Modeling Foam Generation in Porous Media

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Delft University of Technology

Foam Generation

Role of Pressure gradient

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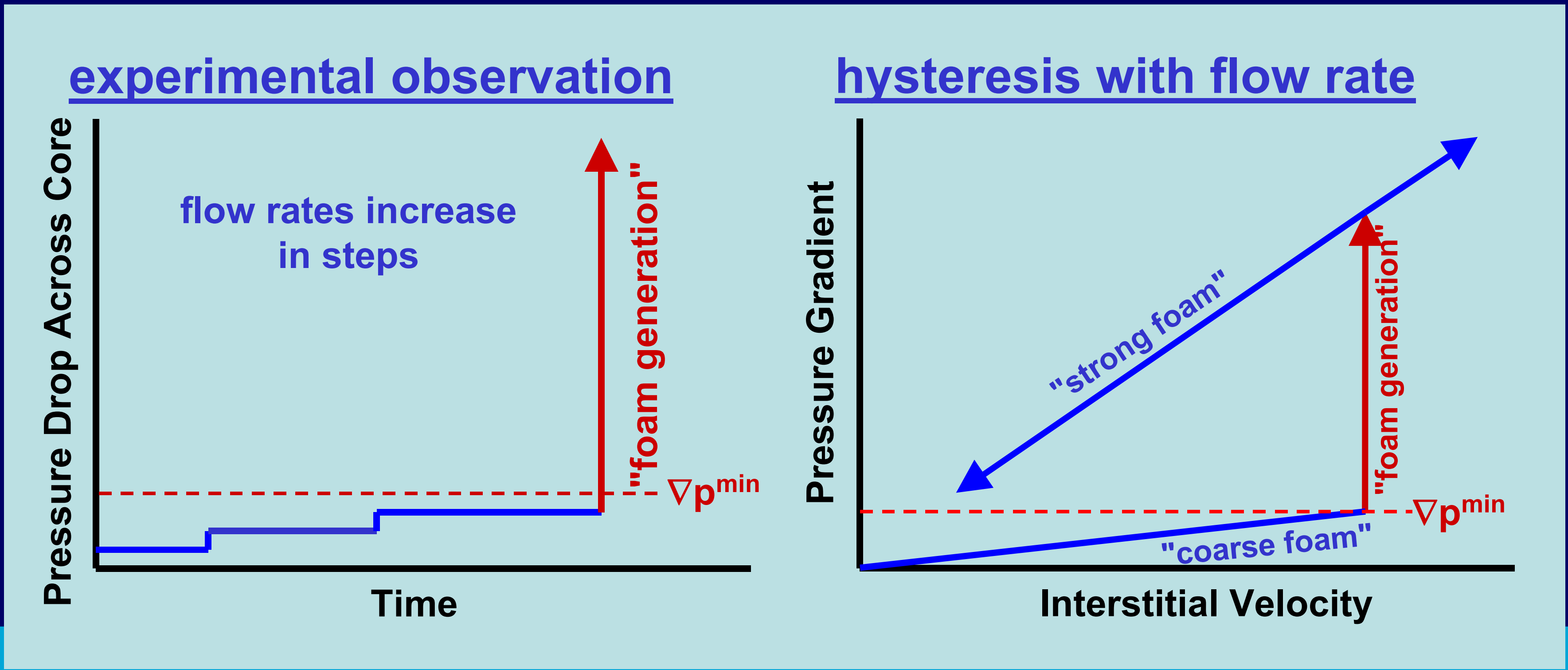
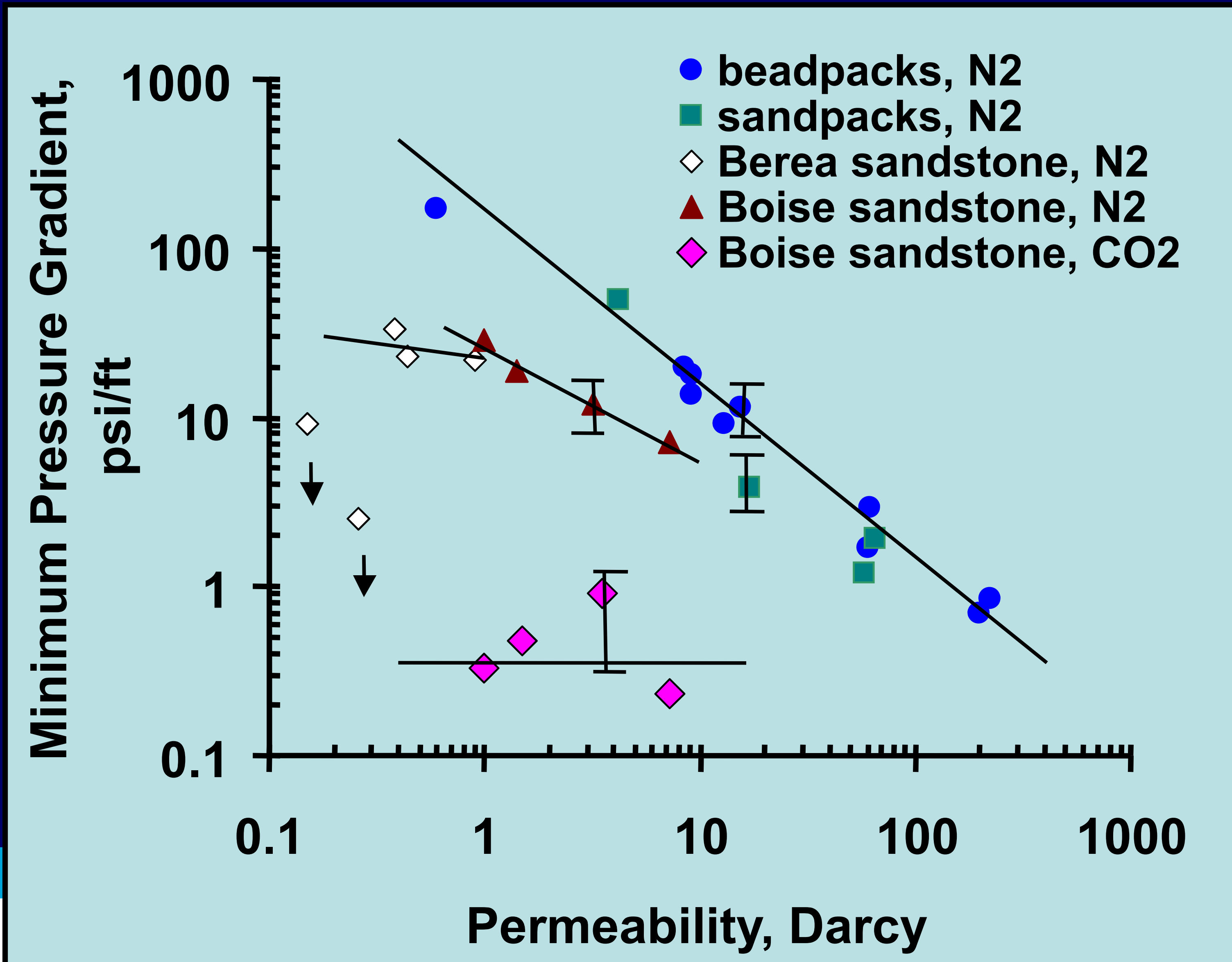
Foam Generation in Porous Media

- Experiments find minimum ∇p for foam generation in steady gas-liquid flow



∇P^{min} vs. Permeability



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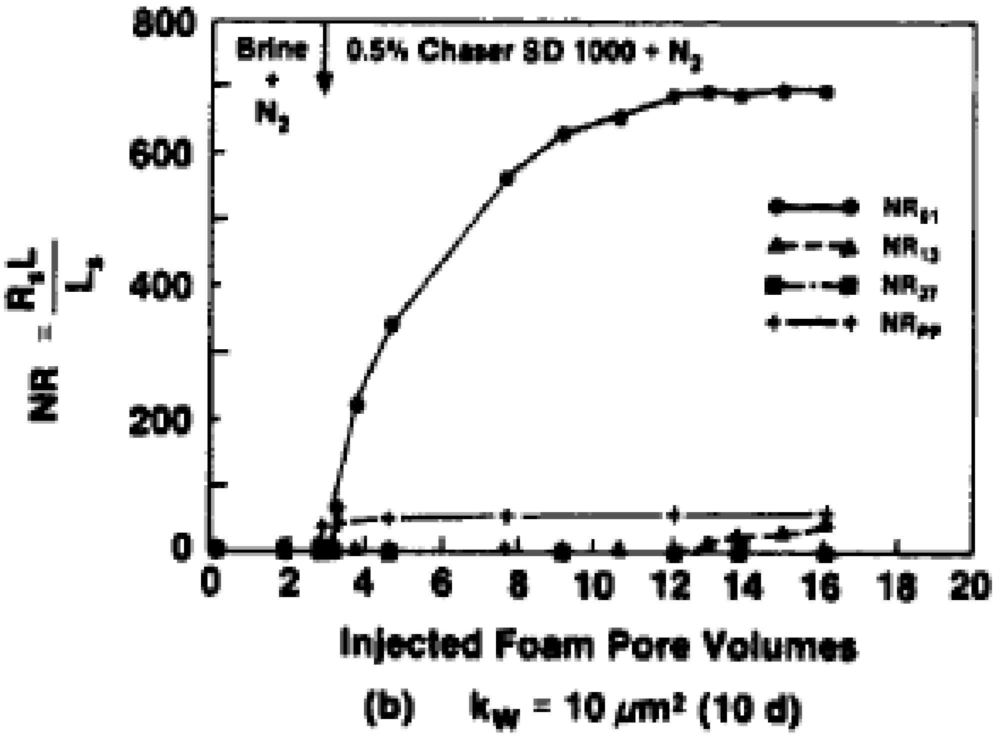
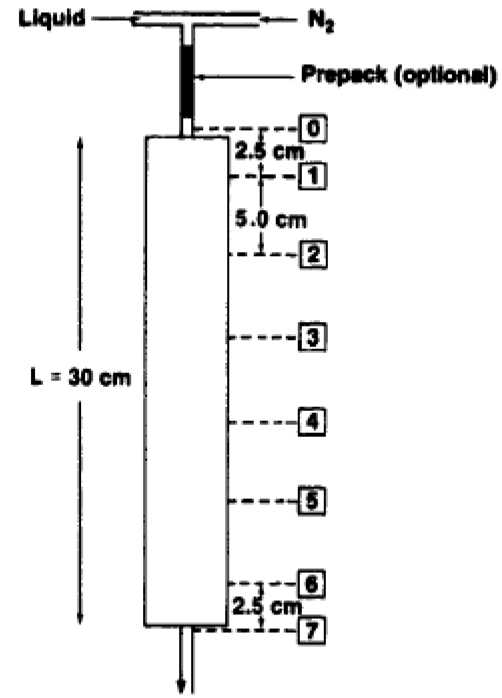
Experiment 1: Friedmann and Jensen (1986)





- Pregenerated foam propagated much more slowly than the surfactant front (k=10 D sandpack) initially filled with gas and water at the injected fractional flow (f_{wJ}=0.1)

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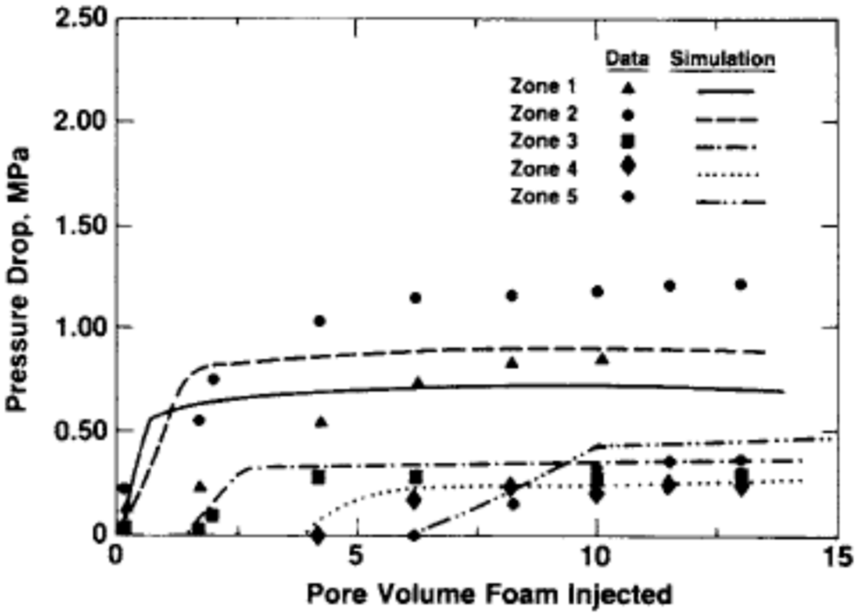
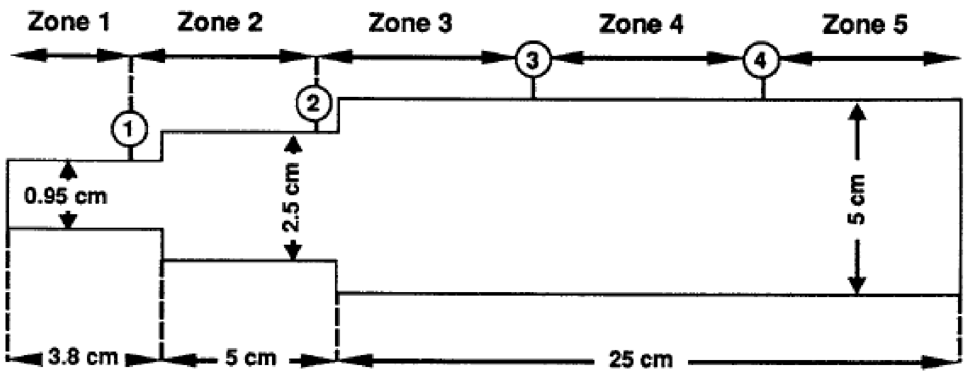
Experiment 2: Friedmann et al. (1991)

- foam created at high velocity could propagate at 20 to 30 times lower superficial velocity than that at which it could be created; foam propagated slowly, behind the surfactant front, which suggests some difficulty in propagation in sandstone core.





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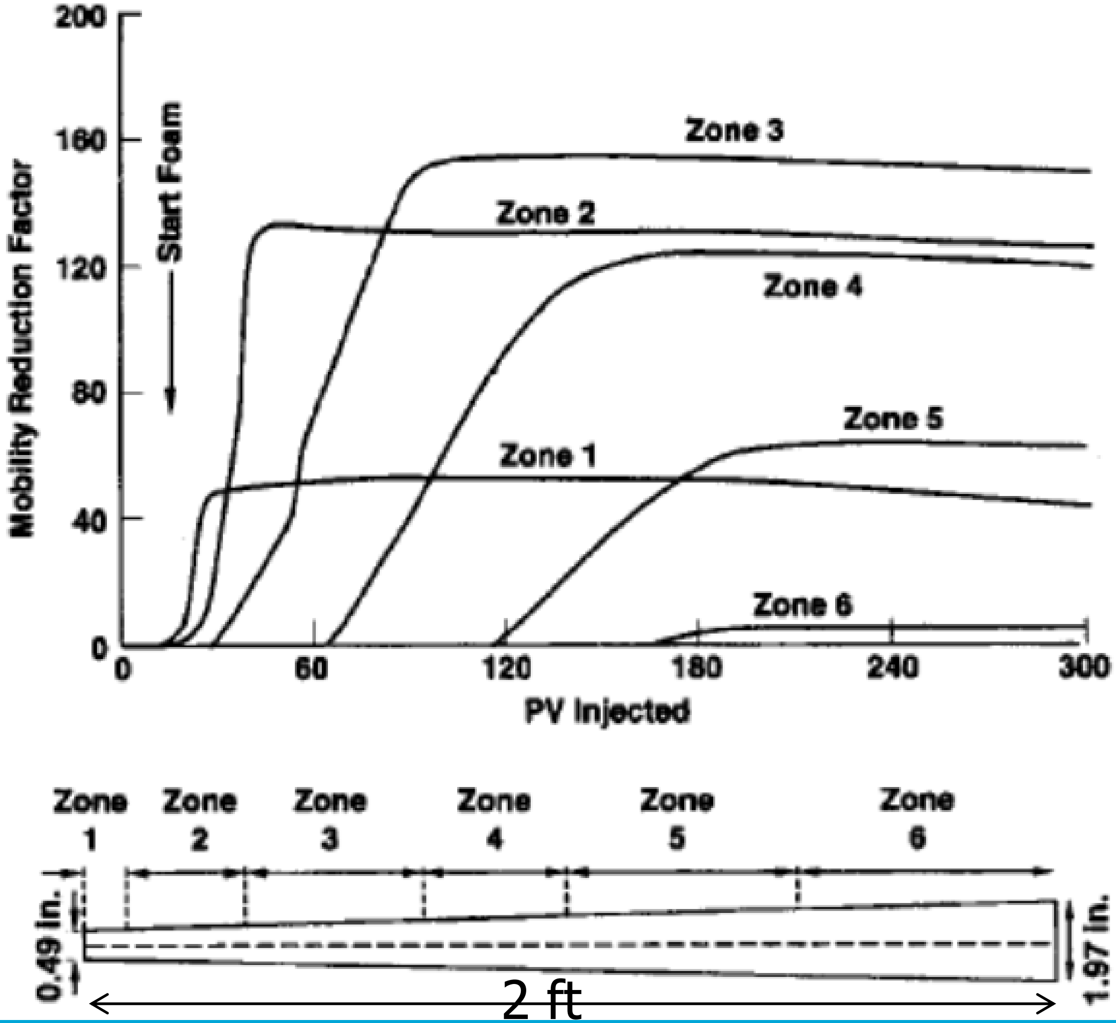
Experiment 3: Friedmann et al. (1994)

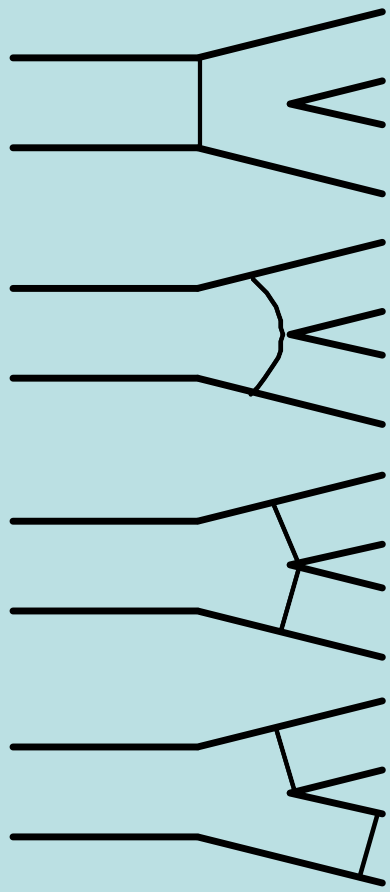
- foam did not propagate through a cone-shaped sandpack, where superficial velocity decreases with distance from the injection face.



Foam Generation in Porous Media

- Experiments find minimum ∇p for foam generation in steady gas-liquid flow:
  - *Why?*
- "Lamella division" is crucial step in foam generation

LAMELLA DIVISION



Foam Generation in Porous Media

- Experiments find minimum ∇p for foam generation in steady gas-liquid flow:
  - *Why?*
- "Lamella division" is crucial step in foam generation
  - requires moving lamellae
  - requires Δp across throat > $(2\sigma/R_t)$
- What is minimum ∇p to mobilize lamellae in pore network?

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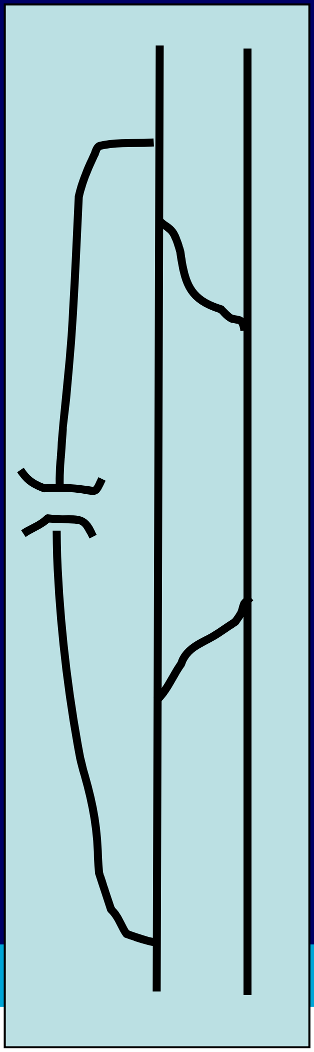
Model for Foam Generation

- Initial state is flowing gas
- Assume fraction (1-f) of pore throats are blocked by liquid lenses
- Assume lamellae are distributed randomly on pore network
- Can relate f to injected liquid fraction using percolation theory
- Can relate length L_c of pore clusters blocked by lamellae to f through percolation theory
- $\nabla p^{min} = \Delta p / L_c \sim [\sigma / (R_t \, L_p \, F_c)]$



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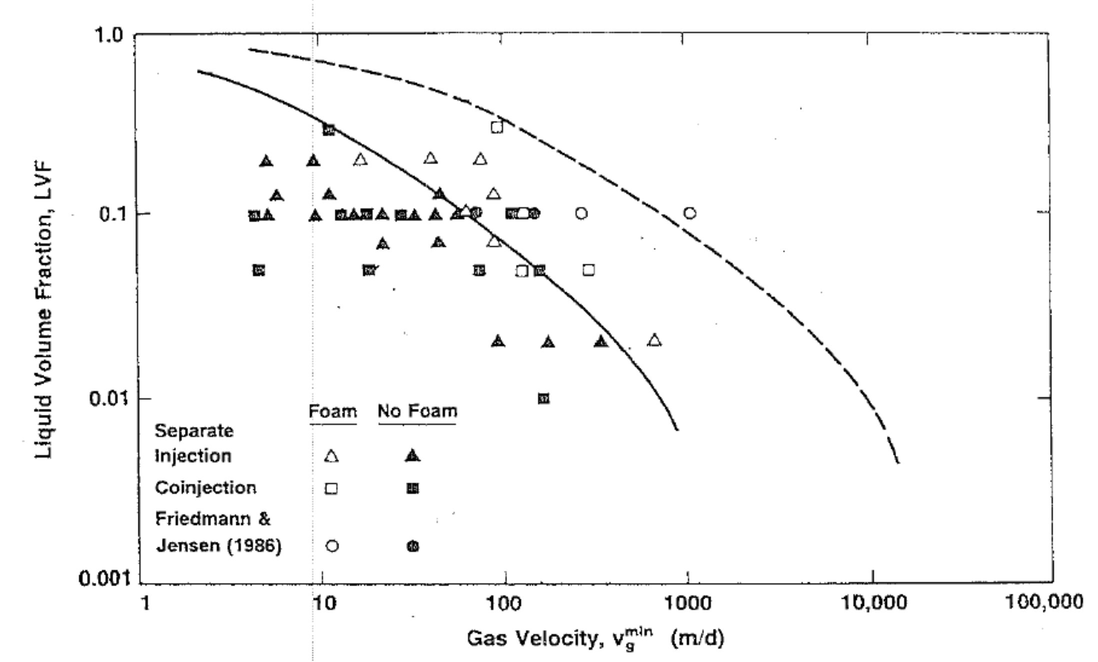
Results of Model

- Foam generation occurs at high injection velocity, high liquid volume fraction
- Model fits data for foam generation as function of velocity, liquid volume fraction
- Predicts ∇p_{min} ~ 1/k, in agreement with N_2 data in sandpacks
- Predicts ∇p_{min} lower for hi-p CO_2 because of low σ



Rossen and Gauglitz, *AIChE J*. 36, 1176 (1990)

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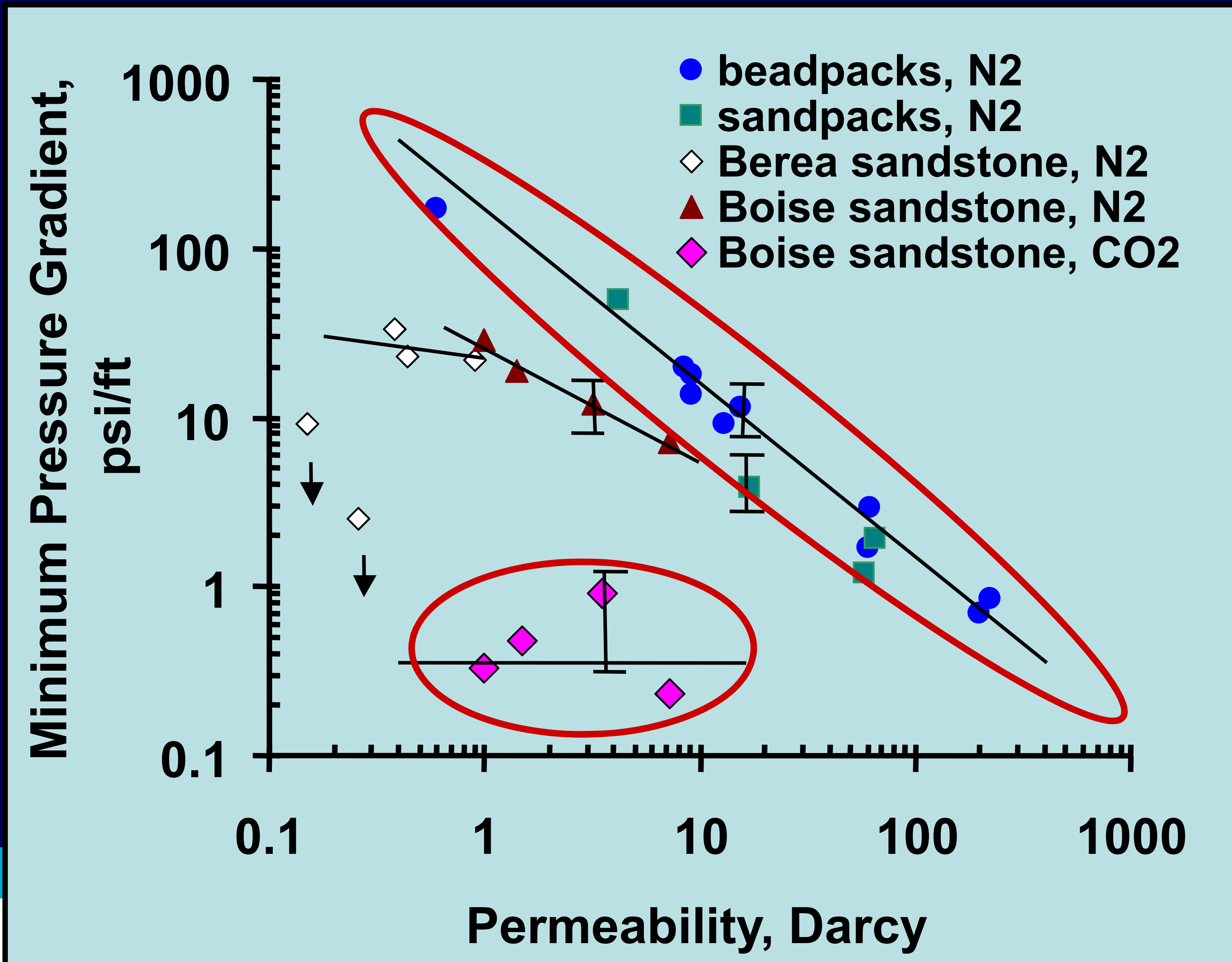
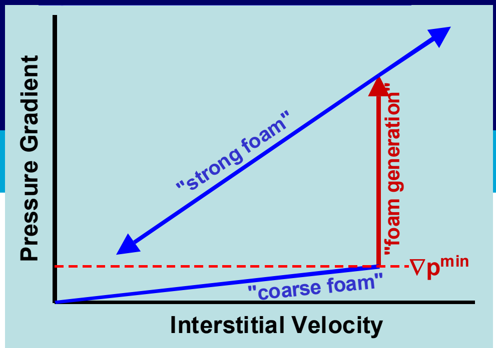
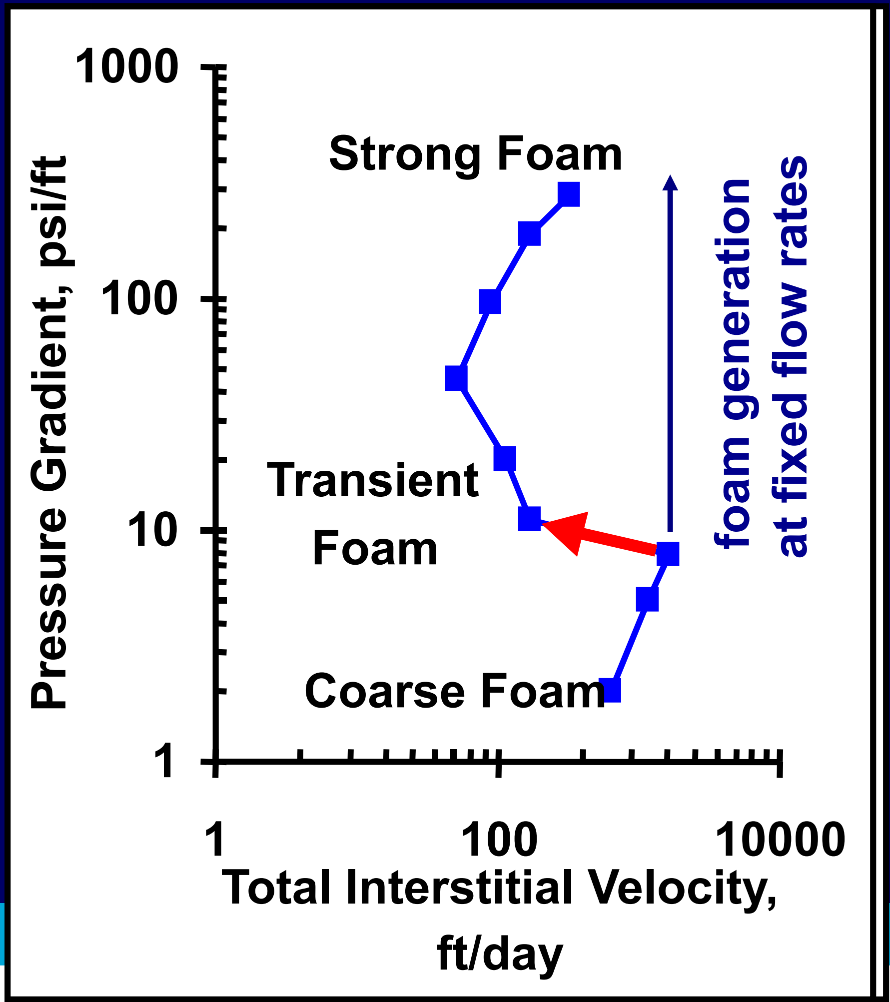
∇P^{min} vs. Permeability



Fixed-Δp Experiments

- Experiments at fixed pressure gradient (SPE 75177) show continuous path from coarse-foam to strong-foam regime
- "Foam generation" at fixed flow rates = jump from coarse-foam to strong-foam regime





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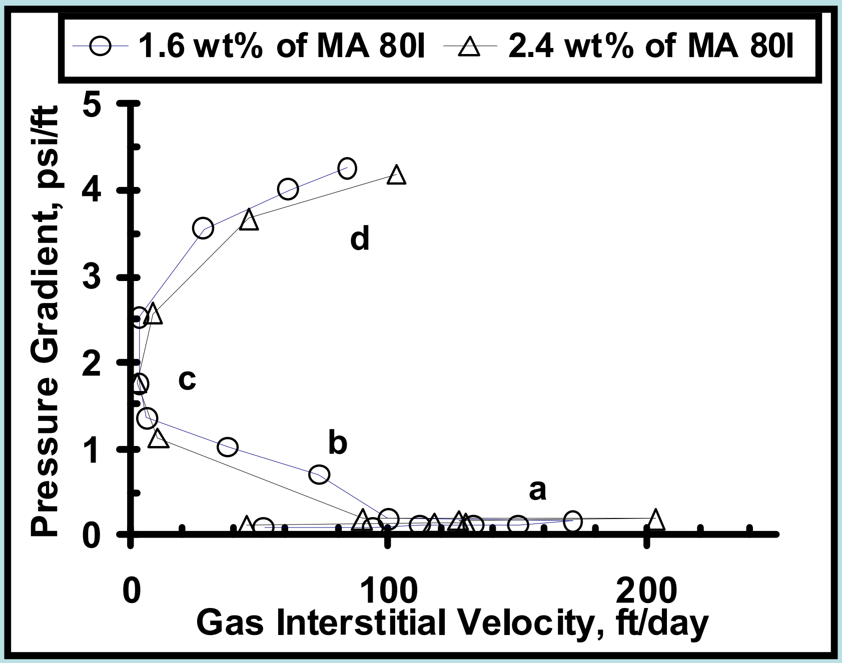
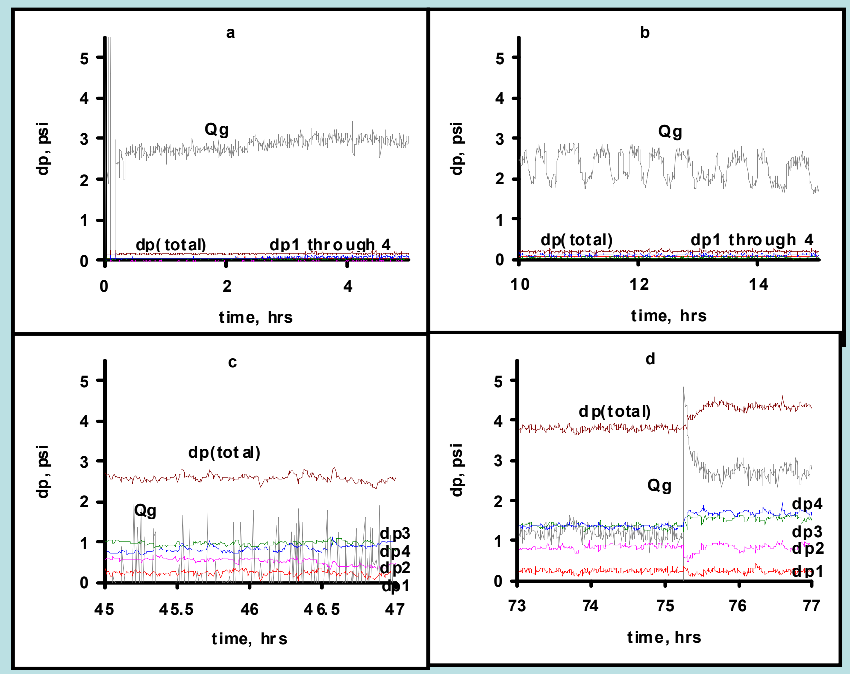
Results: Fixed Liquid Rate, ΔP

Typical Result



Dynamic Behavior



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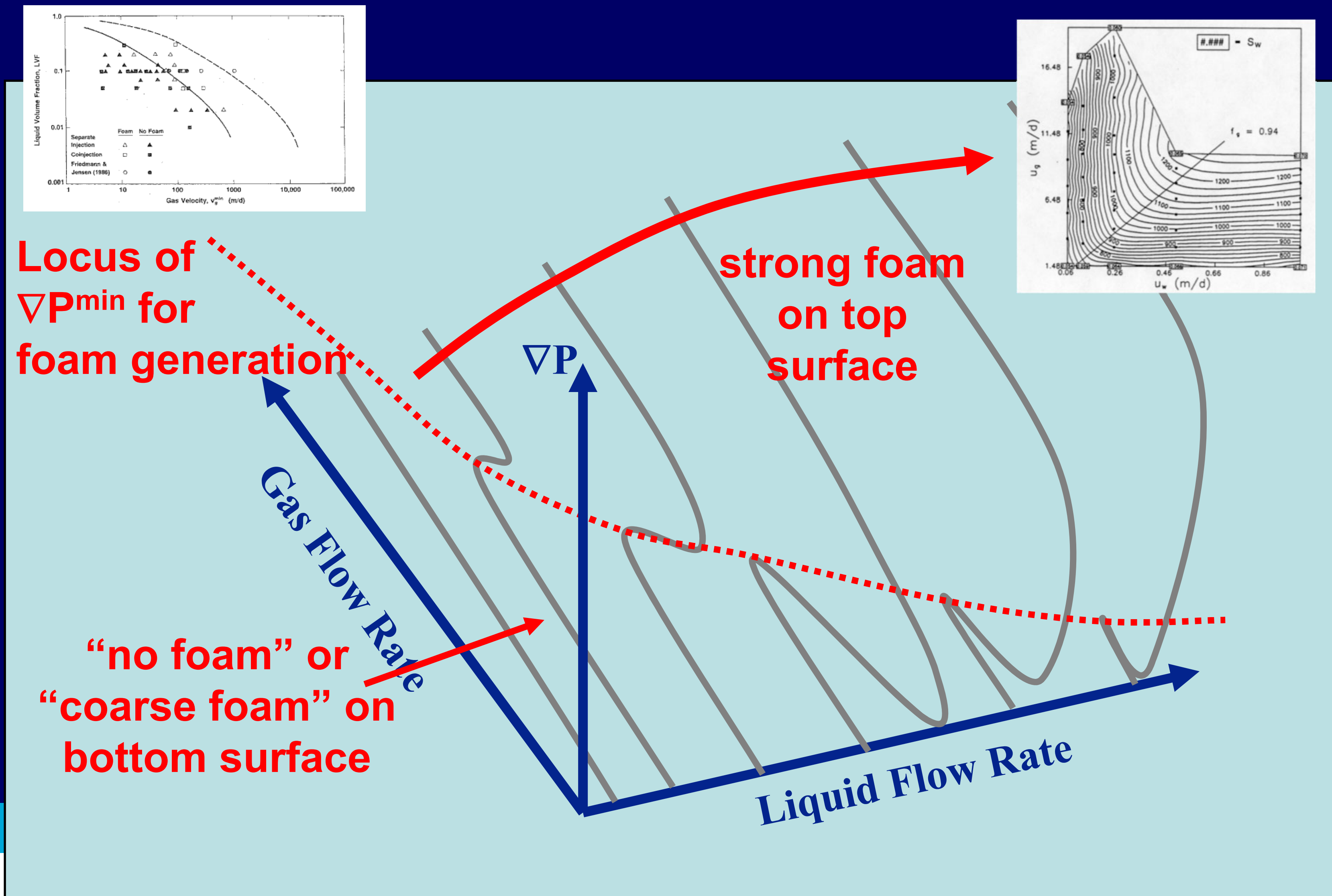
Implications (cont'd)



Foam generation is easier . . .

- when gas + liquid injection follows surfactant injection
  - leave-behind, snap-off during drainage
- with CO_2 (lower σ → easier mobilization)
  - but lower σ is not the whole story . . .
- near injection well, where ∇p is high
  - can foam generated near well propagate outwards at lower ∇p?
- in flow across heterogeneities,
  - snap-off → foam w/ no large ∇p necessary; but displacement still requires ∇p
  - inhibits upward migration of gas
  - explanation for success of foam aquifer remediation?

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"Population Balance" Modeling of Foam:

Steady-State Behavior

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“All models are false, but some models are useful.”

- George E P Box

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Model Equations

lamella creation $$r_g = C_g S_w (\nabla P)^m$$

lamella coalescence $$r_c = C_c n_f \left(S_w - S_w^*\right)^{-n}$$

foam viscosity $$\mu_g^f = \mu_g^o + C_f n_f u_g^{-1/3}$$

s.s. foam texture
($n_f \equiv$ lamellae/vol) $$n_f = \frac{C_g}{C_c} S_w (\nabla P)^m \left(S_w - S_w^*\right)^{-n}$$

plus: pore size sets minimum bubble size, max n_f

- **Four independent s.s. parameters (C_g/C_c, C_f, m, n); one dynamic parameter (magnitude of C_g or C_c)**

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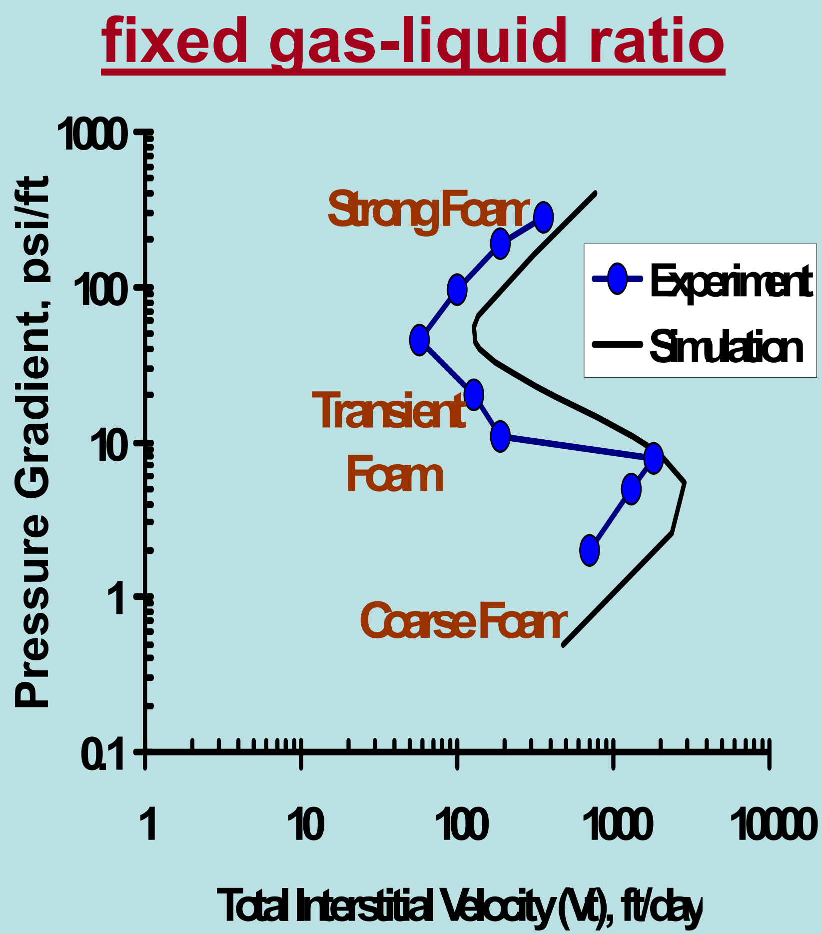
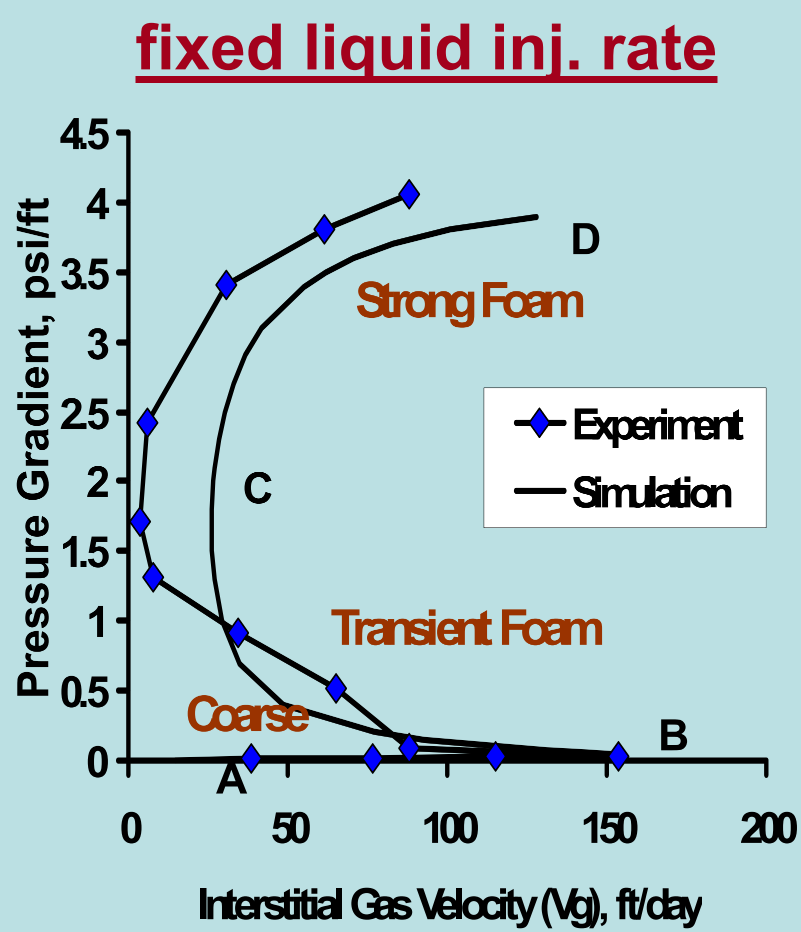
Model Fit to Data





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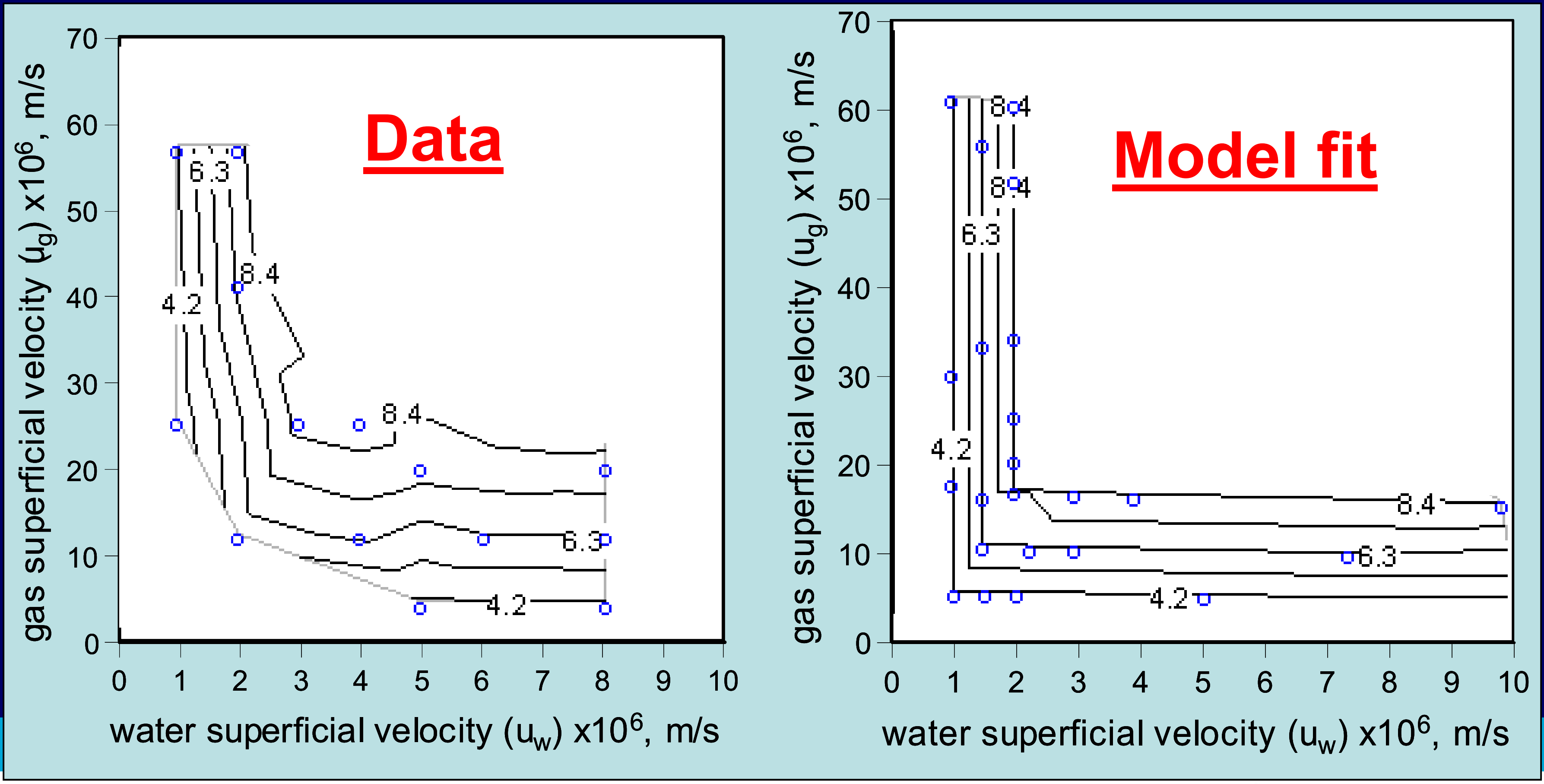
Model Fit to Experiments

- **Steady-state strong-foam regimes**



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Conclusions: Steady-State Modeling

Model fits three foam states:

- coarse-foam at low ∇p
- strong-foam at high ∇p
- transient regime where velocity ↓ as ∇p↑

Model reproduces "high-quality" and "low-quality" steady-state regimes in strong-foam state

Model fits foam-generation data qualitatively

- gas velocity for foam generation decreases as f_w increases, in agreement with data and theory
- gas velocity and ∇p for foam generation decrease for formulations giving stronger steady-state foam

Model is not predictive; does not include all mechanisms

Role of Foam Dynamics in Field-Scale Displacements

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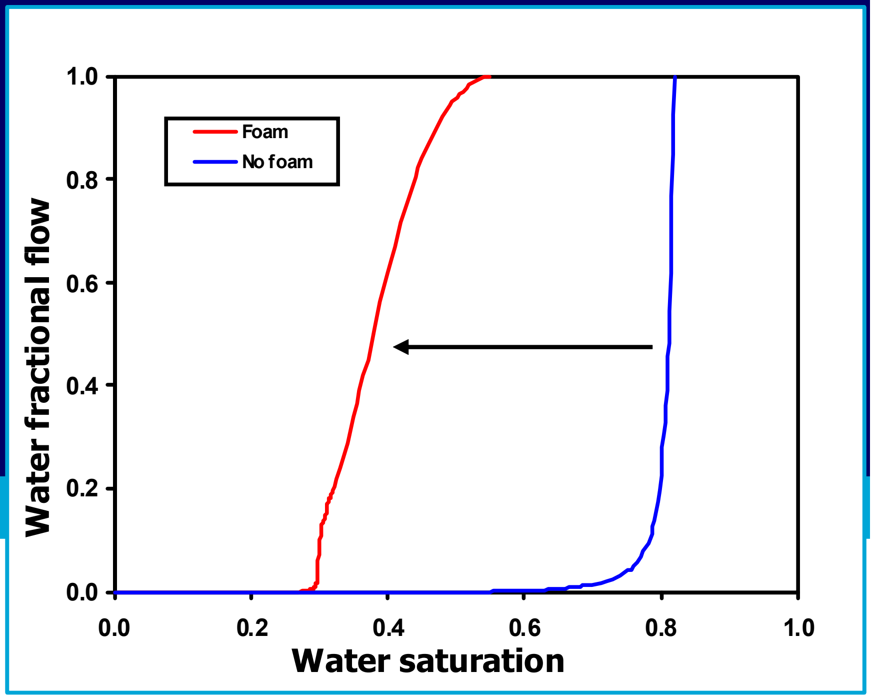
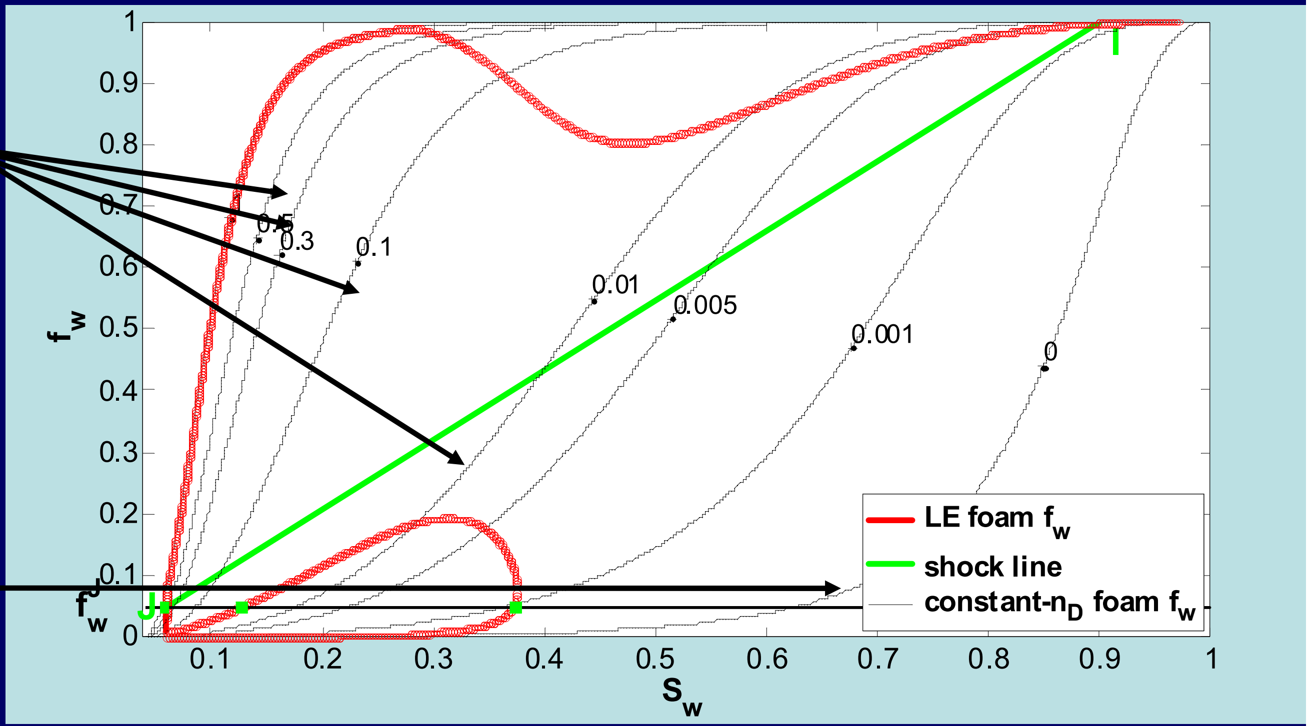
Method of Characteristics

- Consensus: local equilibrium applies to foam displacements on field scale and even lab scale
- If local equilibrium applies, and make additional simplifying assumptions, can describe displacement with Method of Characteristics (fractional flow theory)
- Describes waves and shocks in displacement based on fractional-flow diagram
- Many simplifying assumptions, but useful for insights into complex displacements



Fractional-Flow Diagram for Foam with Multiple Steady States is Complex

- Fractional flow at fixed foam texture n_f (i.e. fixed bubble size)
- no foam



Ashoori et al., *SPE Journal* **17**, 1231-45 (2012)

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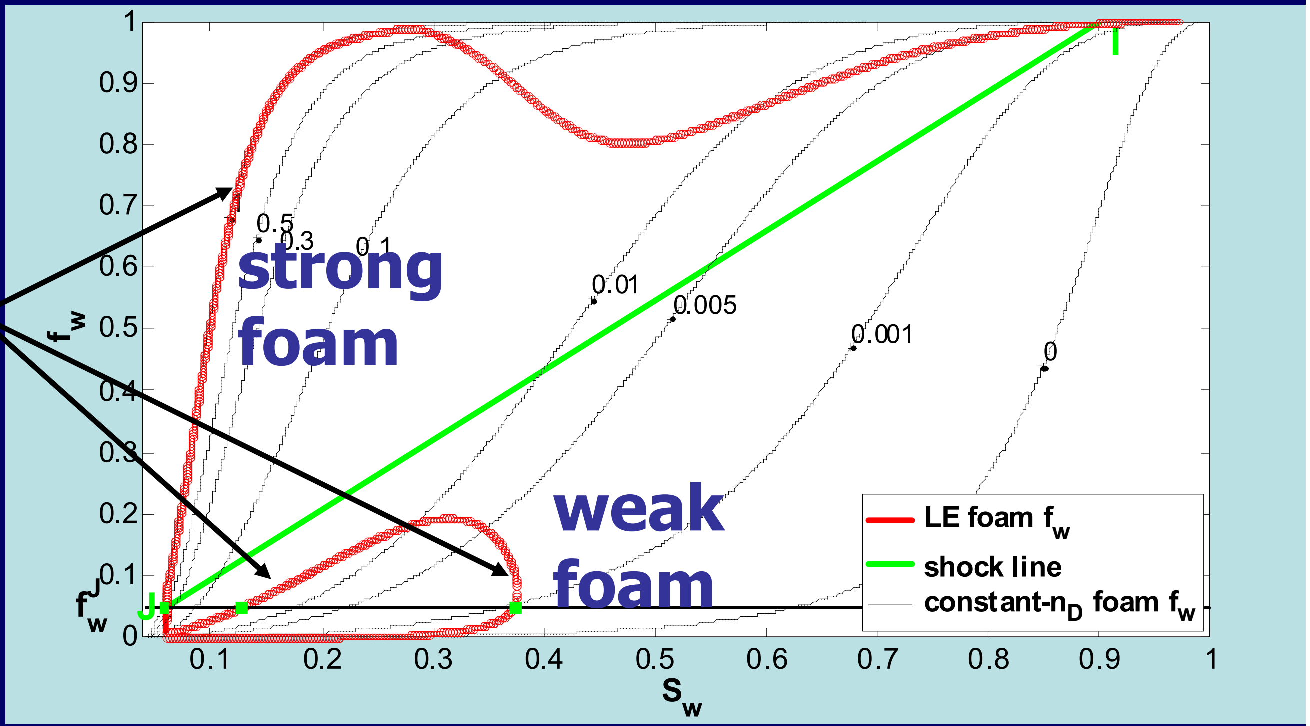
Fractional-Flow Diagram for Foam with Multiple Steady States is Complex

- Fractional flow at fixed foam texture
- Fractional flow for steady-state foam states



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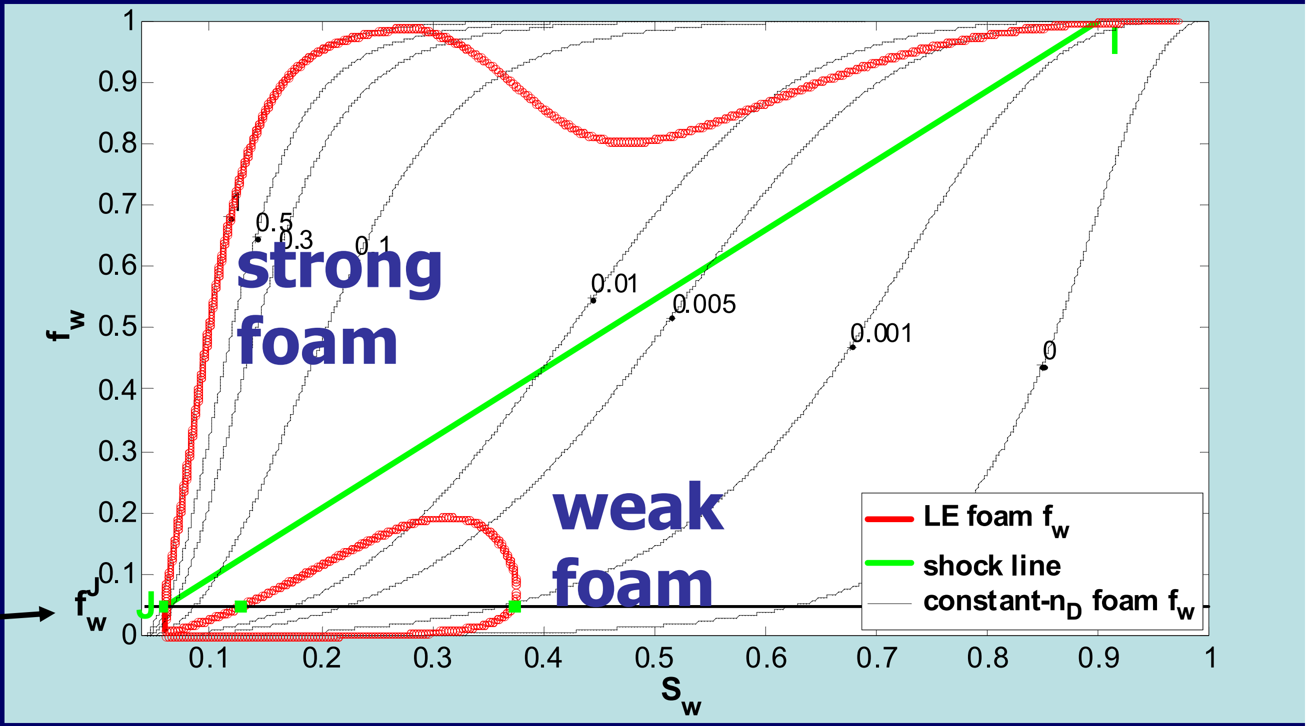
Fractional-Flow Diagram for Foam with Multiple Steady States is Complex

Initial Condition

- Fractional flow at fixed foam texture
- Fractional flow for steady-state foam
- Injected fractional flow



Which state will appear in field?

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Which steady state appears in field?

Assume local equilibrium applies everywhere except

- in entrance region where foam is created from injected fluids
  - solve ODEs for steady state in entrance region*
- in shock fronts, where saturations and bubble size change abruptly
  - solve ODEs for traveling wave at shock front*

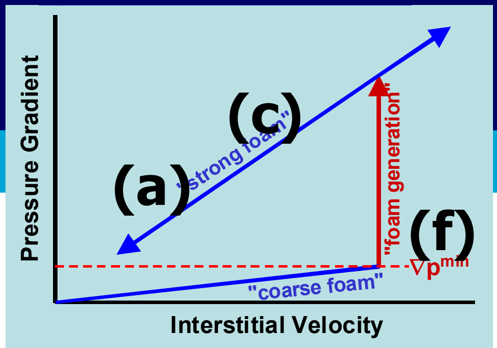
In addition, local-equilibrium state must be stable to small perturbations

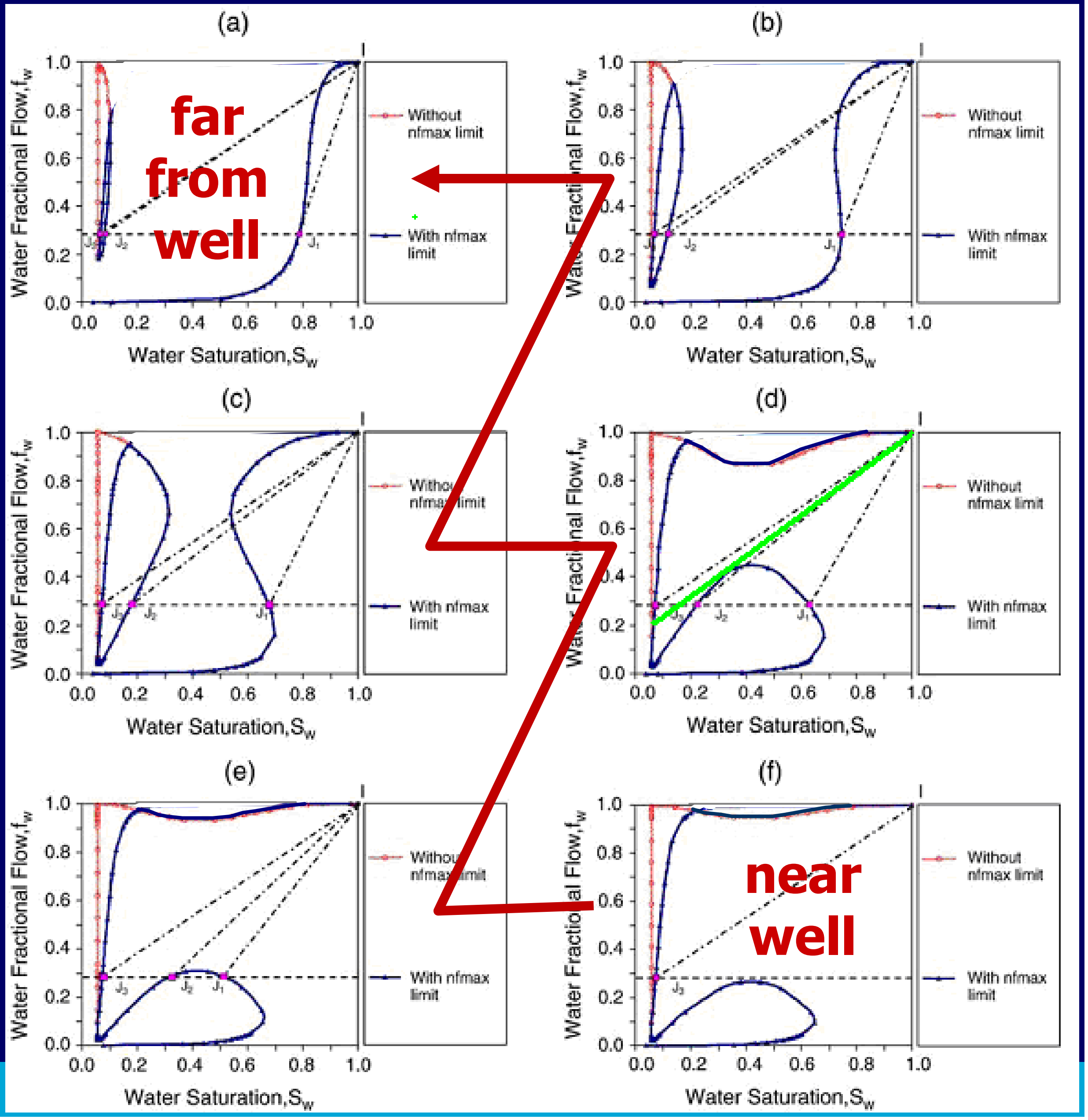
- solve ODEs for sinusoidal perturbation in S_w, bubble size*

** with by D. Marchesin, IMPA*

Can foam created at large ∇p near well propagate at lower ∇p far away?

- Does strong foam state disappear at (a) or (c)?





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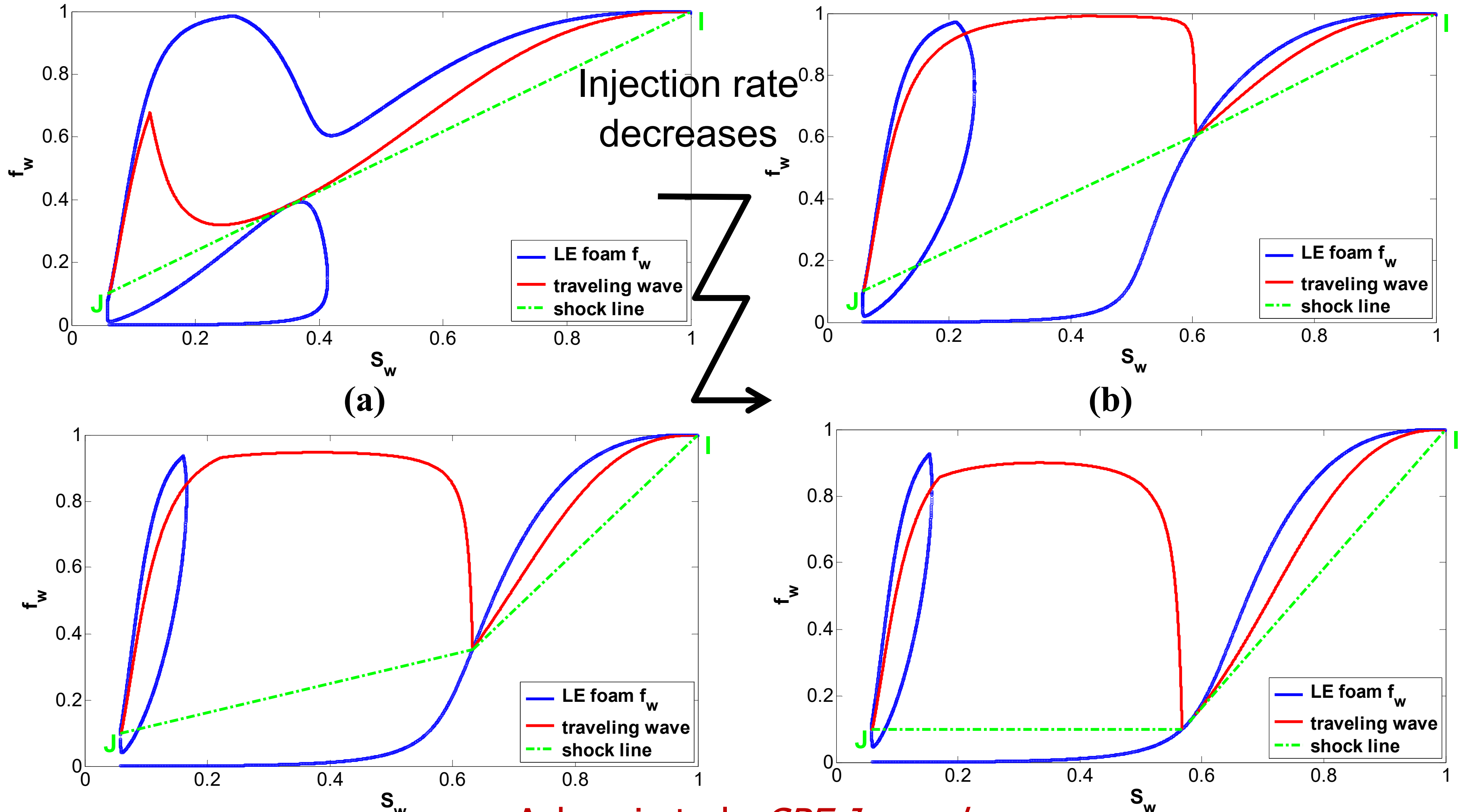
Riemann solutions (red curves)

total superficial velocity u: (a) $u=4.5\times10^{-5}$ m/s, (b) $u=2.798\times10^{-5}$ m/s, (c) $u=1.5\times10^{-5}$ m/s, (d) $=1.351\times10^{-5}$ m/s for $f_{wJ}=0.1$



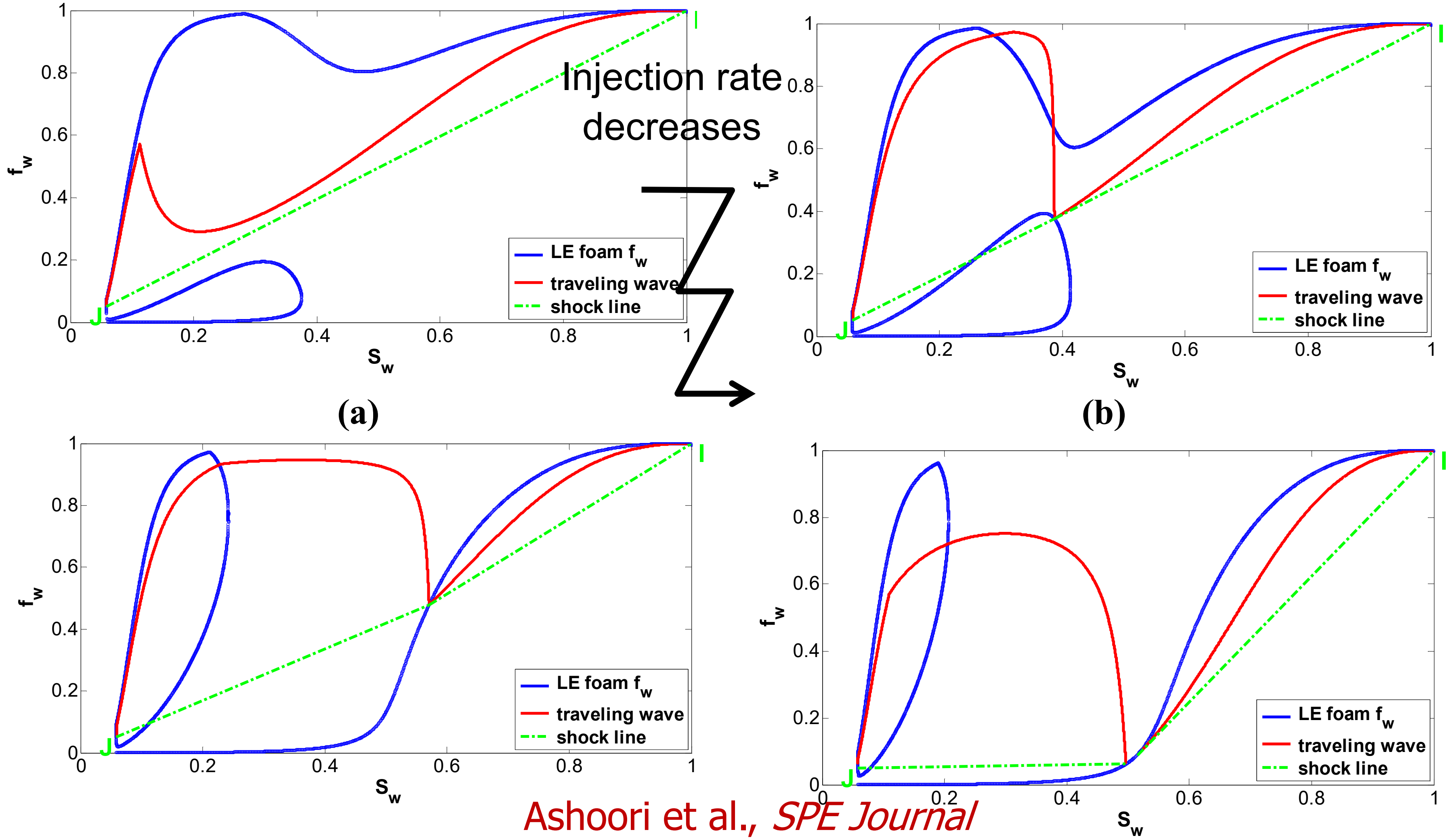
(c)

(d)

Ashoori et al., *SPE Journal* **17**, 1231-45 (2012)

Riemann solutions (red curves)

total superficial velocity u: (a) u=5.29×10^{-5} m/s, (b) u=4.5×10^{-5} m/s, (c) u=2.798×10^{-5} m/s, (d) =2.19×10^{-5} m/s for f_{wJ} =0.05



(a) (b) (c) (d)

Ashoori et al., *SPE Journal* **17**, 1231-45 (2012)

Conclusions:

- In cases we examined, behavior is close to LE within the traveling wave, except for very slow kinetics.
- At low superficial velocities strong foam cannot directly displace the high-water-saturation bank initially in the reservoir; it pushes a weak-foam state with lower velocity that in turn displaces the bank ahead. Strong foam propagates more slowly than the gas front, as seen by Friedmann.
- Strong foam injected at the well can propagate at superficial velocities lower than those at which it can be created, but not for superficial velocities as low as those at which it can in principle still exist. This could possibly explain Friedmann's lab observations that foam propagation stops at some velocity.

Discussion:

- Model parameters are based on **N_2 foam** experiments in a **homogenous**, high-permeability sandpack. It is important to **test the implications** of this model for other foams in other porous media.

- The **foam model does not explicitly represent foam trapping** which might have some effect on results.

- **Our results do not preclude succeeding of other injection strategies**: a weak-foam preflush might change the initial state ahead of the preceding foam-propagation front so that strong-foam can directly displace weak foam. Or weak foam resulting from failed propagation of strong-foam could play as a role as a favorable downstream state for subsequent strong-foam injection.

→ *Future work*

Questions?

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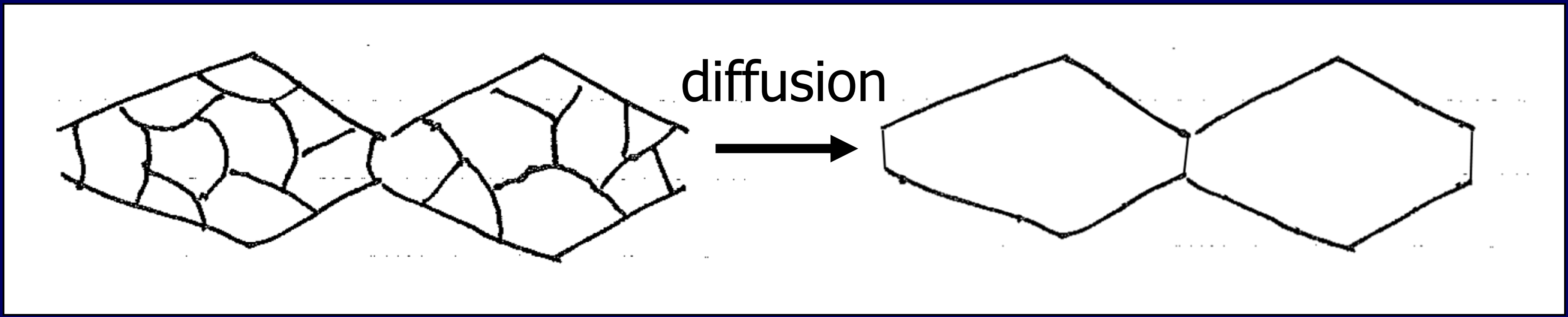
Why a minimum bubble size?

- Lamella creation by lamella division, snap off more difficult for small bubbles
- Diffusion rapidly eliminates bubbles smaller than pores
- Major changes to creation, destruction mechanisms for small bubbles, keeping bubbles ~ pore size
  - easier simply to postulate minimum size



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