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# Releasing Shale-Gas Potential with Fractured Horizontal Wells

**Erdal Ozkan**

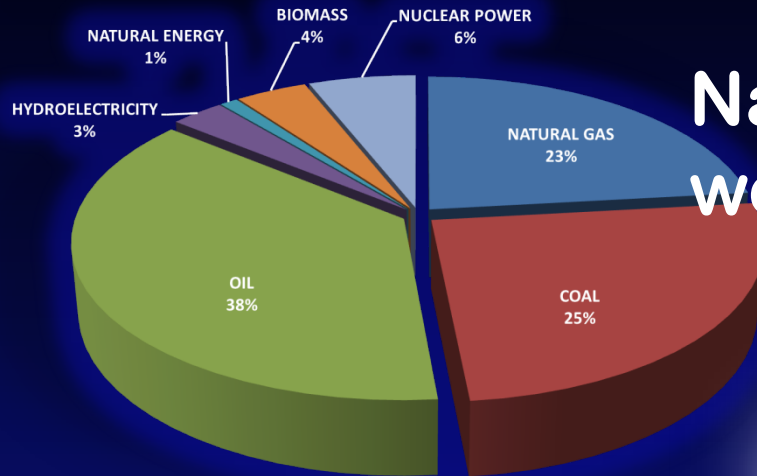


SHALE  
GAS



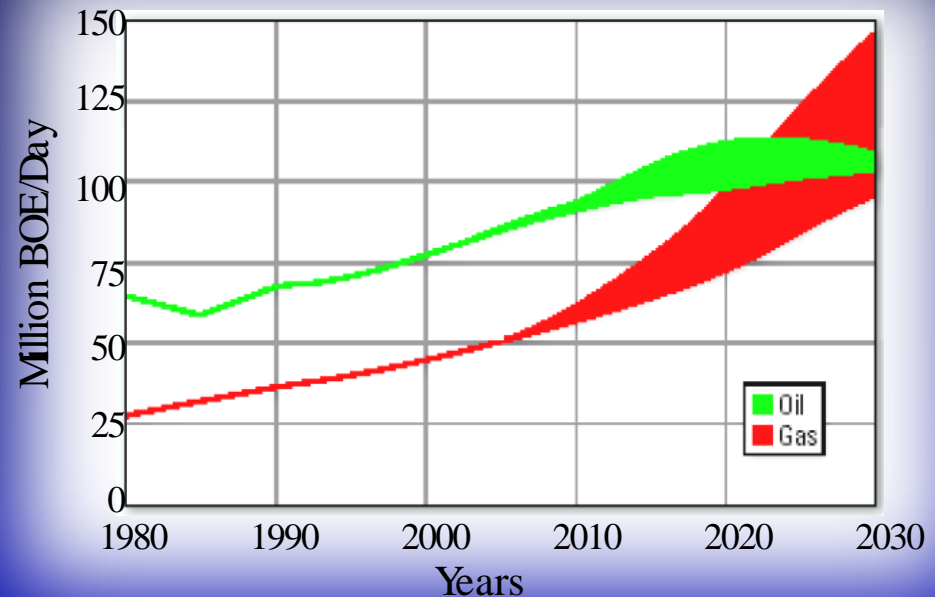
IT'S A NEW  
WORLD OF  
OPPORTUNITIES

## Global Energy Consumption



**Natural gas meets 23% of the world's energy consumption**

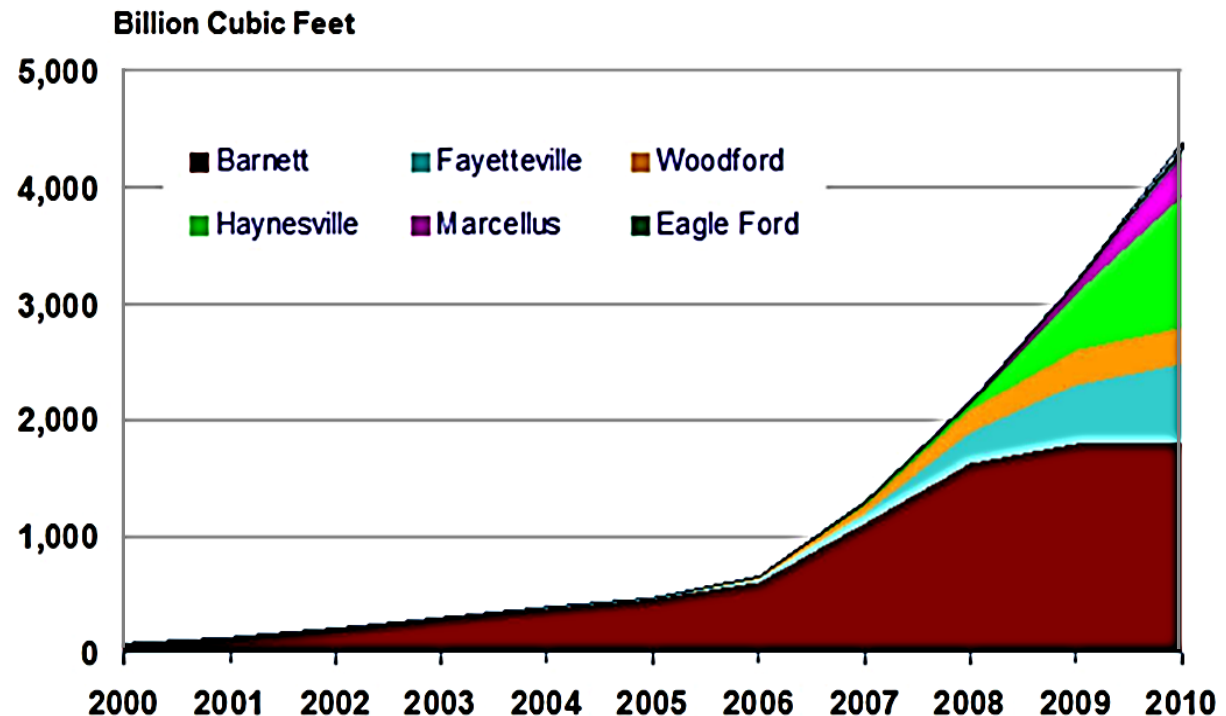
**Prediction: Gas consumption will exceed oil consumption by 2025**



# US gas potential increased 4 to 6 times from 1998 to 2008

*(150 Tcf in 1998 and 500-1000 Tcf in 2008 – Arthur, 2008)*

This is  
due to the  
economic  
success  
of the  
shale  
plays



Source – IAE, Lippman Consulting

# Let 's talk about shale-gas

*What is unconventional in shale gas?*

*Special characteristics of shale*

*Fractures, fractures, fractures, ...*

*Where is the gas coming from? (matrix support?)*

*What governs production performance?*

*Modeling flow in fractured shale*

*Unconventional flow in shale matrix*

*Are microfractures the third porosity?*

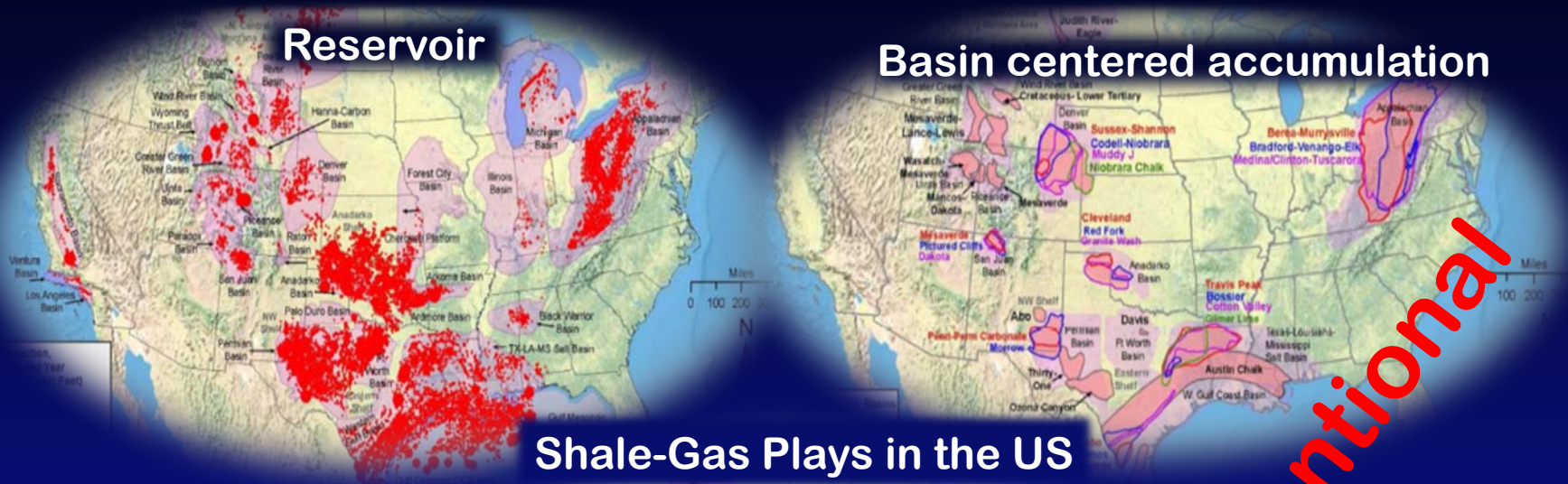
*What is unconventional in shale gas?*

# Conventional and unconventional gas plays

## Conventional Gas Plays in the US



## Tight-Gas Plays in the US



## Shale-Gas Plays in the US



**Unconventional**

# UNCONVENTIONAL

Shale-gas  
Reservoir

Source  
Rock

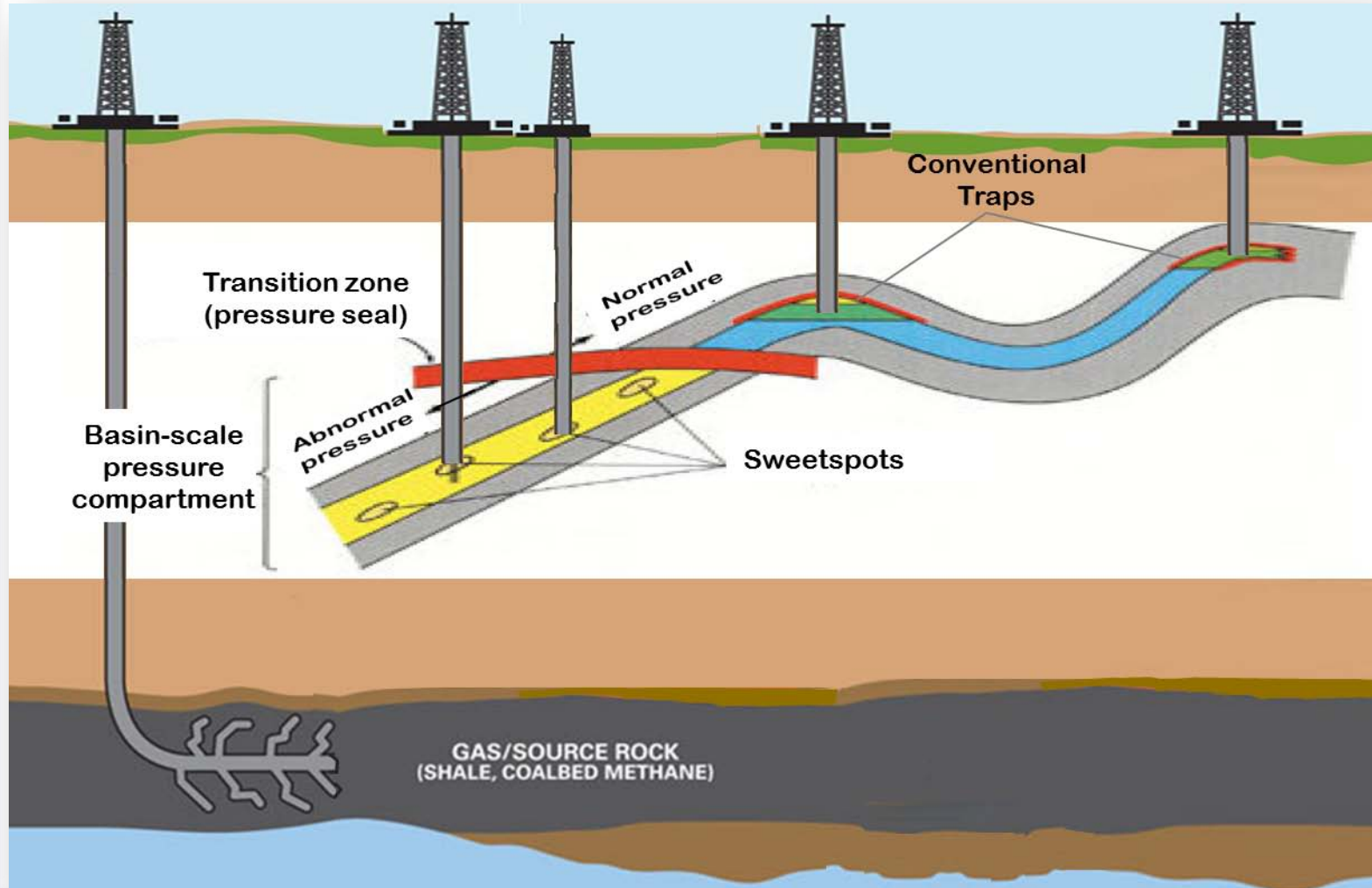
Tight-gas  
Reservoir

Basin-centered  
Accumulation

# CONVENTIONAL

Sandstone  
Gas Reservoir

Conventional  
Trap



# Unconventional shale-gas

Geologically, shale-gas reservoirs are distinguished by their complex and unusual petrophysical properties.

*Good understanding of the petrophysical characteristics of shale-gas reservoirs is essential; however, no paradigm-shift is necessary for the geologic description of shale-gas reservoirs (Shanley et al., 2004)*

This distinction may not be sufficient for all disciplines

*Unless unusual petrophysical properties of shale lead to unconventional physics of flow, shale-gas may not be as unconventional for a reservoir engineer as it is for a geologist*

Unconventional flow physics = Paradigm shift



## *Special characteristics of shale*

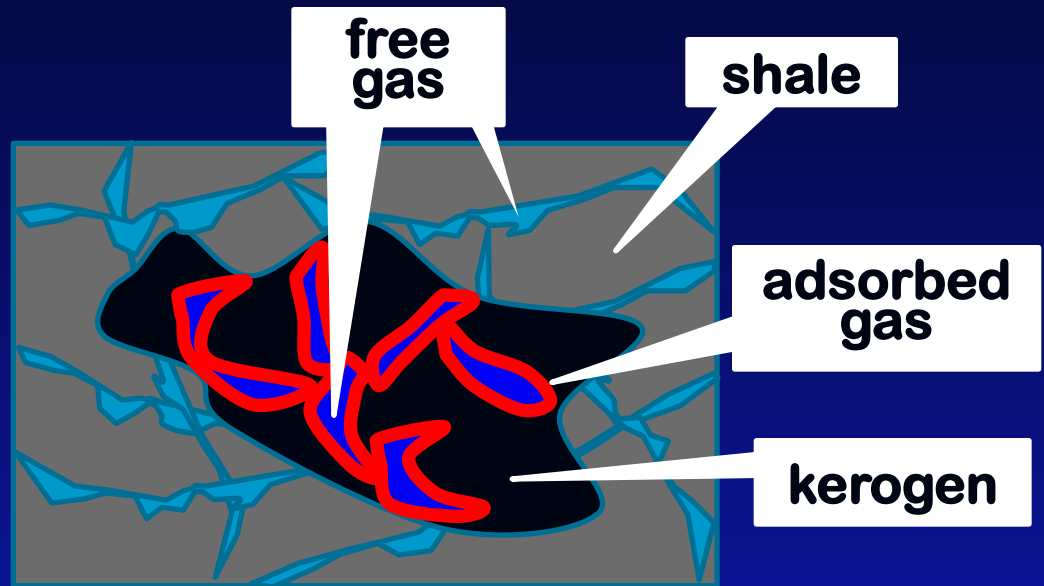
# Shale Gas Reservoirs

**Diameters of pores in shale:**  $10^{-9} \text{ m} \leq d_{\text{pore}} \leq 10^{-6} \text{ m}$

**Shale matrix permeability:**  $10^{-9} \text{ md} \leq k \leq 10^{-3} \text{ md}$

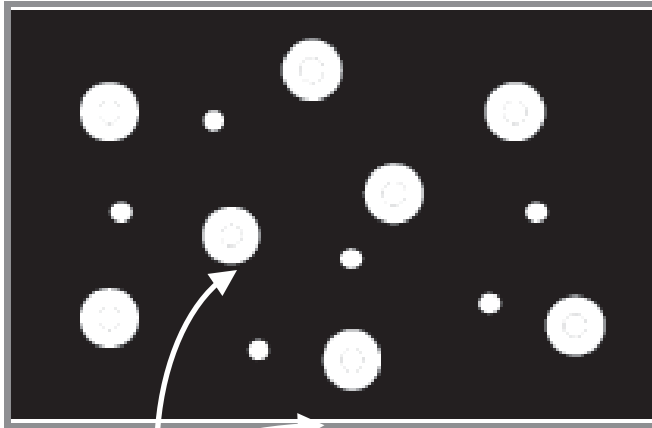
## Gas Storage:

- i) Free gas in intergranular porosity and in the kerogen pores
- ii) Adsorbed gas on the surface of the organic content
- iii) Soluble gas in solid organic materials (kerogen, clays, etc.)



# Porosity and Permeability Ranges

(a) Conventional

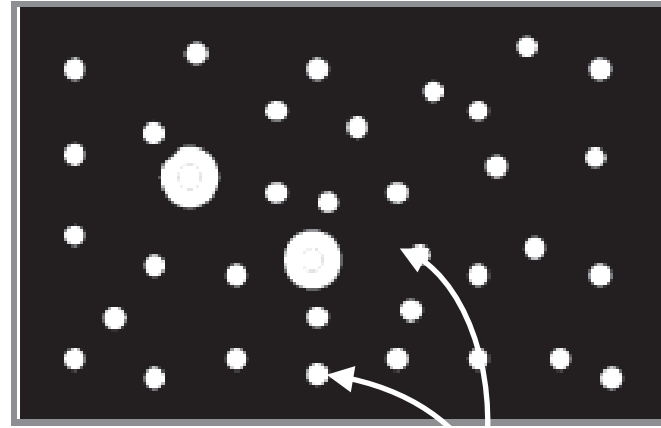


**Micro-pores**

Conventional oil and gas

$$d_{pore} \geq 1\mu\text{m}$$
$$k \geq 1\text{mD}$$

(b) Shale gas



**Nano-pores**

Shale gas

$$1\mu\text{m} \geq d_{pore} \geq 10^{-3}\mu\text{m}$$
$$10^{-3}\mu\text{D} \geq k \geq 10^{-3}\text{nD}$$

Tight gas

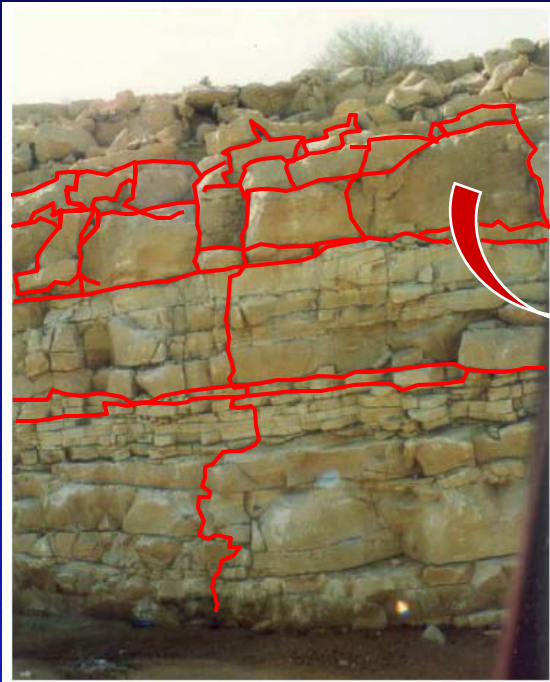
$$1\mu\text{m} \geq d_{pore} \geq 10^{-3}\mu\text{m}$$
$$1\text{mD} \geq k \geq 1\mu\text{D}$$

# Fluid flow in Nano-Darcy Shale

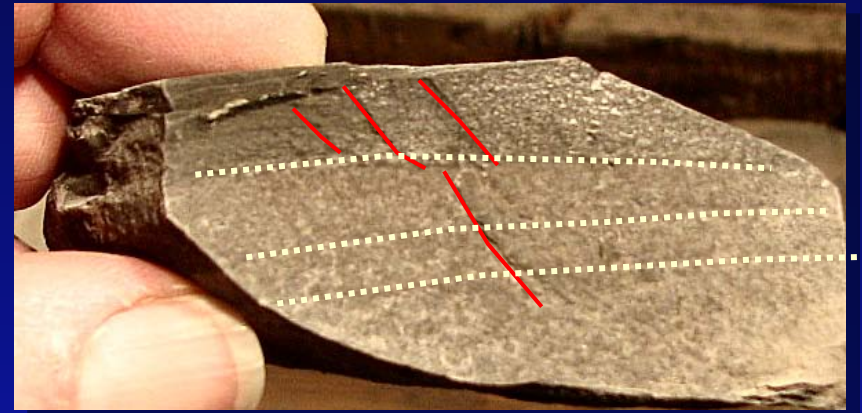
*“... numerical modeling requires gas permeabilities 2 to 4 orders of magnitude greater than observed to match flow rates and ultimate recoveries ... **Some other, higher permeability pathway through shale seems necessary.**”*

*Cluff, Shanley, and Miller, AAPG 2007*

Field Scale (m)



Core  
Scale  
(cm)



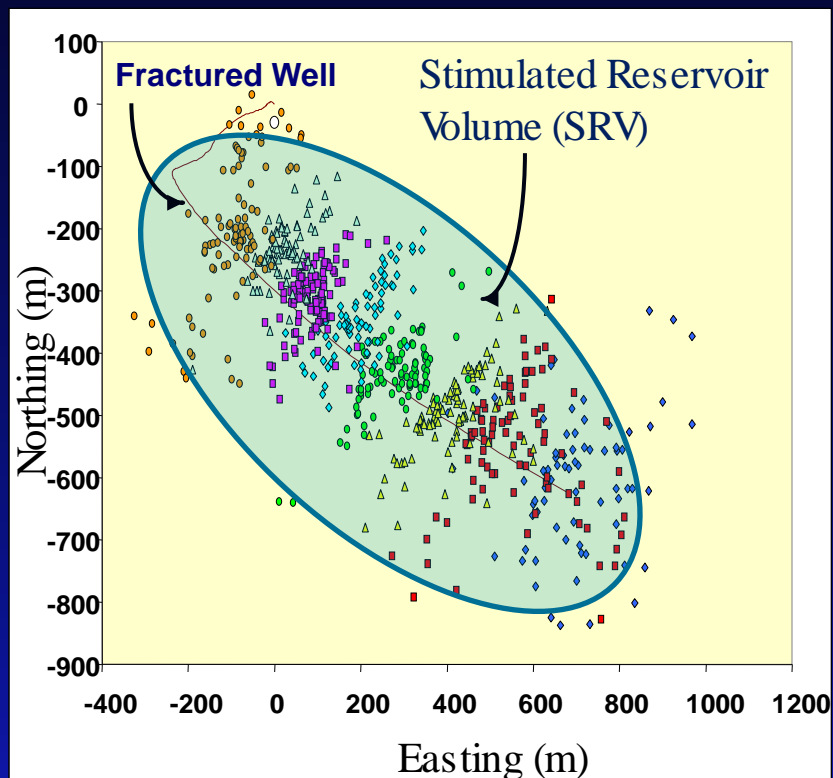
Micro Scale (mm)

**FRACTURES IN SHALE**

*Fractures, fractures, fractures, ...*

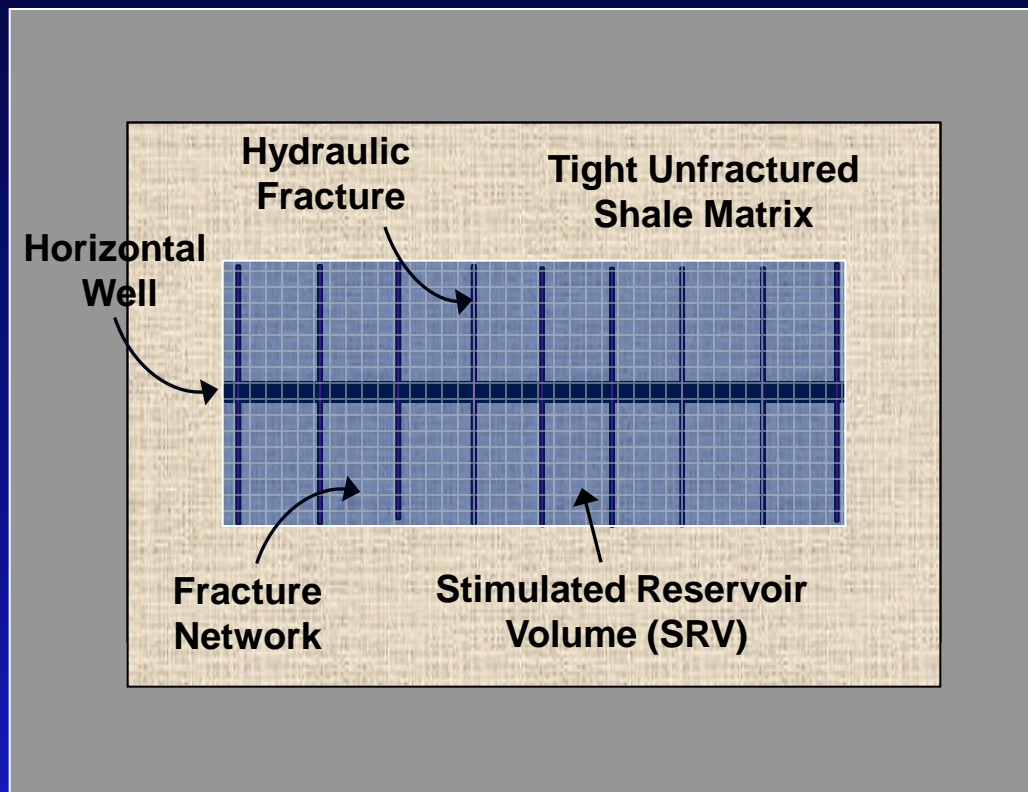
# Hydraulic Fracturing Induces and Rejuvenates Fractures in Shale

## Microseismic Record of Fracturing Events

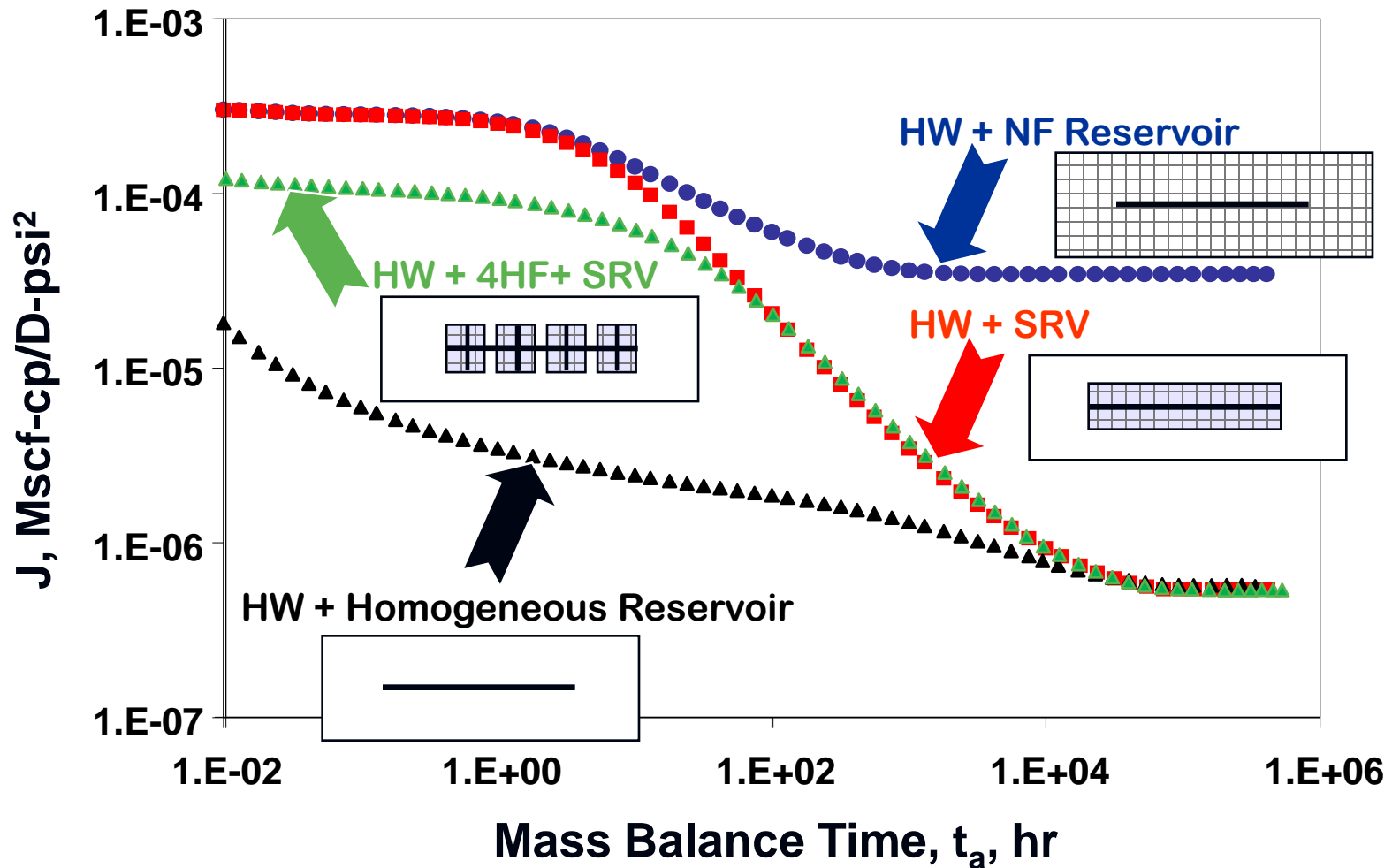


From Rimrock Energy, SPE 119896

## Stimulated Reservoir Volume (SRV) Representation



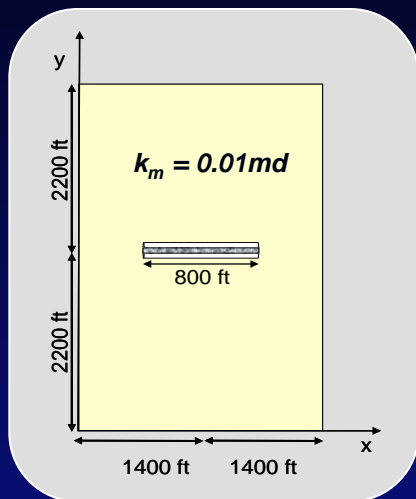
# What's the role of Hydraulic Fractures?



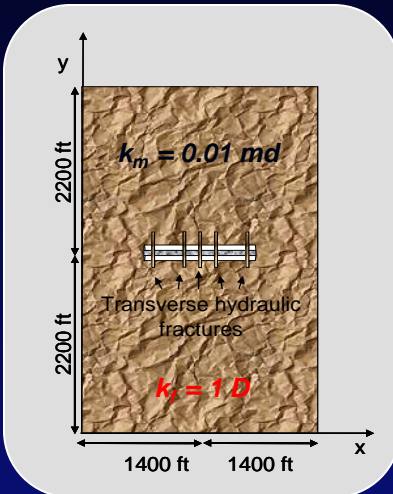
# Drainage area question:

## Larger area or more efficient drainage?

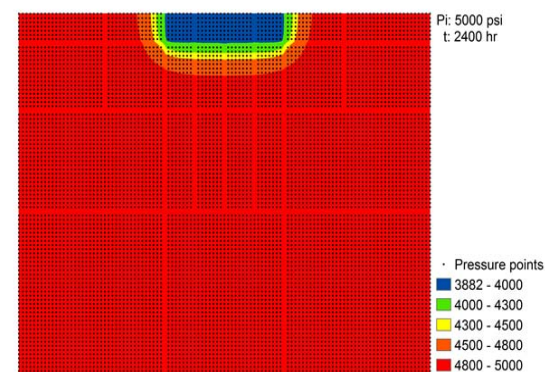
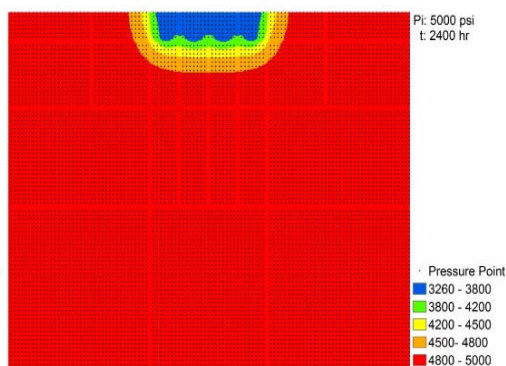
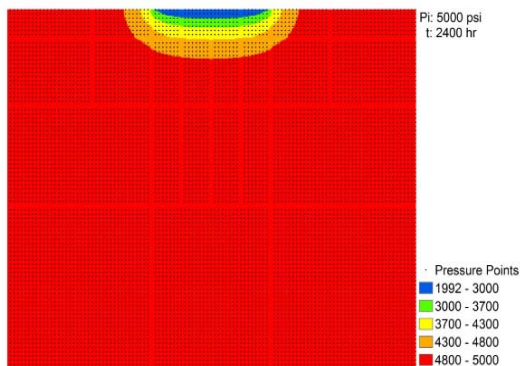
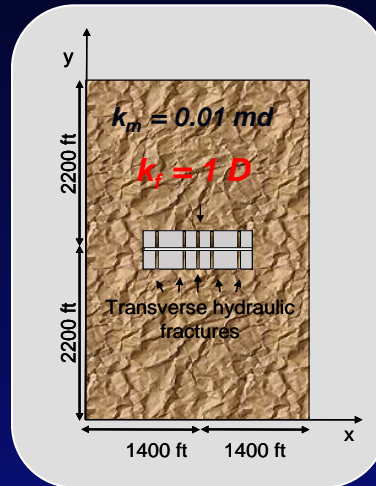
### Horizontal Well only



### Horizontal Well & Hydraulic Fracs.



### Horizontal Well, Hydraulic Fracs. & SRV

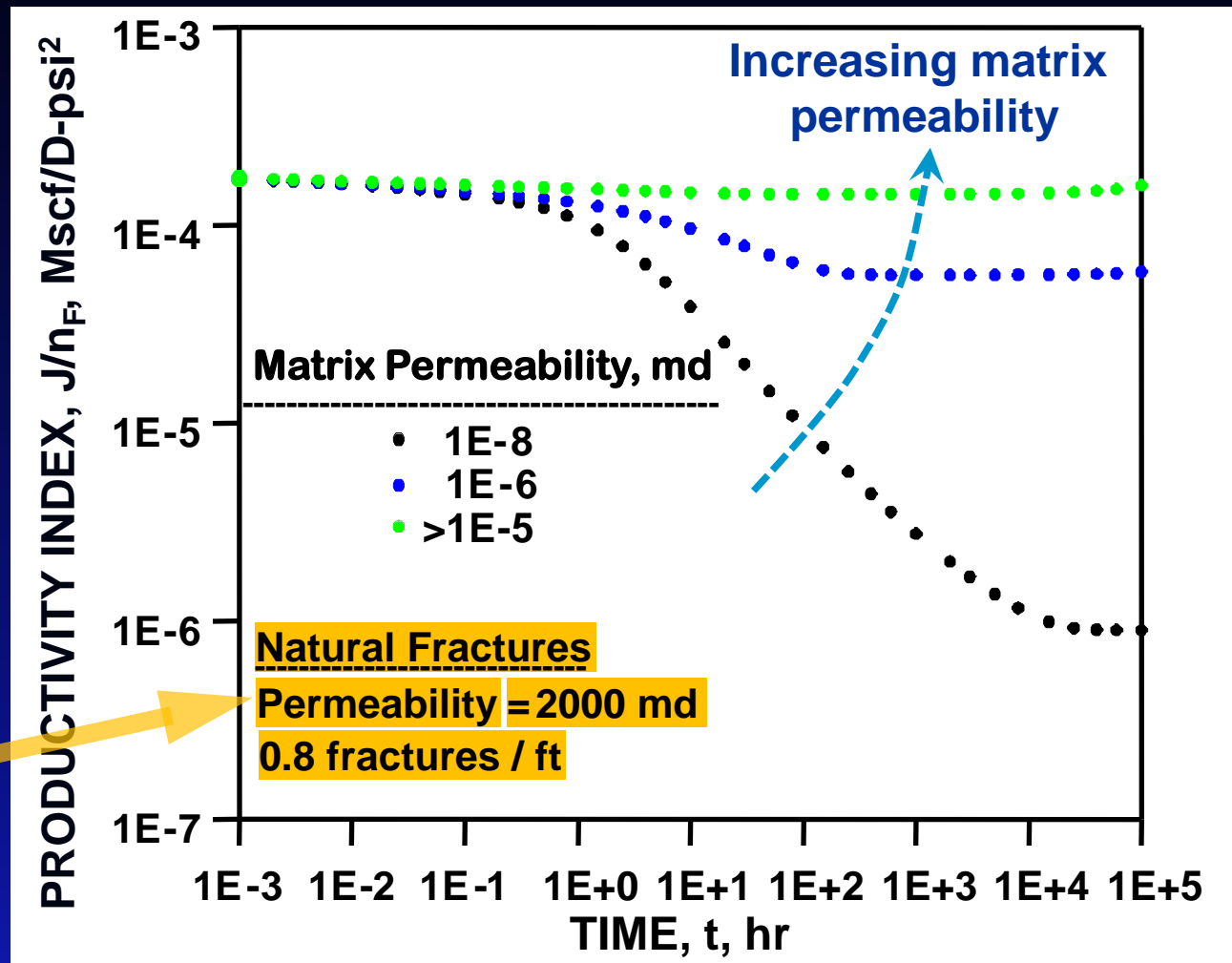


*What governs production performance?*

# Effect of Matrix Permeability

Productivity increases with increasing matrix permeability for  $k_m \leq 10^{-5}$

When flow capacity of natural fractures is reached, no additional productivity is possible

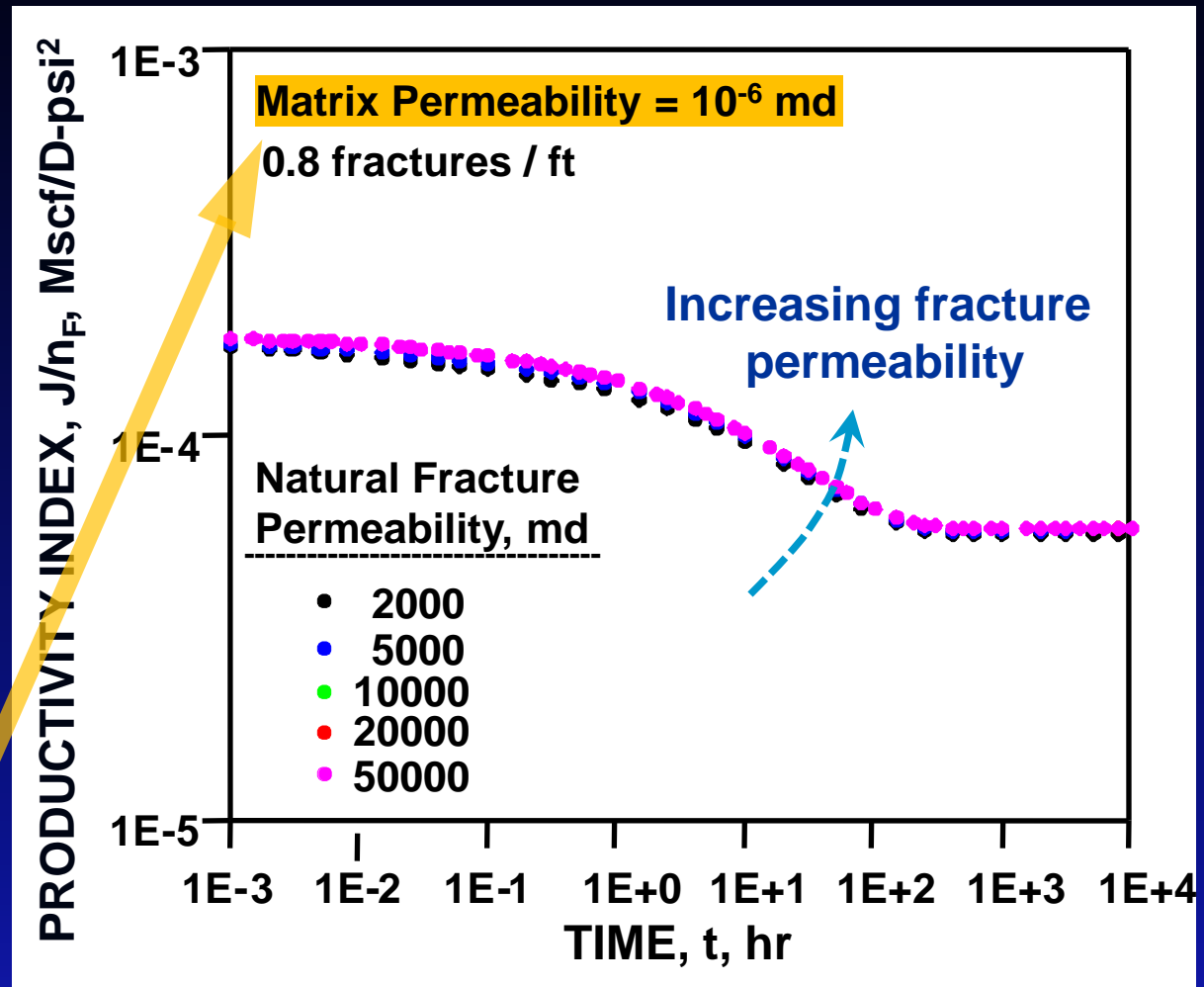


# Effect of Natural Fracture Permeability

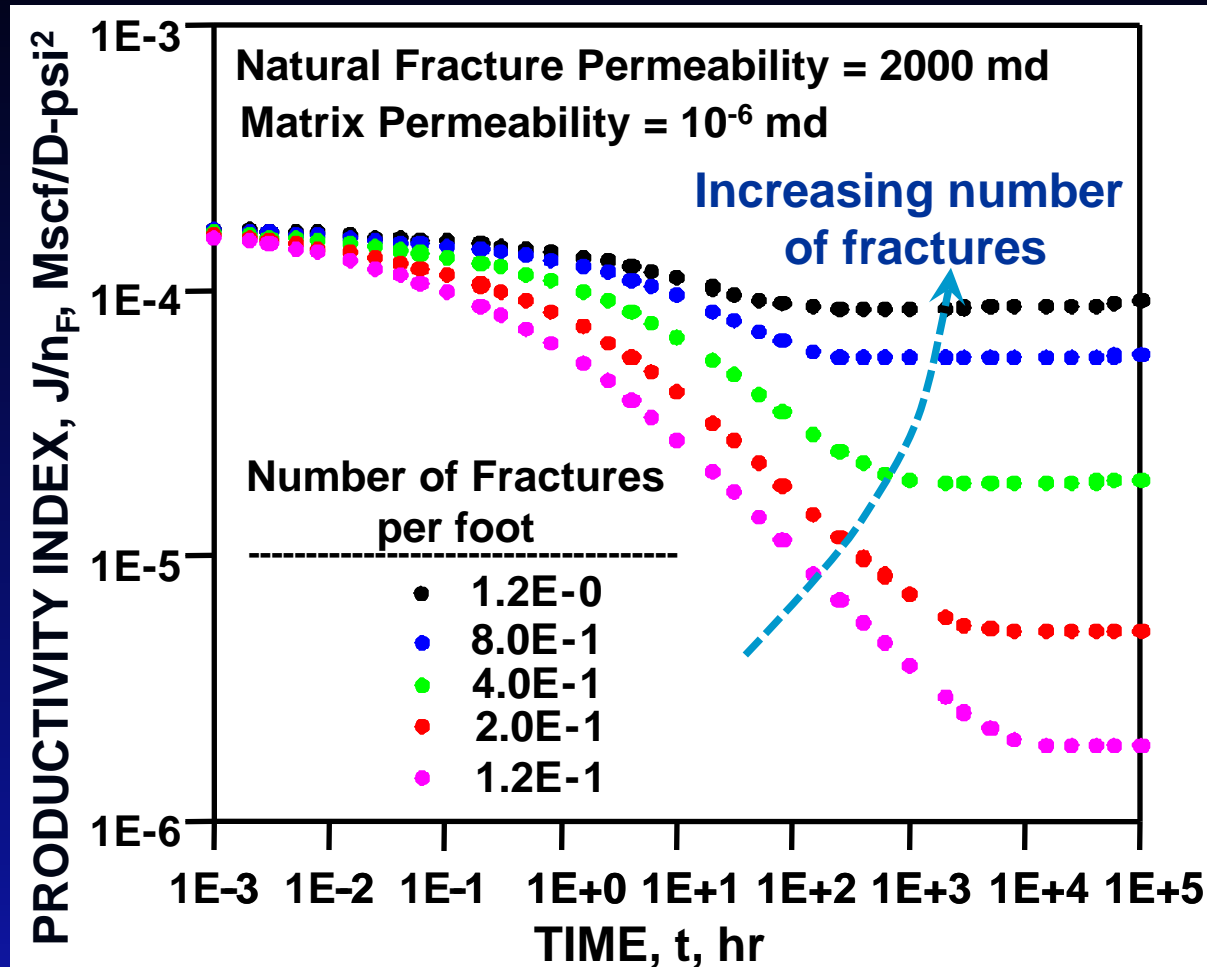
No difference in productivity with increasing natural fracture permeability

Natural fracture permeability has little effect on productivity

Flow capacity of the matrix is the limiting factor



# Effect of Natural Fracture Density



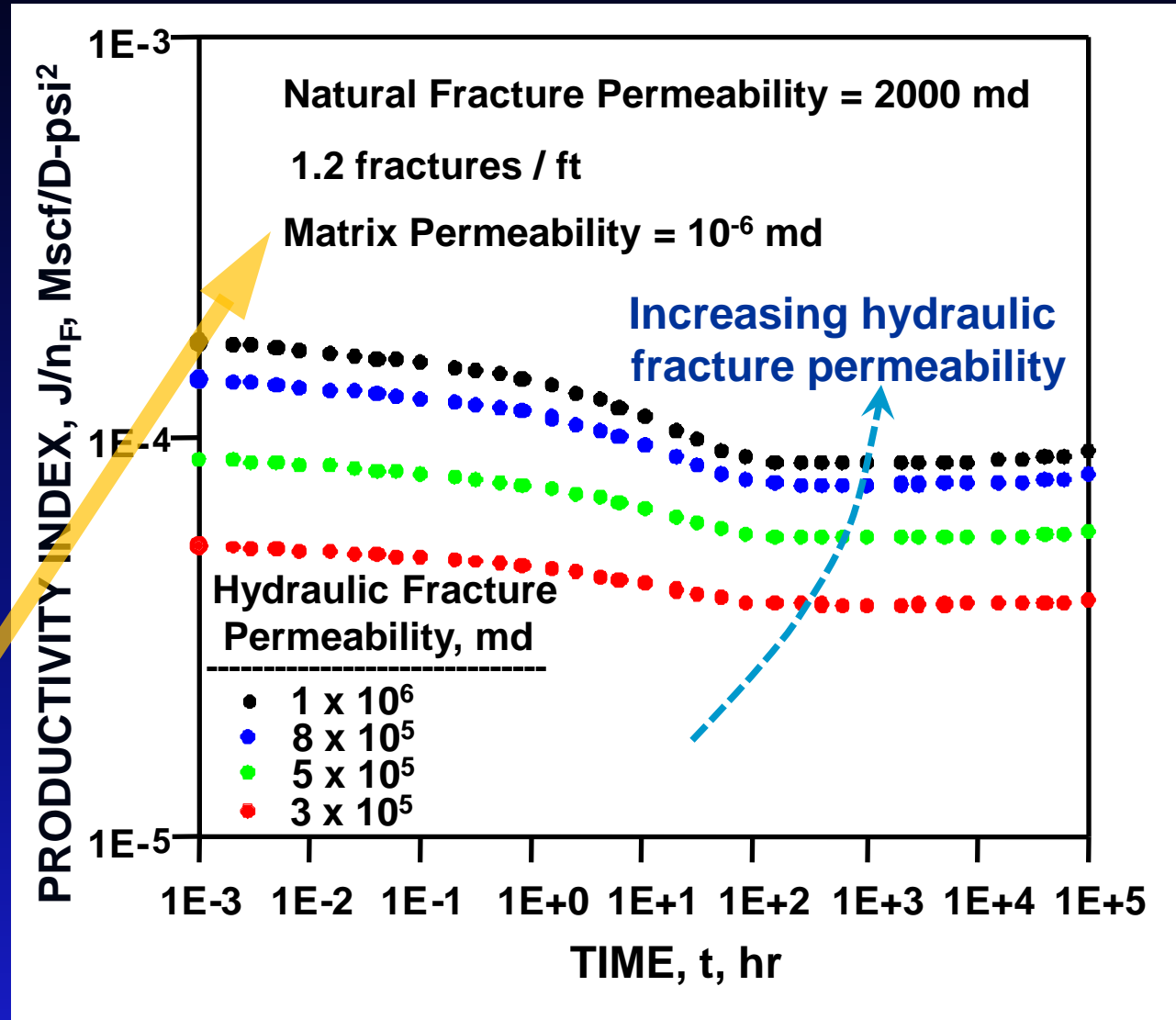
Natural fracture density has significant effect on flow capacity of matrix.

Greater surface area for flow allows for a greater volume of fluid to be moved

# Effect of Hydraulic Fracture Conductivity

Incremental productivity decreases as conductivity increases.

Volume of fluid available to flow is limiting factor



*Where is the gas coming from? (matrix support?)*

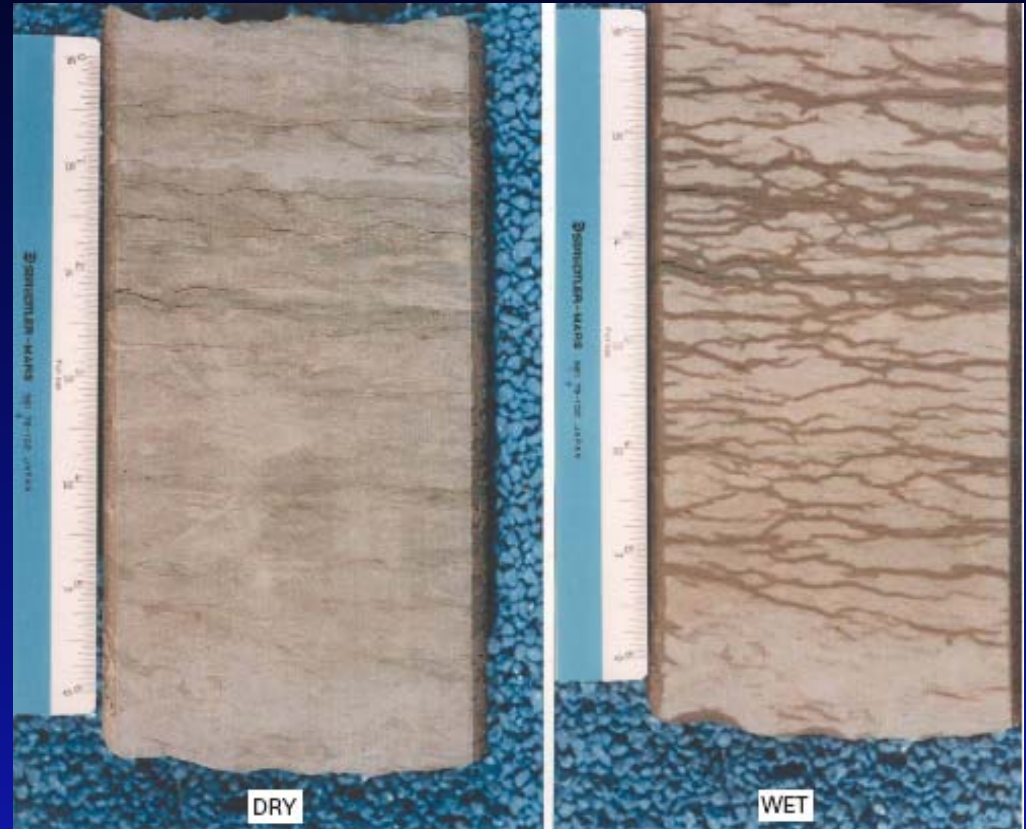
# Missing something?

## Is flow negligible in matrix?

### Natural Fractures in a Bakken Core

*We cannot justify sustained productivities observed in the field based on fracture dominated flow.*

*But, how much fluid can be moved from matrix to fracture network with Darcy flow and nano-Darcy permeability in the matrix?*

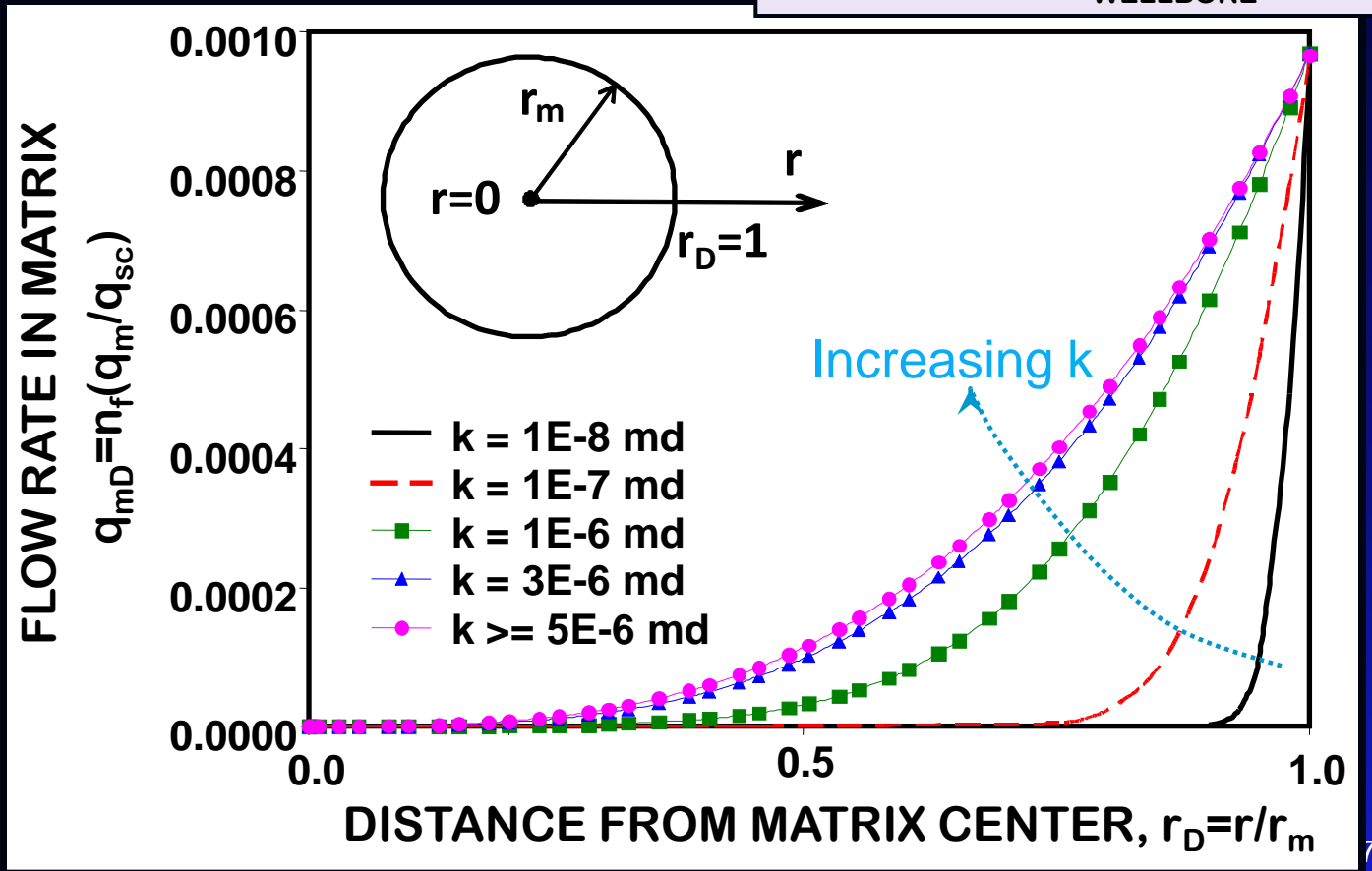
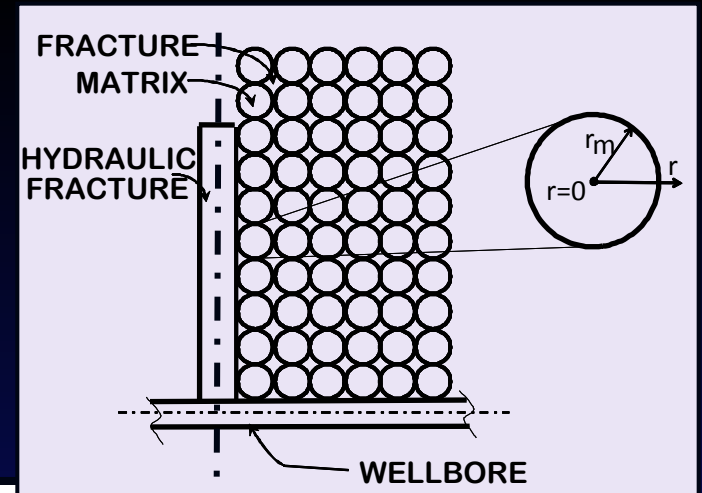


*From Pitman, Price, LeFever, USGS Paper 1653*

# Matrix Flow Rates after 27 Years of Production Darcy Flow

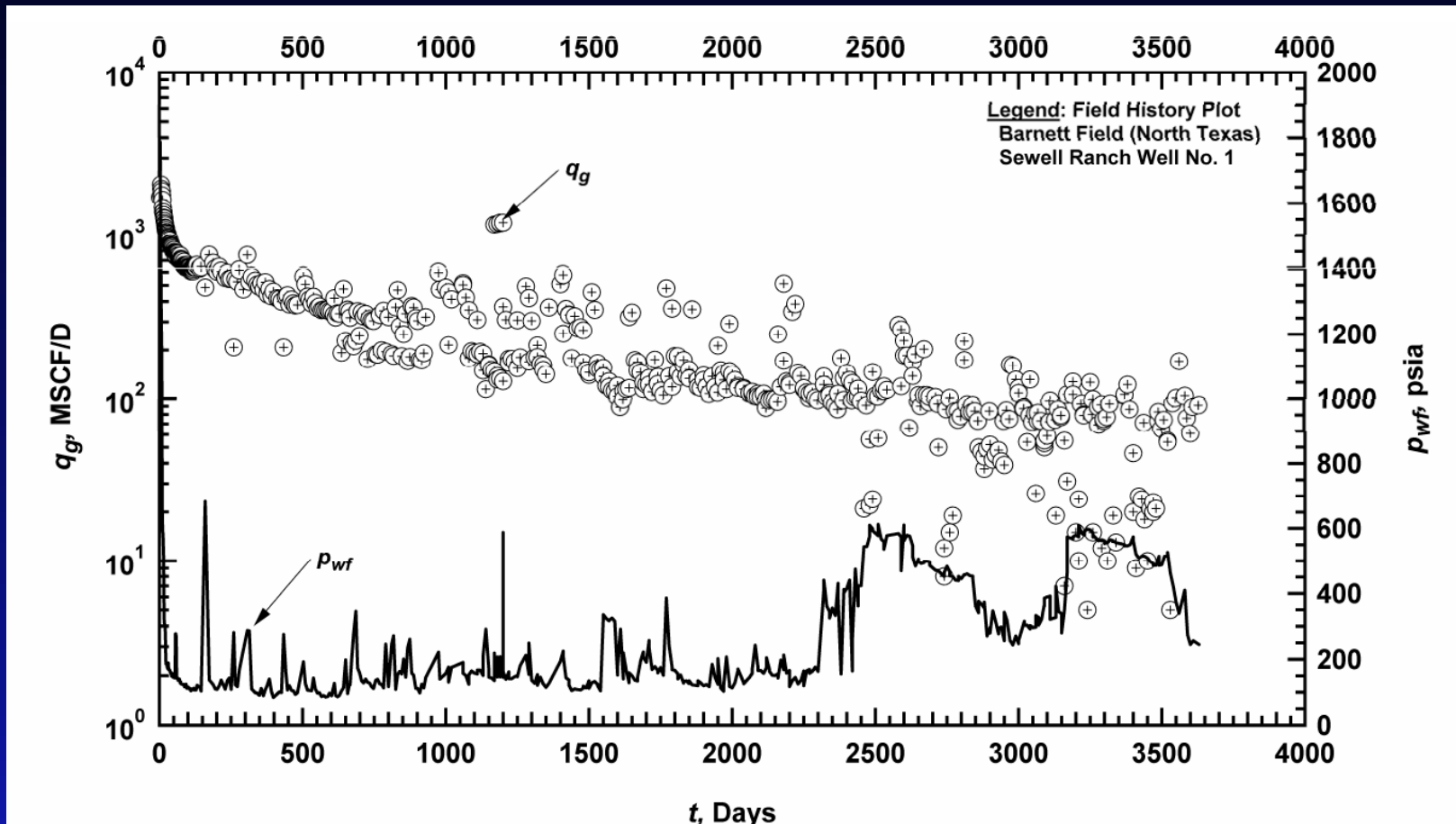
Most of the production comes from the surface of the matrix?

Ozkan et al.  
(2010)



# Going strong after 10 years

## Barnett (North Texas) well production



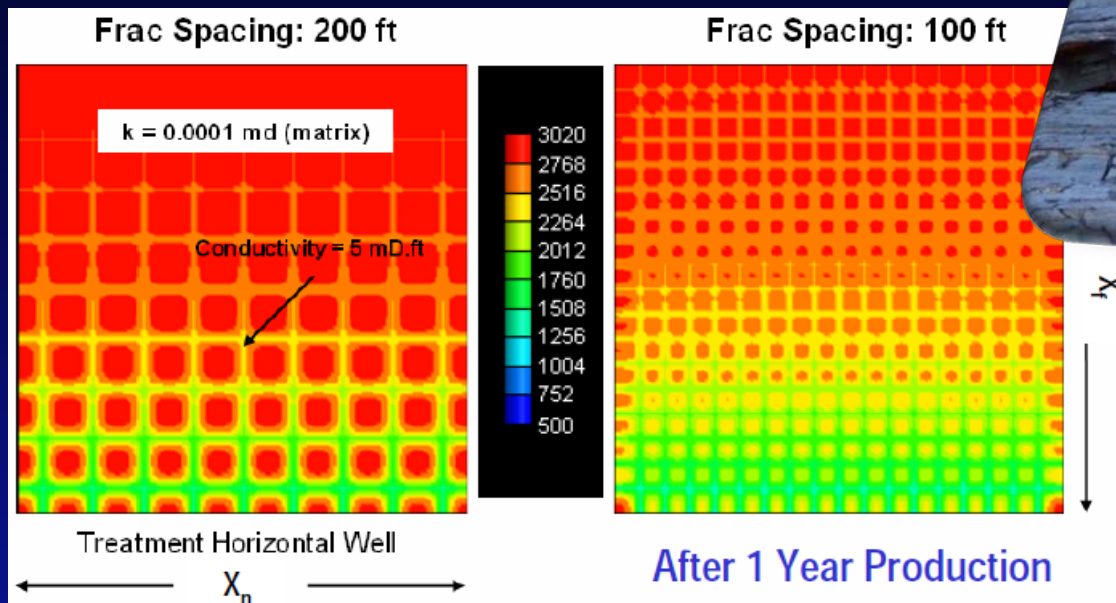
**10 years of production without support of matrix?**

*After T. Blasingame*

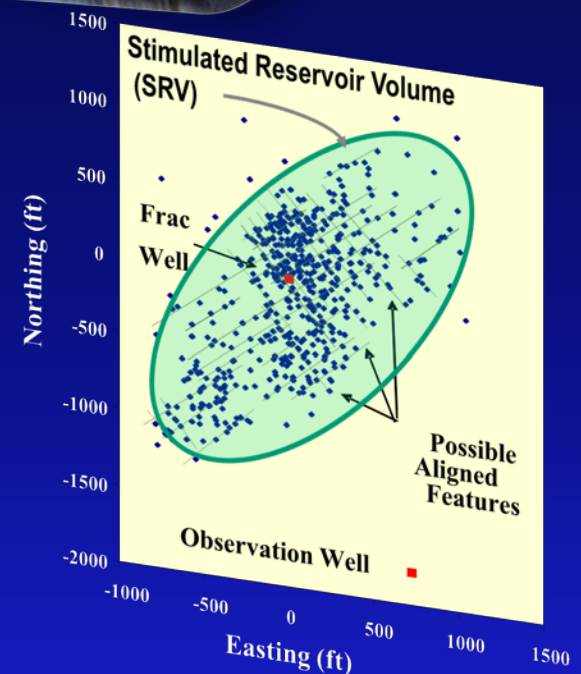
# *Modeling flow in fractured shale*

# Modeling Flow in Fractured Shale

## Modeling Fractures as a Hydraulic Fracture Network



*SPE 119890 Mayerhofer et al. (2007)*



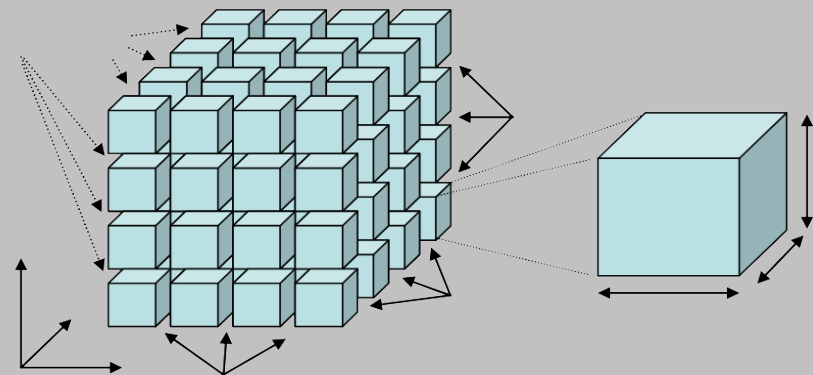
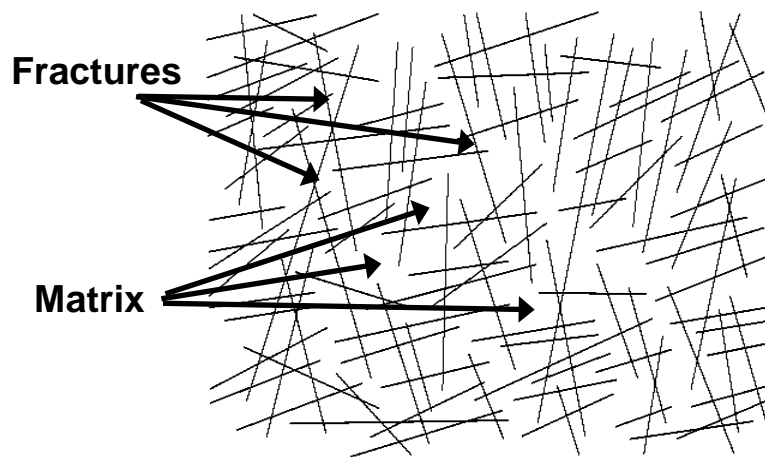
# Modeling Flow in Fractured Shale

## Modeling Fractures as a Network of Natural Fractures

### Physical System



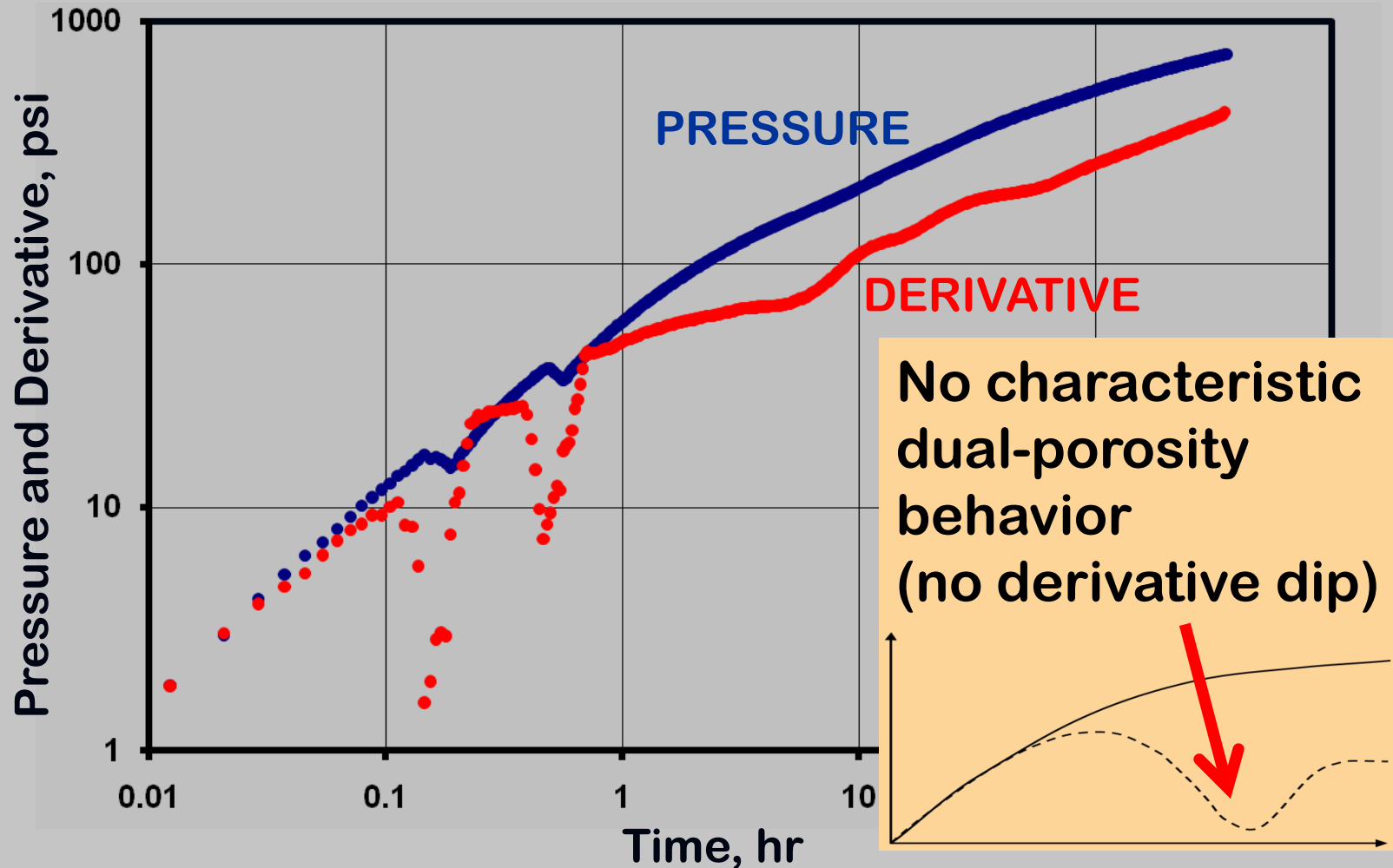
### Discrete Fracture Model



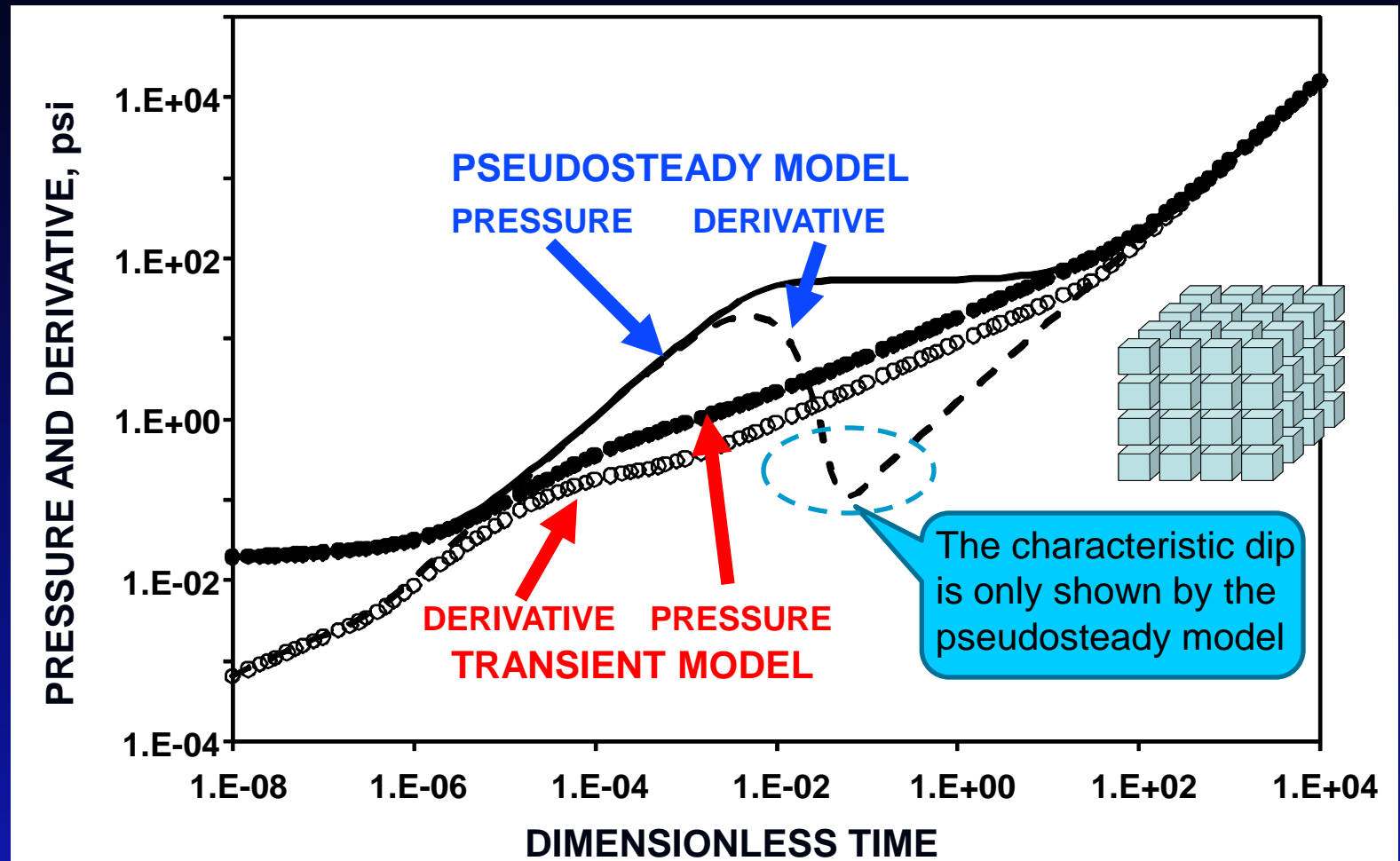
# Missing something?

## Where are the reservoir fractures?

### Pressure Buildup Test in Shale Reservoir (Field Data)



# Effect of the Choice between Dual-Porosity Models

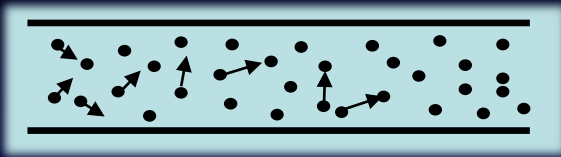


Transient dual-porosity model is more appropriate in shale  
(What is in your reservoir simulator?)

# *Unconventional flow in shale matrix*

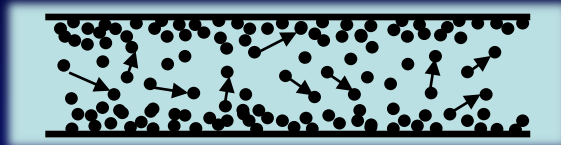
# FLOW REGIMES IN POROUS MEDIA

## High Velocity Flow (Forcheimer's Equation)



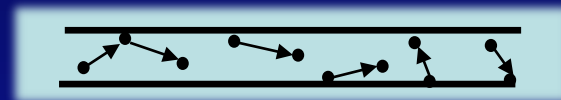
Non-Linear Flow: High  $p$ ,  $v$ , &  $k$   
Macro-pores and fractures

## Moderate Velocity, No-Slip Flow (Darcy's Law)

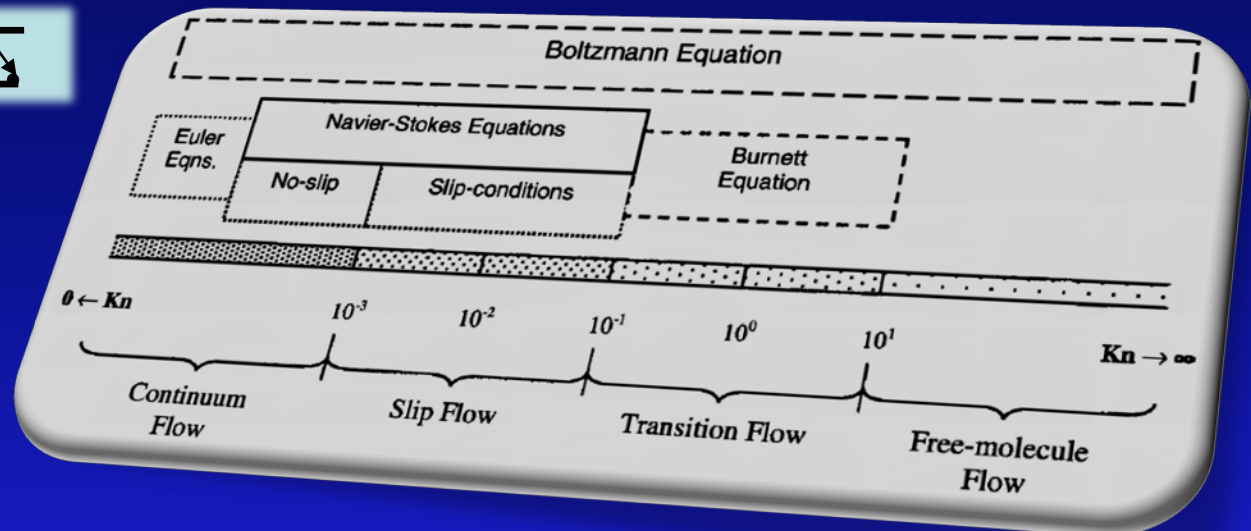


Linear and Laminar Flow: Moderate  $p$ ,  $v$ , &  $k$   
Micro-pores

## Low Velocity, Slip Flow (Klinkenberg effect)

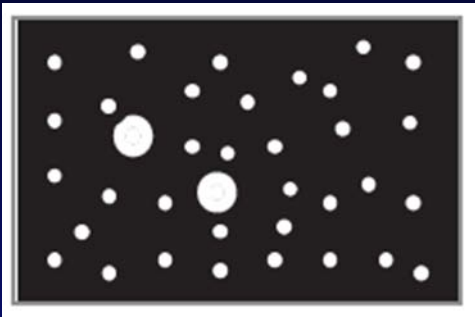


Non-Linear Flow:  
Low  $p$ ,  $v$ , &  $k$   
Core measurements  
nano-pores



# Dual Mechanism-Dual Porosity Flow Model for Shale

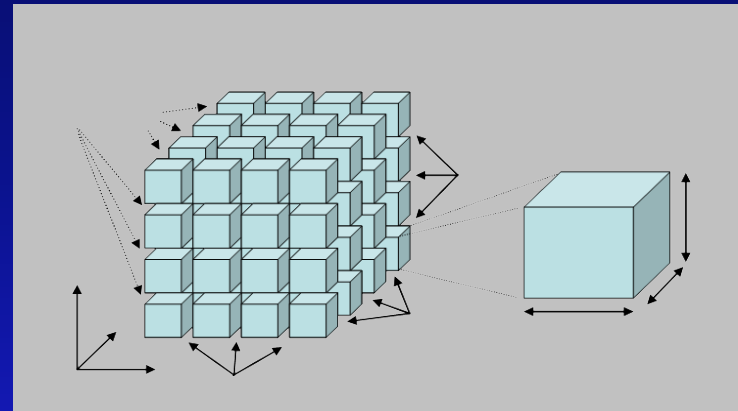
## Mixed flow in shale matrix



Darcy flow in fractures  
Darcy flow in matrix micropores  
Slip flow in matrix nanopores

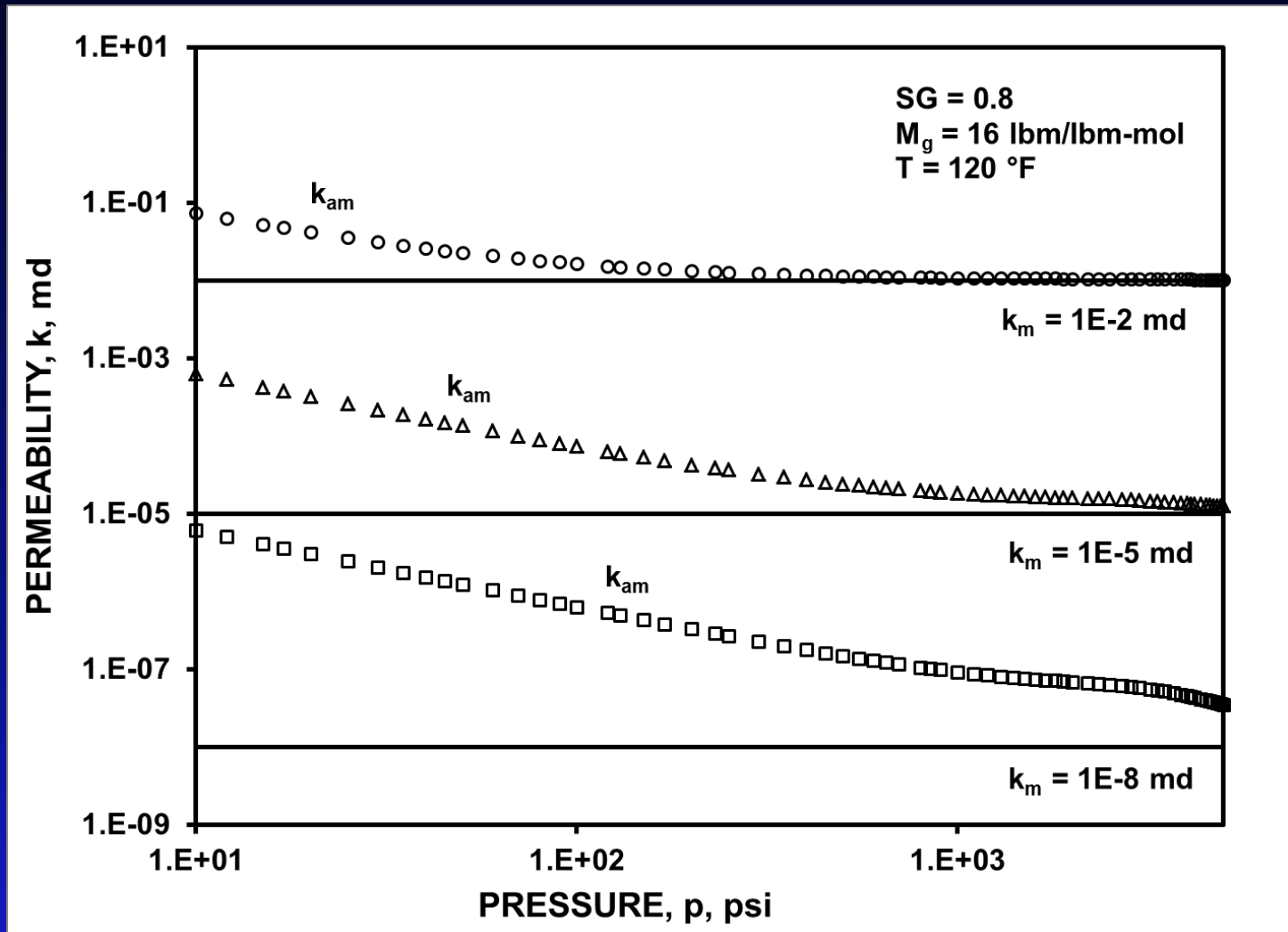
## Dual porosity flow in reservoir

Fractures dominate flow  
Matrix provides storativity  
Flow in matrix is transient



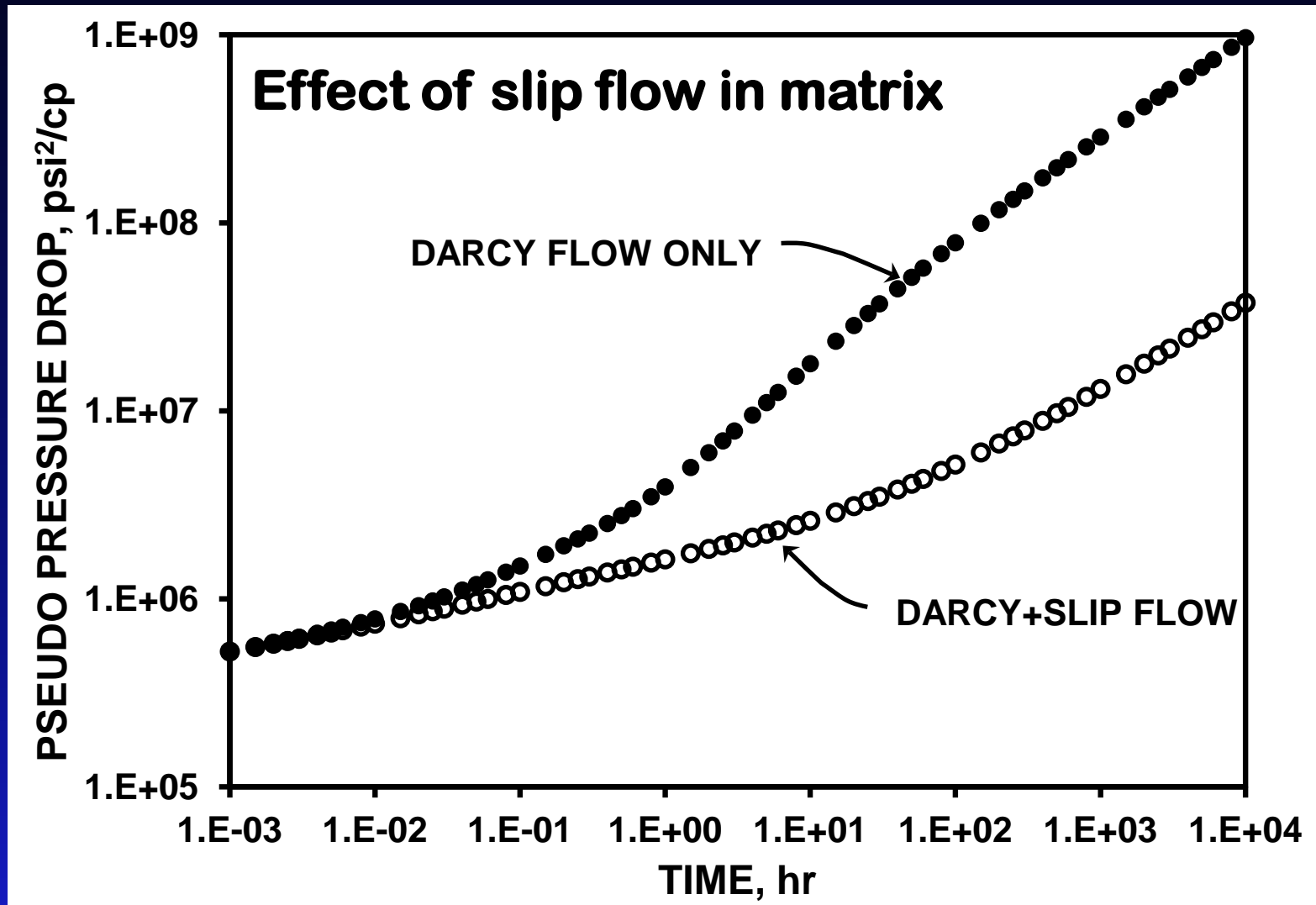
# Mixed Flow in Shale Matrix

## Contribution of slip flow to apparent shale permeability



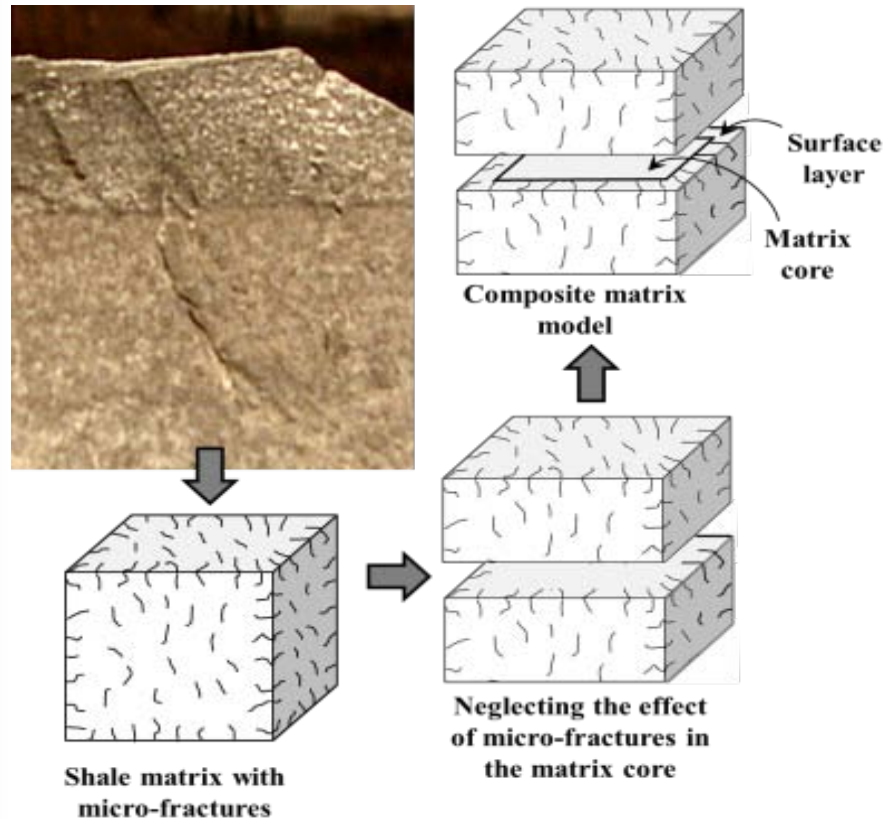
# Dual Mechanism-Dual Porosity Flow Model for Shale

38

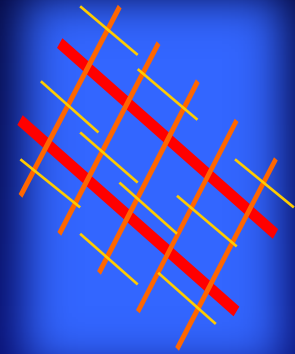


*Are microfractures the third porosity?*

# Microfractures in shale



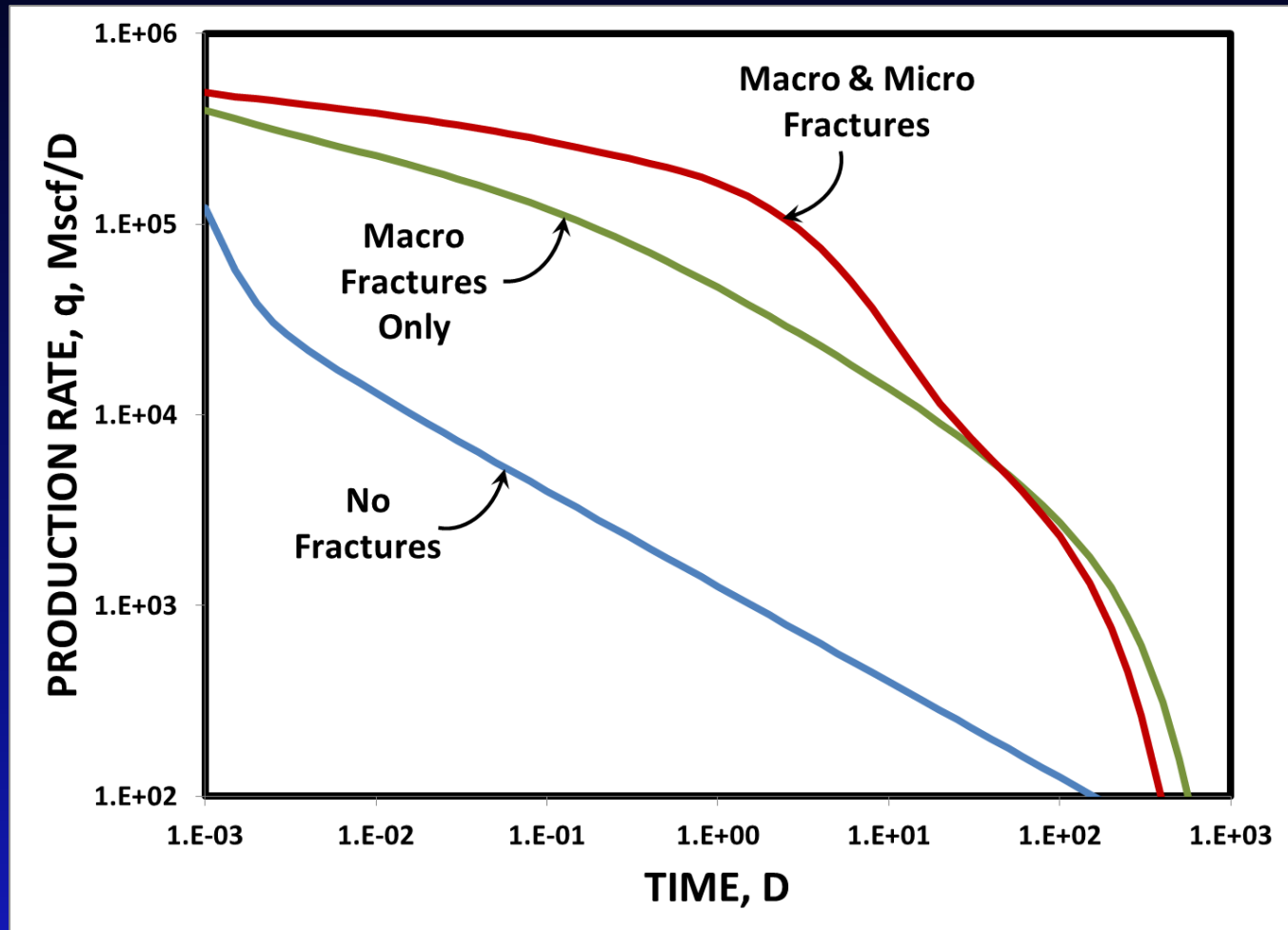
Are microfractures  
the third porosity?



Not in the  
conventional  
sense

Shale-matrix model with microfractures  
(Apaydin et al., 2011)

# Performances of a fractured horizontal well in dual-porosity reservoirs with and without microfractures



Shale-matrix model with microfractures (Apaydin et al., 2011)

# Conclusions

Our potential to recover gas from shale has been increasing due to

- new technologies to fracture horizontal wells
- better understanding of flow and production mechanisms

Marginal economics of shale-gas projects requires more improvements in

- characterization and modeling capabilities
- analysis and prediction tools and techniques

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