Water Partitioning Between Shale Matrix and Fractures

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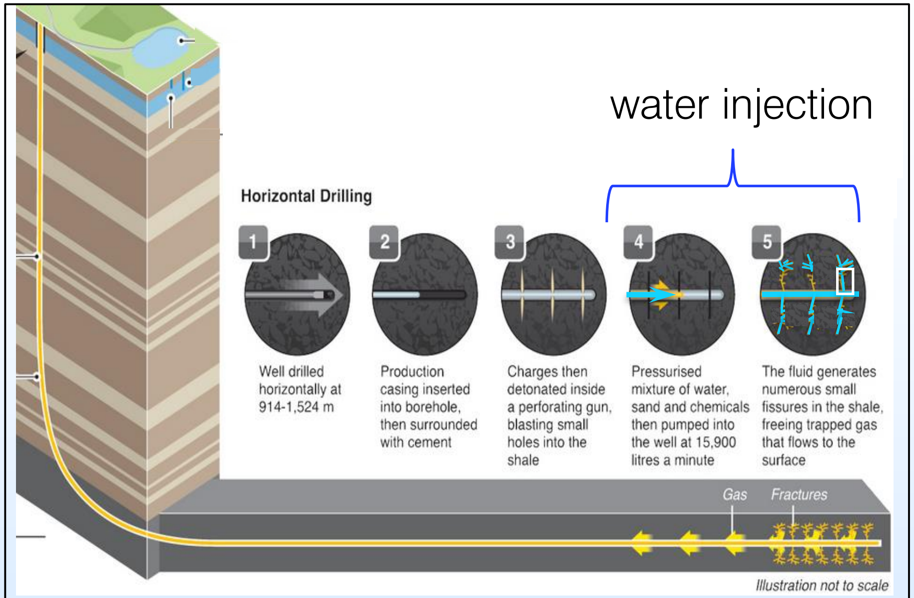
Presentation Outline

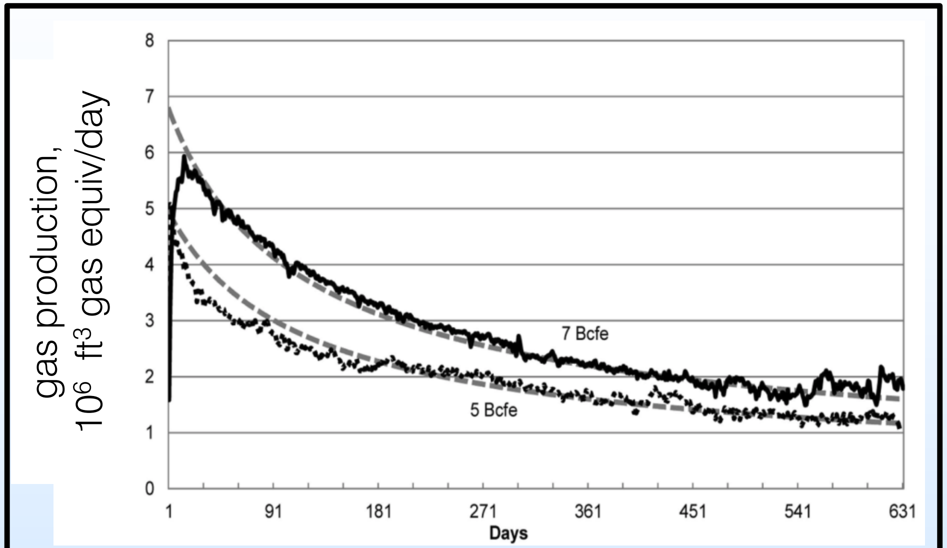
- Problem statement, challenges, needs
- Goals/Objectives
- Summary of current budget period activities
  - Hydraulic fracture drainage
  - Water imbibition dynamics
  - Improving representations of production from unconventional wells
- Next budget period (Oct. 2019 – Sep. 2020) plans

Problems of water use in hydraulic fracturing



modified from *National Geographic, Chesapeake Energy, EIA, & USGS*

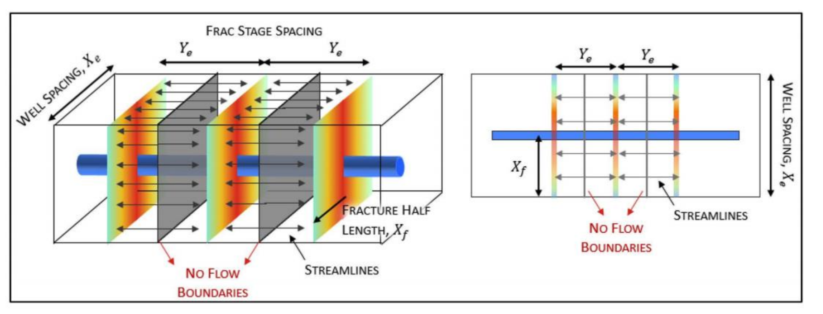
What is optimal injection for production?



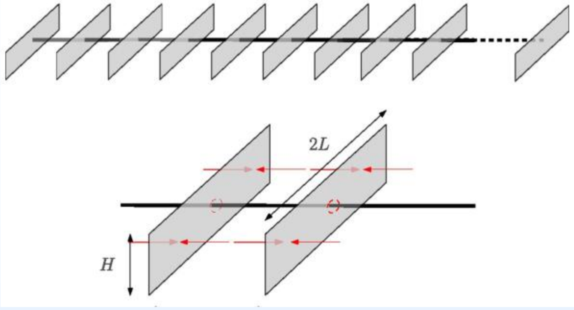
Marcellus Shale wells, Ultra Petroleum, 2012

- 10^6 to 10^7 gallons of water is used per well to hydraulically fracture shale reservoirs.
- Cost of water supply and flow-back water treatment are large ($50K to $1M per well).
- Typically > 70% of injected water remains in the reservoir, and restricts counter-current flow of gas back to wells.
- A rational basis to reduce water use can be beneficial.

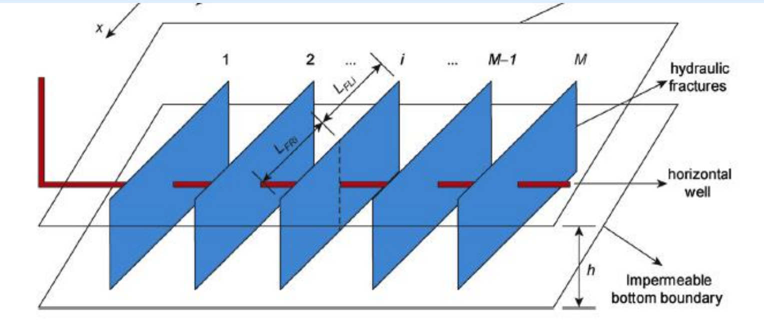
Common simplification of multiple parallel hydraulic fractures



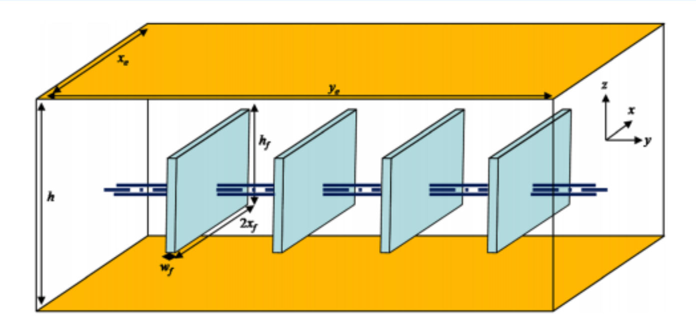
Song & Ehlig-Economides, SPE144031, 2011
Sorek et al., SPE170965-ms, 2014



Patzek et al., PNAS 2013



Gu et al., Petroleum, 2017



Zhang & Yang, J. Energy Resour. Technol., 2018

- Unknown fracture surface area contacting matrix rock
- Unknown impacts of water along the fracture-matrix contacts

Challenges and Needs

- Transport properties controlling water and gas distributions are spatially variable, and fracture connectivity is complex.
- Actual distributions of matrix and fracture permeabilities will never be known.
- Improved, physically-based, practical models are needed to guide improved water use.

Goals and Objectives

- Improve understanding and predictions of water imbibition and redistribution in low permeability materials (matrix and fractures)
- Identify the hierarchy of factors controlling water blocking
- Improve simple models of water-gas transport in reservoirs
- Understand impacts of varying water injection volumes and shut-in times on production

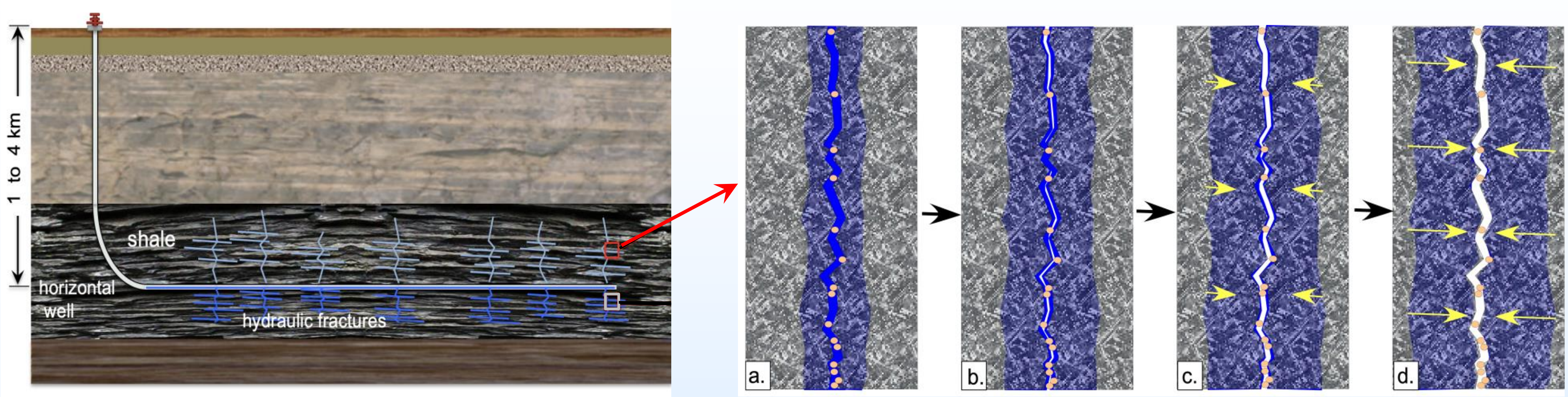
Questions

- How readily are frac fluids drained from fractures?
- How important is gravity at the scale of the stimulated reservoir volume?
- How thick are water-damaged zones along hydraulic fractures?
- What determines optimal water injection volumes and shut-in times?

Focused studies on flow in two elementary zones.

- Fractures
- Matrix along fractures

Water in fractures: how efficient is drainage?



Imbibition of water into the shale matrix is responsible for most of the unrecovered water volume (addressed later).

Gravity facilitates of water removal from fractures above horizontal wells.

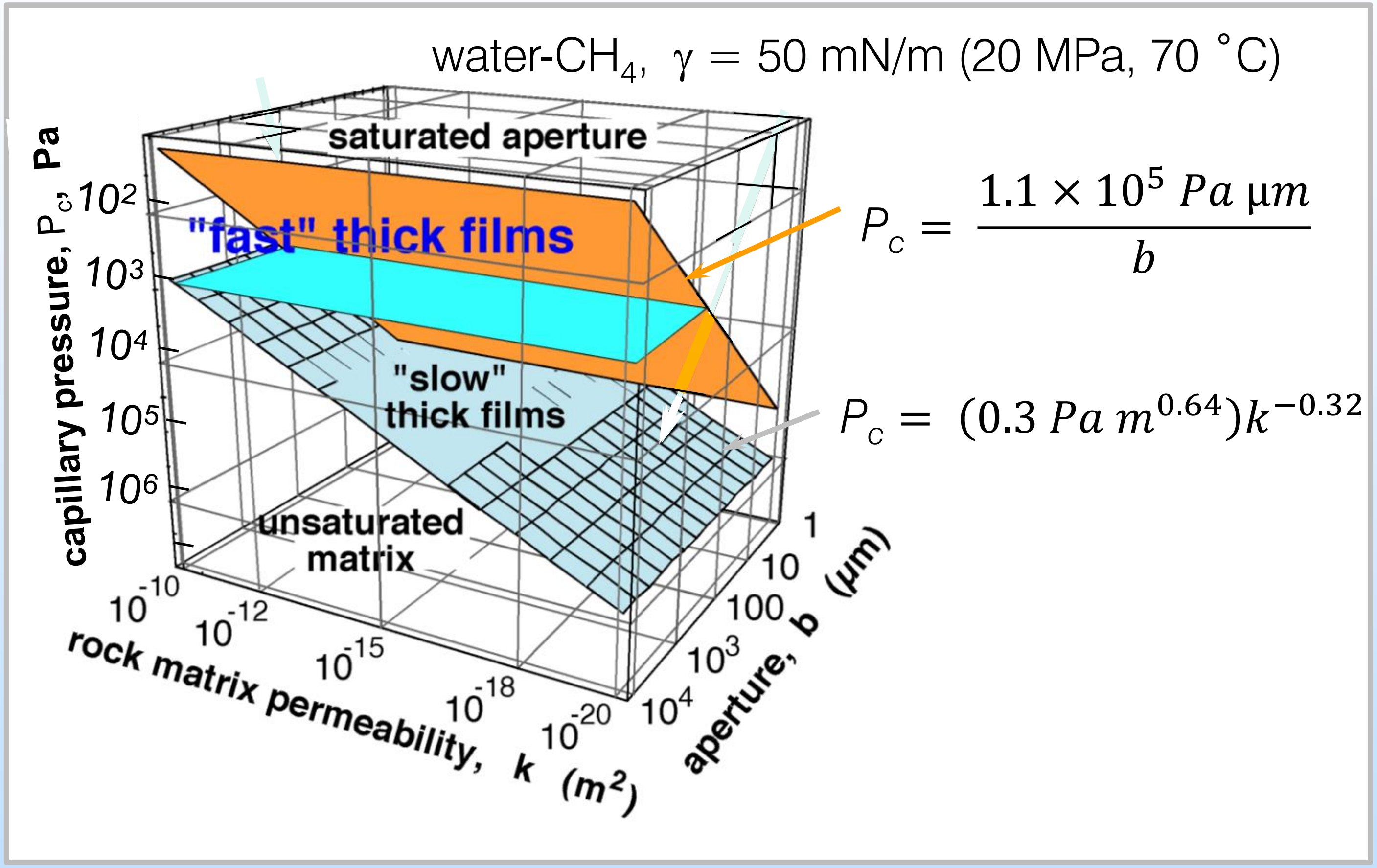
What happens after fractures become unsaturated?

Gravity impairs drainage from fractures below horizontal wells.

Is fracture dewatering from counter-current gas flow effective?

Propped fractures support efficient unsaturated drainage by flow in thick water films

Local hydraulic states along fracture-matrix boundaries



water-CH_4, $\gamma = 50$ mN/m (20 MPa, 70 °C)

$$P_c = \frac{1.1 \times 10^5\ Pa\ \mu m}{b}$$

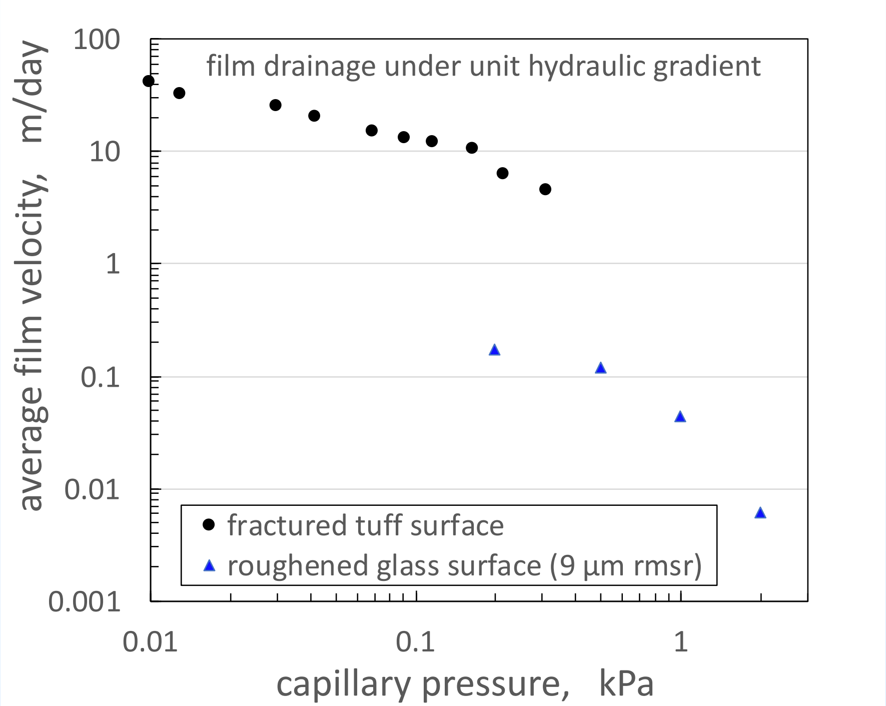
$$P_c = (0.3\ Pa\ m^{0.64})k^{-0.32}$$

Gravity-driven flow of water at low P_c in propped fractures is fast.

Tokunaga et al., in prep.

Propped fractures support efficient unsaturated drainage by flow in thick water films

- At low P_c, thick water films support high water drainage rates, 10s of m/day.
- Therefore, desaturated fractures at low P_c facilitate water drainage IF connected to an underlying "drain", i.e. the horizontal well.
- At higher P_c, water films become too thin to support efficient gravity drainage.
- Frac fluid drainage tests to be run in next phase.

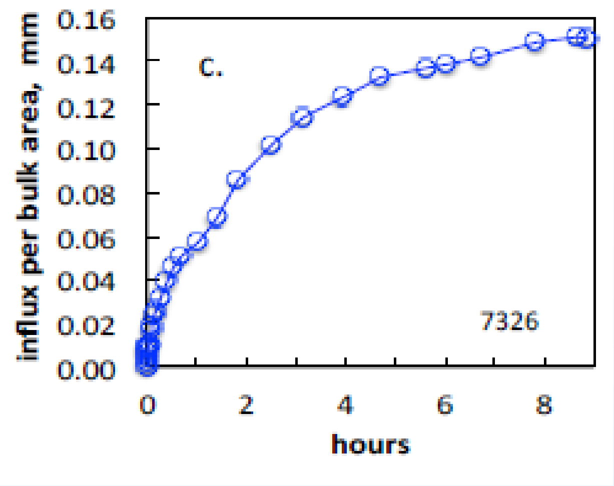


data from Tokunaga et al., Water Resour. Res., 2000

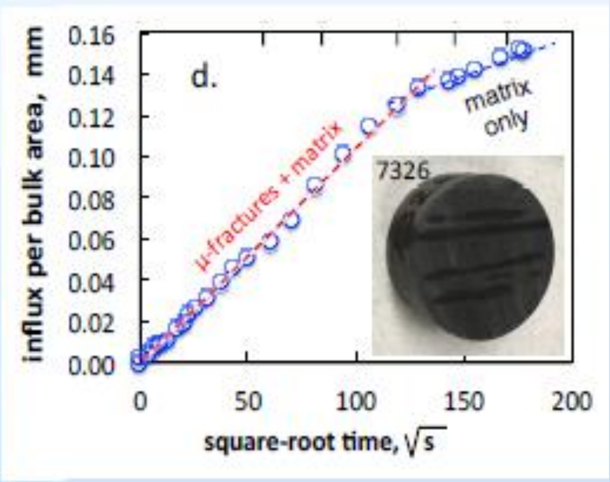
Imbibition of water into porous media:

Need better predictions for imbibition during shut-in

Bell & Cameron (*J. Phys. Chem.*, 1906) identified the basic physics of water imbibition into porous media. Green & Ampt (1911), Lucas (1918), Washburn (1921), and thousands of others followed.



As the wetting front advances, the driving capillary pressure (P_c) gradient dissipates. Permeability multiplied by the dissipating P_c gradient gives the instantaneous flux. Therefore, cumulative imbibition scales roughly with the square-root of time.



Can useful new relations be developed to guide reduction of water use in reservoir stimulation?

Imbibition of water into porous media:

Long-standing high level of uncertainty

The wetting front distance L advances with the square-root of time as

$$L(t) = \sqrt{\frac{2k}{\eta \Delta w}\left(P_{c,f} - P_{c,0}\right)\sqrt{t}} \quad *$$

where k is the permeability, η is the viscosity, Δw is the change in volumetric water content, $P_{c,f}$ is the capillary pressure at the advancing wetting front, and $P_{c,0}$ is the capillary pressure at the surface, Green & Ampt (1911).

* Parameters with highest uncertainty k and $P_{c,f}$, are multiplied, therefore predictions of fluid imbibition are commonly poor.

To circumvent this problem, correlations were identified between k, $P_{c,f}$, and the capillary pressure for gas-entry into water-saturated media, $P_{c,g}$.

Imbibition of water into porous media:

Reduced-order model with lower uncertainty

Insufficient data to correlate k to $P_{c,f}$.

Data are available to correlate k to $P_{c,g}$.

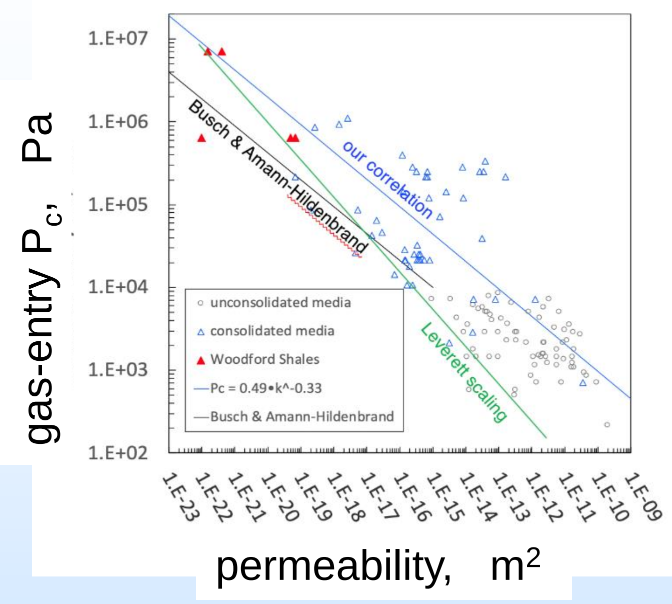
The available $P_{c,g}$ and $P_{c,f}$ span 2 orders of magnitude and are well correlated.

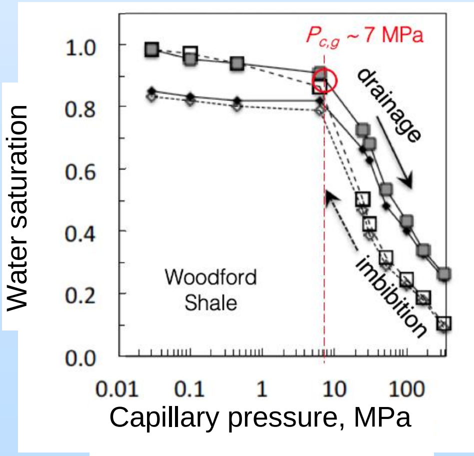
Empirically, $P_{c,f} \sim 1.24P_{c,g}$

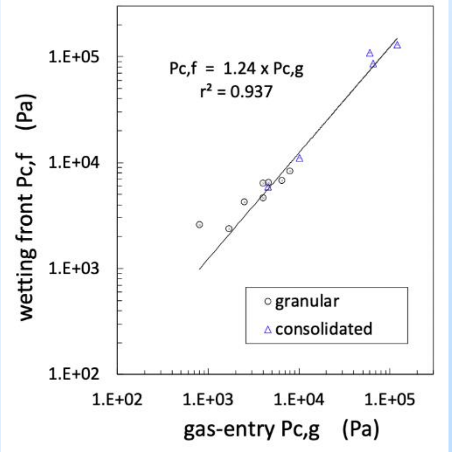
and $P_{c,f} \sim 0.61k^{-0.33}$

The shut-in pressure is scaled as $P_{c,0} = b \bullet P_{c,f}$, ($b < 0$). With these relations, the imbibition front distance is simply

$$L(t) = \sqrt{\frac{2(1+b)}{\eta \Delta w}}\, k^{1/3} \sqrt{t}$$





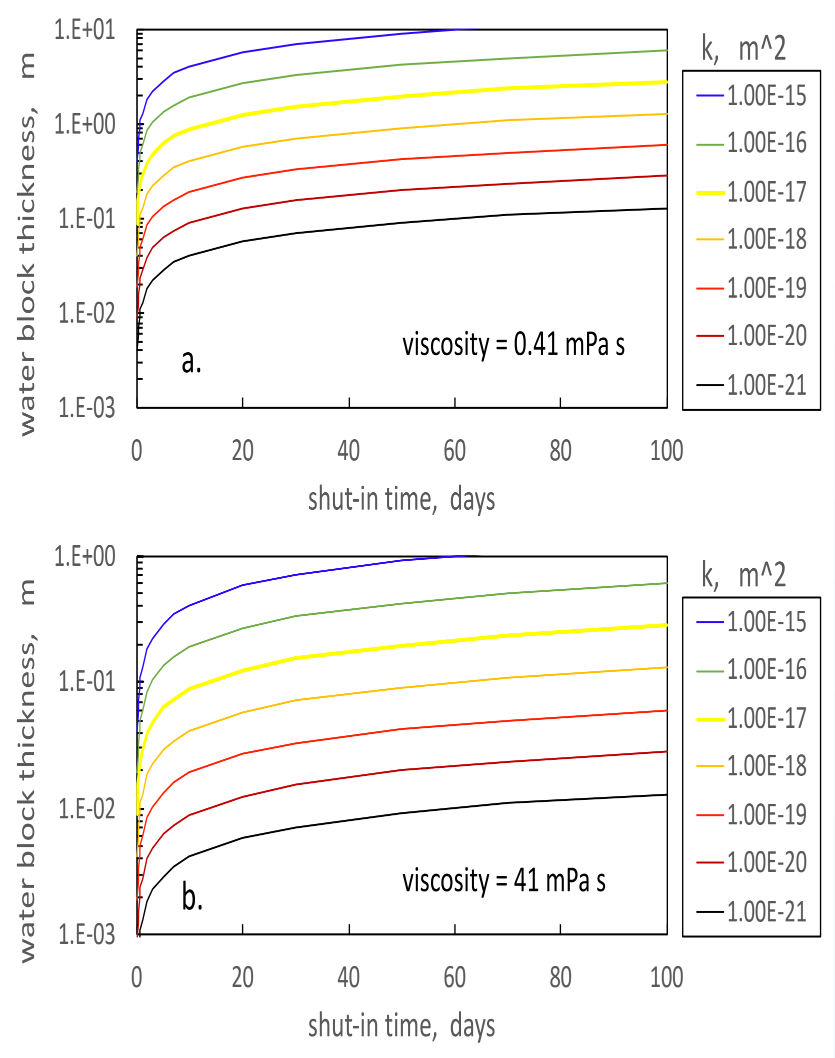


Uncertainty is reduced to *k*

Influences of *k* and shut-in time on water uptake

Imbibition for a range of *k* , with viscosity = 0.41 mPa s (water at 70 ˚C, 20 MPa), and 41 mPa s (100x ‘thickened’).

- Imbibition distances for typical shut-in periods are just a few cm.
- Water block thicknesses envelop the fracture-microfracture network, but only to short distances, even over long periods of shut-in.



Expanded Lab and Modeling Activities

Lab Activities

- Purchase Lab supplies
- Imbibition tests
- Microfluidics
- Fracture drainage experiments

Modeling Activities

- Background study
- Scaling analysis
- Numerical simulation

Parametric Study

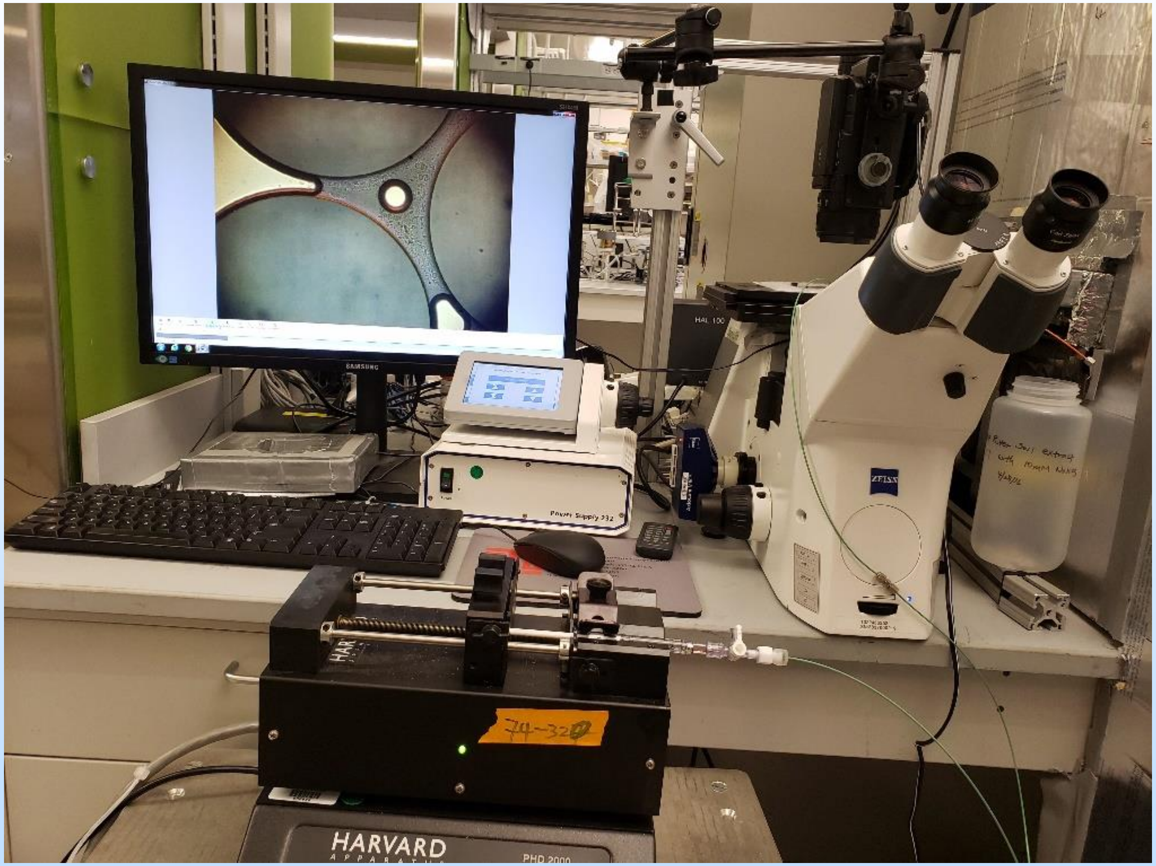
- Fracture properties
- Formation properties
- Shut-in duration

- Ongoing
- Planned

Pore-scale observations using "Lab-on-chip" micromodels

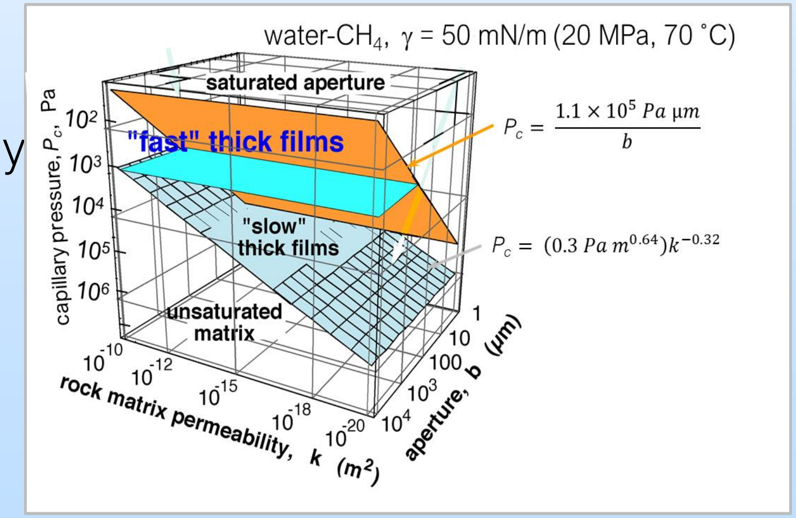
Microfluidics setup

Micromodel



Forces governing multiphase fluid flow in Hydraulic Fractures

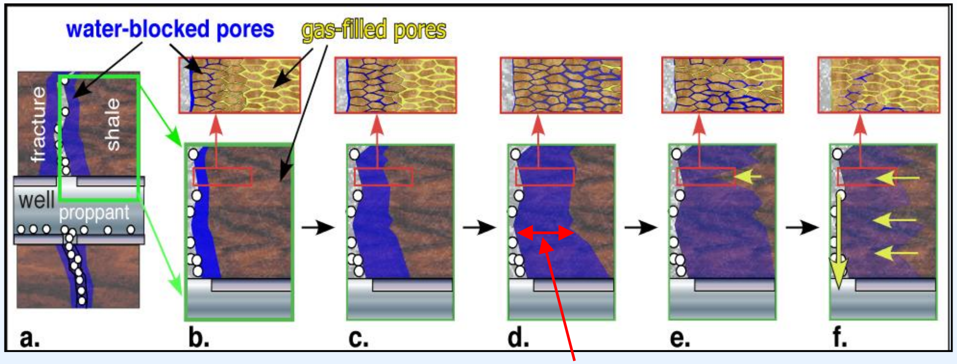
- Capillary force
  - ✓ Imbibition- Drainage mechanisms: Accounts for percolation of frac fluid during shut-in period and post shut-in gas production.
  - ✓ Determines water-gas counter and cocurrent flows near fracture surfaces
  - ✓ Fracture aperture (b), Initial water saturation (S_{wi}), End-point saturations (S_{wc}, S_{gc}), Matrix permeability (k).
  - ✓ P_c – b – S_{wi} – S_{wc} – S_{gc} – k dependence are determined from experiments.
- Viscous forces
  - ✓ Newtonian vs non-Newtonian fluid rheology
- Sorption forces
  - ✓ Adsorption-Desorption
- Gravity force



Water-Block Thickness Relations for Two-Phase Newtonian Fluids Imbibing a Porous Medium

- Capillary and gravity effects (Li and Horne 2006)

$$e^{x_d}\left(1-x_d\right)=e^{-t_d} \quad \text{(Scaled form)}$$



water-block thickness

- Capillary effect alone

$$x=\sqrt{\frac{2M_e p_c}{\left(S_{wf}-S_{wi}\right)\phi}t}=\sqrt{\frac{2M_e p_c}{\left(S_{wf}-S_{wi}\right)\phi}}\sqrt{t} \quad \text{(Unscaled form)}$$

$k_w = f\left(S_w\right)$ = effective permeability of wetting fluid, m^2

$k_{nw} = f\left(S_{nw}\right)$ = effective permeability of non-wetting fluid, m^2

p_c = capillary pressure, Pa or kgm$^{-1}s^{-2}$

S_{wf} = wetting fluid saturation behind the imbibition front

t = Dimensionless time, s

t_d = Dimensionless time

x = Dimensional water block thickness, m

x_d = Dimensionless water block thickness

μ_w = viscosity of wetting fluid, kgm$^{-1}s^{-1}$

μ_{nw} = viscosity of non-wetting fluid, kgm$^{-1}s^{-1}$

where,

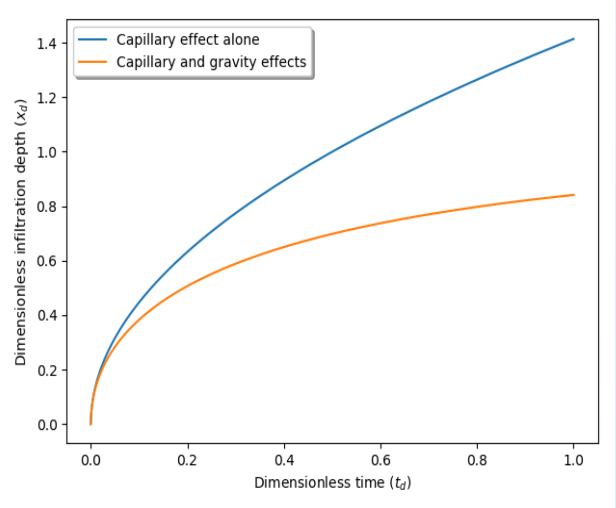
$$M_e=\frac{M_w M_{nw}}{M_{nw}-M_w} \quad \text{(Cocurrent flow)}$$

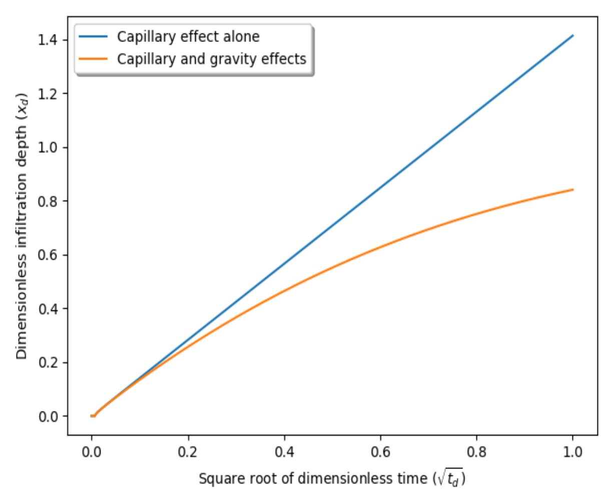
$$M_e=\frac{M_w M_{nw}}{M_{nw}+M_w} \quad \text{(Countercurrent flow)}$$

$$M_w=\frac{k_w}{\mu_w};\ M_{nw}=\frac{k_{nw}}{\mu_{nw}}$$

$$x_d=\sqrt{2t_d} \quad \text{(Scaled form)}$$

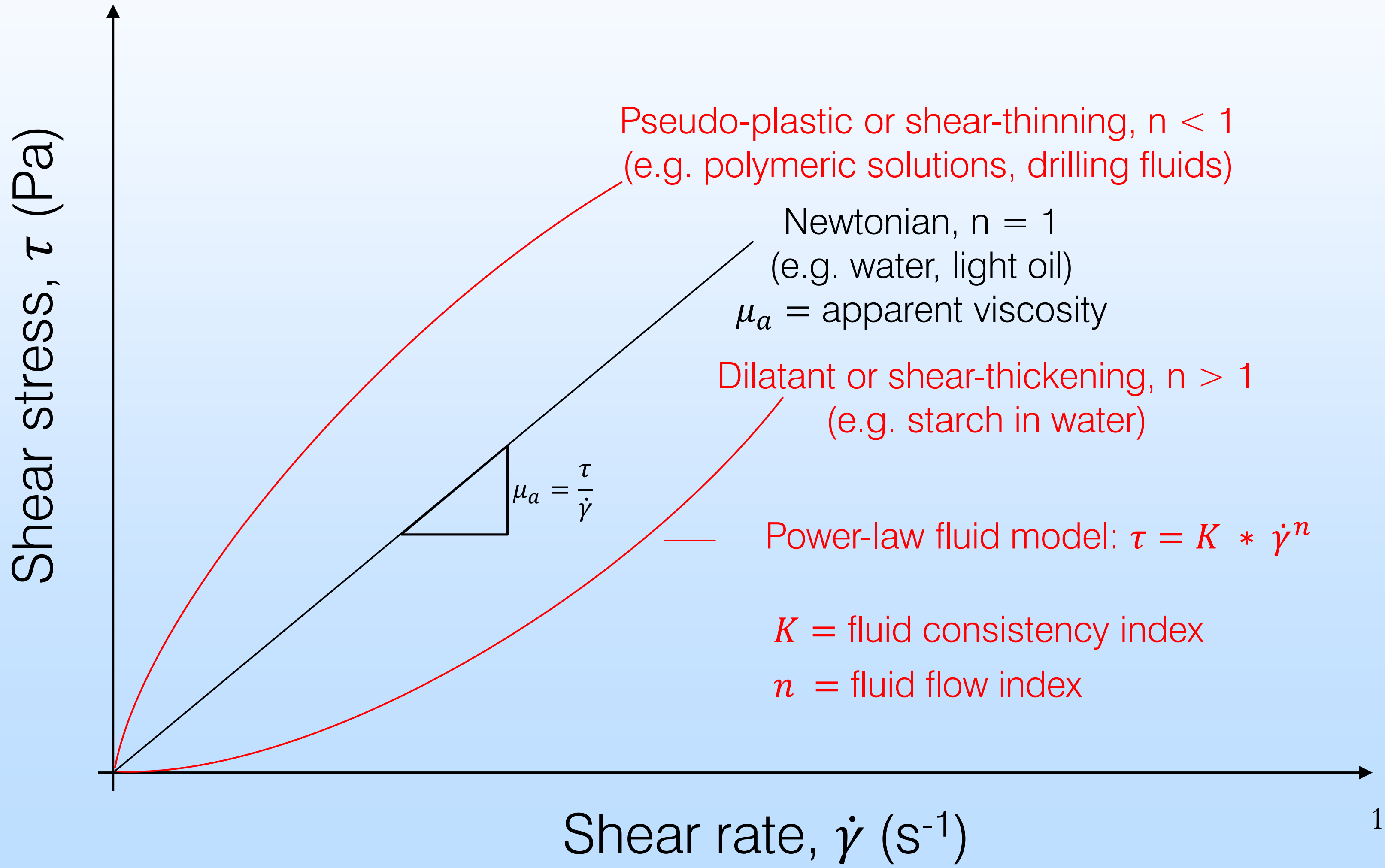
$$L(t)=\sqrt{\frac{2k}{\eta\Delta w}\left(P_{c,f}-P_{c,0}\right)}\sqrt{t}$$





Rheological Effects: Time-Independent Non-Newtonian Fluids

- Viscosity of non-Newtonian fluids is a function of applied stress

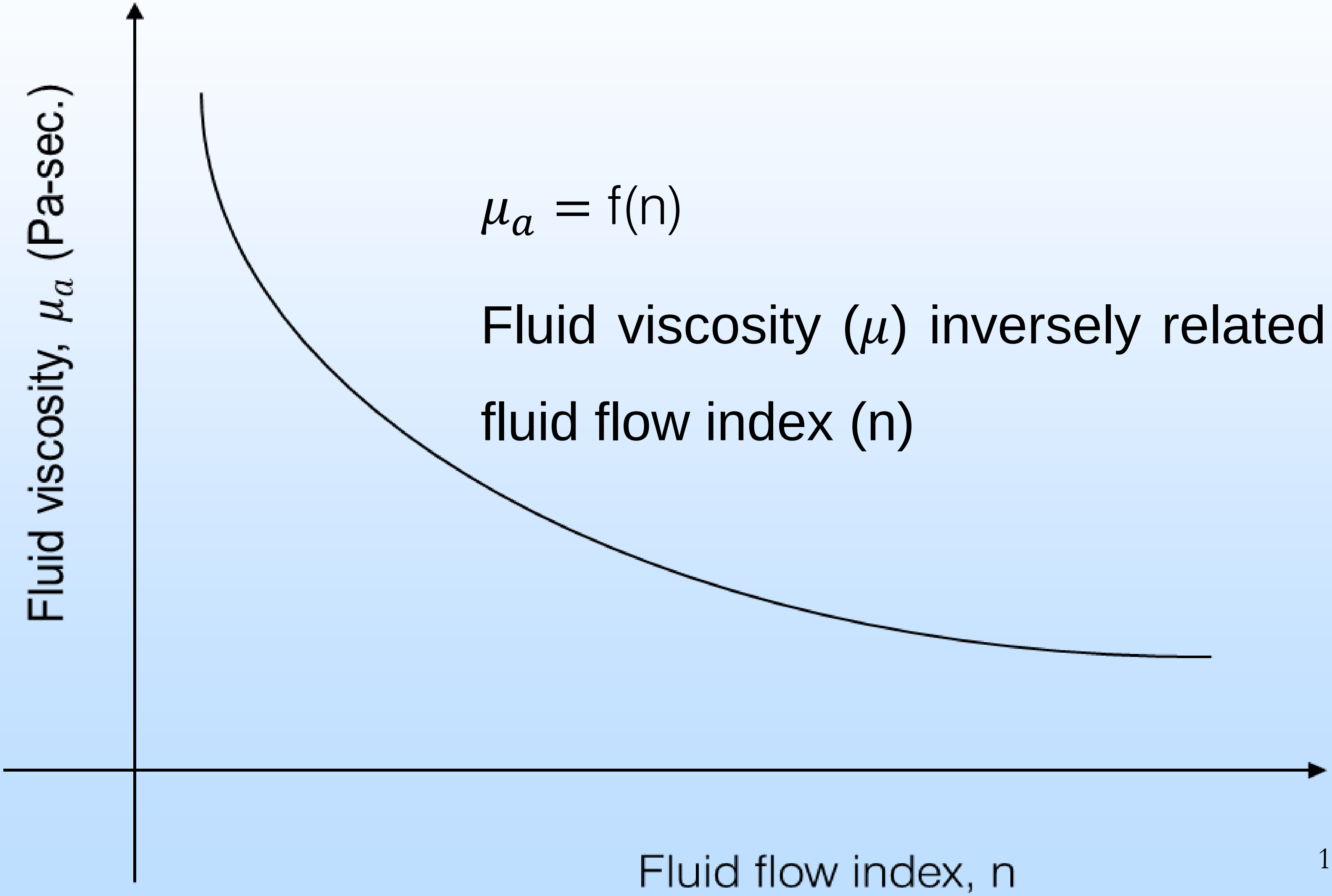


Power-law fluid model: $\tau = K * \dot{\gamma}^n$

K = fluid consistency index

n = fluid flow index

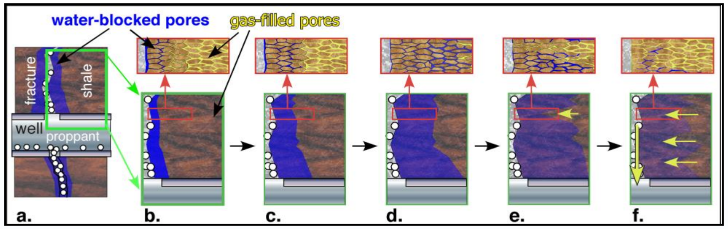
Rheological Effects: Viscosity dependence on fluid rheology

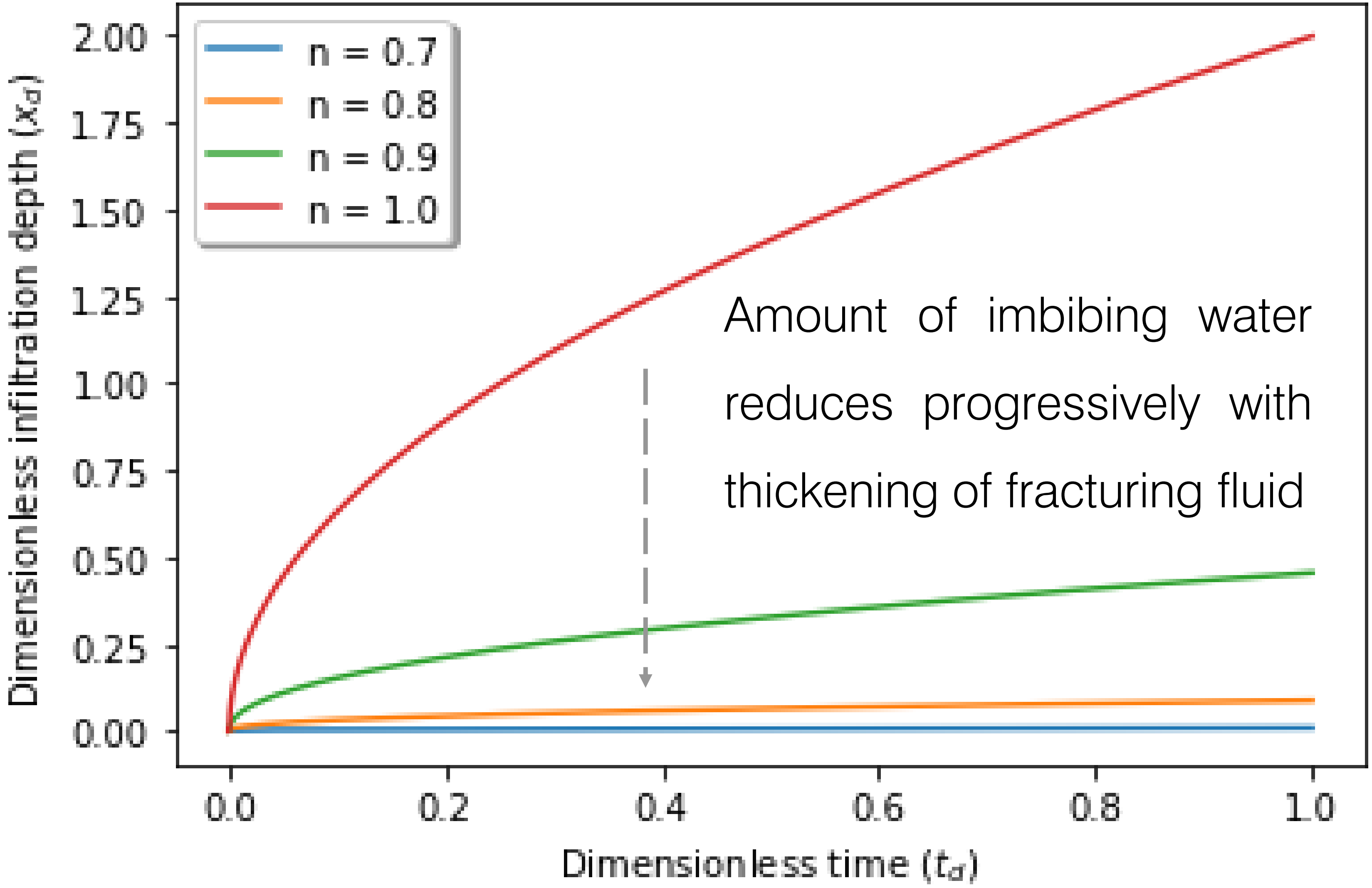


μ_a = f(n)

Fluid viscosity (μ) inversely related to fluid flow index (n)

Rheological Effects: Fluid Thickening (Power-Law Model)





Amount of imbibing water reduces progressively with thickening of fracturing fluid

Lessons Learned

- Research gaps/challenges.
  - Experimental basis for reliably predicting immiscible fluid displacements over a wide range of matrix permeabilities and wettabilities.
- Unanticipated research difficulties.
  - Fragile core samples
  - Questionable ability to re-establish in-situ conditions for experiments on cores recovered from deep reservoirs
- Changes implemented in experimental designs.
  - Experiments on other more competent porous media (geologic and synthetic) spanning the desired wide ranges in permeability and porosity needed to develop reliable scaling predictions for multiphase flow in tight rocks.

Synergy Opportunities

- Synergies with other Fundamental Shales studies on hydraulic fracture fluids interactions with shale being conducted at NETL, LBNL, SLAC, LANL, and Sandia.
- Synergies with other DOE research programs: Investigations of mineral surface chemistry influences on wetting over a wide range of capillary pressures under DOE-BES.
- We are open to developing collaborations with other groups interested in multiphase flow in shales, particularly at complementary scales.

Project Summary, Accomplishments

- Quantification of anisotropic, diffusion-limited equilibration in shale.
- Developed novel, reduced-order, reduced uncertainty model for predicting imbibition during shut-in.
- Developed a general framework for modeling water distribution in shales.
- Developed water-block thickness relations with rheological effects.
- 3 publications in in the past 2 years, others in progress.

Next Steps

- Experimental tests of imbibition and gas counterflow.
- Experiments on fracture drainage dynamics to develop predictive capabilities for gravity drainage of frac fluids.
- Expand model capability to include other fluid models and inclined fractures.

Thank you very much

Acknowledgments

- NETL Fundamental Shales Program: Stephen Henry, Elena Melchert, Yinka Ogunsola
- Oklahoma Geological Survey, Brian Cardott: (Woodford Shale)
- MSEEL (Marcellus Shale)

Appendix

- These slides will not be discussed during the presentation, but are mandatory.

Benefit to the Program

- Gain understanding of water in unconventional reservoir stimulation through studies of water imbibition, redistribution, and gas counter-flow.
- Reduction in water use must be based on understanding of water dynamics in shale matrix pores and fractures.

Project benefits statement.

This research project is developing basic understanding of water partitioning in hydraulically fractured reservoirs, in order to reduce water use and enhance hydrocarbon recovery.

Project Overview

Goals and Objectives:

- Experimentally supported understand of the coupling between water imbibition and gas counter-current gas flow in shales in order to help identify approaches to improving production.
- Understand the impact of gravity drainage of water in hydraulic fractures on counter-current gas flow.
- Develop analytical and numerical relations that will be useful for optimizing water use in hydraulic fracturing.
- Quantifiable metrics: Experiments and analyses span orders of magnitude in permeabilities and flow rates, yielding improved predictive capabilities.

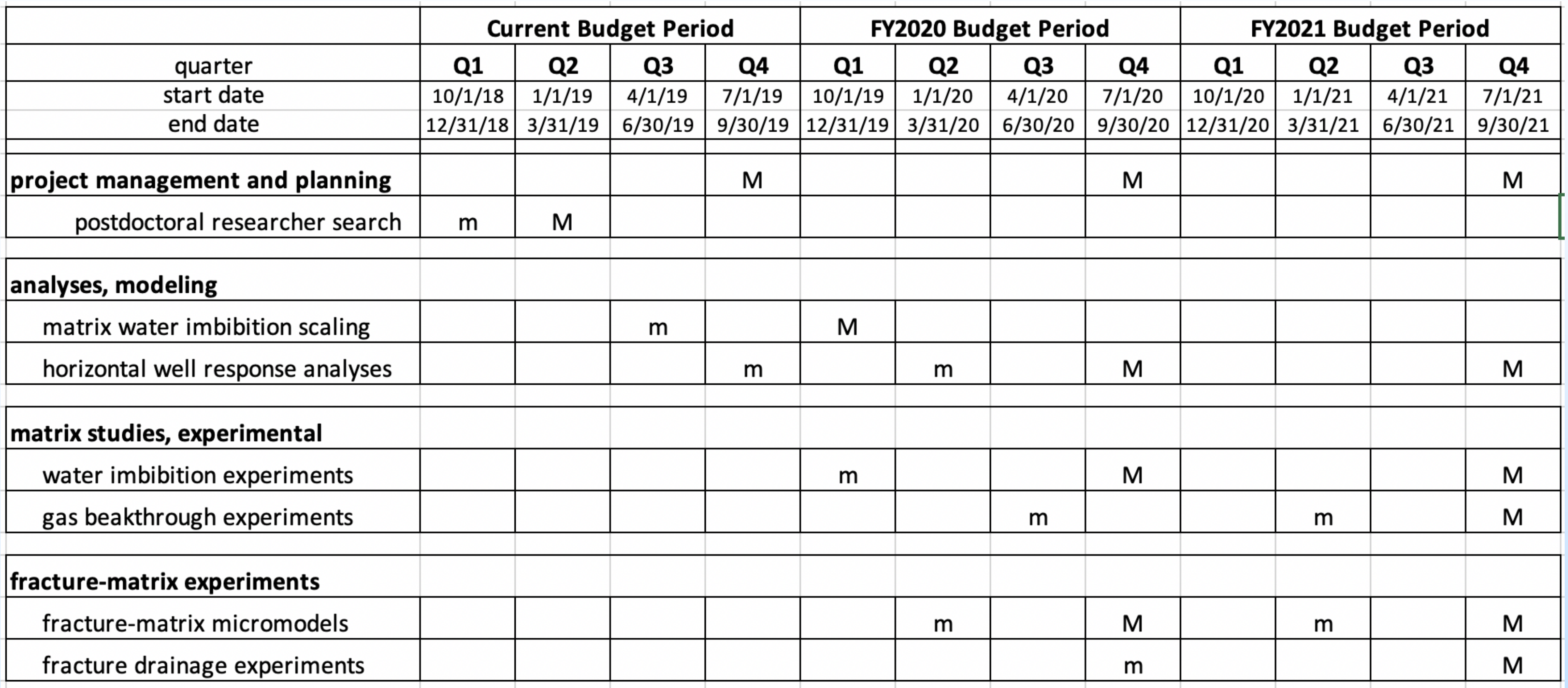
Organization Chart

- Tetsu K. Tokunaga
  - PI, capillary scaling, experimental design
- Omotayo Omosebi
  - Postdoctoral research fellow, modeling and experiments
- Jiamin Wan
  - Staff scientist, microfluidics, project management
- Jia Kong
  - Graduate student assistant, microfluidics

Gantt Chart

- Provide a simple Gantt chart showing project lifetime in years on the horizontal axis and major tasks along the vertical axis. Use symbols to indicate major and minor milestones. Use shaded lines or the like to indicate duration of each task and the amount of work completed to date.

Gantt Chart



	Current Budget Period				FY2020 Budget Period				FY2021 Budget Period			
quarter	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
start date	10/1/18	1/1/19	4/1/19	7/1/19	10/1/19	1/1/20	4/1/20	7/1/20	10/1/20	1/1/21	4/1/21	7/1/21
end date	12/31/18	3/31/19	6/30/19	9/30/19	12/31/19	3/31/20	6/30/20	9/30/20	12/31/20	3/31/21	6/30/21	9/30/21
project management and planning				M				M				M
postdoctoral researcher search	m	M										
analyses, modeling												
matrix water imbibition scaling			m		M							
horizontal well response analyses				m		m		M				M
matrix studies, experimental												
water imbibition experiments					m			M				M
gas beakthrough experiments							m			m		M
fracture-matrix experiments												
fracture-matrix micromodels						m		M		m		M
fracture drainage experiments								m				M

notation

m	minor milestone
M	Major milestone

Research Plan, Original

1. Matrix studies

- Imbibition rates: permeability, porosity, viscosity, wettability
- Gas breakthrough across water blocks: permeability, porosity, viscosity, wettability, and prior imbibition time (shut-in time)

2. Fracture studies

- Drainage rates: fracture aperture, roughness, wettability, and fluid viscosity

3. Generalizing results on matrix-fracture controls on water loss

- Hydraulic scaling of water imbibition at the local fracture-matrix scale
- Hydraulic scaling of fracture drainage
- Integrated predictions for matrix-fracture controls at the well scale

Research Plan, revised order

2. Matrix studies

- Imbibition rates: permeability, porosity, viscosity, wettability
- Gas breakthrough across water blocks: permeability, porosity, viscosity, wettability, and prior imbibition time (shut-in time)

3. Fracture studies

- Drainage rates: fracture aperture, roughness, wettability, and fluid viscosity

1. Generalizing results on matrix-fracture controls on water loss

- Hydraulic scaling of water imbibition at the local fracture-matrix scale
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Bibliography

Peer-reviewed journal publications

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- Cihan, A., Tokunaga, T.K., Birkholzer, J.T., 2019. Adsorption and capillary condensation-induced imbibition in porous media. Langmuir, 35, 9611-9621.

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- Tokunaga, T.K., 2018, Gravitational and Matric/Capillary Potential Controls on Distributing Unsaturated Flow of Water in Fracture Rocks and Talus. Invited talk. American Geophysical Union Fall Meeting, December 2018, Washington D.C.
- Tokunaga, T.K., Finsterle, S, Lanzirotti, A., and Newville, M., 2019. Unsaturated porous media experiments on nanoconfinement influences of water films on diffusion and flow. Goldschmidt Conference, August 18-23, 2019, Barcelona.