Two-phase and three-phase relative permeability of unconventional Niobrara chalk using integrated core and 3D image rock physics

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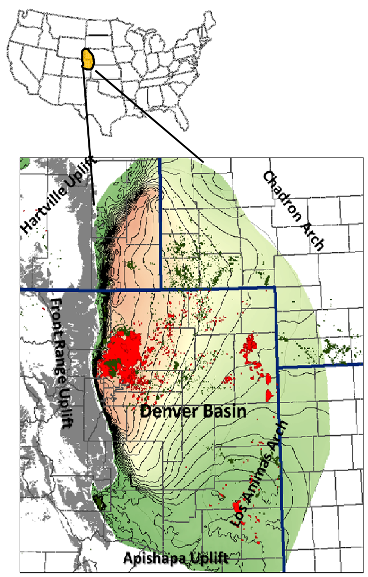
Overview

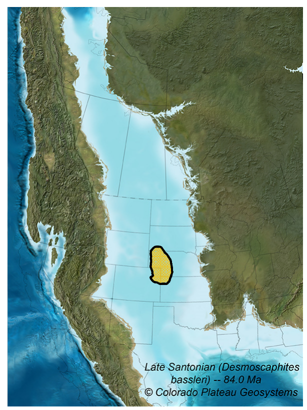
- Key questions – Methodology - Findings
- Geology
- Methodologies (critical to low-k)
- Representative Elementary Volume (REV)
- Permeability – Porosity - Capillary Pressure
- Relative Permeability
- Bound Water
- Conclusions

Overview

- **Key Questions for reservoir characterization and flow modeling**
  - What is the permeability (K) and porosity (ϕ) relationship (K-ϕ)?
  - What are saturations and capillary pressure (Pc) relationships (e.g., Pc-ϕ, Pc-K, Threshold entry Pc, Brooks-Corey λ)?
  - What are the 2-Phase (G-O, O-W) and 3-Phase (G-O-W) ***relative permeability*** (Krg, Krog, Krow, Krw, Krogw) relationships?
  - What is a robust Core Analysis-Image Based Rock Physics ***(CA-IBRP) integrated workflow***?
- **Methodology**
  - Measure ϕ, K, Pc, Kr on using CA and DRP for representative Niobrara (NBRR)
  - Correlate/calibrate CA –IBRP
  - Evaluate Representative Elementary Volume (REV) or statistical REV (SREV) for each property
- **Key Findings**
  - Developed an integrated CA-IBRP cross-validation workflow
  - CA and DRP give similar K-ϕ, Pc, Kr with proper stress correction
  - DRP provides complete Krw and Kro curves not easily measured by CA
  - DRP provides 3-Phase Kro curves never measured by CA
  - Bound water influences K in rocks with K < 0.001 mD

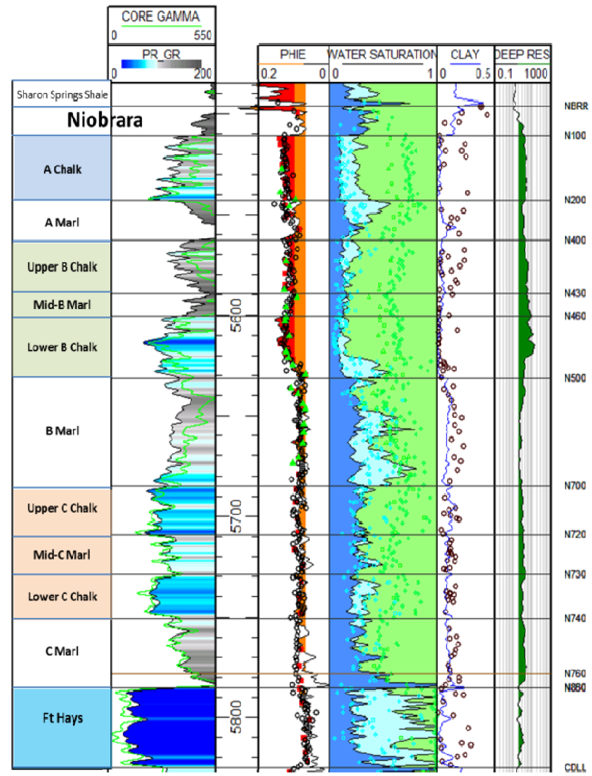
Niobrara in DJ Basin and Vertical Facies Profile





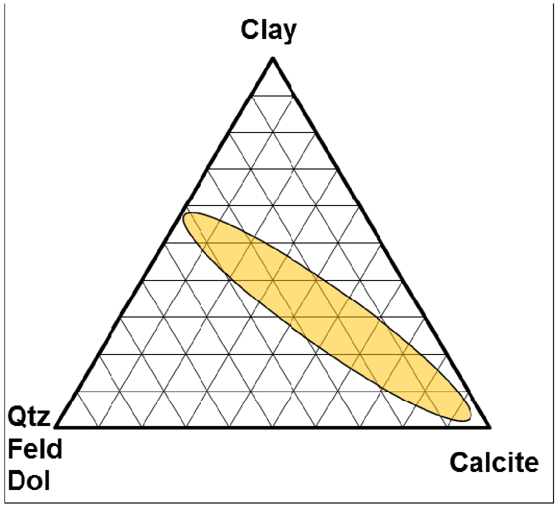
Interior Cretaceous Seaway

deeptimemaps.com



Highstands/Lowstands - Vertical succession of chalks and marlstones

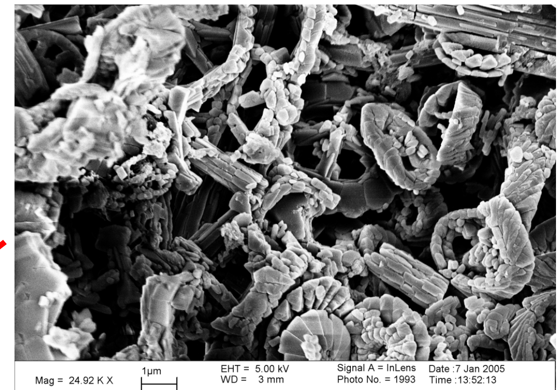
Mineralogy & Diagenesis



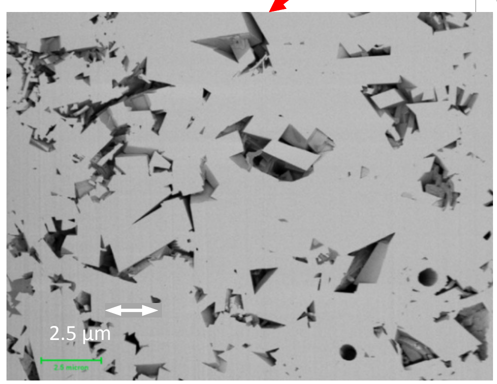
Mineralogy generally represents continuum of Calcite mixing with 1:1.25 (Qtz+Feld+Dol):Clay

Ignoring 0% < OM < 16%

Cementation
Recrystallization
Compaction
Burial



SEM Niobrara chalk; Sherman Co., KS, 1,000 ft, ϕ = 0.411, Kik = 2 mD
(after Byrnes et al, 2005)



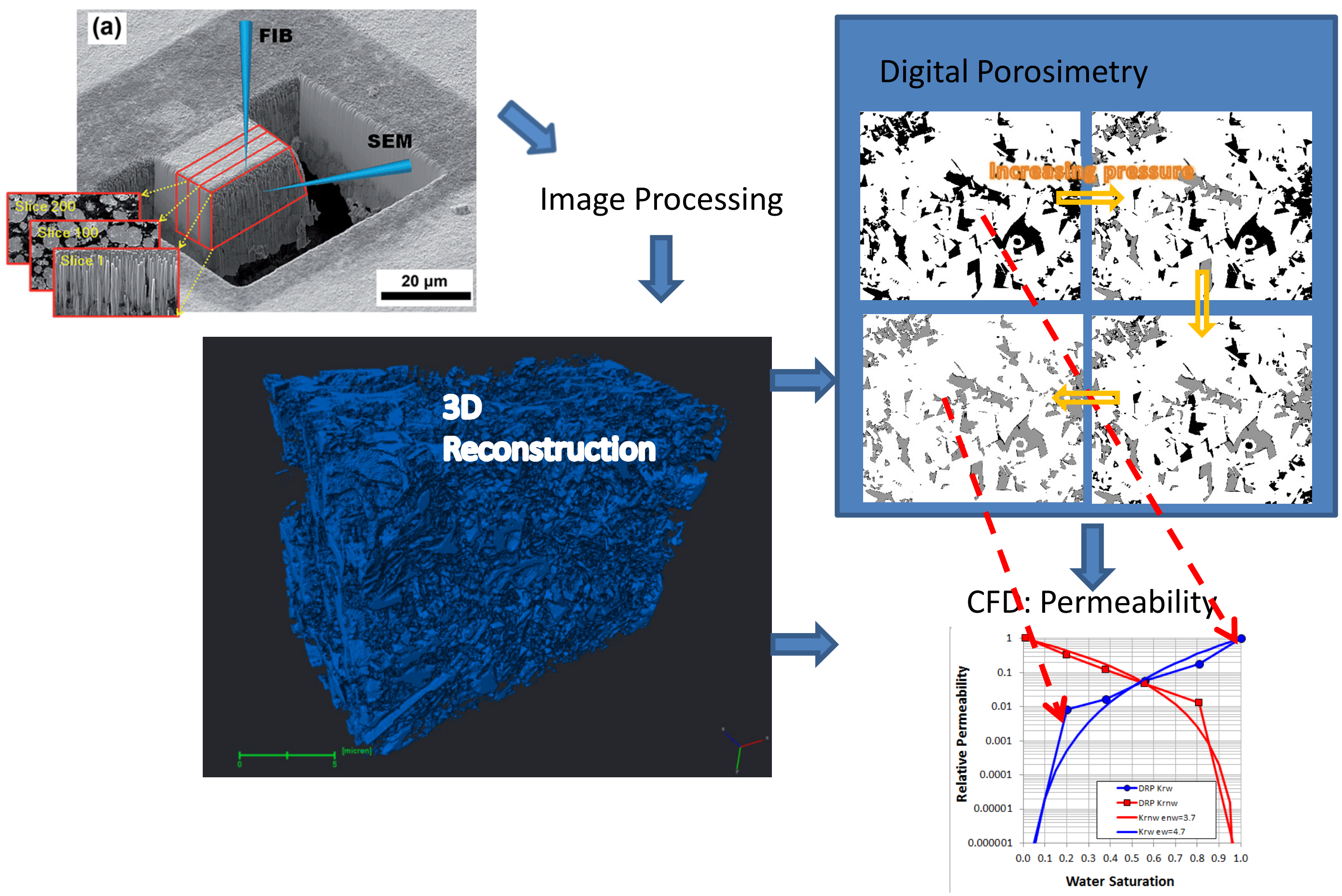
SEM Niobrara chalk; Weld Co., CO, 5,650 ft, ϕ = 0.094, Kik= 0.0016 mD

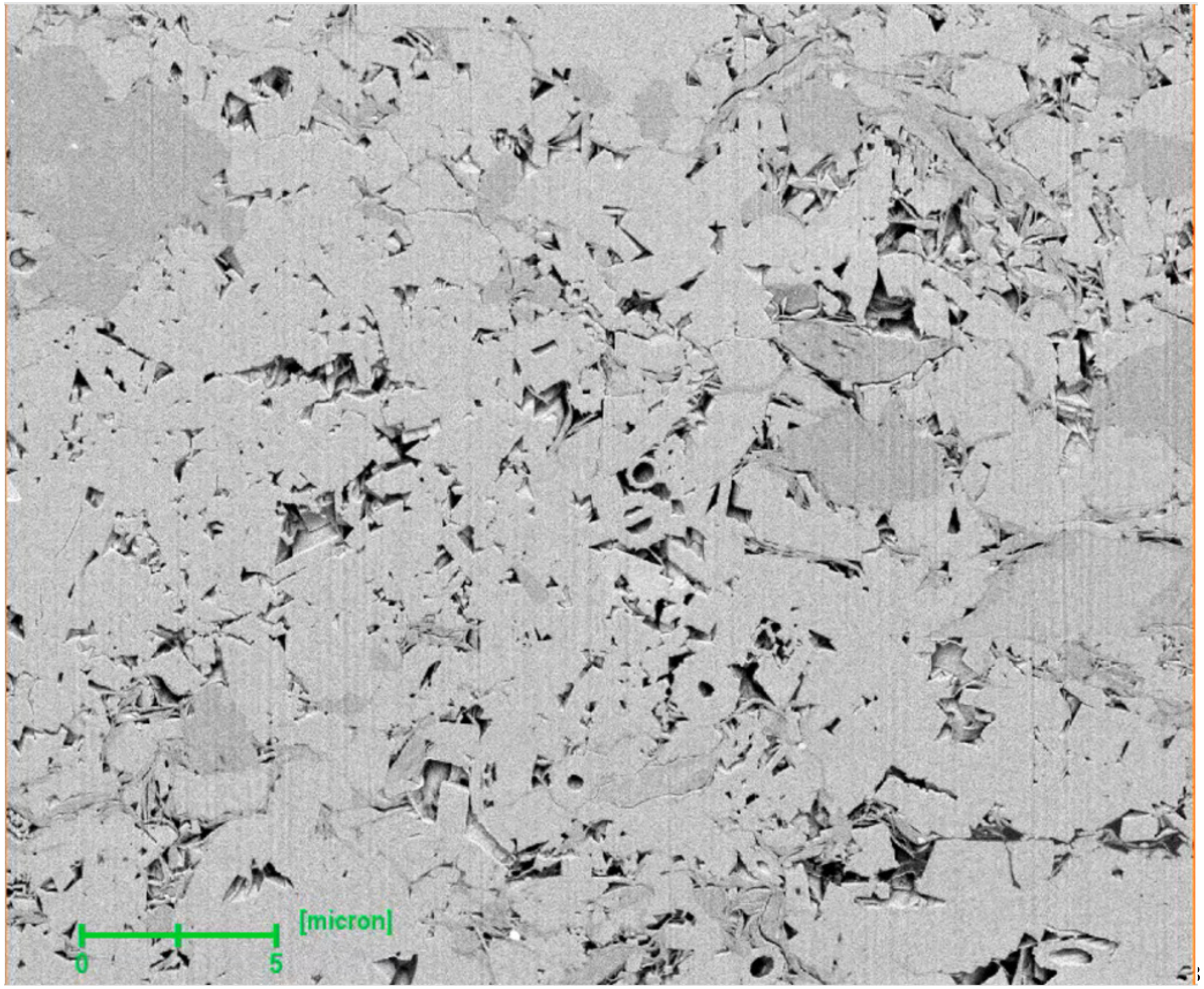
Methodologies

Core Analysis Methodology

- Data from three major labs
- Dean-Stark/Soxhlet cleaning
- **Porosity** – Boyle's Law Helium porosity core and crushed
  - Pore volume compressibility measured on select core plugs
  - Normalized to 2,000 psi Net Confining Stress (NCS)
- **Permeability** – Core plug Klinkenberg (@NCS) & crushed rock (GRI)
  - Permeability (Kik) stress dependence measured on select core plugs
  - Normalized to 2,000 psi NCS
- **Capillary Pressure** – Mercury intrusion (MICP)
  - MICP curves measured under variable NCS <u>as a function of entry pressure</u>
  - Cores with Kik< ~800 nD significantly affected by Hg-NCS (Important!!)
  - Reference permeability of MICP sample adjusted for Hg-NCS
- **Relative Permeability** – As-received and cleaned crushed rock
  - Krg @ SI computed from A-R Kg/cleaned Kg

Steady-State IBRP Relative Permeability Workflow




[micron]
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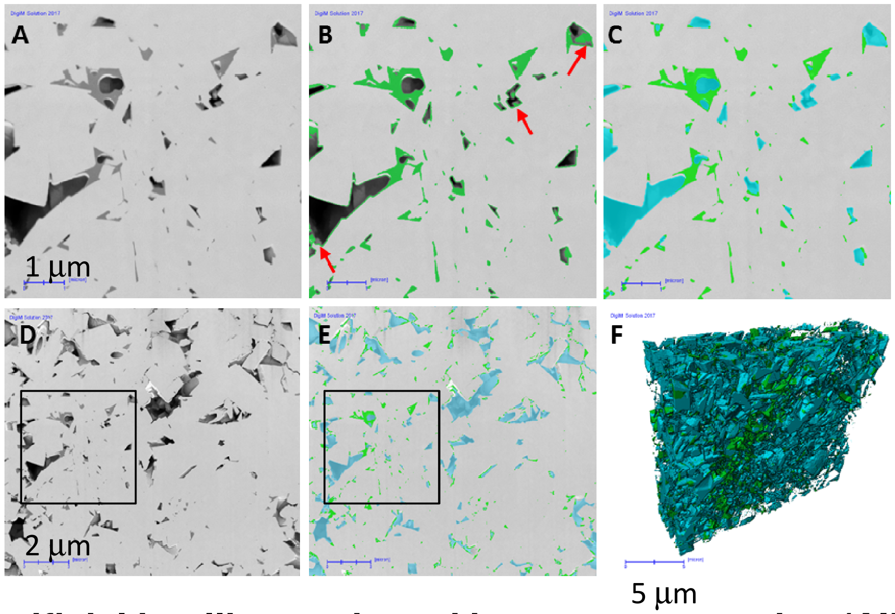
5

Image Processing Methodology



Artificial intelligence based image segmentation (AIBIS)

- Two key issues – pore backs & residual oil (oil vs kerogen)
- Train subset on grey scale <u>and statistical measures</u>
- AIBIS correctly segments OM (C)
- Segmentation on full 2D field (E)
- Segmentation on full 3D image stack (F)

IBRP Permeability Methodology

- Permeability measured/computed/modeled using computational fluid dynamic (CFD) simulation module from the DigiM Image to Simulation (I2S) cloud computing platform
- Connected 3D pore structure from the FIB-SEM image volume is reconstructed from the original imaging resolution not reduced to a pore network model (PNM) and not LB.
- Finite volume spatial discretization is built directly on voxels of the segmented 3D imaging data.
- Navier-Stokes equations solved with an implicit pressure/explicit momentum scheme (Versteeg and Malalasekera, 2007):

$$\nabla \cdot \boldsymbol{u} = 0$$

$$\nabla p = \mu \nabla^2 \boldsymbol{u} - (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} + \boldsymbol{f}$$

- Using pressure and velocity fields solution, Darcy's law used for permeability in each direction (n):

$$k_n = \boldsymbol{u}_n \, \mu \Delta x / \Delta p$$

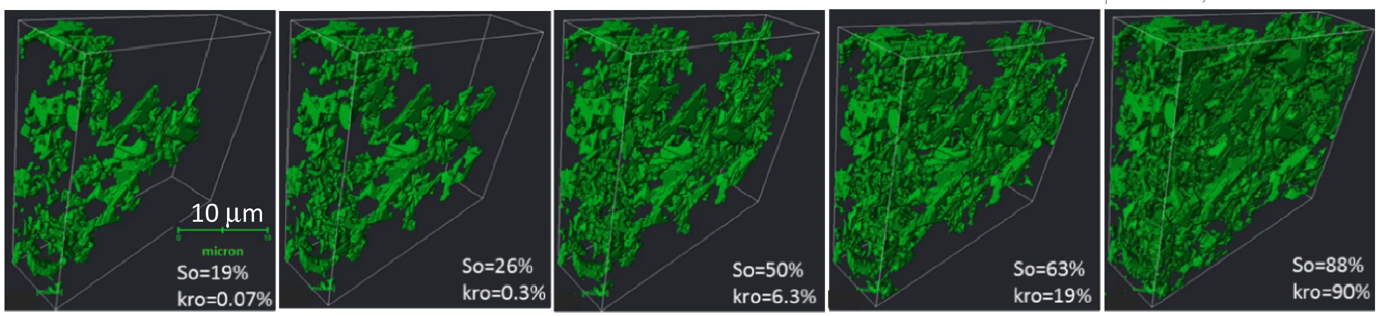
($\boldsymbol{u}$ = fluid velocity vector, p =pressure, μ= dynamic viscosity, $\boldsymbol{f}$ = body force vector = 0)

- Scalar Permeability:

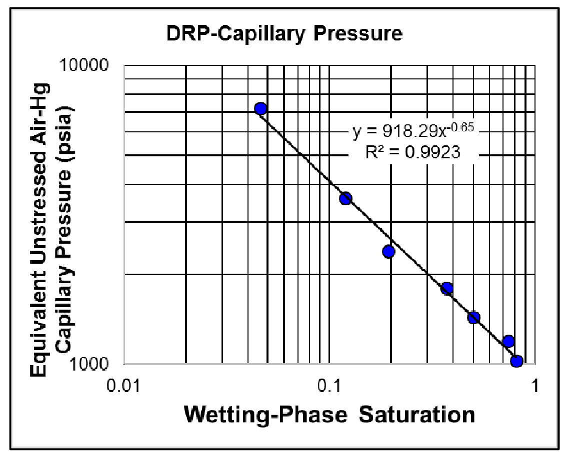
$$k_{mag} = \sqrt{k^2_{e0} + k^2_{e1} + k^2_{e2}}$$

IBRP Capillary Pressure

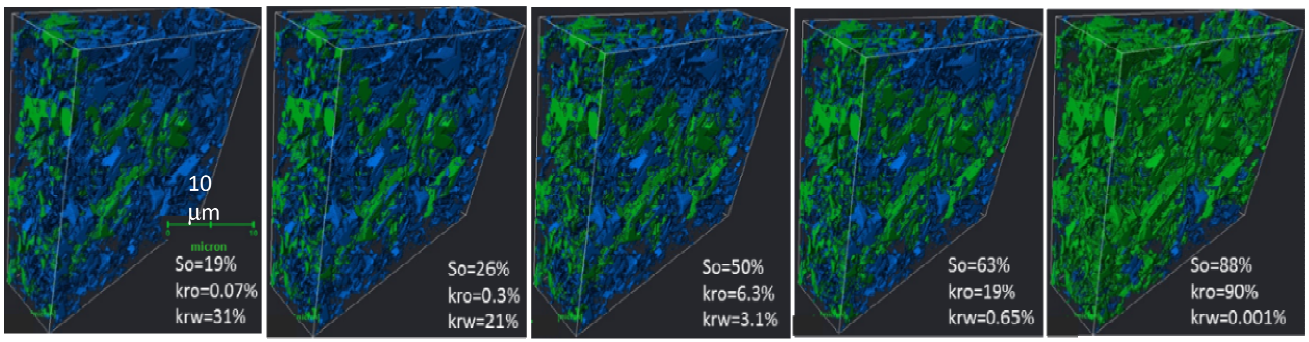
chalk with ϕ = 0.156, Kk=0.0554 mD



- Method derived from Hilpert & Miller (2001)
- Successive invasion of FIB-SEM pore volume with spheres of defined diameter (equivalent to pressure through Washburn (1921) relation: D = 4σCosθ/Pc)

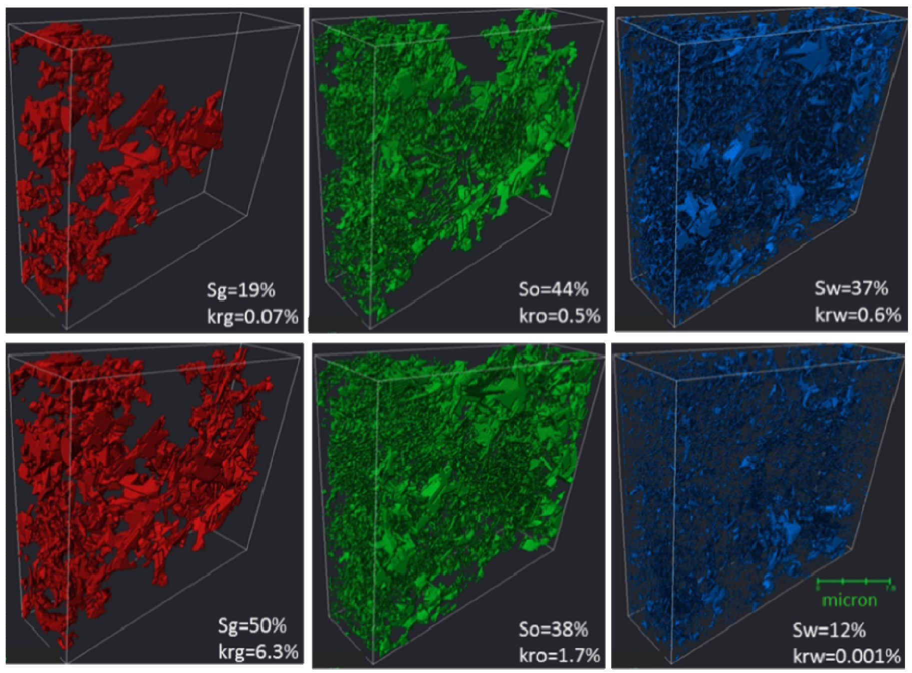


IBRP Drainage Relative Permeability



- Series of saturation states achieved by drainage Pc
- Permeabilities to the non-wetting (e.g., Ko, Kg) and wetting (Kw) phase are computed for their quasi-static distribution (single-phase stationary in CA).
- Relative permeability computed by reference to absolute permeability

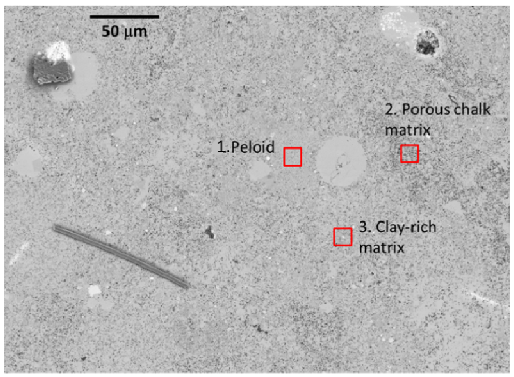
IBRP – 3-Phase Relative Permeability

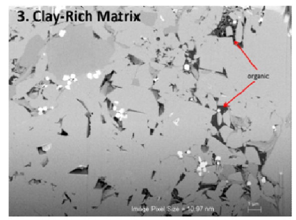


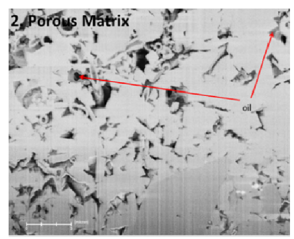
- Similar in process to 2-phase Kr
- Series of saturation states achieved by drainage Pc
  - Oil partially displaces water
  - Gas partially displaces oil
  - Mirrors solution gas drive
- Permeabilities to each phase is computed for their quasi-static distribution.
- Relative permeability computed by reference to absolute permeability

Representative Elementary Volume

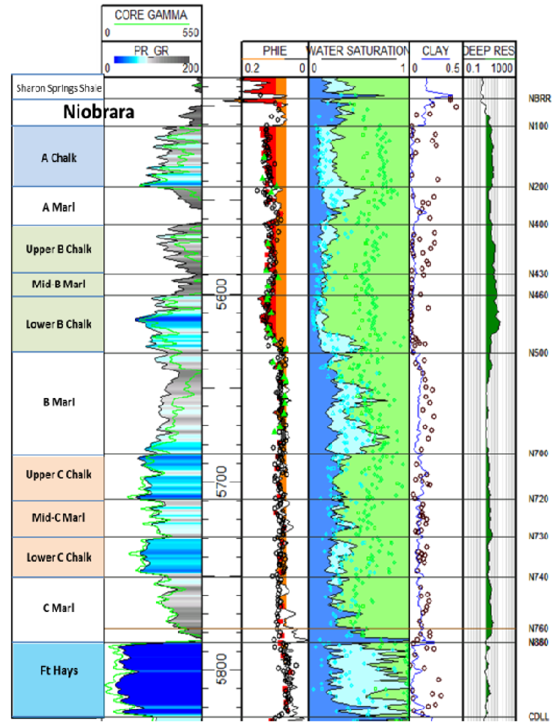
Chalks are Heterogeneous





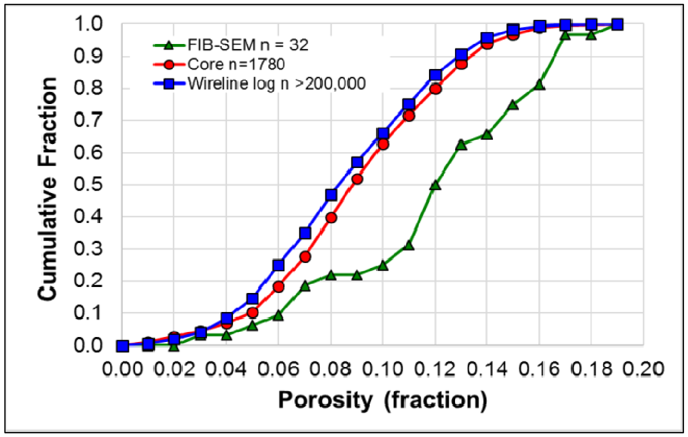


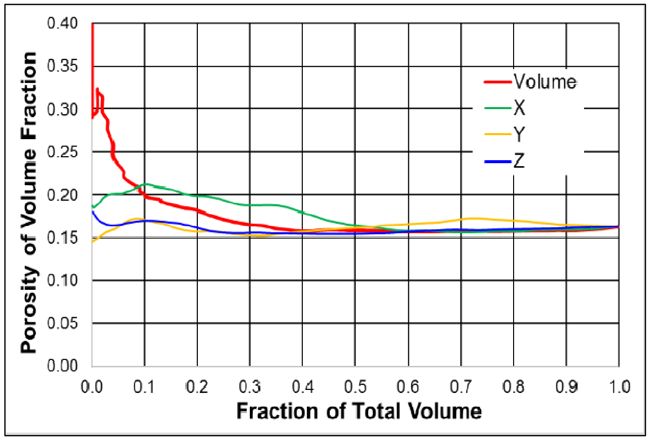
1) Peloids ϕ = 14.9%
2) Porous matrix ϕ = 12.8%
3) Clay-rich matrix ϕ = 12.9%



Vertical heterogeneity at many scales

Porosity Sampling & REV





- FIB-SEM samples span ϕ but limited # samples do not exhibit exact same distribution as core/logs

- FIB/SEM sample with ϕ = 16.3% and sample dimensions of $8^3 \mu m^3$ is ϕREV at 0.6 fraction.

Representative Elementary Volume

- Properties exhibit scale-dependence at micro (SEM), macro (core) and field scales and spatially (horizontal and vertical)
- <u>Both Core and IBRP challenged by deterministic REV definition</u>
- REV varies with property: $REV_{\phi} < REV_{k} < REV_{Pc} < REV_{kr}$
- Lateral continuity → 1x4 km (Horizontal well drainage area)
- Vertical continuity significantly influenced by mm-scale bedding and lithology – no good $REV_{vertical}$
- Define properties at an appropriate fine scale and apply within a geocellular model
  - Statistical REVs or SREV
  - Measure/model properties on samples of a sufficient size to be an SREV for that property
  - Practical to assign within a geomodel
  - Do not expect single SREV to reproduce larger-sample properties – will reproduce larger sample relationships

Types of REV Characterization

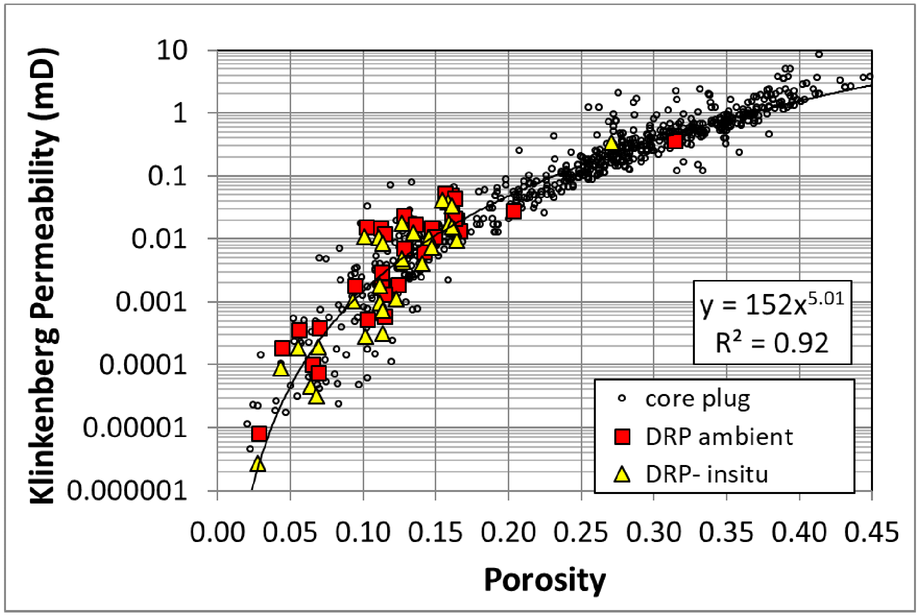
Phase Location/ Property	Property can be characterized at REV resolution	Property cannot be characterized at REV resolution
Location Known	Type 1	Type 2
Location Unknown	N/A	Type 3

To obtain meaningful properties from Image-based rock physics (IBRP)it is required that properties be measured on a REV

For coarser-grained samples it is necessary to obtain properties of components and upscale within a model – similar to reservoir numerical flow simulation

Permeability vs Porosity

ϕ, K, Pc

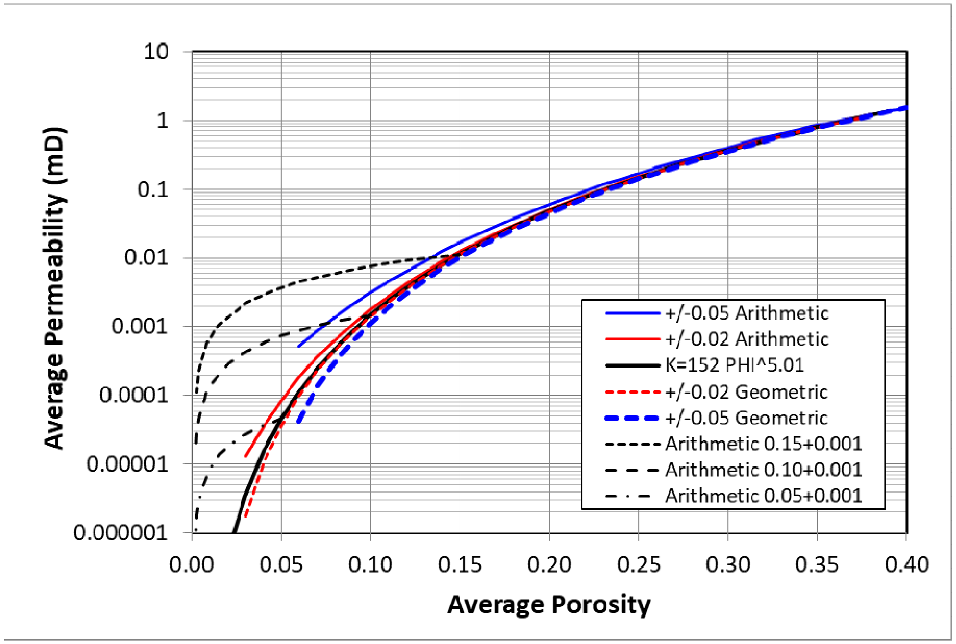


- Kik-ϕ trend for Niobrara chalks and marls
- IBRP=IBRP Kik-ϕ = CA Kik-ϕ

  (Kik = *insitu* Klinkenberg Permeability)
- Important:
  - IBRP FIB-SEM samples do not have microfractures
  - High correlation of IBRP-CA confirms CA ϕ, K, ϕ(NCS), K(NCS) not influenced by microfractures
  - IBRP and CA Kik-ϕ were developed completely independently

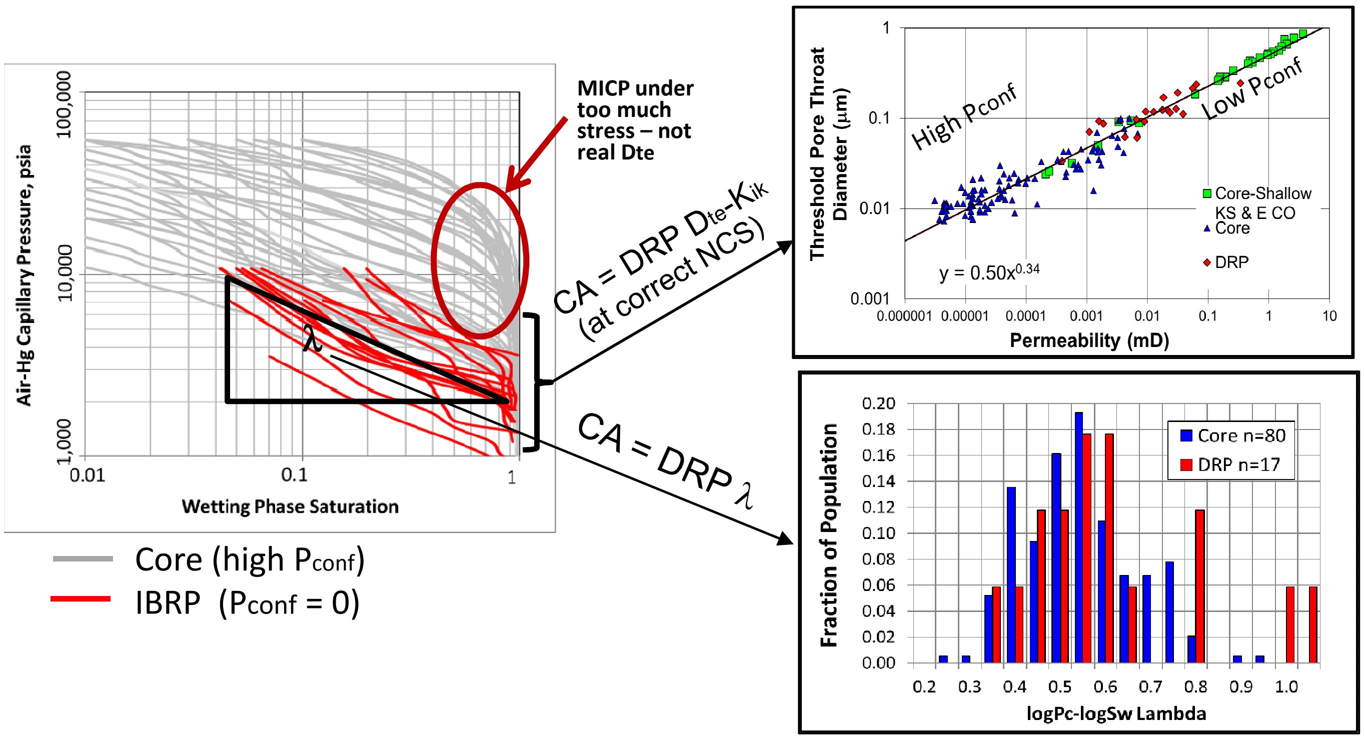
Permeability vs Porosity

ϕ, K, Pc



- Kik-ϕ trend for Niobrara chalks and marls
- Variance in Kik-ϕ trends results from combinations of SREVs in a single sample – samples are actually pseudo-samples combining many layers
- If samples contain thin beds of very high porosity Kik-ϕ can deviate from power-law type trend.

CA & DRP Capillary Pressure



Pore Throat Size Distribution

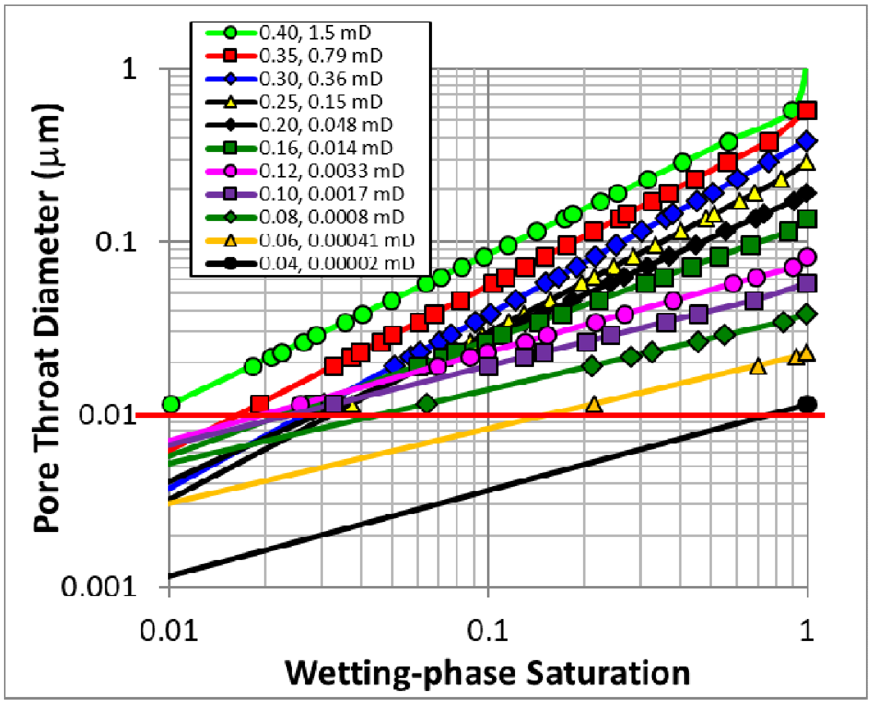
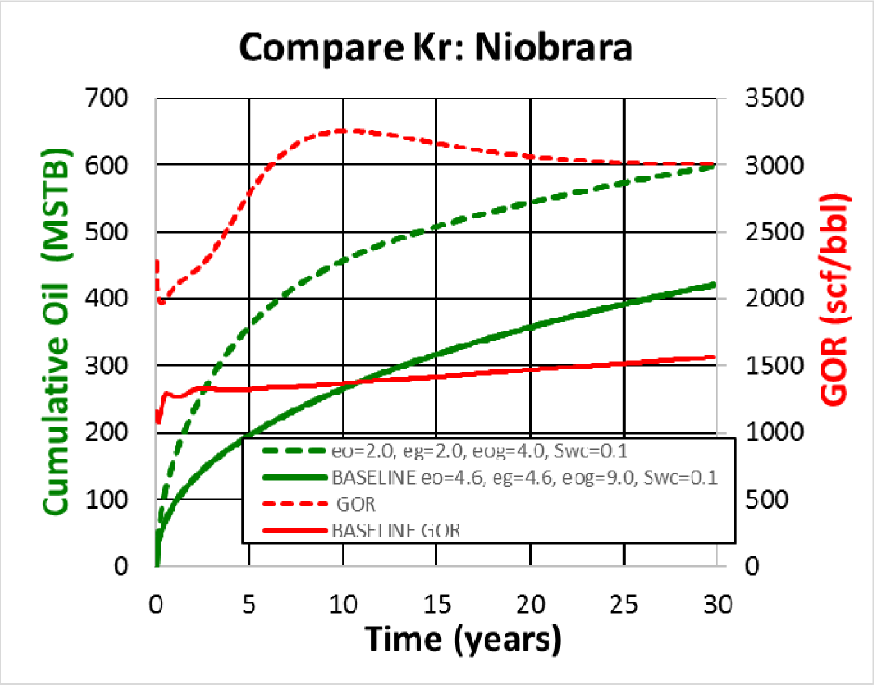


Image Resolution 5-20 nm
Sample Size 10-40 µm

- Use Dte-K and λ-K relationships
- 10 nm (0.01 µm) image resolution
  - ϕ>8%: <u>pore throats</u> of 95% PV
  - ϕ=6%: <u>pore throats</u> of 80% PV
  - ϕ<6%: need 5 nm resolution but may compromise REV

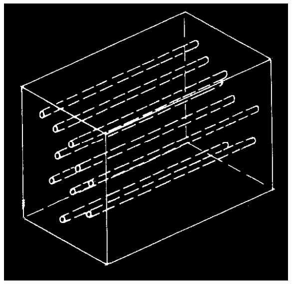
Importance of Relative Permeability to Recovery



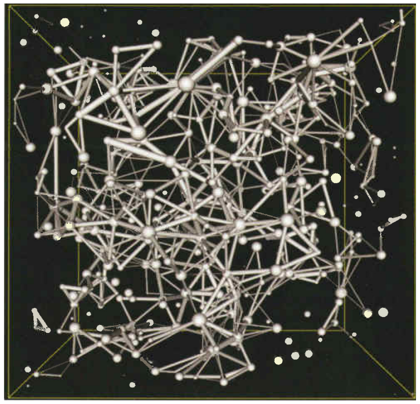
- Using accurate relative permeability relationships is critical to accurately predicting gas and oil production
  - For Niobrara “standard Corey parameters over-predict early-time performance and GOR.

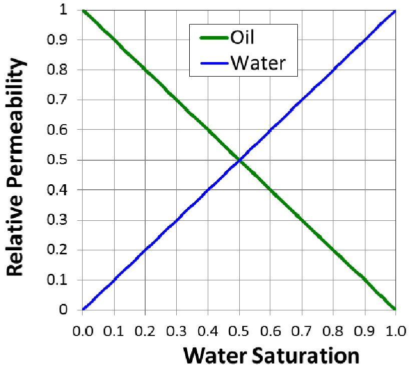
Relative Permeability - Simple Systems

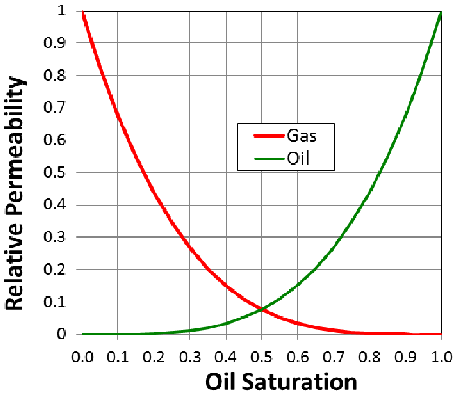
- Straight capillaries
- Equal radius
- No wetting saturation (Swi=0)
- kro+krw=1

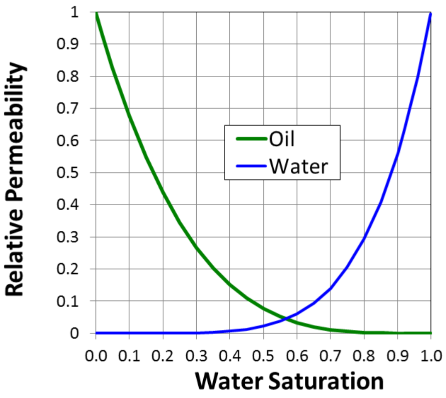


- Complex pore body-pore throat architecture
- Non-uniform fluid distribution
- Decisions at junctions
- Non-equal pore size distribution
- No wetting saturation (Swi=0)
- kro+krw≠1

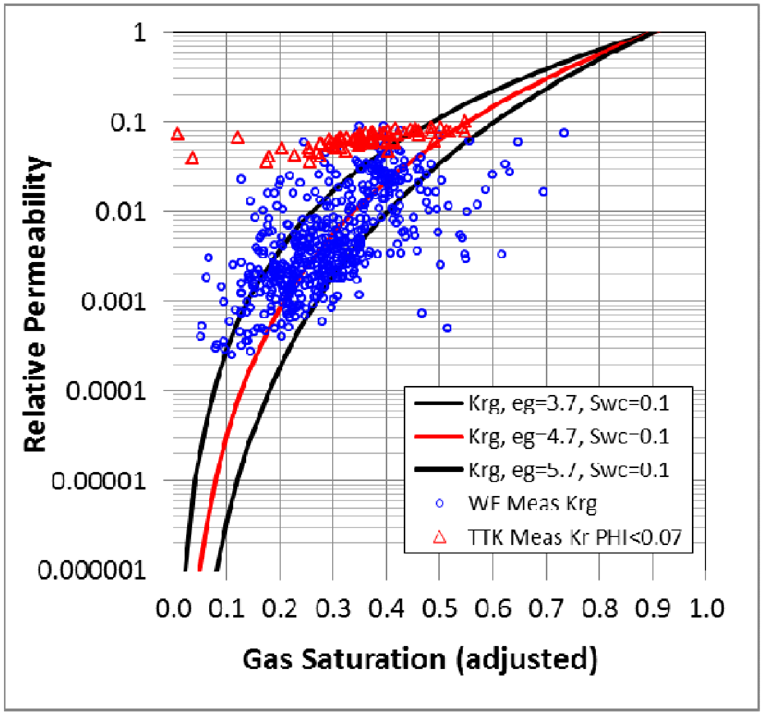






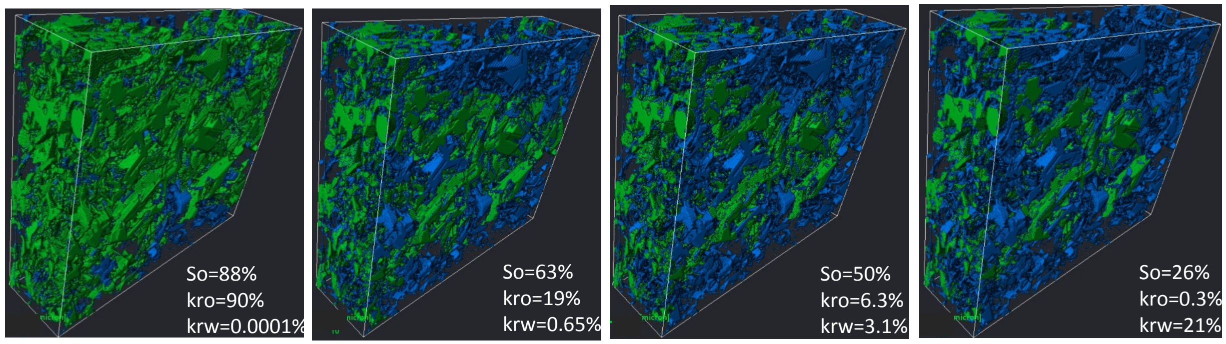


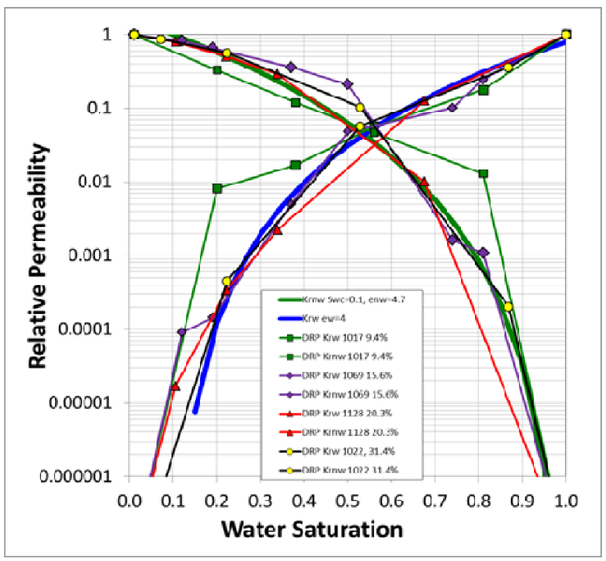
Niobrara Gas Relative Permeability



- Weatherford and TerraTek As-Received effective gas permeability measurements generally exhibit Krg values consistent with a Corey exponent for gas, eg = 4.7$\pm$1 where;
- Krg = (Sg/(1-Swc))^{eg} ; Swc=0.1
- Krg=Keg/$K_{air\text{-}routine}$

Digital Rock Physics Relative Permeability





Niobrara

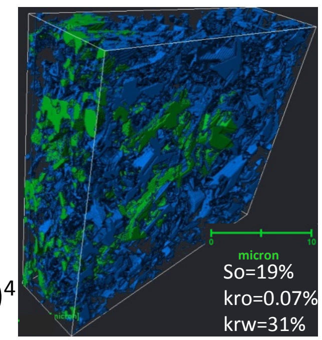
ϕ = 9.4%

k = 1.59 μD

$kro = (So/(1-Swc))^{4.7}$

Swc = 0.10

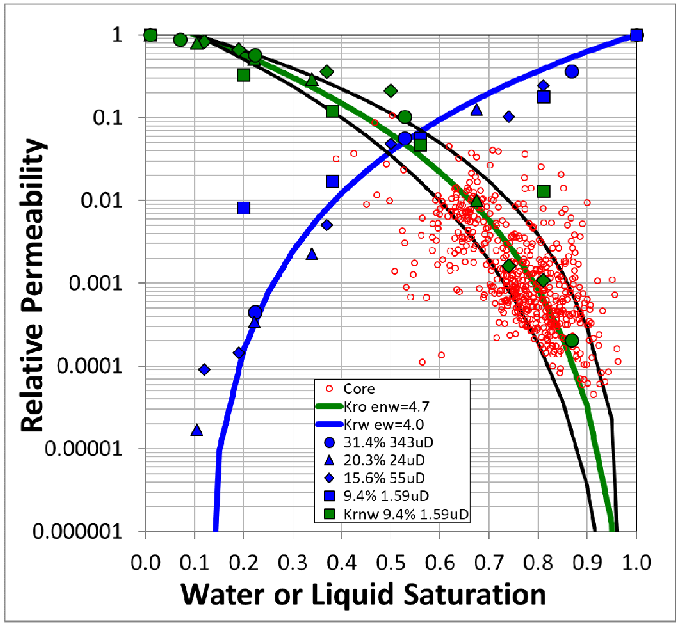
$krw = ((Sw-Swc)/(1-Swc))^{4}$



- Fluid saturation (oil-green, water-blue) is computed by digital porosimetry.
- Permeability at each saturation is computed with computational fluid dynamics solving Navier-Stokes equations.
- Relative permeability referenced to Kabs
- krw not corrected for kw/kik

Relative Permeability

2-Phase CA-Kr vs IBRP-Kr

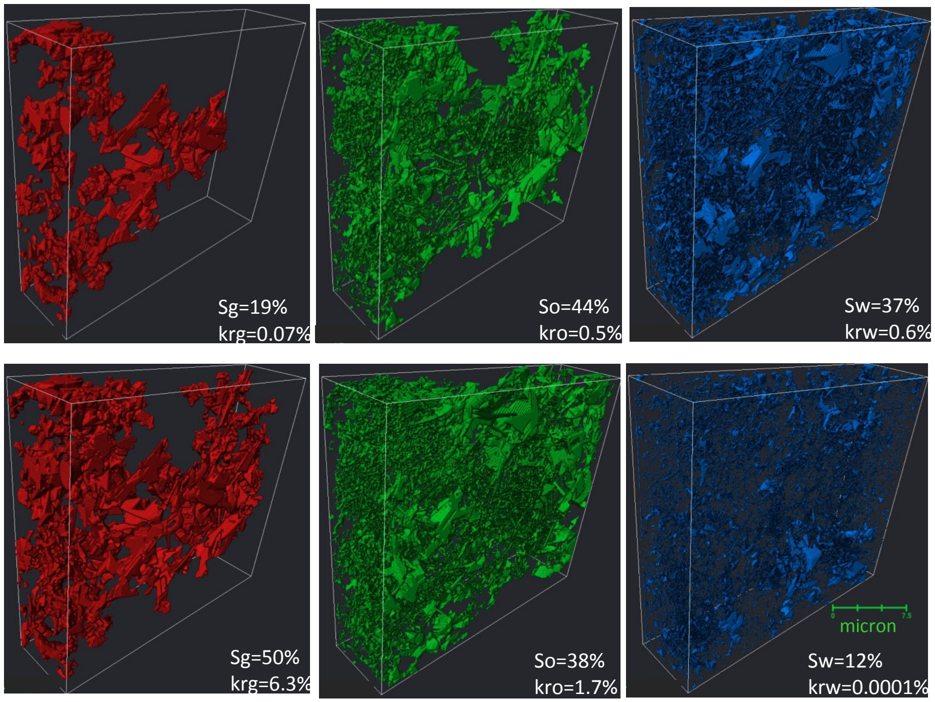


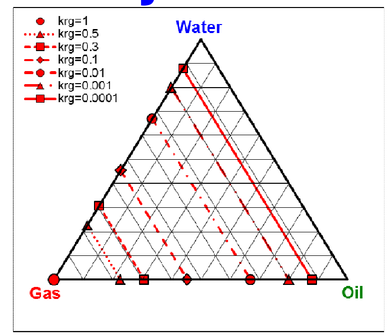
- In low-k rocks, solution gas drive, drainage Kr dominates
  - (except early-time hyd frac face)
- IBRP-Krg = CA-Krg
  - –completely independent measures
- IBRP provides complete curves
  - ϕ = 9.4%-31.4%; Kik = 1.6 µD-343 µD
- IBRP Corey parameters
  - Snwc = Sgc = Soc = 0, Swc=0.1
  - enw = eg = eo = 4.7 (black enw=3.7 & 5.7)
  - ew = 4
- <u>Similar Kro and Krw for wide range of K-ϕ</u>
  - <u>No systematic shift in eo or ew</u>

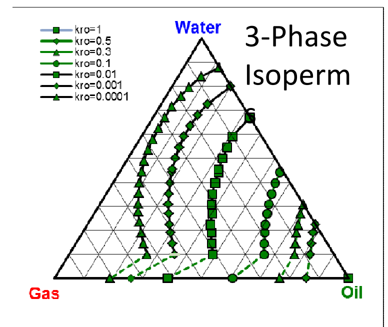
$$k_{rnw} = k_{ro} = k_{rg} = k^{o}_{rnw} \left[\frac{S_{nw} - S_{nwc}}{(1 - S_{nwc} - S_{wc})}\right]^{e_{nw}}$$

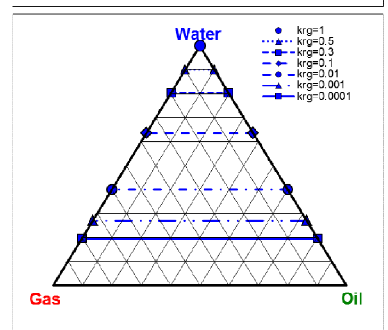
$$k_{rw} = k^{o}_{rw} \left[\frac{S_{w} - S_{wc}}{(1 - S_{nwc} - S_{wc})}\right]^{e_{w}}$$

Three-Phase Relative Permeability





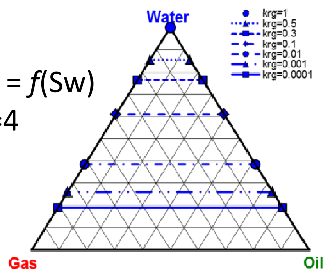




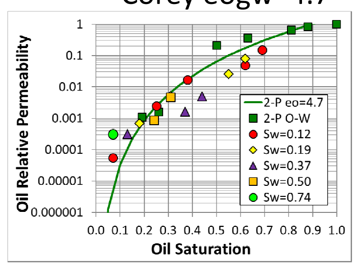
- When 3 phases are present in a drainage cycle:
  - Gas (red) occupies largest pores and krg is dependent only on Sg
  - Water (blue) occupies smallest pores and krw is dependent only on Sw
  - Oil (green) occupies intermediate pores and kro is more complex function of Sg, So, and Sw

IBRP – 3-Phase Relative Permeability

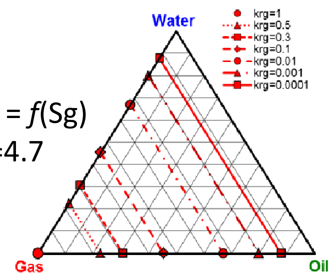
Krw = f(Sw)
ew=4

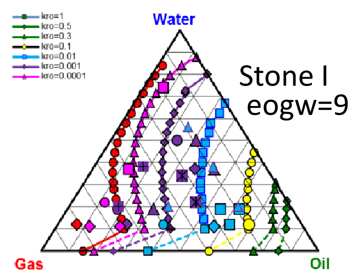


Corey eogw=4.7



Krg = f(Sg)
eg=4.7





- CA 3-P Krogw almost impossible to measure on low-k and no CA data exist
- IBRP 3-P Krogw modeling similar to 2-P where Kro is computed for quasi-static So
- 3-P Krogw Corey eogw = 4.7
- 3-P Krogw Stone I eogw = 9.0

$$k_{row} = k^o_{row}\left[\frac{S_o - S_{oc}}{(1 - S_{wc} - S_{oc})}\right]^{e_{ow}}$$

$$k_{rog} = k^o_{rog}\left[\frac{1 - S_g - S_{wc} - S_{oc}}{(1 - S_{wc} - S_{oc} - S_{gc})}\right]^{e_{ogw}}$$

$$Stone\ I:\ \ k_{ro} = \left[\frac{S^*_o k_{row} k_{rog}}{(1 - S^*_w)(1 - S^*_g)}\right]$$

$$Corey:\ \ k_{ro} = k^o_{ro}\left[\frac{S_o - S_{oc}}{(1 - S_{wc} - S_{oc} - S_{gc})}\right]^{e_{ogw}}$$

Bound Water vs Permeability

In situ Permeability (mD)	Pore Throat Diameter @ Sw=1 (Dte, μm)	Pore Throat Diameter @ Sw=0.1 (De, μm)	Permeability reduction for 1-layer Boundwater K_{BW}/K @ Dte (fraction)	Permeability reduction for 1-layer Boundwater K_{BW}/K @ De (fraction)	Permeability reduction for 3-layer Boundwater K_{BW}/K @ Dte (fraction)	Permeability reduction for 3-layer Boundwater K_{BW}/K @ De (fraction)
0.1	0.229	0.076	0.994	0.983	0.983	0.950
0.01	0.104	0.035	0.988	0.964	0.964	0.893
0.001	0.048	0.016	0.973	0.921	0.921	0.773
0.0001	0.022	0.007	0.942	0.832	0.832	0.542

Water Types

1. Free (capillary force<<viscous force)
2. Capillary-bound (capillary force>>viscous force)
3. External surface electrostatic-bound (adsorbed, ~2-molecules thick)
4. Internal surface electrostatic-bound (between clay sheets, =*f*(salinity))
5. Structural (ionic-covalent bond force dominate)

- Focusing only on water on pore wall surface and ignoring water retained in very small pores by Pc
- Bound water alone exerts minor influence on K for K>0.01 mD
- Bound water exerts significant influence on K for K < 0.001 mD

Conclusions

- Demonstrated an integrated workflow for cross-validating CA-DRP in low-k rock
- Both core plugs and FIB/SEM samples are SREVs in Niobrara
- CA and DRP give similar K-ϕ, Pc, Kr with proper stress correction
  - Just as with CA, influence of NCS must be considered for DRP properties
  - For K< ~800 nD, Pc curves are strongly influenced by Hg-induced stress
  - DRP indicates Niobrara core K-ϕ, K-NCS and ϕ-NCS not influenced by micro-cracks
- DRP provides complete Krw and Kro curves not easily measured by CA
- DRP provides 3-Phase Kro curves (never measured by CA?)
- Bound water influences K in rocks with K < 0.001 mD

- Important to note that results in this study are specific to Niobrara rocks (Type 1) - other methodologies are required for samples with larger REVs (Type 2 & 3)
- Properties measured in this study have been utilized in flow modeling to support exploration, completion, and production management decisions

Thank You for Your Time

Questions?

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