A Practical Recommendation for Permeability Measurement in Tight-Sand and Shale Reservoirs*

Albert X. Cui[1] and Ken Glover[1]

Search and Discovery Article #41407 (2014)**
Posted August 11, 2014

*Adapted from oral presentation given at 2014 AAPG Annual Convention and Exhibition, Houston, Texas, April 6-9, 2014

[1]Trican Geological Solutions, Calgary, Alberta, Canada (acui@trican.ca)

Abstract

Permeability is one of the critical parameters for evaluating and developing tight-sand and shale reservoirs. It is well known that unconventional shale and tight-sand reservoirs are highly heterogeneous in mineralogy, fabric and pore structure. Pore-throats of unconventional formations commonly have a wide range of sizes from hundreds to just several nanometers. Due to the nanometer-size pores, gas transport in tight-sand and gas shale has a significant component of diffusion, consequently resulting in strong pore-pressure-dependent gas permeability. Different approaches for a Klinkenberg diffusion correction to gas permeability have been discussed theoretically by recent studies with limited experimental data. With nanometer-size pores, the intrinsic or liquid permeability corrected from gas permeability also changes with different test gases. Furthermore, permeability of unconventional rock depends on in-situ confining stress that also changes as the reservoir pressure depletes during production. Therefore, for rigorous evaluation and development of an unconventional reservoir, it becomes necessary to understand how intrinsic permeability changes with in-situ stress and the pore-pressure and stress-dependence of gas diffusivity, which are difficult and time-consuming to determine separately in the laboratory. However, in present practice, most engineering calculations and reservoir simulation software packages do not take the diffusivity as an input.

In this study, a simple but rigorous approach is suggested to practically determine the in-situ permeability (combined intrinsic permeability and diffusivity) with consideration of the effects of pore pressure and in-situ confining stress. The permeability is

measured under conditions that closely simulate the in-situ stress path of a producing reservoir and can be simply represented as a function of reservoir pressure and therefore be readily usable for various engineering calculations and reservoir simulations. Discussions on various aspects of the permeability measurements of unconventional reservoirs are presented and applications of the measured permeability are illustrated.

References Cited

Brezoveki, R., and A. Cui, 2013, Laboratory permeability measurements of unconventional reservoirs: Useless of full of information? A Montney example from the Western Canadian sedimentary basin: OnePetro, SPE 167047, 12 p.

Cui, L., and S. He, 2009, Study on production formula for horizontal wells in reservoirs with bottom water: Journal of Oil and Gas Technology, v. 31/3, p. 110-114.

Faraj, B., and M. Brown, 2010, Key attributes of Canadian and U.S. productive shales: Scales and variability: AAPG Search and Discovery Article #110129, 25 p. Website accessed July 21, 2014. http://www.searchanddiscovery.com/pdfz/documents/2010/110129faraj/ndx_faraj.pdf.html

AAPG Annual Convention & Exhibition 2014

6–9 APRIL • HOUSTON, TEXAS
GEORGE R. BROWN CONVENTION CENTER

A practical recommendation on permeability measurement for tight-sand and shale reservoirs

Albert Cui and Ken Glover

Trican Geological Solutions

Calgary, Alberta CANADA | Woodland, Texas USA

Email: acui@trican.ca

TRICAN

AAPG

Outline

- Introduction
- GRI or pressure-decay technique
- Pressure pulse-decay technique
- Pressure and stress dependence of in-situ permeability
- Recommendations & conclusions

Fracture vs. matrix permeability

- For shale gas and oil reservoirs, if there are **no fractures**, there will be **no economical hydrocarbon productions.**
- **Permeability of intact matrix rock** is also **important**, and **critical** for optimal well stimulations.
- **Matrix permeability** should be **properly determined in lab** (and in field).

Fracture vs. matrix permeability

Photo Curtsey:

Woodford Shale

Fracture vs. matrix permeability

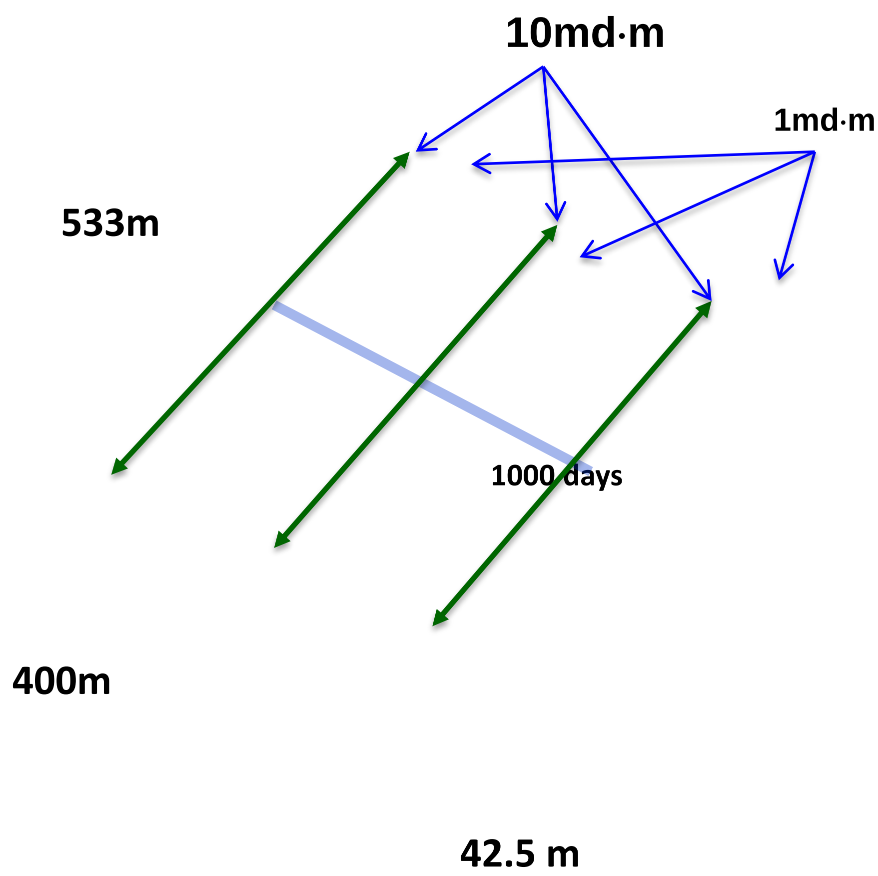
Montney Shale at Williston Lake, BC

(Photo Curtsey: Faraj and Brown, 2010)

Complex fractures!

Matrix permeability is important

- A 300m-long cemented & perforated horizontal well.
- ϕ = 0.06, S_w=0.15, T= 115°C, P_i=25 MPa
- Formation permeability varies from 1e^{-3}md to 1e^{-4}md.
- Fracture network consists of
  - 3 primary hydraulic fractures (half length, X_f = 150m, C_f = 10md-m, 120m spacing)
  - Orthogonal secondary fractures networks with C_f = 1md-m

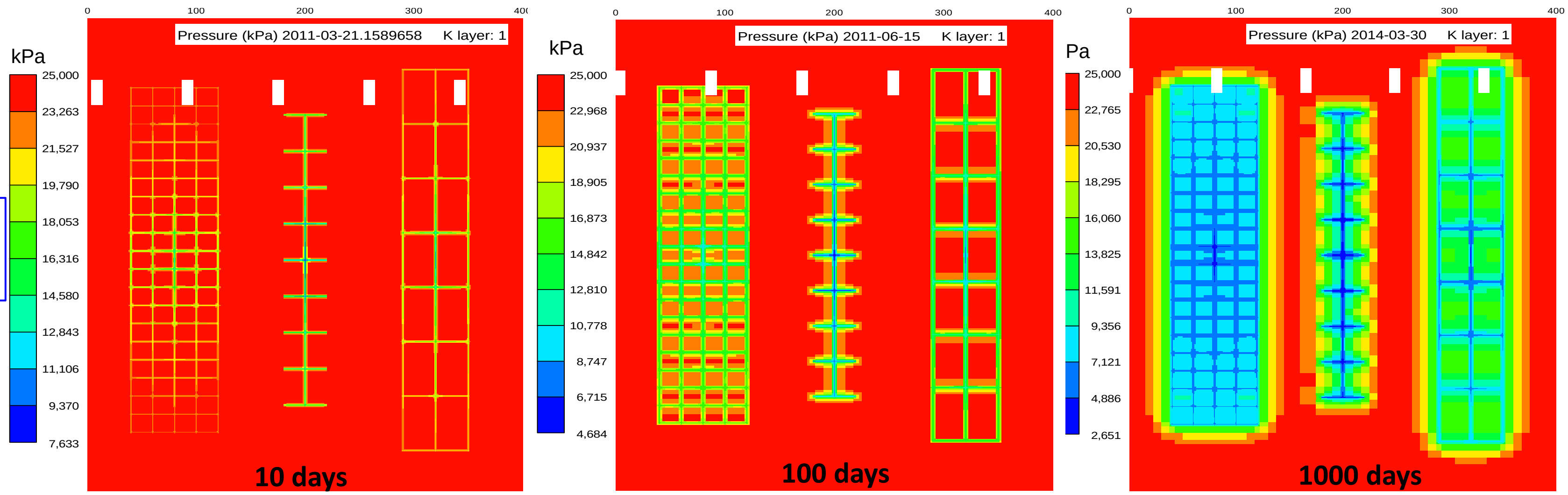


TRICAN

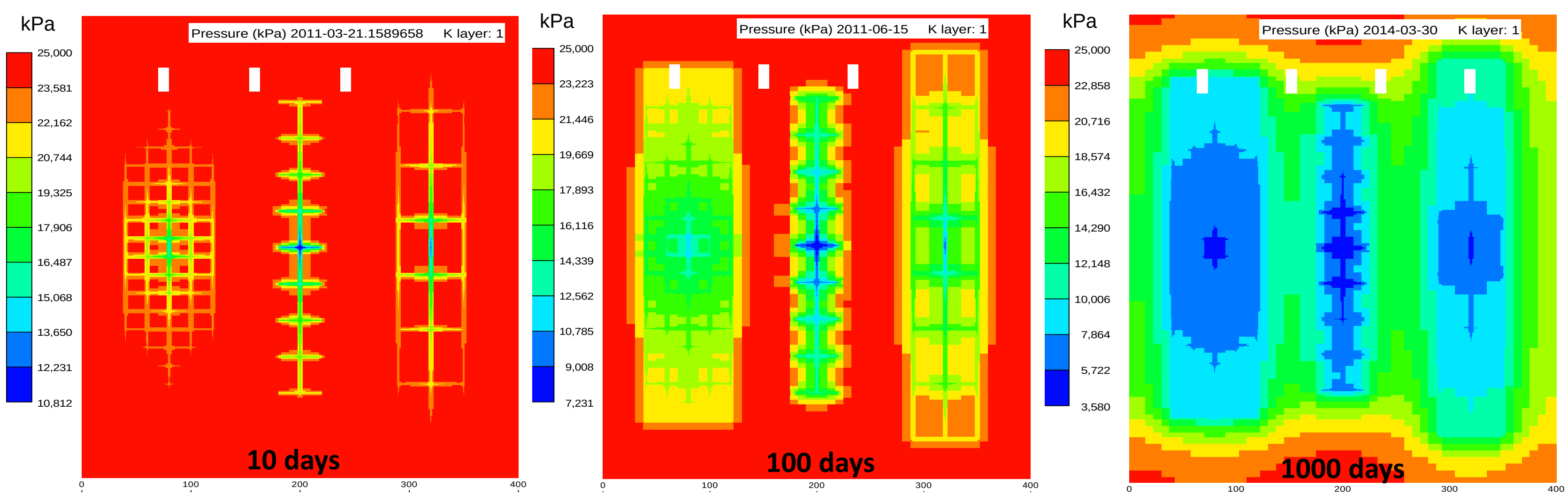
AAPG

Controls of K_m on drainage pattern

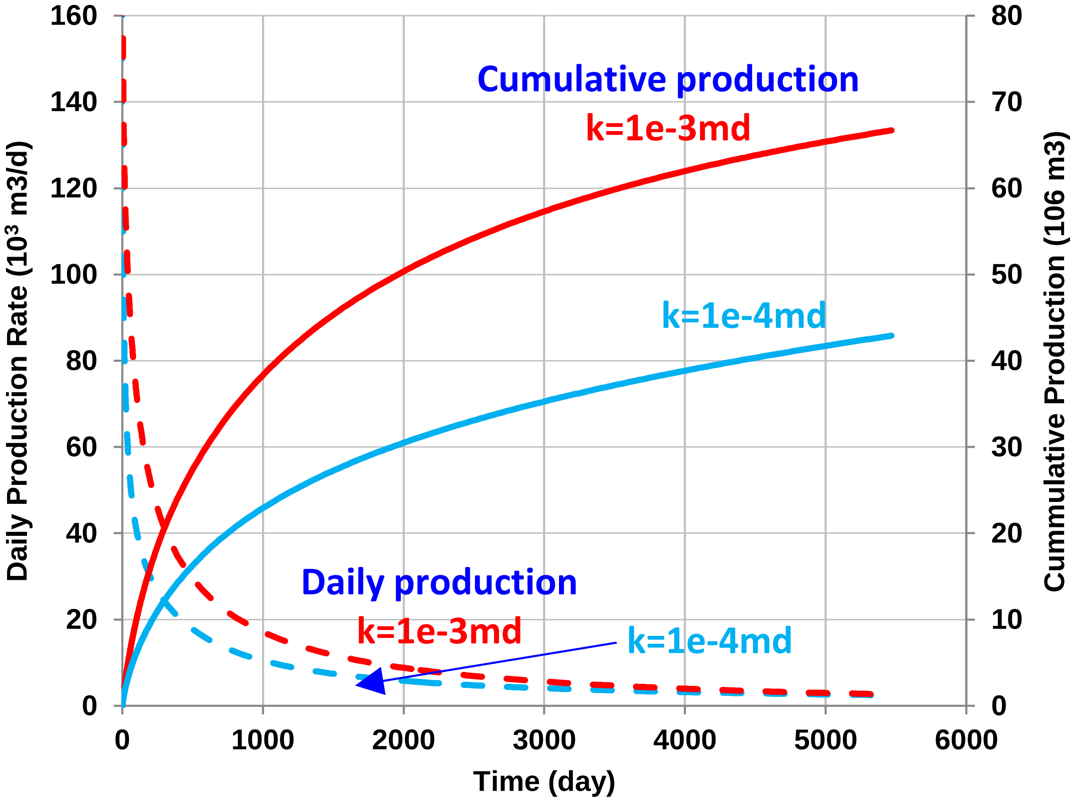
K_m= 0.0001 md



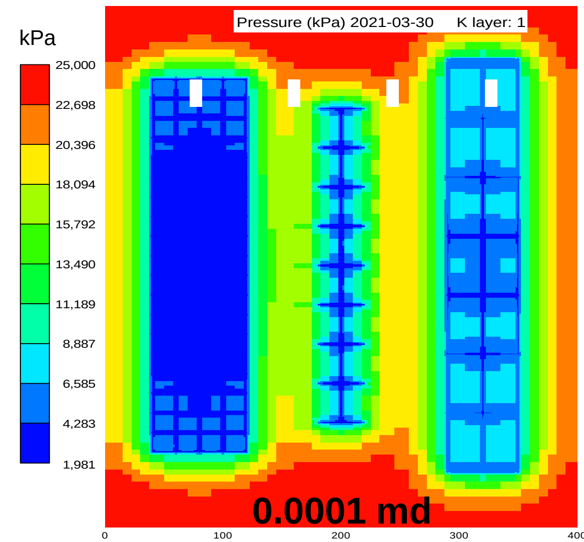
K_m= 0.001 md

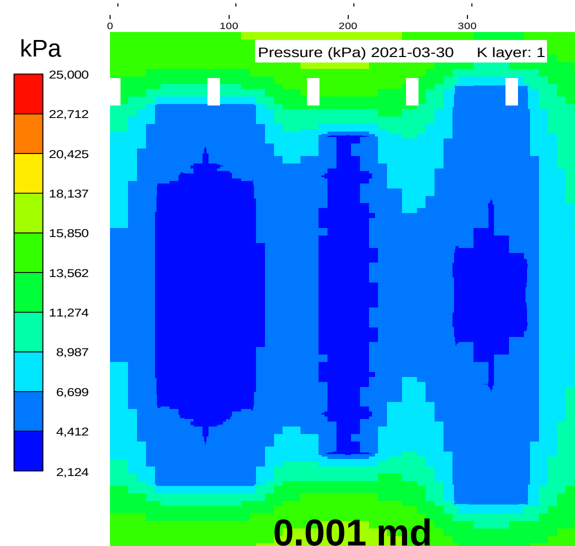


Controls of K_m on production



10 Years



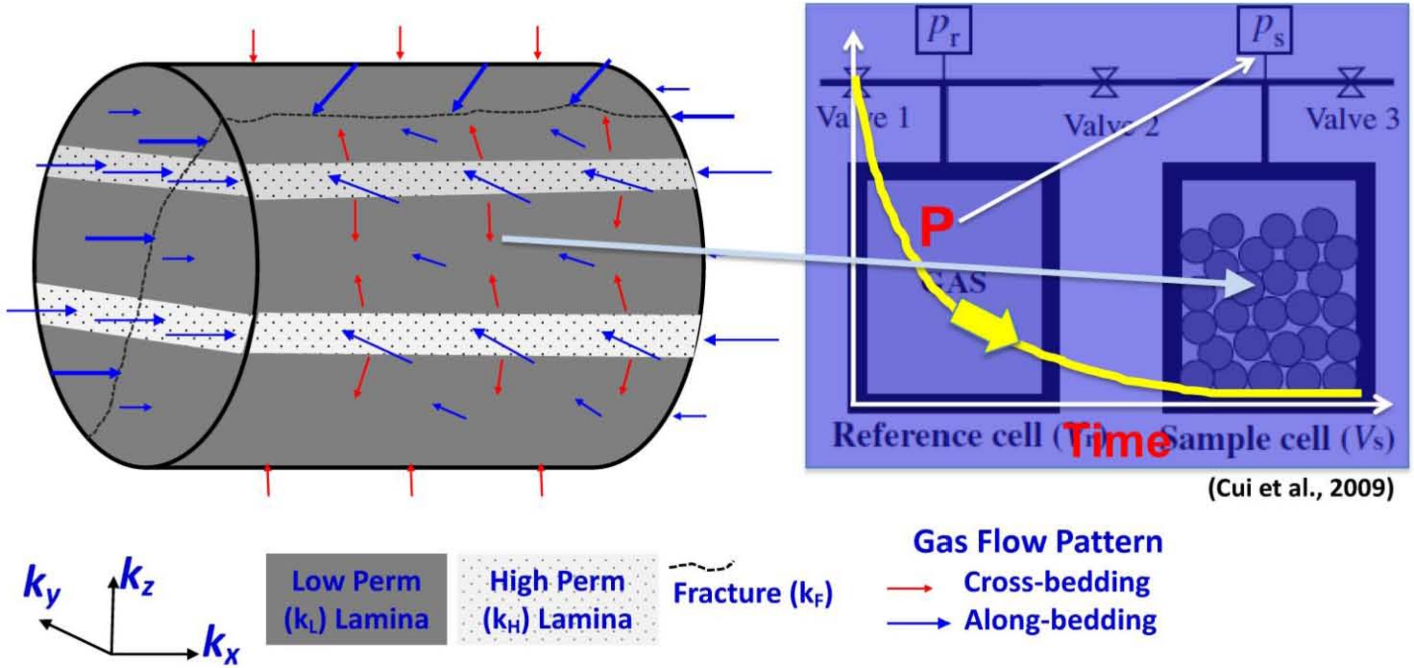


Techniques for permeability measurement

- GRI or pressure-decay or pressure-fall-off technique
  - Crushed samples or core plugs
  - Confined or unconfined but commonly unconfined
  - Low gas pressure
  - Approximate
- Pressure-Pulse decay (PPD) technique
  - Core plugs
  - Confined to in-situ stress with high or low fluid pressure (Pf)
- Steady-state technique
  - Air/N2 permeability
  - Commonly under low confining stress and low Pf
- Other techniques

GRI / pressure-decay / falloff permeability

- Gas fills up pore space from all directions with cross-bedding transfer



(Cui et al., 2009)

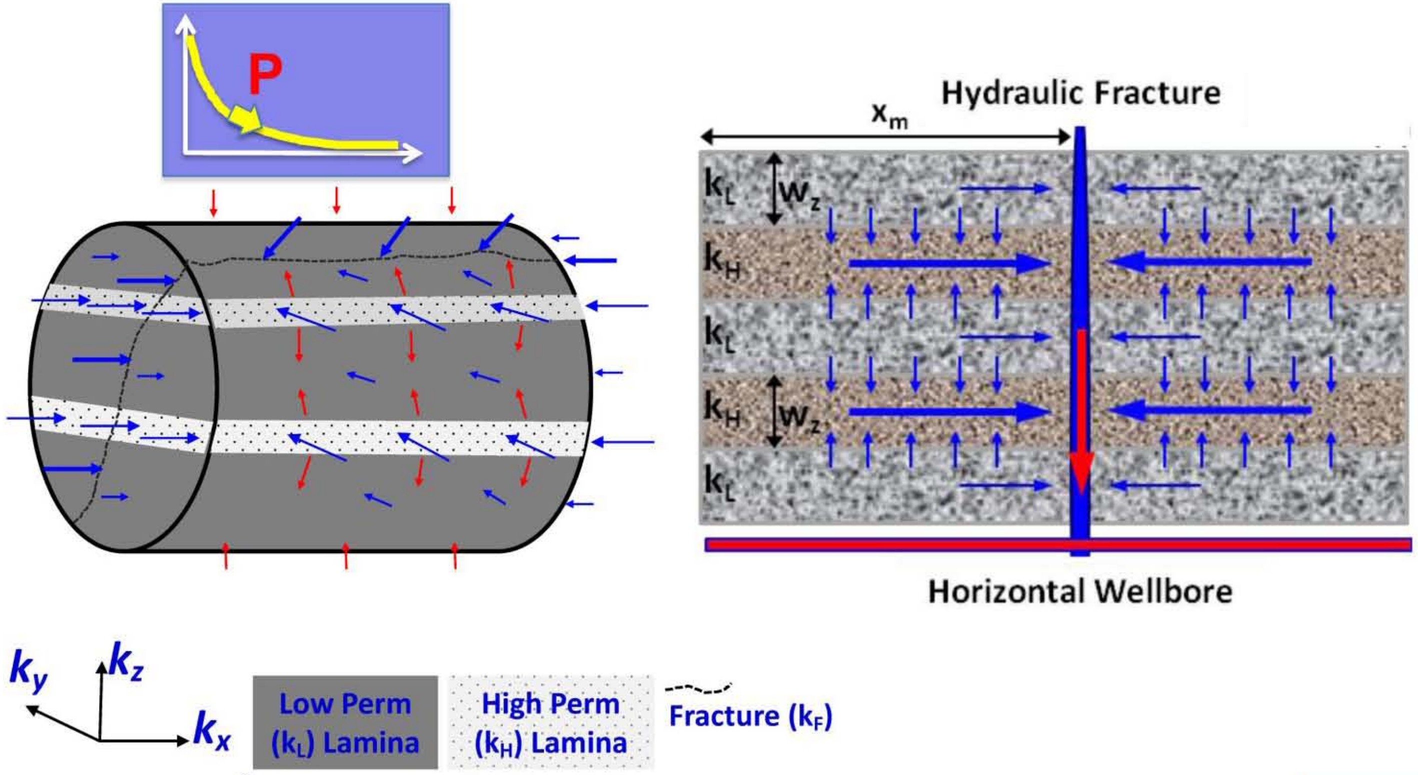
TRICAN

AAPG

Presenter's Notes: Different methods measure different permeability. Permeability is direction dependent.

GRI permeability – continued 1

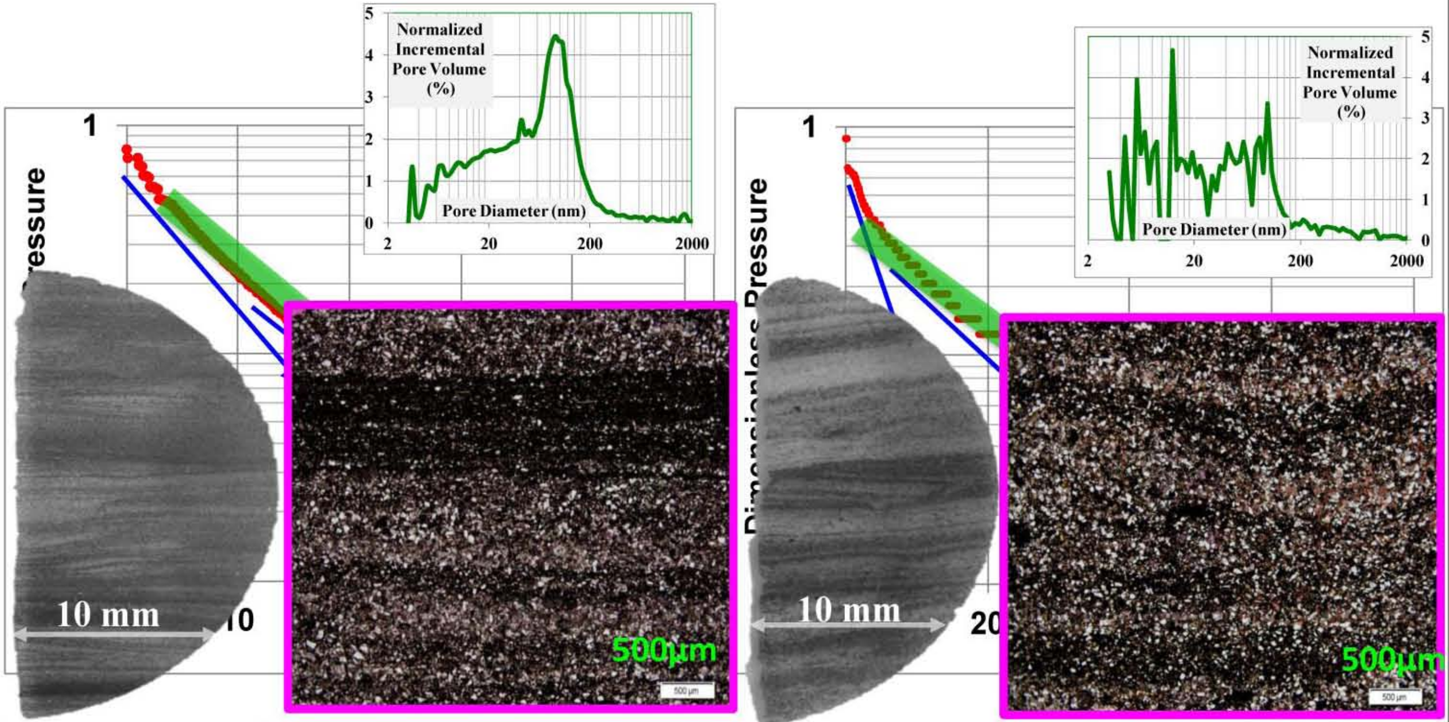
- **Average permeability value in all directions**



Presenter's Notes: Different methods measure different permeability. Permeability is direction dependent.

GRI permeability – continued 2

- Average permeability for different pore-throat sizes
- Not good for highly heterogeneous samples



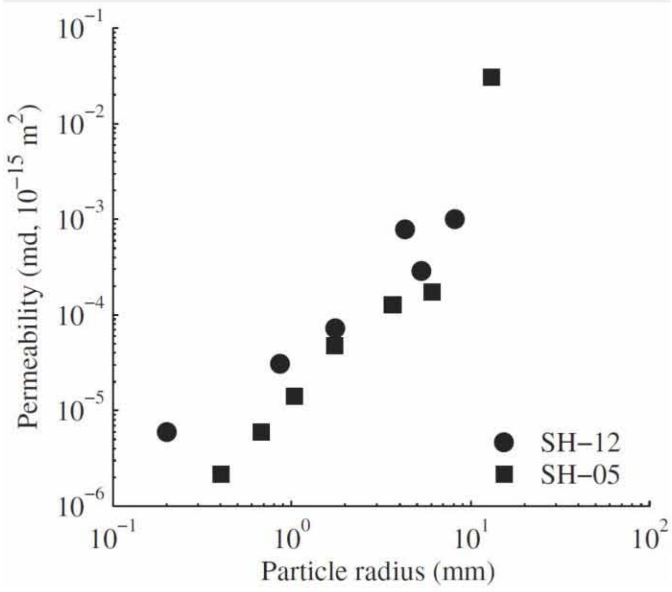
TRICAN

AAPG

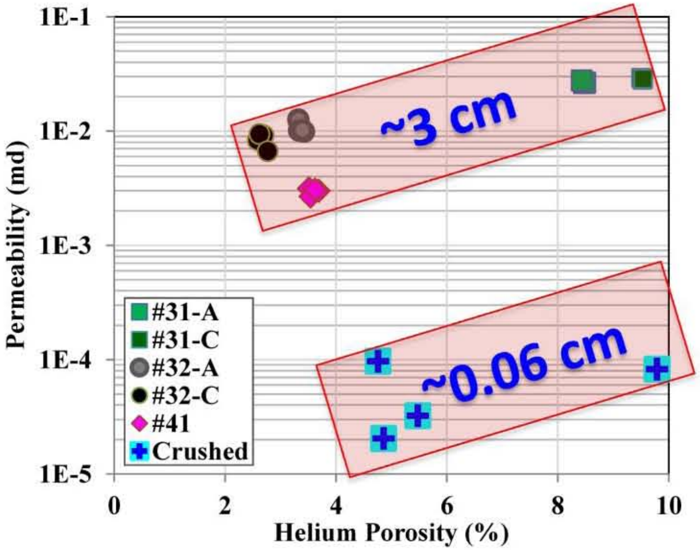
Presenter's Notes: Different methods measure different permeability. Permeability is direction dependent.

GRI permeability - continued 3

- **Strong dependence of sample size**



(Cui et al., 2009)



(cui et al., 2013)

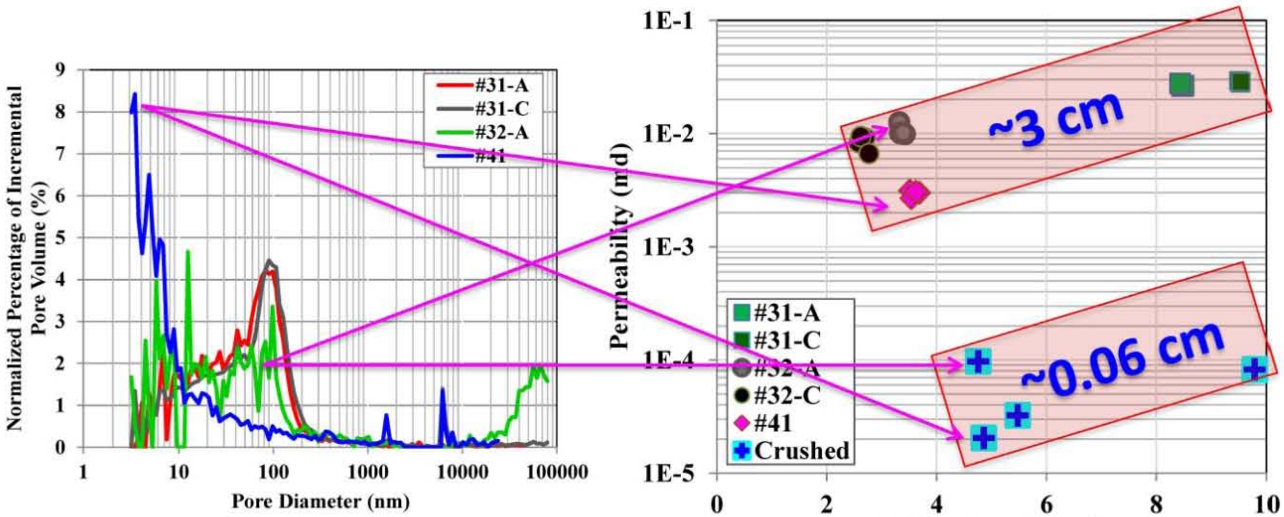
TRICAN

AAPG

Presenter's Notes: Different methods measure different permeability. Permeability is direction dependent.

GRI permeability – continued 4

- No consideration of effective in-situ stress
- Low gas pressure – diffusion dominated
- Not good for production analysis
- Valid reservoir quality index (porosity & pore size)

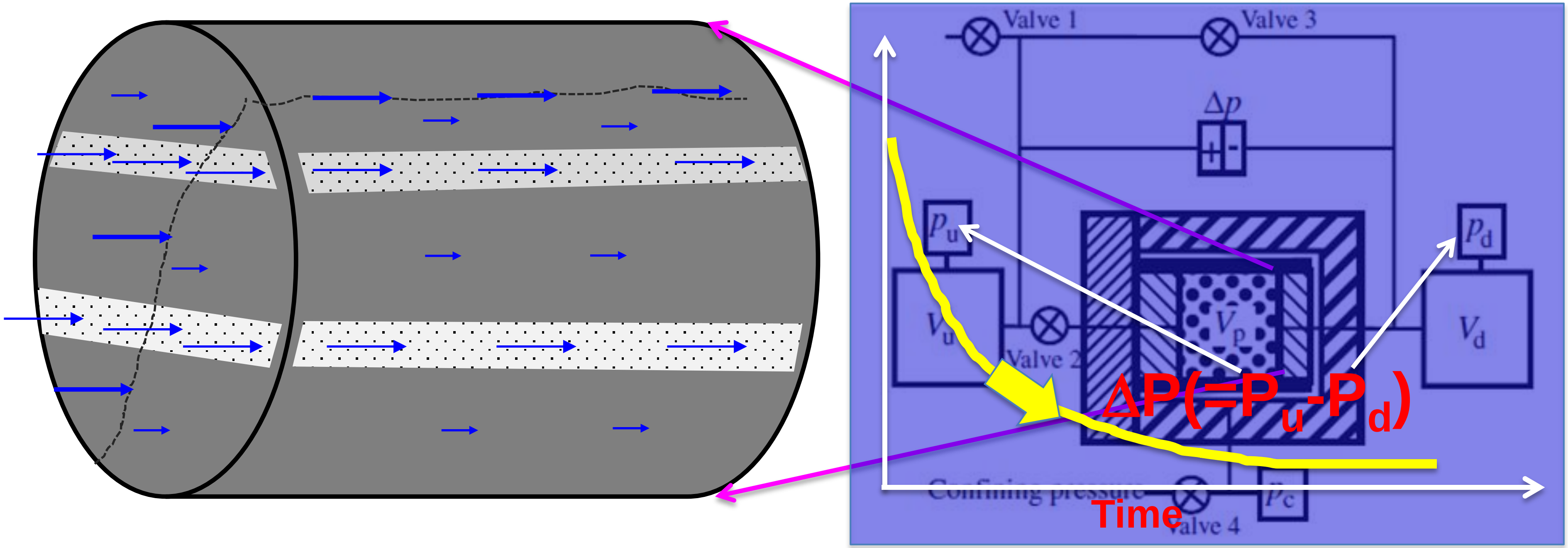


(Cui et al., 2013)

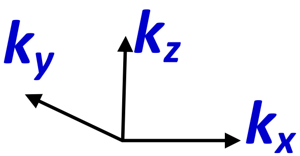
Presenter's Notes: Different methods measure different permeability. Permeability is direction dependent.

Pressure-pulse decay (PPD) permeability

- **Gas transfers from left to right mainly through fracture/high permeability lamina**



(Cui et al., 2009)



Low Perm (k_L) Lamina

High Perm (k_H) Lamina

Fracture (k_F)

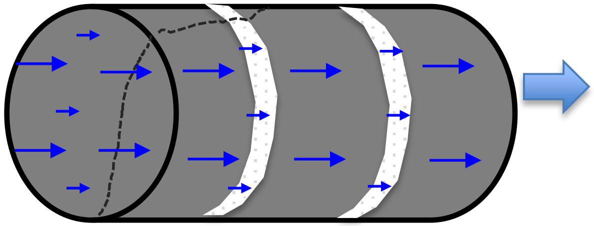
Gas Flow Pattern

Cross-bedding

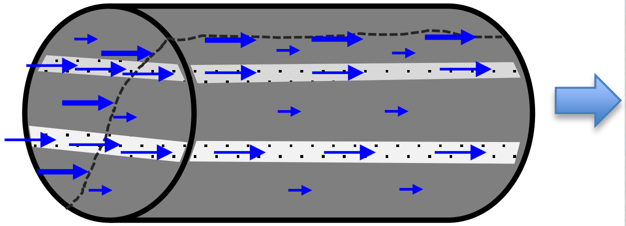
Along-bedding

Directional PPD permeability

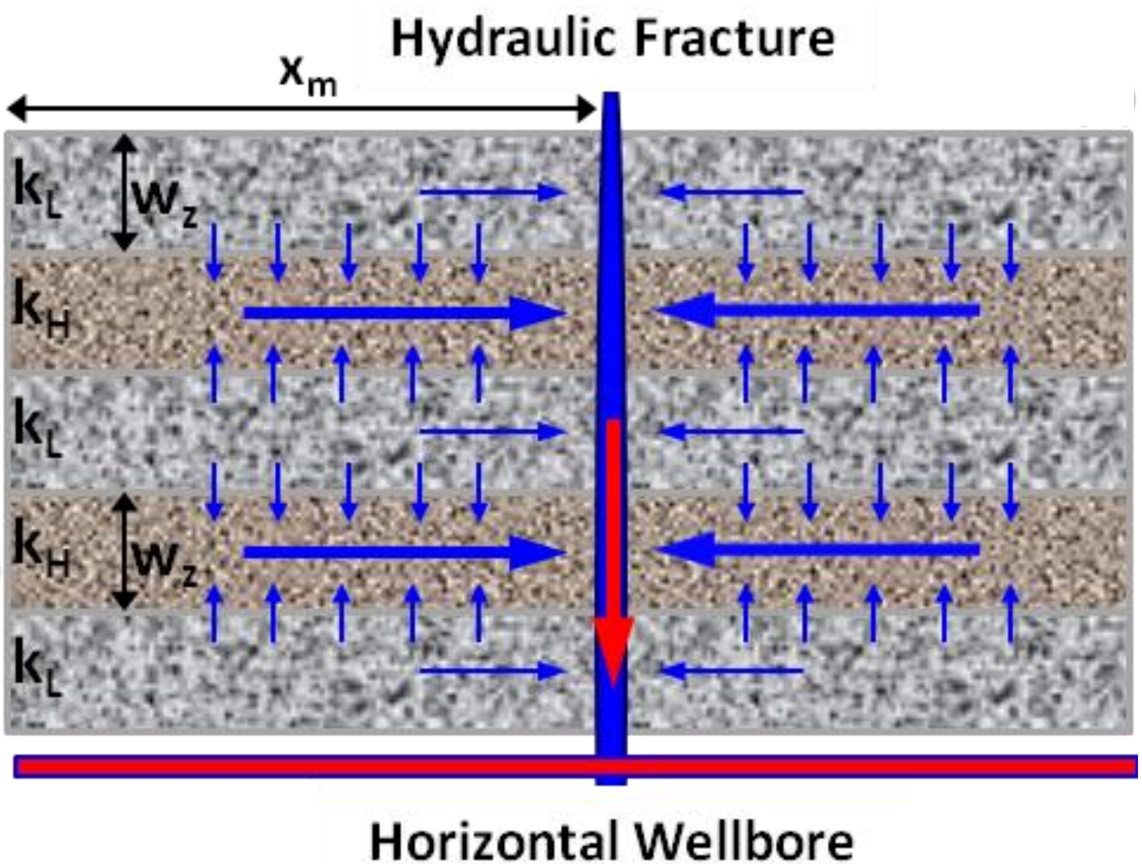
- **Horizontal or vertical permeability can be measured separately on core plugs with different orientations**



Vertical

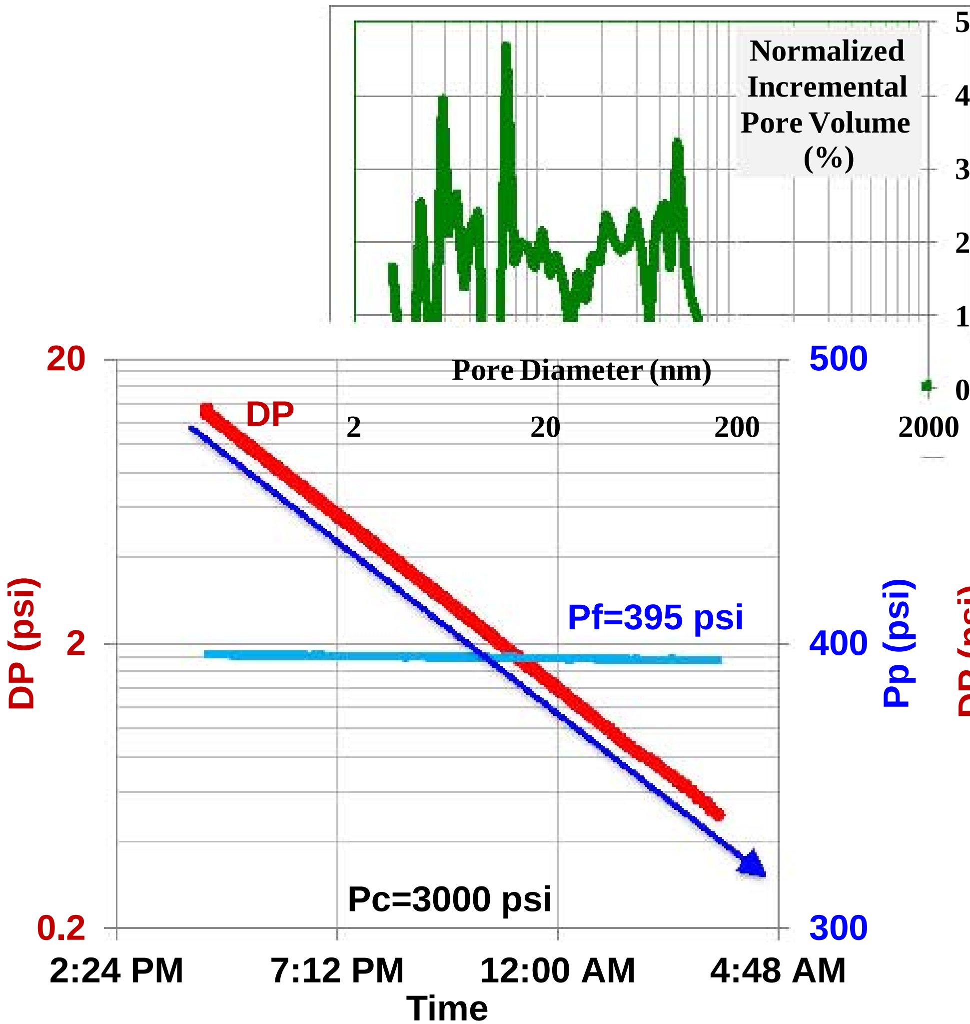


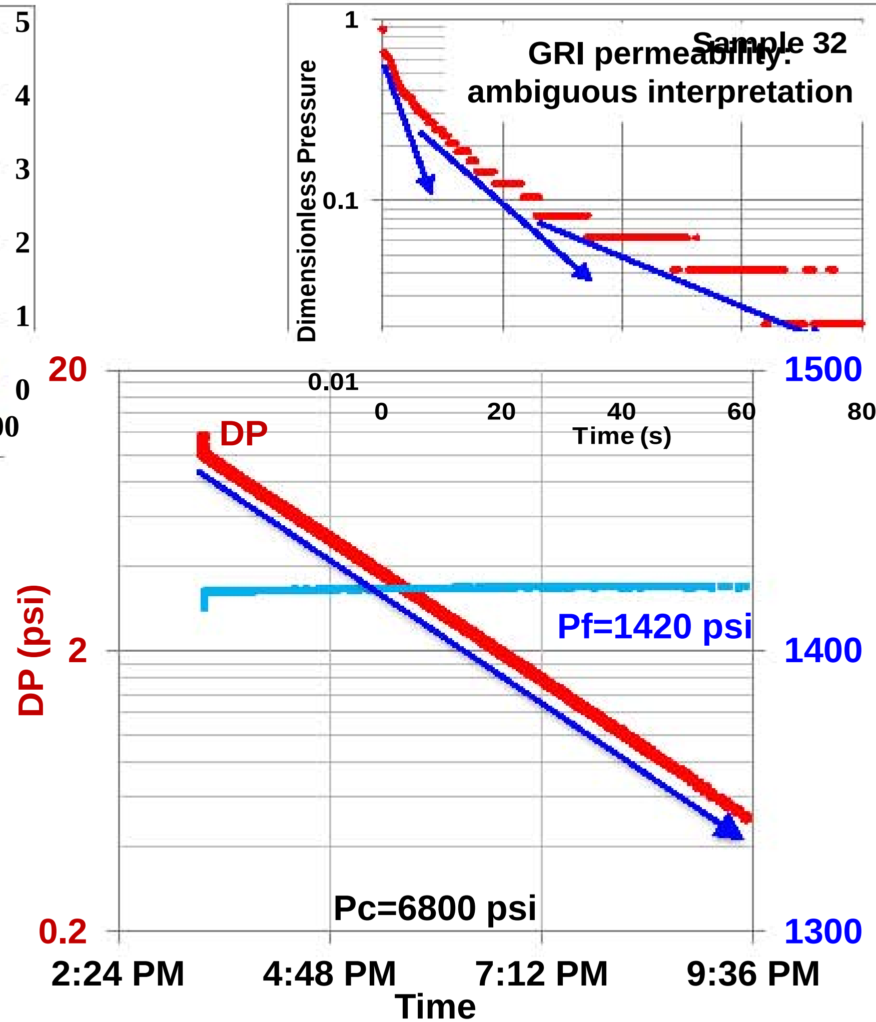
Horizontal



Rigorously-defined (PPD) permeability

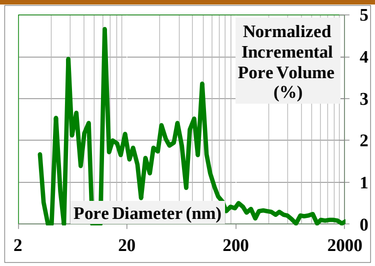
- No ambiguity for permeability interpretation

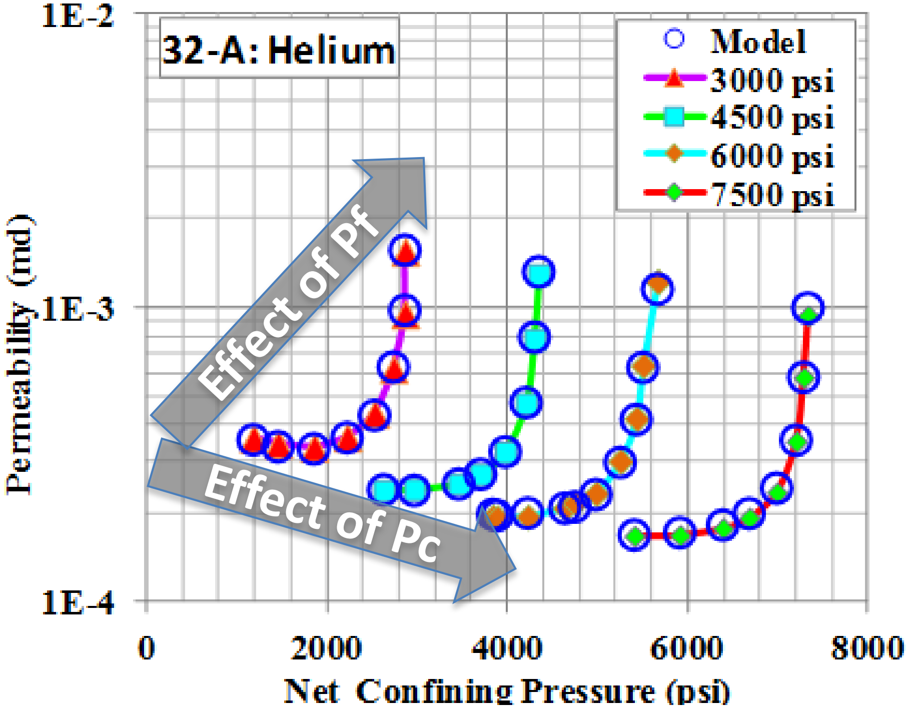


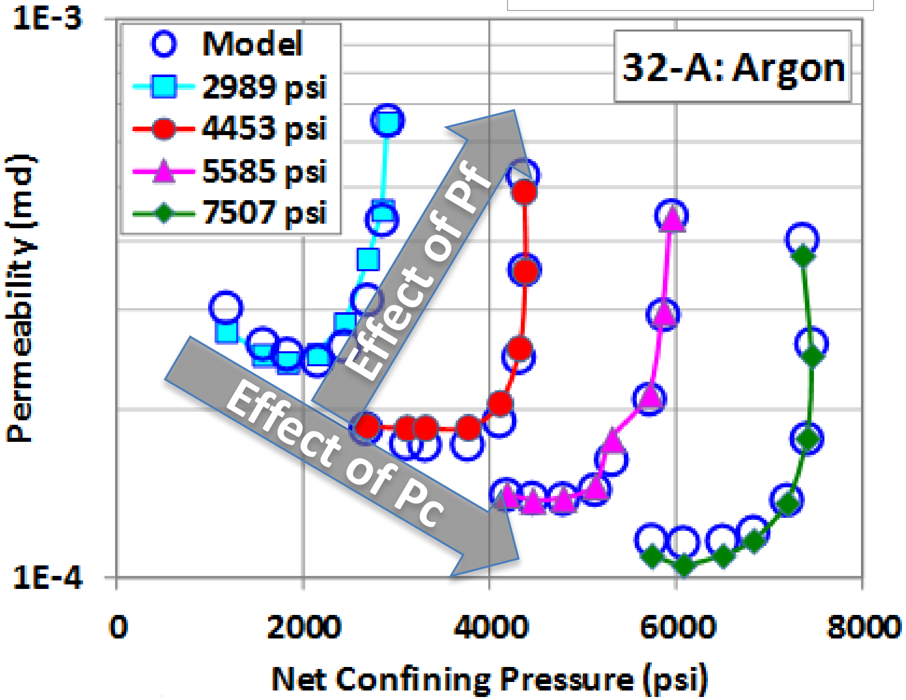


P_f- and P_c-dependences of permeability

- Pf: diffusion or Klinkenberg effects
- Pc: confining stress effects



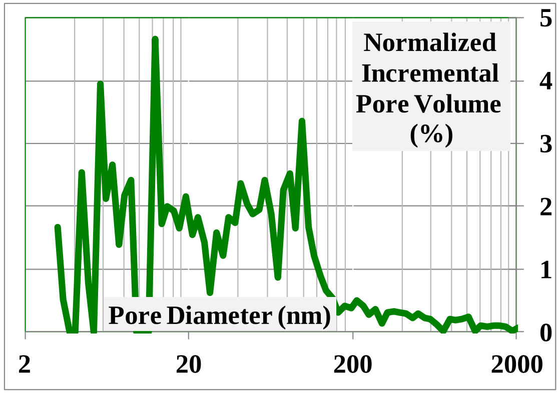


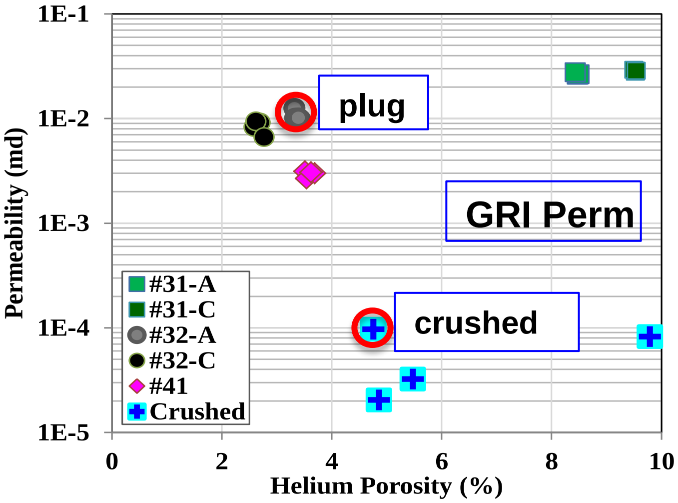


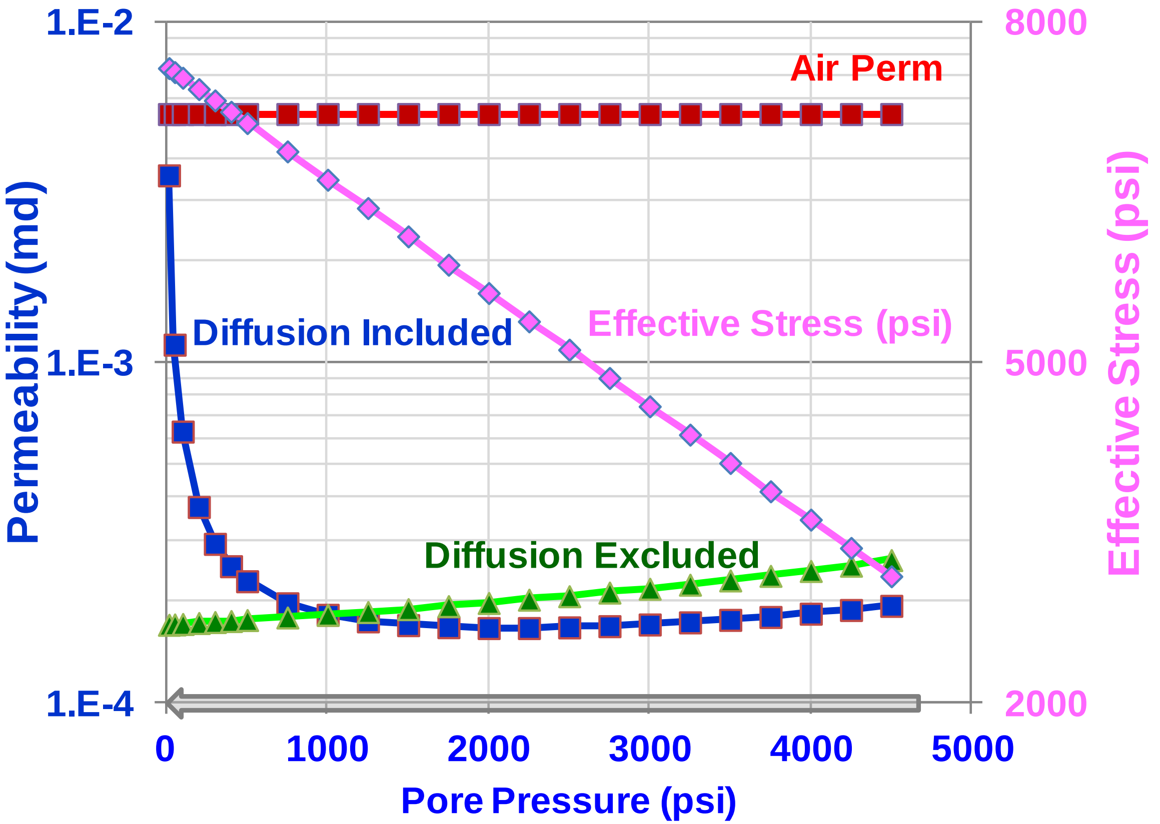
$$k_a = k_\infty (P_C - P_f)^{c_k} [1 + b_0 (P_C - P_f)^{c_b} / P_f]$$

(Cui et al, 2013, SPE167047)

In-situ permeability along the stress-path of a producing reservoirs

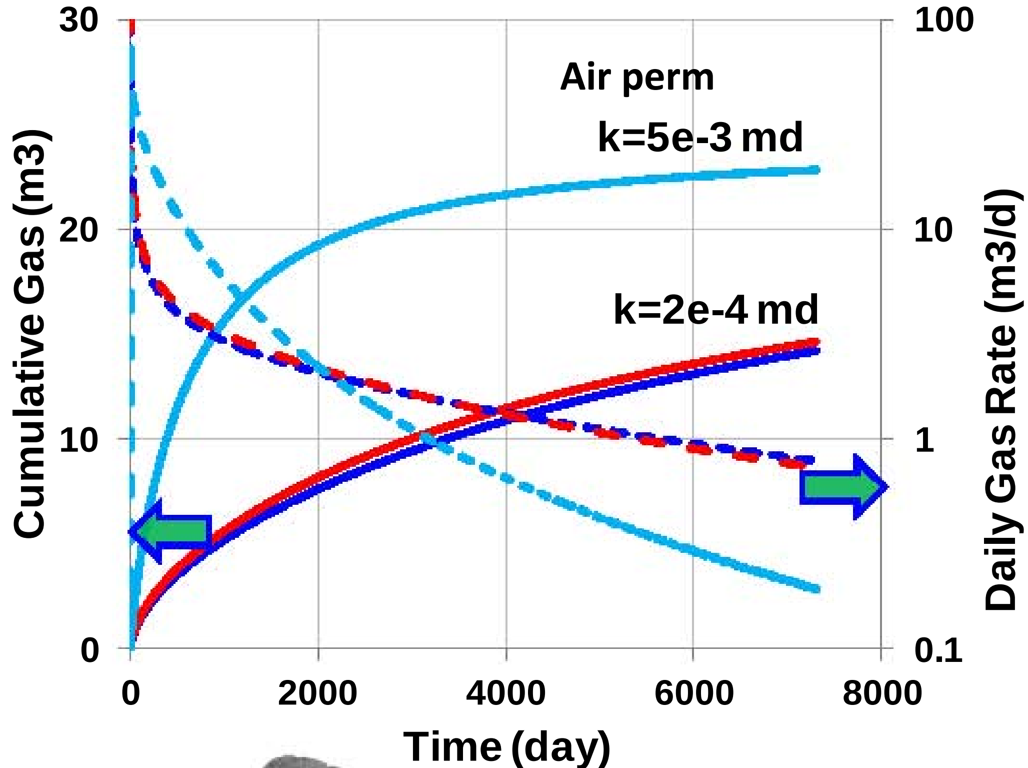


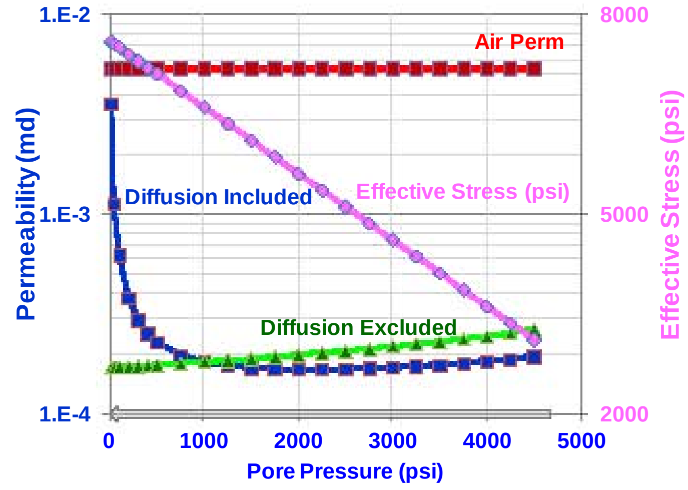




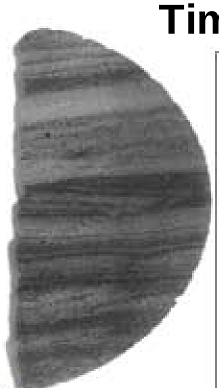
(cui et al., 2013)

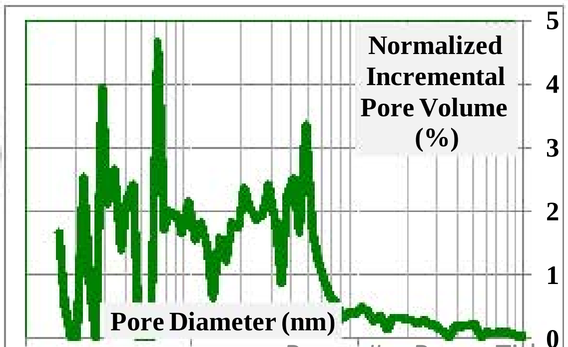
Using correct permeability for production analyses



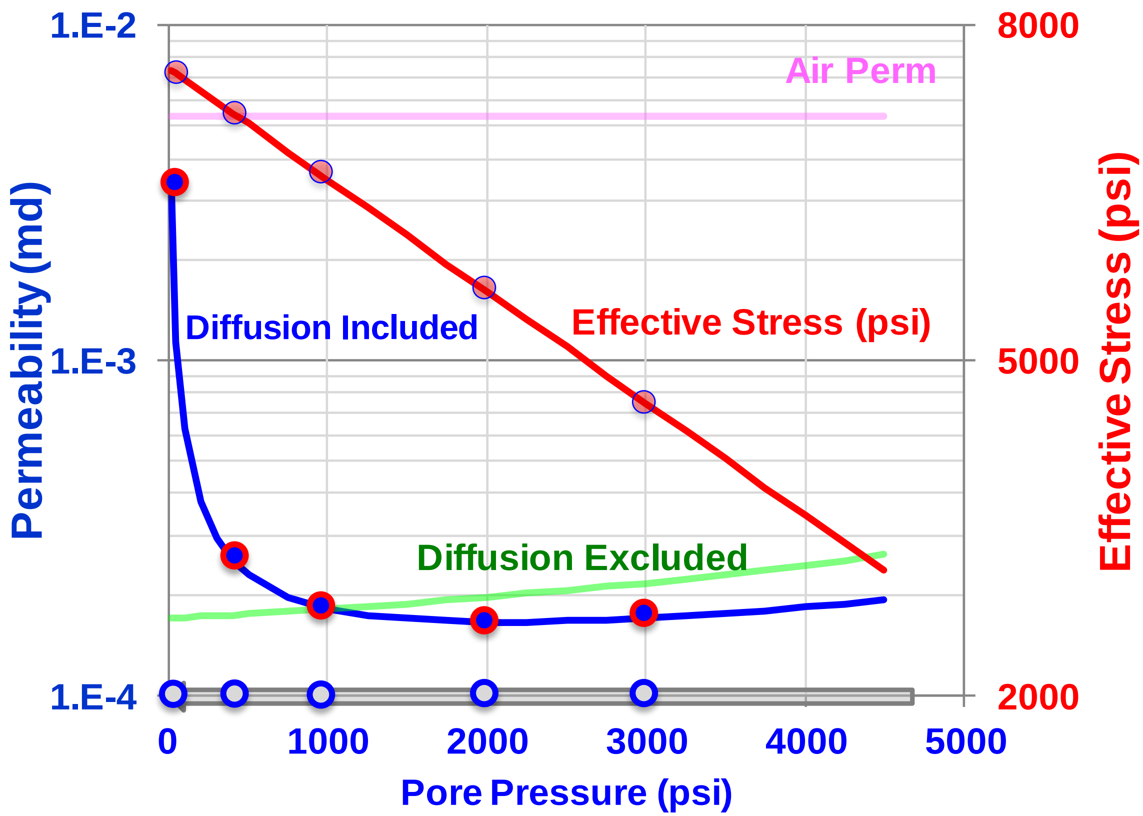


kPa

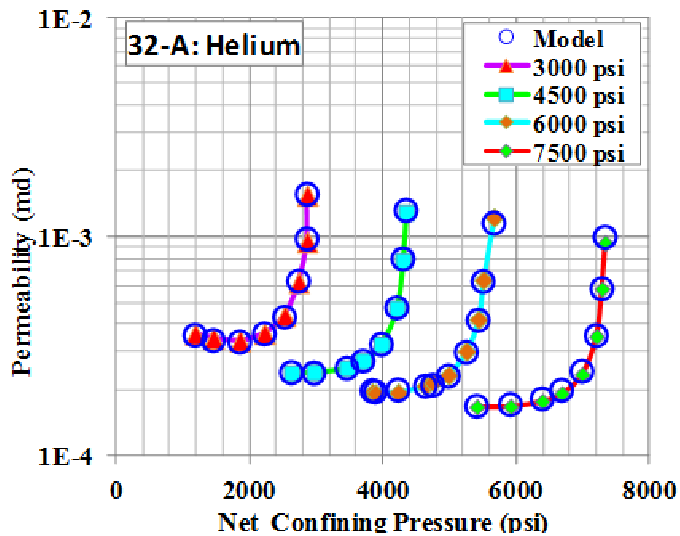




Practical permeability measurement



- For practical purpose, permeability measured in laboratory should include viscous flow and diffusion, and be specific to the actual reservoir's stress-path.



$$k_a = k_\infty (P_C - P_f)^{c_k} [1 + b_0 (P_C - P_f)^{c_b} / P_f]$$

Conclusions

- GRI permeability is an approximation and should not be used for engineering analyses of production. But it is a good index for reservoir quality evaluation.
- Directional permeability including diffusion and viscous flow, and effects of effective stress should be determined using the PPD or other similar techniques.
- Permeability along the stress-path of a producing reservoir can be determined in laboratory without separating viscous flow and diffusion.

Acknowledgements

- Trican Geological Solutions

Thank You!