Seismic stimulation for enhanced oil production

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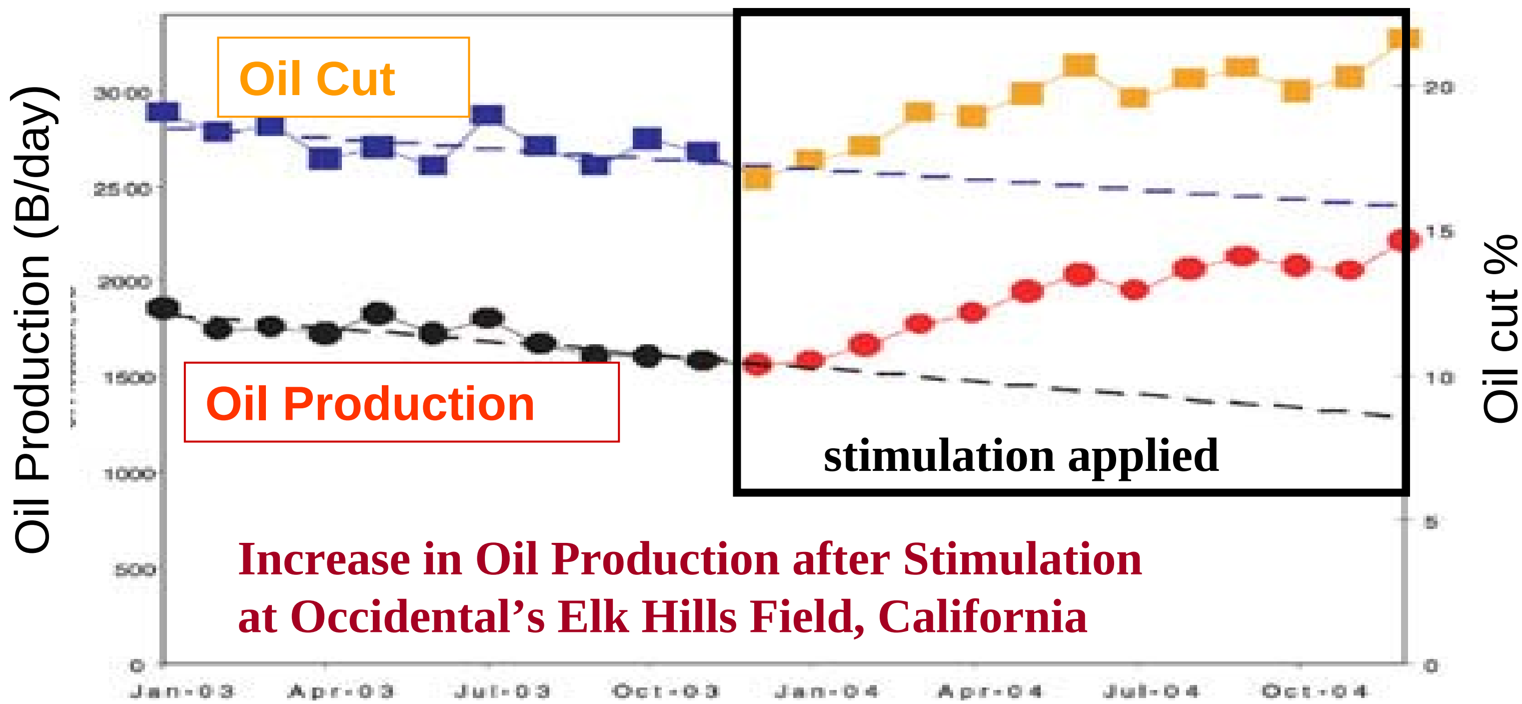
Outline

- Field observations
- Pore scale intro and elements of theory
- Lattice Boltzmann and experiments
- Moving up from pore scale: Network models and experiments
- Transversal versus longitudinal stimulation
- Effects of compressibility

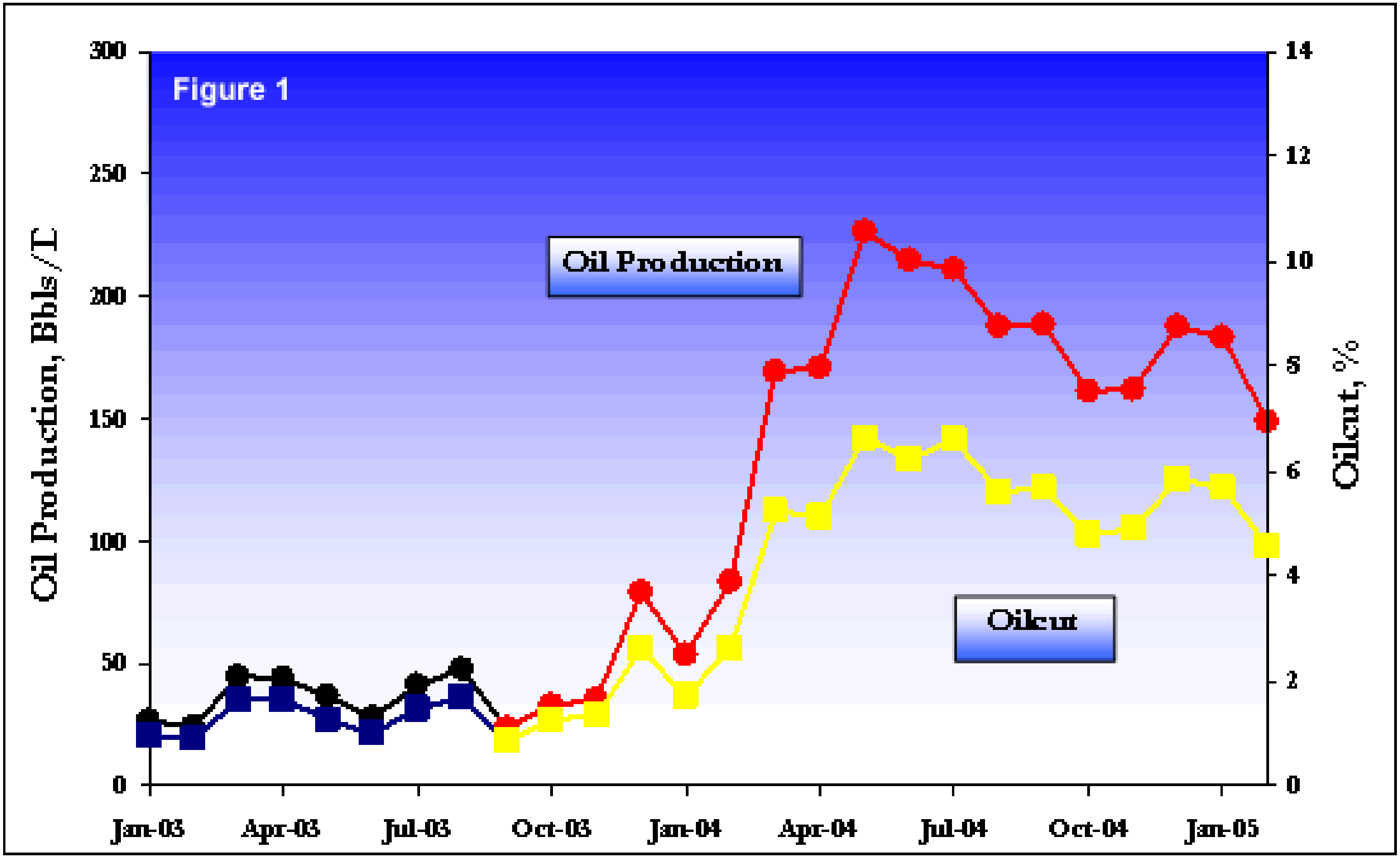
FIELD EVIDENCE FOR SEISMIC STIMULATION

- Earthquakes or hammers, as in this case:



Increase in Oil Production after Stimulation at Occidental's Elk Hills Field, California

Water extraction wells:

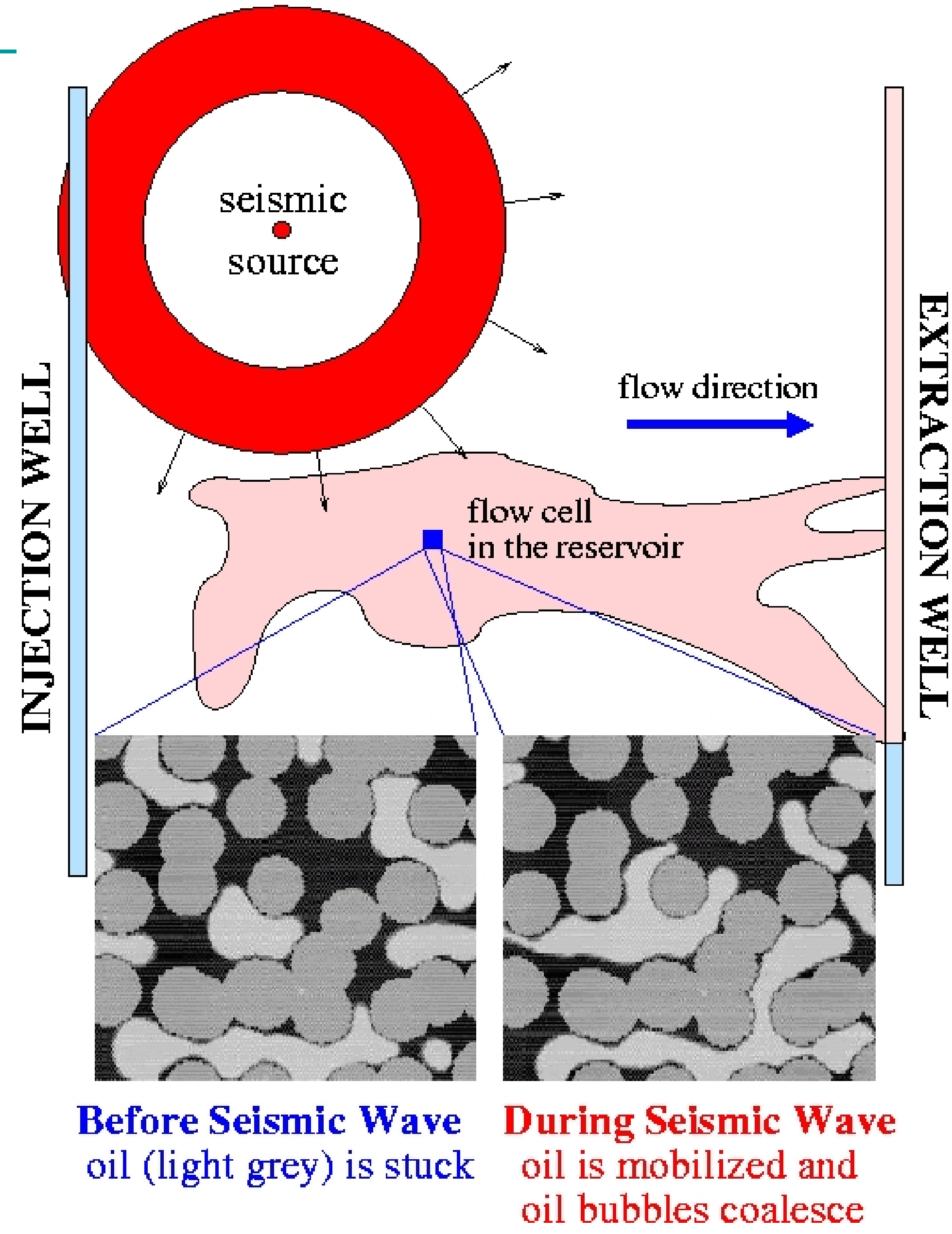


Context:

As much as 70% of the world's oil is in known reservoirs but is trapped on capillary barriers and is effectively "***stuck***".

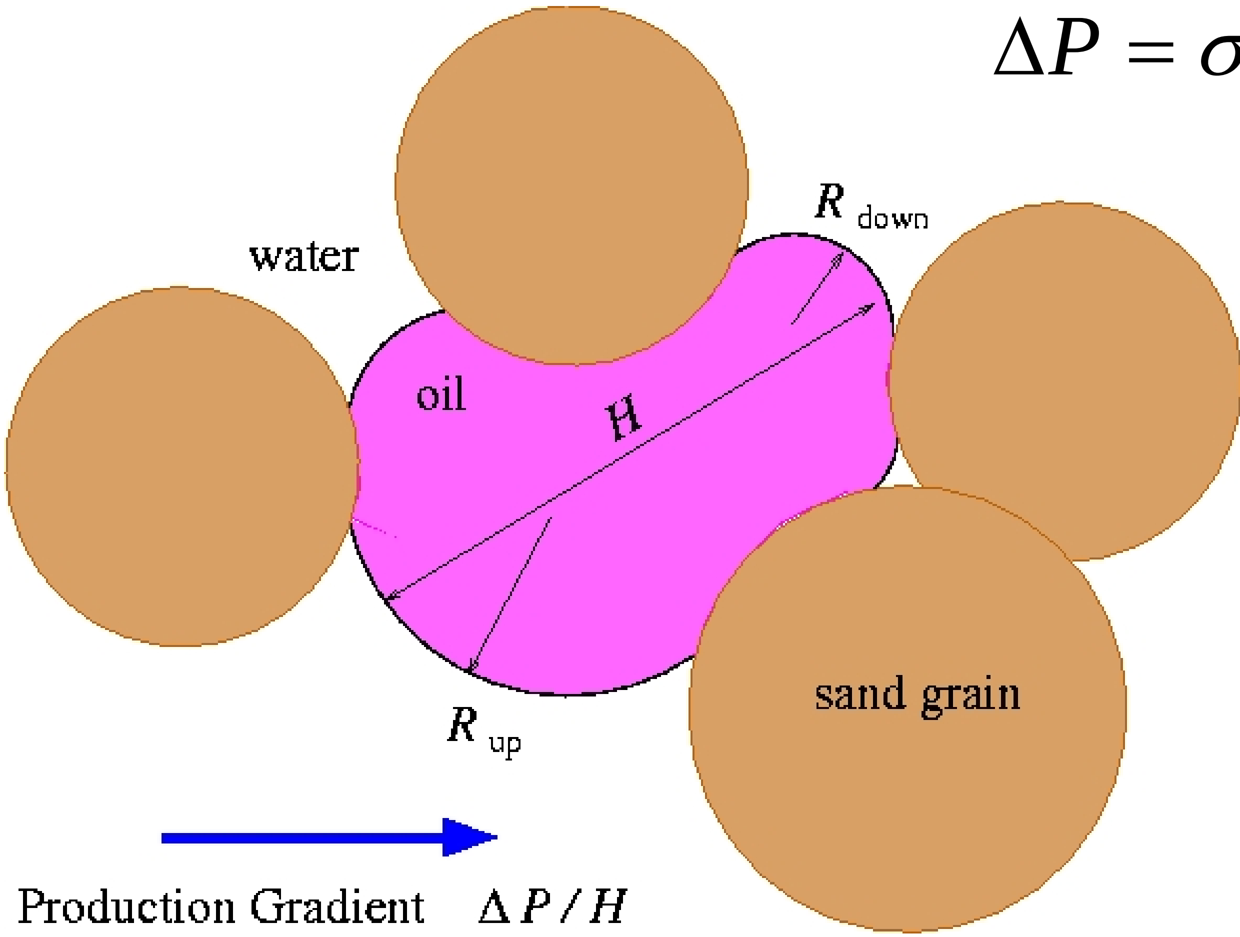
Seismic Stimulation:

A seismic wave is to "***shake the stuck oil loose***" and get it flowing again toward a production well.



The condition for a stuck oil bubble:

$$\Delta P = \sigma\left(\frac{1}{R_{\mathrm{down}}} - \frac{1}{R_{\mathrm{up}}}\right)$$



"the production pressure drop along the bubble is just balanced by a capillary-pressure increase"

Beresnev et al., 2005

The production-gradient force that always acts on the fluids:

$$F_0 = \Delta P / H$$

Poroelasticity determines the seismic force acting on the fluids:

$$F_S = c_p \left(\rho_f + \frac{\rho B}{1 + 4G/3K_U} \right) \dot{\theta}$$

"acceleration of grains"

"wavelength-scale fluid-pressure gradient"

where $\dot{\theta}$ is the seismic strain rate.

The seismic force adds to the production gradient and can overcome the capillary barrier whenever:

$$\frac{F_S}{F_0} \geq \frac{S_c}{S} - 1$$

"***stimulation criterion***"

where

$$S = \frac{F_0 \, k}{\phi^2 \, \sigma}$$

dimensionless "*stimulation number*" (a type of capillary number)

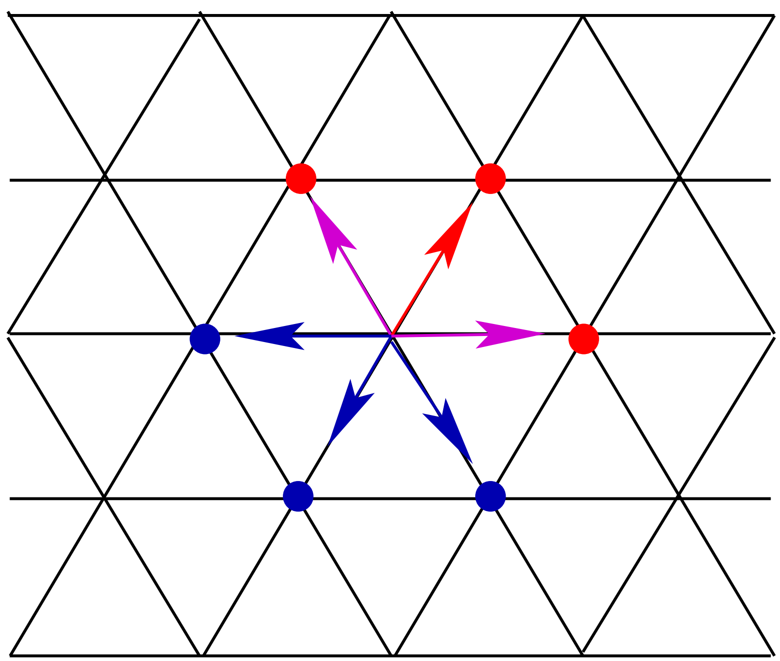
$$S_c = \frac{\sqrt{k}}{\phi \, H}$$

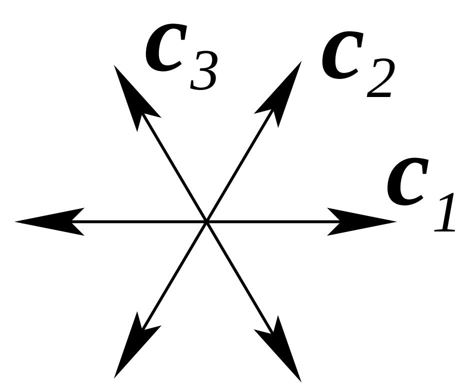
"*critical threshold* of *stimulation number*" (purely geometry dependent)

and where k is permeability and ϕ is porosity.

Lattice Boltzmann model

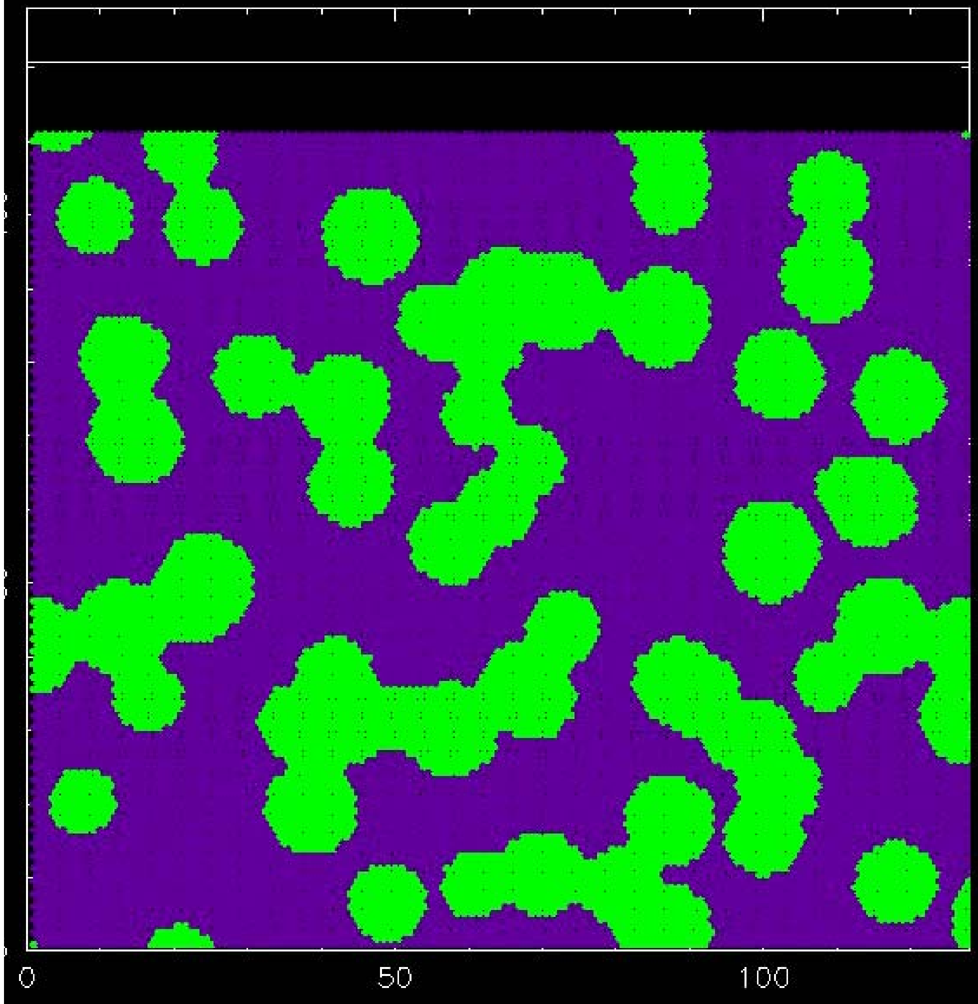
- Hydrodynamics comes from mass- and momentum conservation:





G. McNamara and G. Zanetti 1986

Lattice-Boltzmann Movie

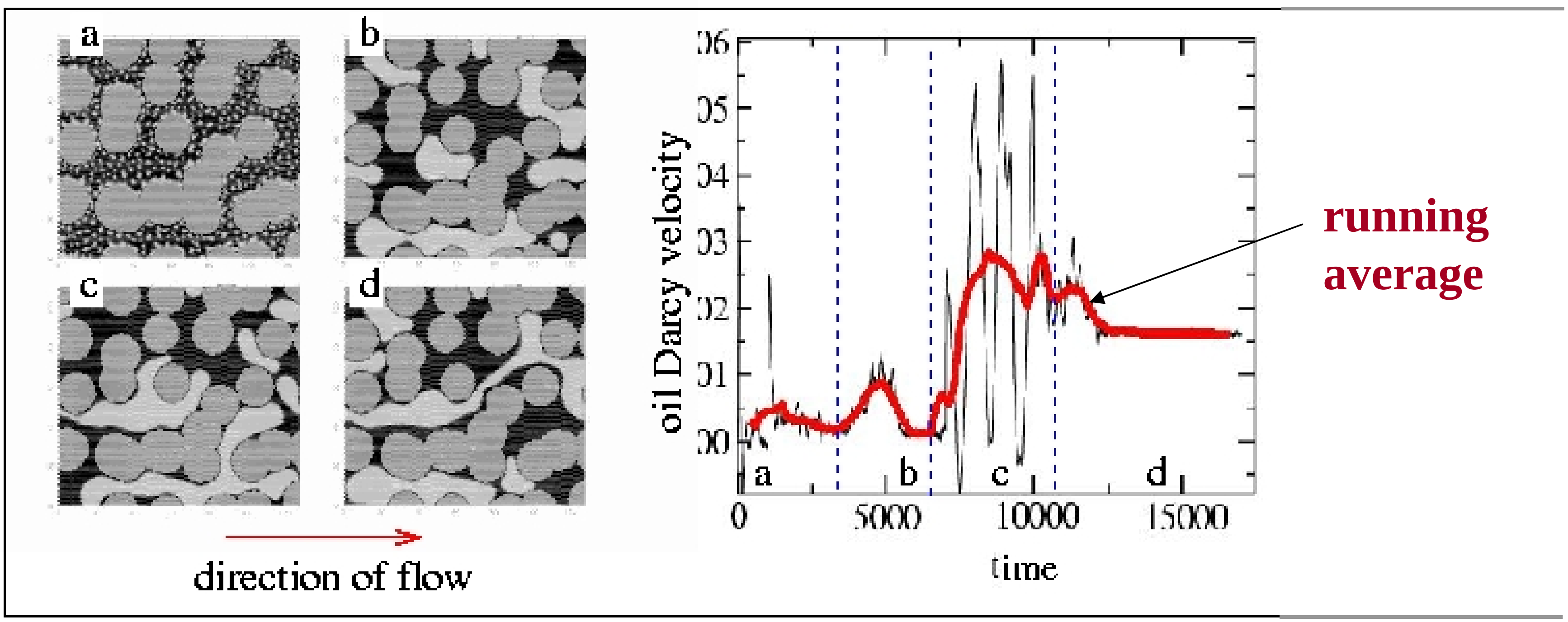


NOTES

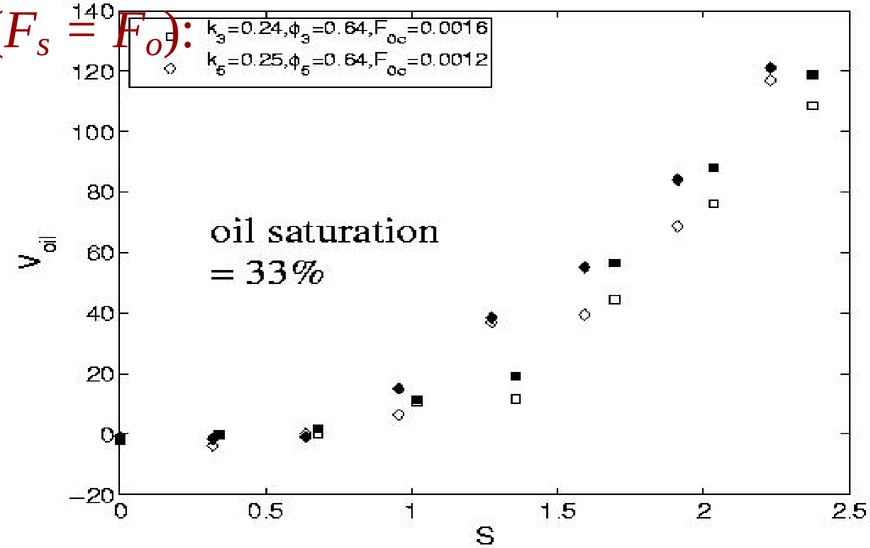
- No green arrow =
  no applied forcing
- Single green arrow =
  production-gradient only
- Double green arrow =
  two periods of seismic stress + production-gradient

"when stimulation is applied, bubbles coalesce creating a longer stream of oil that flows even in absence of stimulation"

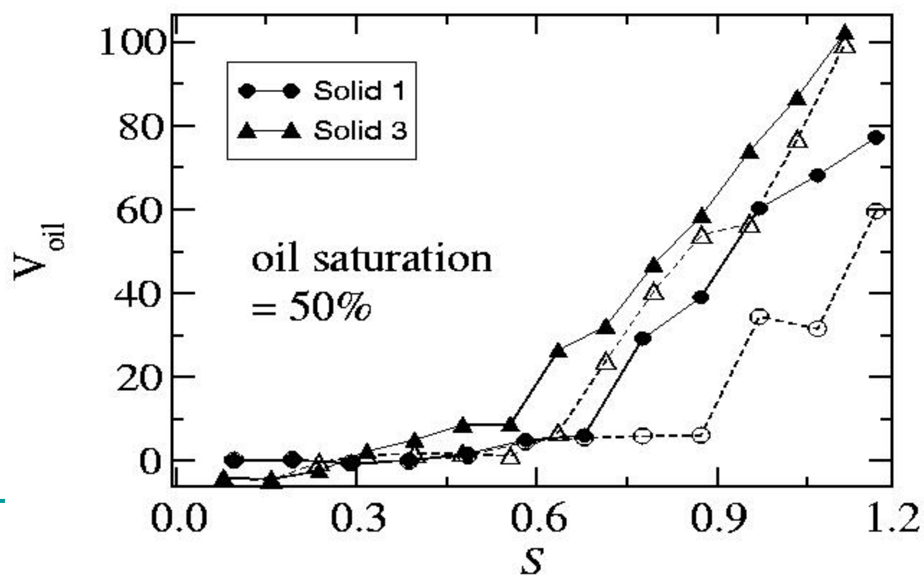
Snapshots and average oil speed during the four stages of a typical "production run":



Total volume of oil production with (solid symbols) and without (open symbols) three cycles of stimulation applied ($F_s = F_o$):

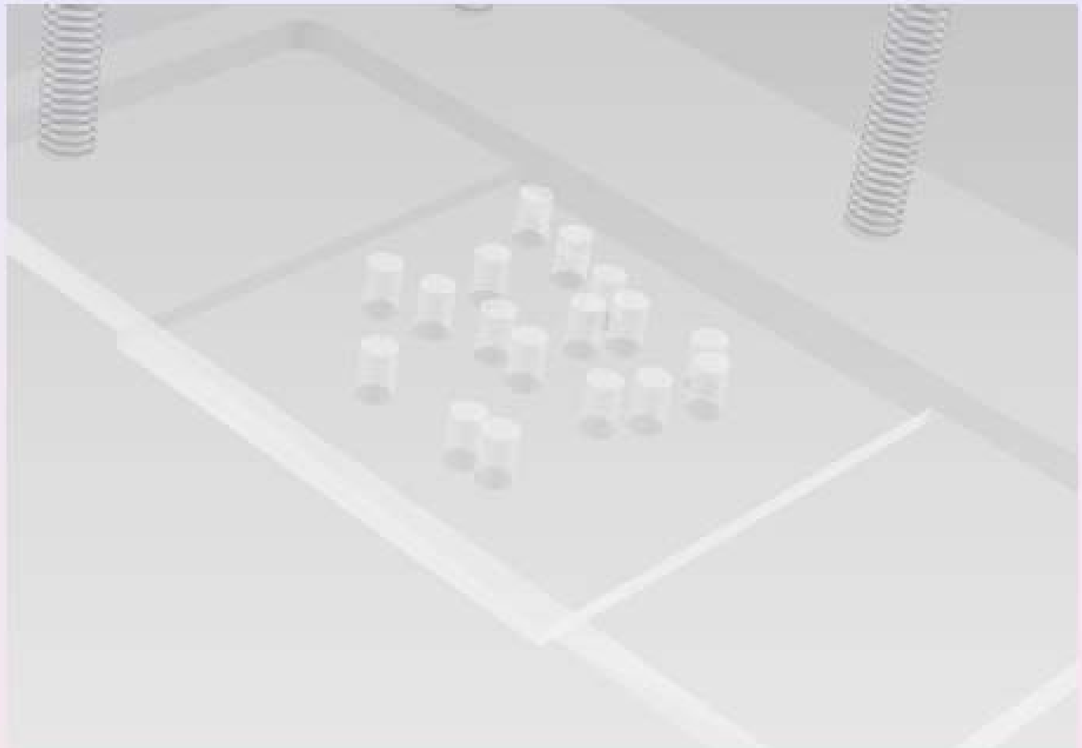


Less of a stimulation effect because at 33% saturation, oil cannot form a continuous stream across system.



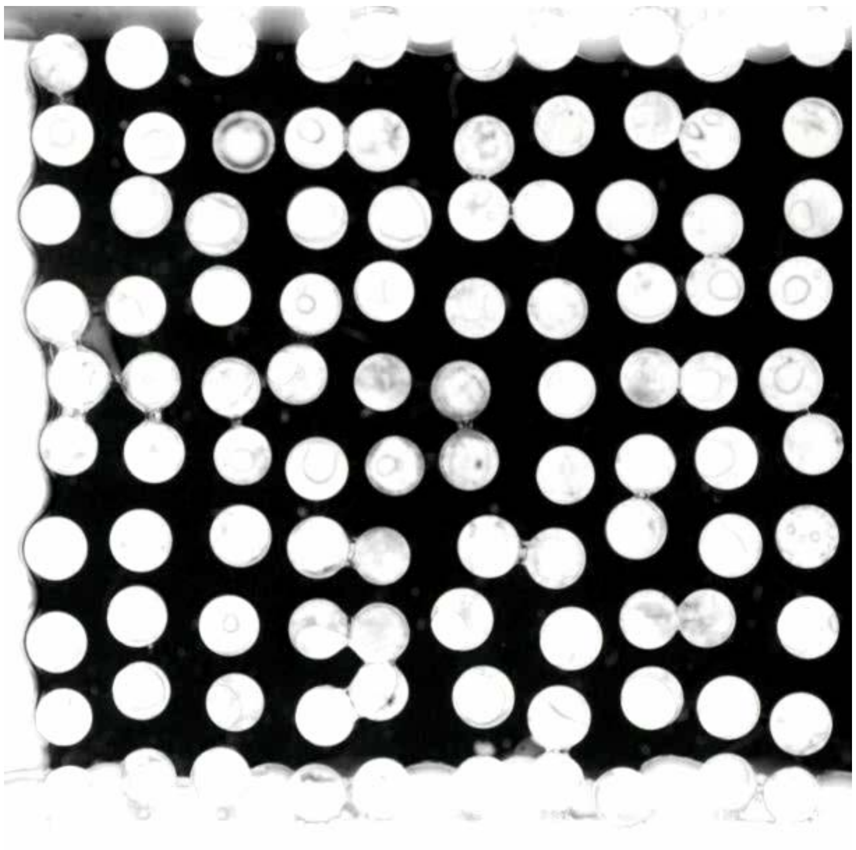
More of a stimulation effect because at 50% saturation, coalescence can result in oil forming a continuous stream across system

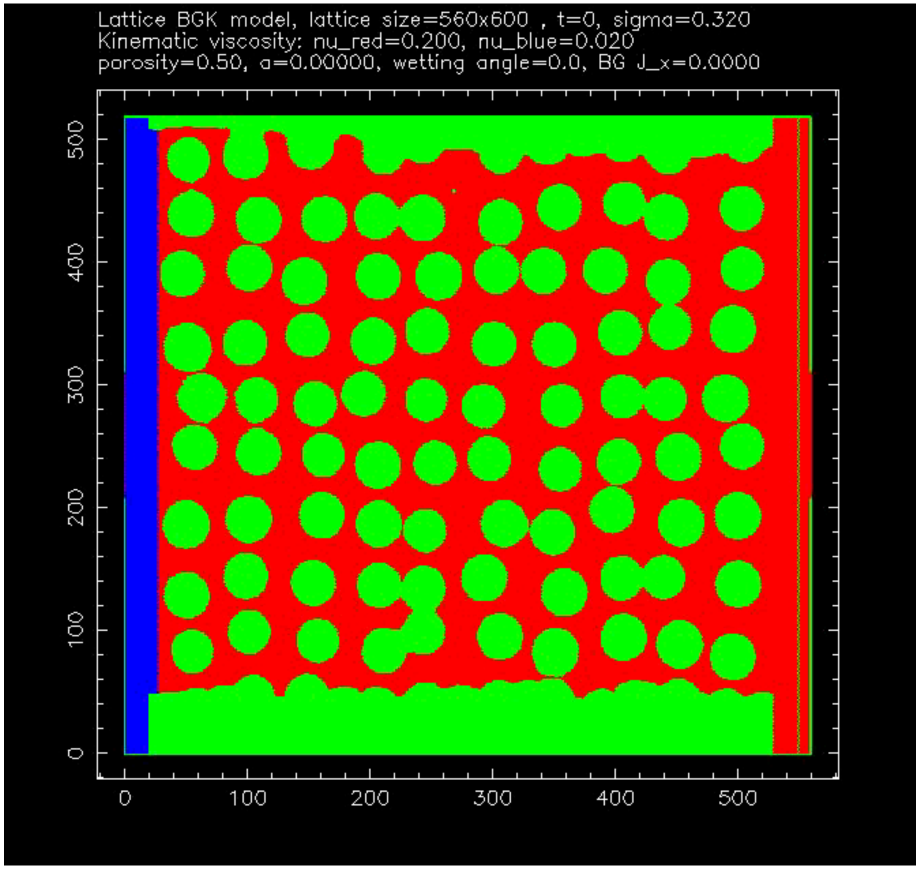
A tiny experiment:



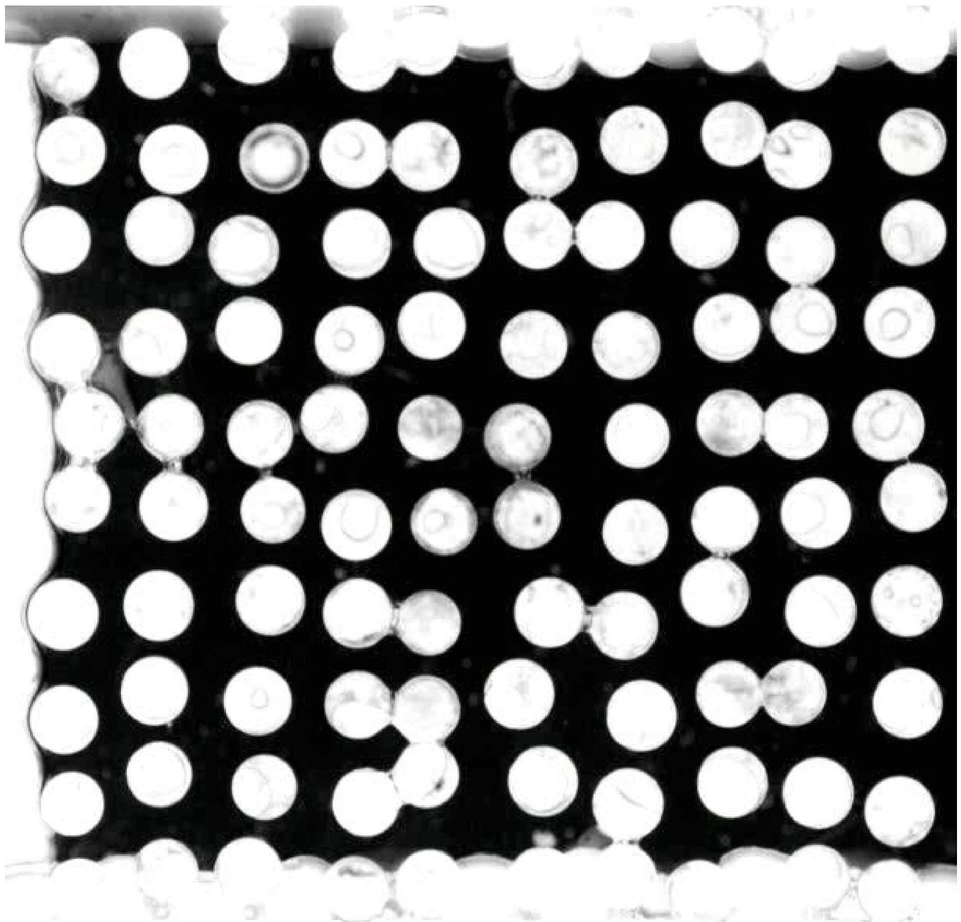
- Well defined system of size $\sim 10 \times 10$ pores
- Milled channel: $30 \times 30 \times 1$ mm milled channel
- Randomly placed Ø 2 mm cylinders

Lattice Boltzmann and experiments



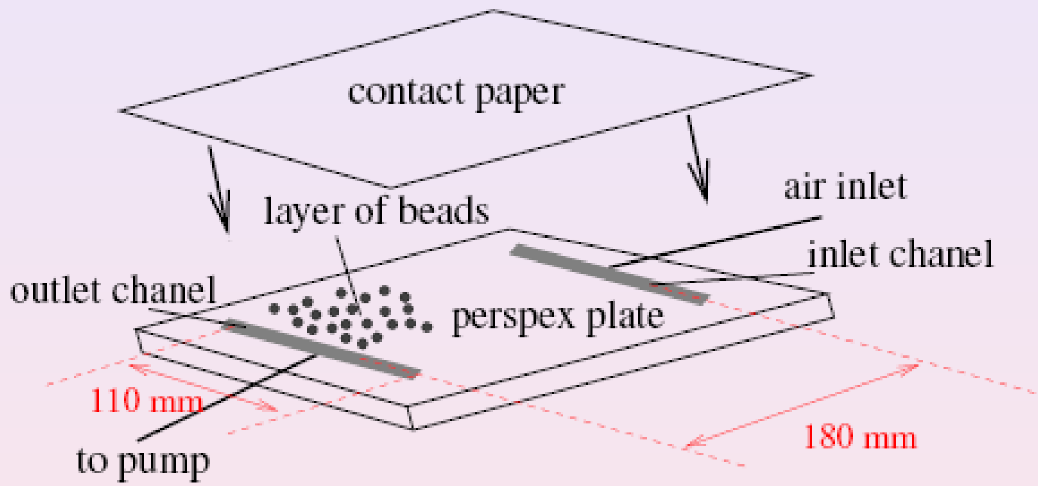


Towards larger scales:



Experiments:

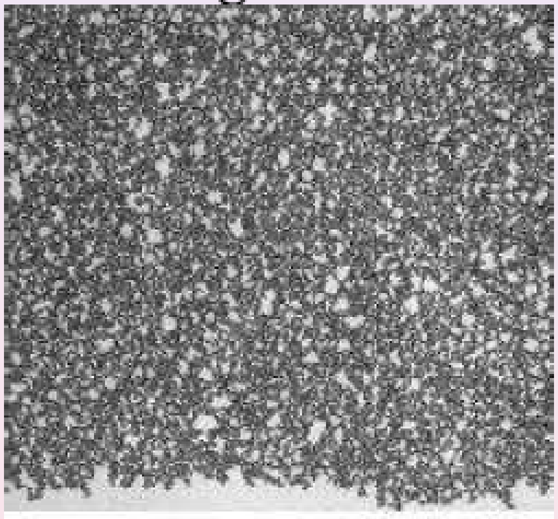
- Random monolayer of 1 mm glassbeads between plates
- $\sim 180 \times 110$ pores system size



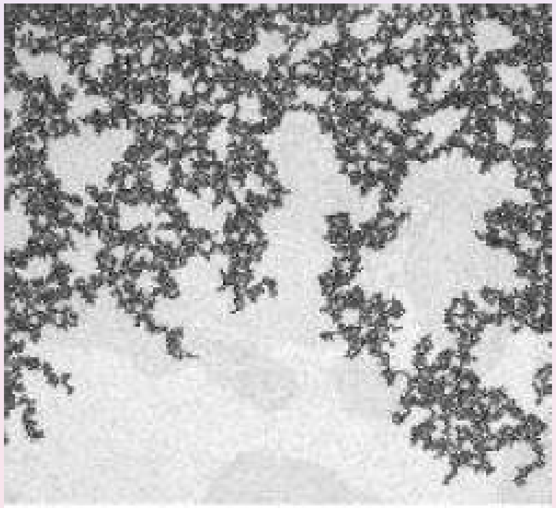
- System parameters:
  - Porosity $\phi = 0.62$
  - Permeability $\kappa = 1.7 \times 10^{-7}$ cm^{-2}
  - All invasion experiments done at: $Ca = 4.3 \times 10^{-4}$

Displacement structures depend on velocity and viscosities and gravity:

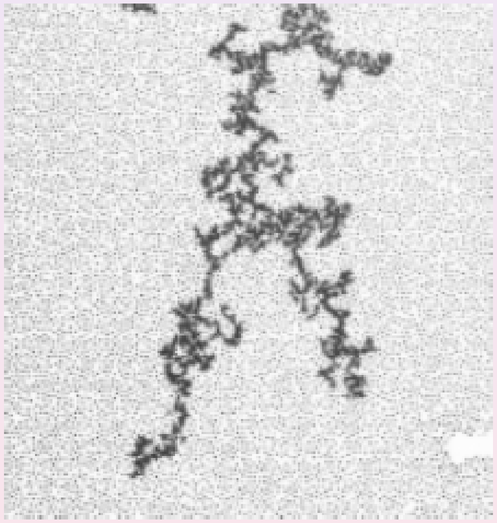
- *Viscous contrast:* $M = \frac{\mu_{nw}}{\mu_{w}}$
- *Capillary number:* $\mathrm{Ca} = \frac{\mu v a^2}{\gamma \kappa}$ (for $M \simeq 0$)
- *Flow regimes:*



$M > 1$ and high Ca

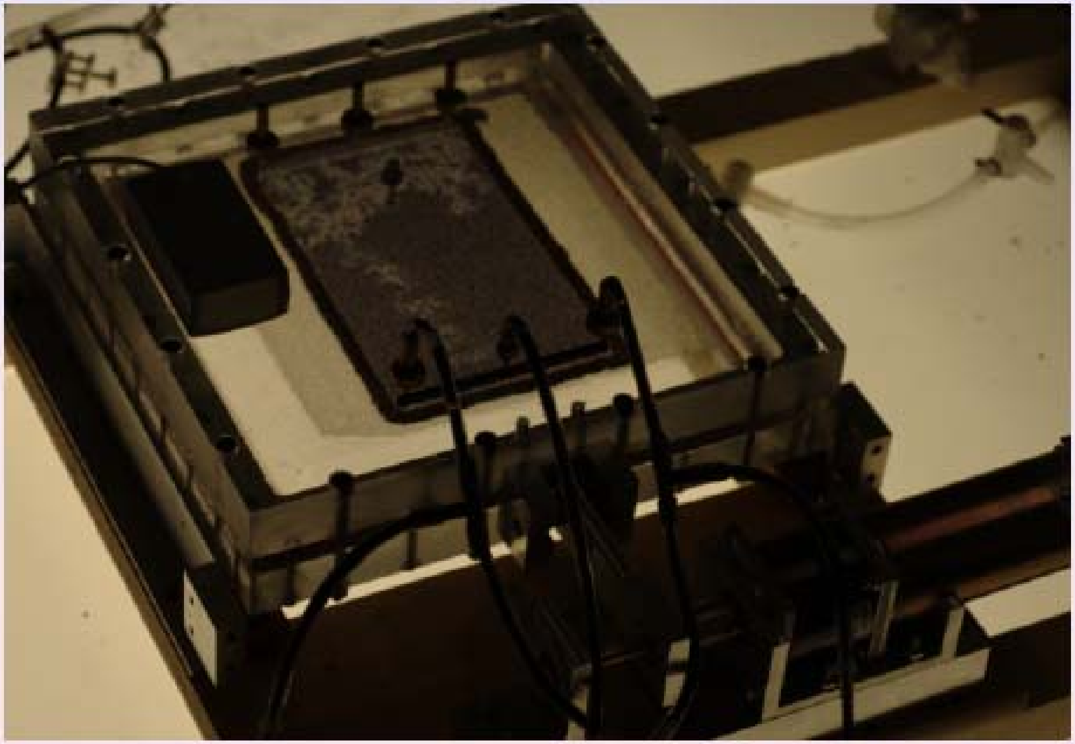


$M \ll 1$ and low Ca



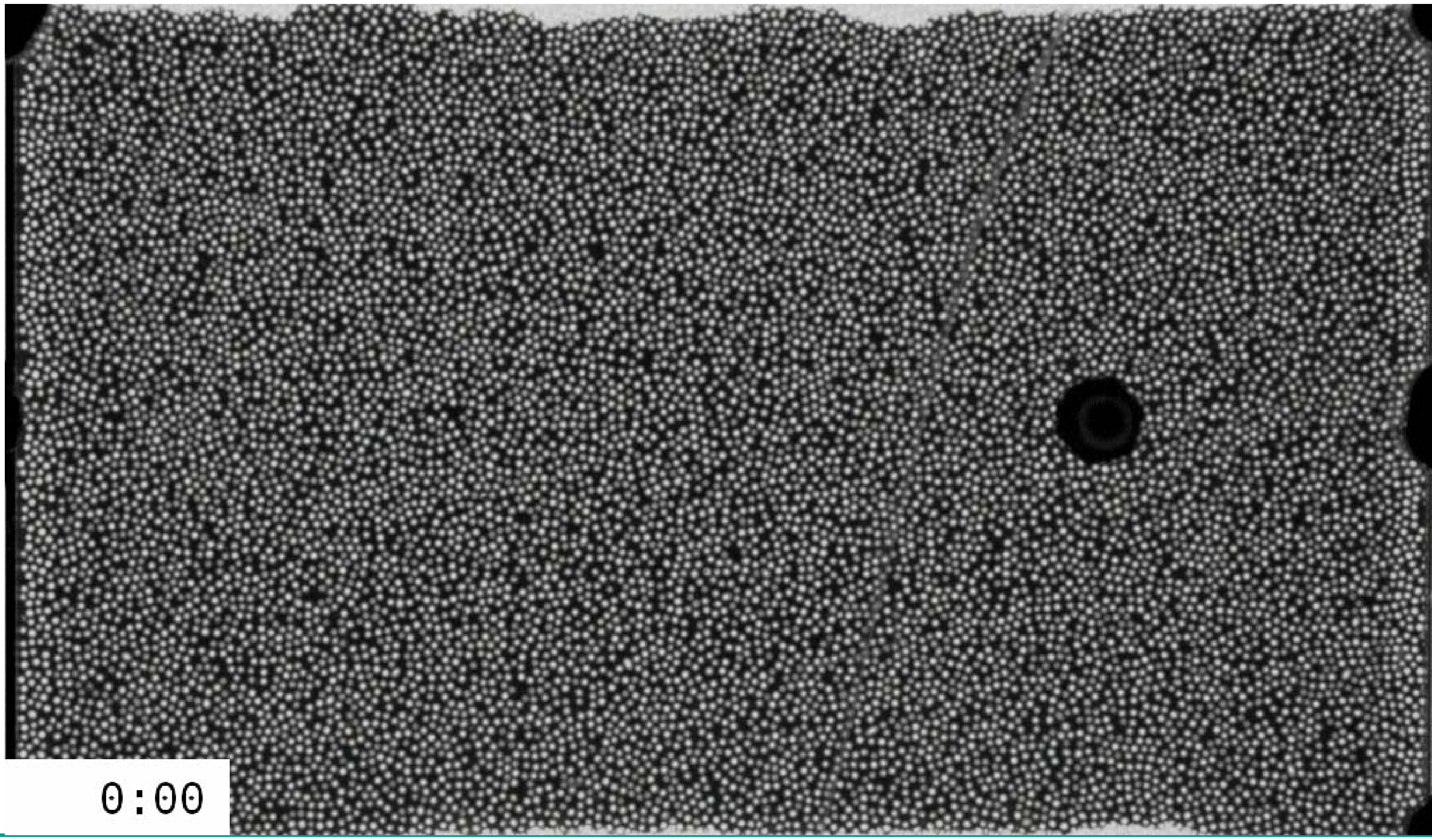
$M \ll 1$ and high Ca

Experimental setup:



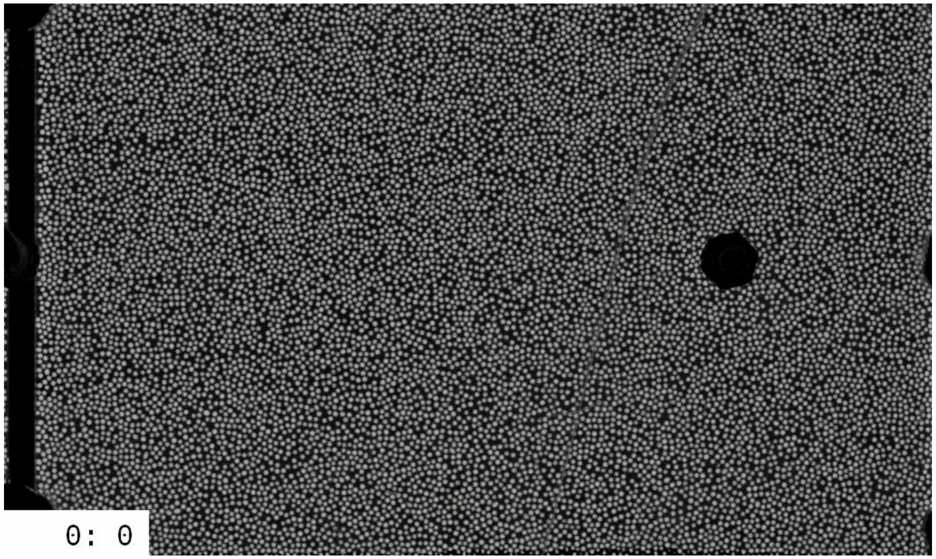
- Model on light box
- Shaking done with DC motor
- Acceleration measured with acceleration sensor

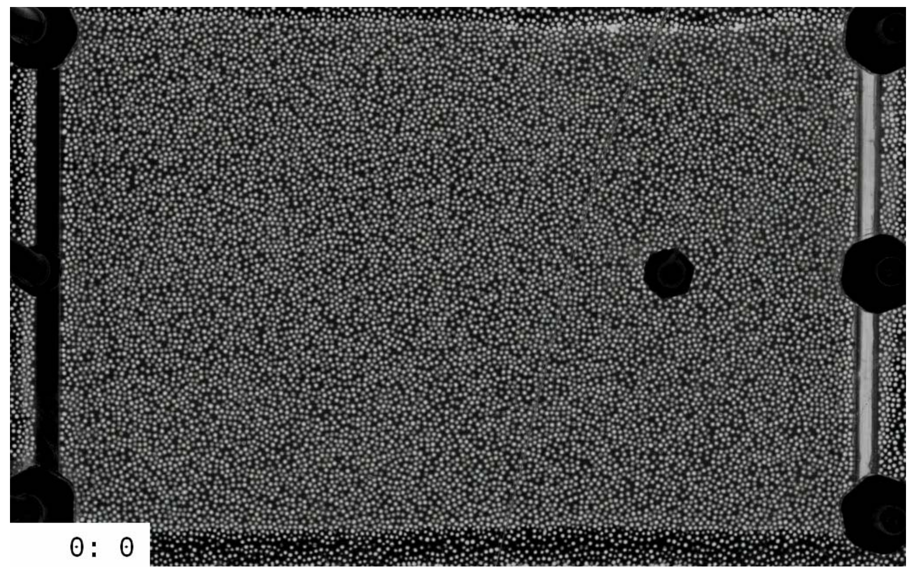
Experiment movie- no oscillations



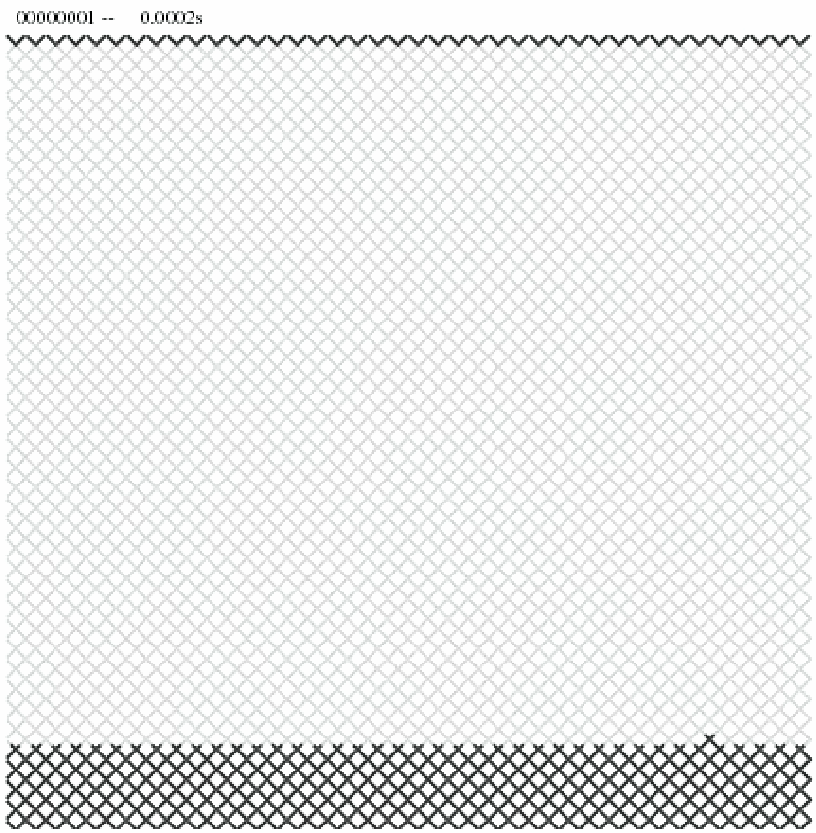
With parallel oscillations: (Ca=0.0004)

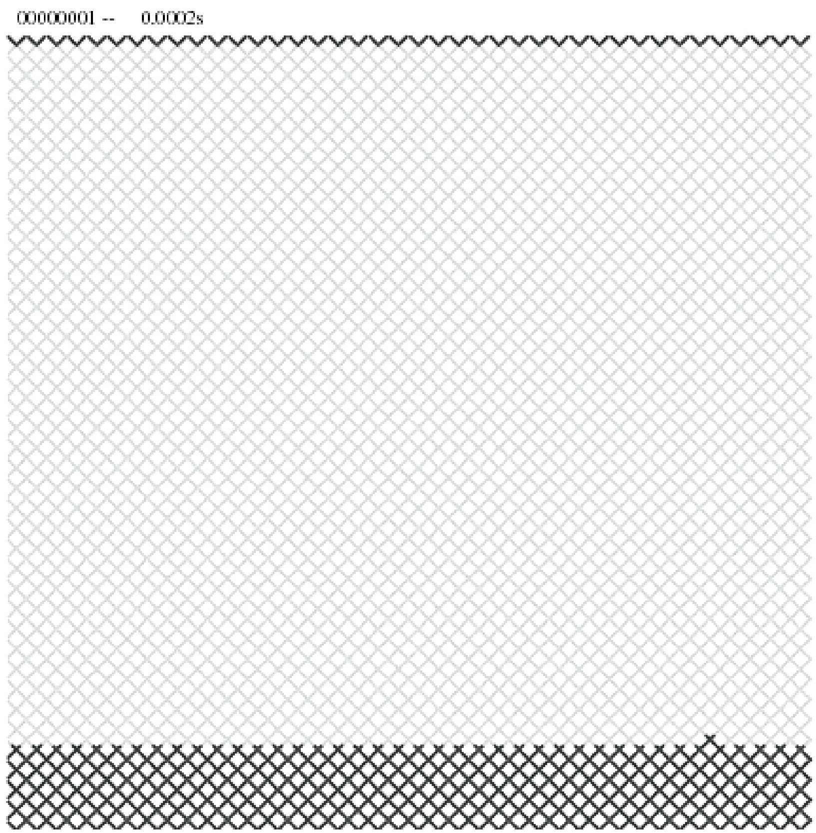
- a=0.8 g
  a=2.6 g



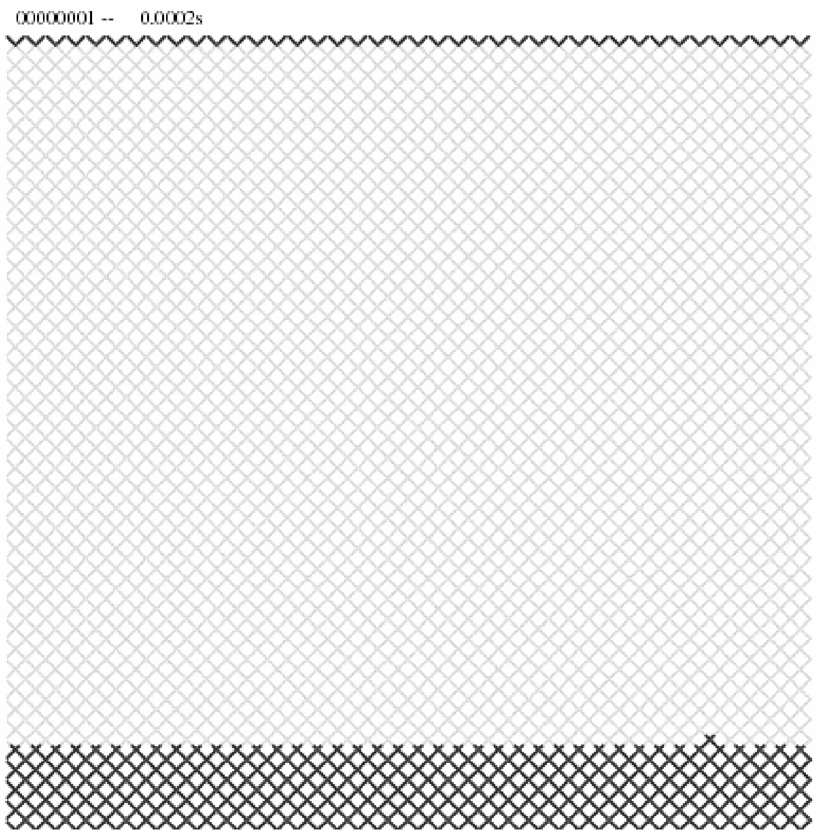

0: 0

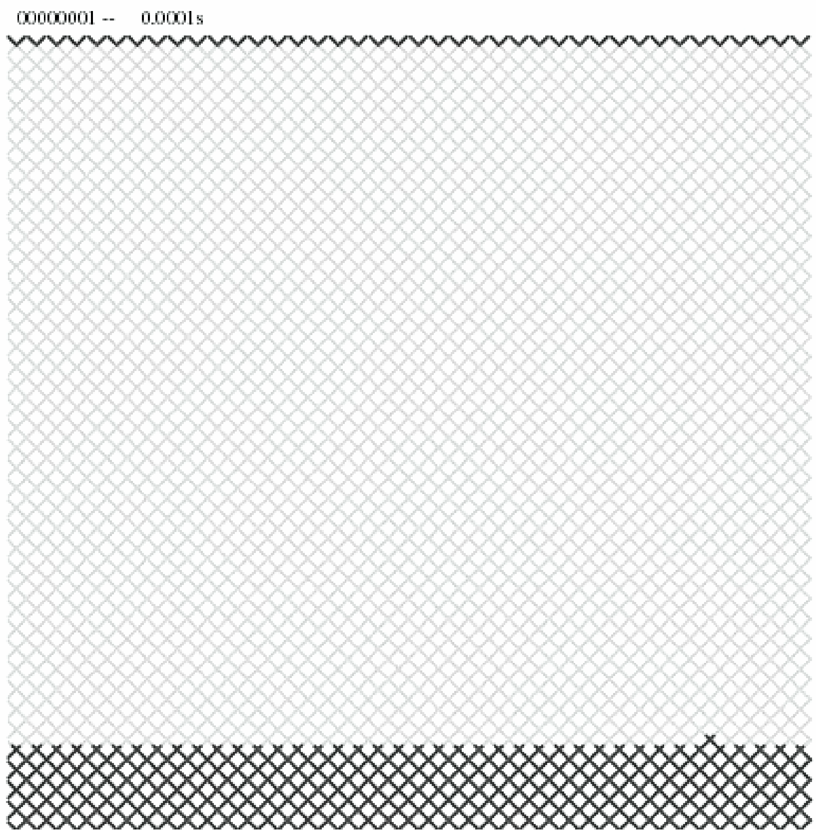
Corresponding network simulations:





..and with transverse oscillations:



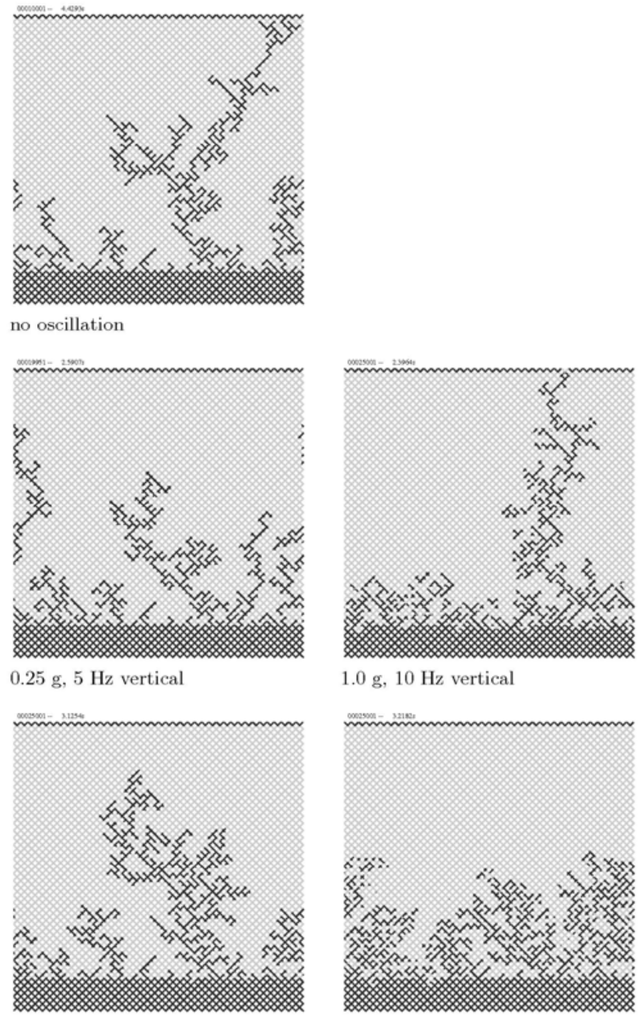


The different frequencies and accelerations:

- No oscillations

- Parallel osc:

- Transverse osc:



no oscillation

0.25 g, 5 Hz vertical

1.0 g, 10 Hz vertical

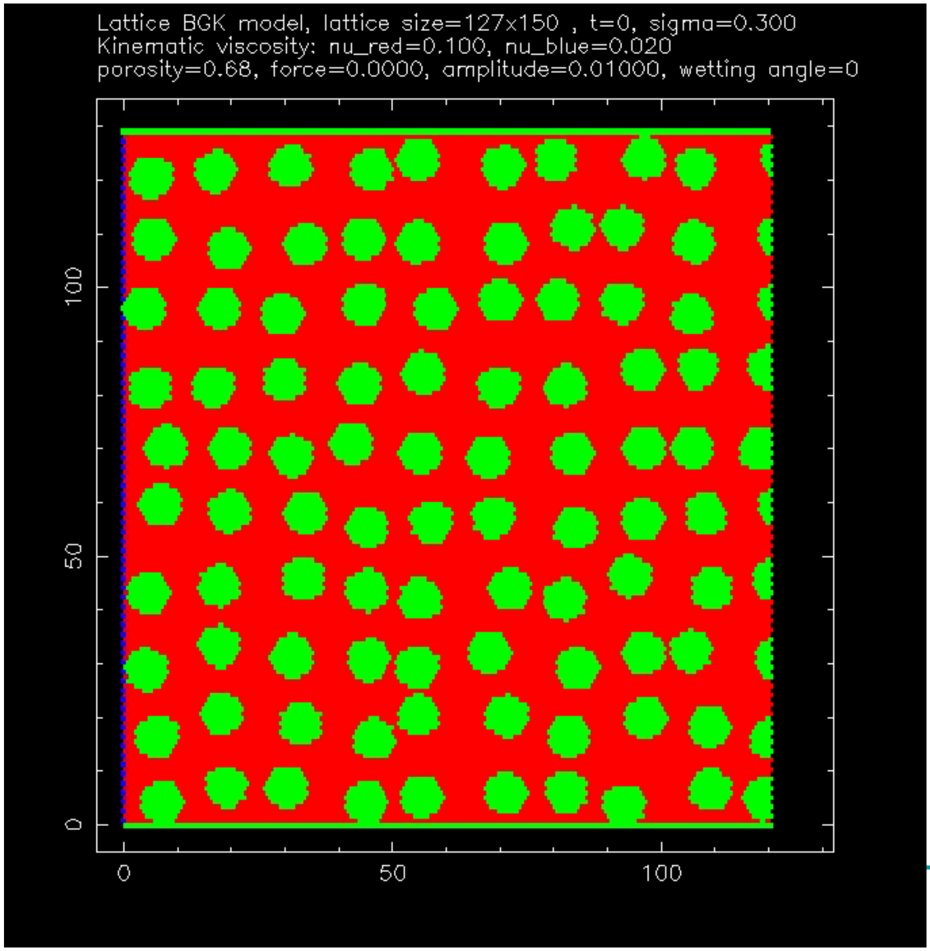
0.25 g, 5 Hz horizontal

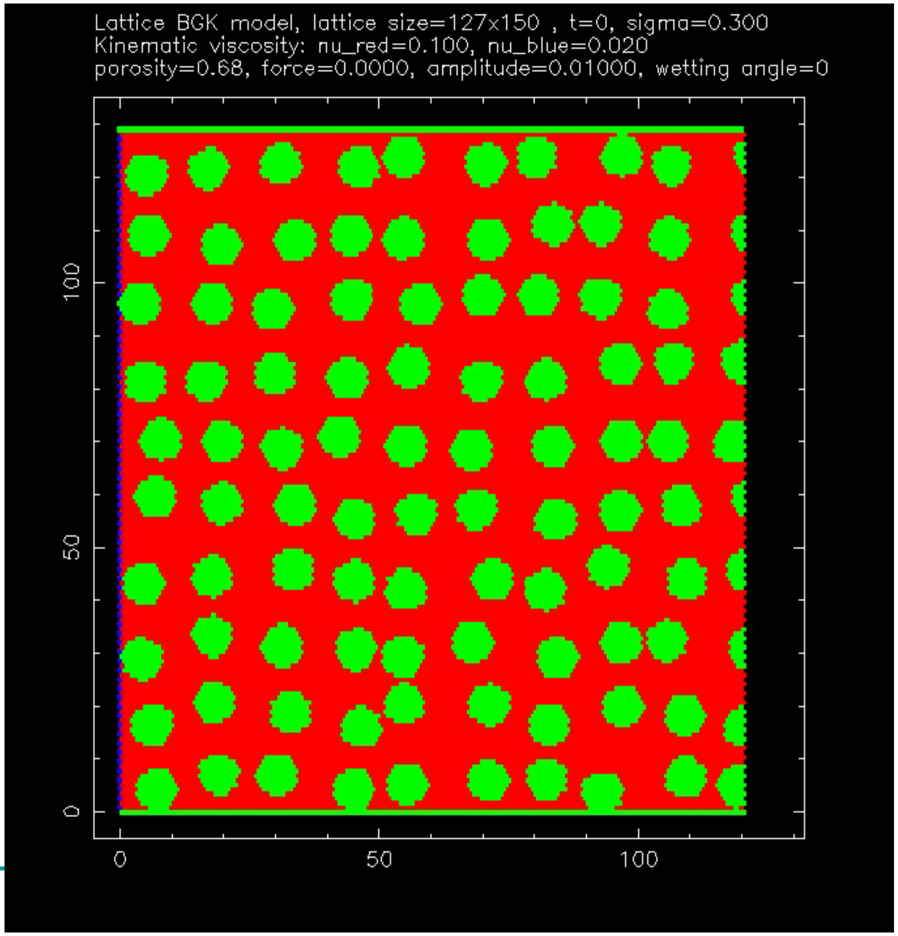
1.0 g, 10 Hz horizontal

2

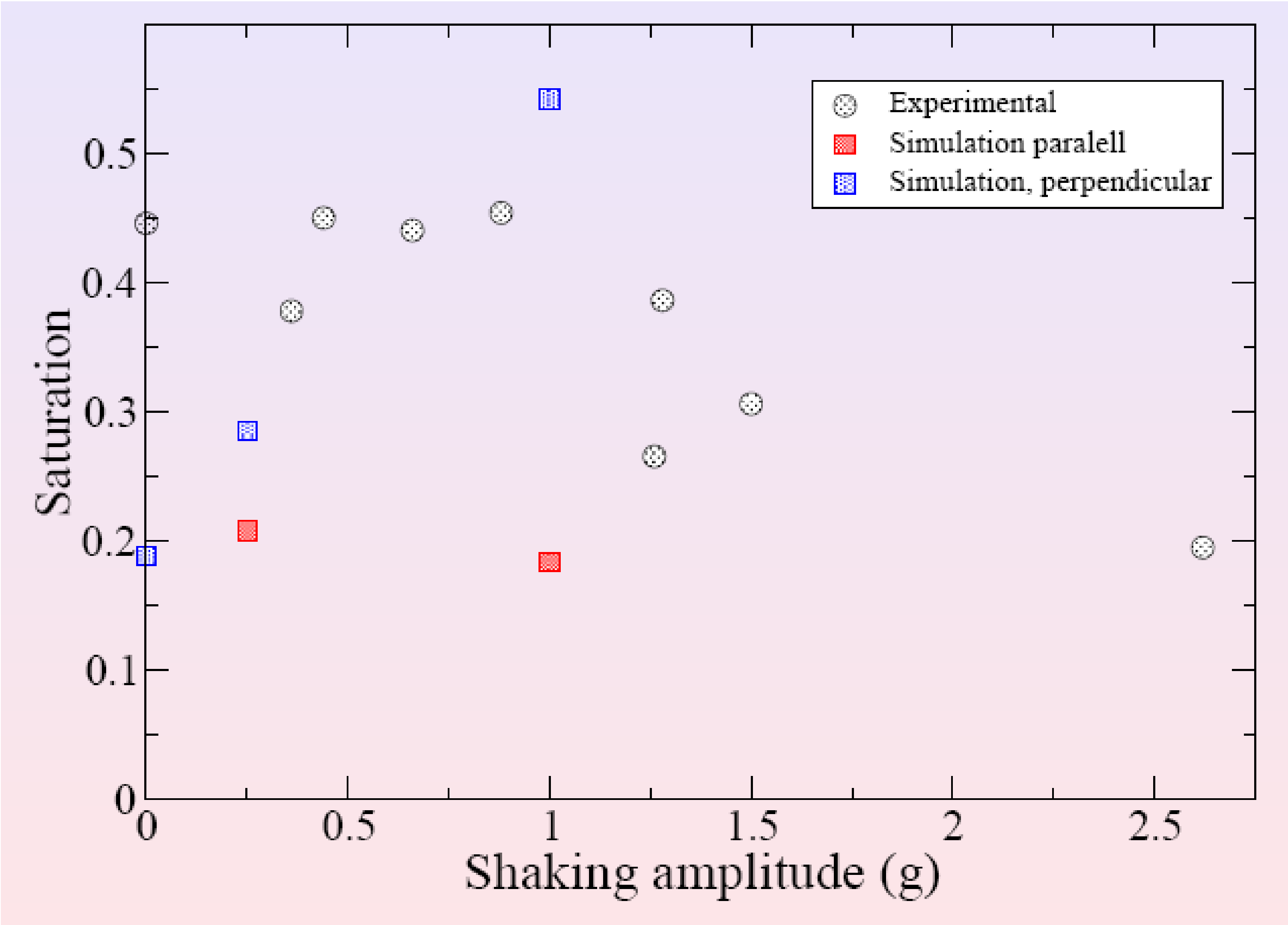
Lattice Boltzmann

- Longitudinal and transverse oscillations

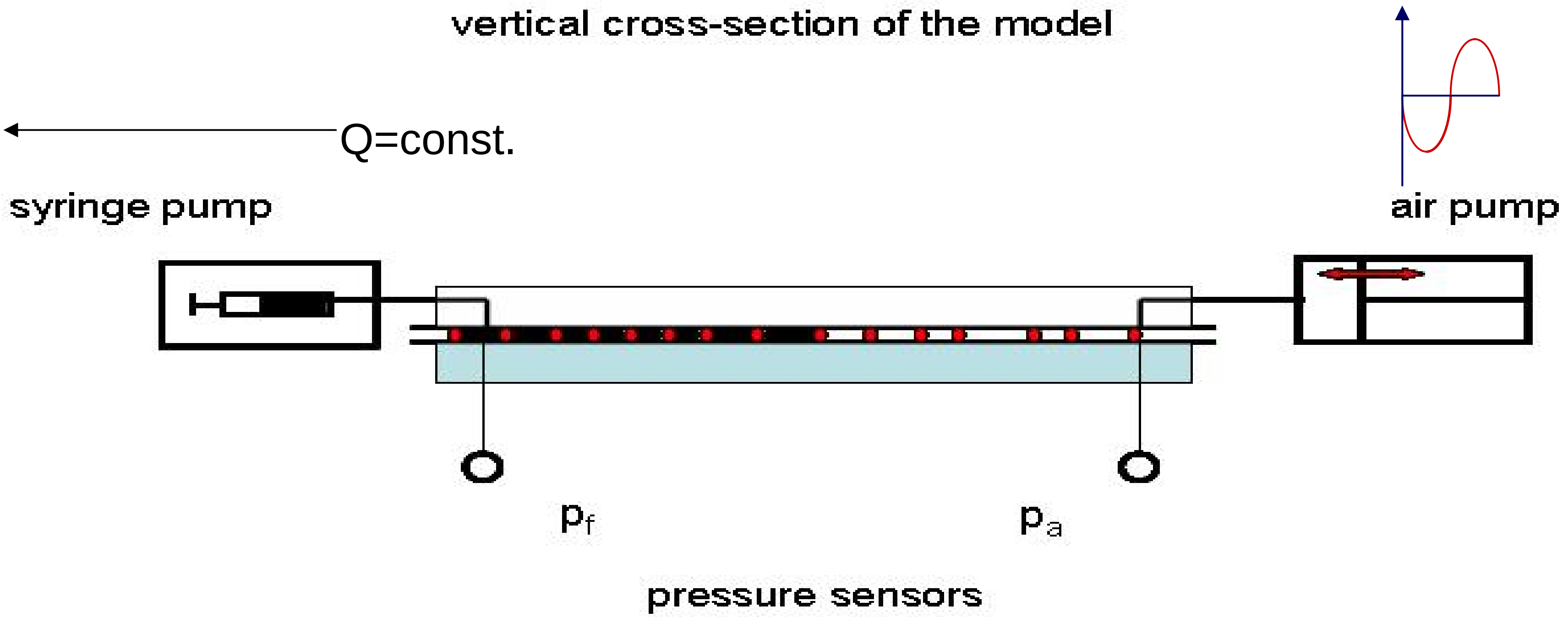




Resulting, end saturations of wetting fluid:

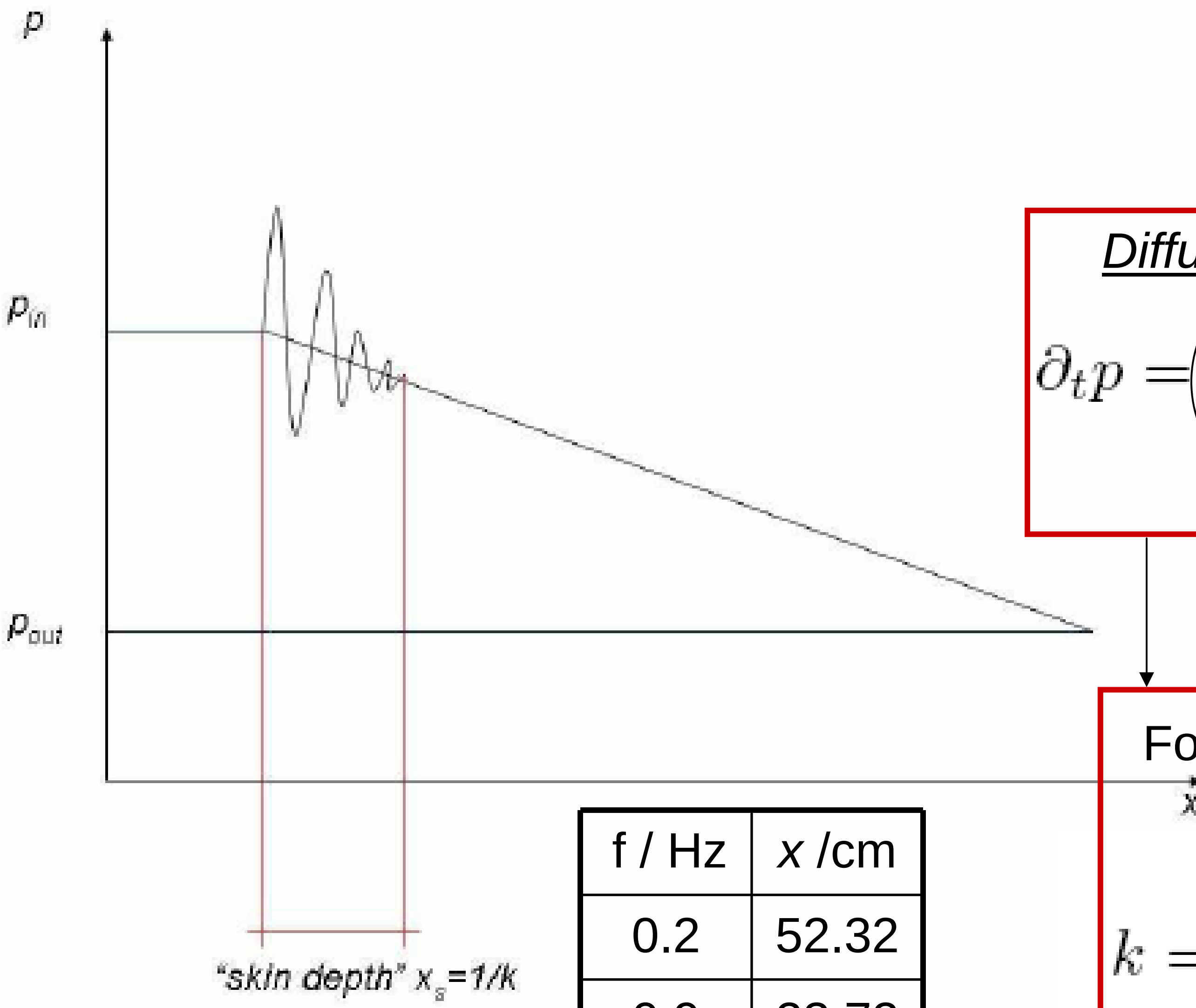


An experiment with compressibility:



Linear elastic response of both air and local plate displacements may model fluid compressibility under much higher pressures.

Elastic response gives finite skin-depth:



f / Hz	x /cm
0.2	52.32
0.9	23.72
4	11

Diffusion equation

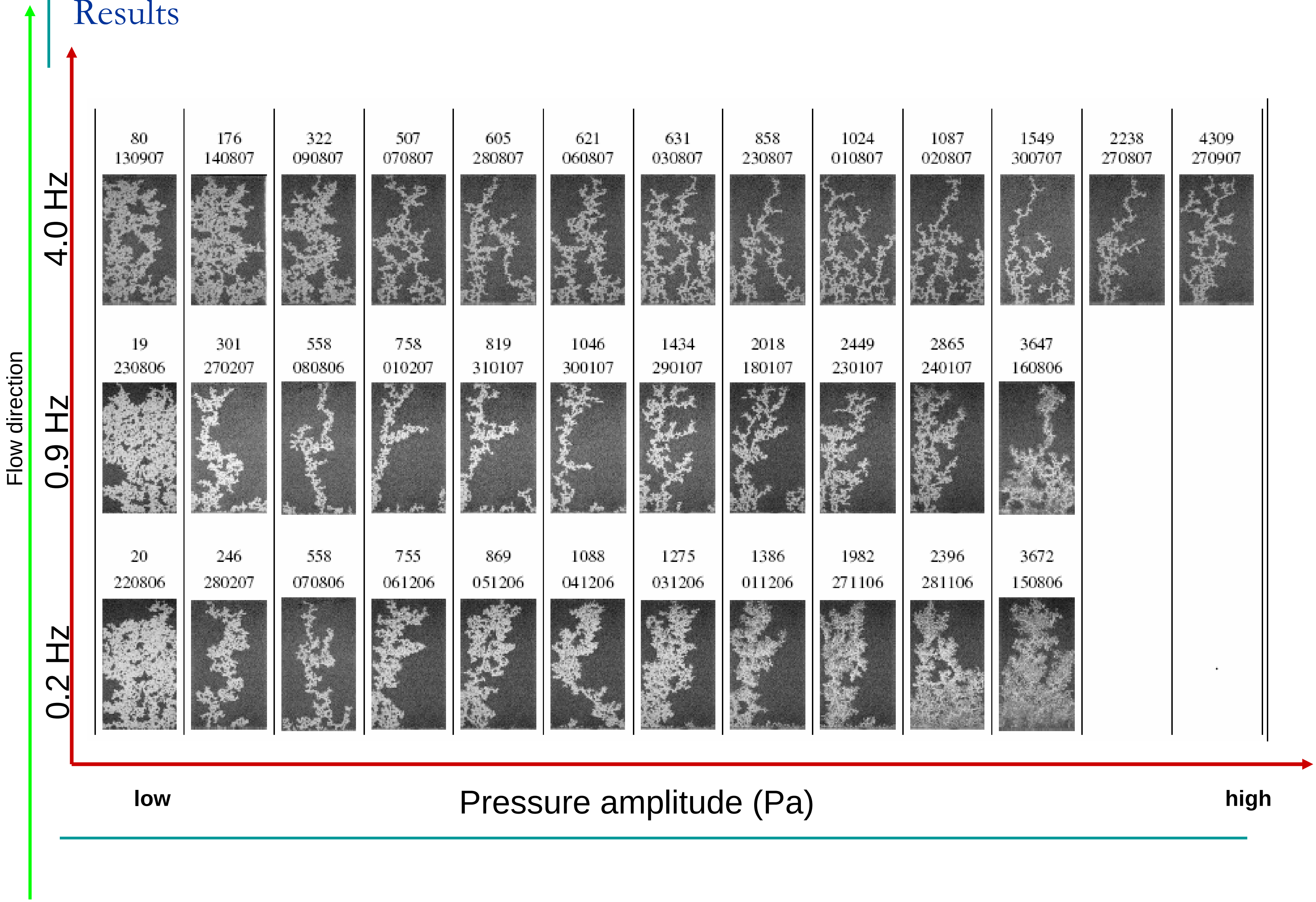
$$\partial_t p = \frac{\kappa h_0 p_0}{\eta \phi a} \nabla^2 (p)$$

D

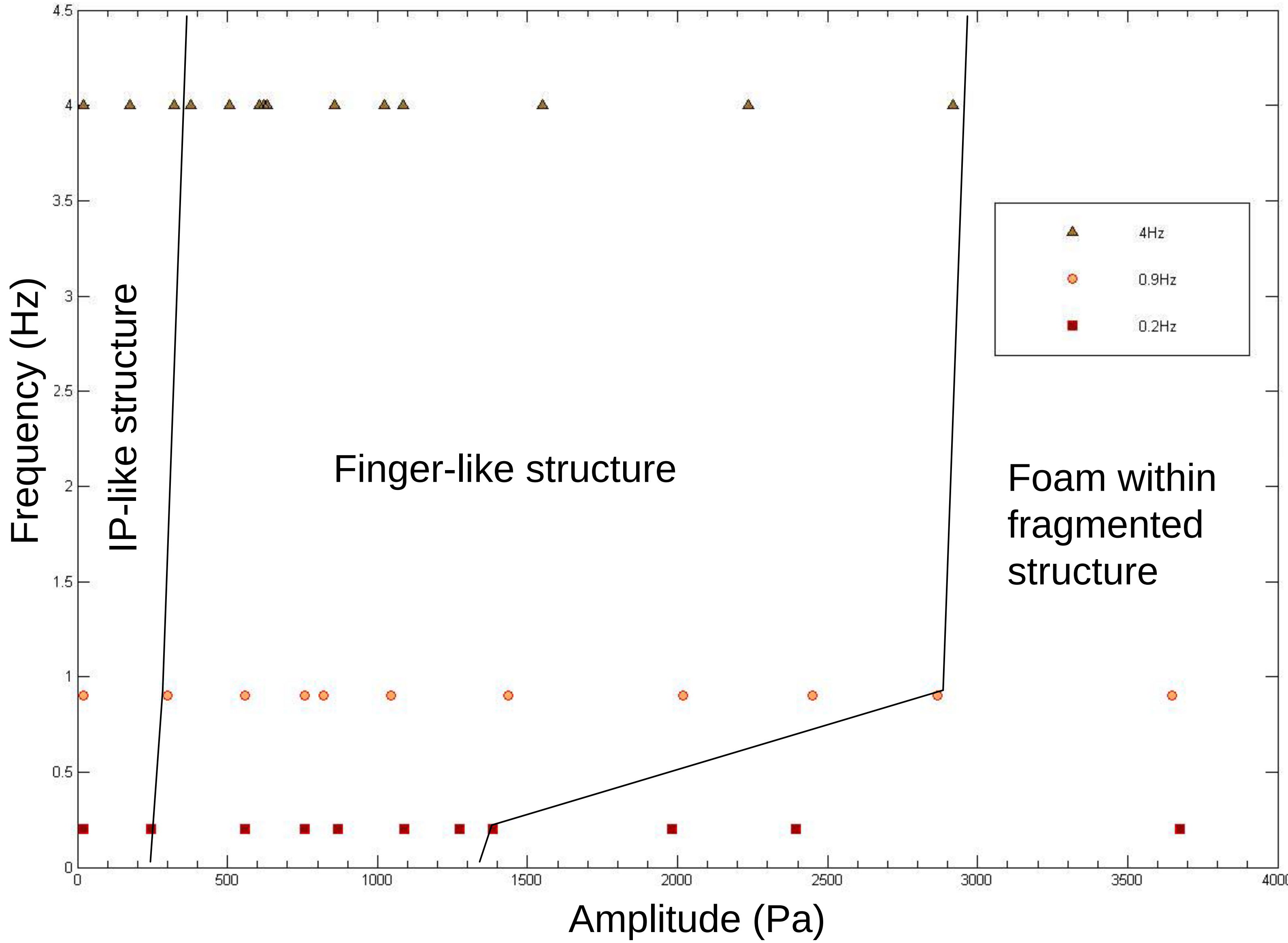
For damped oscillations:

$$k = -\frac{\sqrt{2}}{2} \sqrt{\frac{\omega \eta \phi a}{p_0 h_0 \kappa}}$$

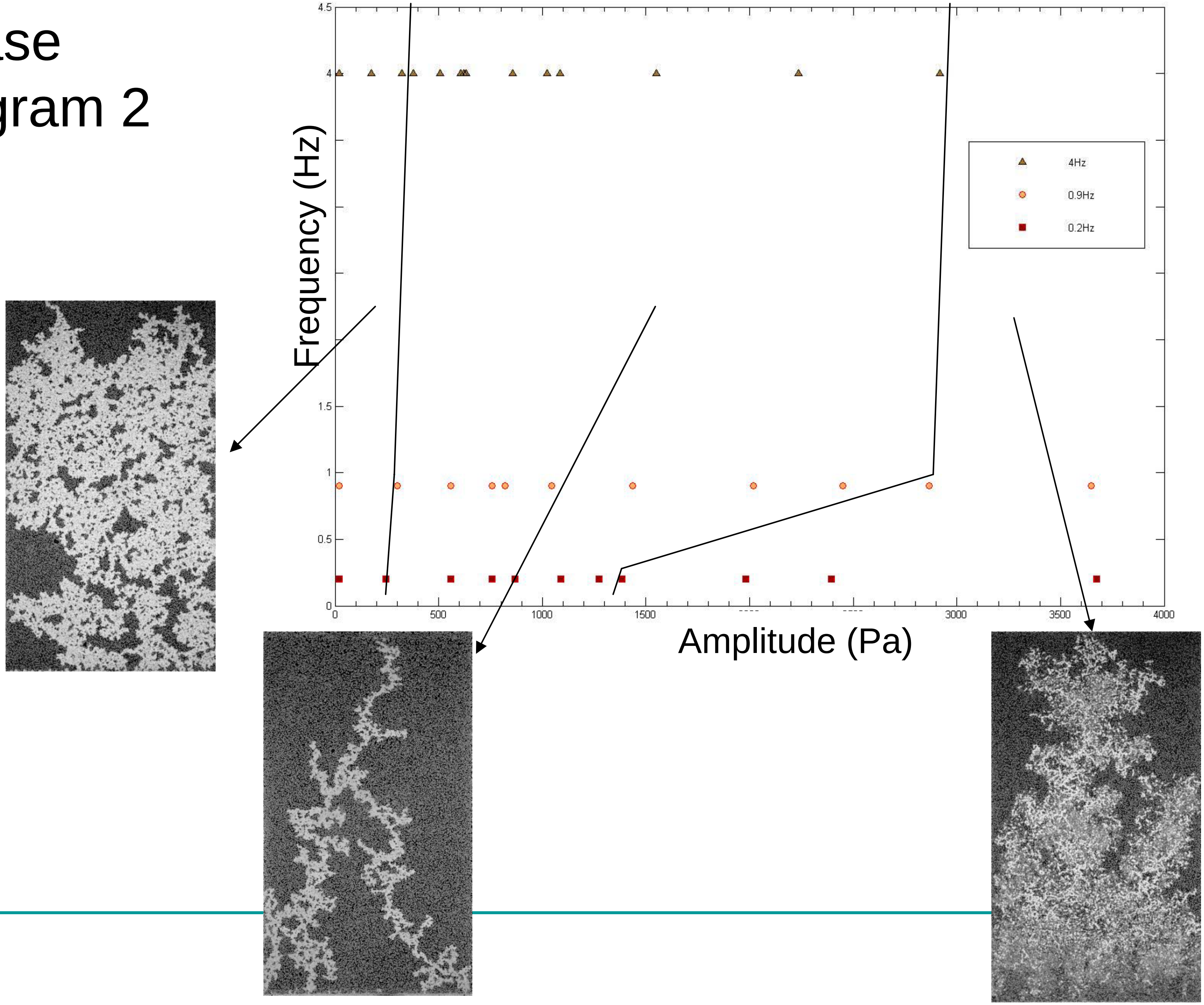
Results


Flow direction
4.0 Hz
80 130907
176 140807
322 090807
507 070807
605 280807
621 060807
631 030807
858 230807
1024 010807
1087 020807
1549 300707
2238 270807
4309 270907
0.9 Hz
19 230806
301 270207
558 080806
758 010207
819 310107
1046 300107
1434 290107
2018 180107
2449 230107
2865 240107
3647 160806
0.2 Hz
20 220806
246 280207
558 070806
755 061206
869 051206
1088 041206
1275 031206
1386 011206
1982 271106
2396 281106
3672 150806
low
Pressure amplitude (Pa)
high

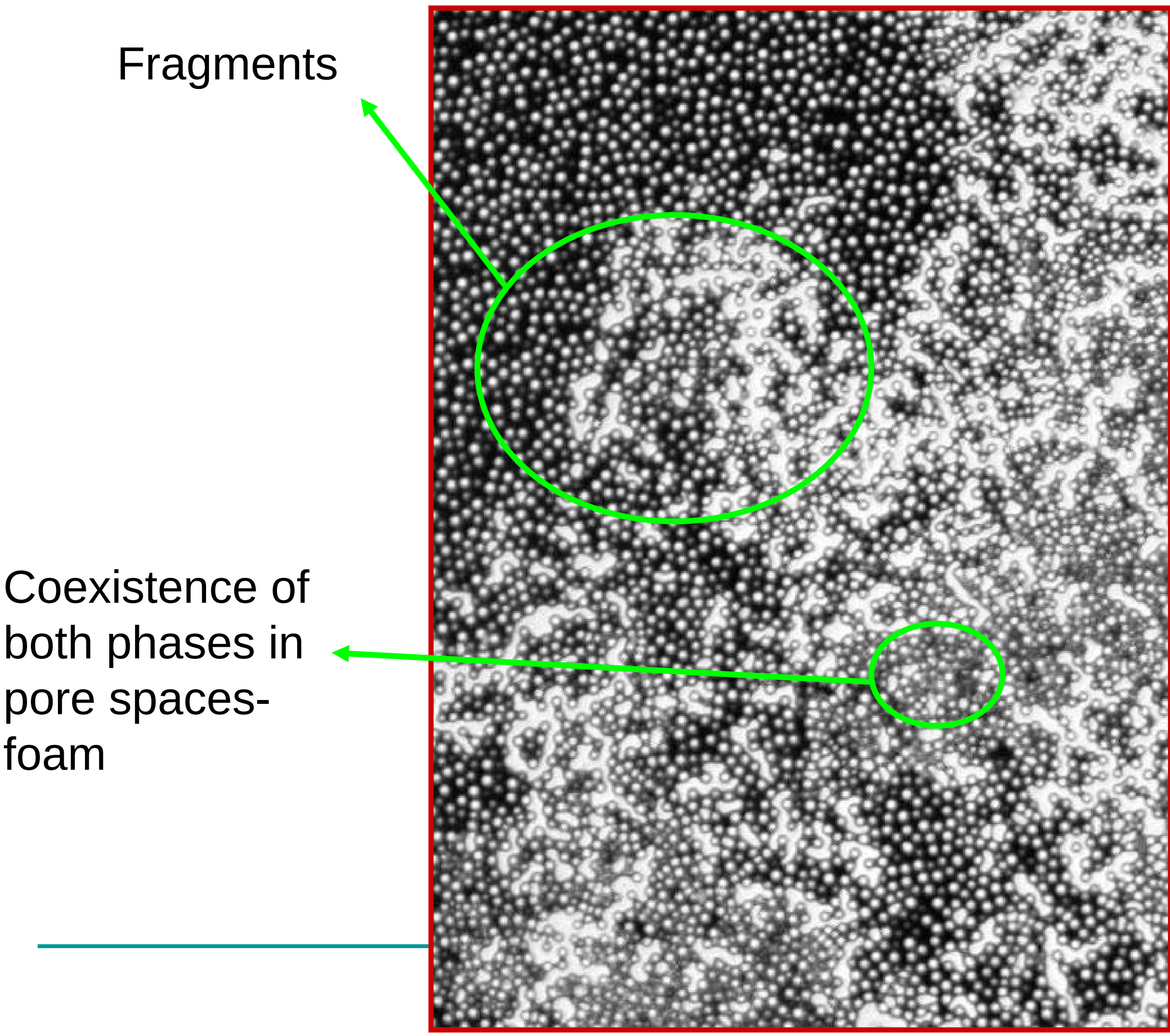
Phase diagram

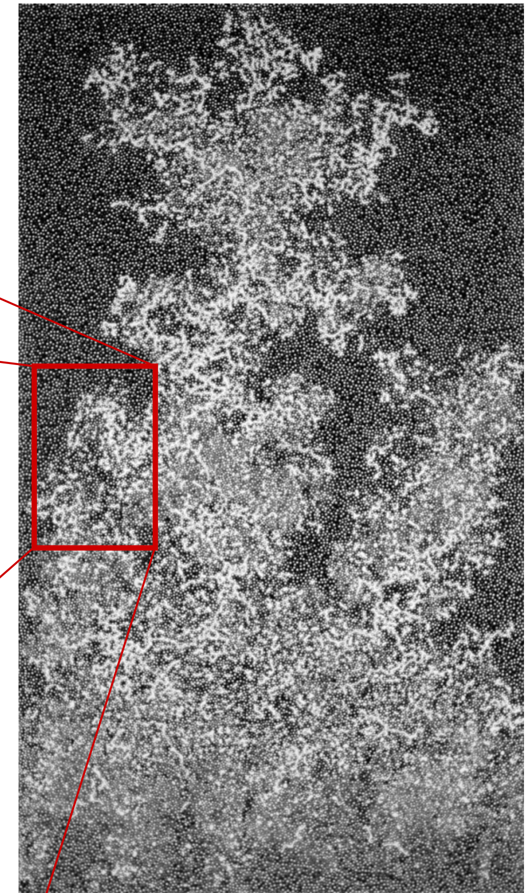


Phase diagram 2



Closer look





Conclusions

- Transverse stimulation more efficient than parallel stimulation, at least for high fractions of invading fluid
- Smaller scale coalescence potentially more efficient at smaller volume fractions
- Compressibility gives skin-depth
- Simplified (network) and 2D simulations (Lattice Boltzmann) capture experiments
- Quantification, analysis and scaling laws still lacking