Analytical Pore-Network Approach (APNA): A novel method for rapid prediction of capillary pressure-saturation relationship in porous media

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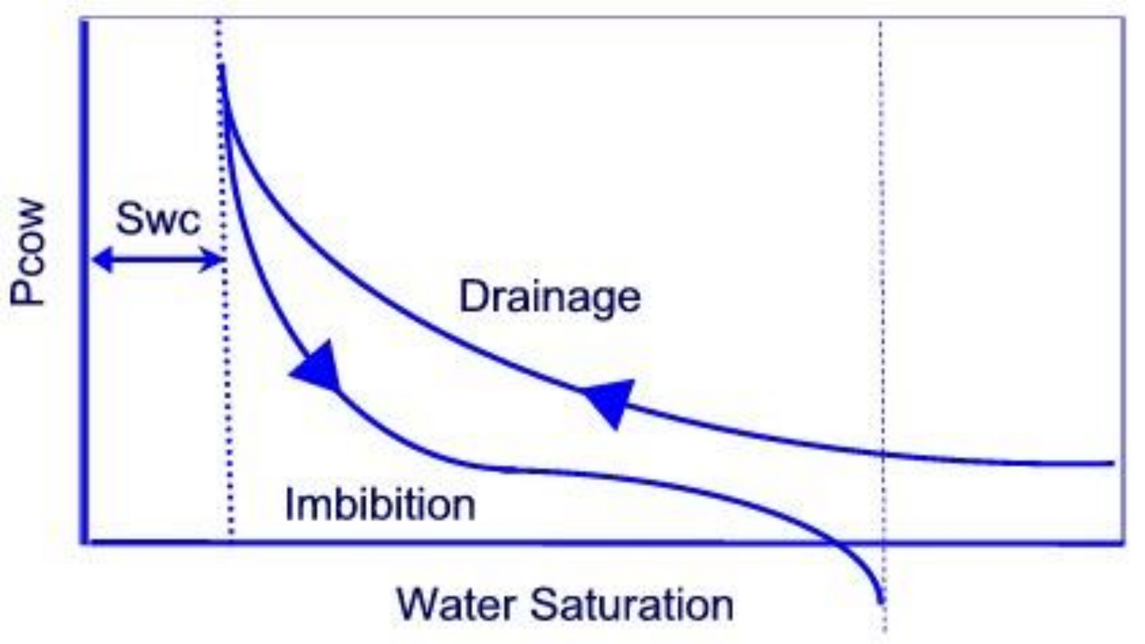
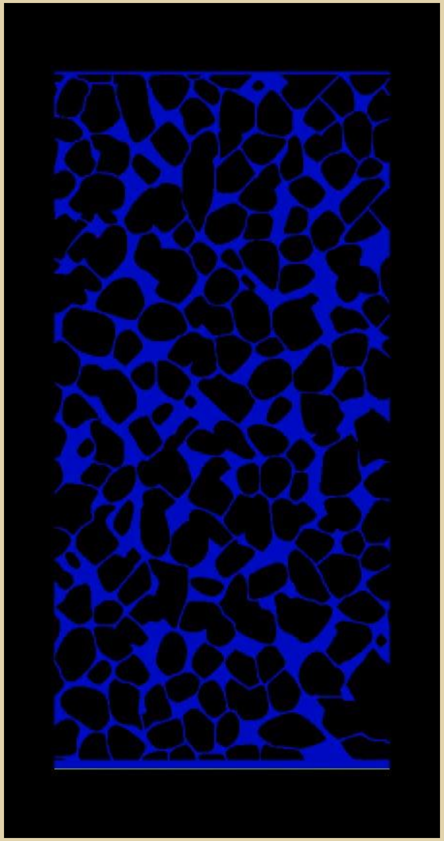
27th January 2020

Outline

- Theory of capillary action
- Role of capillary pressure in petroleum Industry
- Pore geometry control on capillary pressure
- Analytical pore network approach (APNA)
- Dynamic coupling of APNA and reservoir model
- Digital rock physics gadget
- Conclusion
- Acknowledgments



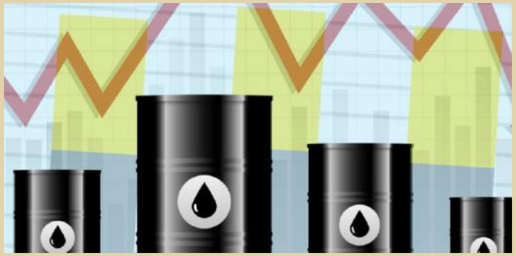


Drainage: Fluid flow processes in which the saturation of non-wetting phase increases.

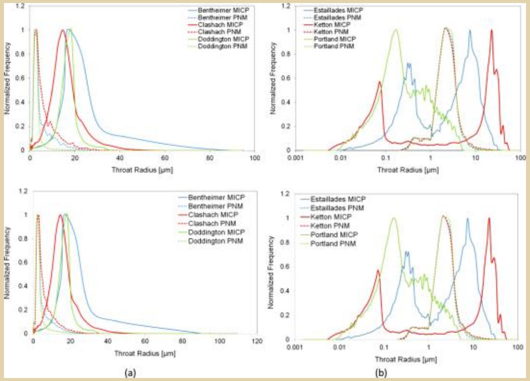
Imbibition: Fluid flow processes in which the saturation of wetting phase increases.

Role of Capillary pressure in Petroleum Industry

Upscale

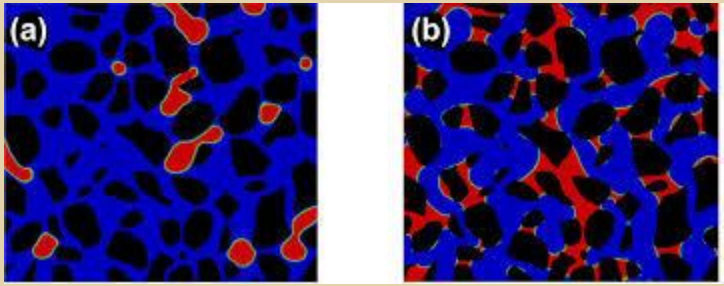


Reserves evaluation

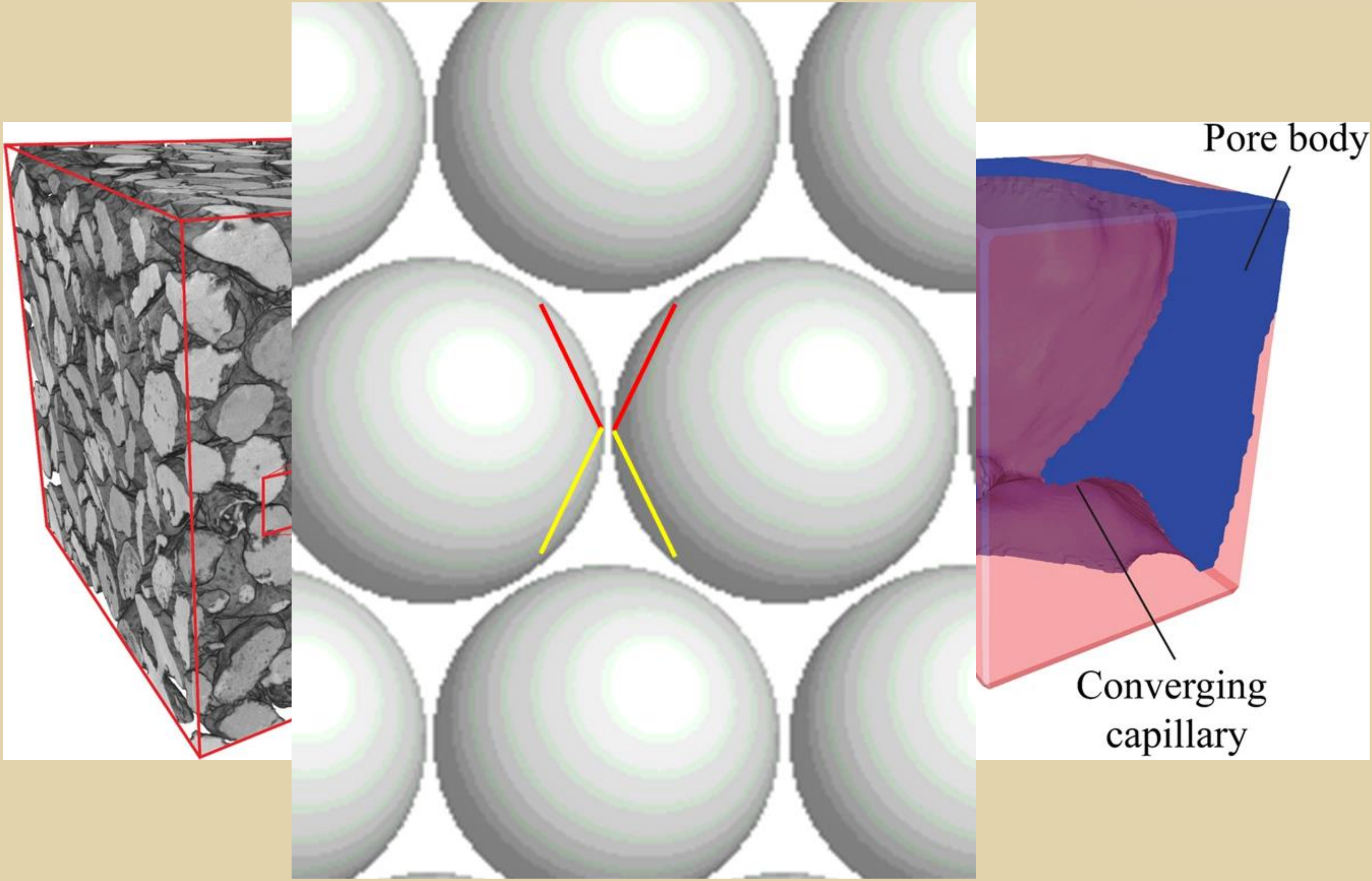


Heterogeneity of sample

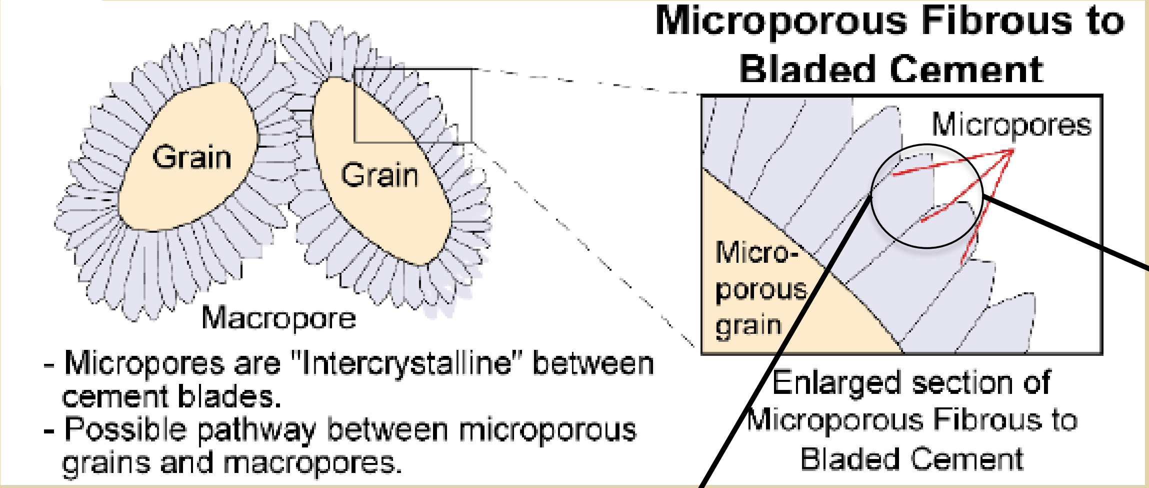
Distribution of fluids



Pore geometry control on capillary pressure



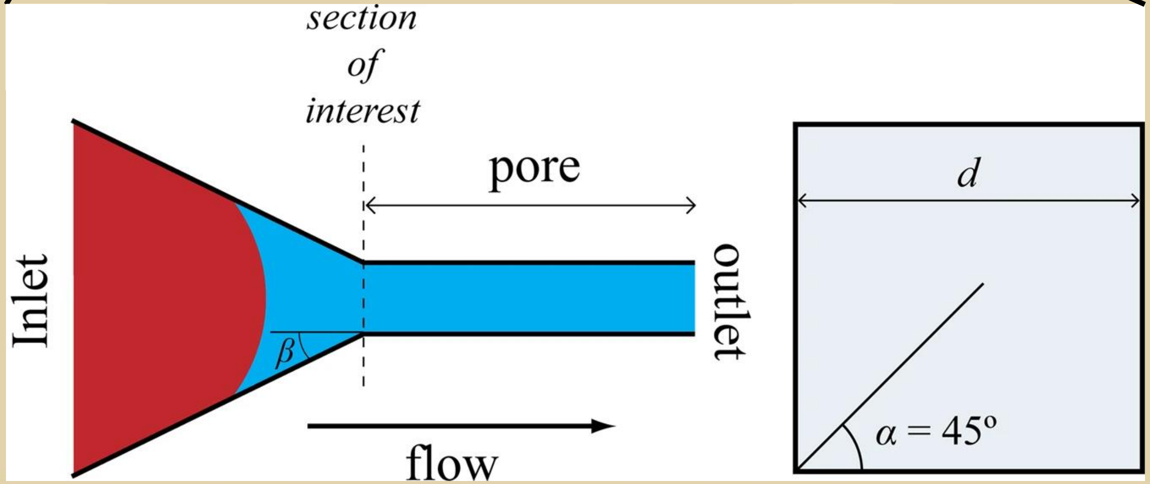
- *Capillary pressure at juncture between converging-uniform channel*

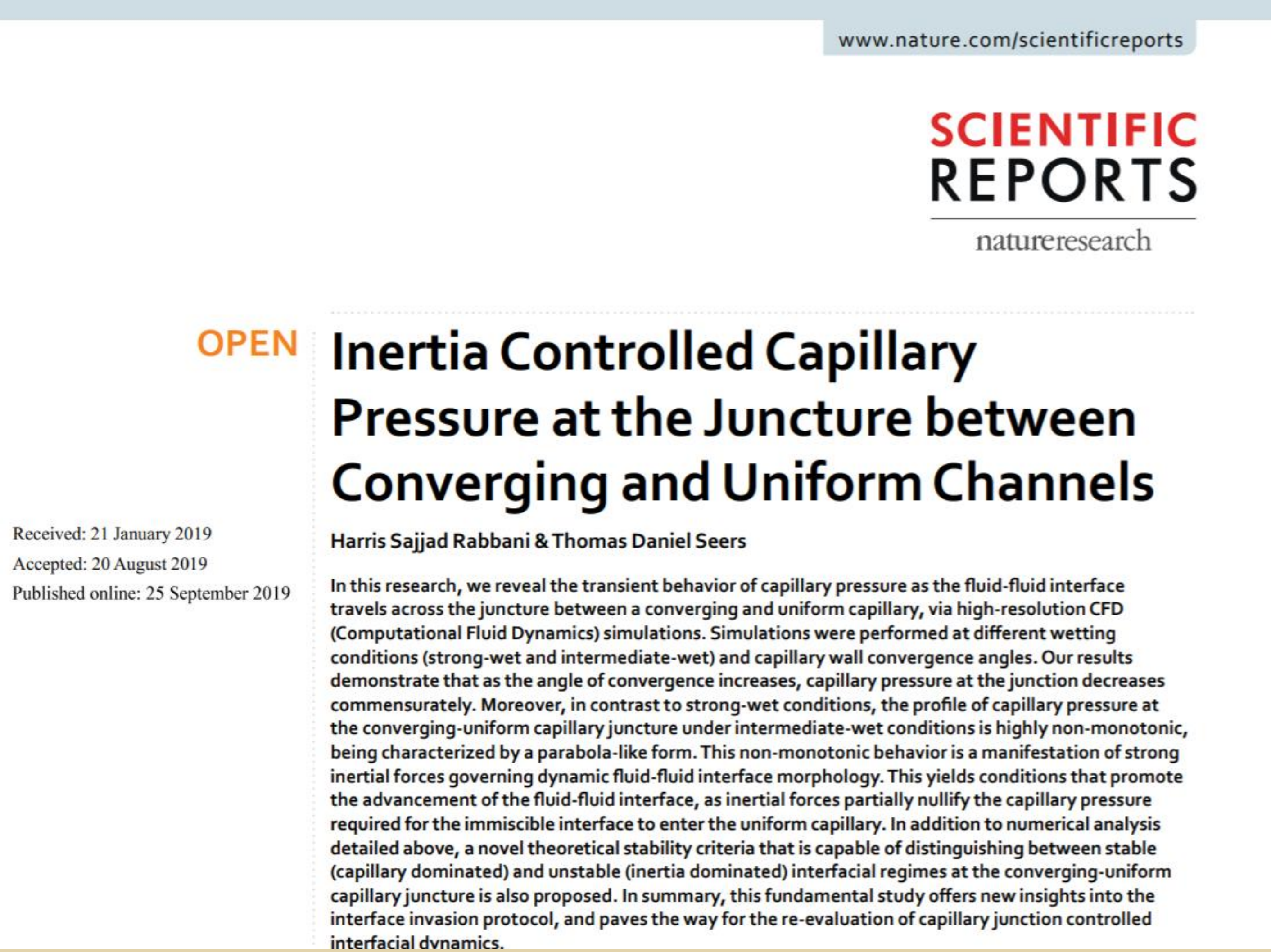


Microporous Fibrous to Bladed Cement

- Micropores are "Intercrystalline" between cement blades.
- Possible pathway between microporous grains and macropores.

Enlarged section of Microporous Fibrous to Bladed Cement





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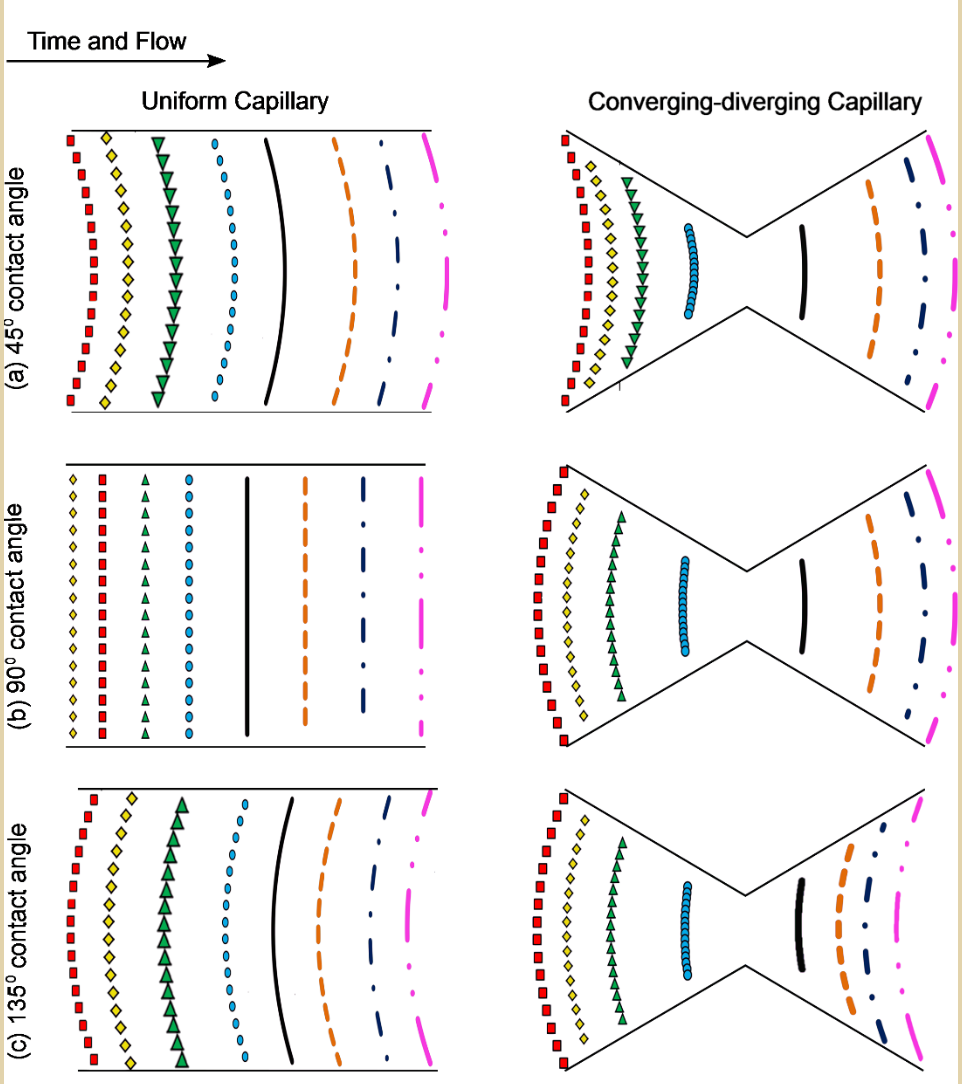
Inertia Controlled Capillary Pressure at the Juncture between Converging and Uniform Channels

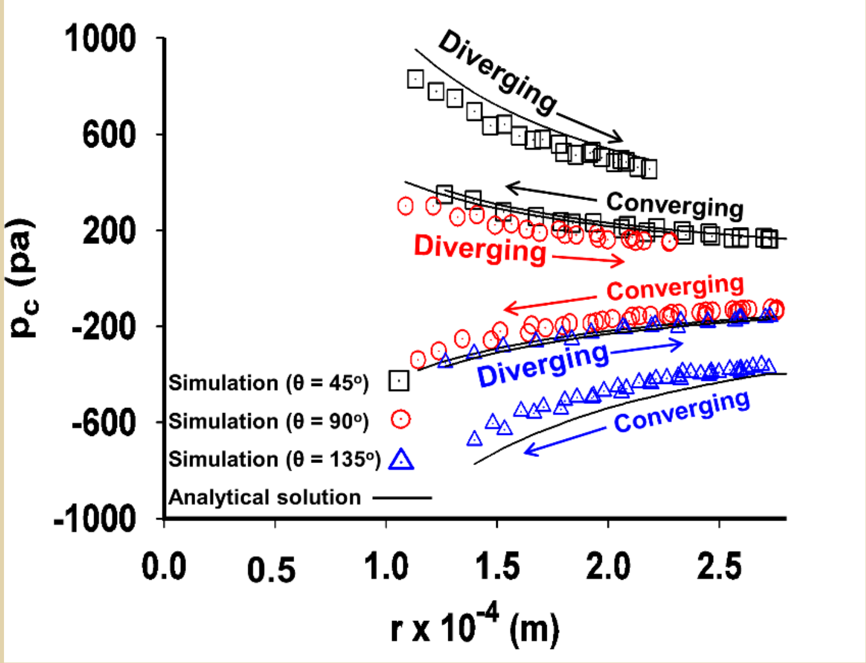
Received: 21 January 2019
Accepted: 20 August 2019

Harris Sajjad Rabbani & Thomas Daniel Seers

In this research, we reveal the transient behavior of capillary pressure as the fluid-fluid interface travels across the juncture between a converging and uniform capillary, via high-resolution CFD (Computational Fluid Dynamics) simulations. Simulations were performed at different wetting conditions (strong-wet and intermediate-wet) and capillary wall convergence angles. Our results demonstrate that as the angle of convergence increases, capillary pressure at the junction decreases commensurately. Moreover, in contrast to strong-wet conditions, the profile of capillary pressure at the converging-uniform capillary juncture under intermediate-wet conditions is highly non-monotonic, being characterized by a parabola-like form. This non-monotonic behavior is a manifestation of strong inertial forces governing dynamic fluid-fluid interface morphology. This yields conditions that promote the advancement of the fluid-fluid interface, as inertial forces partially nullify the capillary pressure required for the immiscible interface to enter the uniform capillary. In addition to numerical analysis detailed above, a novel theoretical stability criteria that is capable of distinguishing between stable (capillary dominated) and unstable (inertia dominated) interfacial regimes at the converging-uniform capillary juncture is also proposed. In summary, this fundamental study offers new insights into the interface invasion protocol, and paves the way for the re-evaluation of capillary junction controlled interfacial dynamics.

- *Capillary pressure converging-diverging channel*





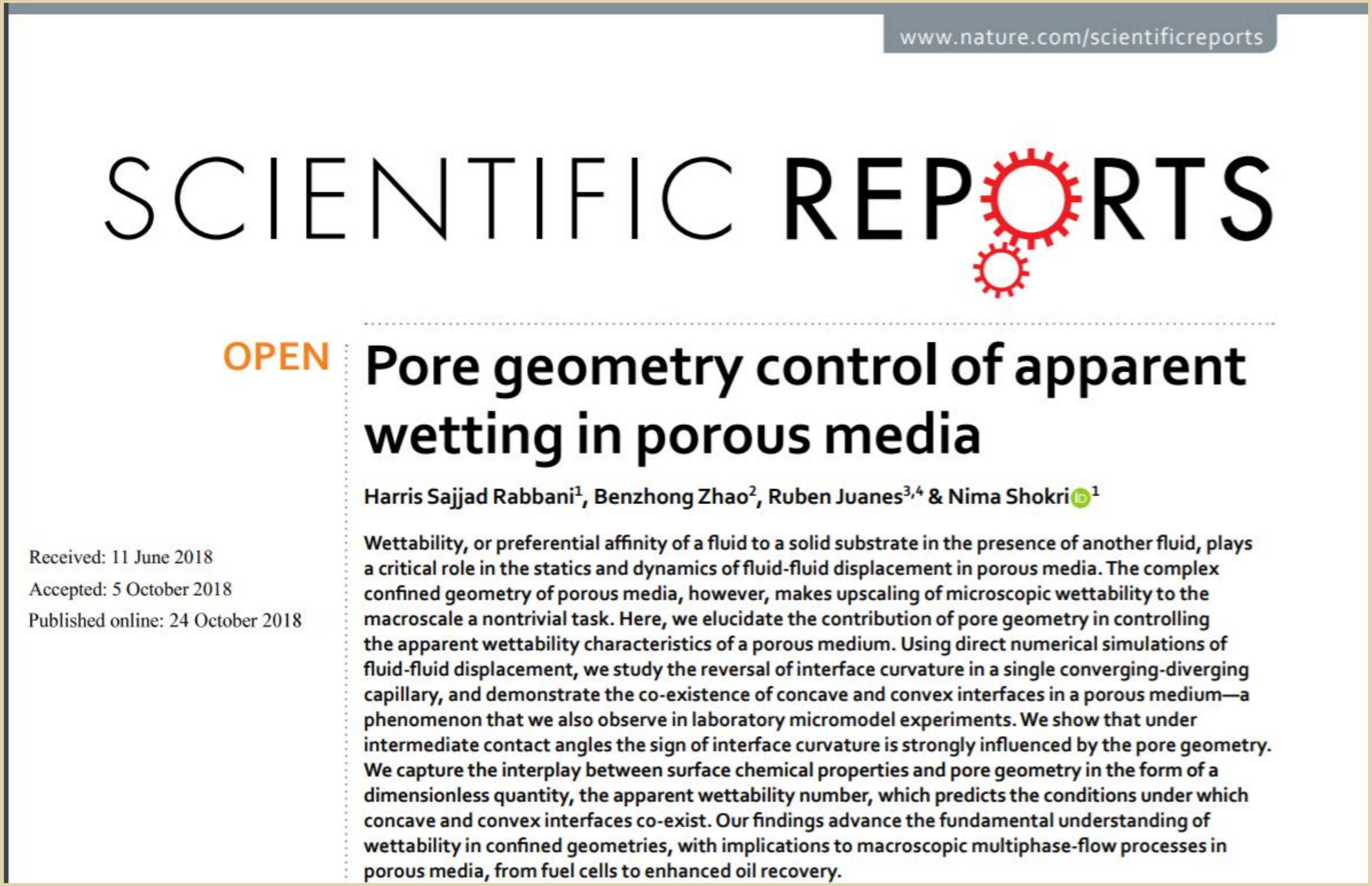
- **Converging section:**

$$p_c = \frac{2\pi r\sigma cos(\theta+\beta)\left(1-\frac{h}{\pi}\right)}{GP^2}\frac{sin(\pi-2h)}{sin(h)}$$

$$p_c = \frac{2\sigma\cos(\theta)}{r}$$

- **Diverging section:**

$$p_c = \frac{2\pi r\sigma cos(\theta-\beta)\left(1-\frac{h}{\pi}\right)}{GP^2}\frac{sin(\pi-2h)}{sin(h)}$$



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Pore geometry control of apparent wetting in porous media

Harris Sajjad Rabbani[1], Benzhong Zhao[2], Ruben Juanes[3,4] & Nima Shokri[1]

Received: 11 June 2018
Accepted: 5 October 2018

Wettability, or preferential affinity of a fluid to a solid substrate in the presence of another fluid, plays a critical role in the statics and dynamics of fluid-fluid displacement in porous media. The complex confined geometry of porous media, however, makes upscaling of microscopic wettability to the macroscale a nontrivial task. Here, we elucidate the contribution of pore geometry in controlling the apparent wettability characteristics of a porous medium. Using direct numerical simulations of fluid-fluid displacement, we study the reversal of interface curvature in a single converging-diverging capillary, and demonstrate the co-existence of concave and convex interfaces in a porous medium—a phenomenon that we also observe in laboratory micromodel experiments. We show that under intermediate contact angles the sign of interface curvature is strongly influenced by the pore geometry. We capture the interplay between surface chemical properties and pore geometry in the form of a dimensionless quantity, the apparent wettability number, which predicts the conditions under which concave and convex interfaces co-exist. Our findings advance the fundamental understanding of wettability in confined geometries, with implications to macroscopic multiphase-flow processes in porous media, from fuel cells to enhanced oil recovery.

Analytical Pore Network Approach (APNA)

- Capillary Pressure Measurement
  - Experiments
    - Porous Plate Method
    - Mercury Injection.
    - Centrifuge Techniques
  - Digital Rock Physics
    - Pore Network Modelling
    - Analytical Pore Network Approach

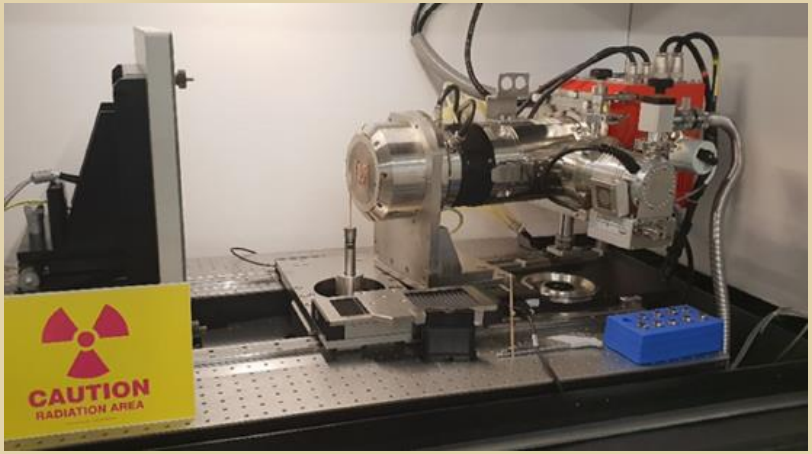
- Experimental methodologies are subject to practical limitations
- Pore Network modelling technique is computationally expensive and complicated tor run.
- We introduce a novel method to predict capillary pressure-saturation relationships for porous media called Analytical Pore-Network Approach (APNA). (US 62/741,847)
- APNA is faster and more accurate than Pore Network Modelling Approach

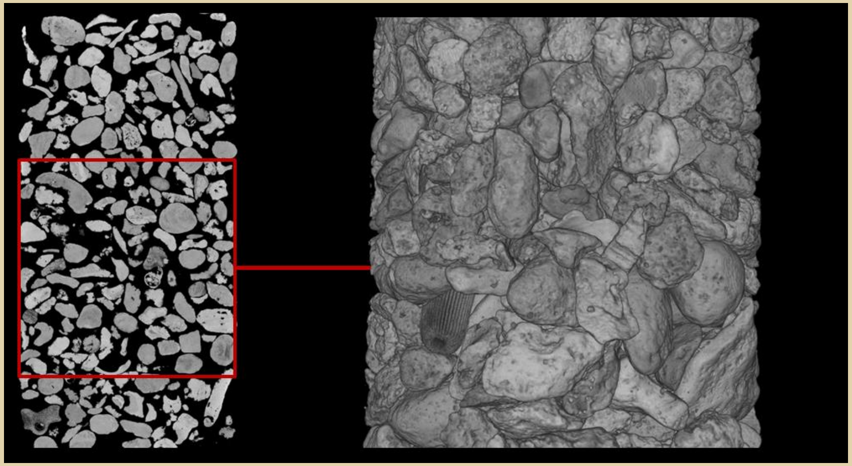
- Inventors

Dr. Harris Sajjad Rabbani
(Lead Inventor)

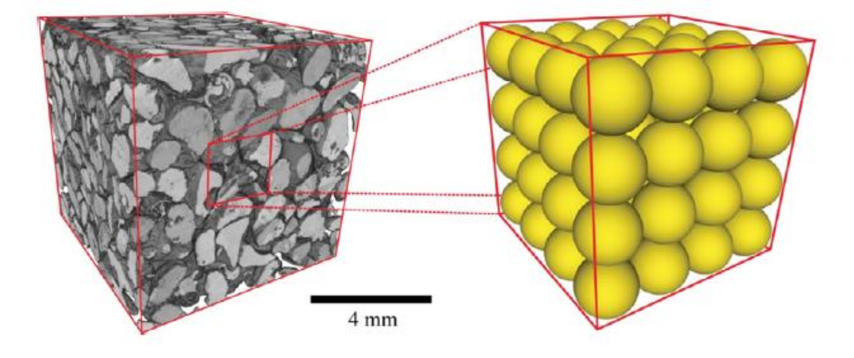
Prof. Dominique Guerillot
(Co Inventor)

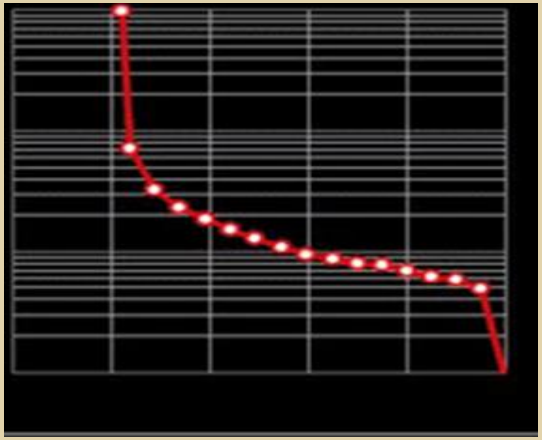
Dr. Thomas Seers
(Co Inventor)





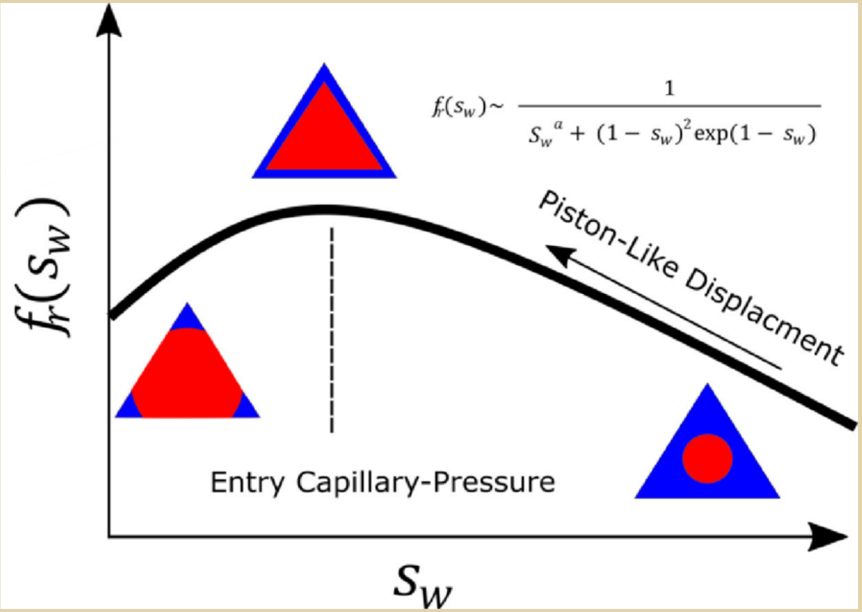
APNA model



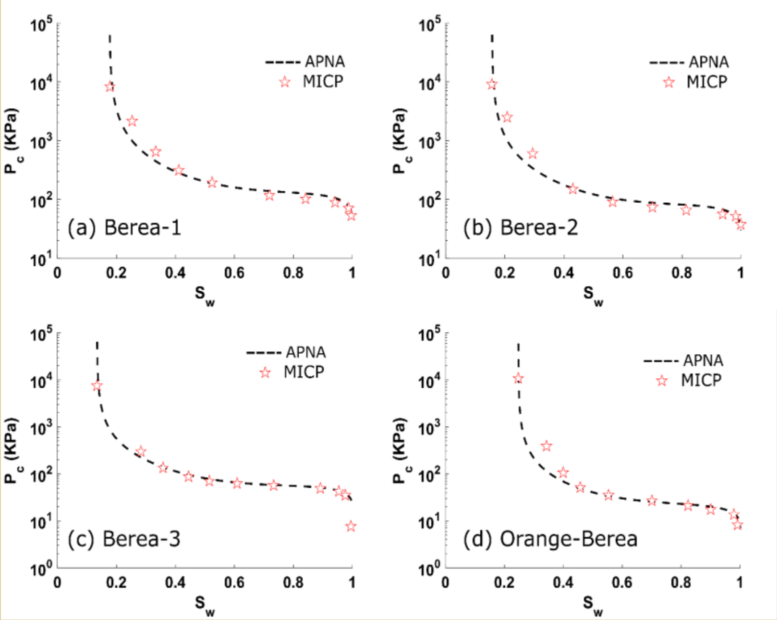


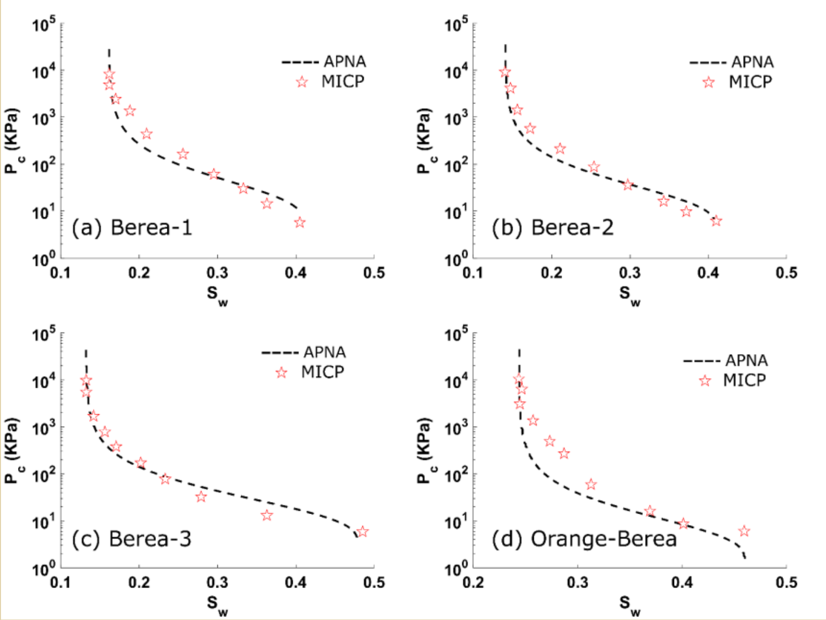
- $\frac{\delta \bar{R}_t}{\delta s_n} = -\frac{\sqrt[3]{\emptyset s_n(1-\tan\beta) {r_g}^3}}{3}\left[\frac{8+27(1-\tan\beta)^3}{\left[{s_n}^*[8+27(1-\tan\beta)^3]-\emptyset s_n[8+27(1-\tan\beta)^3]\right]^{\frac{4}{3}}}\right]$

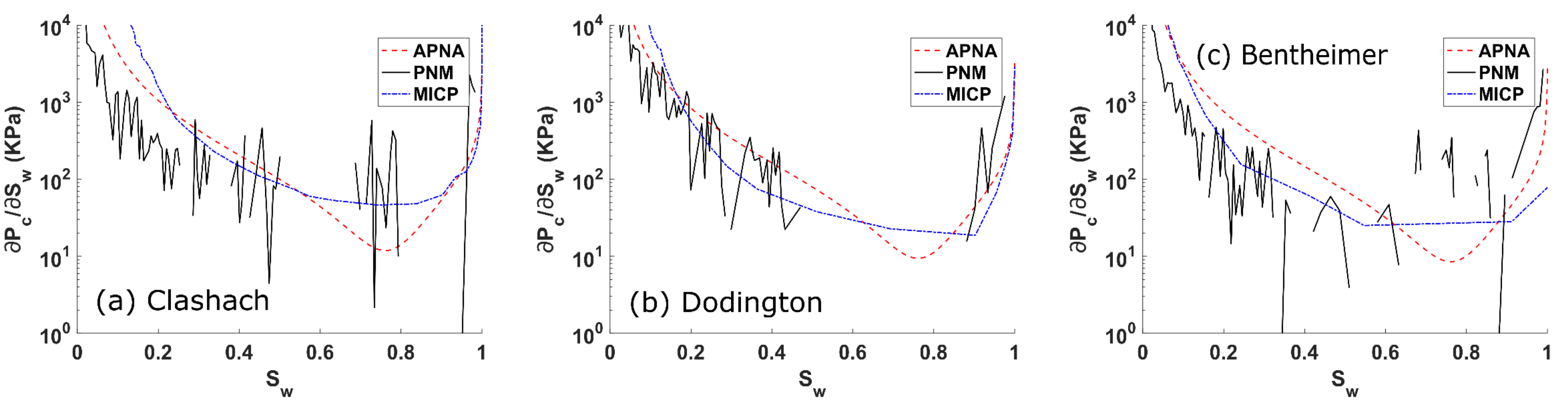
- ${\bar{R}_t}^*(s_n) = \ f_r(s_w)\ \bar{R}_t(s_n)$
- ${\bar{R}_t}^*(s_n) = \frac{\bar{R}_t(s_n)}{({S_w}^a+{S_n}^2)\exp(s_w)}$
- $p_c(s_w) \ = \frac{2\sigma\cos(\theta)}{{\bar{R}_t}^*(s_n)}$
- ${\bar{R}_b}^*(s_n) \ = \frac{{\bar{R}_t}^*(s_n)}{1-\tan(\beta)}$
- $p_c(s_w) = \frac{2\sigma\cos(\theta)}{{\bar{R}_b}^*(s_n)}$

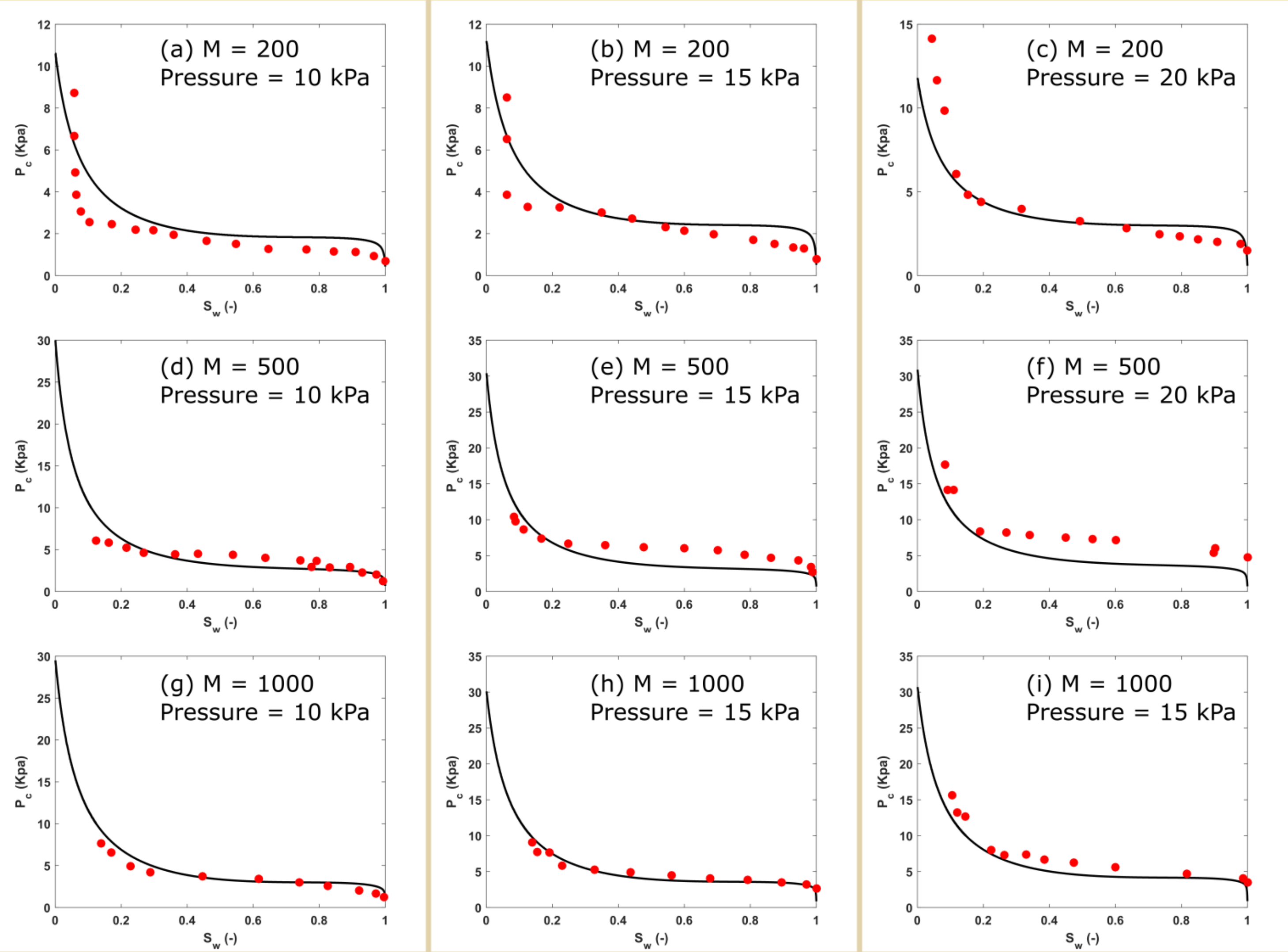


APNA	Conventional Pore Network Modelling Approach
Very fast	*Computationally expensive*
Accuracy depends upon input data (very few input properties required)	*Accuracy depends upon pore-scale images as well as numerical stability of algorithm*
Not limited to sample size	*Limited to smaller samples*
Trivial to implement	*Require complex coding*

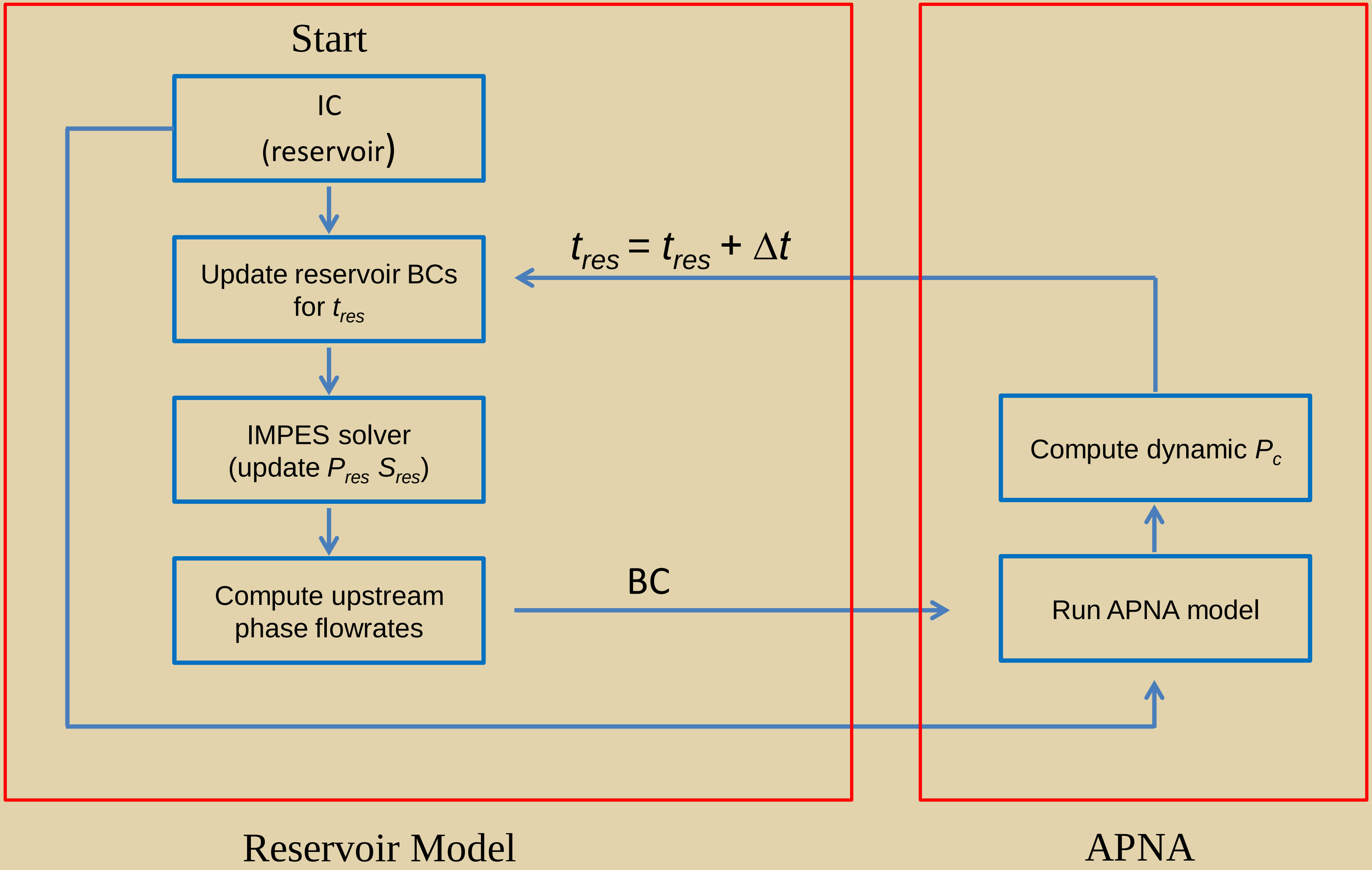

(a) Berea-1
(b) Berea-2
(c) Berea-3
(d) Orange-Berea
APNA
MICP
P_c (KPa)
S_w
10^1
10^2
10^3
10^4
10^5
10^0
0
0.2
0.4
0.6
0.8
1


(a) Berea-1
(b) Berea-2
(c) Berea-3
(d) Orange-Berea
APNA
MICP
P_c (KPa)
S_w
10^0
10^1
10^2
10^3
10^4
10^5
0.1
0.2
0.3
0.4
0.5


(a) Clashach
(b) Dodington
(c) Bentheimer
APNA
PNM
MICP
$\partial P_c/\partial S_w$ (KPa)
S_w
10^0
10^1
10^2
10^3
10^4
0
0.2
0.4
0.6
0.8
1


(a) M = 200
Pressure = 10 kPa
(b) M = 200
Pressure = 15 kPa
(c) M = 200
Pressure = 20 kPa
(d) M = 500
Pressure = 10 kPa
(e) M = 500
Pressure = 15 kPa
(f) M = 500
Pressure = 20 kPa
(g) M = 1000
Pressure = 10 kPa
(h) M = 1000
Pressure = 15 kPa
(i) M = 1000
Pressure = 15 kPa
P c (Kpa)
S w (-)
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8
10
12
15
5
20
25
30
35

Dynamic coupling of APNA and reservoir model



Start

IC
(reservoir)

Update reservoir BCs for t_{res}

IMPES solver (update P_{res} S_{res})

Compute upstream phase flowrates

BC

Run APNA model

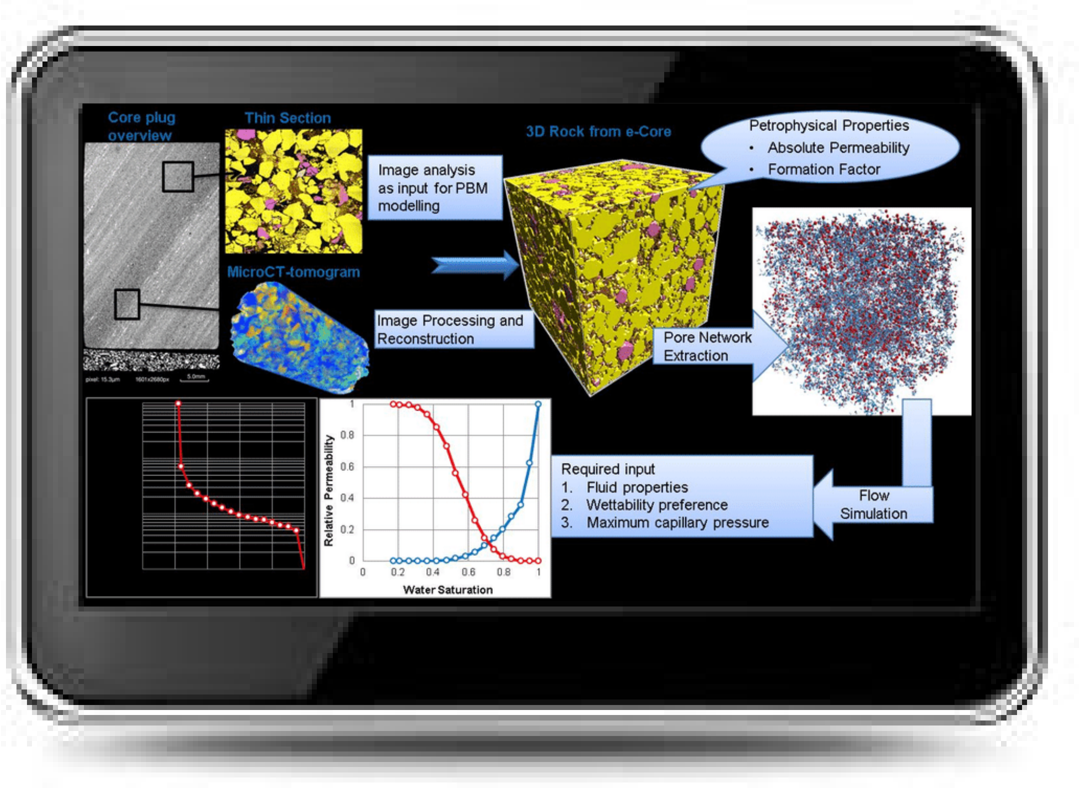
Compute dynamic P_c

$t_{res} = t_{res} + \Delta t$

Reservoir Model

APNA

Digital Rock Physics Gadget



Conclusion

- A novel method to predict capillary pressure-saturation relationships for porous media called Analytical Pore-Network Approach (APNA) is presented. (US 62/741,847)
- APNA is fully coupled analytical model is derived from the pore-scale physics.
- APNA is faster and more accurate than Pore Network Modelling Approach.
- APNA allows dynamic coupling of pore-scale and reservoir model
- APNA allows integration of digital rock physics work flow into a portable device.

Acknowledgements

مؤسسة قطر
Qatar Foundation

TOTAL