The Use of Micromodels to Visualize Foam Transport Processes in Porous Media

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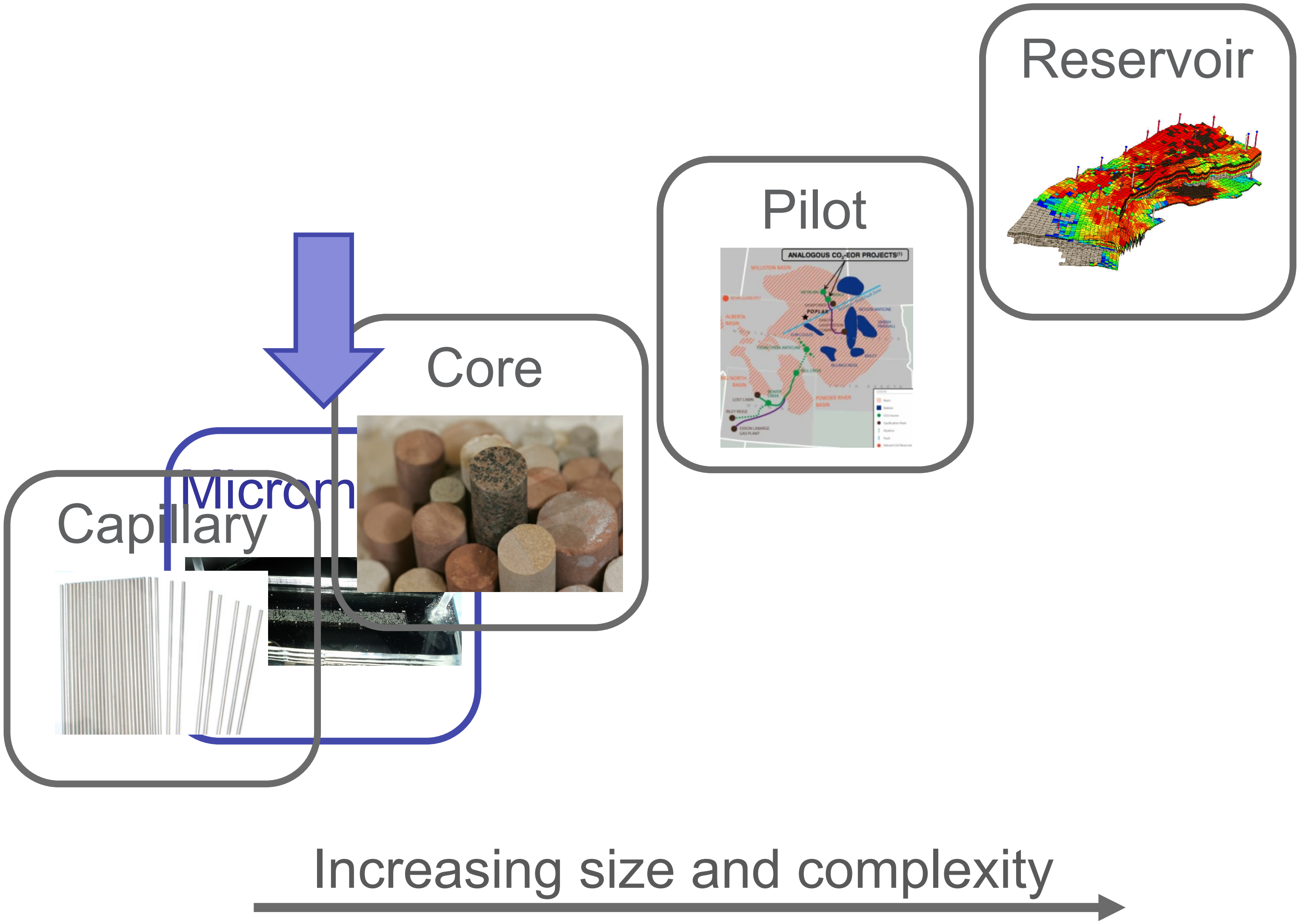
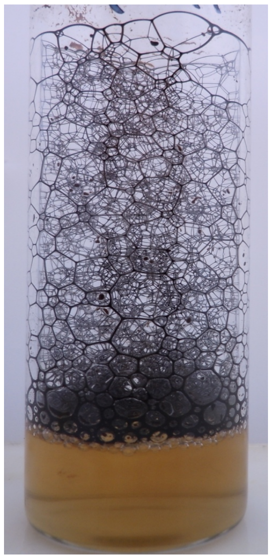
Microfluidics for EOR

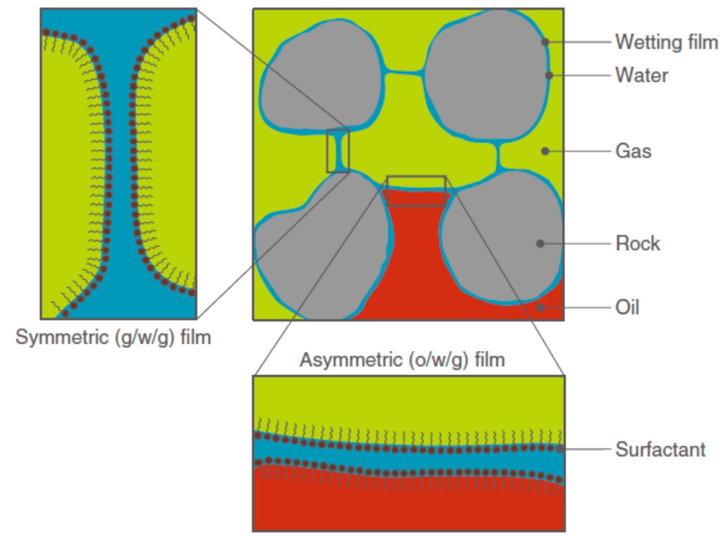


Foam EOR

Foam reduces the apparent **viscosity** of the injected fluid by



→ providing resistance to flow
→ diverting injected fluids
→ contacting more trapped oil



Guiding Questions:

*How can we **visualize** foam in porous media?*

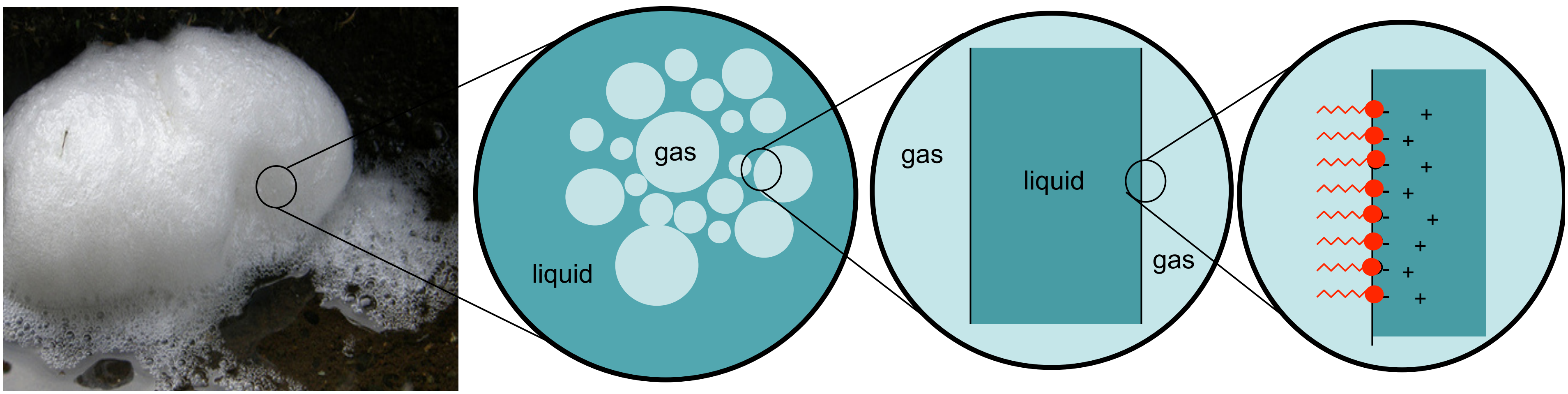
*How does foam behave in **heterogeneities** (e.g. fractures)?*

*How does foam **quality** and **texture** change in-situ?*

Farajzadeh, R., A. Andrianov, R. Krastev, G.J. Hirasaki, and W.R. Rossen 2012 Foam–oil Interaction in Porous Media: Implications for Foam Assisted Enhanced Oil Recovery. Advances in Colloid and Interface Science 183–184(0): 1–13.

Length Scales in Foam

Foam is defined as a dispersion of gas bubbles in liquid such that the liquid phase is continuous and at least some part of the gas phase is made discontinuous by thin liquid films called lamellae.



Aqueous Foam
macroscopic

Dispersion of gas in a liquid
microscopic
10μm – 1cm

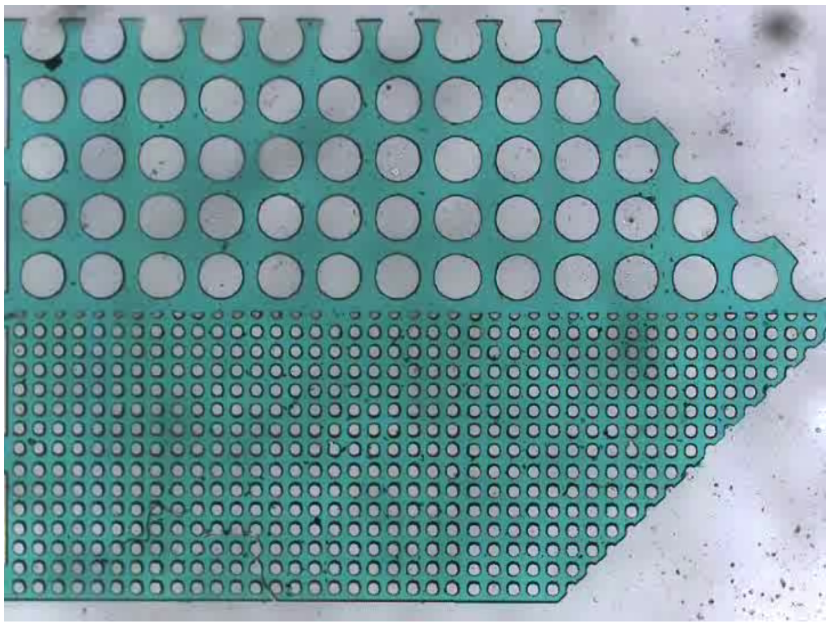
Liquid lamella
~100 nm

$$P_{film} = P_{gas} + \Pi(l)$$

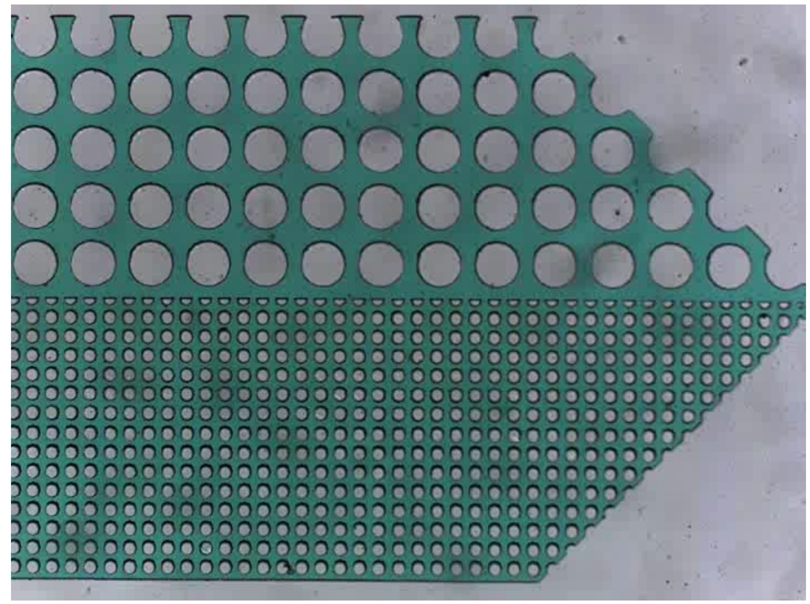
Interface
~1 nm

RICE Foam Transport in Micromodels

Gas (air)



Foam



- *gas* only displaces high-perm, bypass of low-perm

- *foam* displaces both high-perm and low-perm regions

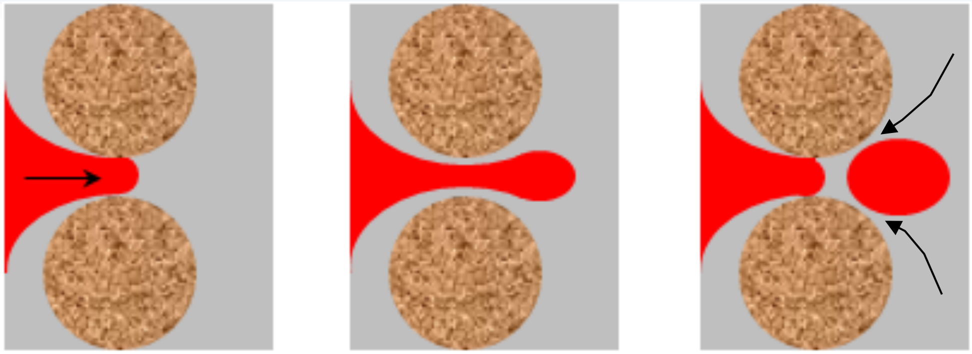
trapped bubbles

lamellae resistance

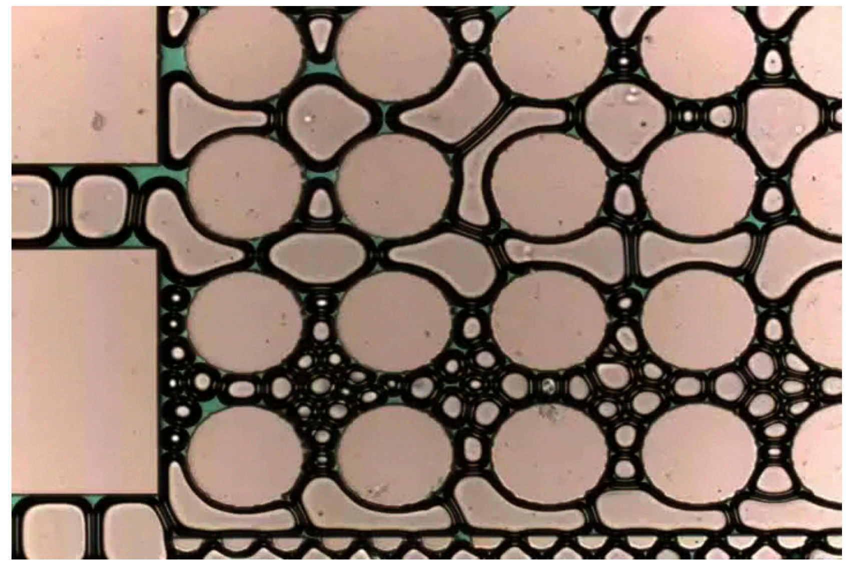
Mobility Ratio: $$M = \frac{k_{r,Displacing} / \mu_{Displacing}}{k_{r,displaced} / \mu_{displaced}}$$

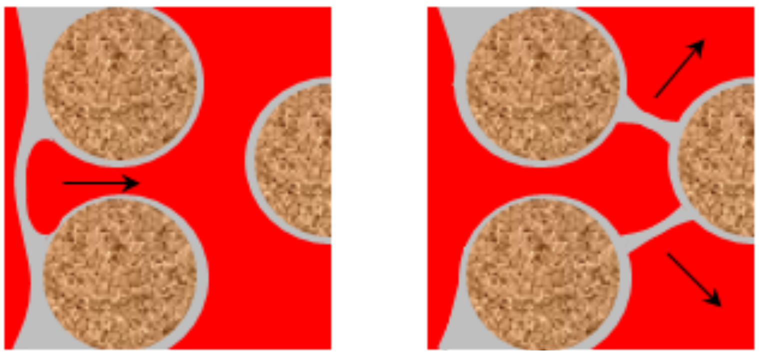
Effective displacement: **M < 1**

Classic Mechanisms for Foam Generation

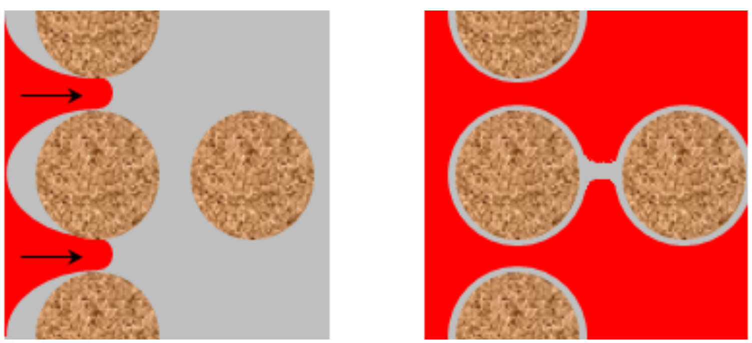


Snap -off





Lamella Division

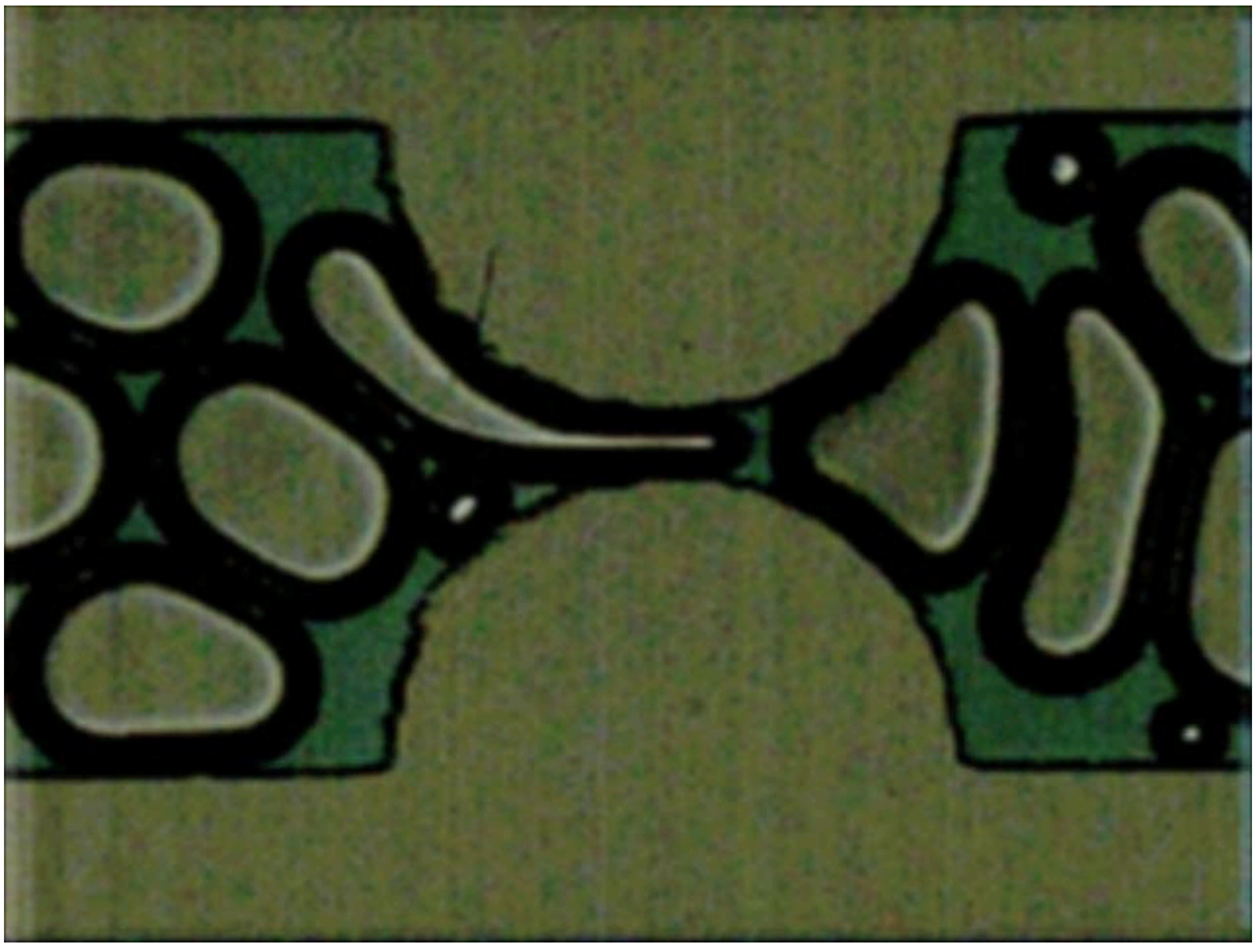


Leave-behind

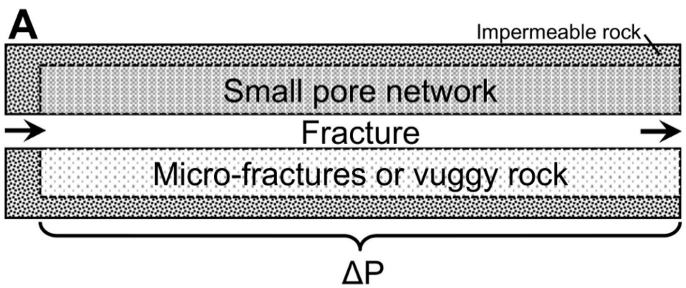
Ref: Hiraskai, Kovscek and Radke

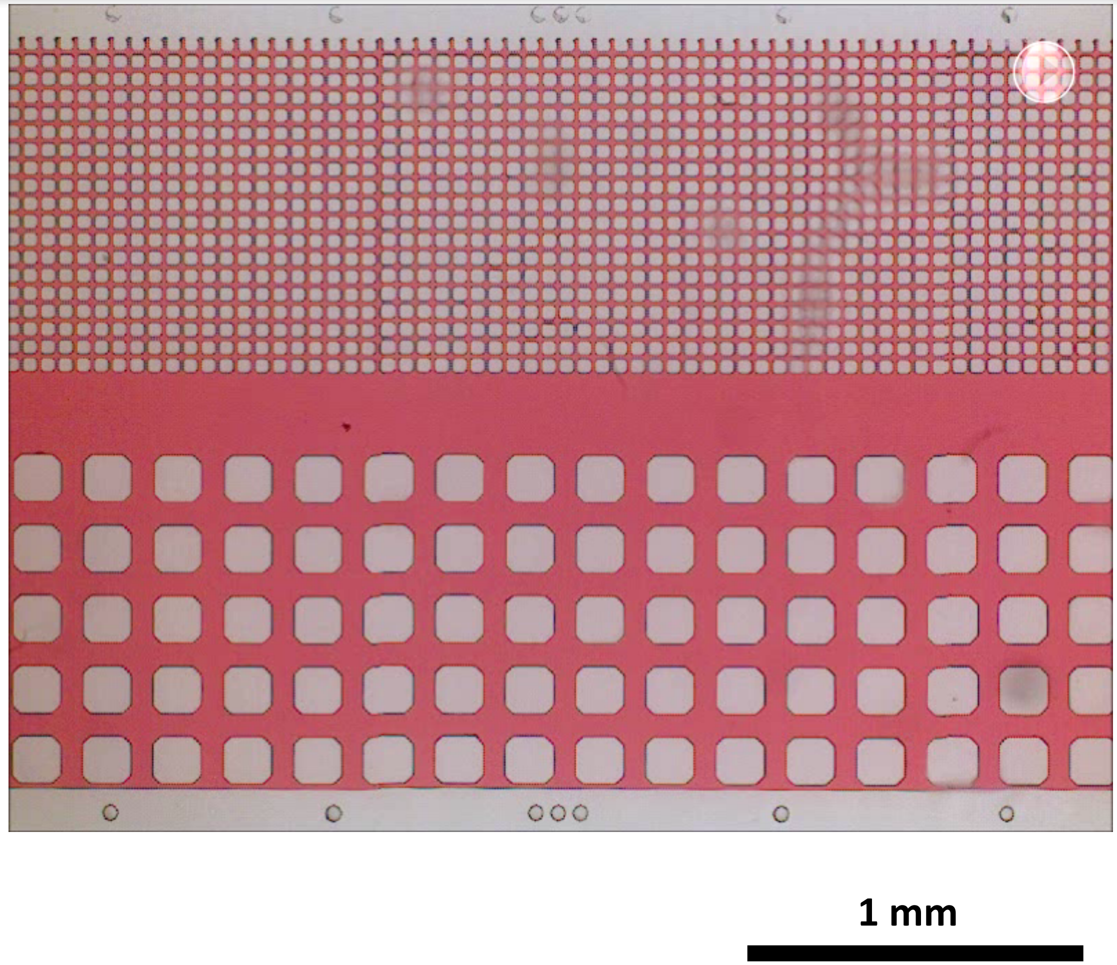
Pinch-Off

When multiple bubbles enter a constriction, foam lamella is generated via a pinch-off mechanism



Foam Flood with Oil



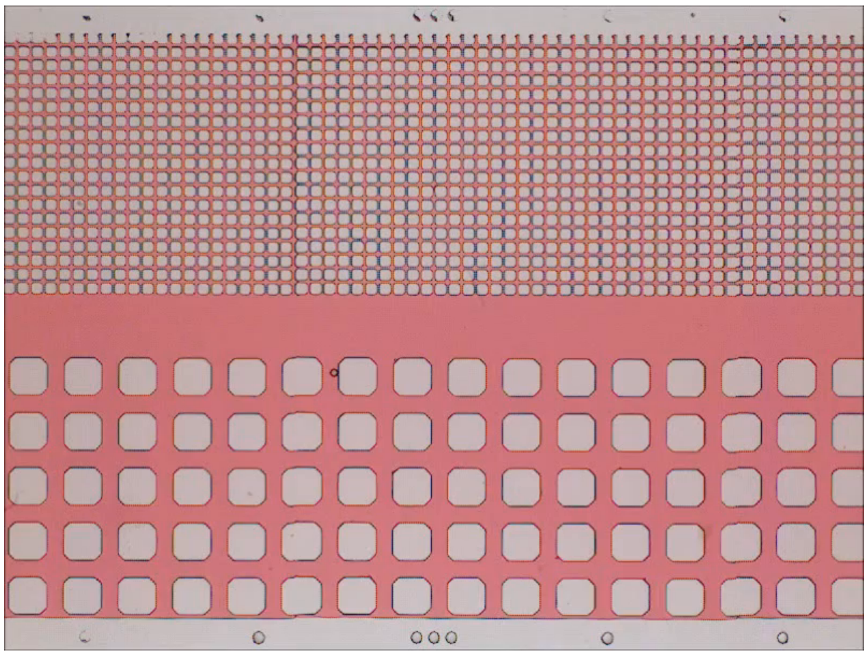


Mechanisms

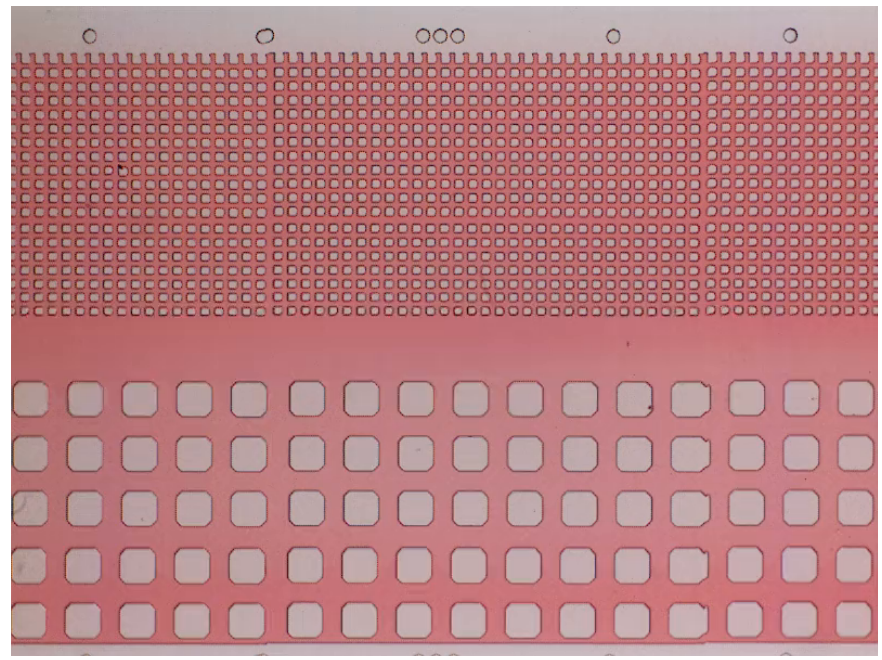
- Bubble blocking, lamellae resistance in high-perm zones
- Phase separation due to different capillary entry pressures

Alternative Floods

Low permeable regions are left oil-filled with either water or water/gas flooding



Surfactant flood

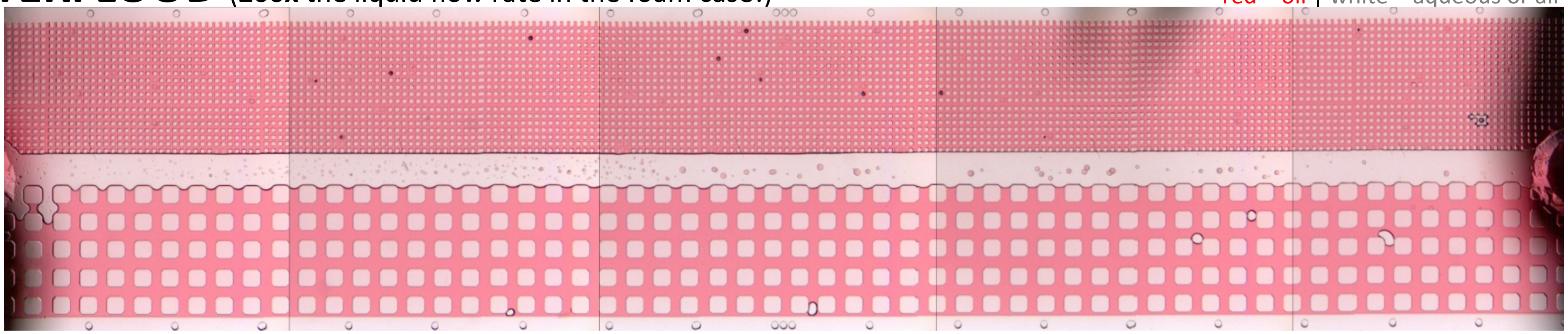


Surfactant-Alternating-Gas flood

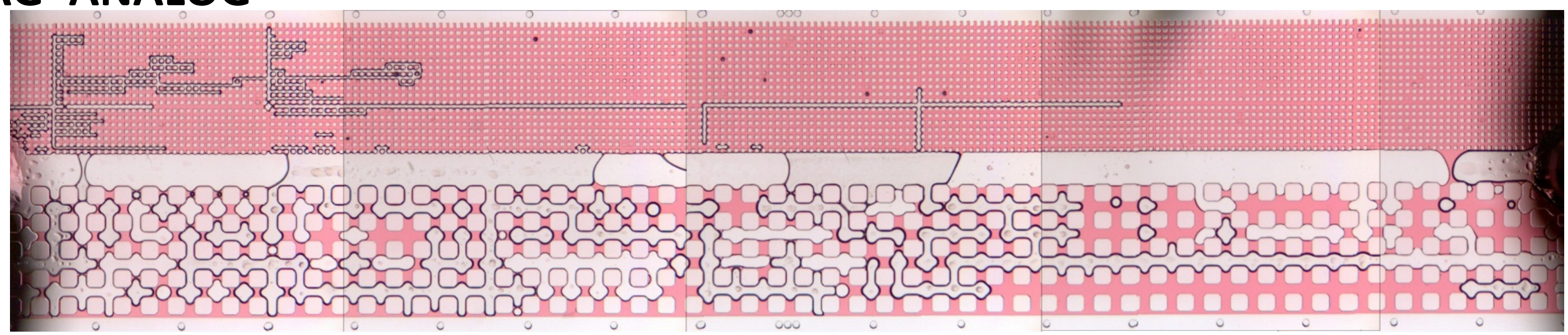
Foam Performance Compared

WATERFLOOD (**200x** the liquid flow rate in the foam case!)

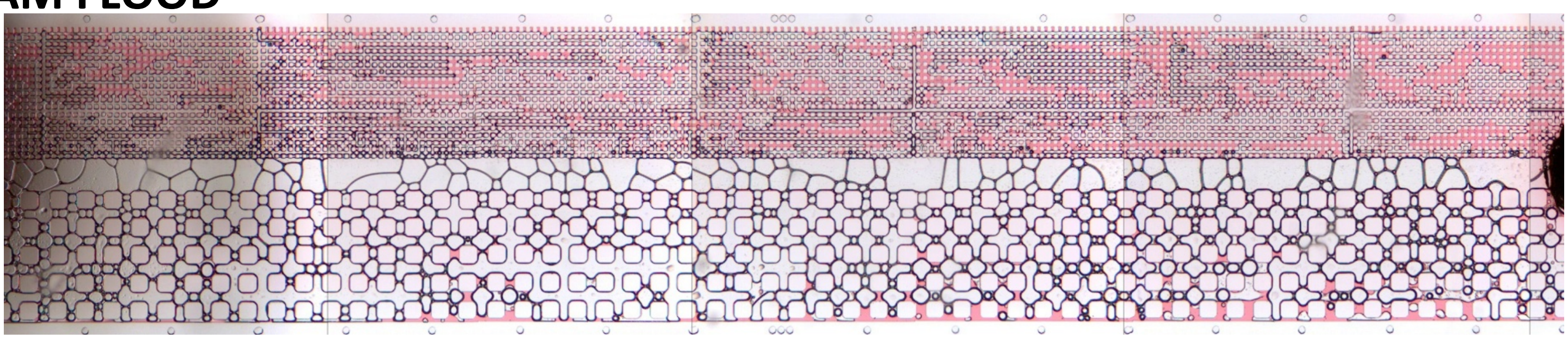
red = oil | white = aqueous or air



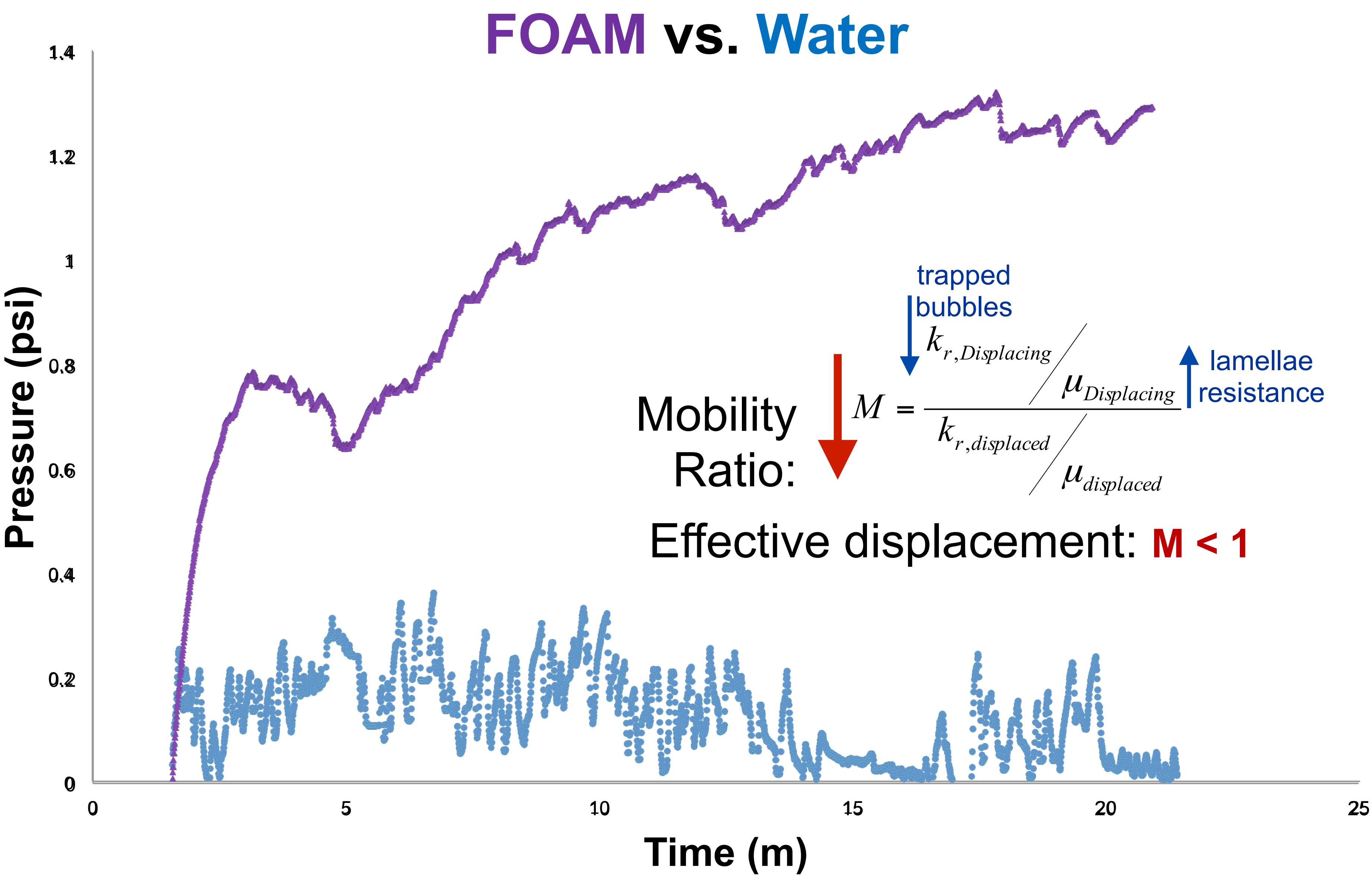
'WAG' ANALOG



FOAM FLOOD

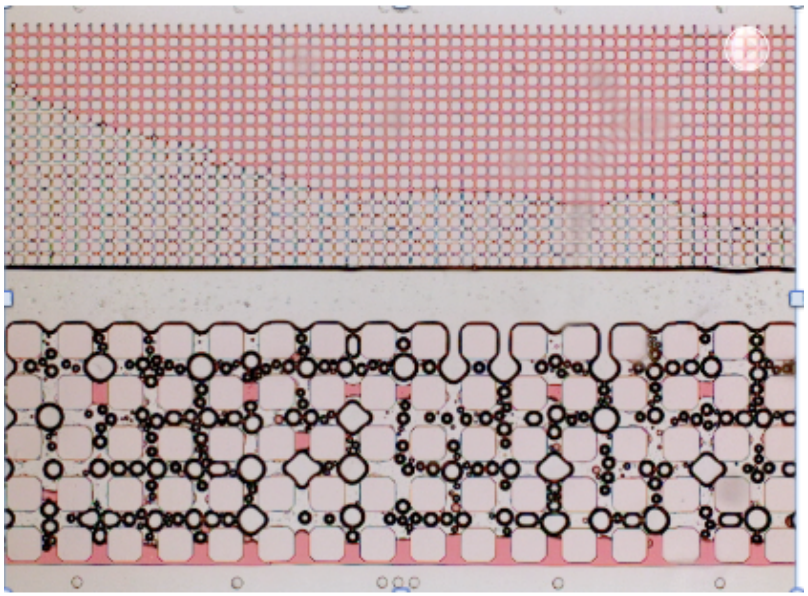


Increased Pressure with Foam



Foam as a surfactant delivery tool

*The **liquid** phase can more easily enter small pores than gas because of its lower **capillary entry pressure***



$$P_{c,go} = \frac{2\gamma_{go}\cos\theta_{go}}{r}$$

$\gamma_{go} = 21.76 \pm 0.02$ mN/m

$4.4 \text{ x } 10^3$ Pa (0.63 psi)

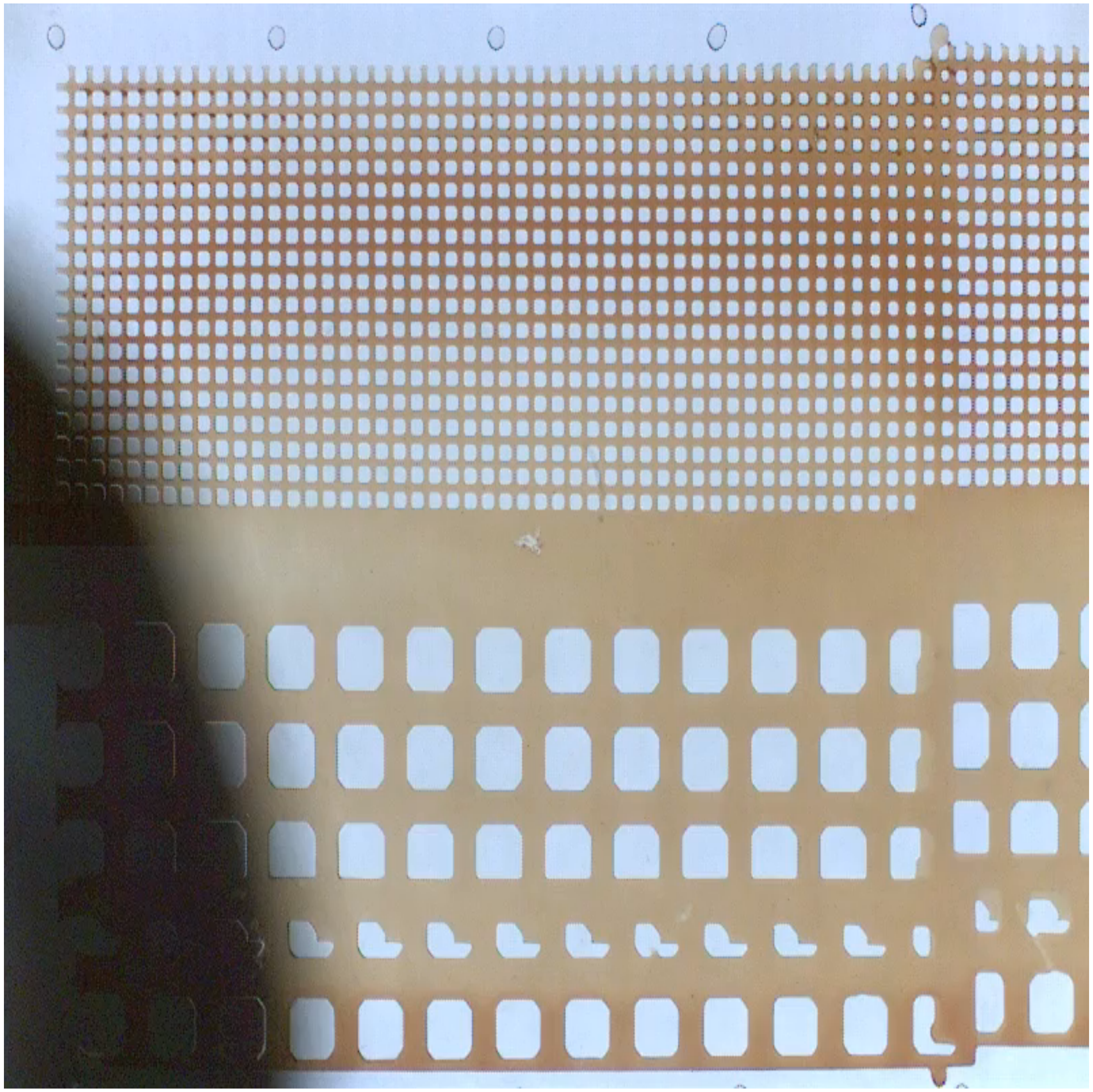
$$P_{c,ow} = \frac{2\gamma_{ow}\cos\theta_{ow}}{r}$$

$\gamma_{ow} = 1.16 \pm 0.01$ mN/m,

$2.3 \text{ x} 10^5$ Pa (0.03 psi)

	Pore Throat	Porosity	Permeability	Measured critical displacement pressure for air	Measured critical displacement pressure for surfactant
Fracture	380 x 50 µm	–	223 darcy	<0.01 psi	<0.01 psi
High-permeability	105 x 50 µm	39.7%	47 darcy	0.13 psi	0.02 psi
Low-permeability	20 x 50 µm	27.5%	24 darcy	0.23-0.46 psi	0.03-0.60 psi

Phase Behavior: Changing to a Crude Oil

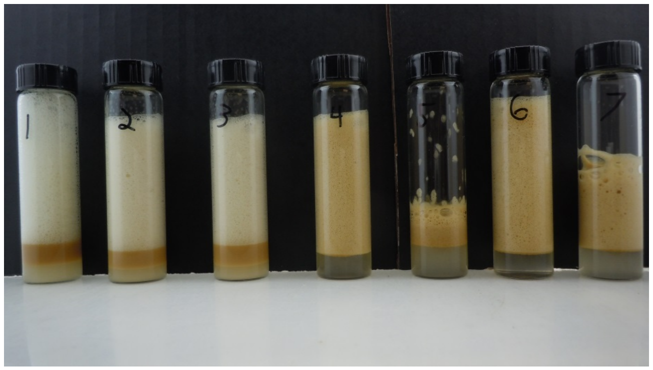


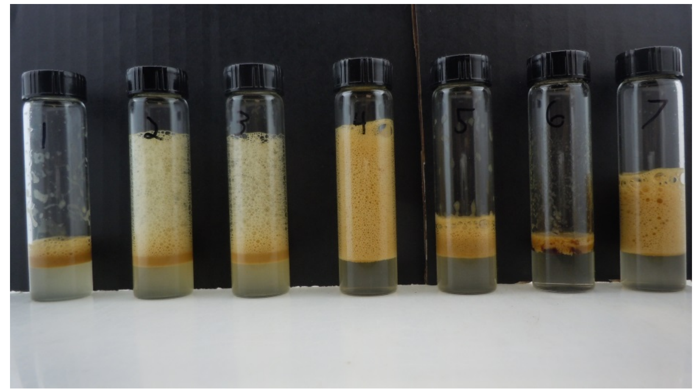
Phase behavior is altered by different oils and alters transport

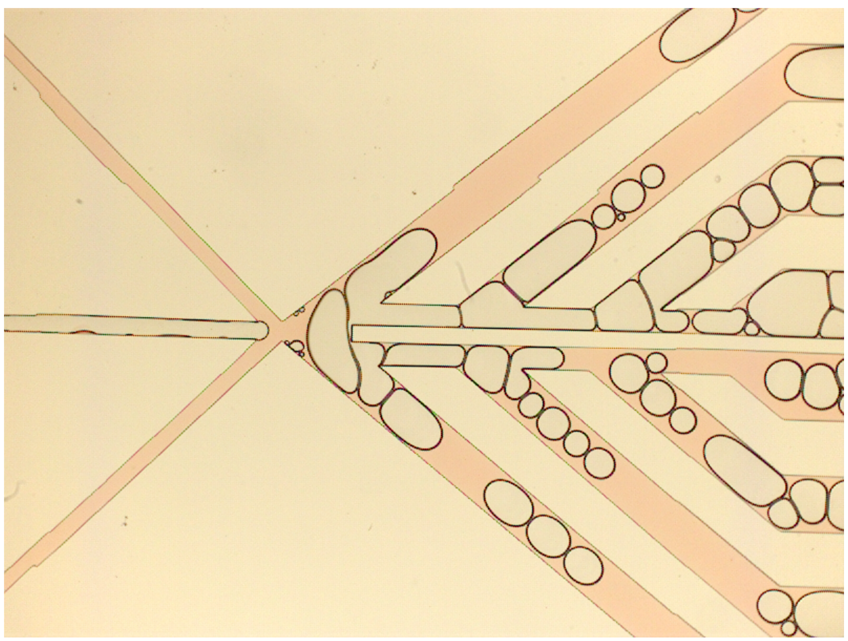
1.2ml/hr N2 through capillary with 0.4ml/hr 1%wt LB:AOS(1:1), sweep crude oil

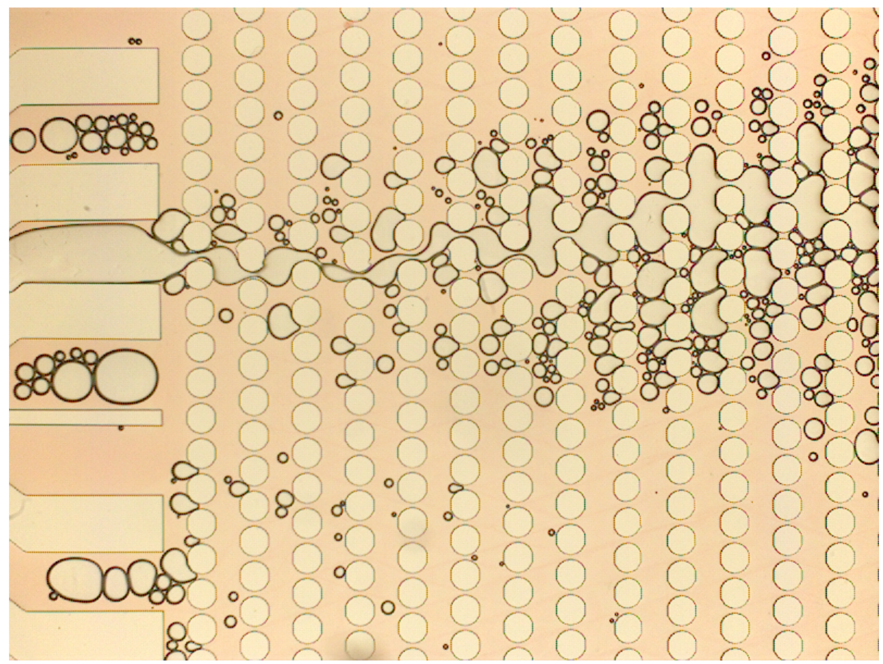
Screening Foam Formulations

AOS C14-16/ lauryl betaine ratios



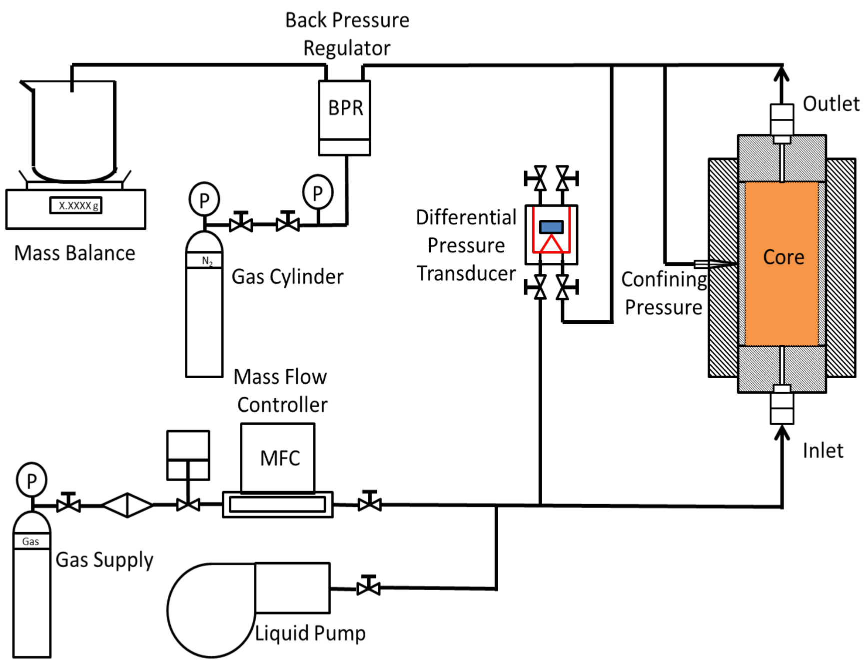


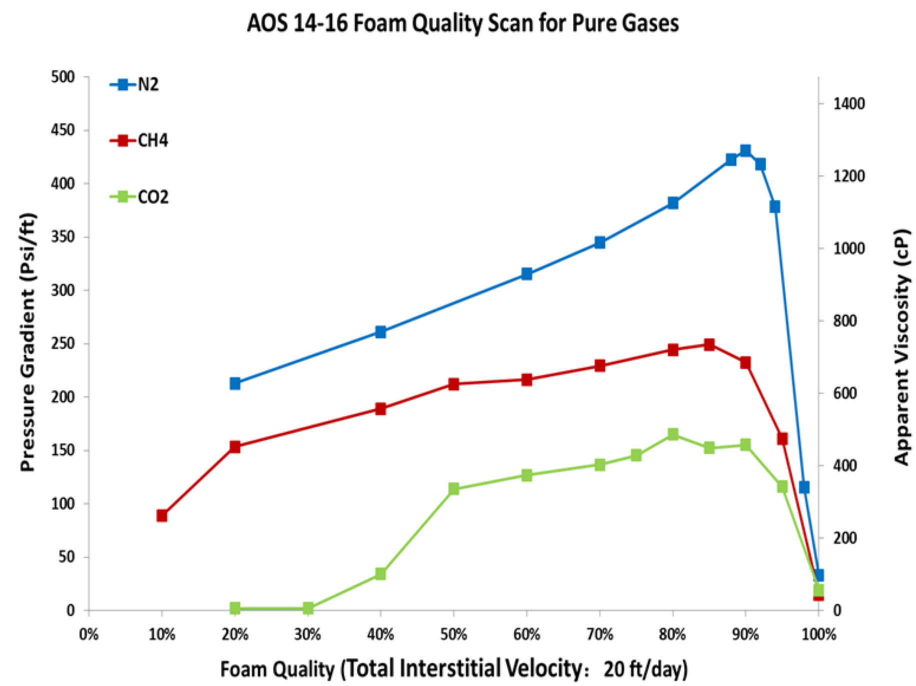




Determining Foam Quality

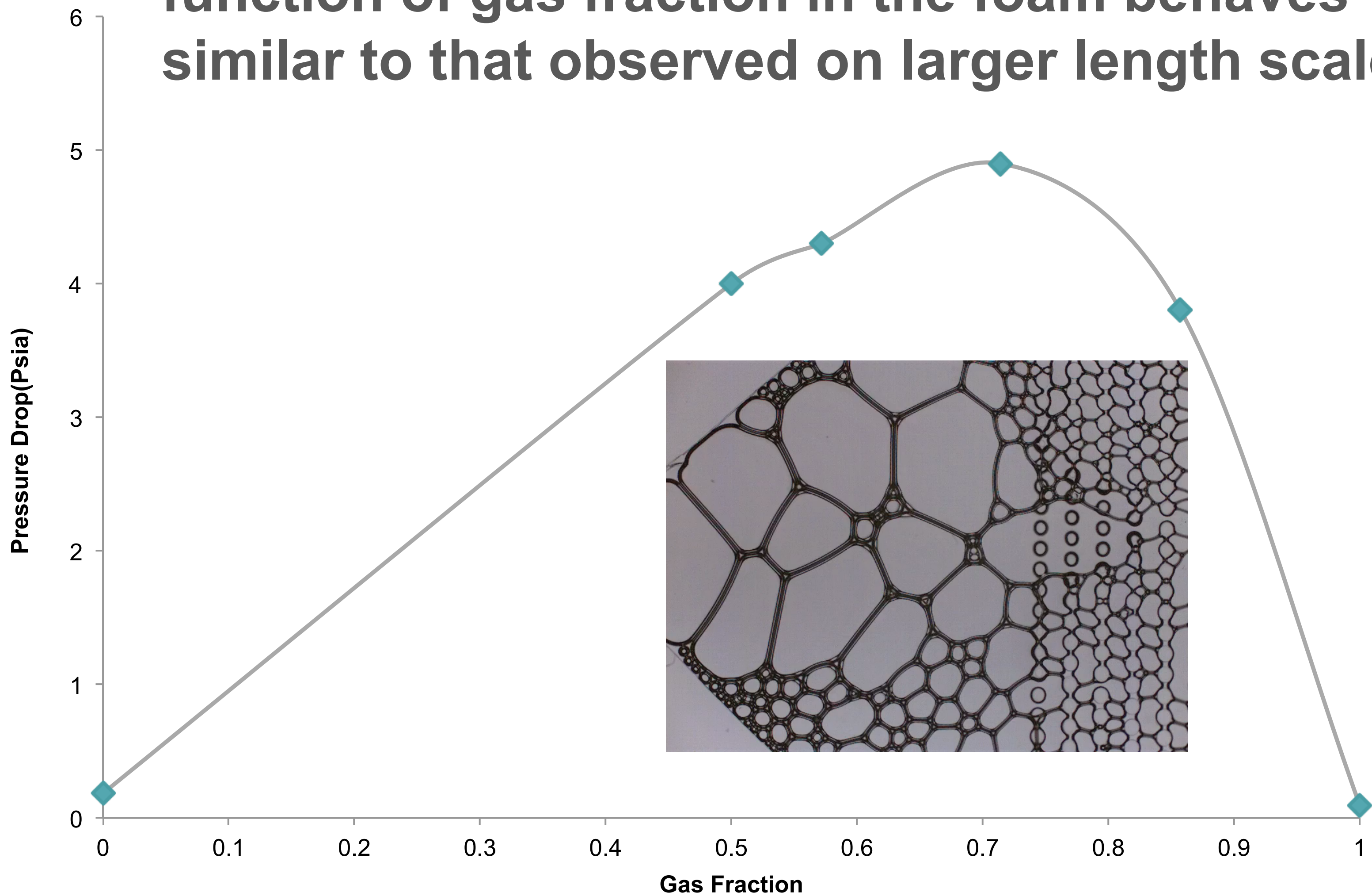
Scanning for Foam Strength as a Function of Foam Quality typically requires tedious measurements





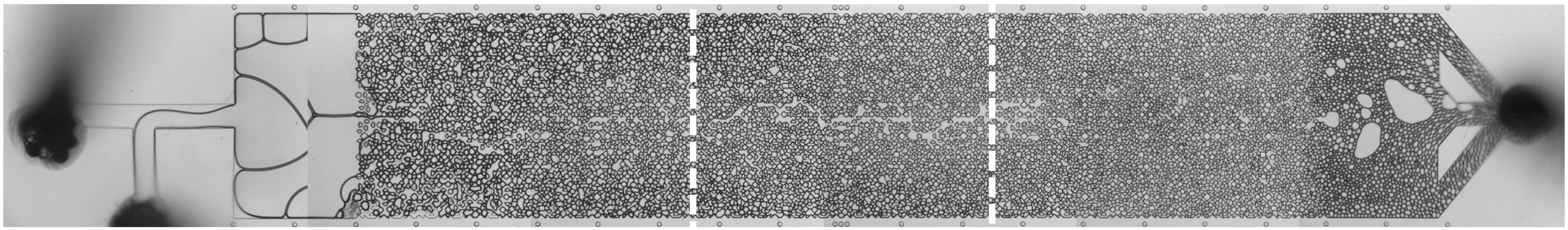
Micromodels to Scan for Foam Strength

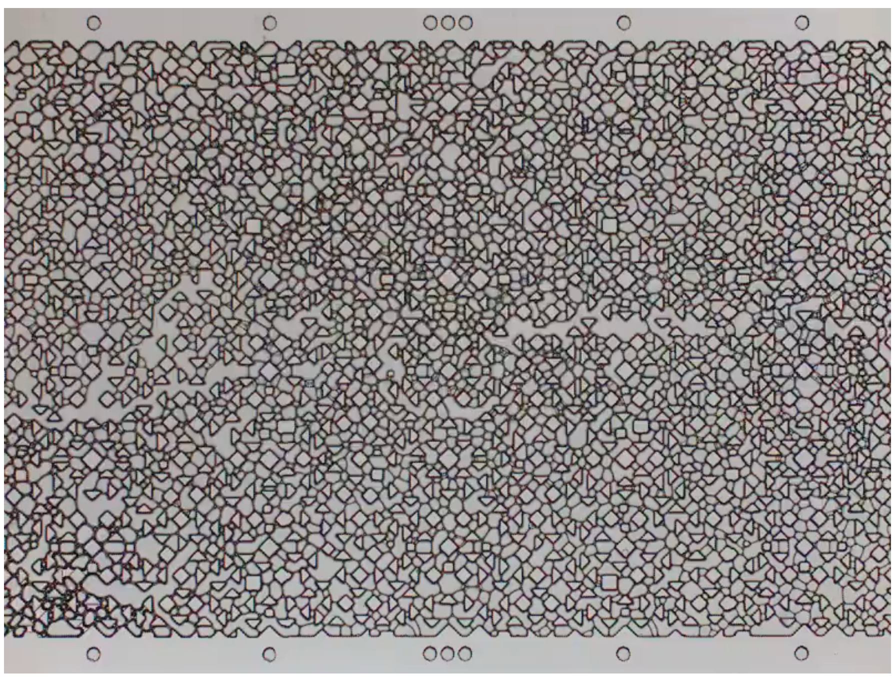
The pressure drop across the micromodel as a function of gas fraction in the foam behaves similar to that observed on larger length scales

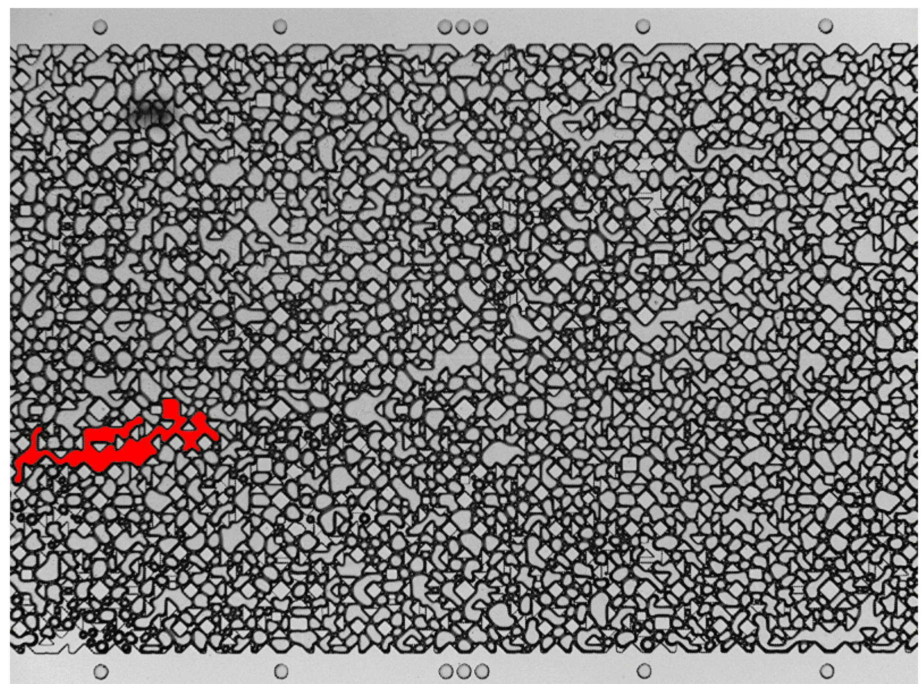


Heterogeneous Porous Media

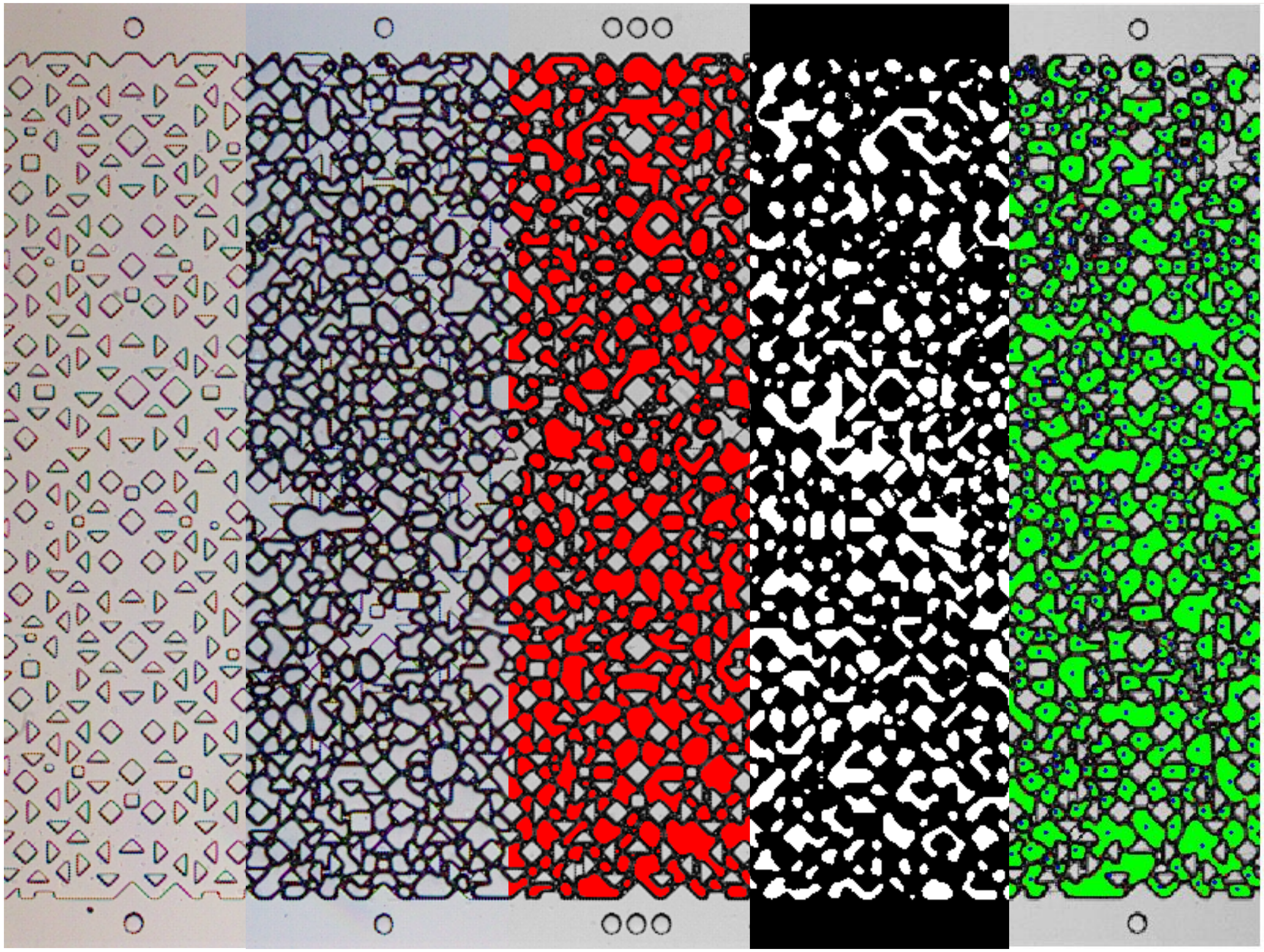
Foam generation in-situ can be used to tra







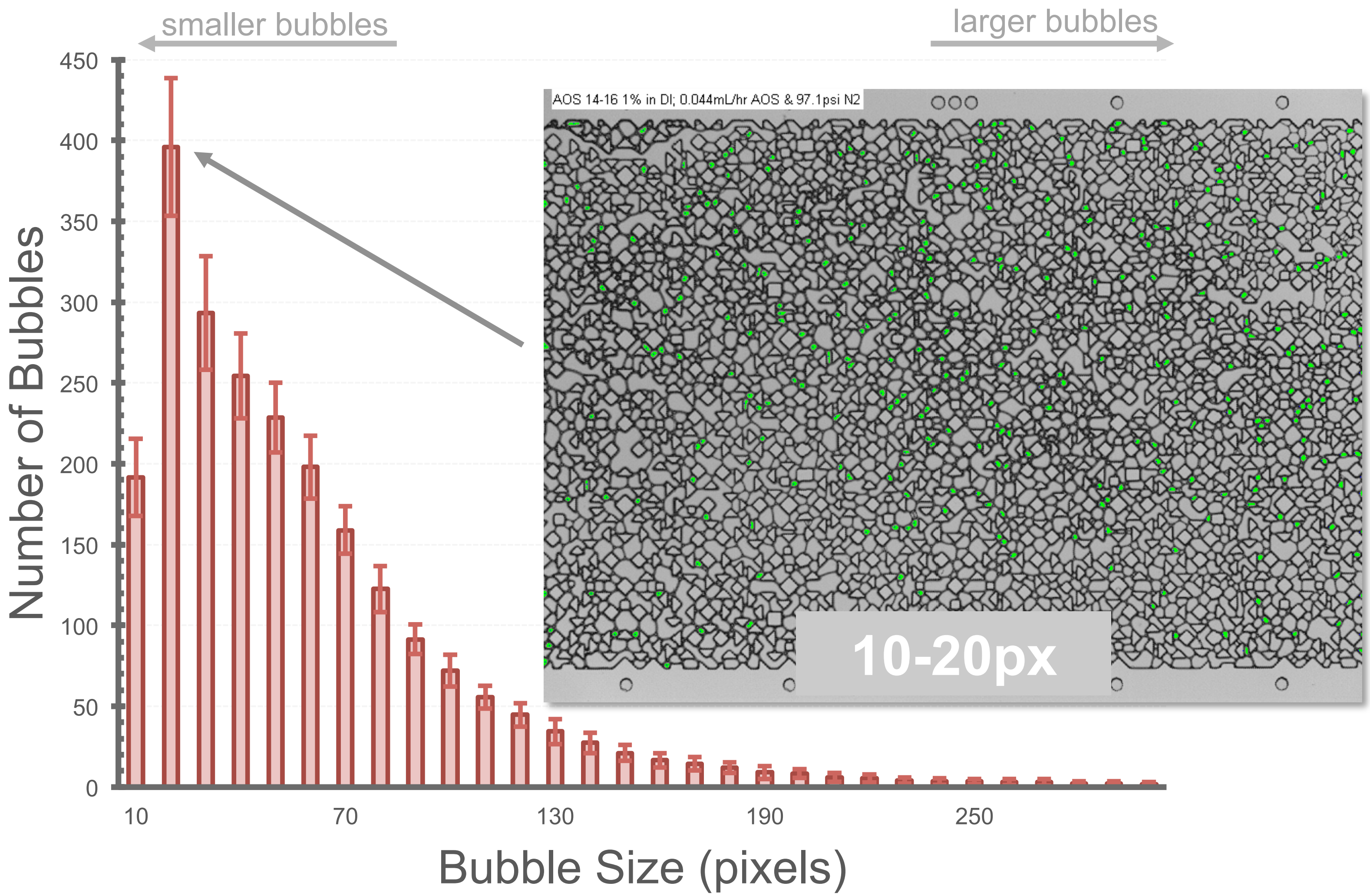
How do we quantify **foam texture?**



Results – Texture Histograms

AOS 1%

Constant quality: 90%



Source: Conn (2014)

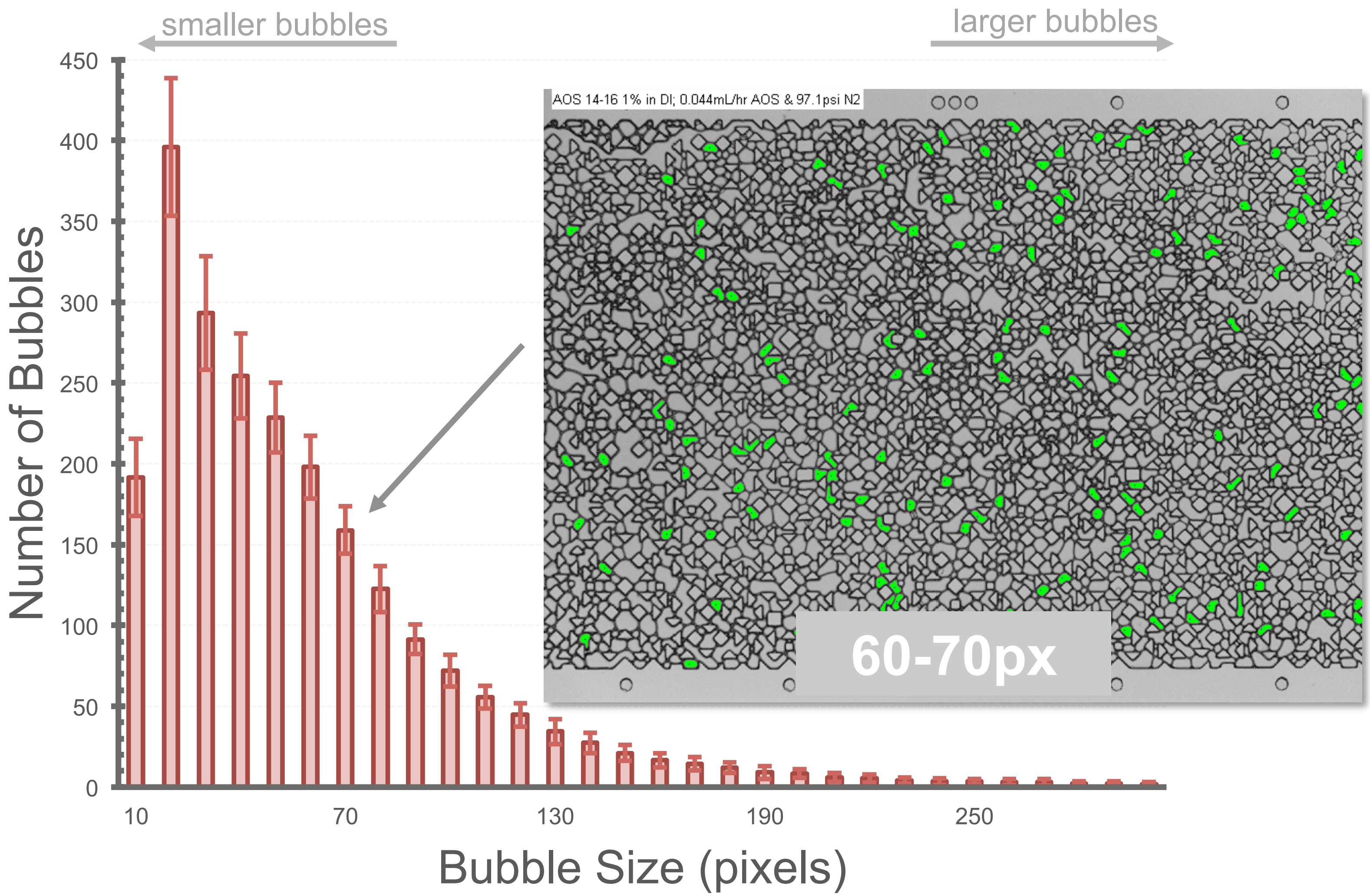
Average of 30 independent images over 1 hr

RICE

Constant quality: 90%

Results – Texture Histograms

AOS 1%



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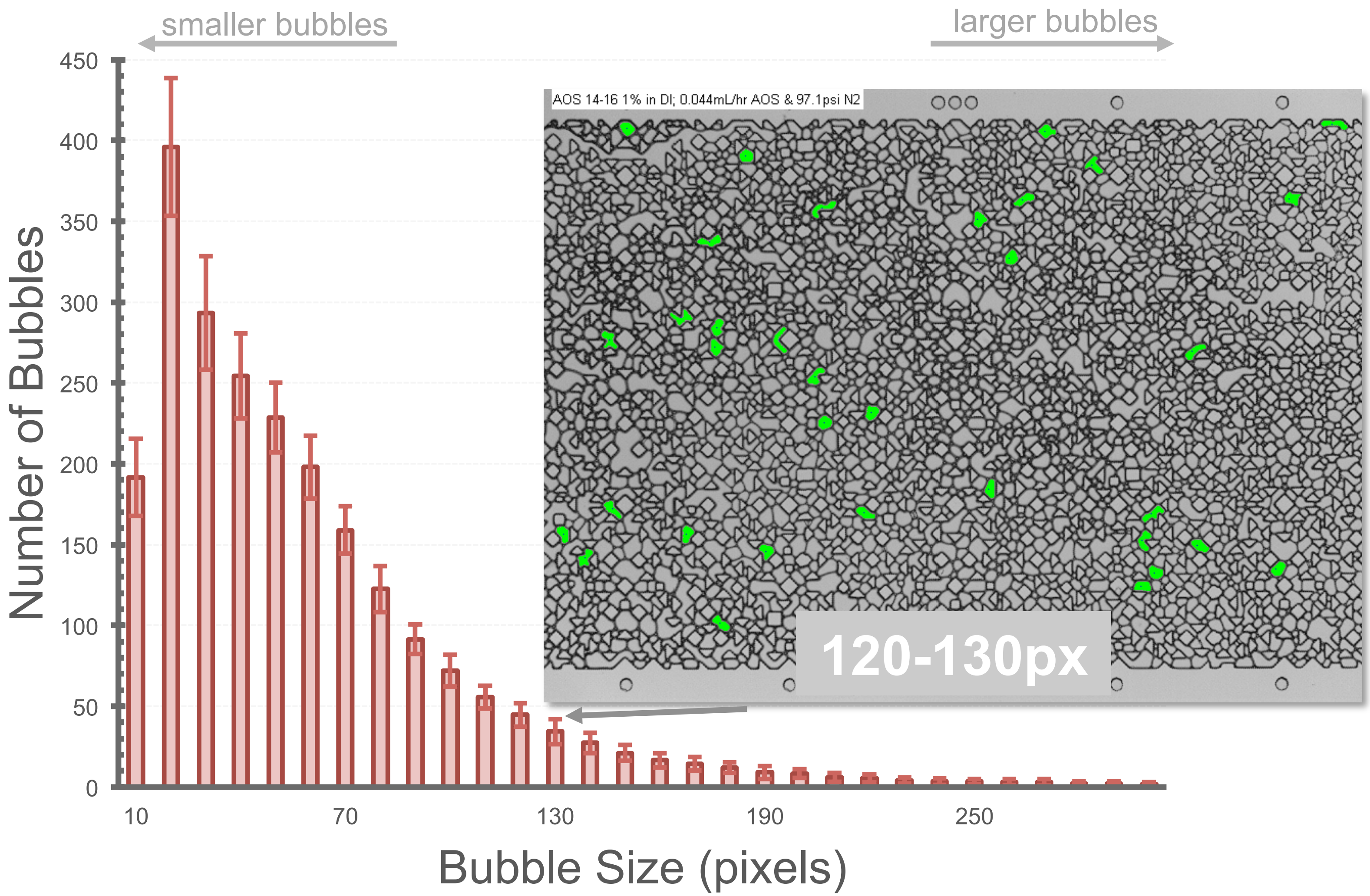
AOS 1%



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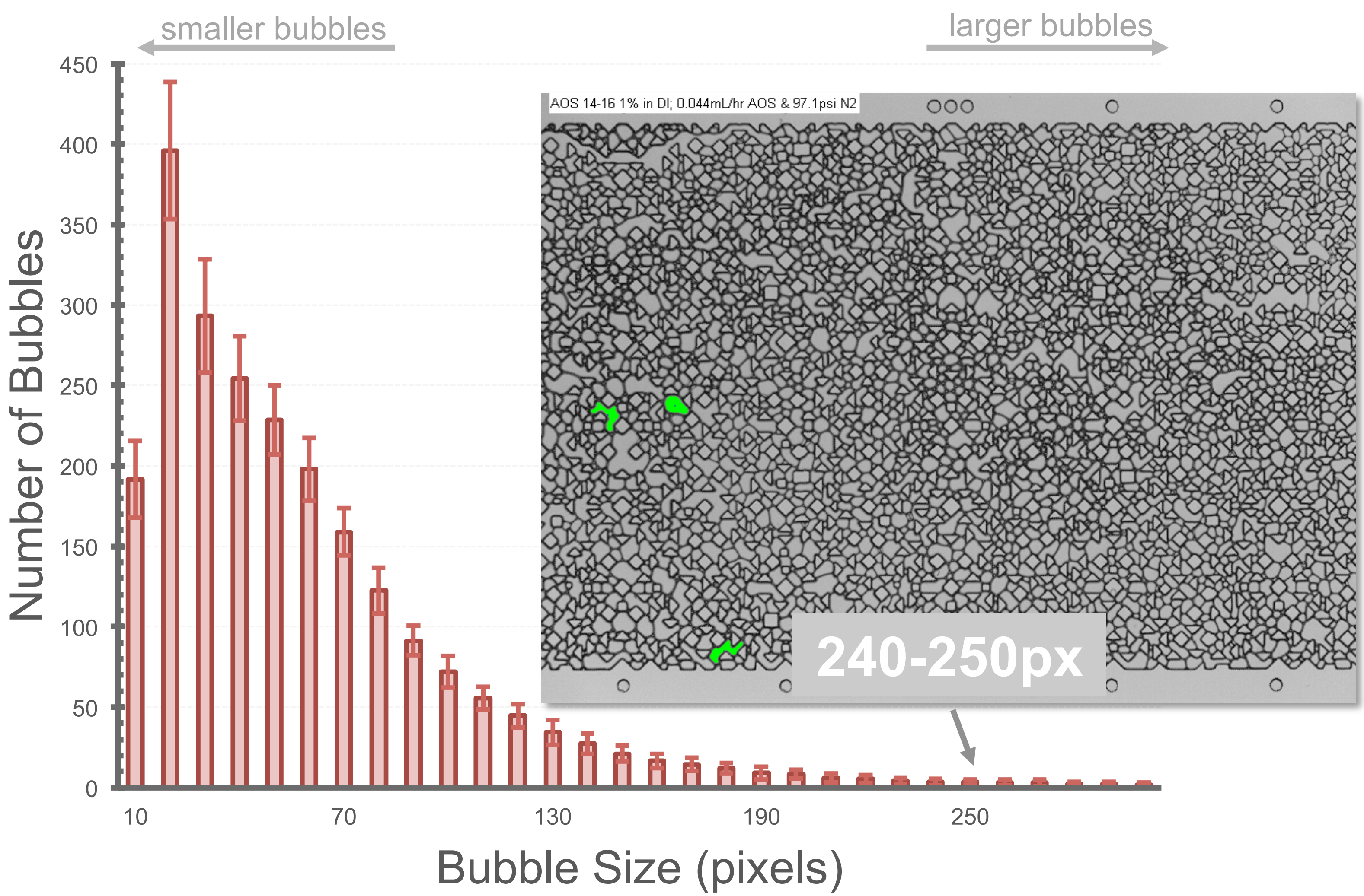

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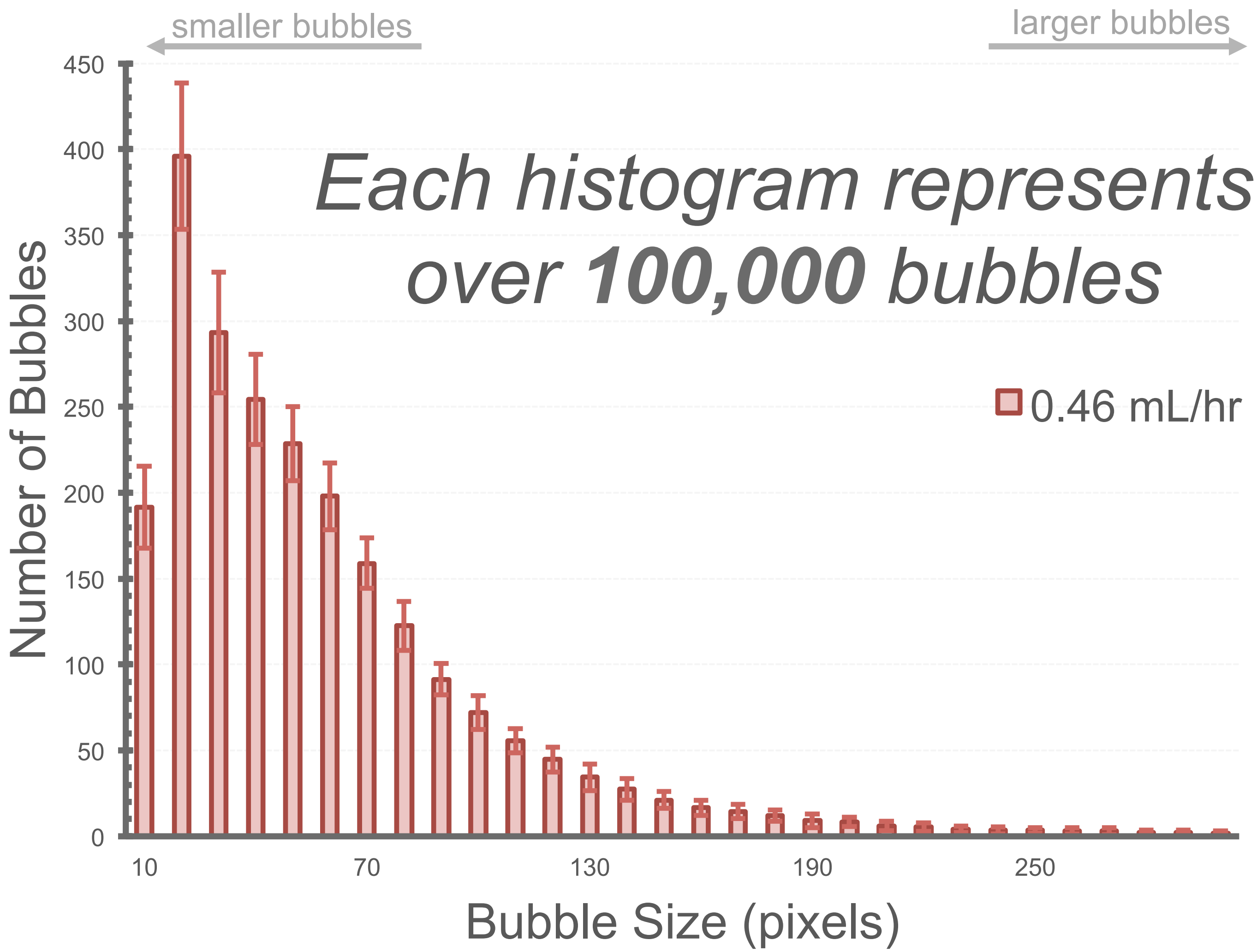


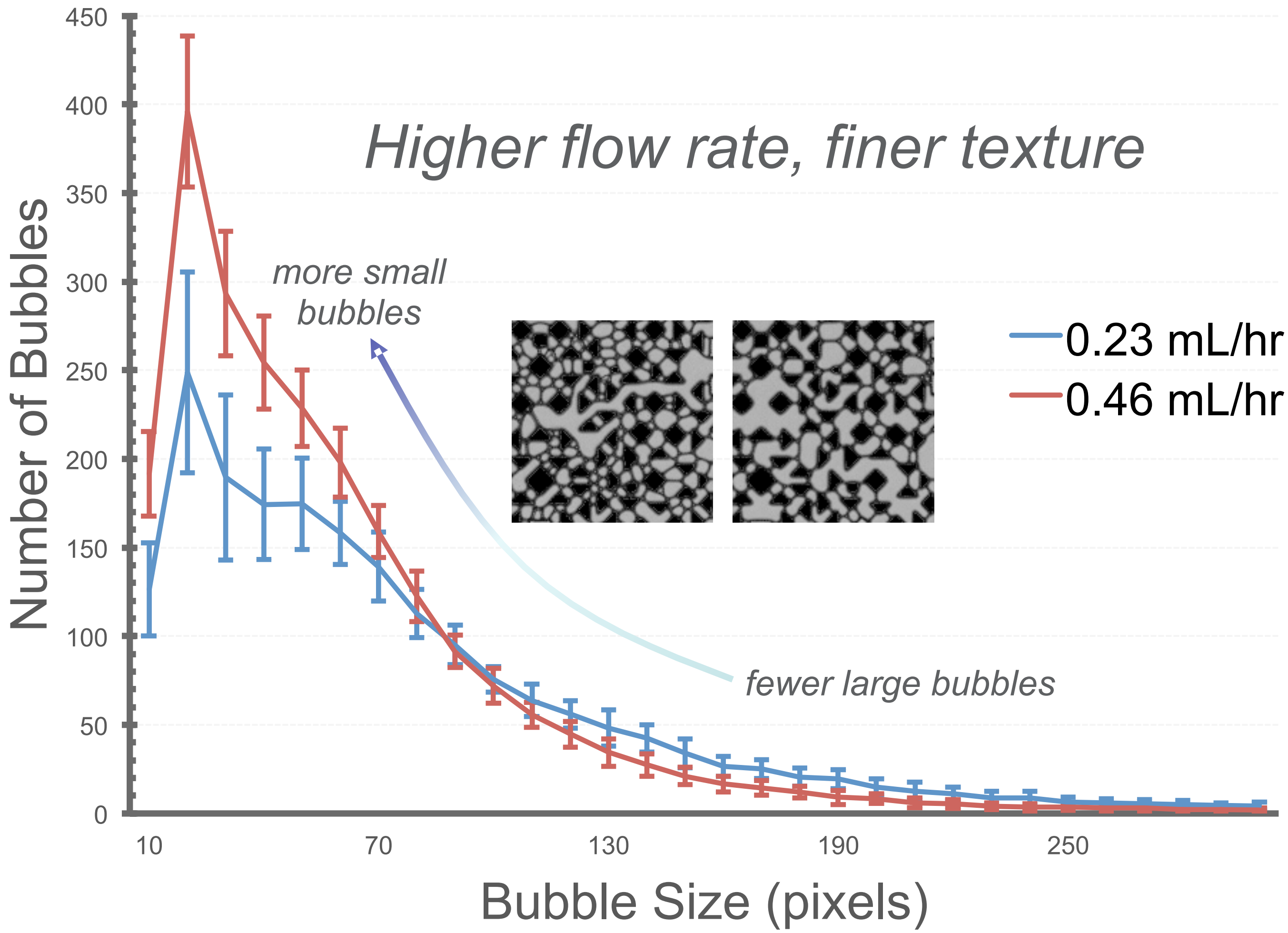
*Each histogram represents over **100,000** bubbles*

Source: Conn (2014)

Average of 30 independent images over 1 hr

Texture *vs.* Flow Rate

90% Foam Quality = ratio of gas/liquid



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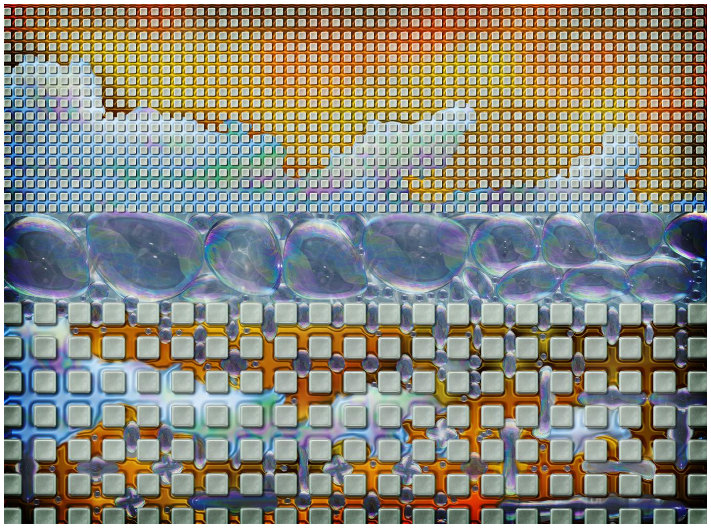
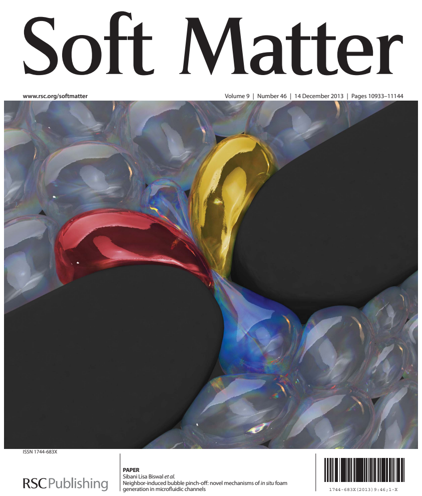
Conclusions and Acknowledgements



- Foam can significantly increase the solution viscosity, effectively offering mobility control
- Microfluidic models provide an unique method by which we can gain better understanding of the flow behavior in confined systems

Soft Matter, 9, 10971-10984 (2013)
Lab on a Chip, DOI: 10.1039/C4LC00620H (2014)



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