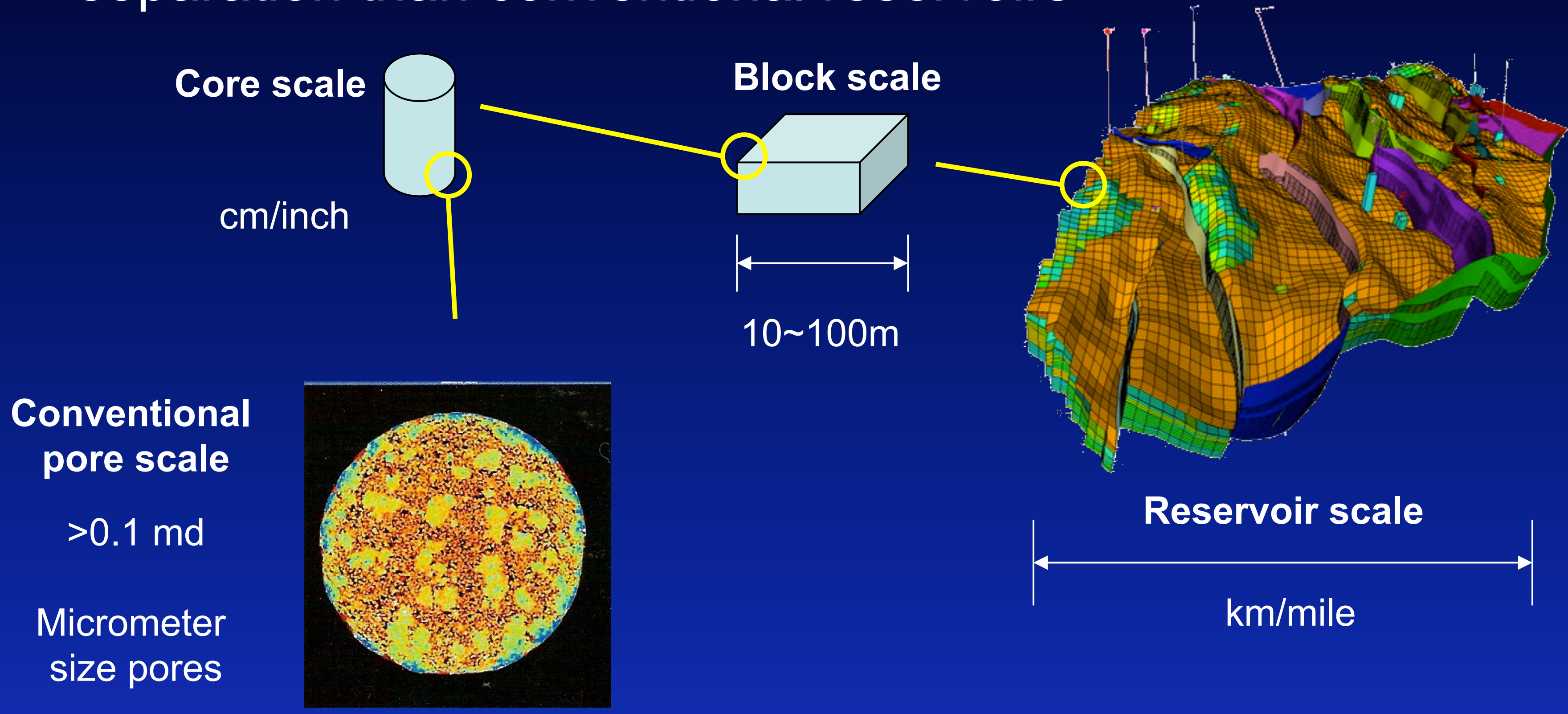
Nanoscale Flow and Transport

Pore-scale simulation of slip flow

Xiaolong Yin, Assistant Professor
Petroleum Engineering Department
Colorado School of Mines

Problem of Scales

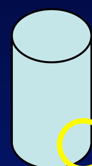
Unconventional reservoirs have more significant scale separation than conventional reservoirs



Problem of Scales

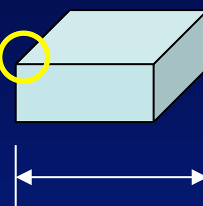
Unconventional reservoirs have more significant scale separation than conventional reservoirs

Core scale

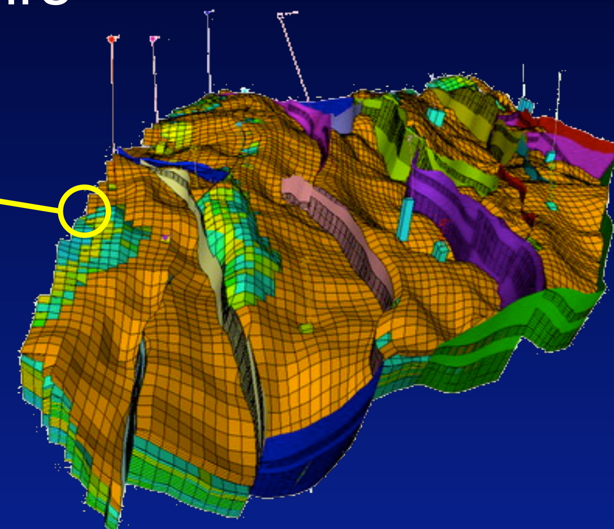


cm/inch

Block scale

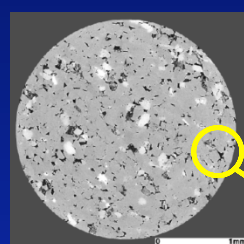


10~100m

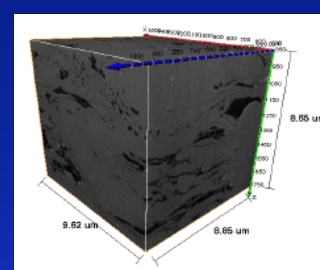


Unconventional

Porosity is identified on the scale of micrometers



Pore-to-pore connections are on the scale of nanometers



Reservoir scale

km/mile

References: IPTC14919, SPE144050

Challenges on the Nano-Scale

Fundamental laws for storage and transport are challenged

Conventional

- Storage – pore volume + phase behavior = Gas/Oil in Place
- Transport – pressure driven + Stokes flow = Darcy's law

Unconventional

- Storage – pore volume + surface adsorption
- Storage – surface-fluid interaction modifies fluid properties and phase behavior
- Transport – non-continuum effect (slip)
- Transport – other mechanisms (diffusion)

Scope of Research

Direct Simulation of Slip Flow of Gas in Nanopores

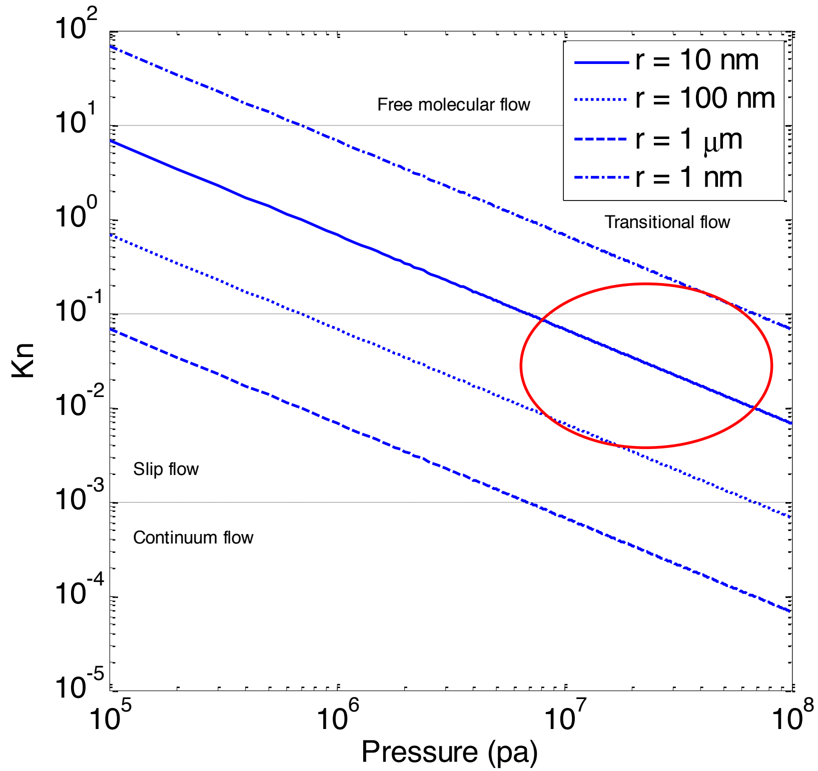
Objectives

1. Develop pore-scale simulator for nanoscale flow and transport
2. Simulate gas flow in complex pore geometries
3. Study the effect of heterogeneity and scales
4. Establish correlations to quantitatively describe the effect of pore structure, pore size, heterogeneity, and scale on apparent permeability

Approach

The Slip Flow Regime

- Most unconventional reservoir conditions predict a **Knudsen number between 0.001 and 0.1**
- Pressure driven flow in this regime is governed by **Stokes law + slip boundary condition**



$U_s = 0$ No slip – fluid velocity on solid surface = 0

$$U_s = \lambda_s \frac{\partial U}{\partial n}$$

Slip – fluid velocity on solid surface proportional to the slip length and the shear velocity gradient

Approach

Gas Flow – Maxwell Model for the Slip Length

$$\lambda_s \propto \frac{2-\sigma}{\sigma}\lambda_{MFP}$$

Slip length is proportional to the mean free path (**MFP**) of the gas and is a function of the tangential momentum accommodation coefficient (**TMAC**) (0: reflective; 1: diffusive)

Klinkenberg coefficient *b* for simple geometries can be obtained from solving Stokes law + Maxwell slip model

$$k_{app} = k\left(1+\frac{b}{P}\right)$$

For a fracture of height H

$$b = \frac{2-\sigma}{\sigma}\frac{3\sqrt{2}k_B T}{\pi\delta^2 H}$$

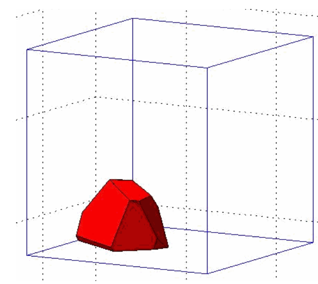
For a cylindrical tube of diameter D

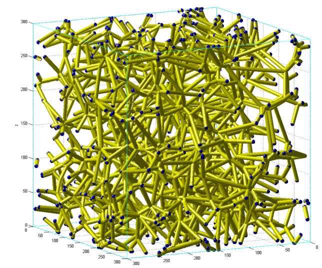
$$b = \frac{2-\sigma}{\sigma}\frac{4\sqrt{2}k_B T}{\pi\delta^2 D}$$

Approach

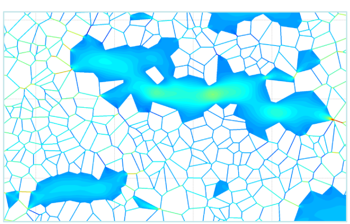
Complex Geometry – Direct Simulation using Lattice Boltzmann Method

Lattice Boltzmann is a pore-scale method that directly simulates fluid flow in pore space





Geometry constructed directly from FIB/SEM



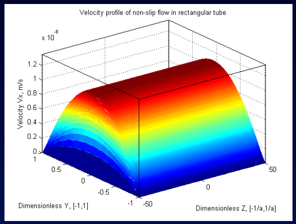
Stochastically constructed 2D/3D geometries

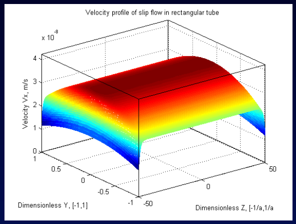
Lattice Boltzmann Simulator → Klinkenberg coefficient *b* in the flow law

Current Progress and Projects in Synergy

Analytical Solutions (established)

Fracture, tube, rectangular-shape ducts





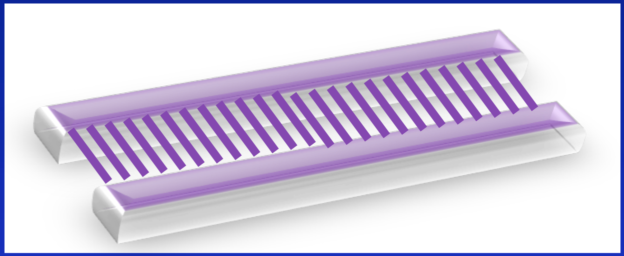
Develop numerical methods for non-continuum flows (ACS PRF, 2012-2014)

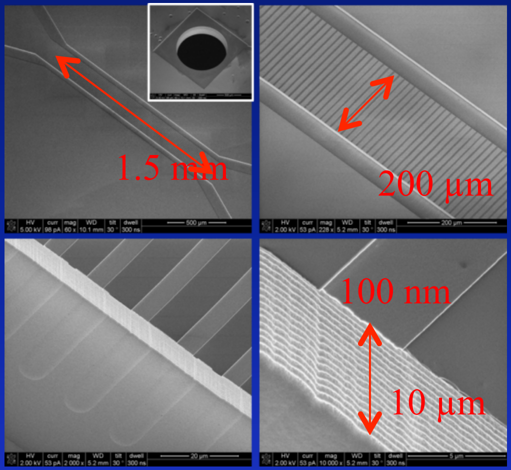
Lattice Boltzmann, DSMC

Use nanofluidics to study nanoscale flow (RPSEA, 2011-2014)

Application of real rock data (UNGI, 2012-2015)

Effect of complex geometry and heterogeneity and scale





Acknowledgements

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