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CFD Simulation of Pore Pressure Oscillation Method for the Measurement of Permeability in Tight Porous-Media

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Unconventional Hydrocarbon Resources

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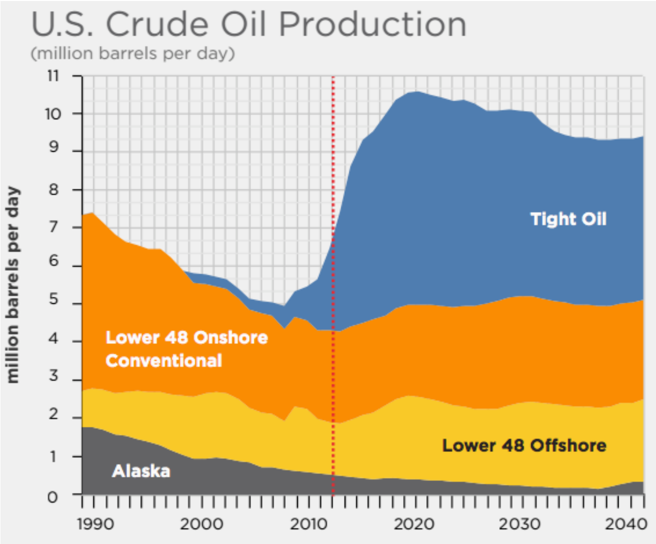

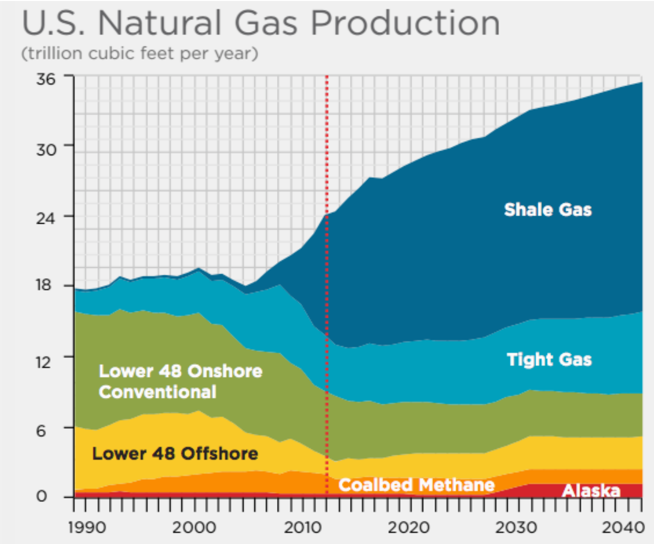

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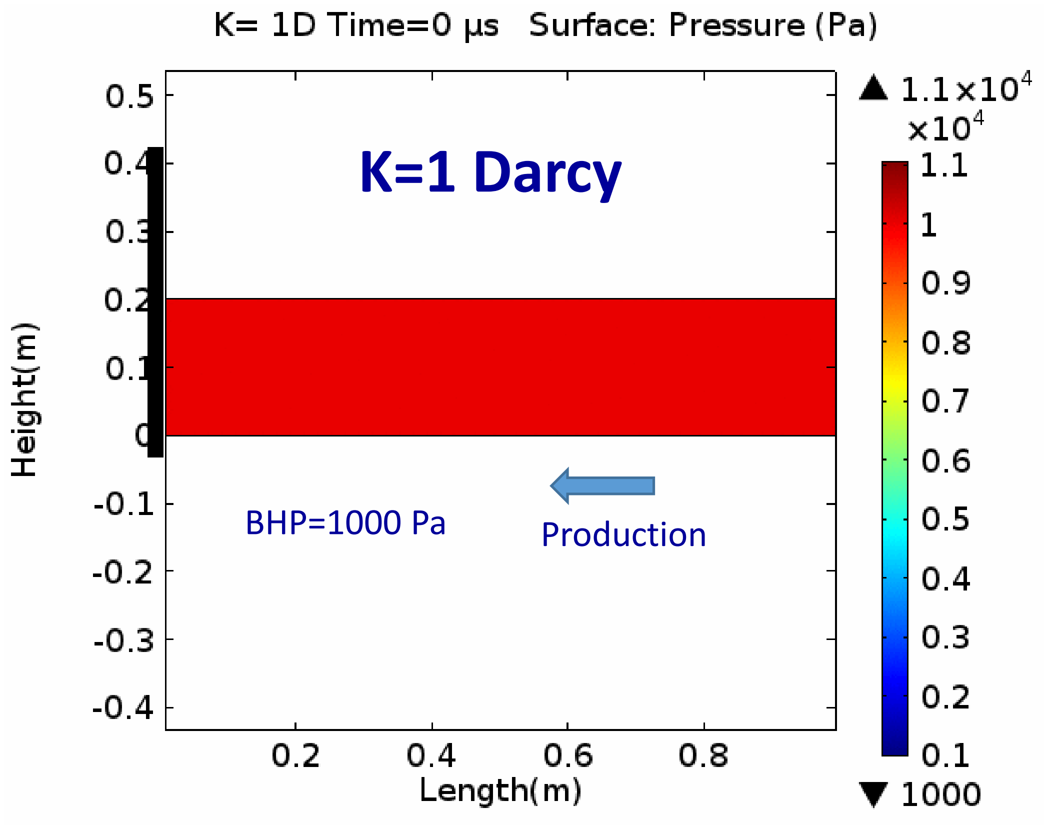
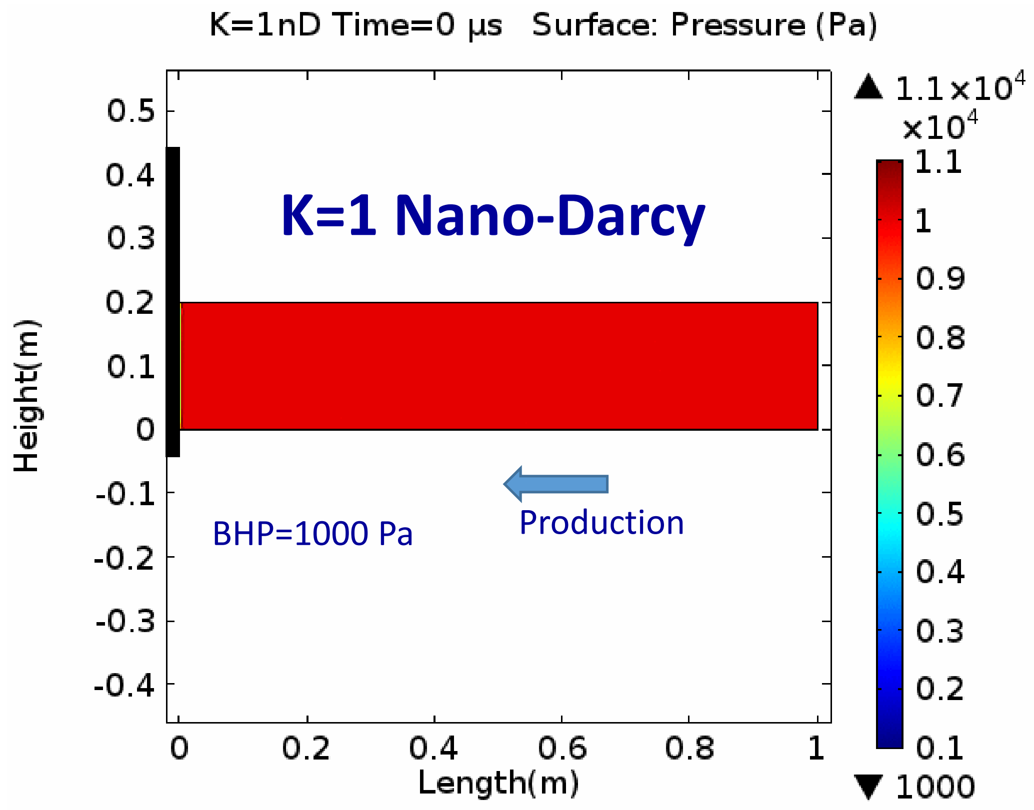
Conventional vs. Unconventional Reservoirs





Effect of Fracturing on Production

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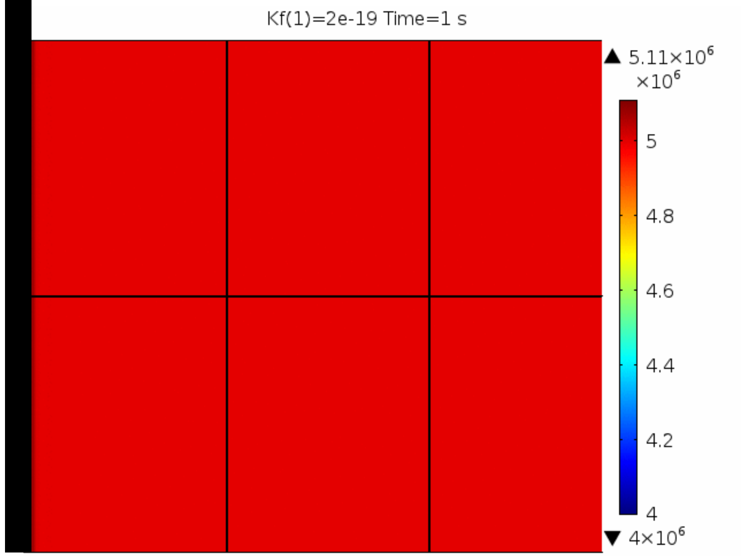
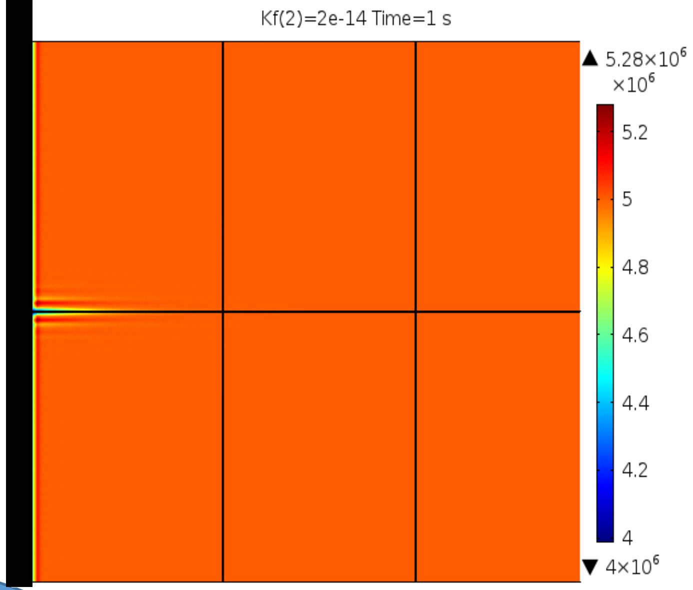
Intact



Sad Pistachio

Fracturing

Fractured



Smiley Pistachio

Outline

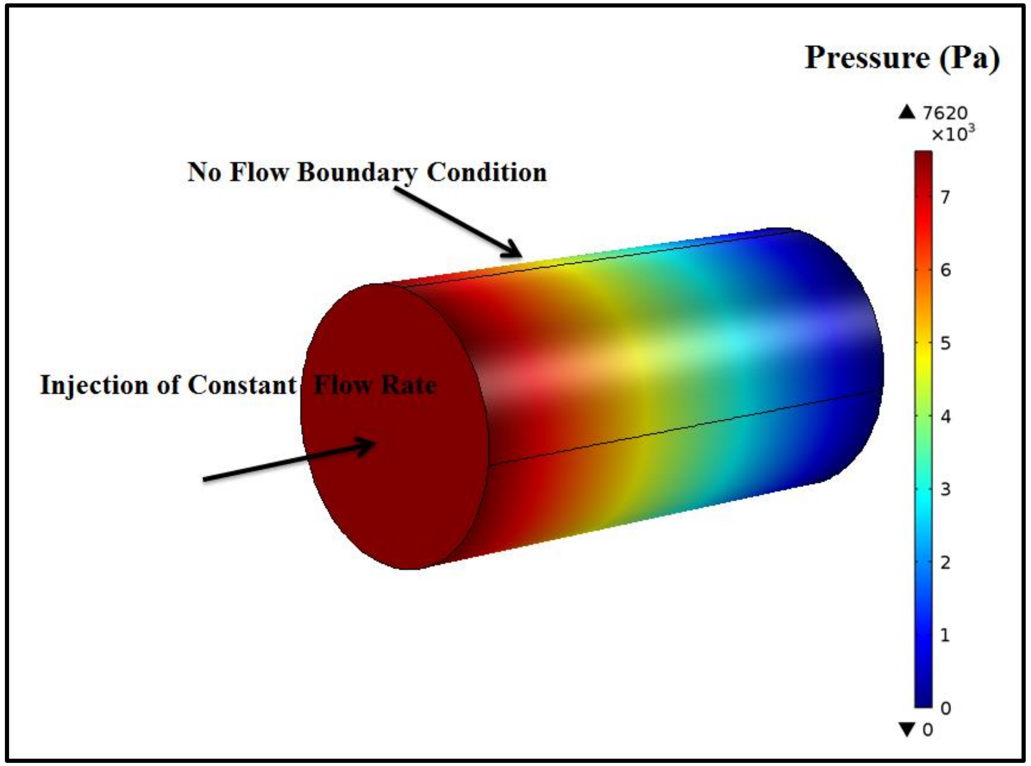
- ✓ Introduction
  - ✓ Steady State Method of Permeability Measurement
  - ✓ Unsteady State Method: Pulse Decay Method
  - ✓ Unsteady State Method: Crushed Sample Method

- ✓ Unsteady State Method: Pressure Oscillation Method
  - ✓ How it works?
  - ✓ Theory
  - ✓ Numerical Simulation
  - ✓ Analyze of experimental parameters
  - ✓ Preliminary results on Anisotropy

Steady State Method of Permeability Measurement

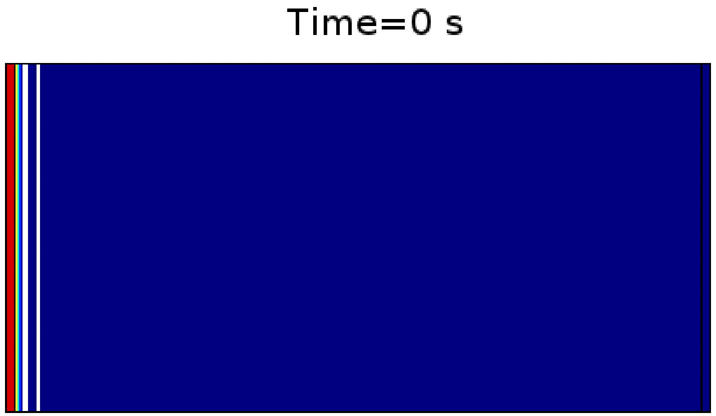
Core analysis and permeability measurement techniques

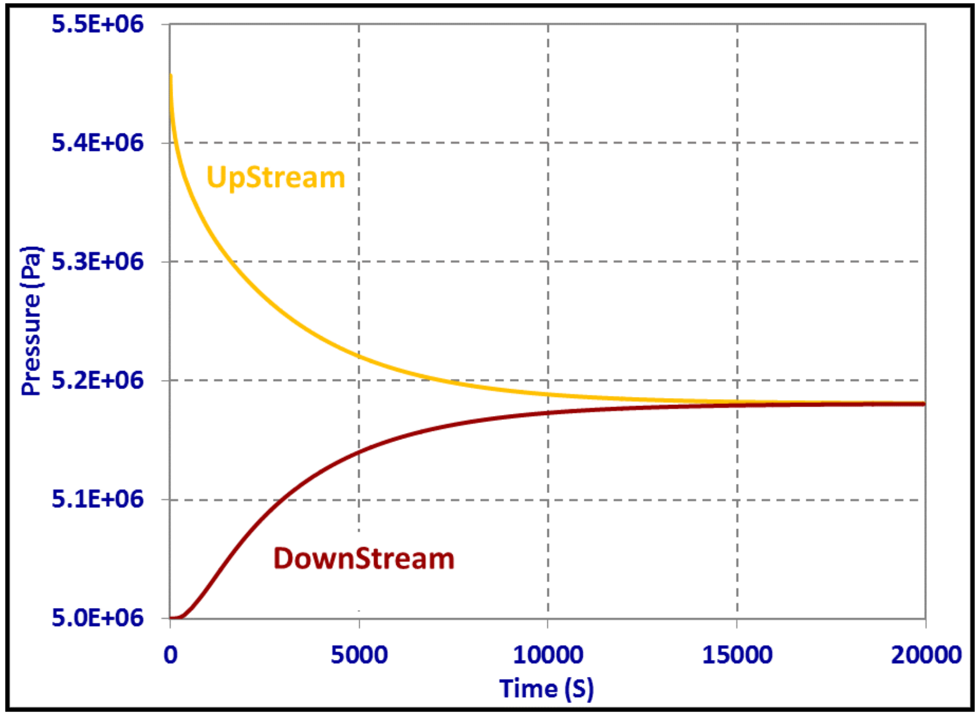
- Steady state methods
  - ✓ Constant flow or constant pressure head methods
  - ✓ Darcy’s equation
  - ✓ Suitable for high permeability samples
  - ✓ Time consuming for low permeability samples (days to weeks)



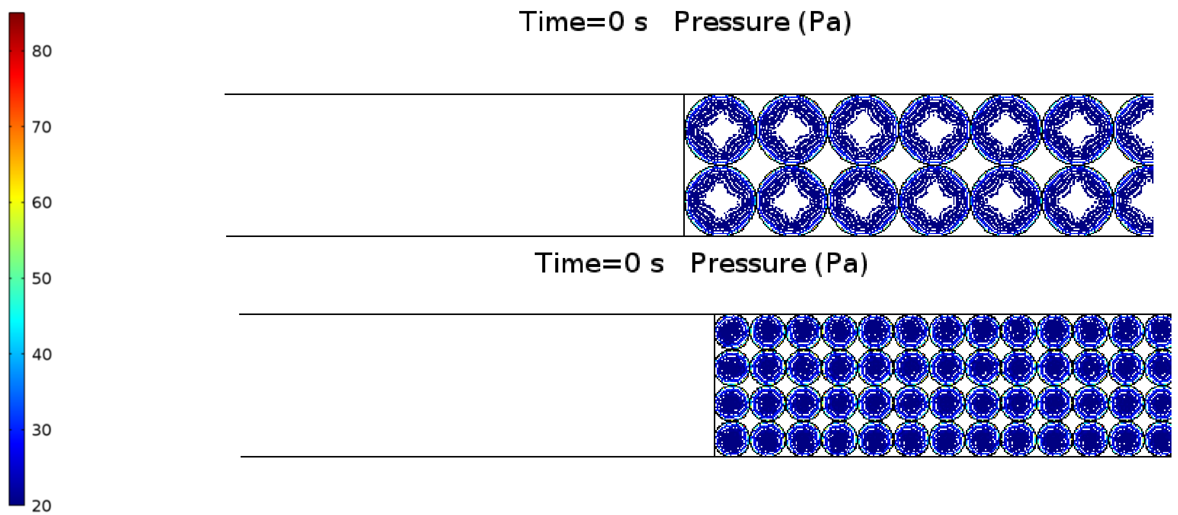
$$\mathbf{k} = \frac{-q\mu L}{\mathbf{A}\,\Delta P}$$

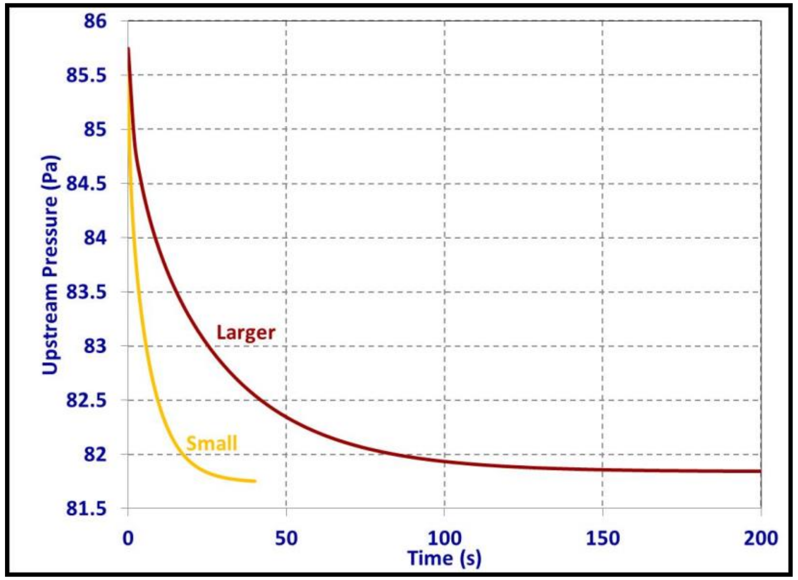
Unsteady State Method of Permeability Measurement: Pulse Decay Method





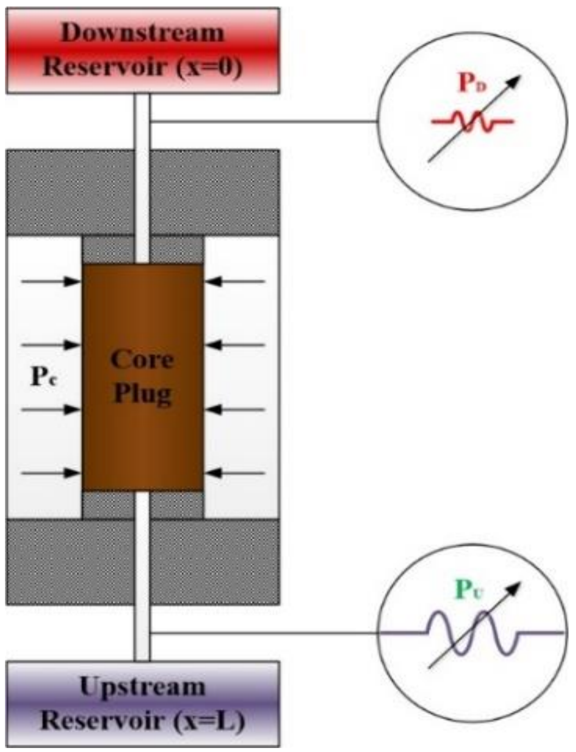
Unsteady State Method of Permeability Measurement: Crushed Sample Method

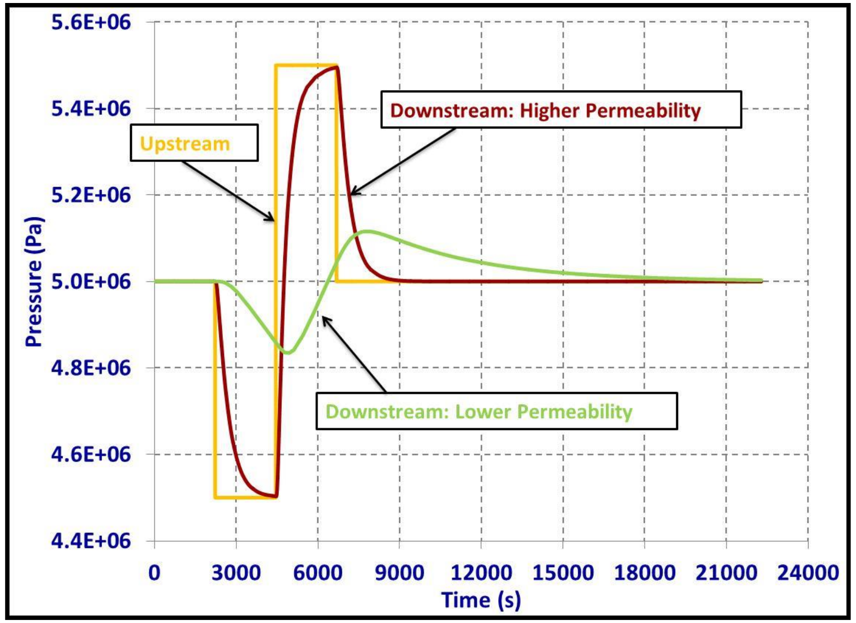


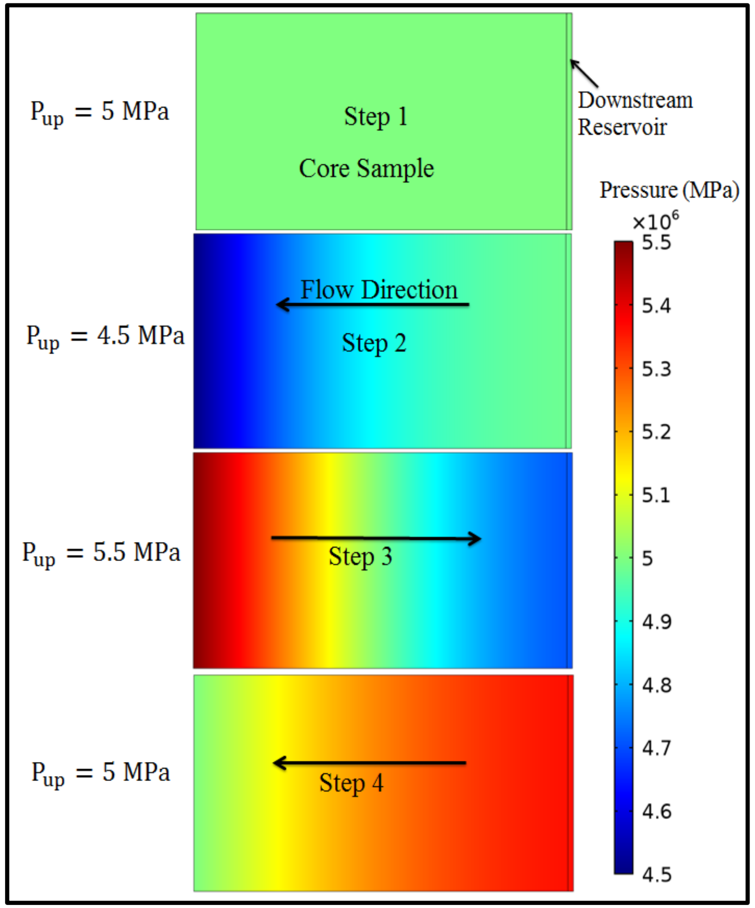


Permeability is Size-Dependent in GRI Method

Pressure Oscillation Method







Schematic diagram of experimental setup

Pressure data recorded at upstream and downstream reservoirs

Methodology – (analytical formulation)

Kranz et. al. at (1990)

- Governing equations in pressure oscillation method (homogenous and isotropic sample)

$$\frac{\partial(\varphi\rho)}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0$$ Conservation of mass

$$u = -\frac{k}{\mu}\frac{dp}{dx}$$ Darcy's equation

Combined together →

$$\frac{\partial p}{\partial t} - \frac{k}{\mu\beta_s}\frac{\partial^2 p}{\partial x^2} = 0$$

$$\beta_s = \varphi / p$$

- Governing boundary conditions in pressure oscillation method

$$p(L,t) = P_A \sin(\omega t + \delta), \quad x = L$$

$$\frac{dp}{dt} - \frac{kA}{\mu\beta_d}\frac{\partial p}{\partial x} = 0, \quad x = 0$$

$$\beta_d = V_D / p$$

- Governing initial condition $p(x,0) = p_0$

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Methodology – (analytical formulation)

- Solution of governing partial differential equation

$$p = \alpha P_A \sin(\omega t + \delta + \vartheta) + 2P_A \frac{k}{\mu}\beta_s AL \sum_{n=1}^{\infty} \left(\frac{(\beta_s L^2 \omega \cos\delta - \frac{k}{\mu}\psi_n^2 \sin\delta)[\cos(\xi\psi_n) - \frac{\beta_d \psi_n}{\beta_s AL}\sin(\xi\psi_n)]}{((\frac{k}{\mu})^2 \psi_n^4 + \beta_s^2 L^4 \omega^2)[(\beta_d \psi_n^2 + \beta_s AL)\cos\psi_n + (\beta_s AL + 2\beta_d)\sin\psi_n]} \psi_n^2 e^{-\frac{k\psi_n^2}{\mu\beta_s L^2}t} \right)$$

Permanent solution

Transient and temporary solution

$$\alpha = \left| \frac{\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)\cosh[\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)x] + \frac{\beta_d i\omega\mu}{kA}\sinh[\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)x]}{\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)\cosh[\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)L] + \frac{\beta_d i\omega\mu}{kA}\sinh[\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)L]} \right|$$

$$\vartheta = \arg\left\{ \frac{\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)\cosh[\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)x] + \frac{\beta_d i\omega\mu}{kA}\sinh[\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)x]}{\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)\cosh[\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)L] + \frac{\beta_d i\omega\mu}{kA}\sinh[\sqrt{\frac{\beta_s \omega\mu}{2k}}(1+i)L]} \right\}$$

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Methodology – (analytical formulation)

Solution at location of downstream reservoir (x=0)

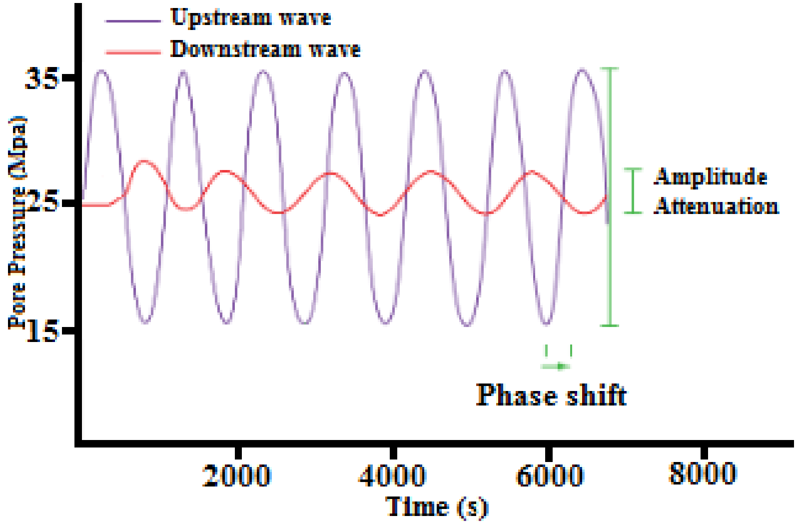
$$A_r e^{-i\theta} = \left(\frac{1+i}{\sqrt{\xi\eta}}\sinh[(1+i)\sqrt{\frac{\xi}{\eta}}] + \cosh[(1+i)\sqrt{\frac{\xi}{\eta}}]\right)^{-1}$$

A_r Pressure wave amplitude attenuation from upstream to downstream

θ Pressure wave phase shift from upstream to downstream

$\xi = \frac{AL\beta_S}{\beta_d}$ Dimensionless porosity

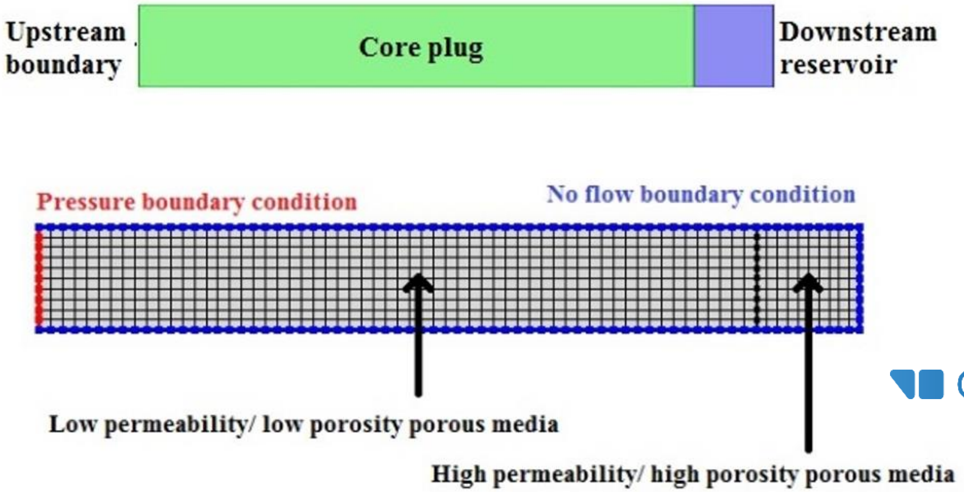
$\eta = \frac{ATk}{\pi L\mu\beta_d}$ Dimensionless permeability



Methodology – (CFD modeling)

COMSOL Geometry and computational mesh

- Core length: 50 mm
- Core height: 10 mm
- Downstream reservoir length: variable



- Mesh size: 1 mm (2D model – quad mesh)
- Aspect ratio: 1
- Time step size: 1 second

- Time dependent direct solver: Multifrontal Massively Parallel sparse direct Solver (MUMPS)
- Porous media fluid properties: Ideal gas
- Total simulation time: 36 times of pressure wave period (to have only the permanent part of solution)
- Initial pore pressure: 5e6 Pa

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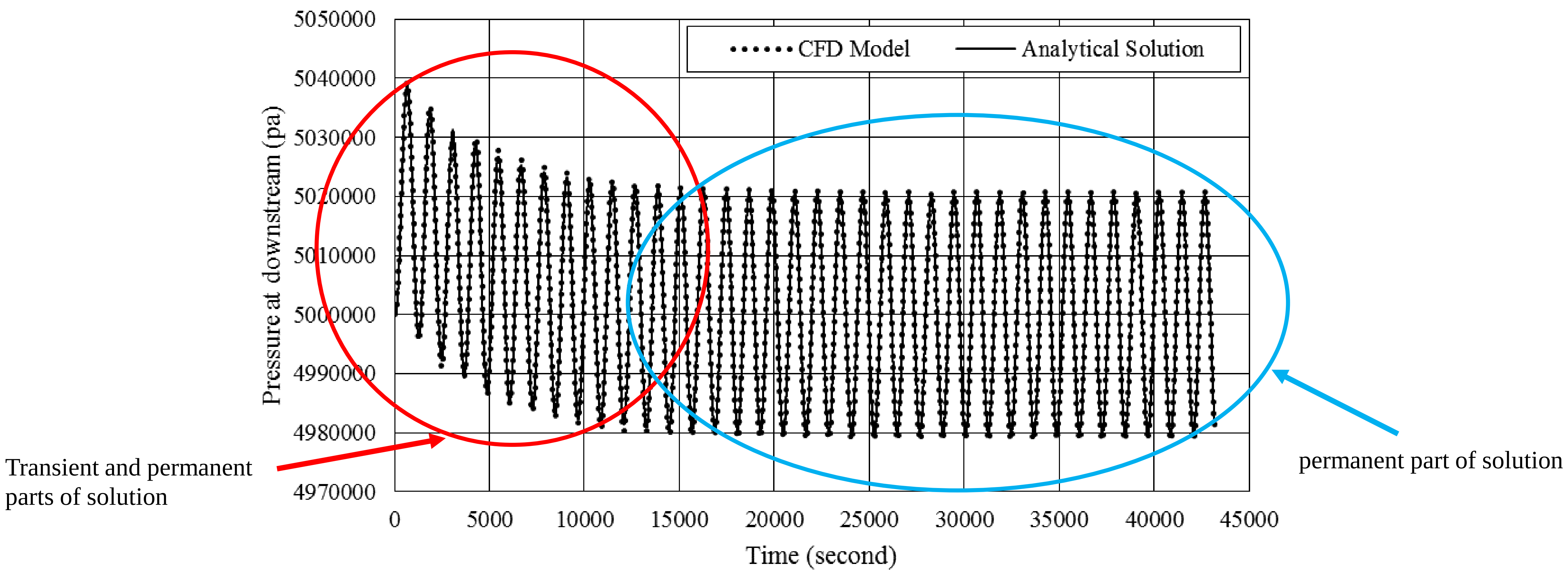
Results and Discussions

Pressure response at downstream reservoir (CFD and analytical solution results)



Analyzing Laboratory Data to Calculate Shale Permeability using Oscillation Method

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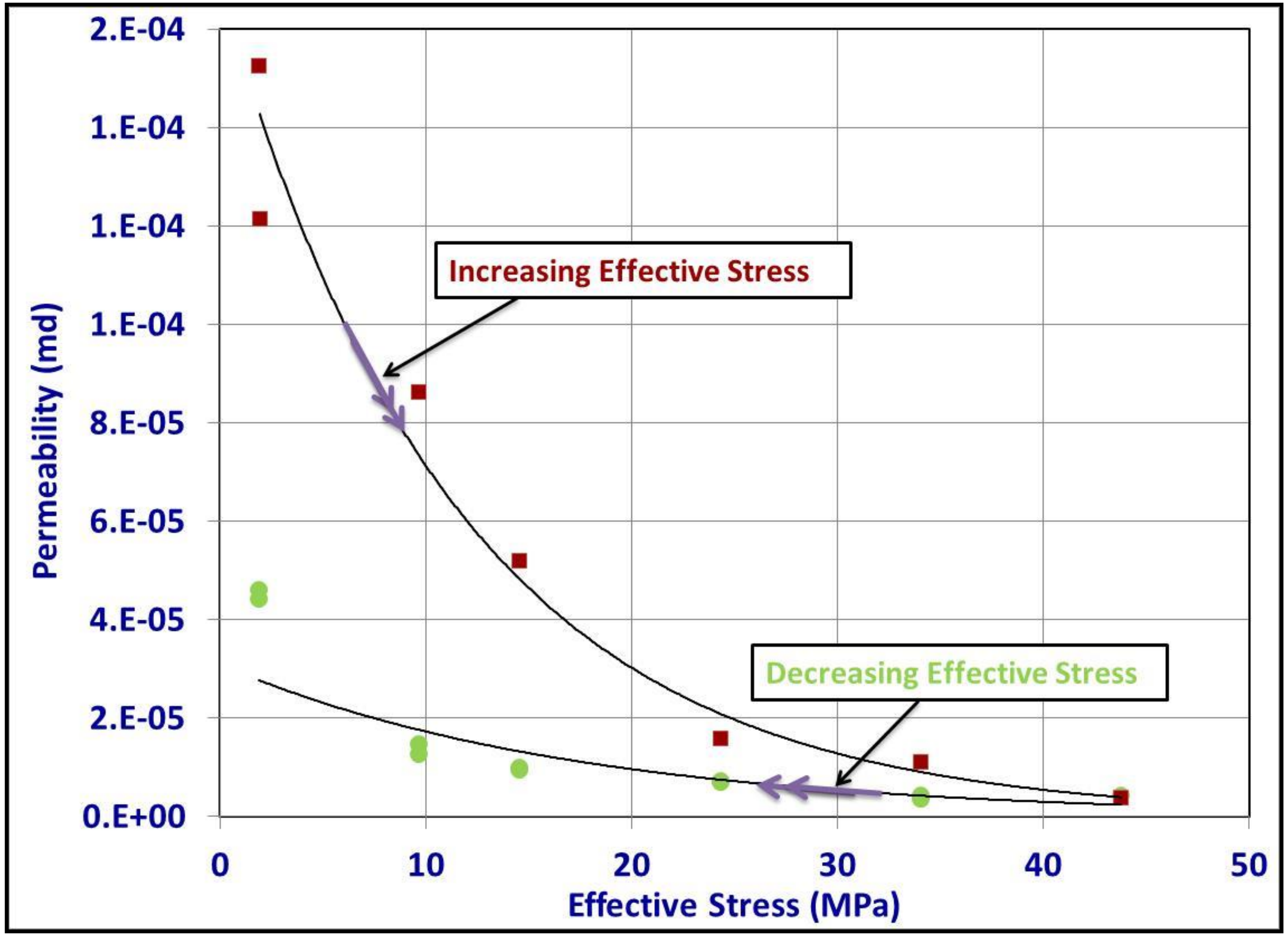
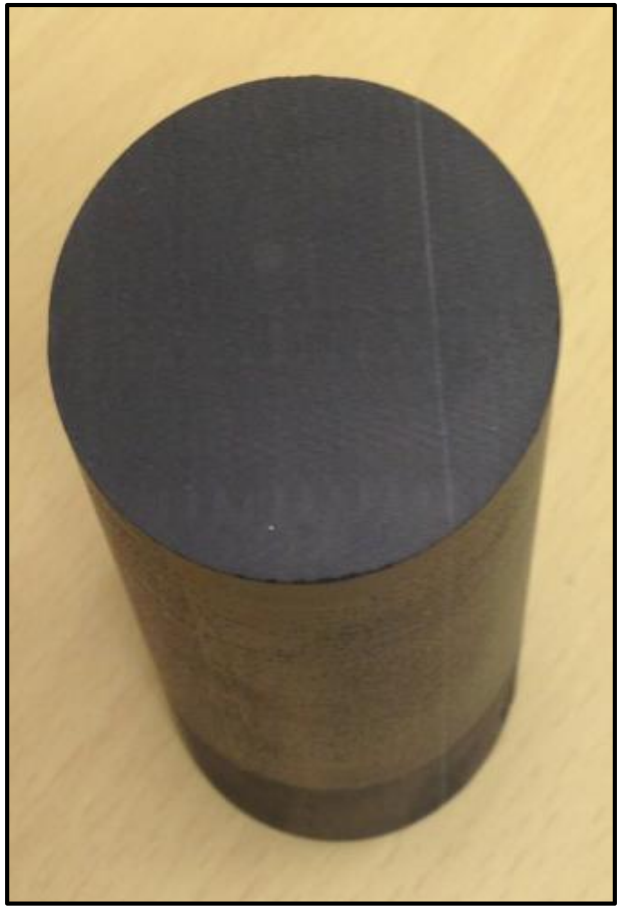
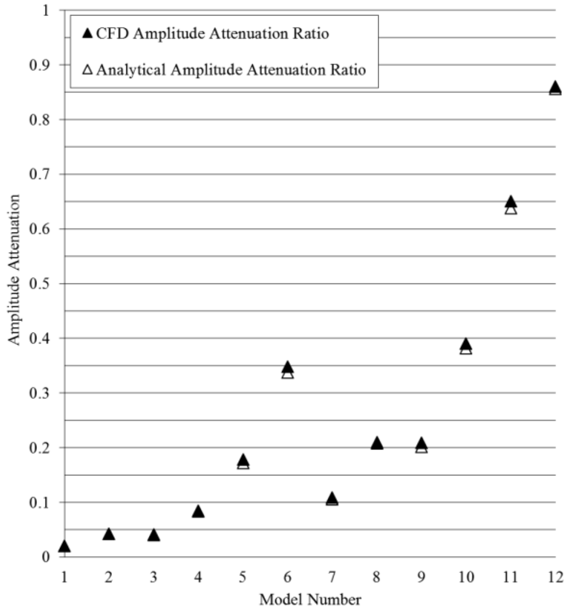
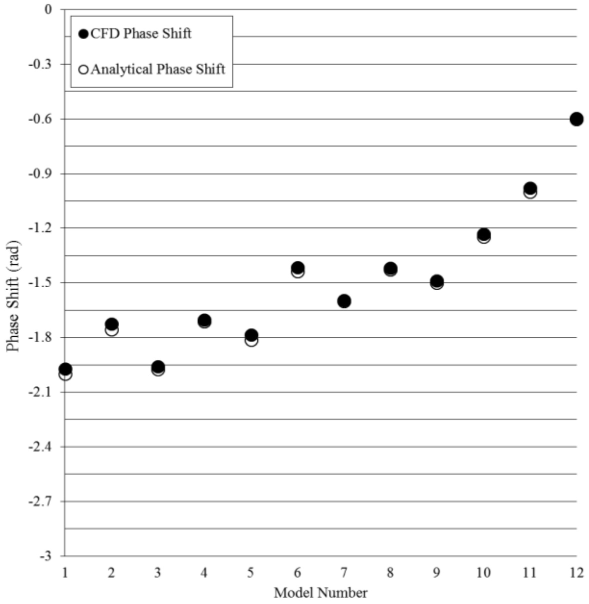




Methodology – (CFD modeling)

Model	$k\,(m^2)$	φ	$L_D\,(mm)$	$T\,(s)$
1	10^{-18}	0.06	50	1200
2	10^{-18}	0.06	50	2400
3	10^{-18}	0.06	25	1200
4	10^{-18}	0.06	25	2400
5	10^{-18}	0.06	5	1200
6	10^{-18}	0.06	5	2400
7	10^{-17}	0.09	50	600
8	10^{-17}	0.09	50	1200
9	10^{-17}	0.09	25	600
10	10^{-17}	0.09	25	1200
11	10^{-17}	0.09	5	600
12	10^{-17}	0.09	5	1200





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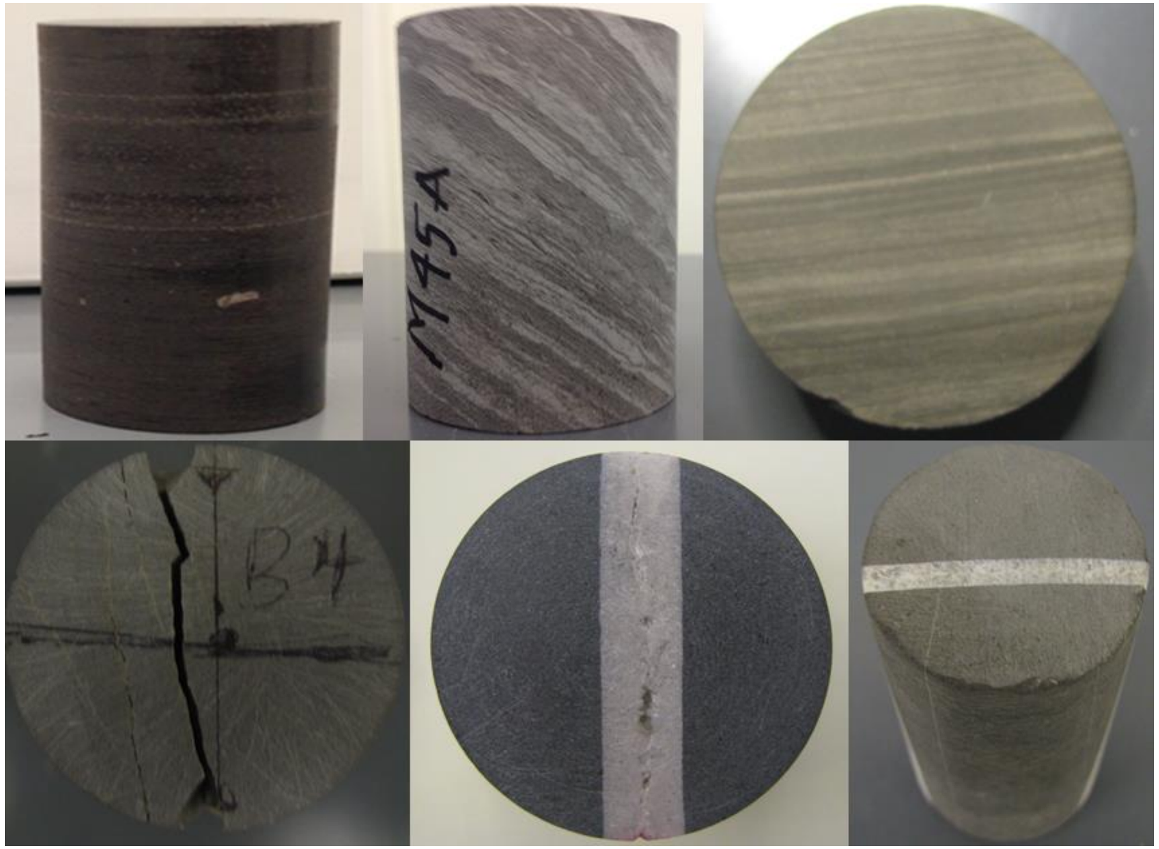
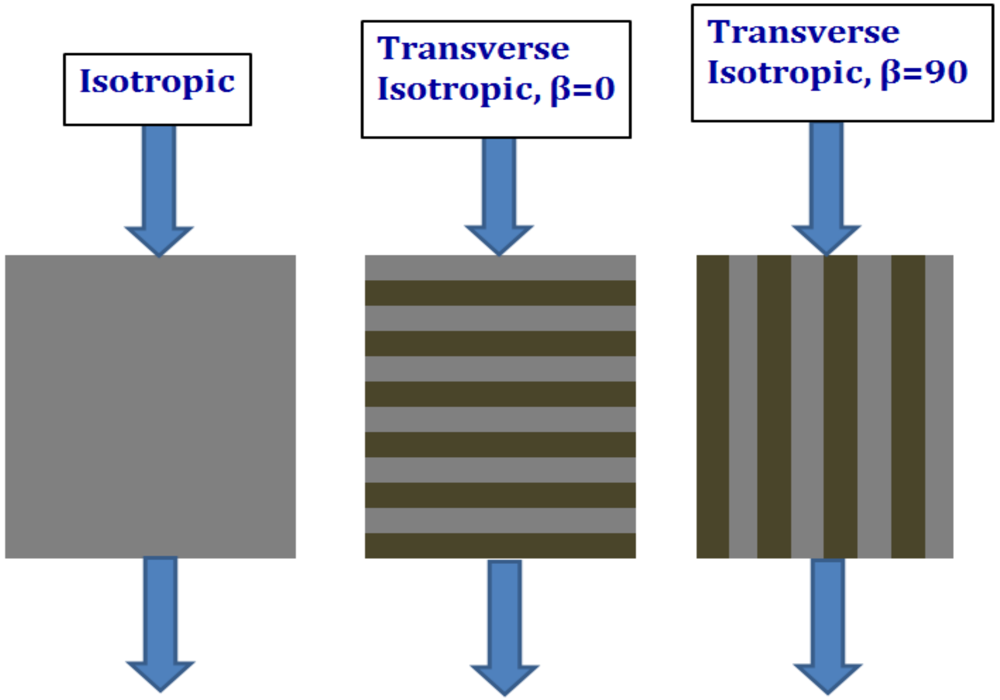
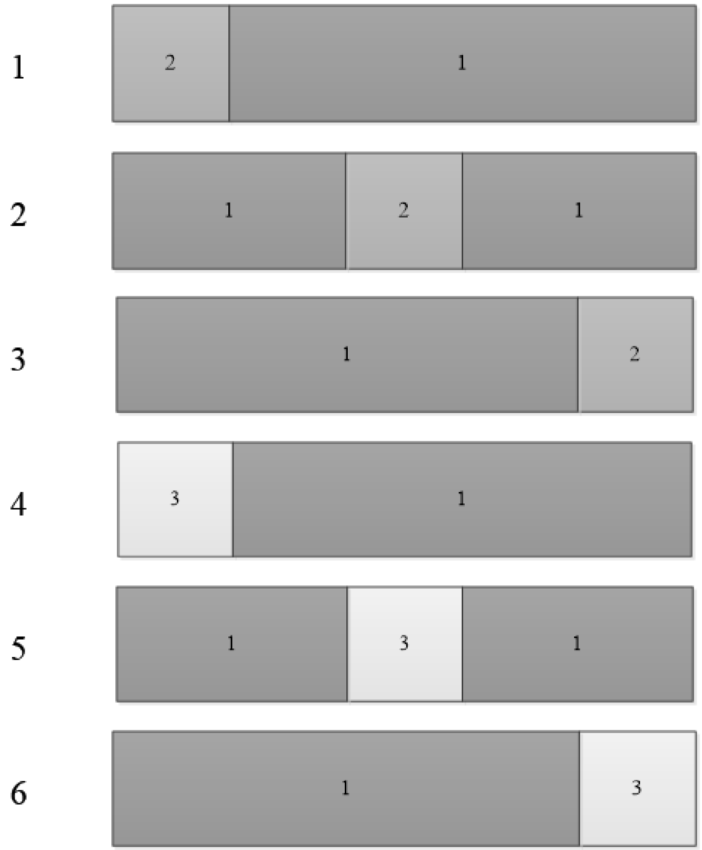
Anisotropy in Shales





Results and Discussions

Model number	Amplitude attenuation	Phase shift
1	0.358	-1.376
2	0.345	-1.470
3	0.310	-1.432
4	0.365	-1.357
5	0.352	-1.457
6	0.315	-1.416



- Layer 1
  - Permeability: 10^{-18} m^2
  - Porosity: 0.06
- Layer 2
  - Permeability: 10^{-17} m^2
  - Porosity: 0.09
- Layer 3
  - Permeability: 10^{-16} m^2
  - Porosity: 0.1

Conclusion

- ✓ Pressure oscillation method was successfully simulated by COMSOL CFD module to calculate the permeability of tight rocks in the range of nano-Darcy.
- ✓ Excellent agreement between CFD and analytical formulation results was observed in isotropic models.
- ✓ Parametric study of simulations is in progress to optimize experiments for permeability measurement.
- ✓ Numerical simulation of anisotropic rocks is in progress to get more accurate interpretation of results in heterogeneous and anisotropic shale formations.

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CFD Simulation of Pore Pressure Oscillation Method for the Measurement of Permeability in Tight Porous-Media

Thank you!

Any questions?