Pore-scale processes
A revolution in describing multiphase flow

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Qatar Carbonates and Carbon Storage Research Centre

Ten-year, $70 million programme: 2008 – 2018.

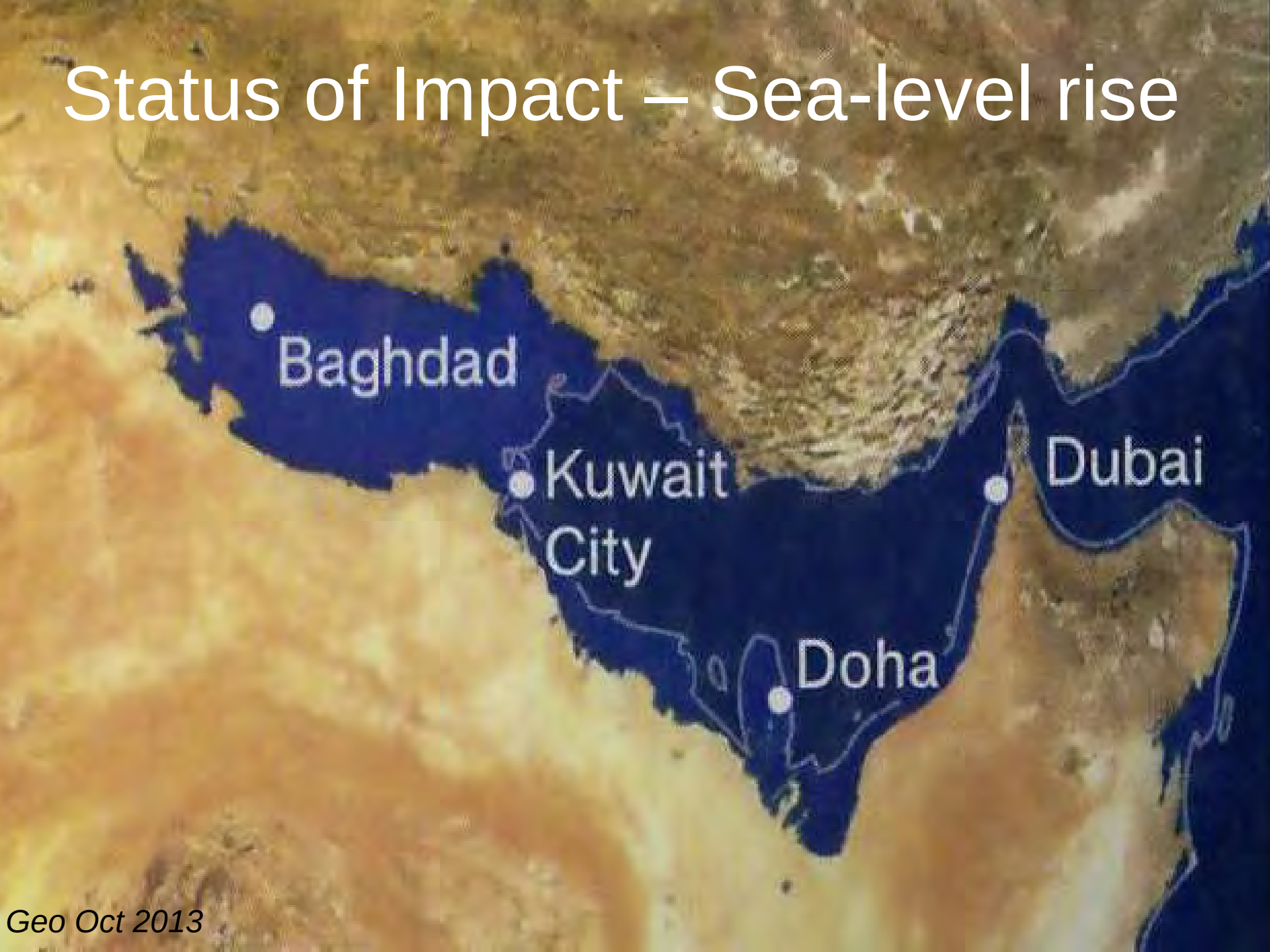
To understand carbon dioxide storage in a Qatari context (carbonates). Major experimental and modelling activity. Based at Imperial College.

Work all published in the public domain.

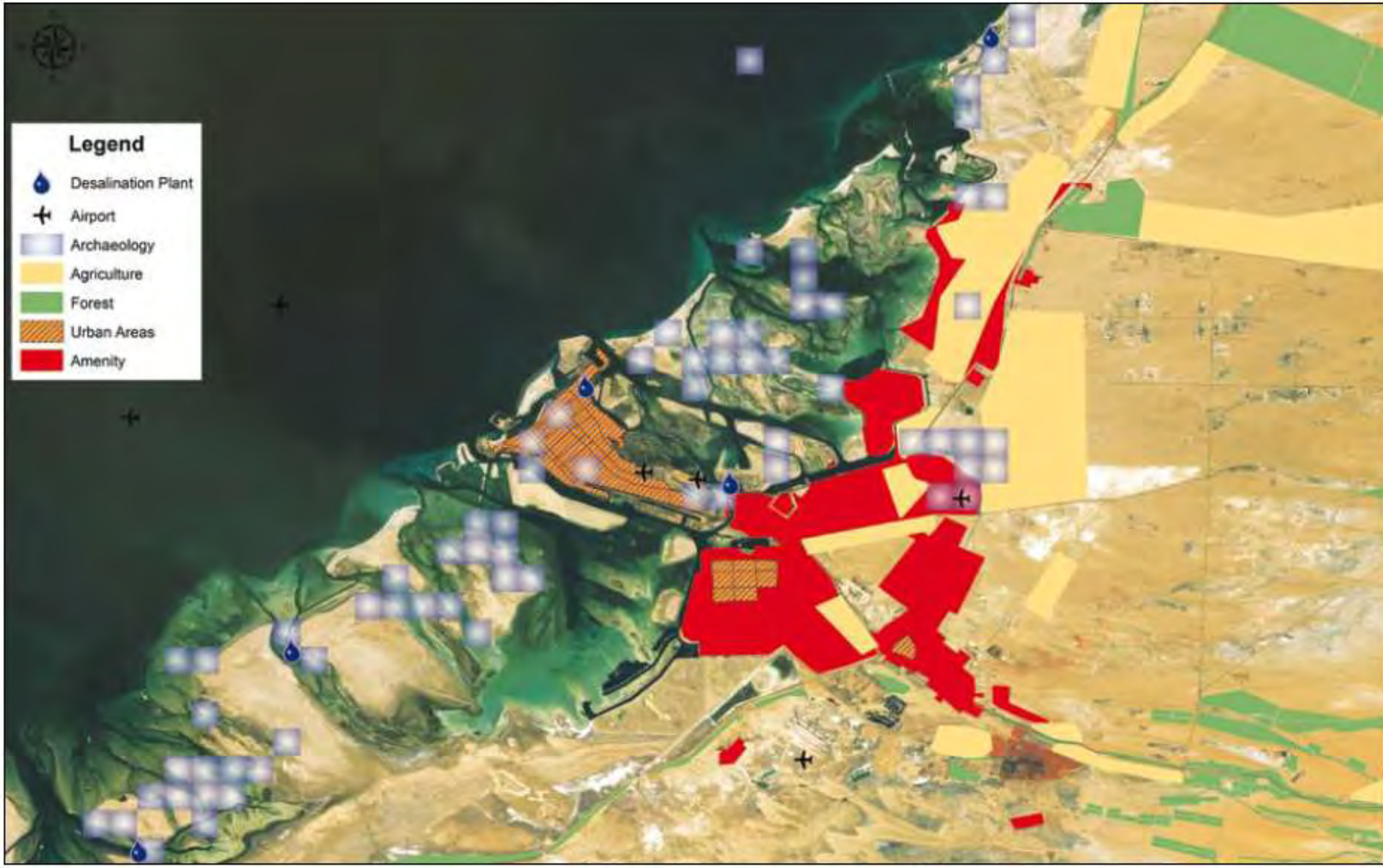
Multidisciplinary (Chem. Eng. / Earth Sci. & Eng.). Three major themes: rocks, fluids and rock-fluid interaction.

Four dedicated lecturers, other faculty, post-docs and PhD students (some from Qatar): involves >70 researchers.

Status of Impact – Sea-level rise



Geo Oct 2013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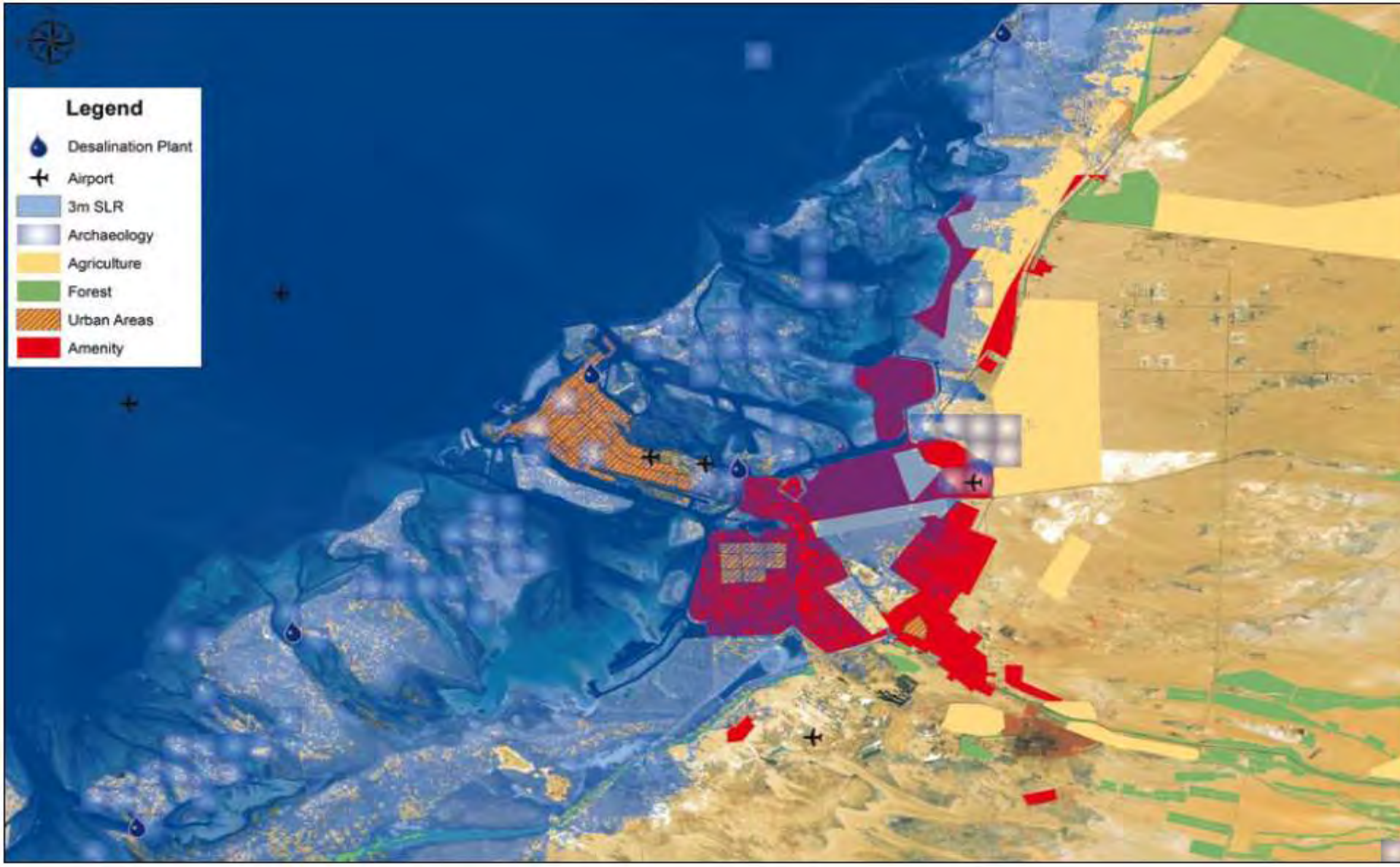
Desalination Plant
Airport
Archaeology
Agriculture
Forest
Urban Areas
Amenity


Legend
Desalination Plant
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Agriculture
Forest
Urban Areas
Amenity

Motivation

Historically high oil prices, even at $40/barrel – peak oil per person in 1979 and current discoveries running at half global production (30 billion stb/year). Need to produce more of the oil in existing fields.

Exploitation of unconventional oil and gas.

Wise use of groundwater.

Global-scale CO_2 storage.

All involve understanding of flow of fluids in porous rocks.

New tools

Multi-scale imaging – particularly ability to image the pore space of rock and fluids at 10 nm to micron resolution.

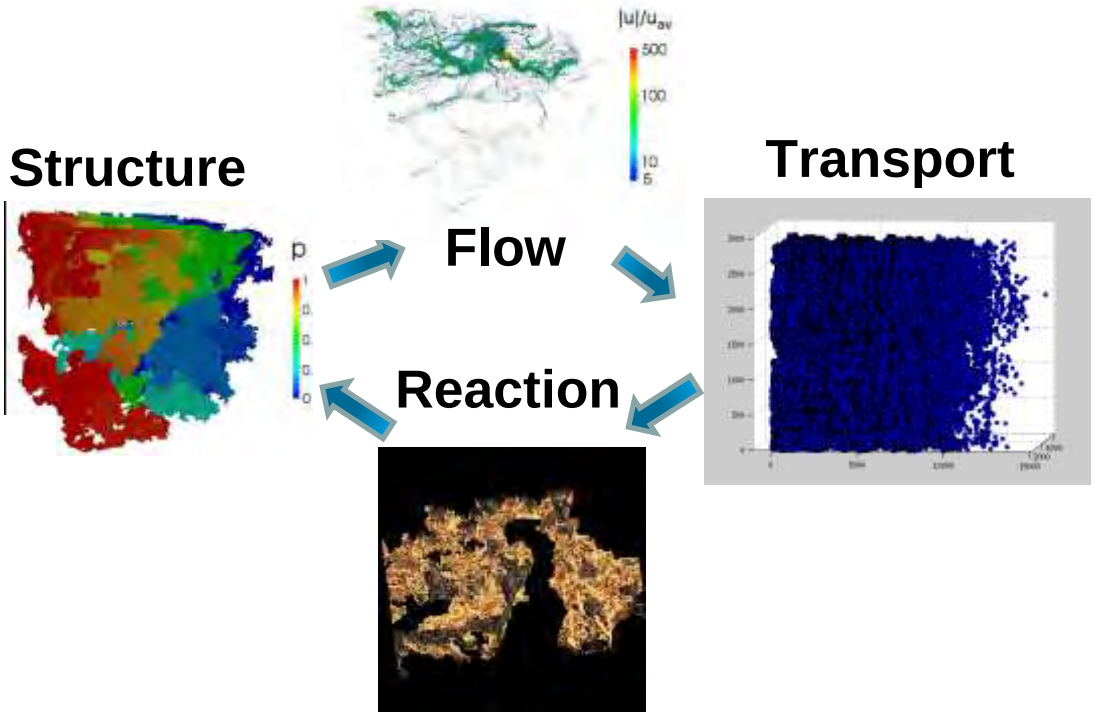
Public-domain availability of good-quality software for scientific computing – changes the way we develop computational models.

What is digital rock analysis? A physically-based model for flow, based on pore-scale displacement. A nm – cm model (6 orders of magnitude in scale). A necessary complement and input to a field-scale geological/reservoir model (cm – km, or another 6 orders of magnitude).

What we can do

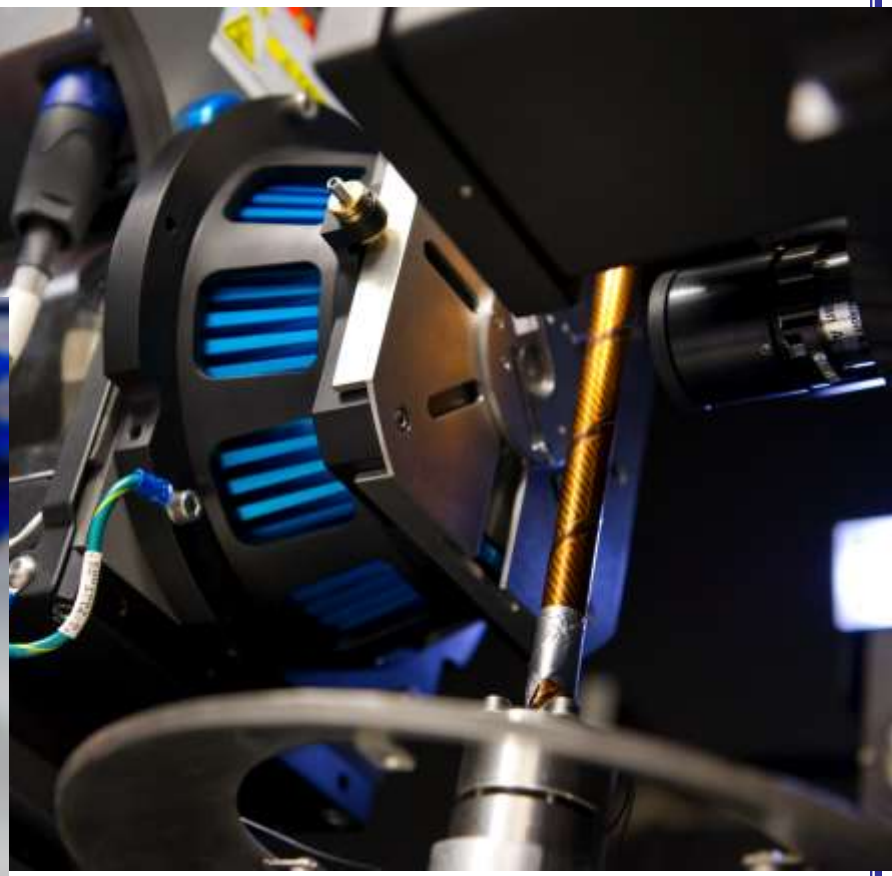
Original work on 3D X-ray microtomography by Flannery *et al.* (1987) states in conclusion: "*we believe that it will be possible to study contained systems under conditions of temperature, pressure, and environment representative of process conditions*." Can now!

Will discuss imaging and flow simulation: transport, reaction and multiphase flow.



Imperial College multi-scale imaging lab

Start with the fundamentals – understand processes experimentally at the pore scale. Micron-to-metre imaging with *in situ* displacement at reservoir conditions.



Micro-CT – Flow loop

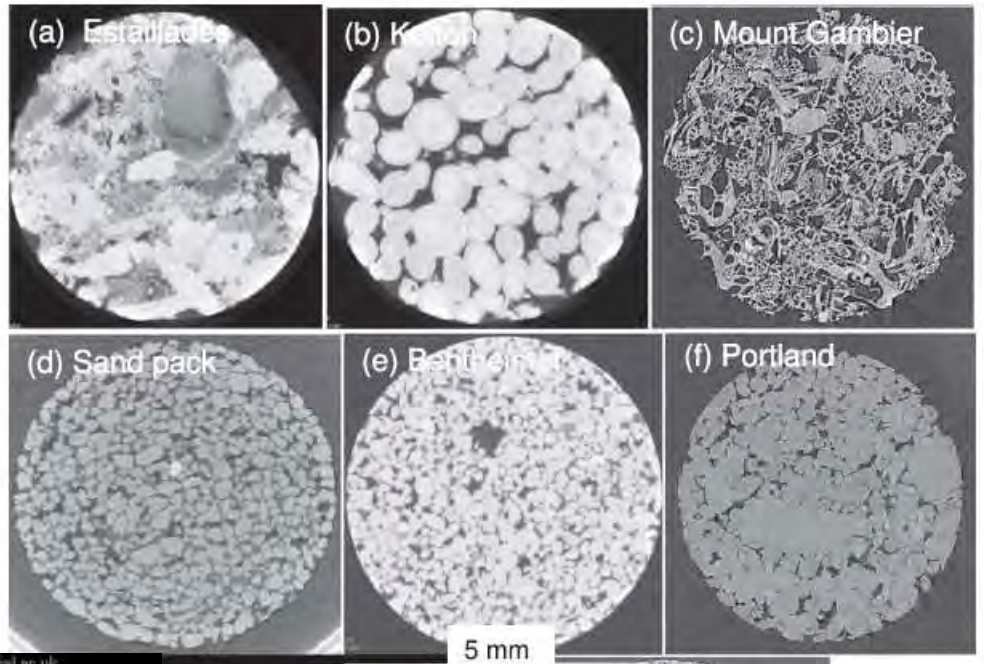
Imaging and computing

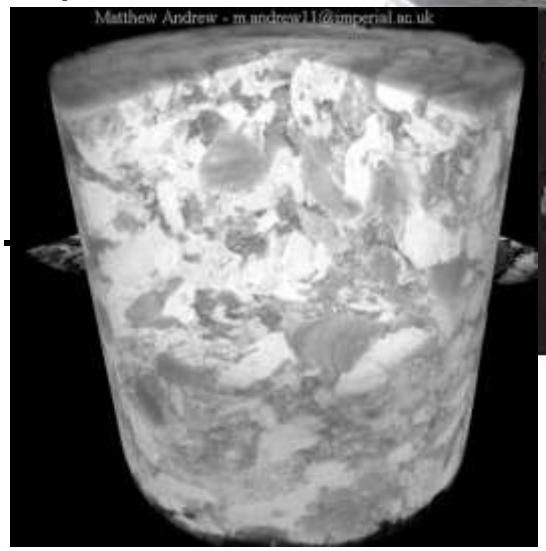
Bench-top **micro-CT** scanners are convenient, no time limitations and modern systems have optics.

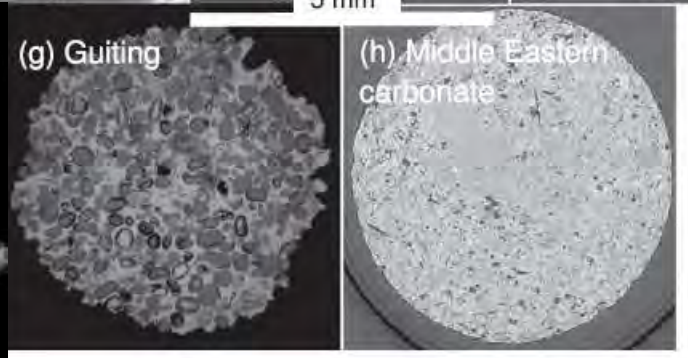
Synchrotron sources. Bright, mono-chromatic and fast.

Computationally, not interested in GPU, parallel, but better algorithms.

Availability of excellent public-domain solvers: algebraic multigrid, OpenFoam Navier-Stokes solver. Fluid mechanics: unstructured adaptive grids.





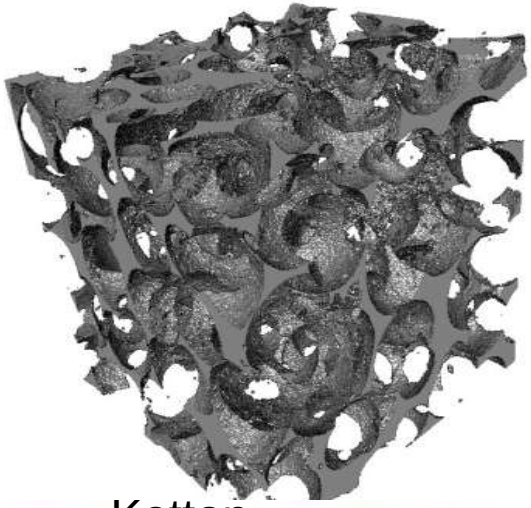


Blunt *et al., Adv. Water Res.* 2013

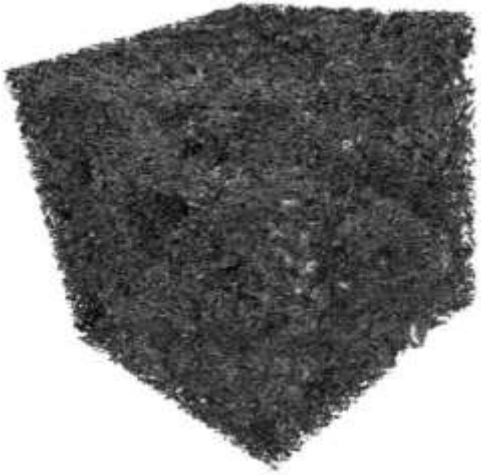
Images and networks for carbonates

Represent the pore space topologically and compute displacement semi-analytically through the network. Also accommodate micro-porosity.

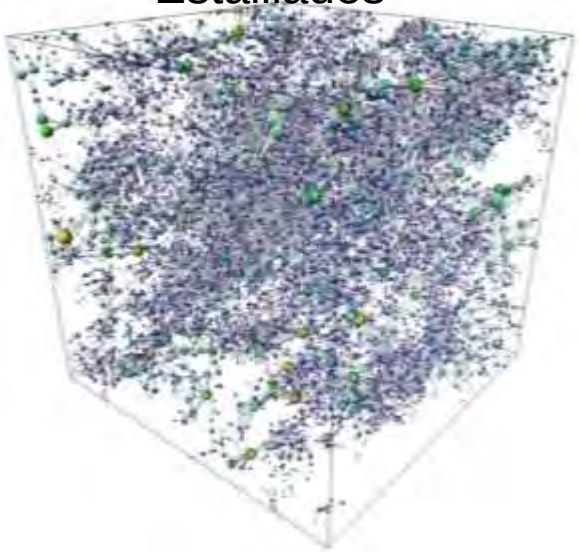
Estaillades

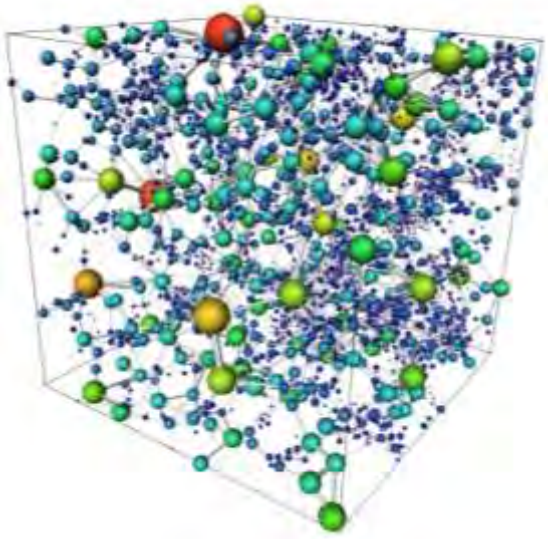


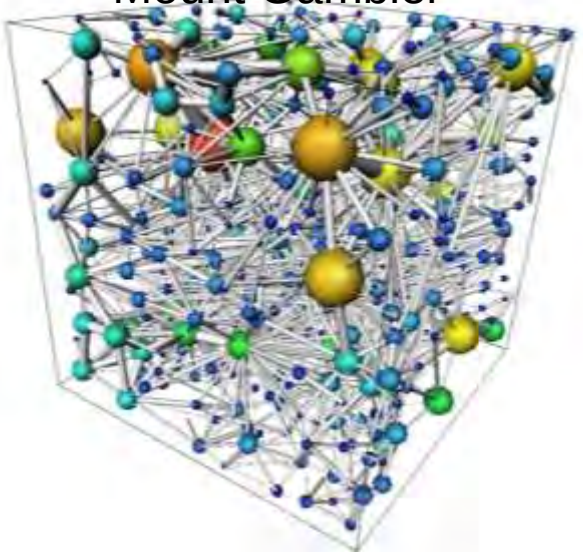
Ketton



Mount Gambier





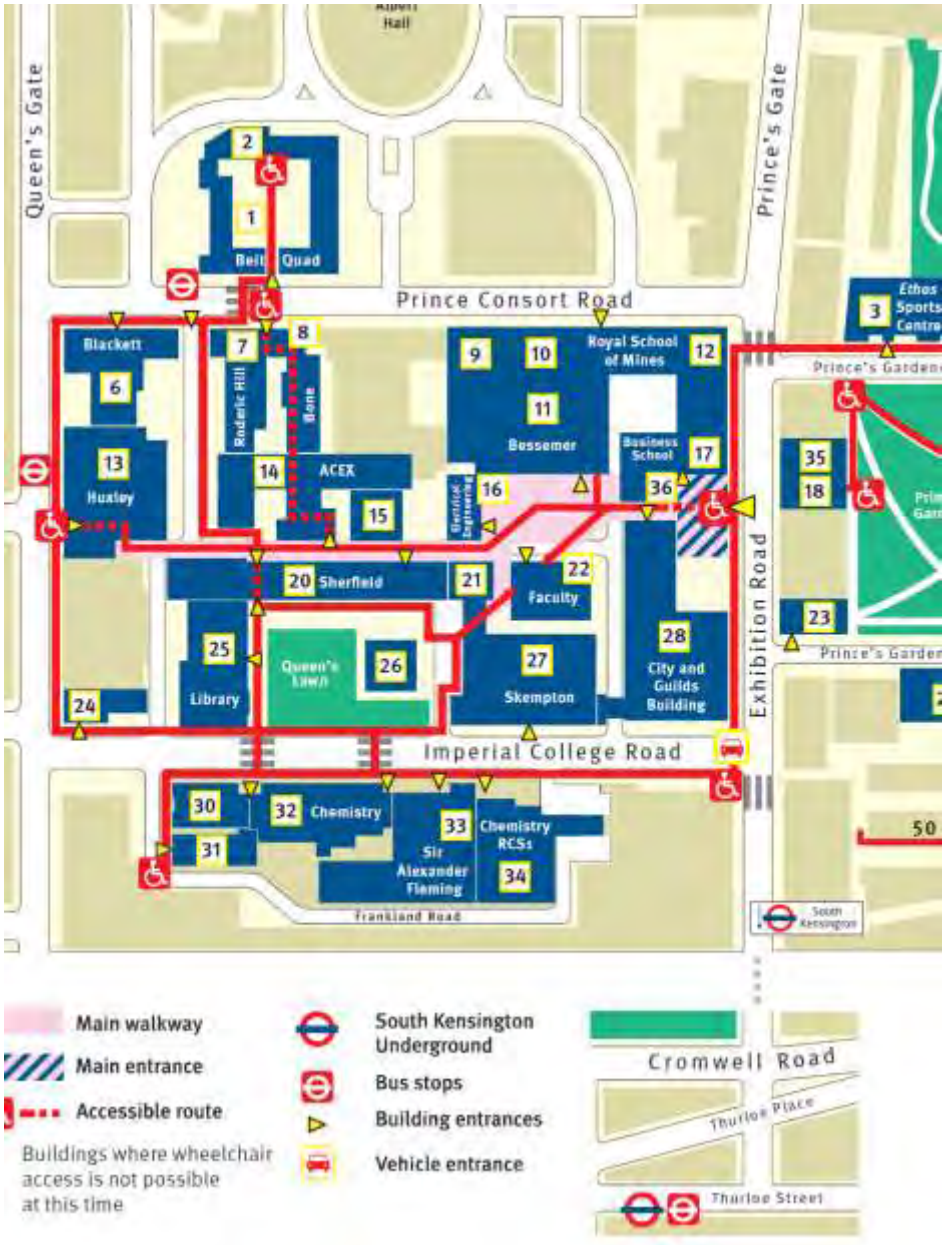


Transport – rocks and people

How to get to Imperial from Heathrow airport?

Direct simulation: use a shallow seismic image of the subsurface of London?!

London Underground map (the macro-pores) plus a local map (the micro-pores)

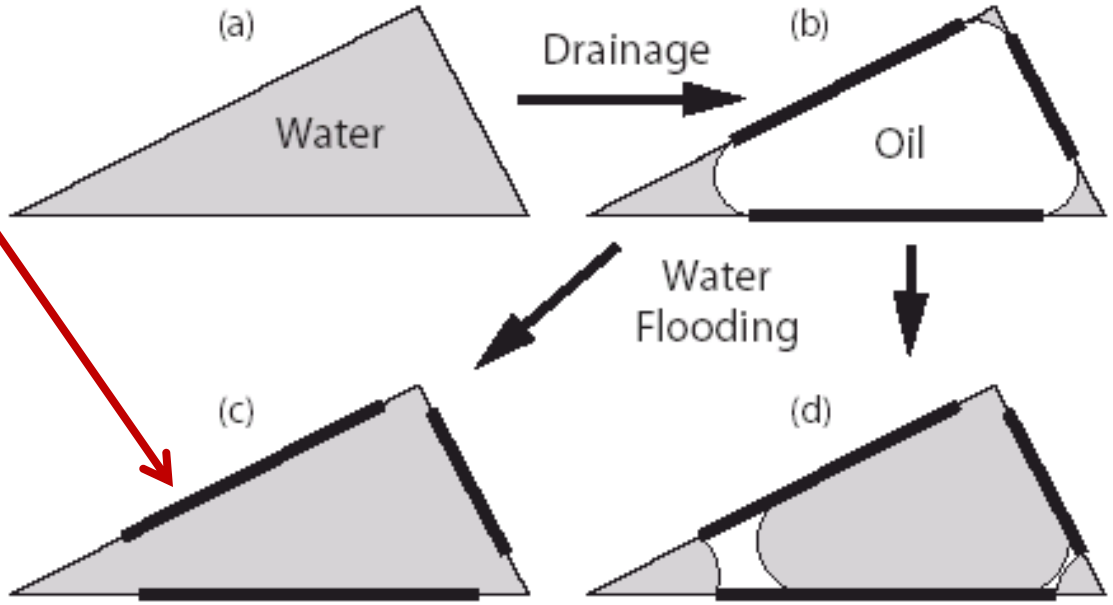


Waterflooding and wettability

Complex displacement sequences, shown here for a single idealized pore. What are the contact angles? Can now measure them *in situ*.

Altered wettability surfaces after primary drainage: mixed-wettability.

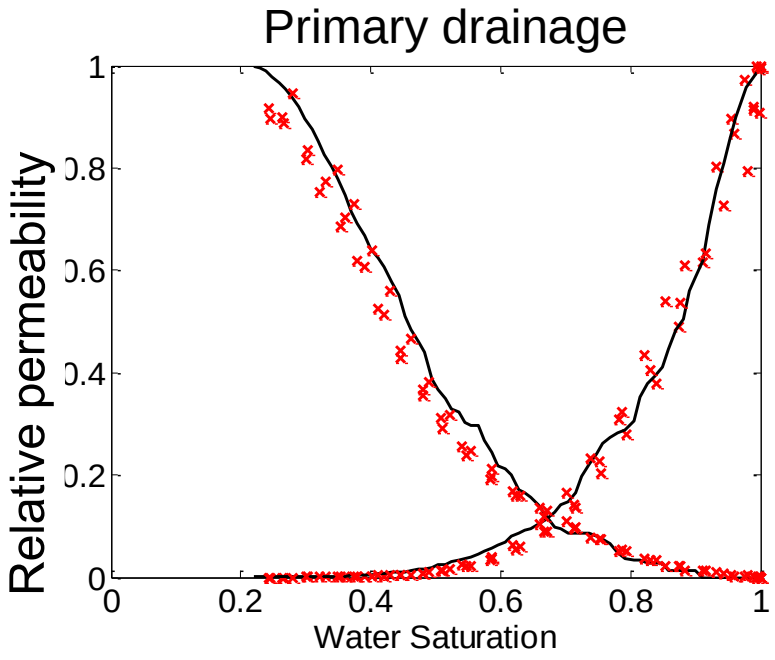
Relative permeability is governed by the interplay of displacement, structure and wettability, which can vary across the field

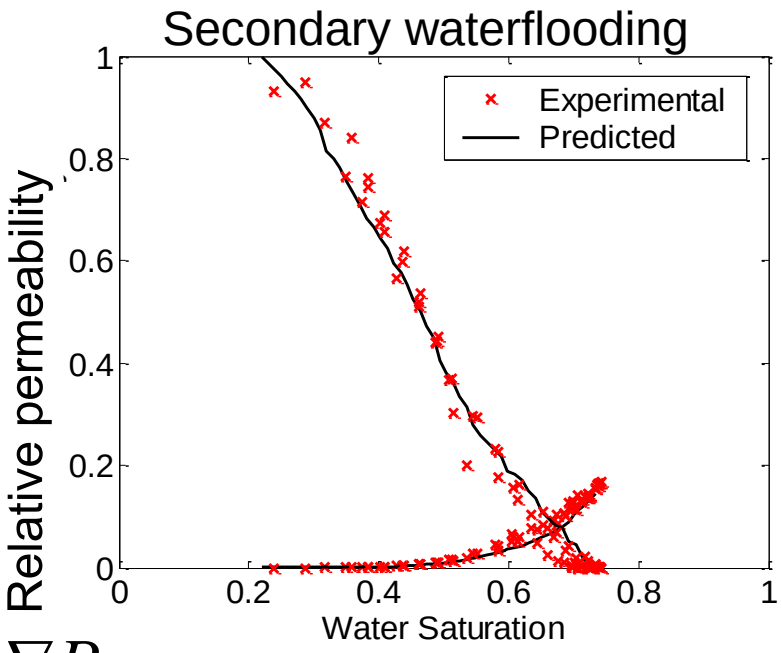


Water-wet two-phase predictions

Experimental data from Berea sandstone cores (Oak, 1990)

- No tuning of network (Øren and Bakke, 2003) necessary
- The fluids are water and oil
- Water-wet data – predictions made with θ_a = [50°, 80°]





$$q_p = -\frac{Kk_{rp}}{\mu_p}\nabla P_p$$

Valvatne and Blunt, *Water Resources Research* (2004)

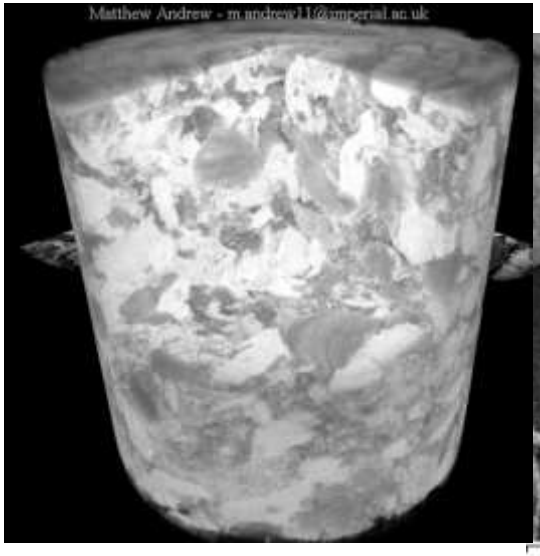
The tyranny of scale

Typically have a million-fold variation in length scale, from 10 nm for the smallest micro-pores to cms for whole cores.

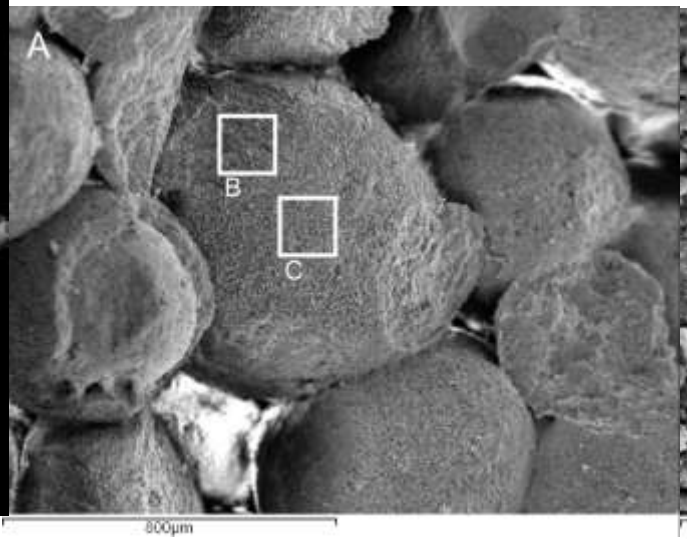
Need to upscale.

No one method can capture complex displacement processes over this range of scales.

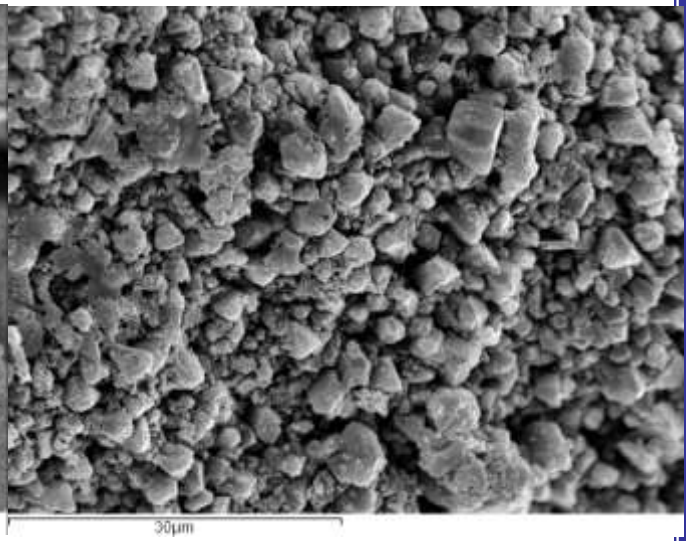
Whole core – 1 cm



Macro pore - 1 mm

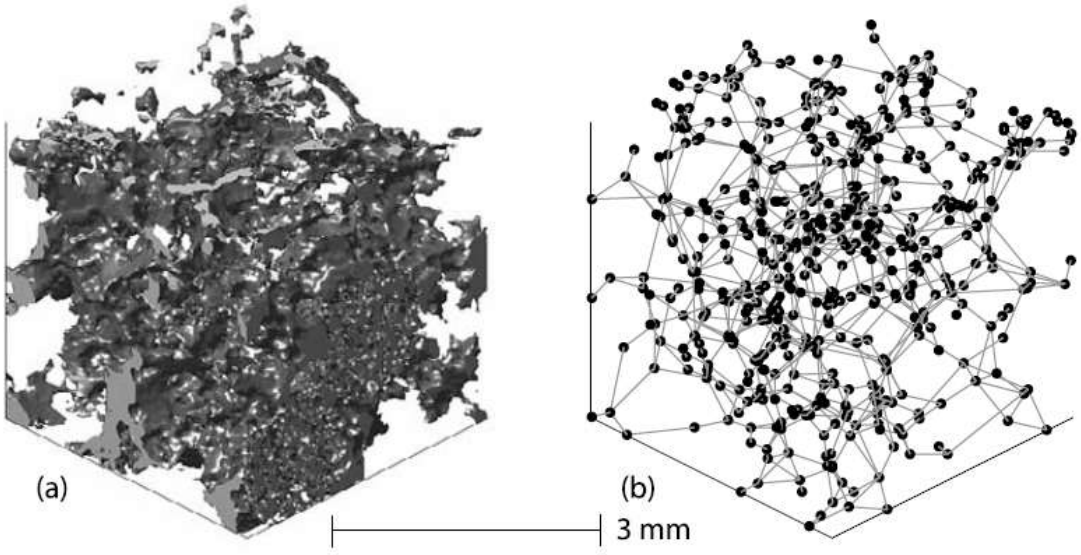


Micro pore - 10 µm



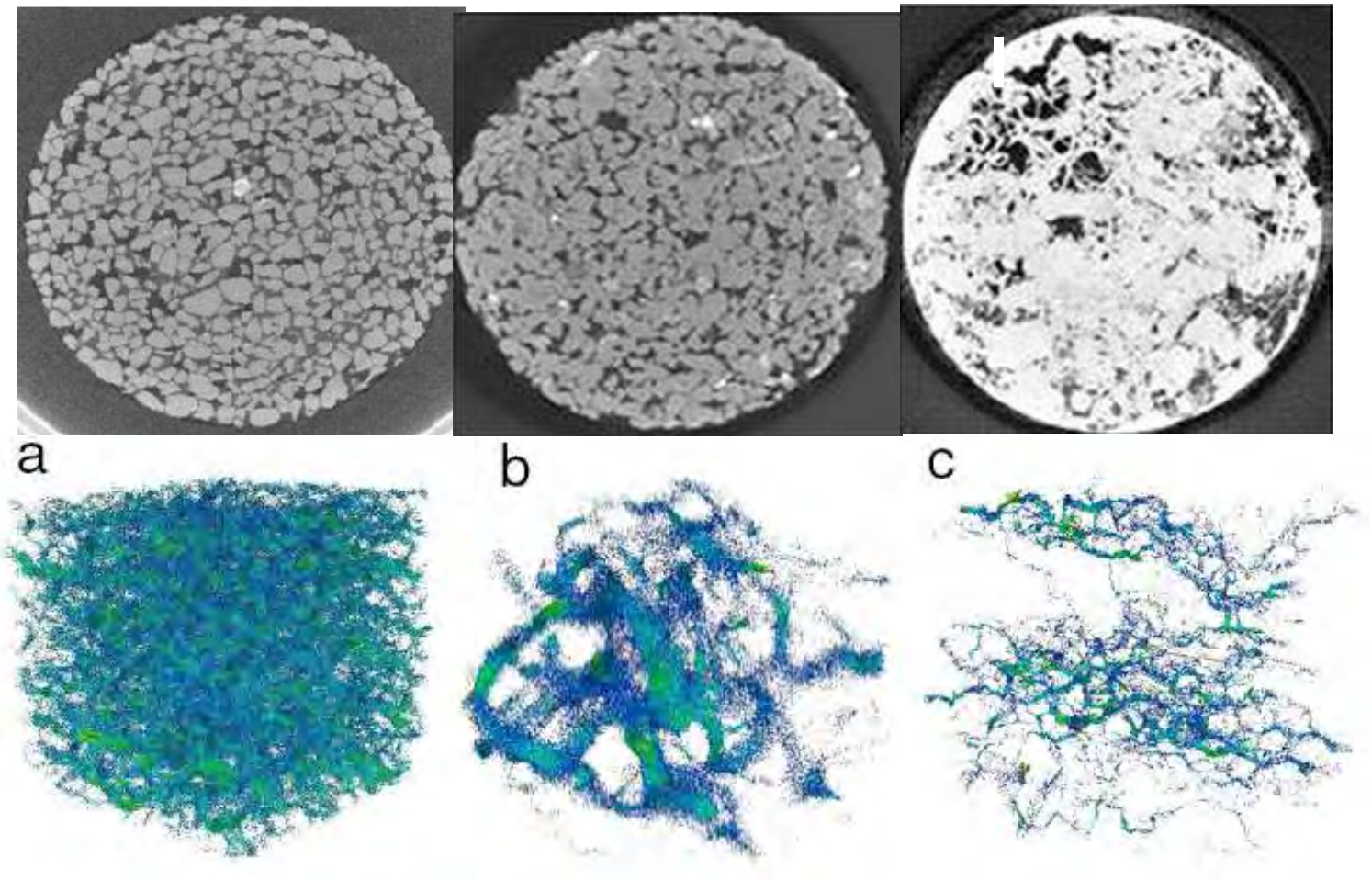
Direct simulation and networks

- Cannot compute multiphase flow directly on images that can resolve the smallest pores, and processes within them.
- Direct simulation would require of order 10^{21} grid blocks. No, not even the fastest in-the-future computer will ever be able to do this.
- Need to combine methods: direct simulation for pore-scale events, “simple” images; network modelling to upscale behaviour and capture the correct displacement sequence.



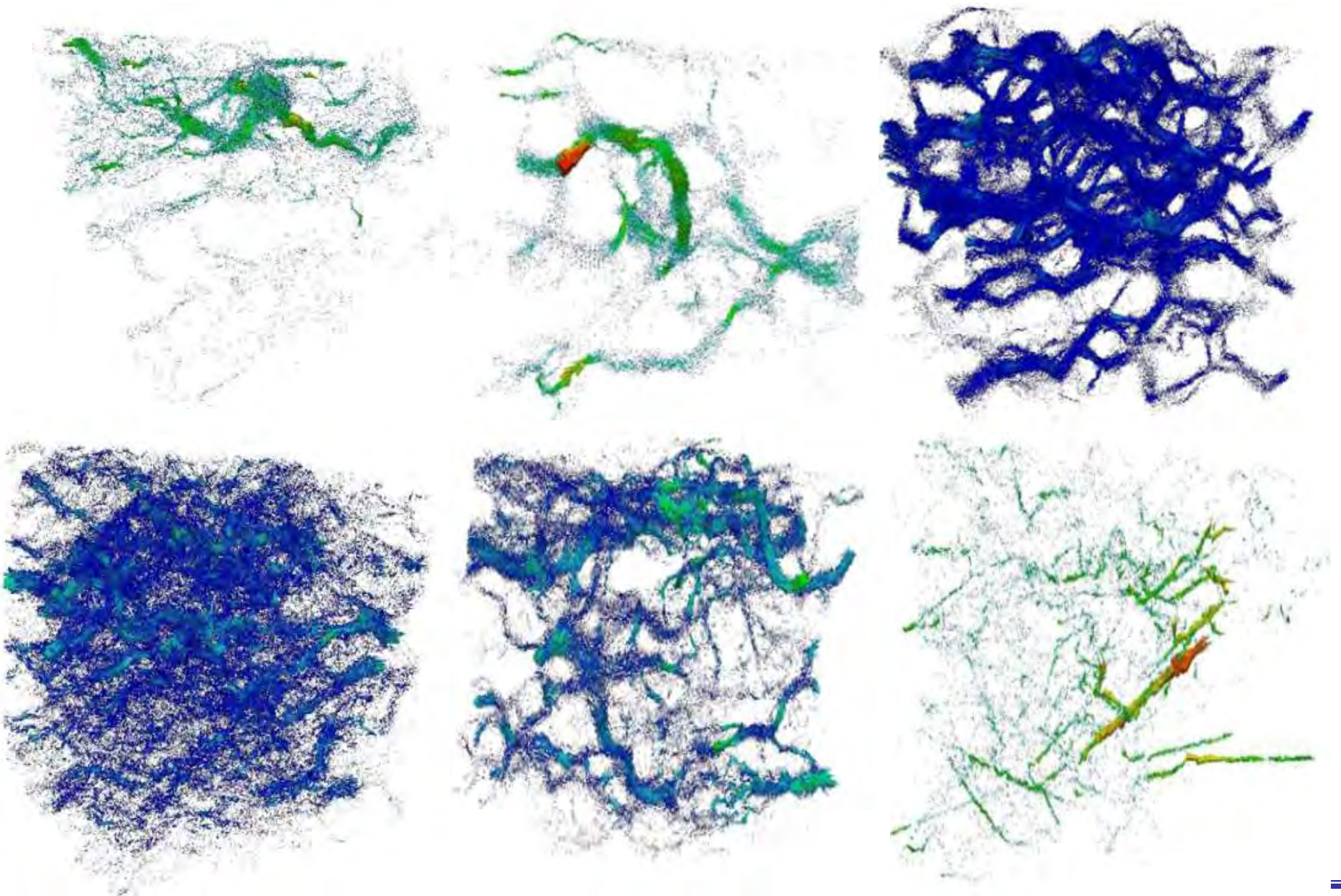
Back to the science - dispersion

Direct simulation on the pore-space images.
Stokes solver, streamline tracing, random motion for diffusion.



Sandpack Sandstone (Bentheimer) Carbonate (Portland)

Carbonate images and flow fields

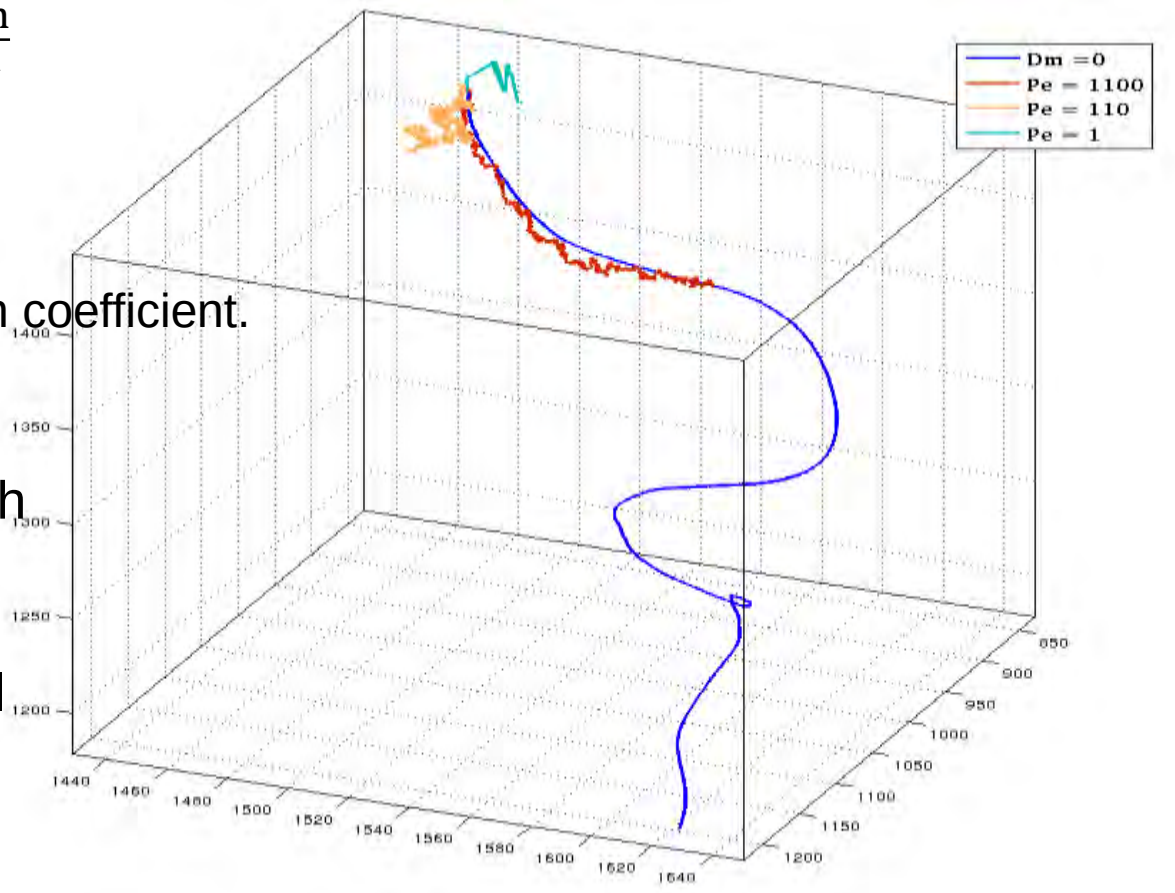


Particle trajectories in the pore space

$$Pe = \frac{vL}{D_m} = \frac{\text{advection}}{\text{diffusion}}$$

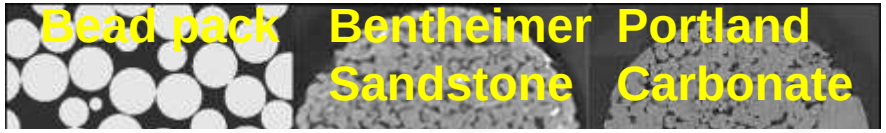
v = velocity;
L = grain/pore size;
D_m = molecular diffusion coefficient.

Combine analytical streamline tracing with a random hop to represent diffusion. Solute particles travel longer distances for larger *Pe* number.

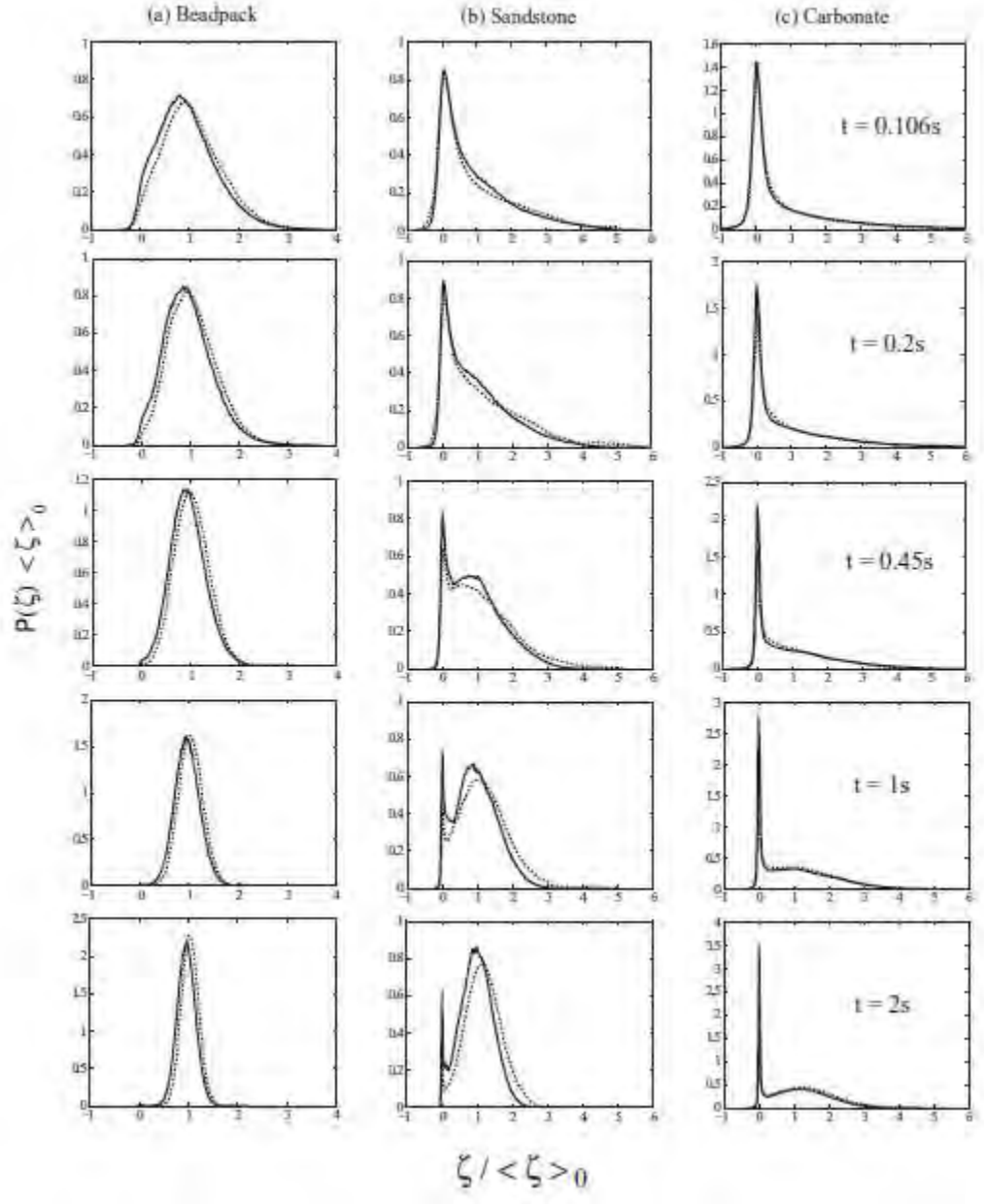


Include reaction by allowing particles within a diffusion distance to react, including solid. Probability of reaction relates to reaction rate.

Concentration profiles



Time



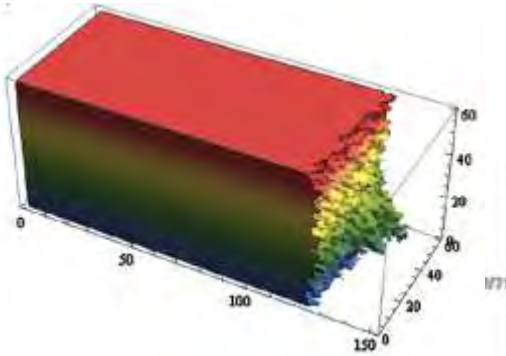
Compare prediction of concentration vs. distance for different times and rock types against NMR experiments.

Can make first principles predictions once the pore geometry is imaged.

Bijeljic *et al.* PRL (2011); PRE (2013); WRR (2013).

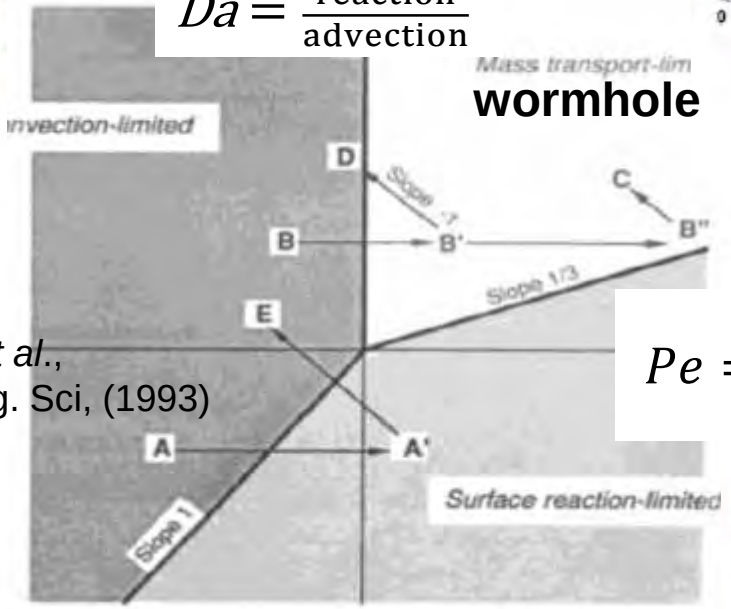
Reaction with the solid: Dissolution regimes

Compare pore-scale experiments and models. In the models if a particle hits solid in the diffusive step, dissolve solid after a given number of hits: determines reaction rate.

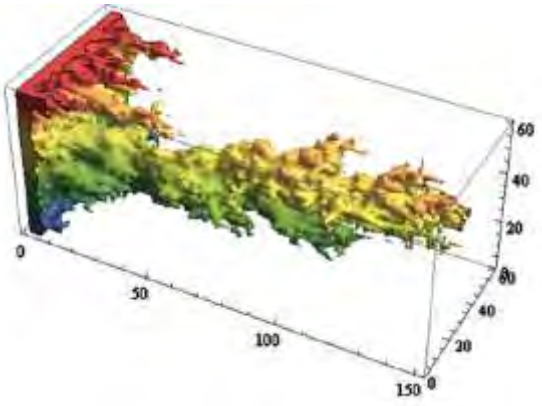


compact

$$Da = \frac{\text{reaction}}{\text{advection}}$$



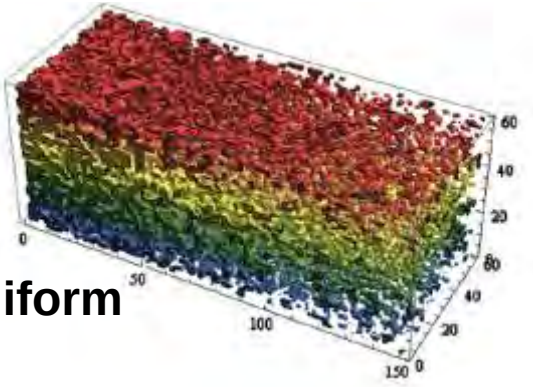
Daccord *et al.*,
Chem. Eng. Sci, (1993)



wormhole

Maheshwari *et al.*,
Chem. Eng. Sci, (2013)

$$Pe = \frac{vL}{D_m} = \frac{\text{advection}}{\text{diffusion}}$$

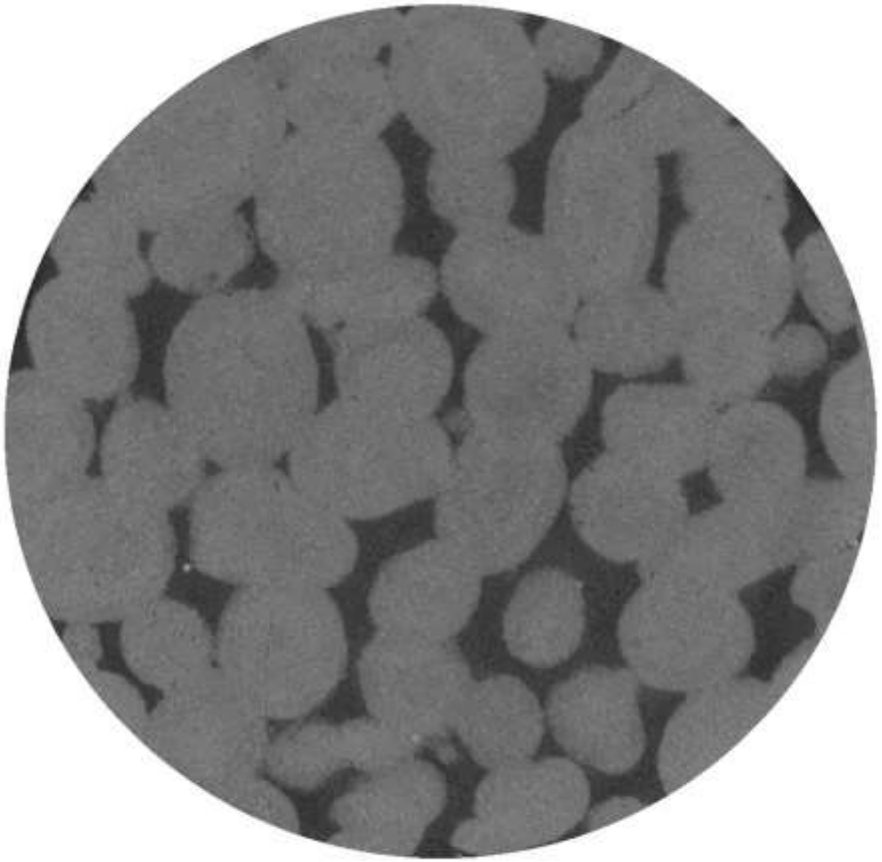


uniform

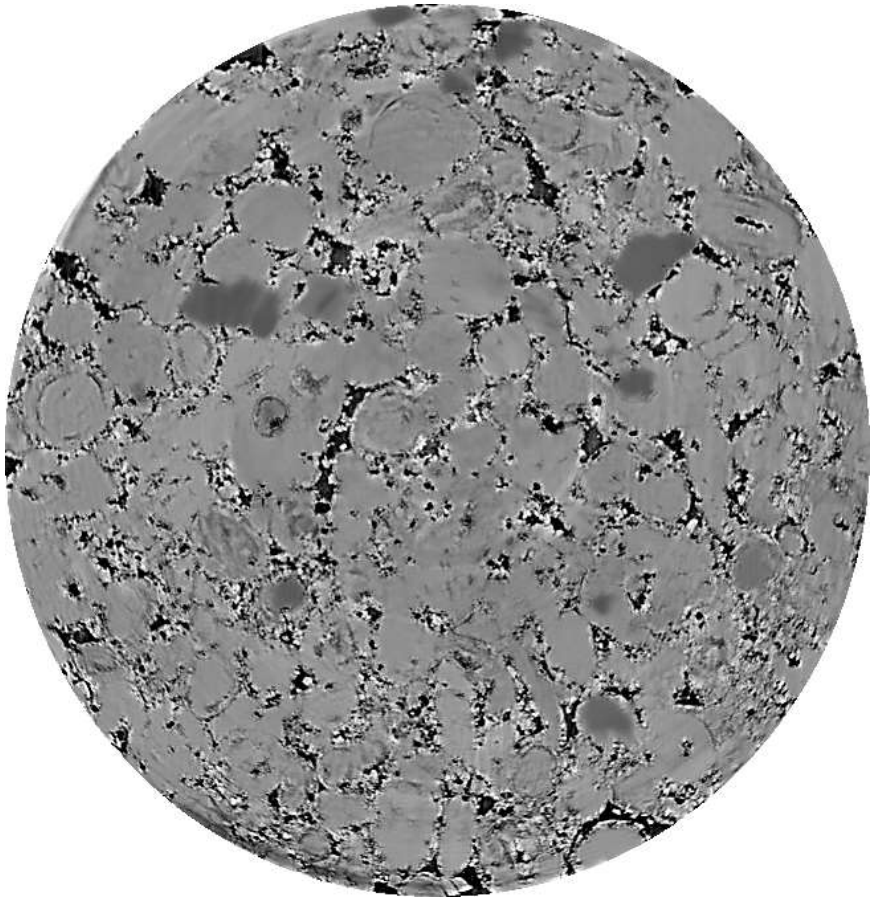
Pore-scale dissolution experiments

Flow rate: 0.5 ml/min for 2.5 hrs [*Pe* ~10^3; Da ~10^{-4}]
Brine composition: 1% KCl 5% NaCl brine saturated with CO_2
at 10 MPa and 50^{o}C [pH=3.1]

Ketton carbonate - homogeneous



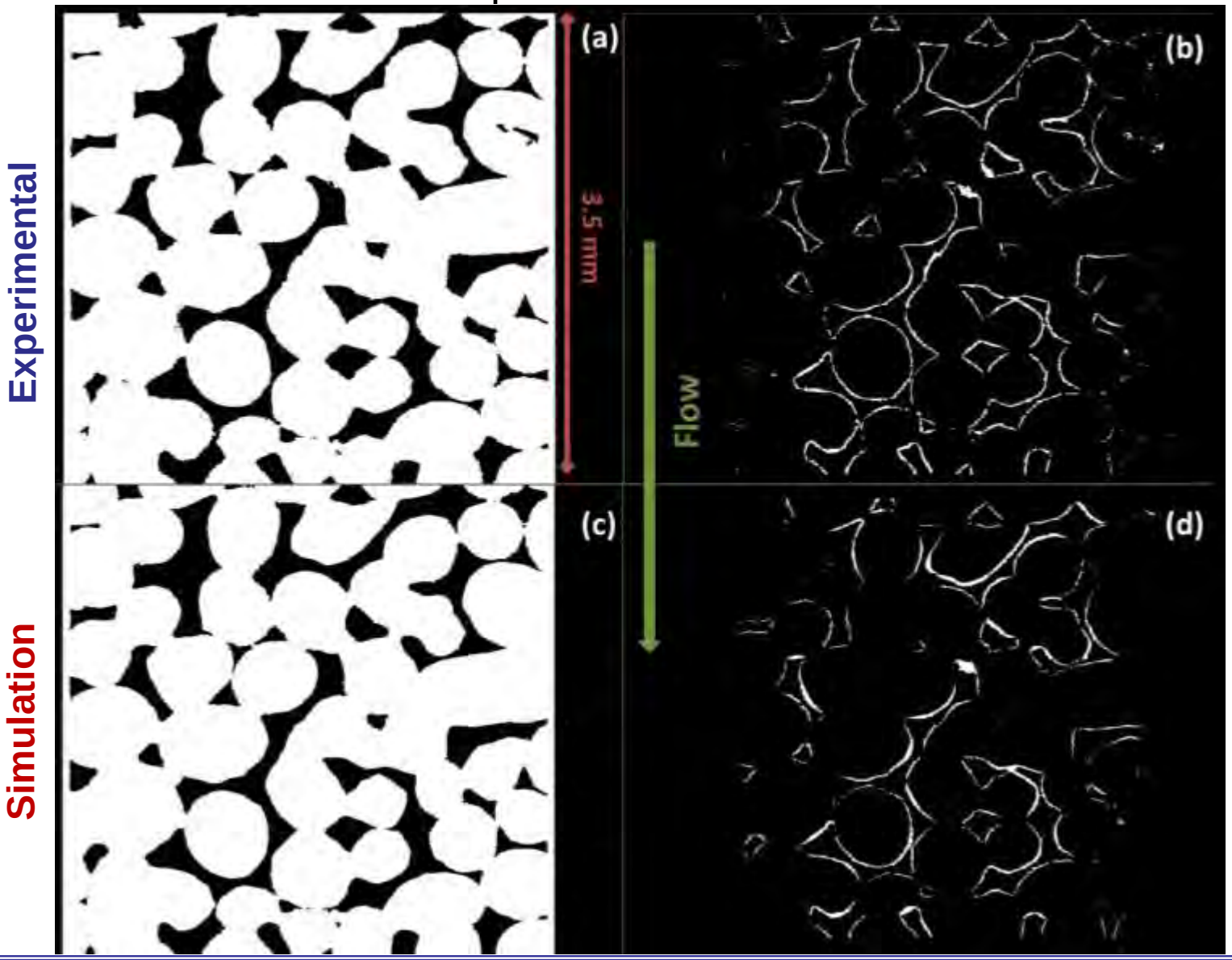
Portland carbonate - heterogeneous



Menke *et al.*, EST (2015)

Model vs. experiment

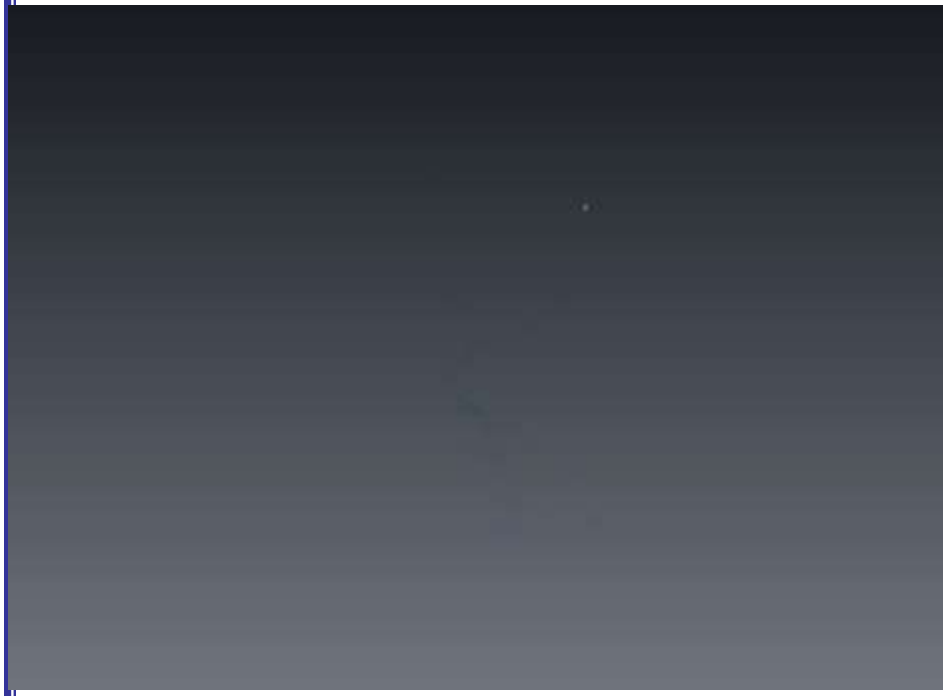
Dissolution – parallel to flow direction



Three-dimensional results (low flow rate)

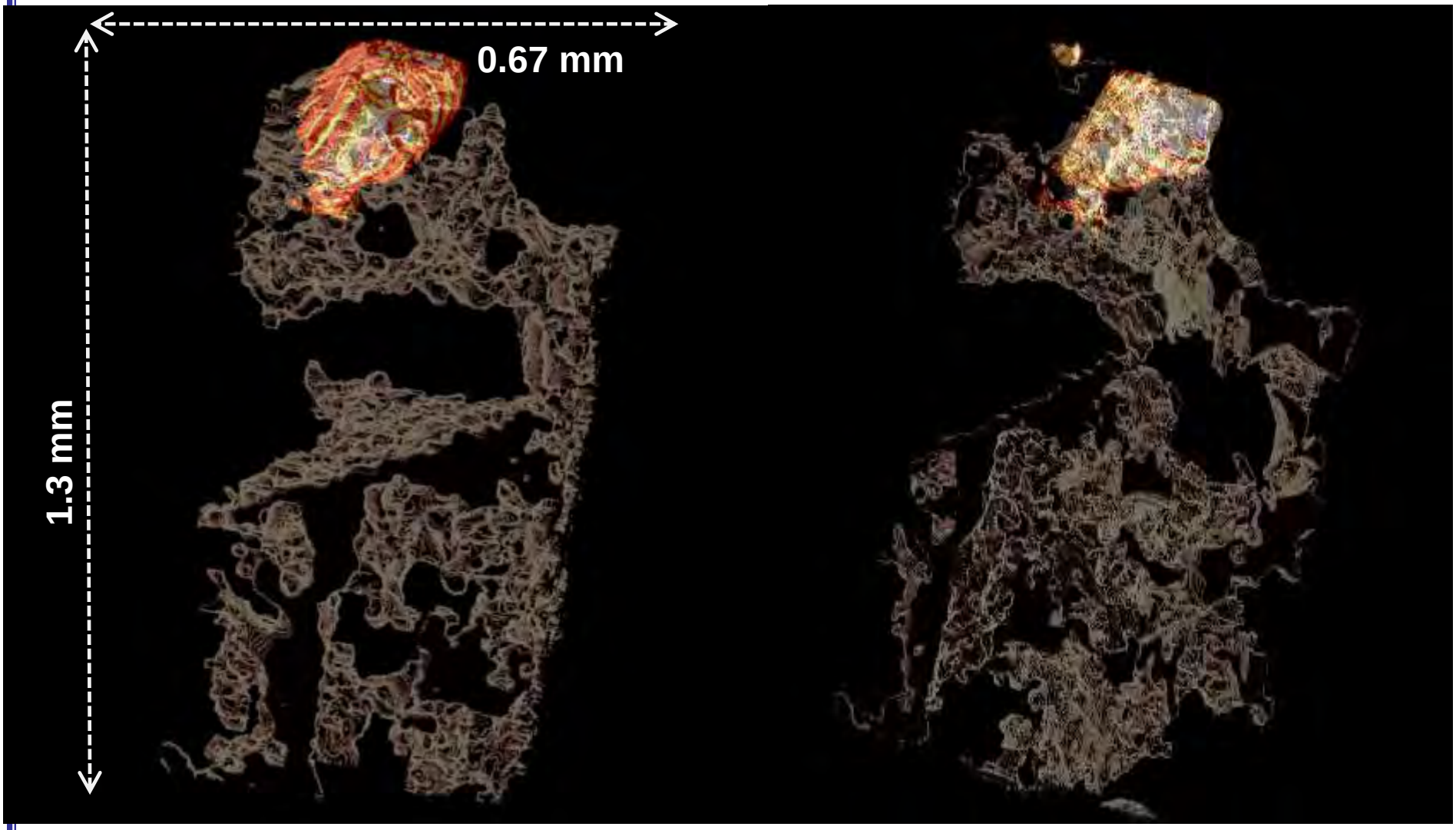
0.05 ml/min [*Pe* ~10^{2}; Da ~10^{-3}]

Ketton carbonate – chanelling



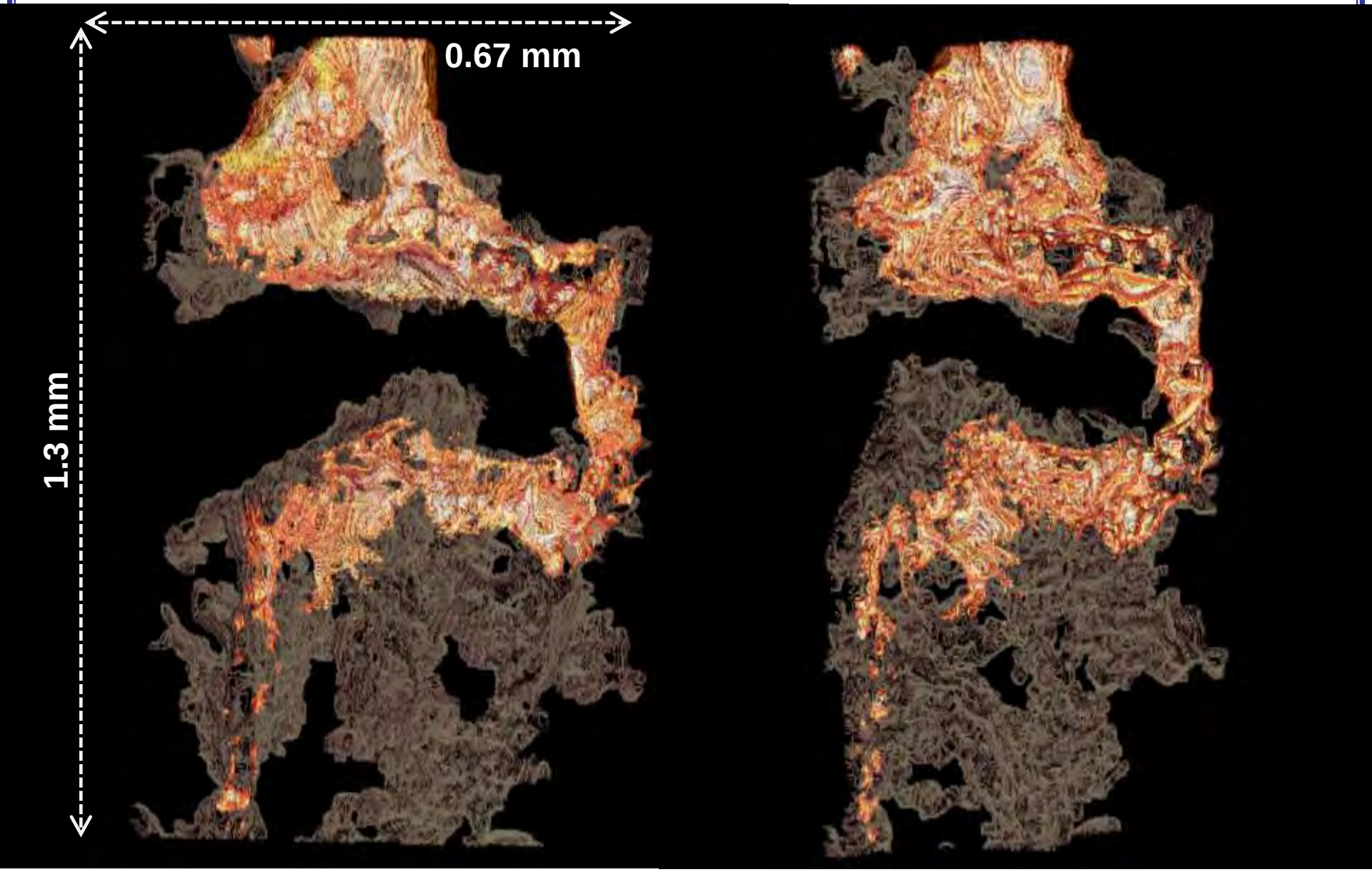
Portland carbonate – compact dissolution

Simulations: Estaillades *Pe*, *Péclet = 1, slow flow*

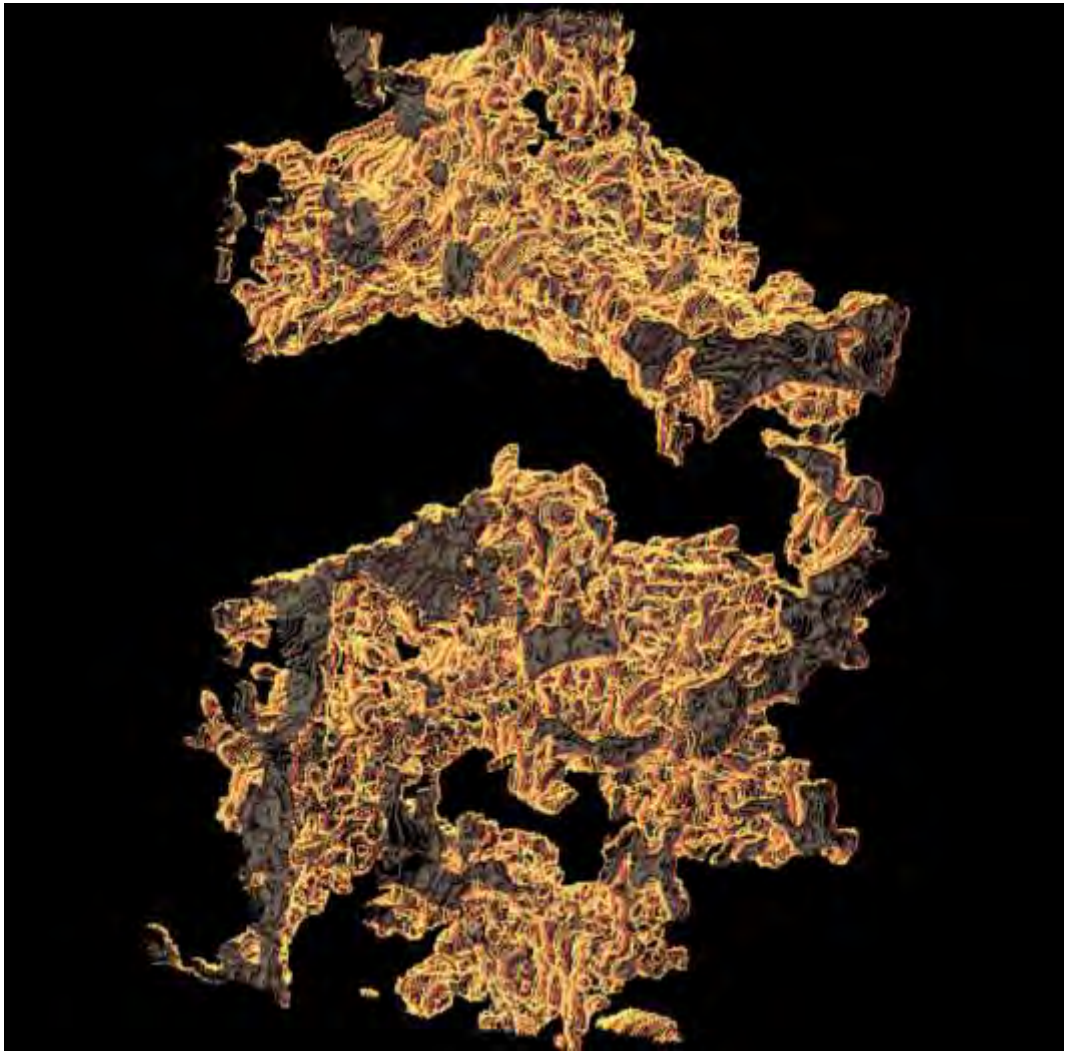


Small *Pe* regime only “face dissolution” - Whole grains are being dissolved
No significant impact in permeability.

Simulations: Estaillades *Pe*, *Péclet = 50*



Simulations: Estaillades ***Pe*, *Péclet = 280, fast flow***

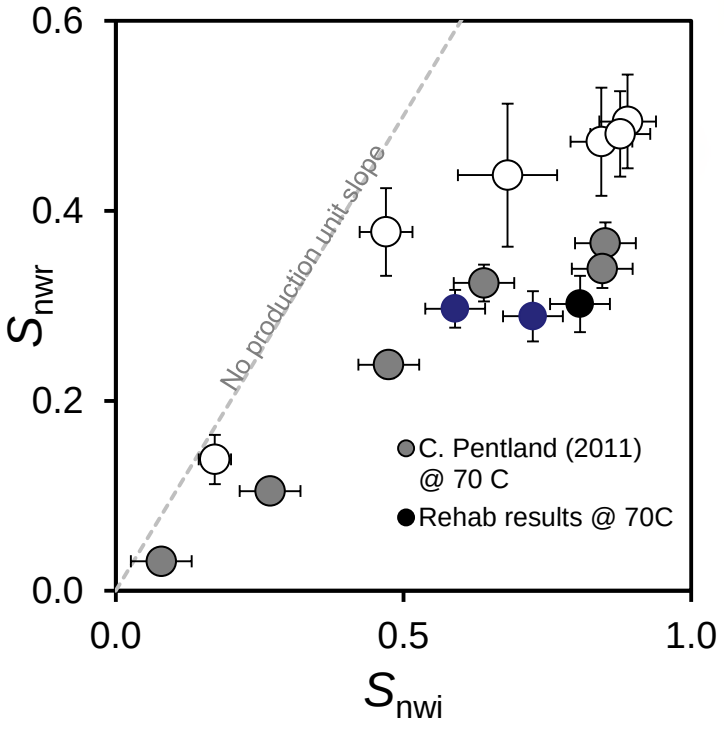


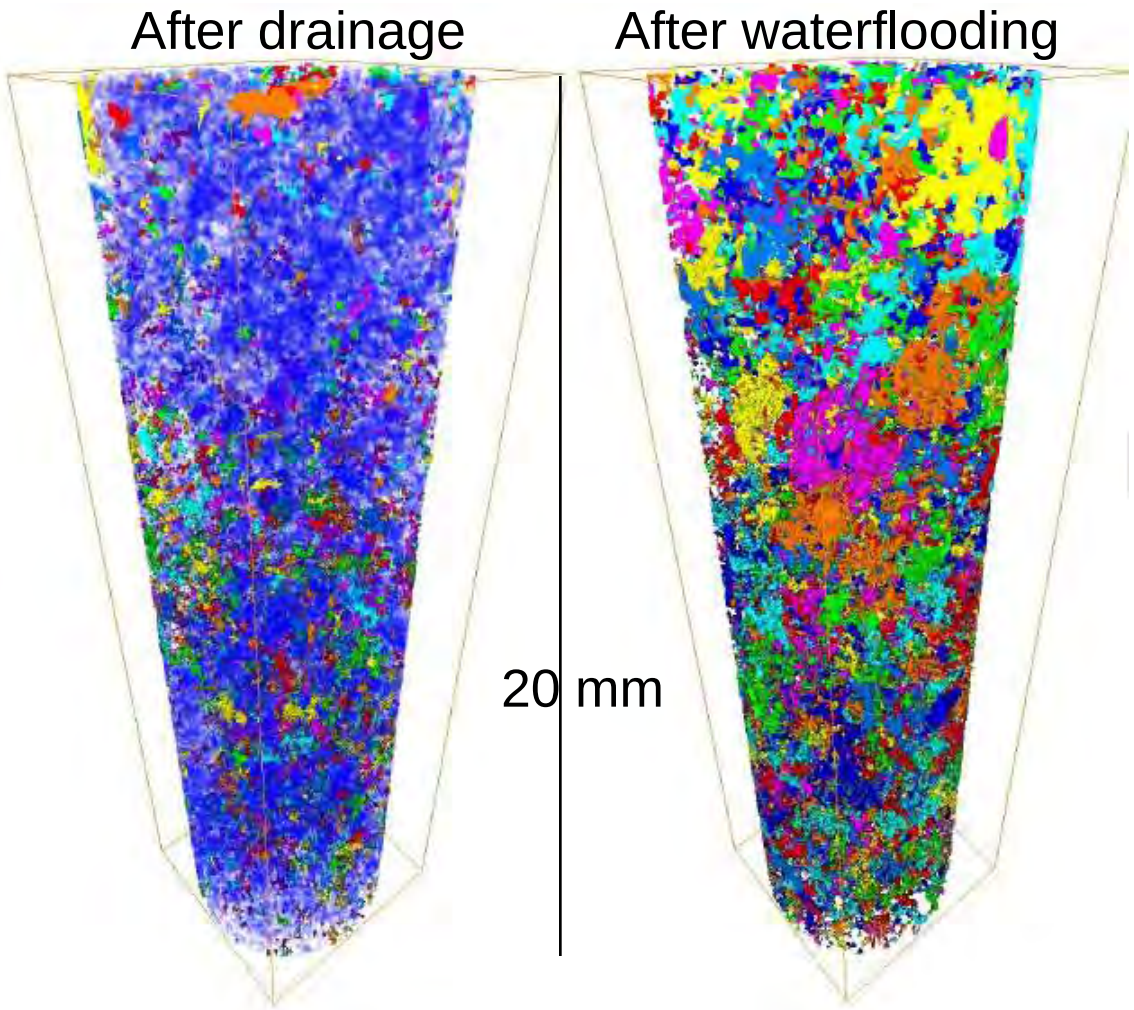
High *Pe* regime see more uniform dissolution, as the reactant can penetrate the rock before reacting. As seen experimentally.

Trapped CO_2 clusters – colour indicates size

How much is trapped and how much can be stored?

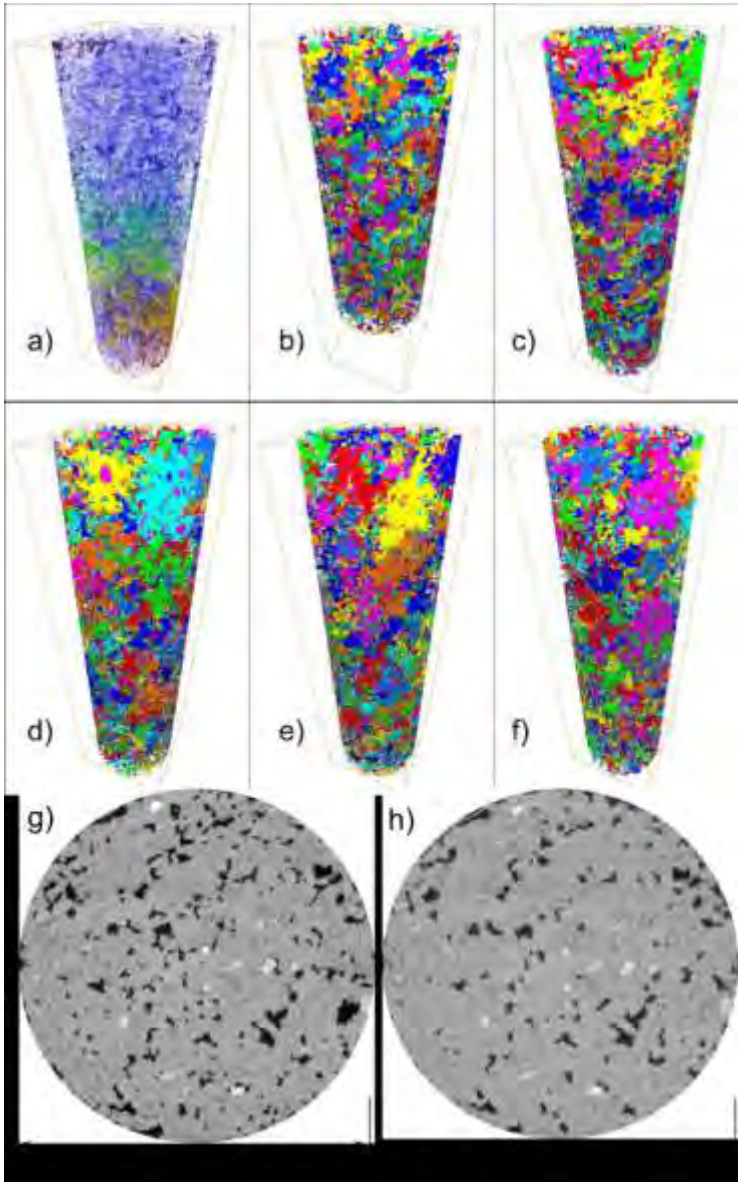
Results in sandstones (Doddington, Bentheimer and Berea).

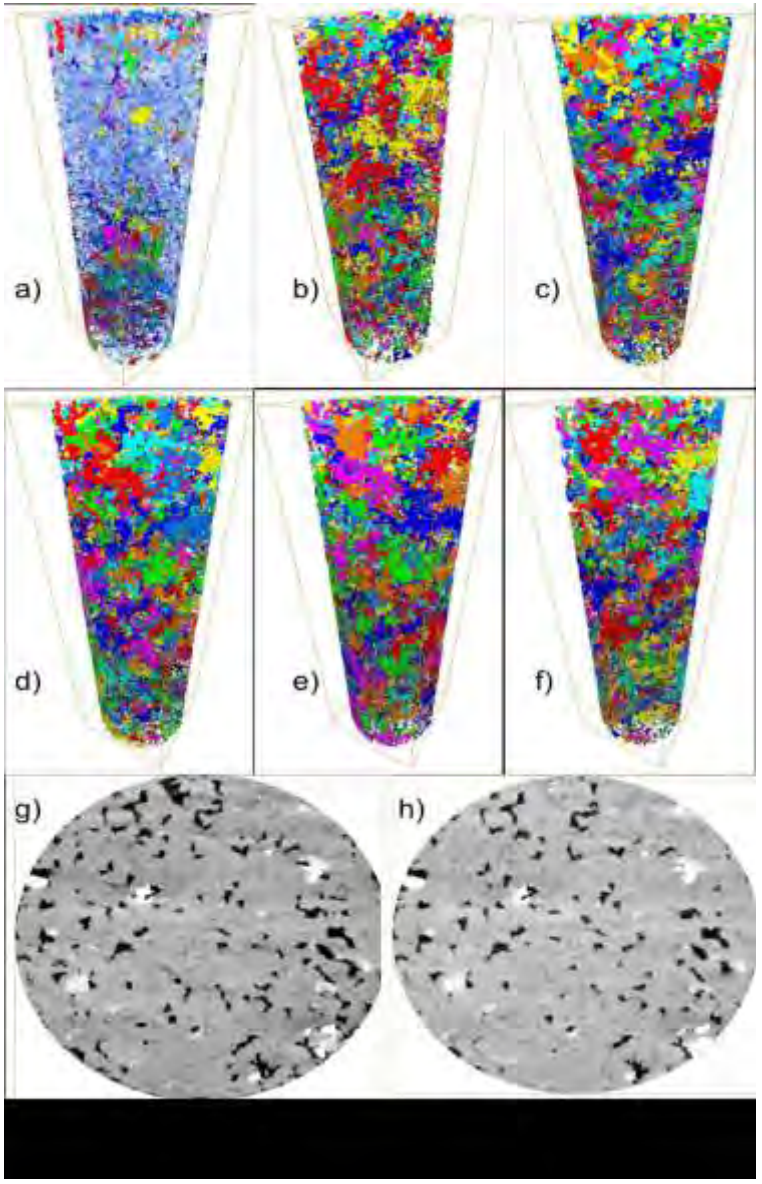




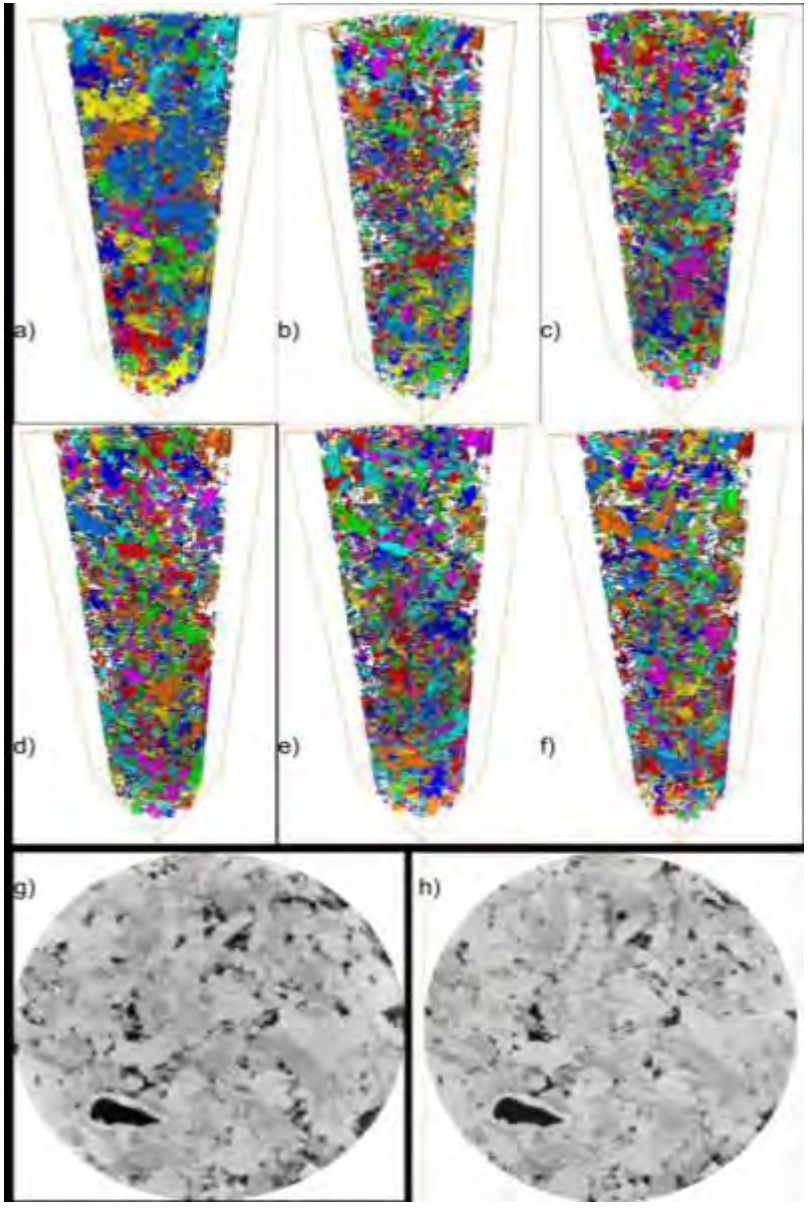
Pentland *et al., Geophysical Research Letters* (2011)

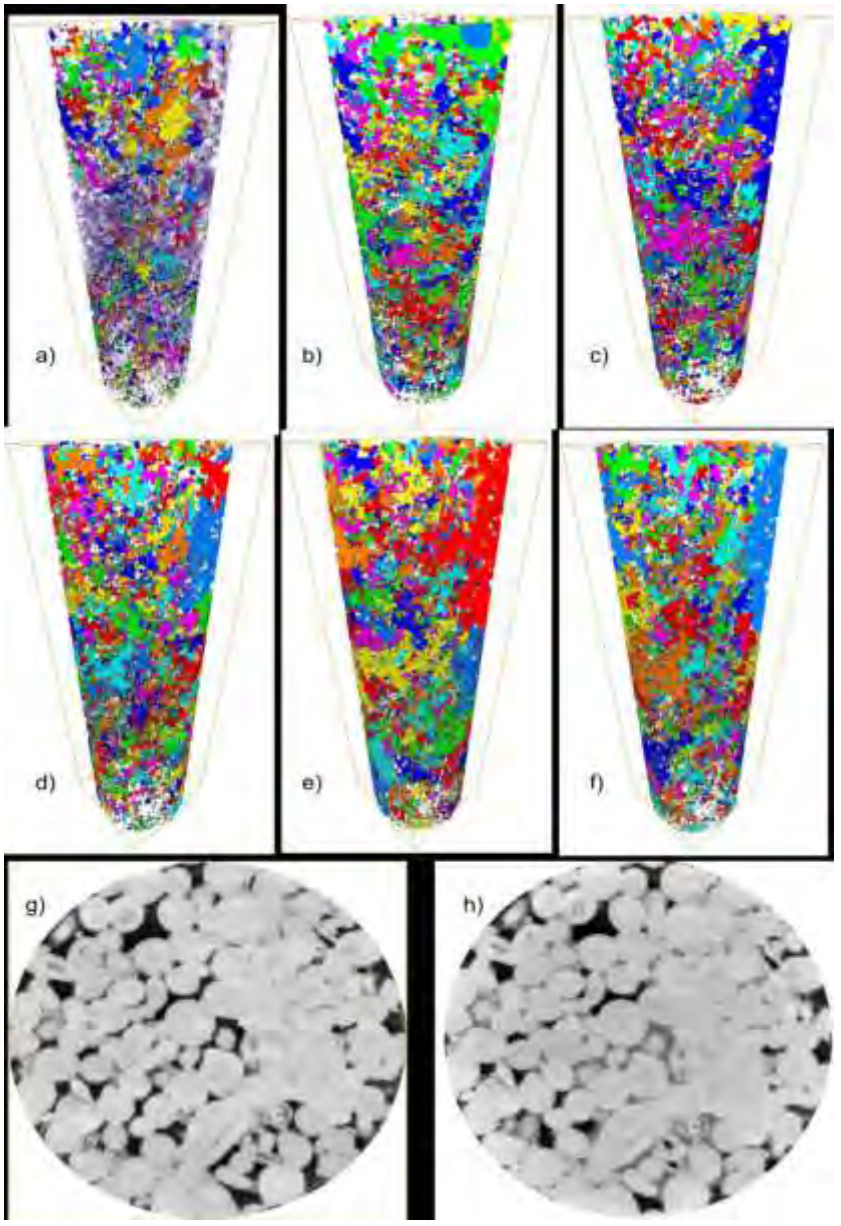
Can study many systems – Bentheimer and Doddington



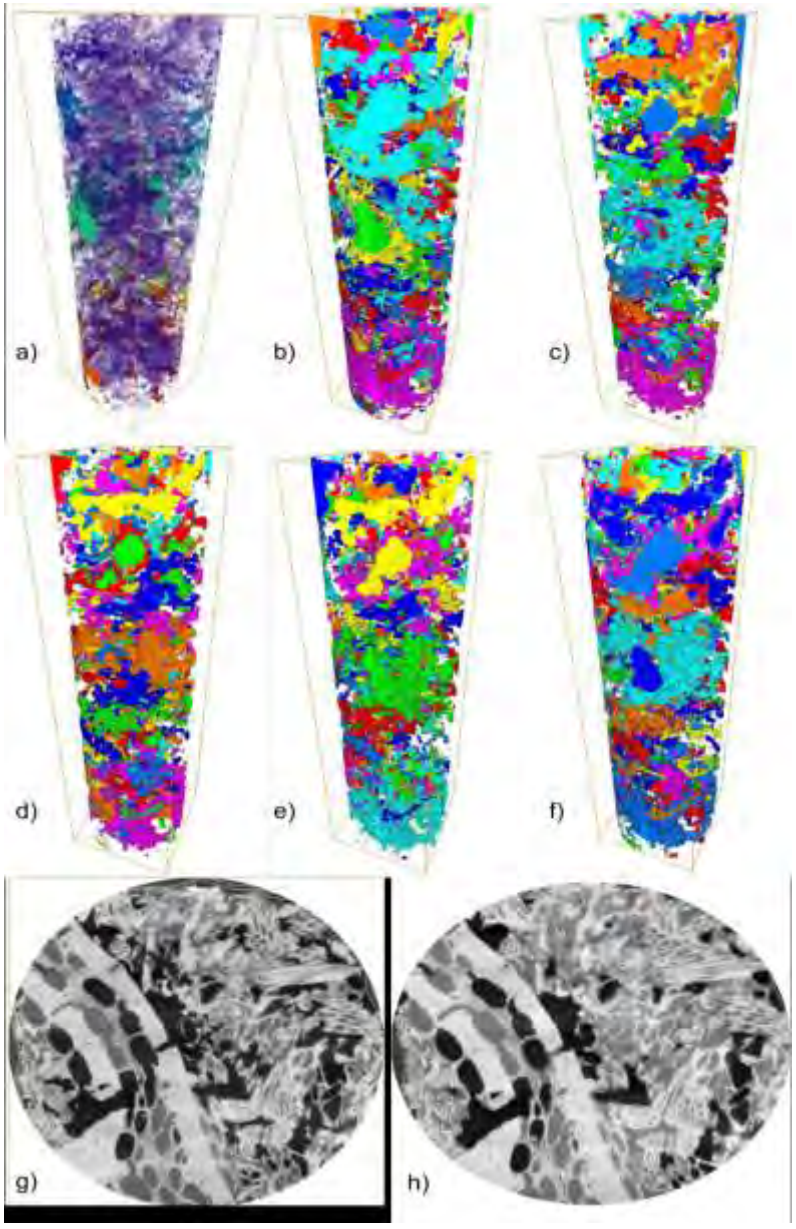


Can study many systems – Estaillades and Ketton





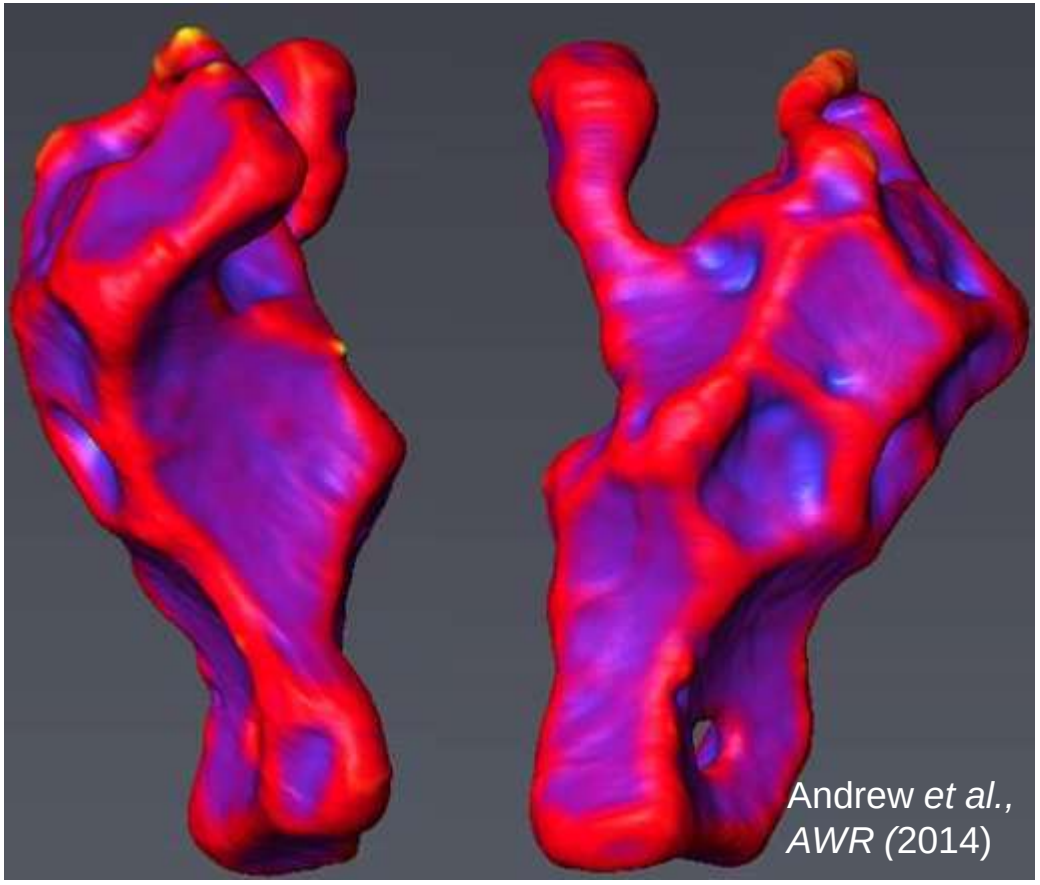
Can study many systems – Portland



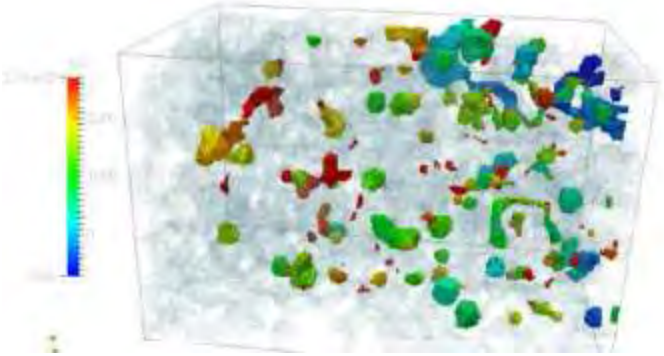
Andrew *et al.*, *Geophysical Research Letters (*2011); *IJGGC (*2014)

Curvature, contact angle and validation

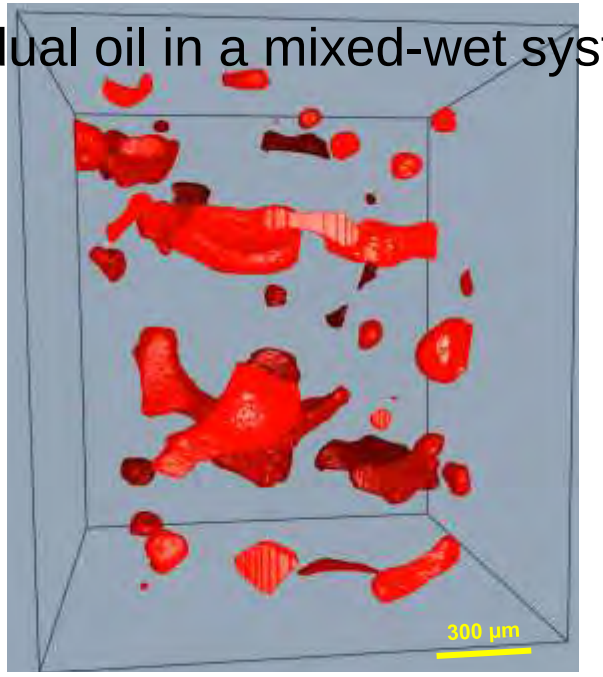
Can also use high-resolution images to determine: curvature – capillary pressure, and local pressure for each ganglion; and surface contacts to determine contact angles.



Direct simulation (volume of fluid) of trapping

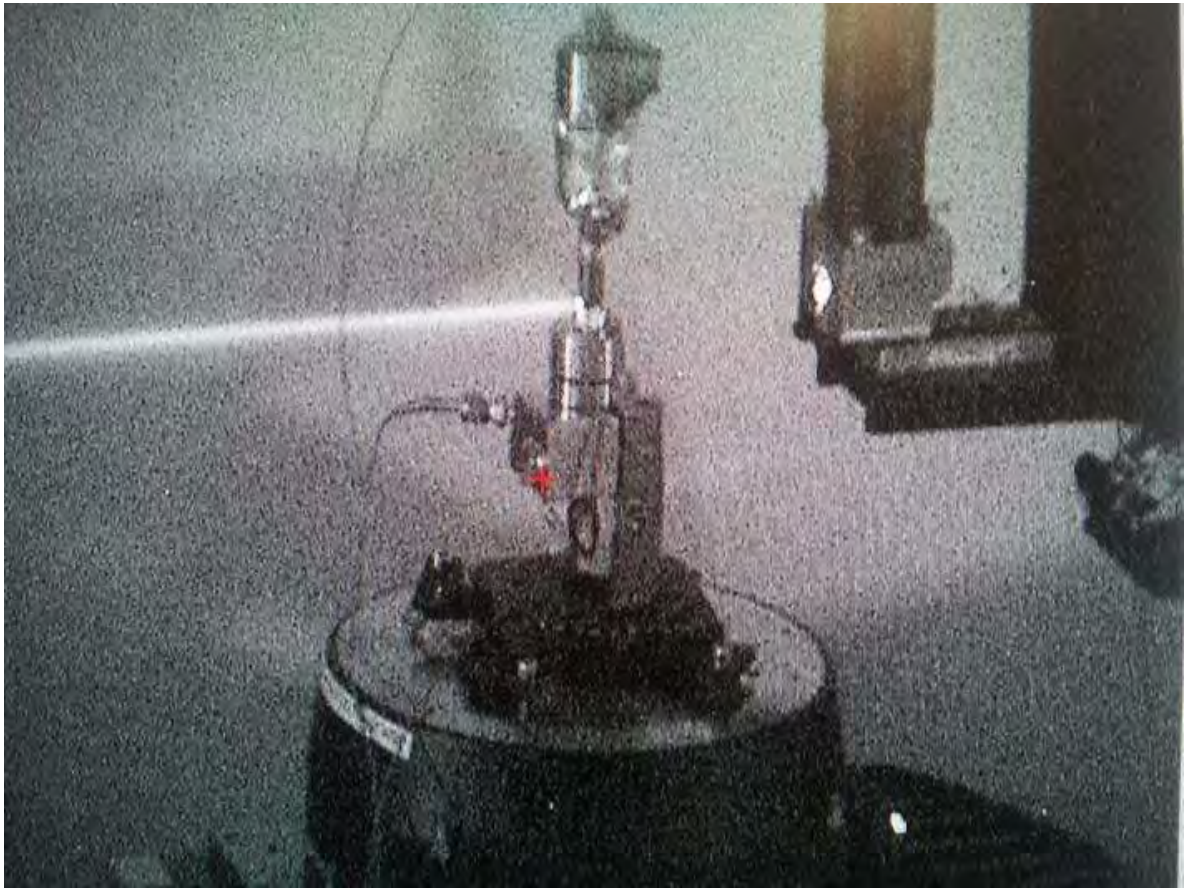


Residual oil in a mixed-wet system



Measurement of contact angle

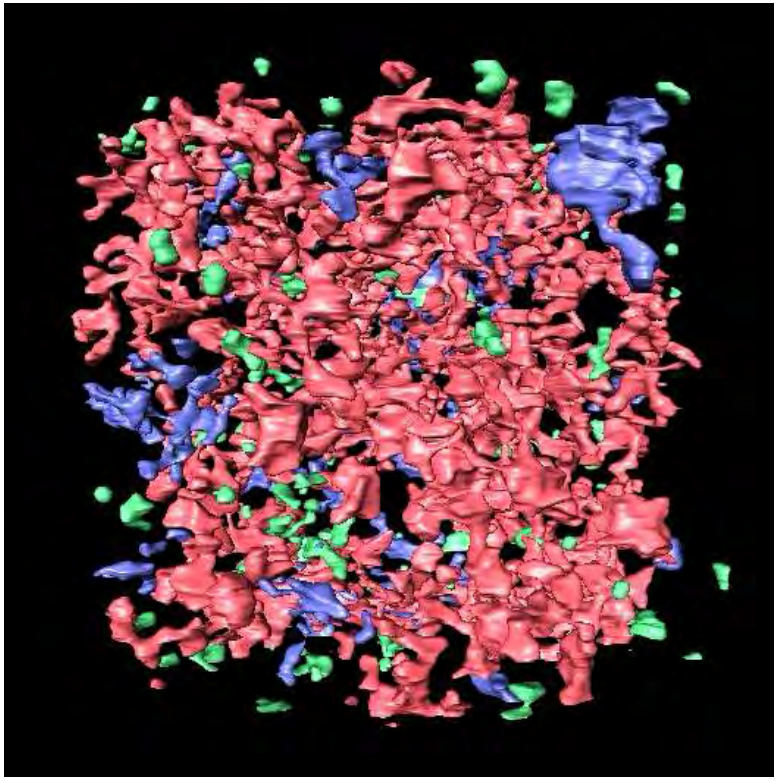
Dynamic Tomography at Synchrotron Sources



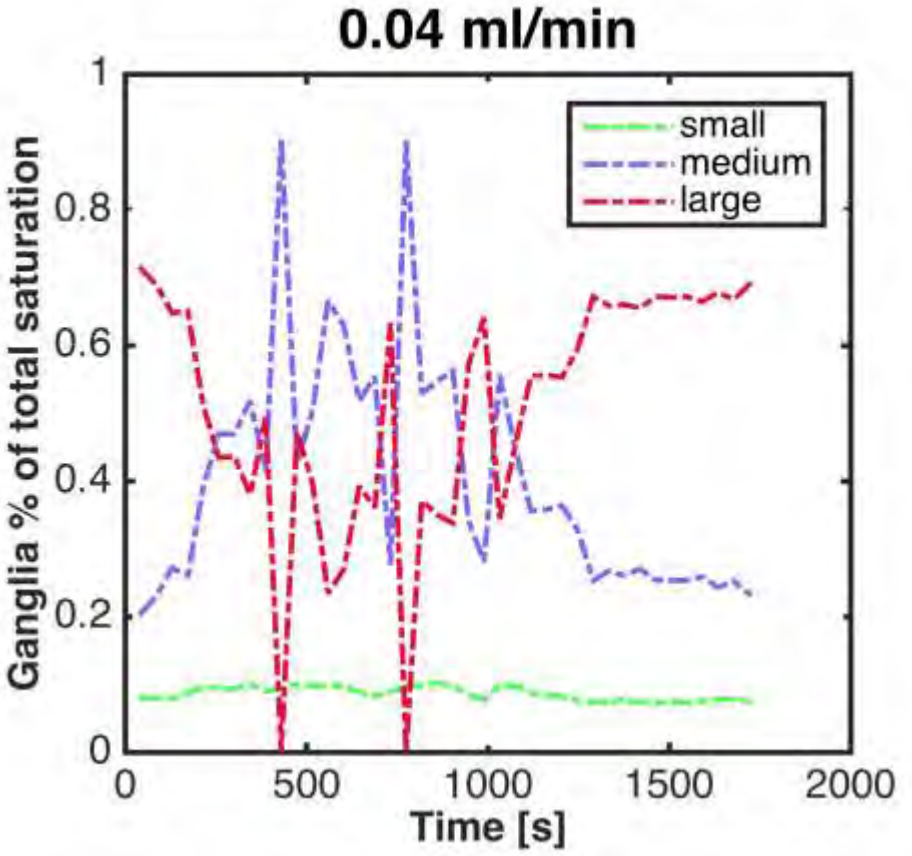
Synchrotron Experimental Team:

Matthew Andrew
Hannah Menke
Cat Reynolds
Kamal Singh
Branko Bijeljic
Martin Blunt

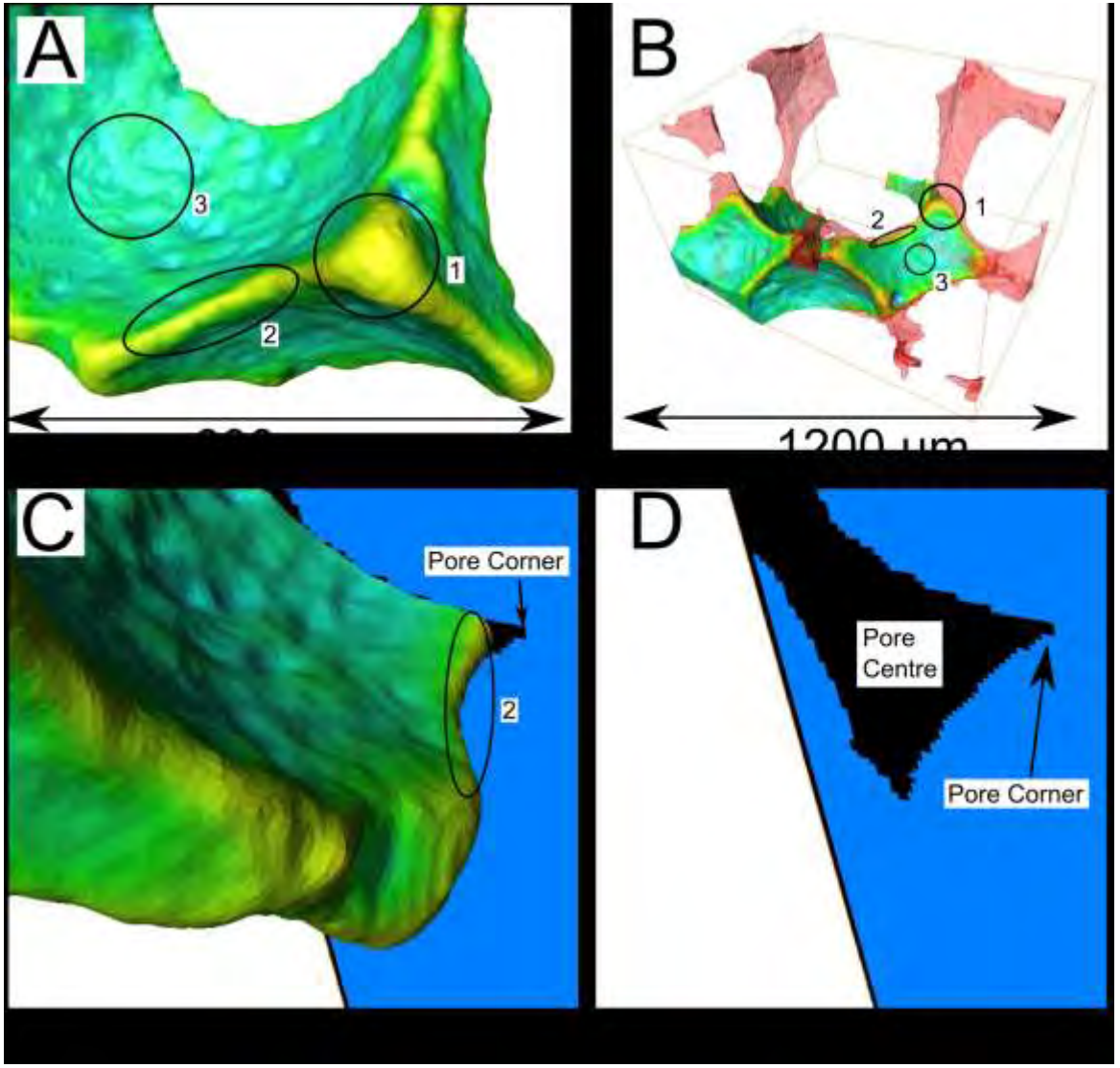
Connected pathway and ganglia flow



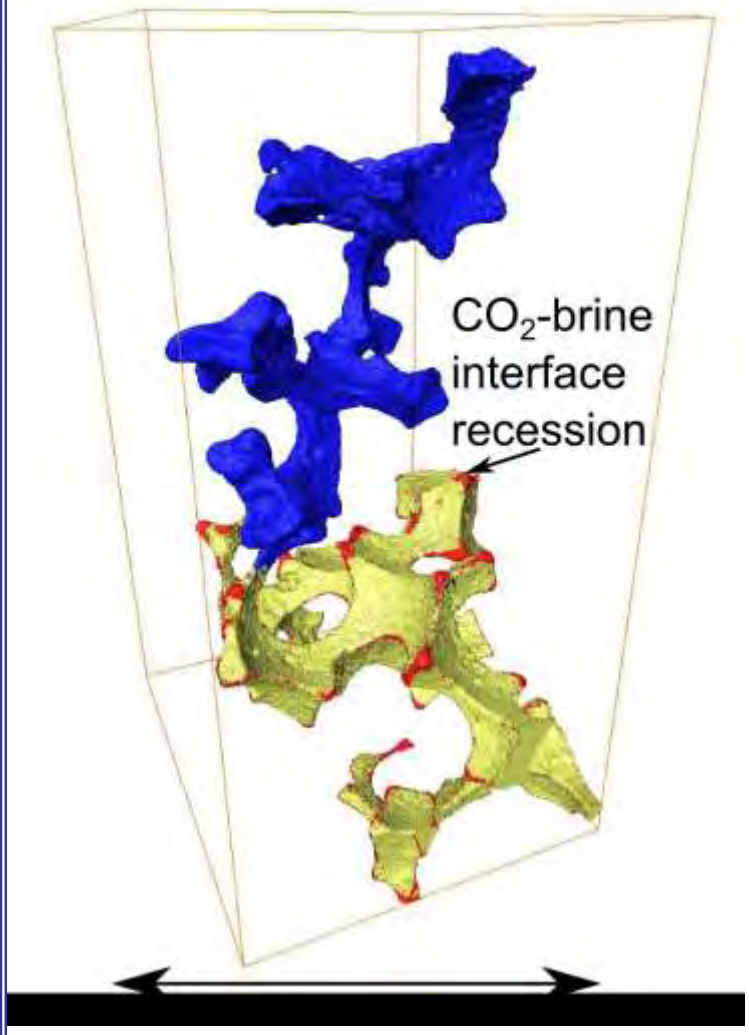
Scan time ≈ 20 s, Time step = 43 s,
10 PV

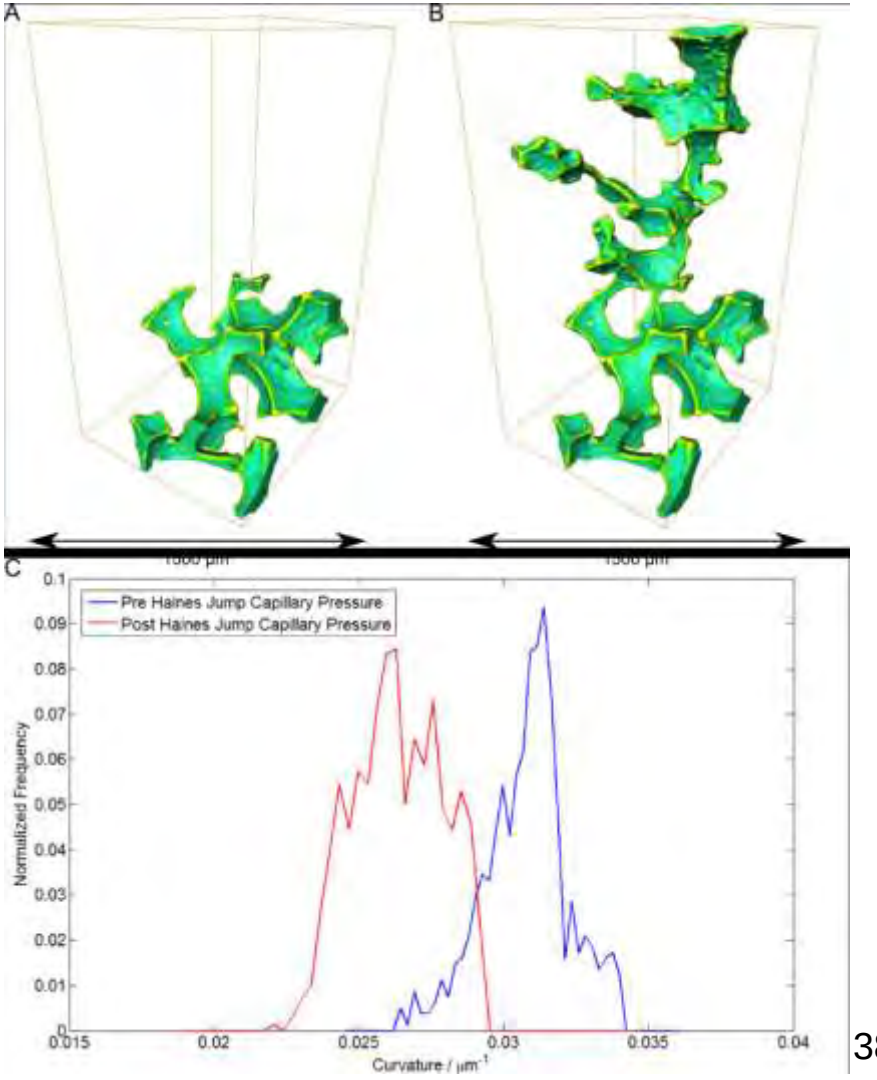


Interfacial curvature

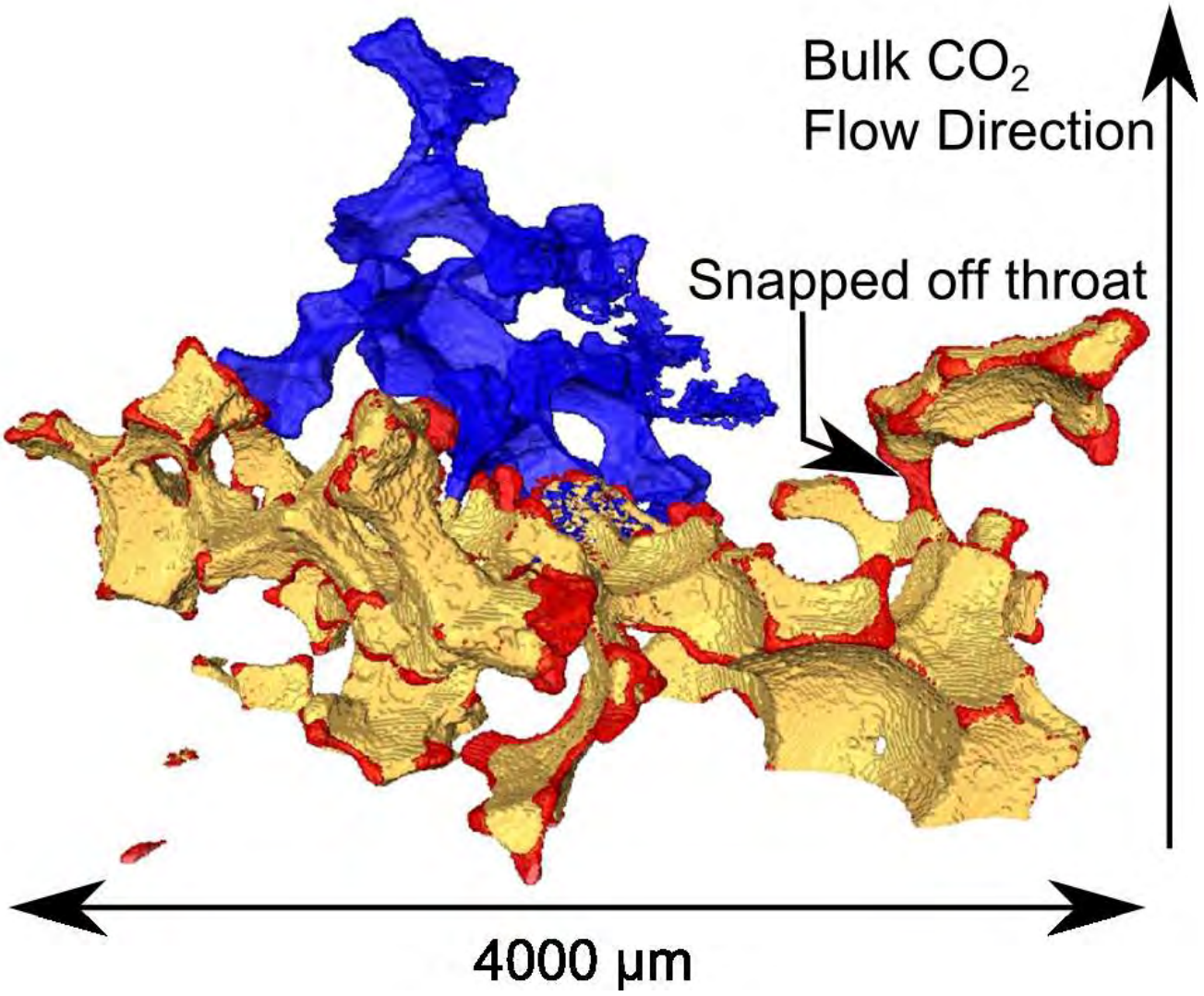


Equilibrium capillary pressure change





Distal (non-local) snap-off

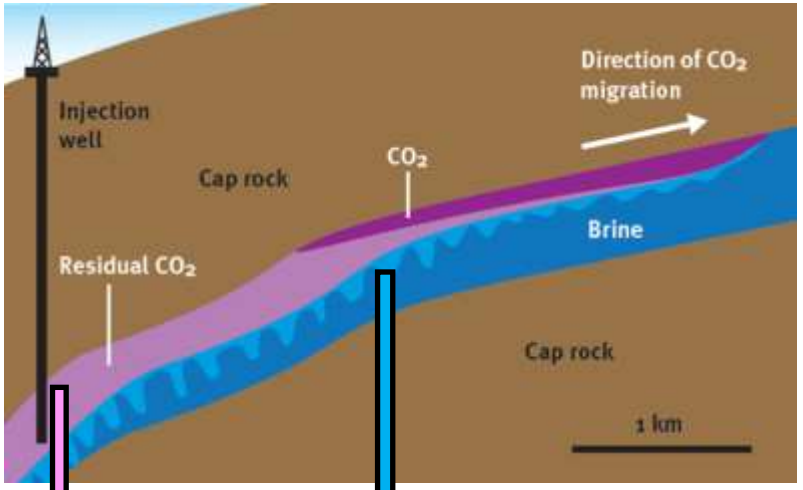


Does it matter?

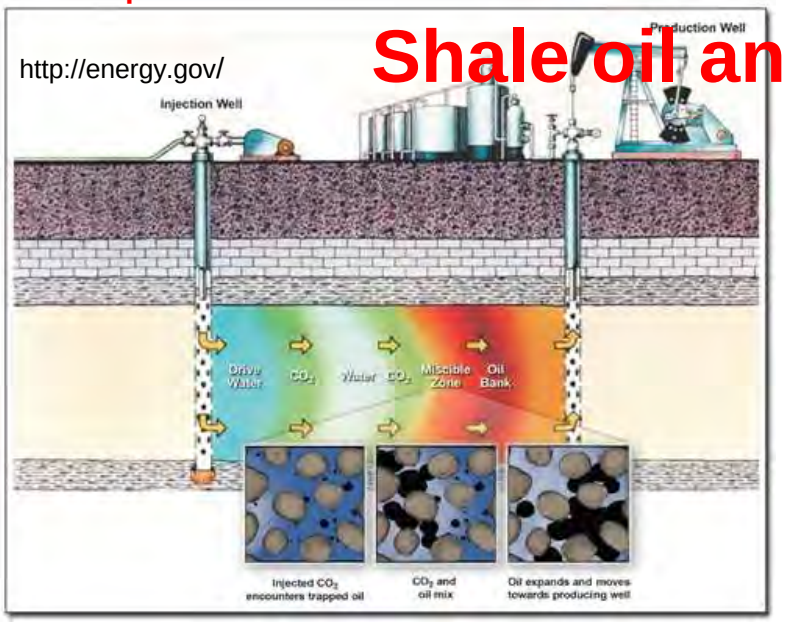
Carbon Storage

http://www.euwfd.com/html/groundwater.html

Contaminant Transport

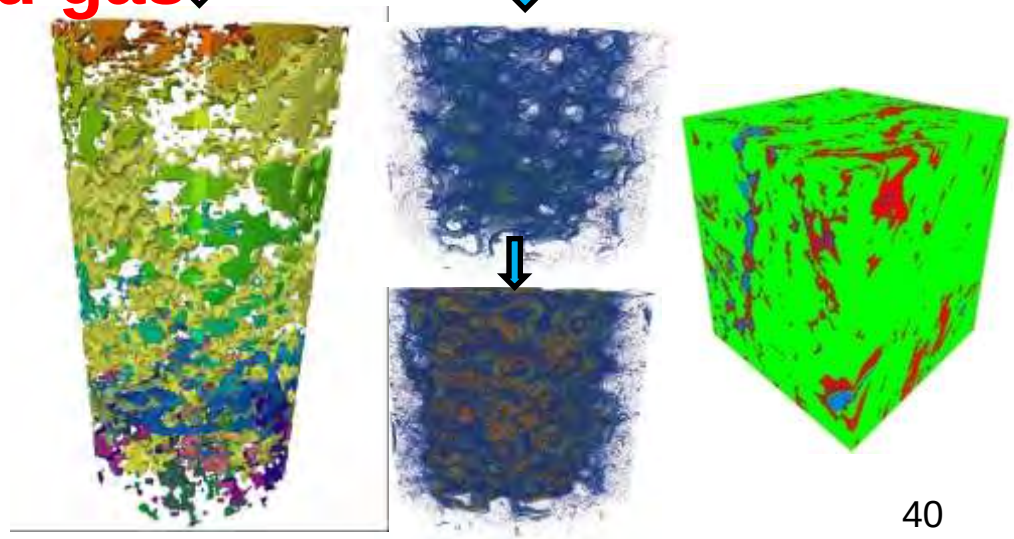


Shale oil and gas



http://energy.gov/

Enhanced Oil Recovery



3D X-ray Micro-CT imaging of a rock sample

Conclusions

New tools – both experimentally and numerically allow us to observe and model flow and transport in great detail from the pore scale upwards.

Huge practical challenges also drive the science.

We are on the cusp of a revolution.

Acknowledgements

Qatar Petroleum, Shell and the Qatar Science and Technology Park under the Qatar Carbonates and Carbon Storage Research Centre

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Member of Qatar Foundation

Imperial College London

قطر للبترول
Qatar Petroleum

iRock Technologies

TOTAL

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