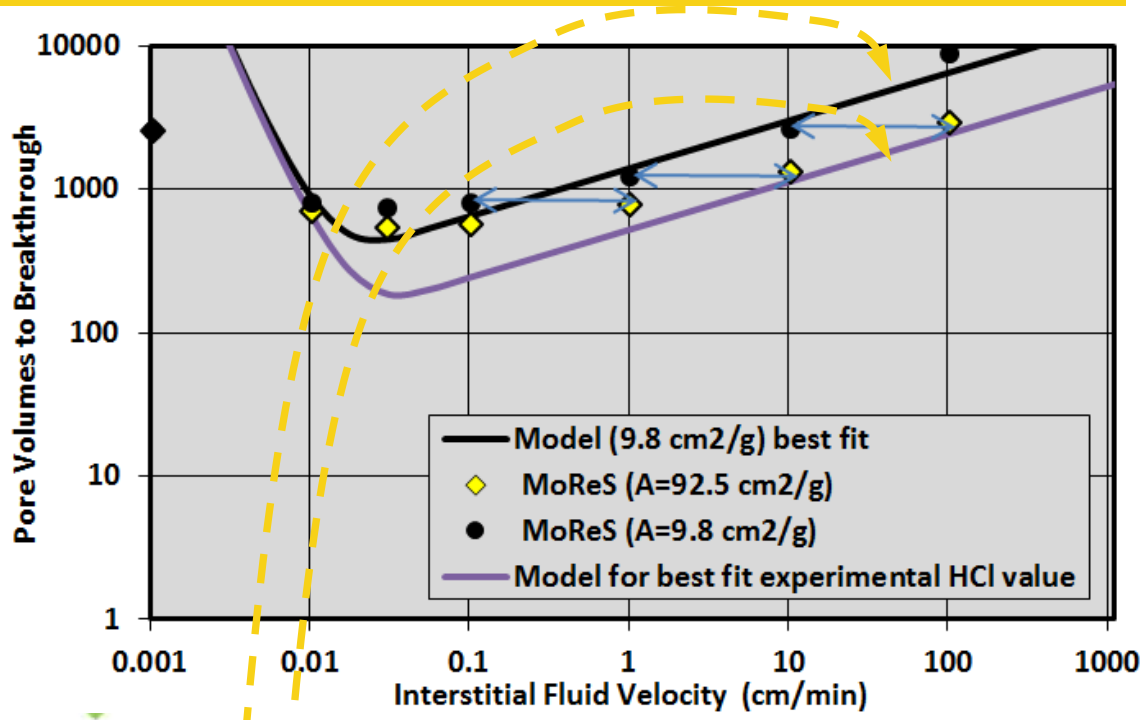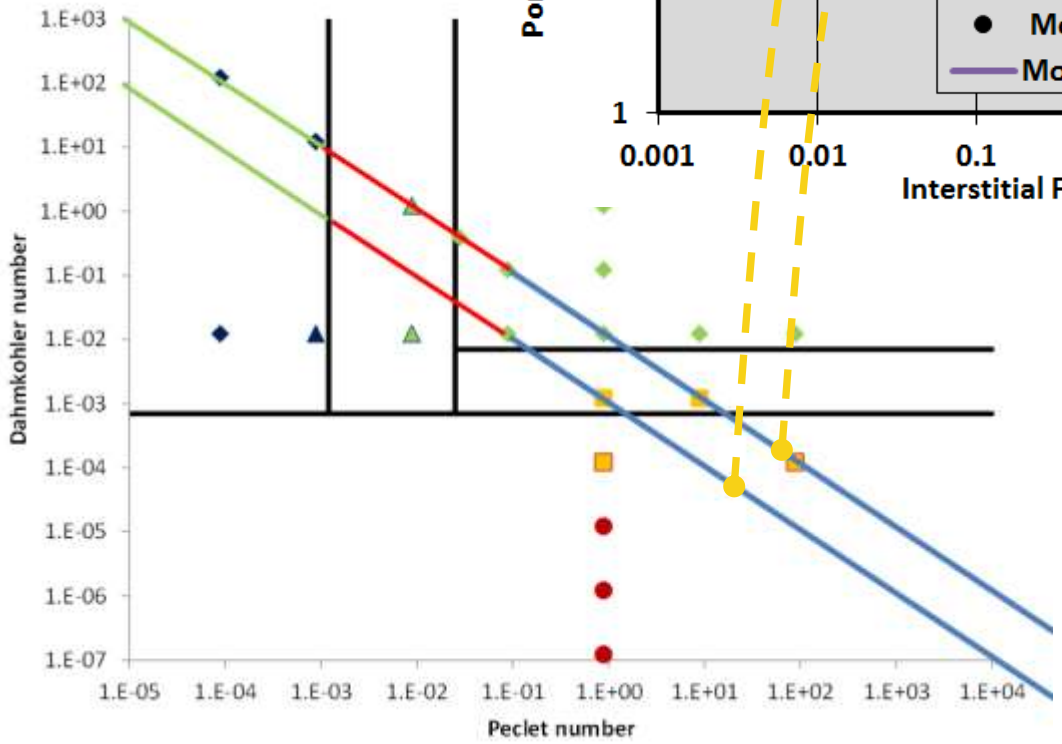
REMARK ON REACTION KINETICS VS GWM PARAMETERS