Peering into the pore space
a revolution in describing multiphase flow?

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How we model transport in porous media

PRL **106,** 194502 (2011) PHYSICAL REVIEW LETTERS week ending 13 MAY 2011

Fluid Mixing from Viscous Fingering

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(Received 3 December 2010; published 12 May 2011)

$$\partial_t c + \nabla \cdot \left(\boldsymbol{u} c - \frac{1}{\mathrm{Pe}} \nabla c \right) = 0, \qquad \boldsymbol{u} = -\frac{1}{\mu(c)} \nabla p, \qquad \nabla \cdot \boldsymbol{u} = 0, \tag{1}$$

J. Fluid Mech. (2006), *vol.* 548, *pp.* 87–111. 87
doi:10.1017/S0022112005007494 Printed in the United Kingdom

Onset of convection in a gravitationally unstable diffusive boundary layer in porous media

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Department of Petroleum Engineering, Stanford University, Stanford, CA 94305, USA

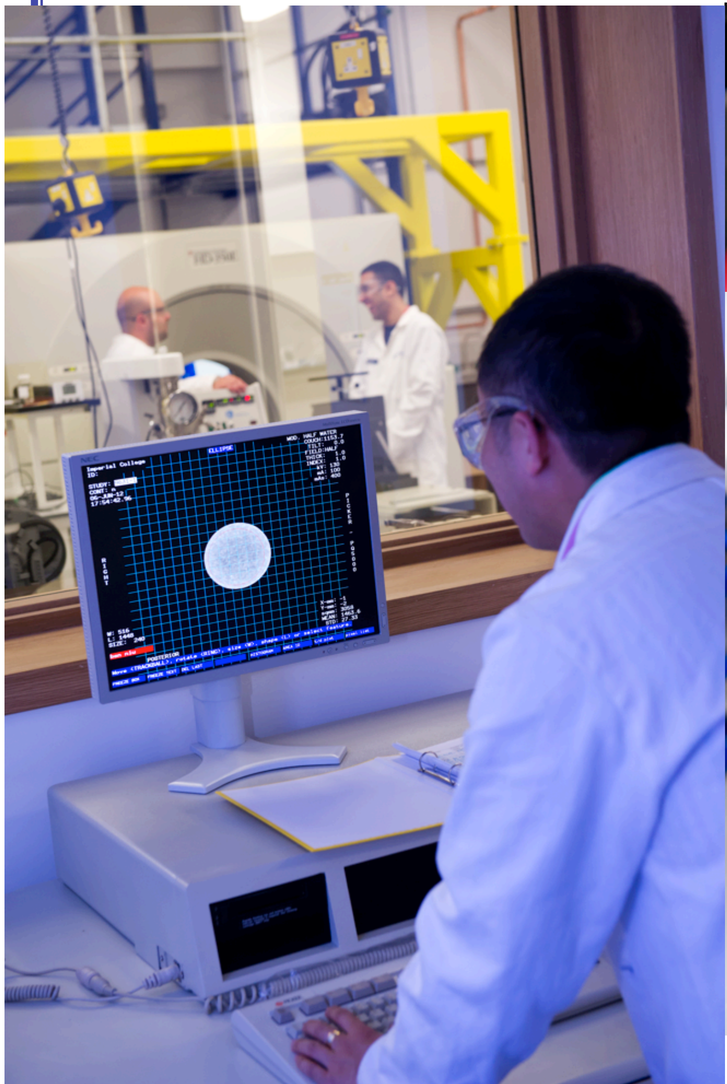
$$\boldsymbol{u} = -\frac{K}{\mu}(\nabla P - \rho g \hat{z}),$$

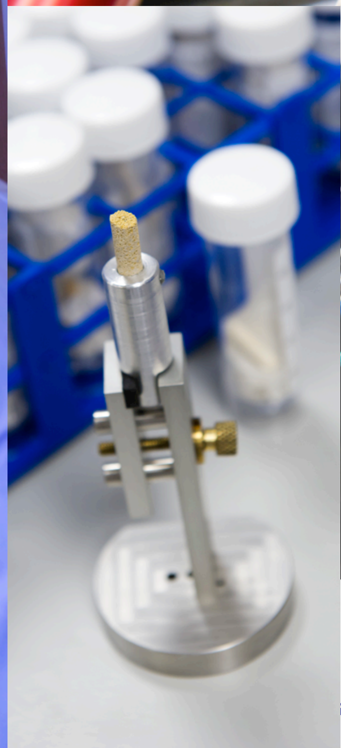
$$\phi \frac{\partial C}{\partial t} = -\boldsymbol{u} \cdot \nabla C + \phi D \nabla^2 C,$$

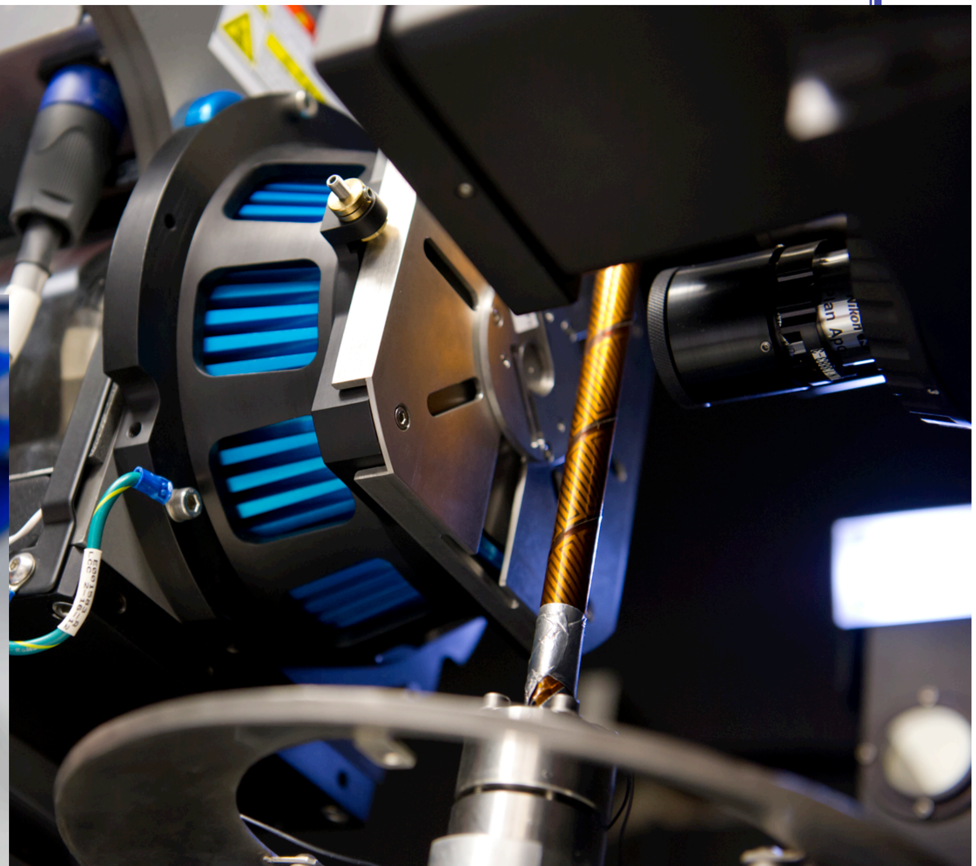
$$\nabla \cdot \boldsymbol{u} = 0,$$

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.







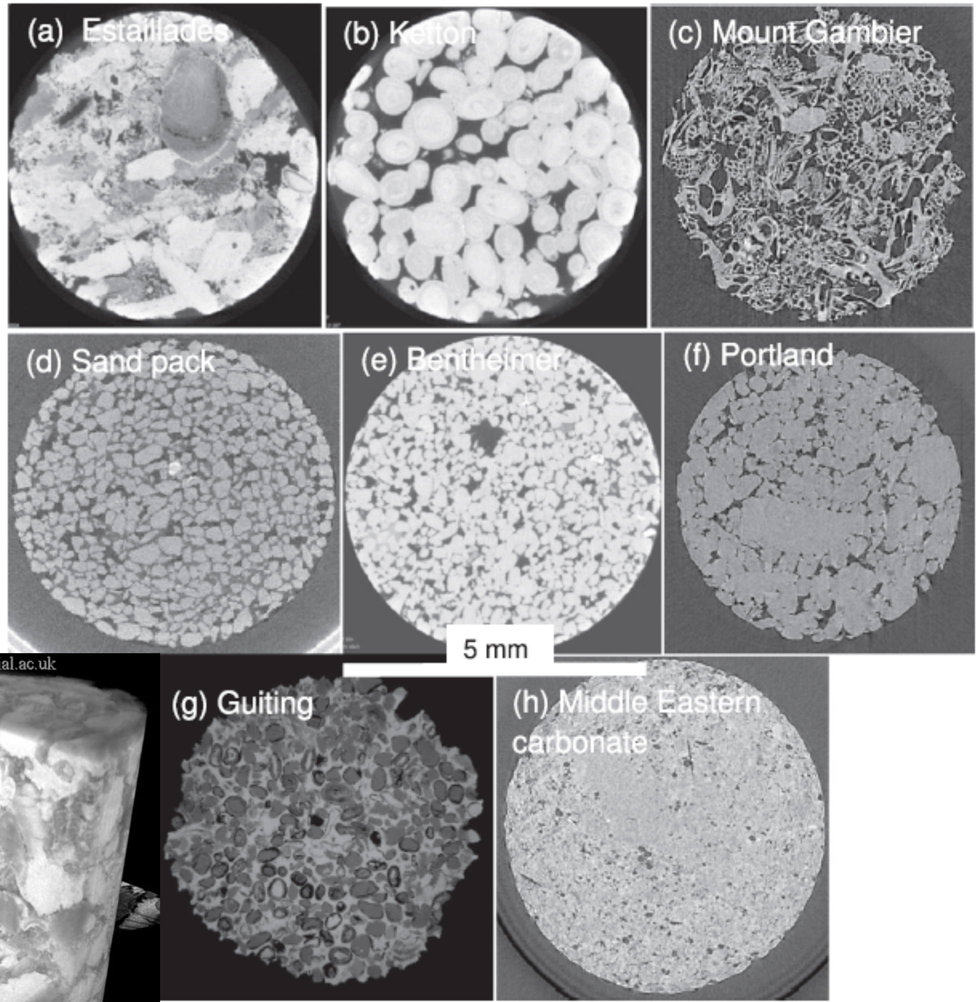
Imaging and computing

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

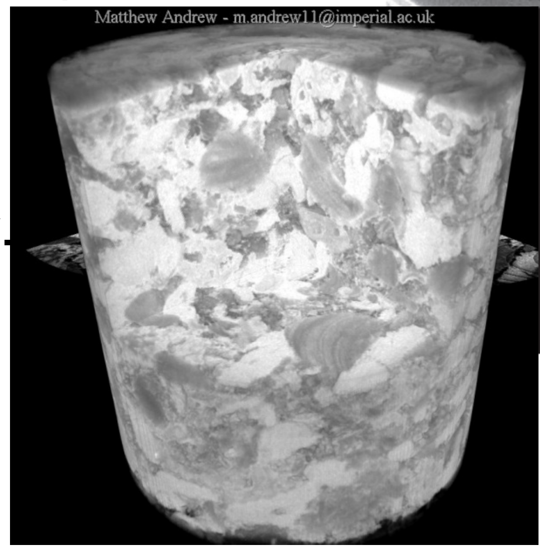
Synchrotron sources. Bright, mono-chromatic and fast.

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

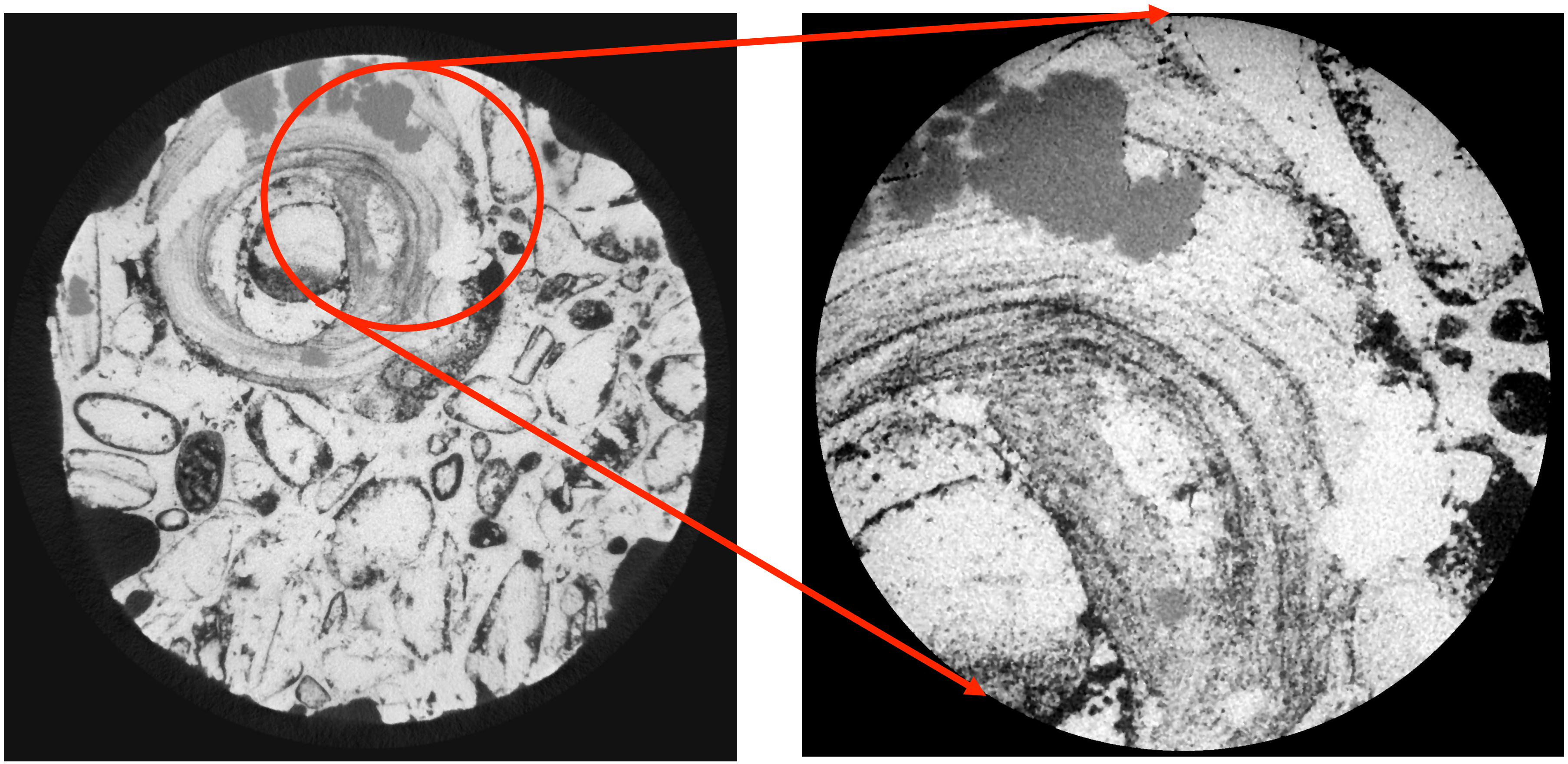
Availability of excellent public-domain solvers: algebraic multigrid, OpenFoam Navier-Stokes solver. Fluid mechanics: unstructured adaptive grids.



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



Carbonate at two resolutions



Voxel size 2.7 μm

Voxel size 0.9 μm

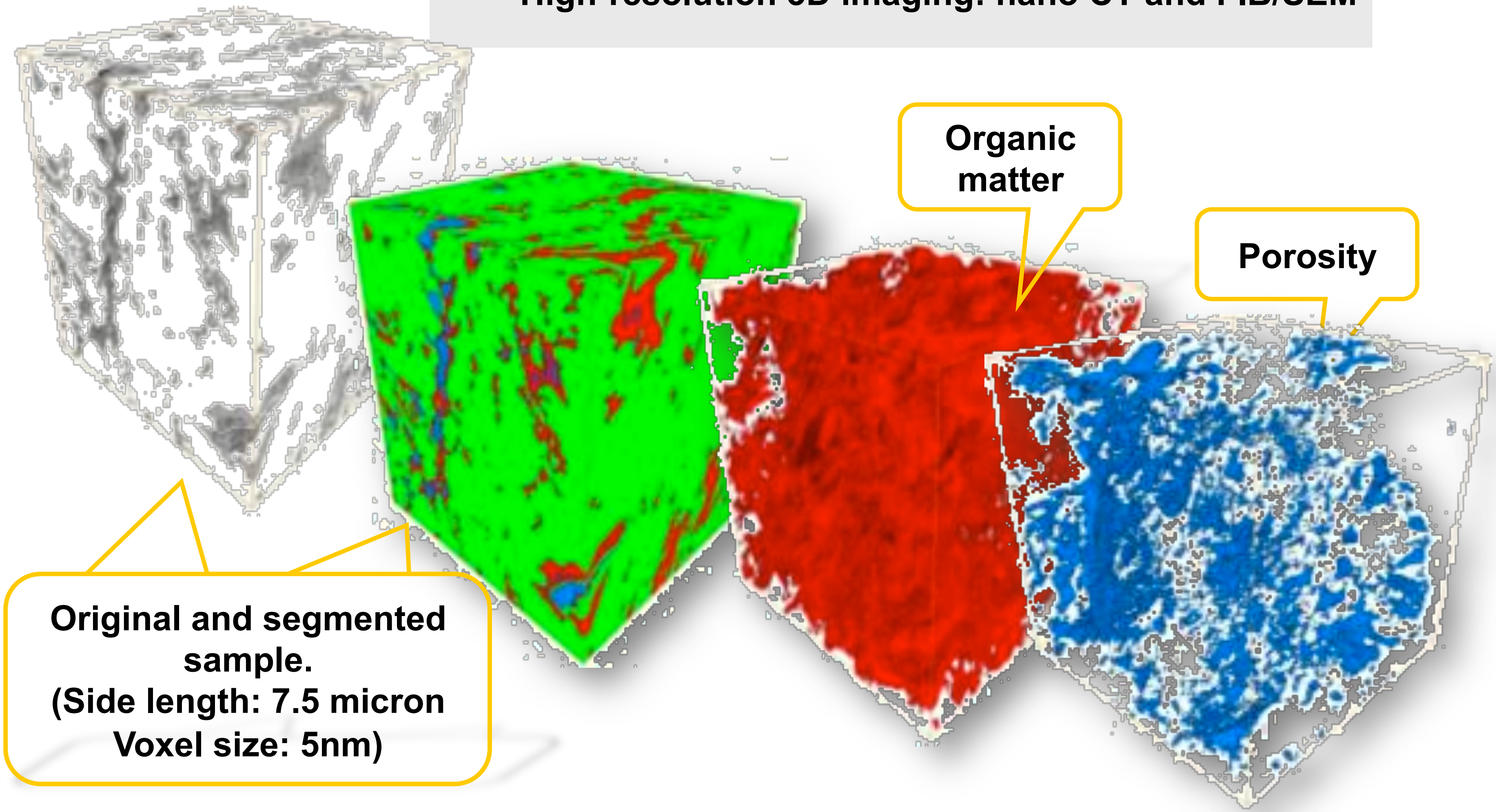
Edward limestone from Texas:

Lab measured permeability of 20 mD vs. 19 mD from pore network modelling

Spot the odd one out

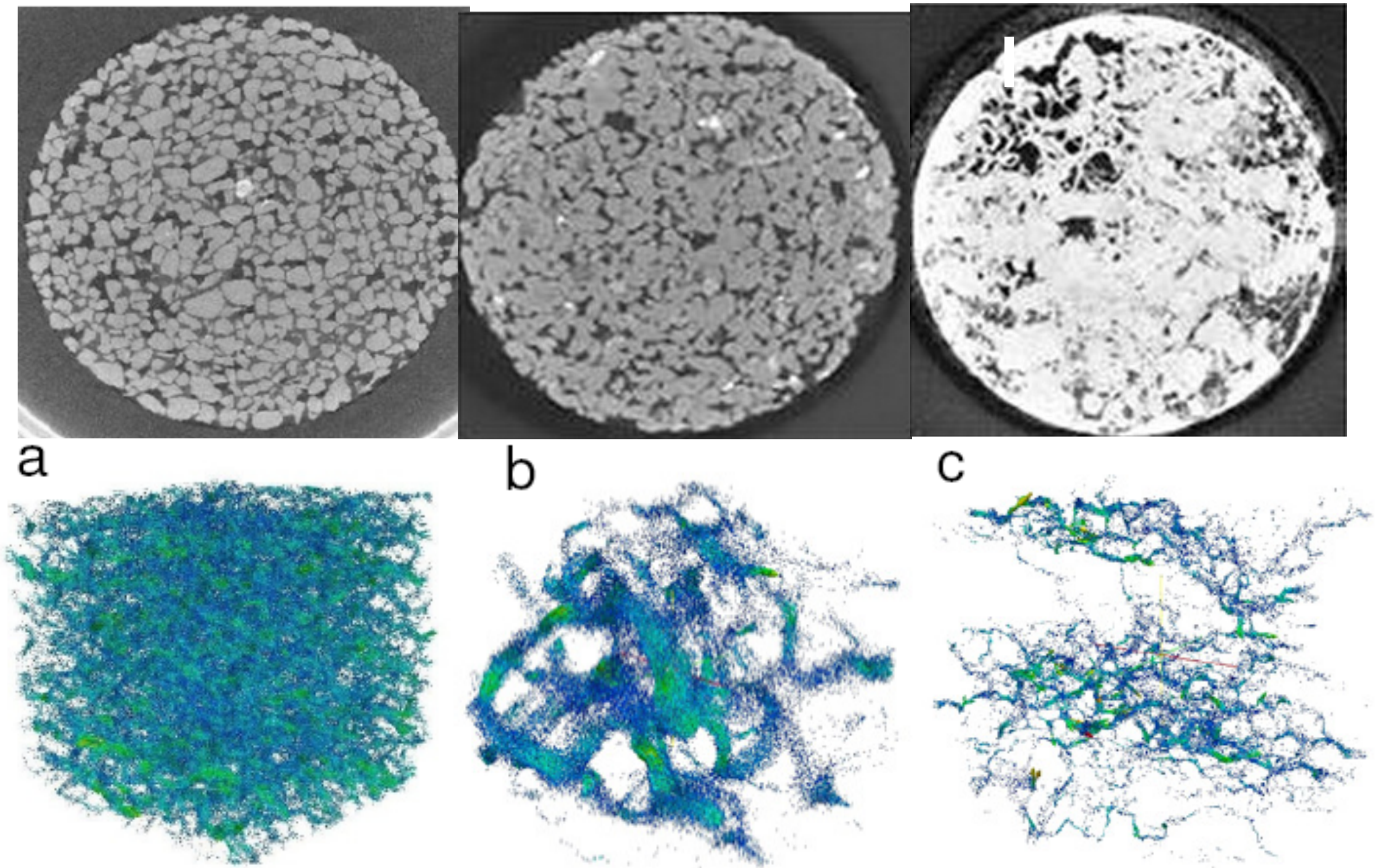
Nano-scale imaging of gas shale

High-resolution 3D imaging: nano CT and FIB/SEM



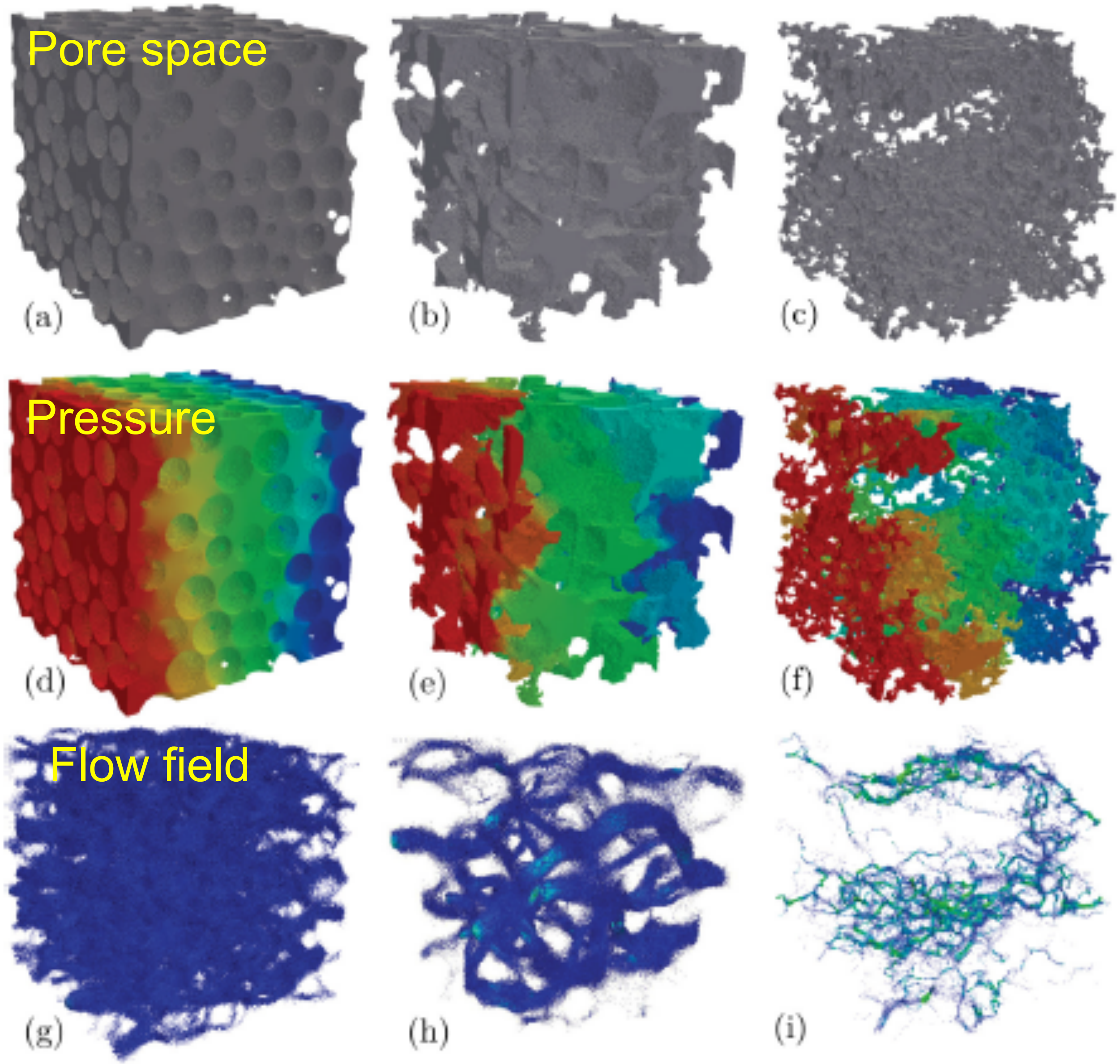
Flow and dispersion – single-phase transport

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

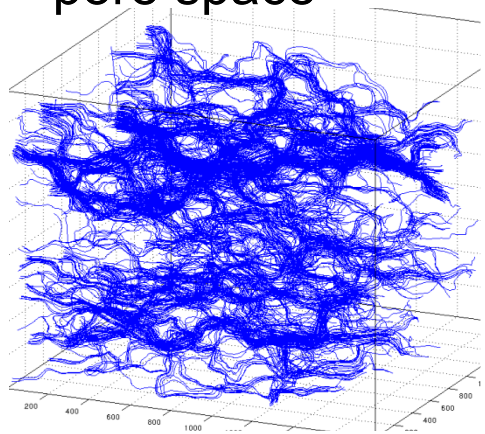


Sandpack Sandstone (Bentheimer) Carbonate (Portland)

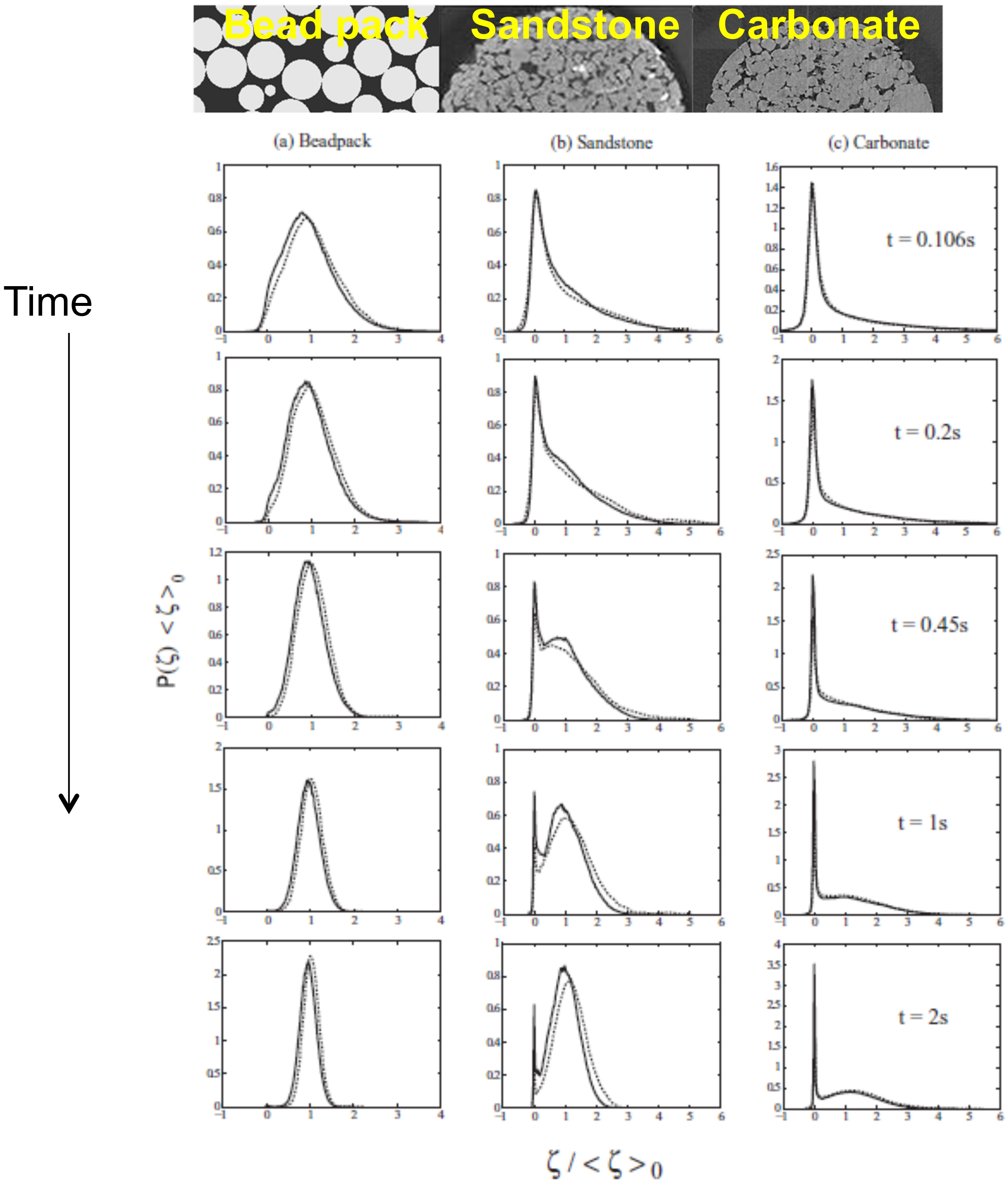
Flow and dispersion – single-phase transport



Streamlines in the pore space



Concentration profiles

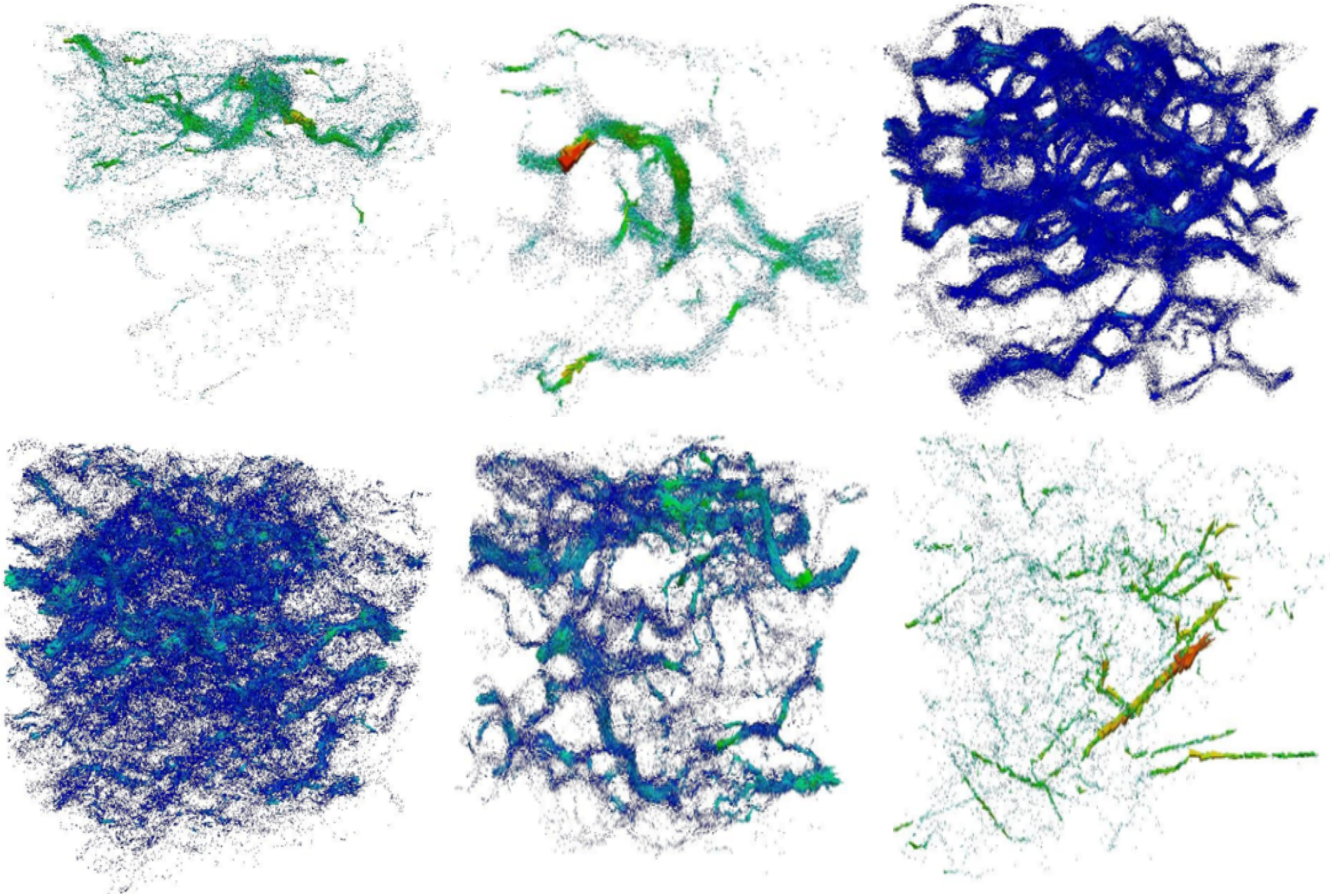


Compare prediction of concentration vs. distance for different times and rock types against NMR experiments.

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

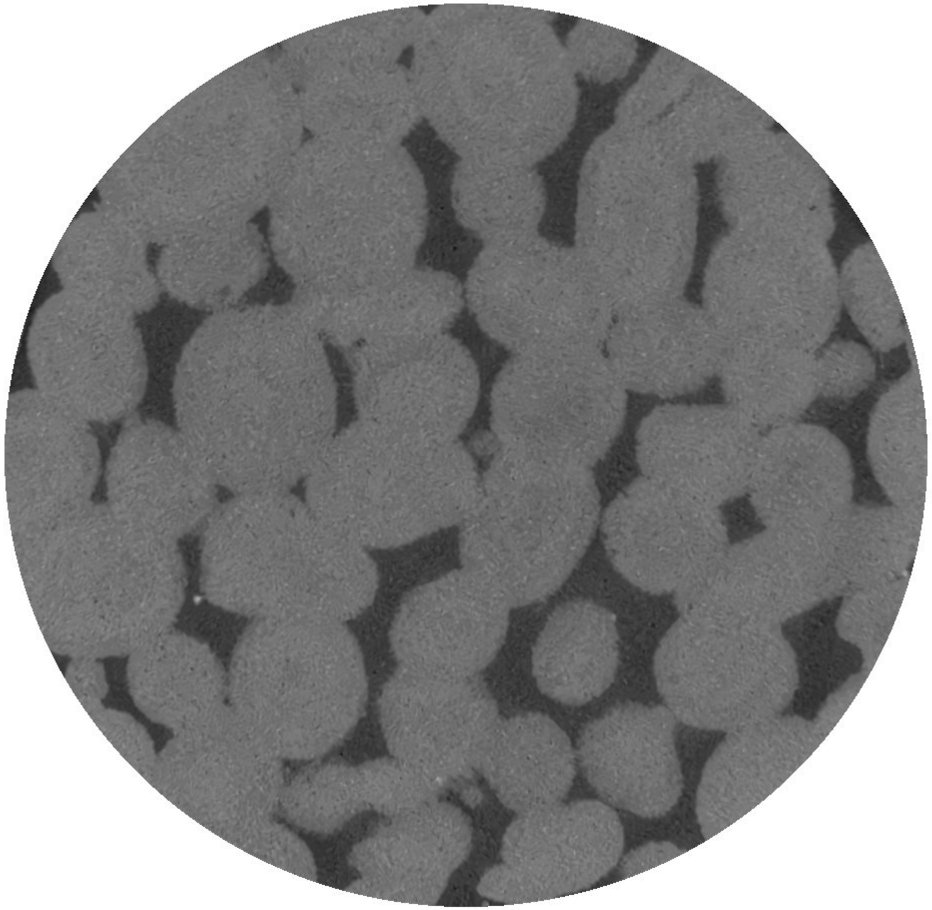
Bijeljic *et al.* PRL (2011); PRE (2012); WRR (2013).

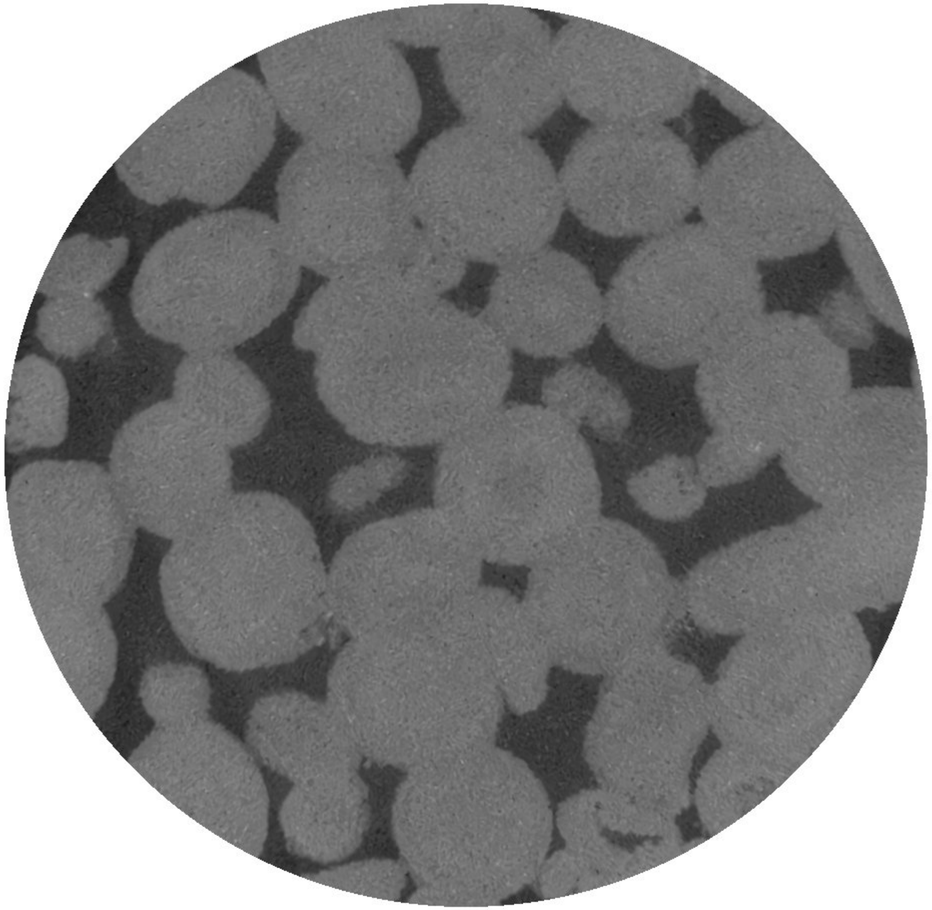
Carbonate images and flow fields



Extensions to reactive transport

Brine saturated with CO_2 injected into Ketton carbonate. Acidic brine dissolves the pore space. Application to CCS – carbon capture and storage.

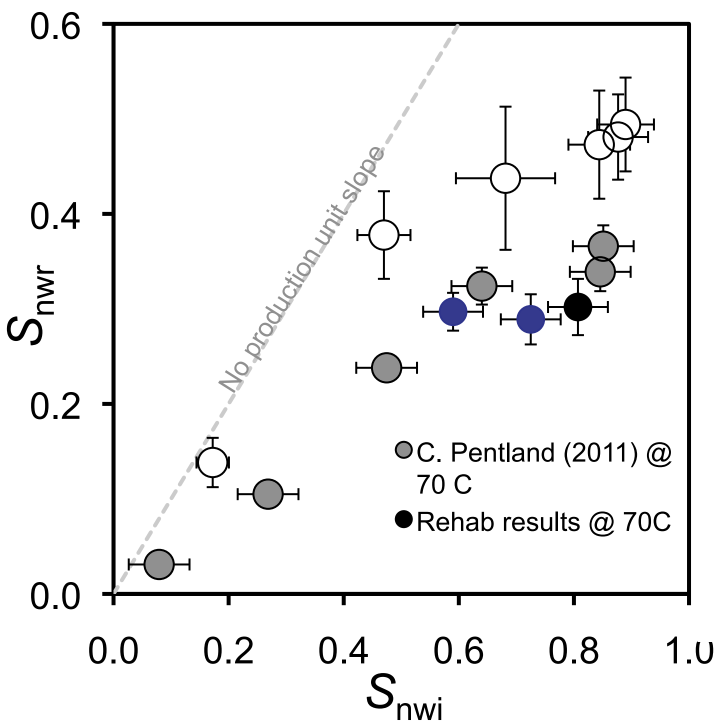


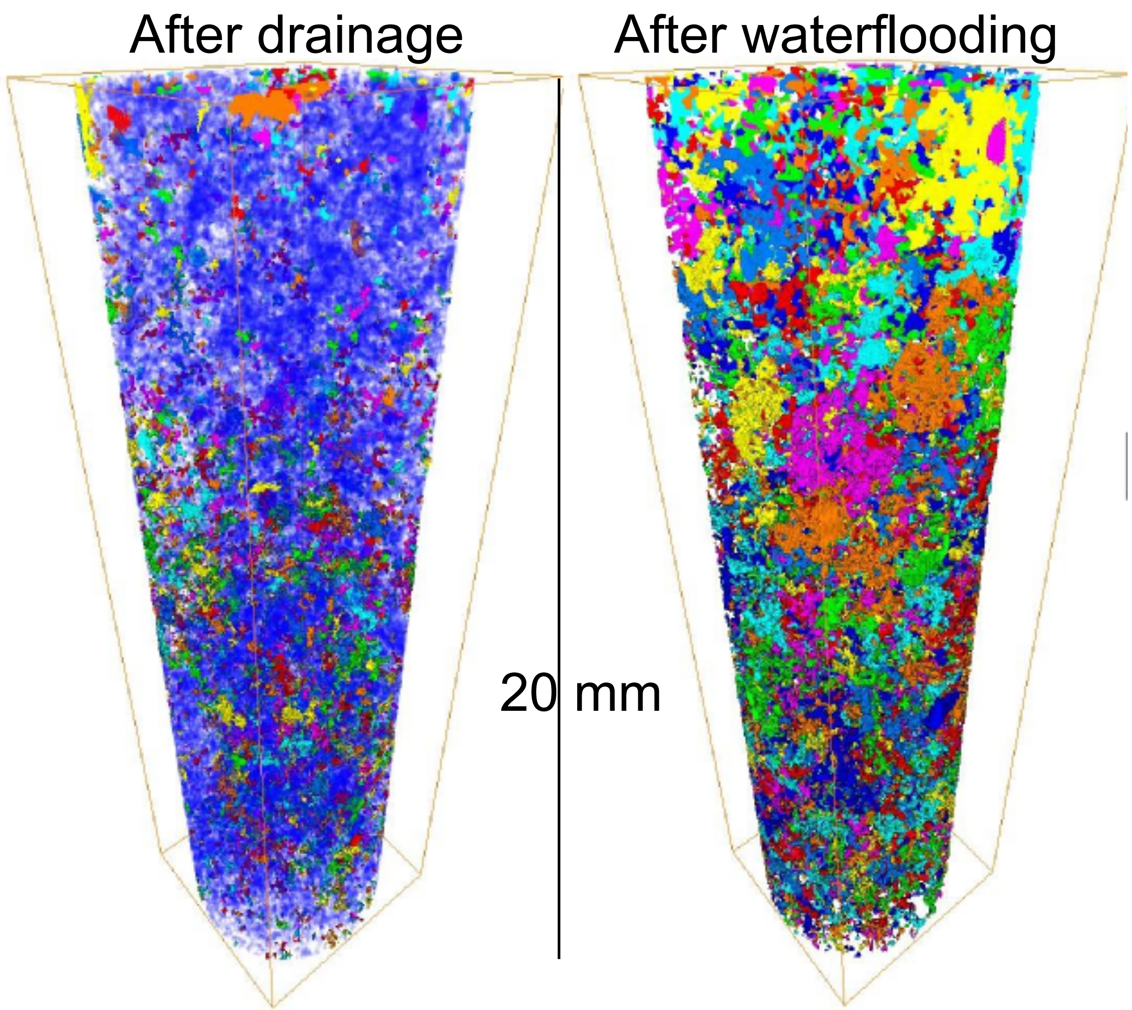


Trapped CO_2 clusters – colour indicates size

How much is trapped and how much can be stored?

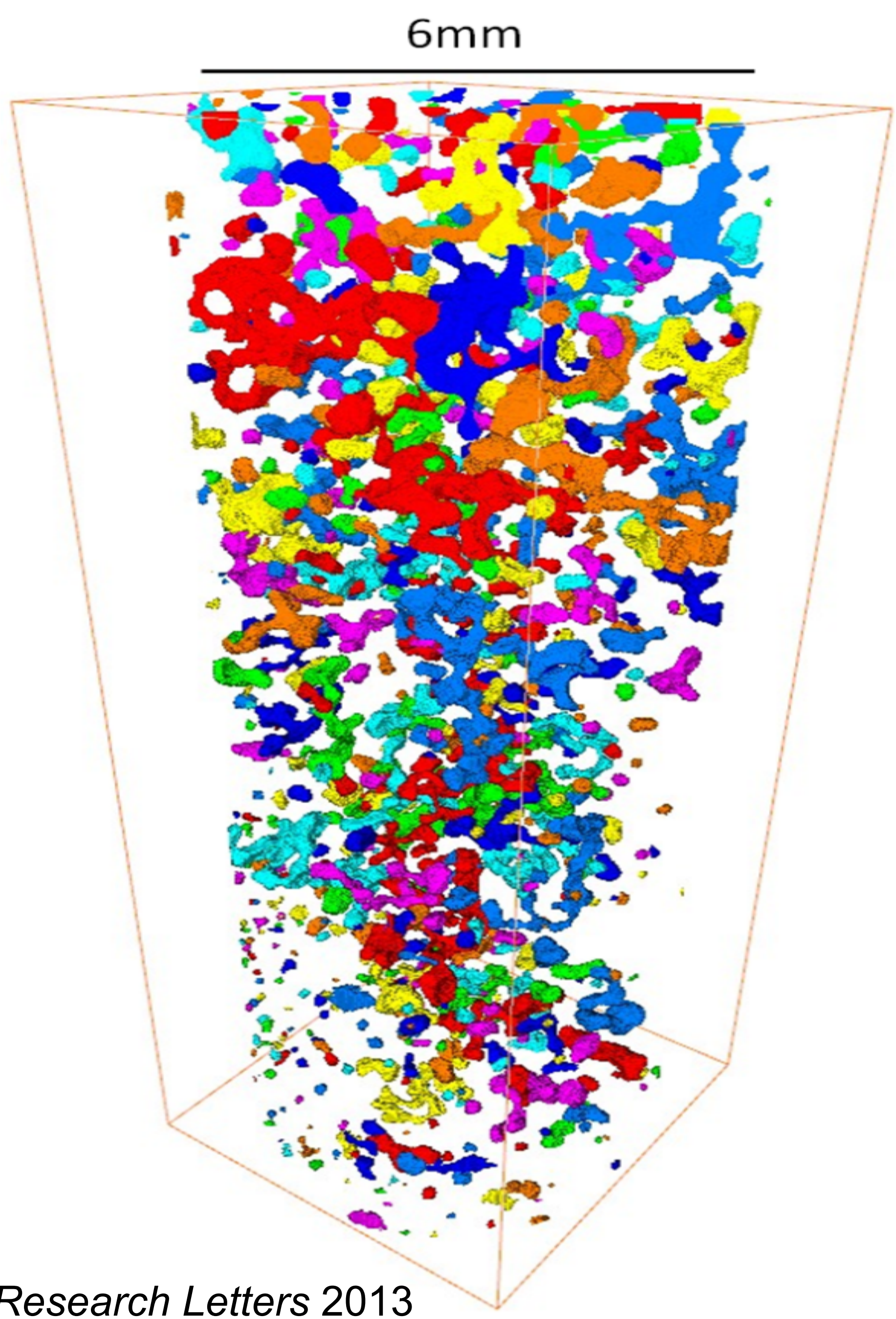
Results in sandstones (Doddington, Bentheimer and Berea).





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

Trapping in a carbonate

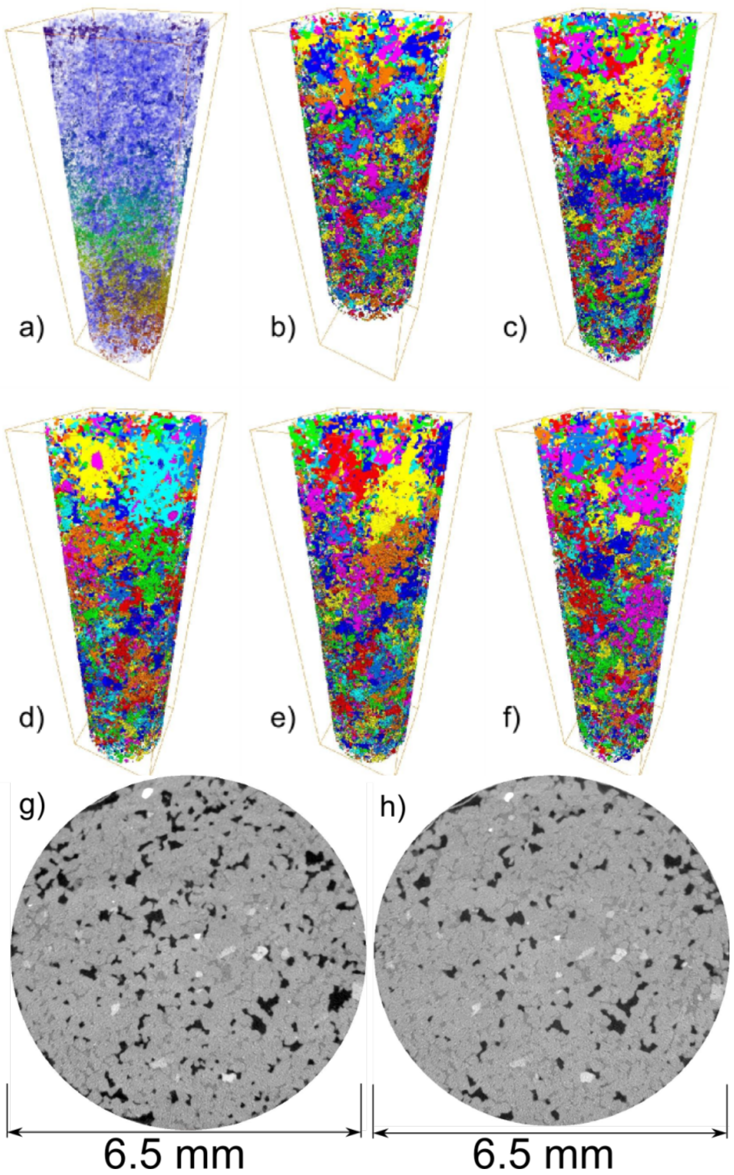


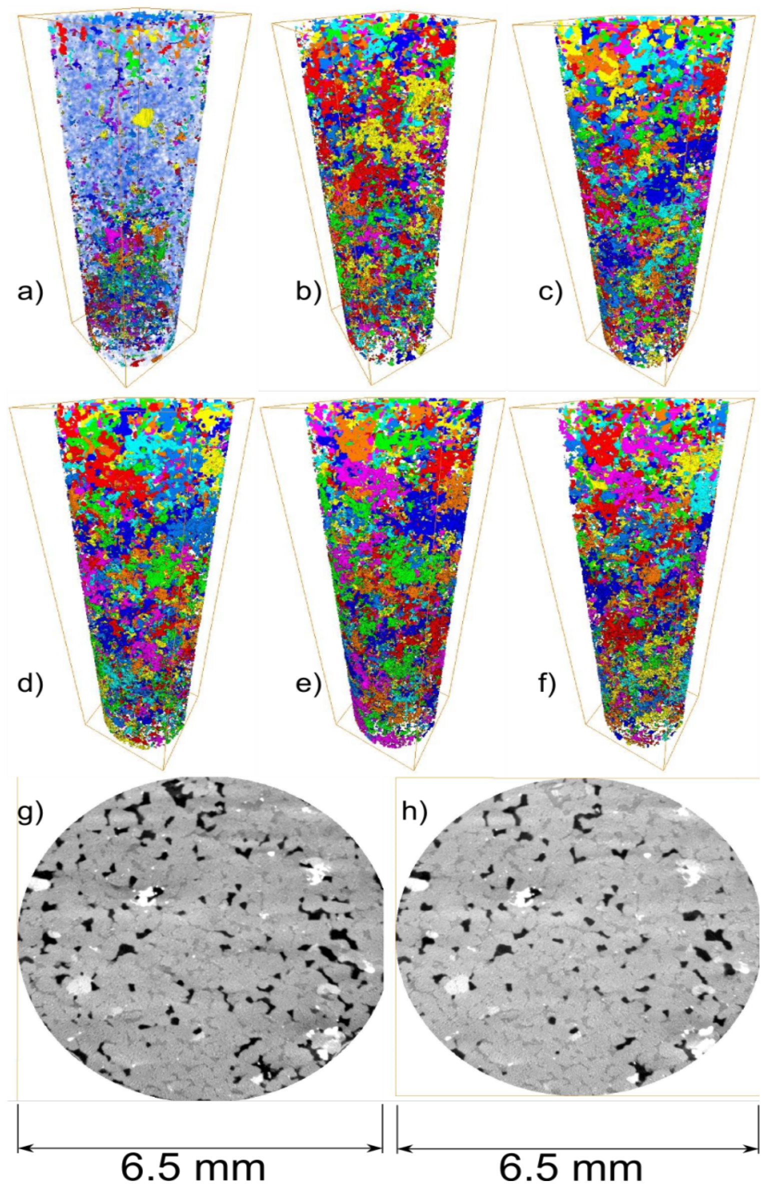
Pre-equilibriate rock, CO_2 and brine at reservoir conditions.

Study trapping in a range of carbonates: Ketton (shown here), Estaillades and Portland.

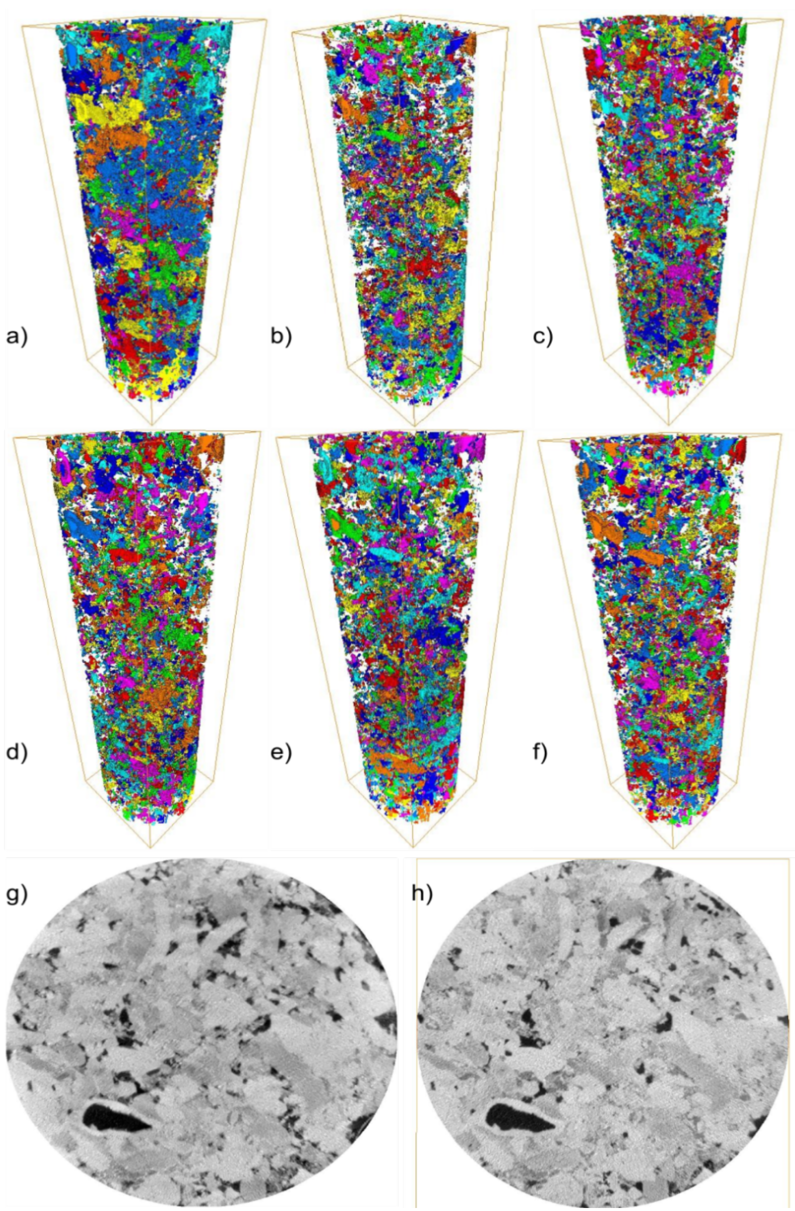
Andrew *et al.*, *Geophysical Research Letters* 2013

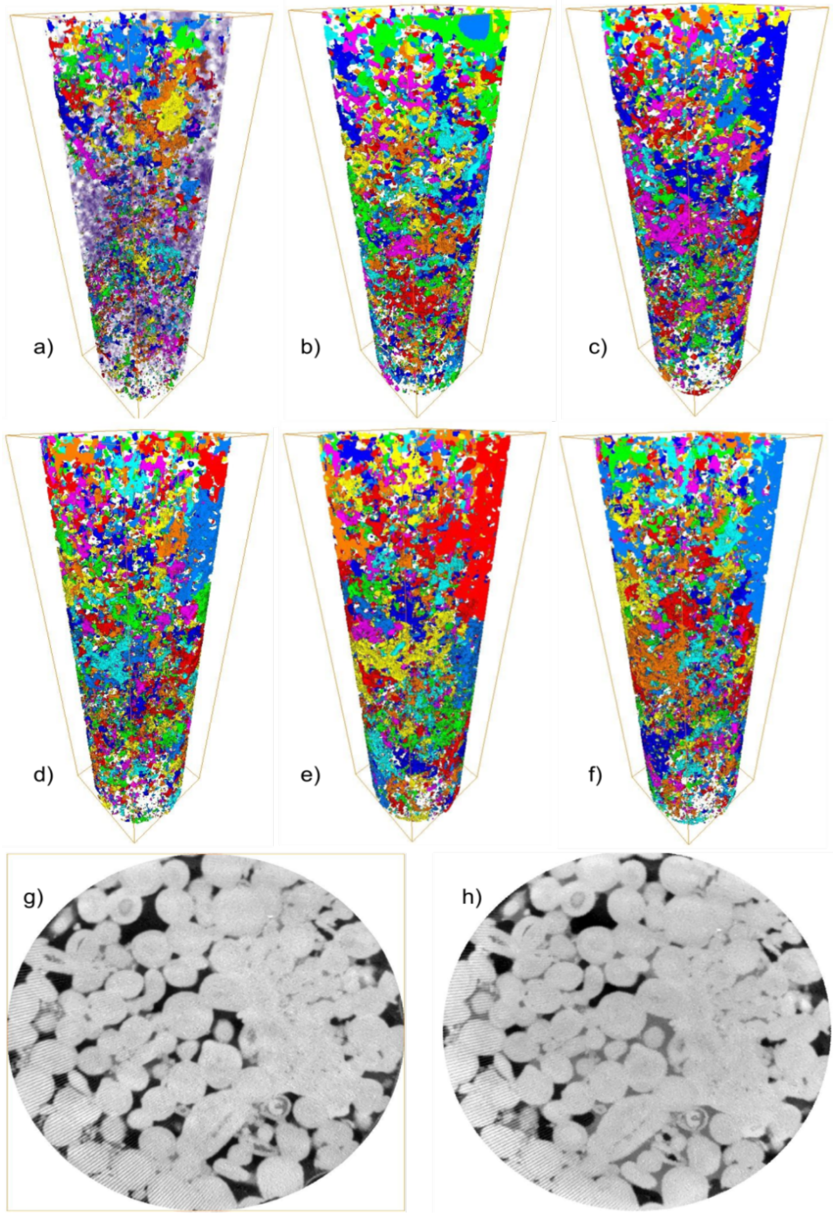
Can study many systems – Bentheimer and Doddington



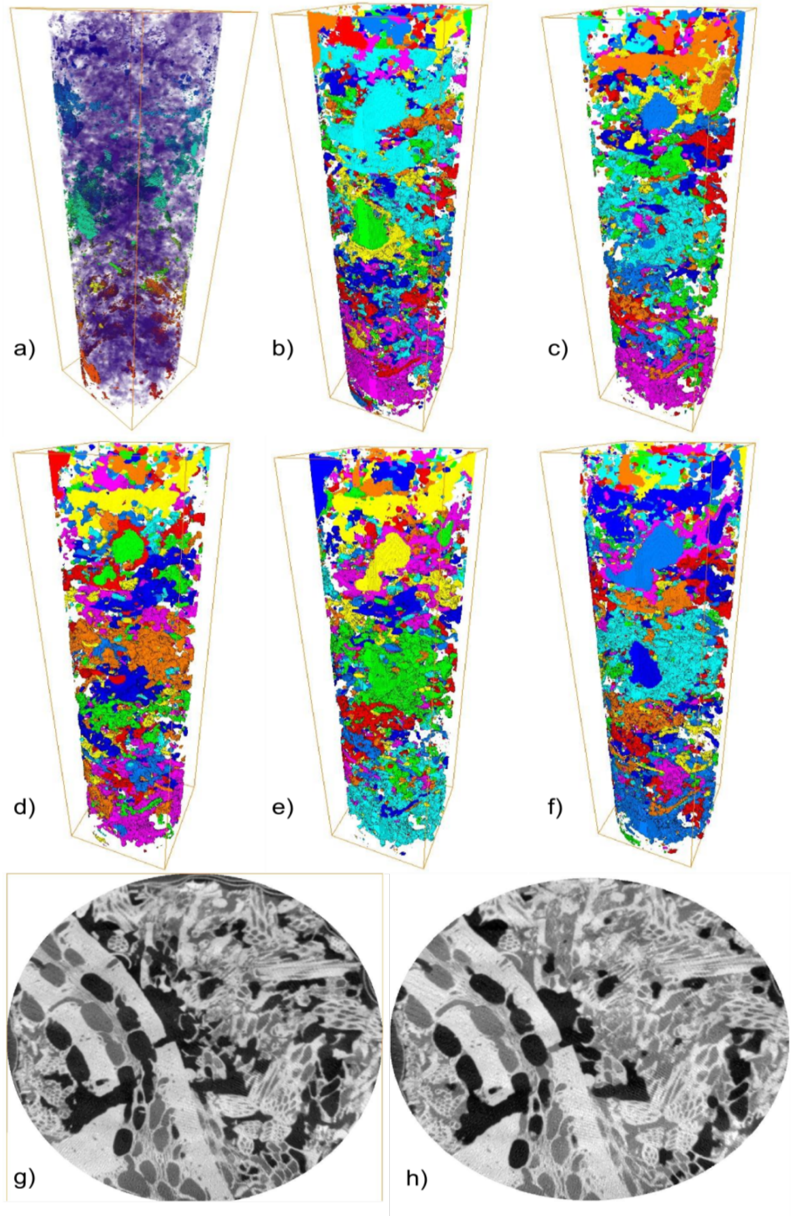


Can study many systems – Estaillades and Ketton





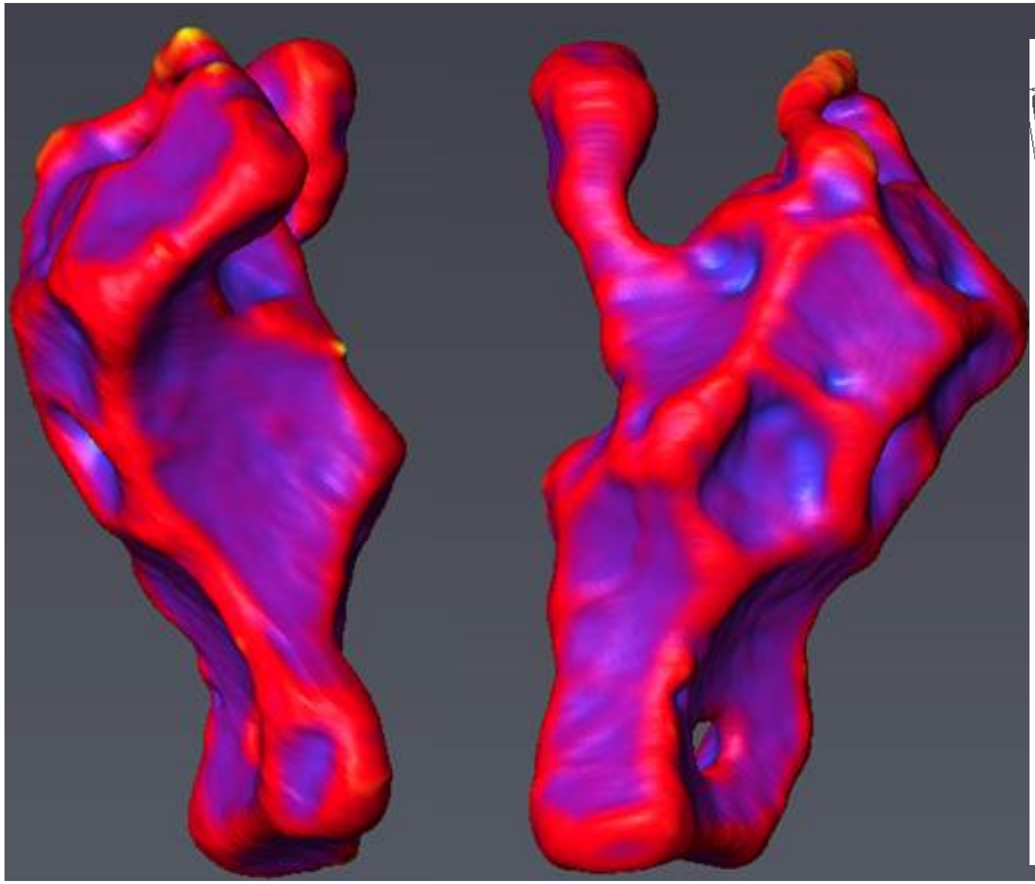
Can study many systems – Portland

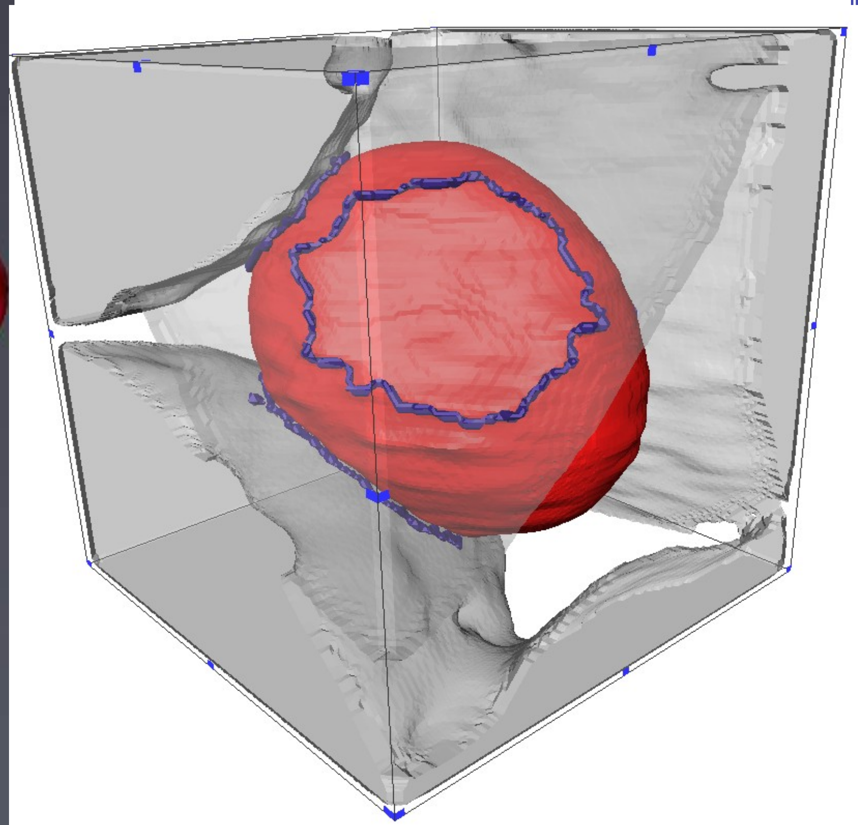


Curvature and contact angle

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

Also study dynamics from fast (synchrotron) imaging.





How do we upscale?

What are the averaged transport equations at the core scale that reproduces the average behaviour?

What are the implications for processes on long spatial and temporal scales?

Can we be predictive?

Do we need a fundamentally new way to describe reactive, coupled transport processes?

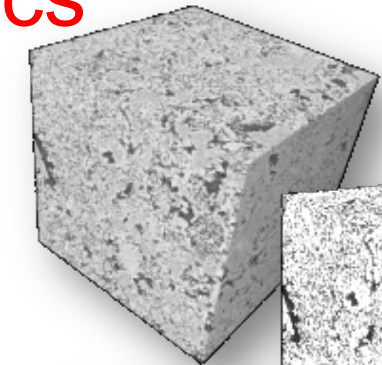
Digital rock physics

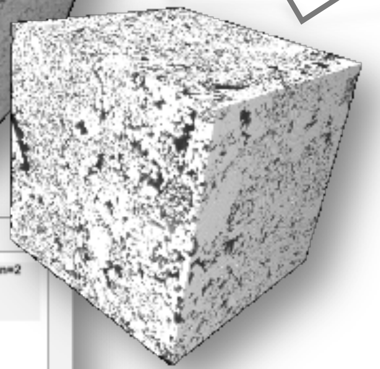
Commercial provision of predictions based on pore-space images.

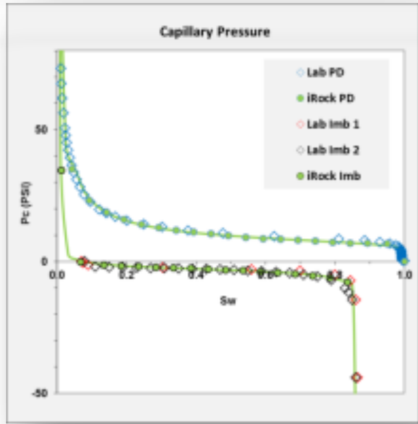
Still research issues to capture displacement processes, characterize wettability, micro-porosity, upscaling, and network vs. direct simulation.

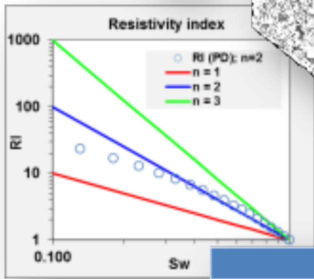
But: what does it means in terms of recovery and oilfield management?

Original and segmented sample (Side length: 308 micron, Voxel size: 0.28 micron)

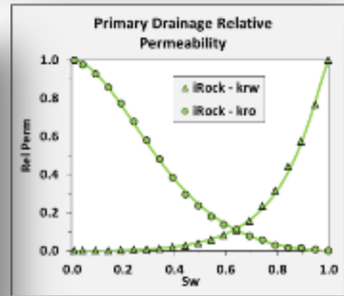


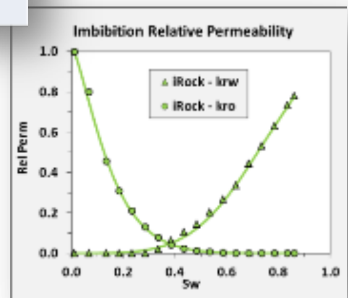


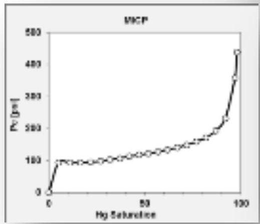


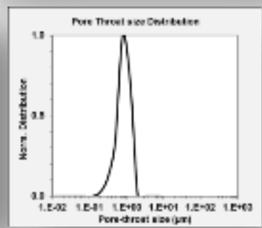


	iRock DRP	Laboratory 1	Laboratory 2
Grid size	1100^3	--	--
Physical size [µm]	308^3	--	--
Voxel size [µm]	0.28	--	--
Φ	0.252	0.268	
Φ Percolating	0.248	--	--
K abs [mD]	6.04	4.9 (air), 8.8 (brine)	
FRF	19.2	--	--
Swi	0.01	0.011	
Sor	0.138	0.13	0.14
krw@Sor	0.779	--	--







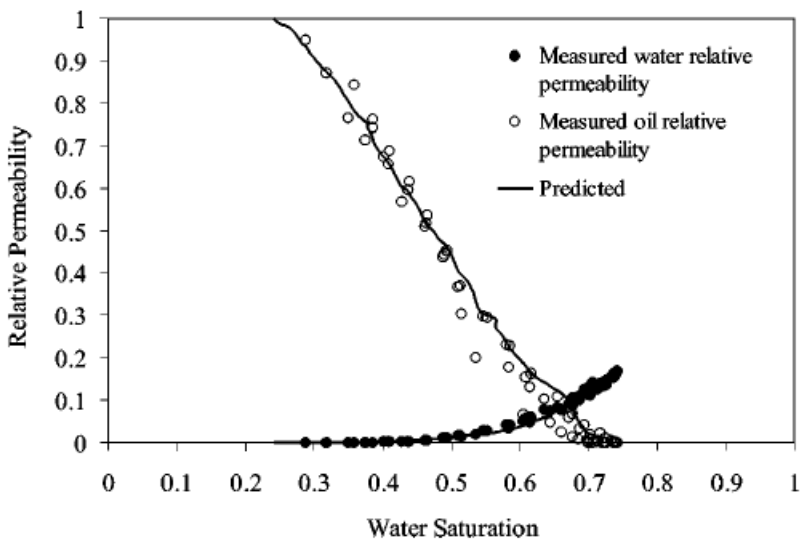


Predictions of relative permeability

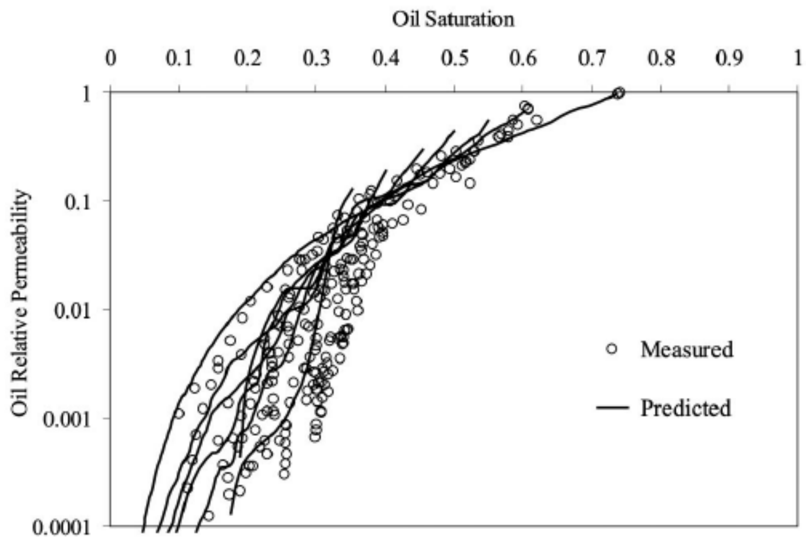
Experimental data from Berea sandstone cores (Oak 1990).

- Use network based on rock structure (Øren and Bakke 2003).
- Predict waterflood and gasflood relative permeabilities.

Waterflooding



Gas injection



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

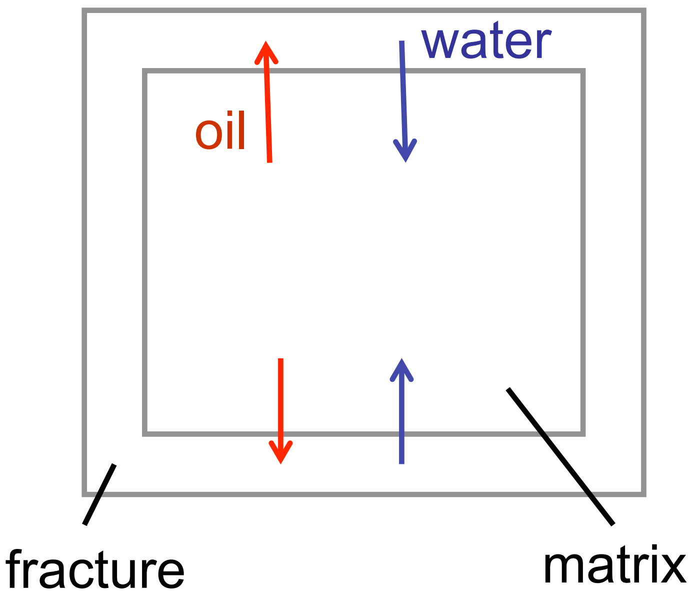
Piri and Blunt, *Physical Review E,* 2005

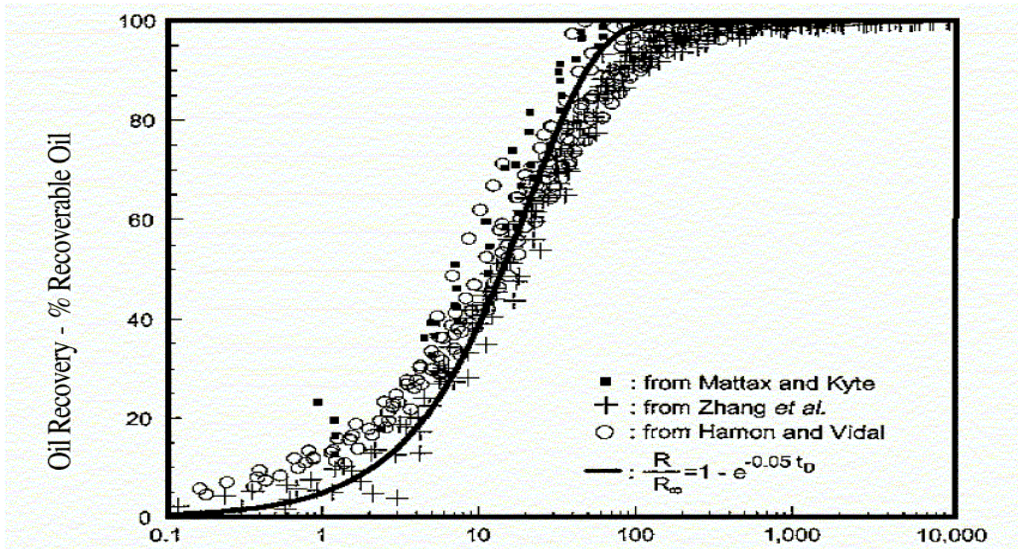
Two displacement processes

Two key displacement processes in porous media:

Waterflooding (water injection to displace oil);

Counter-current imbibition (water injection in a fractured medium, where water imbibes from fractures and oil escapes).

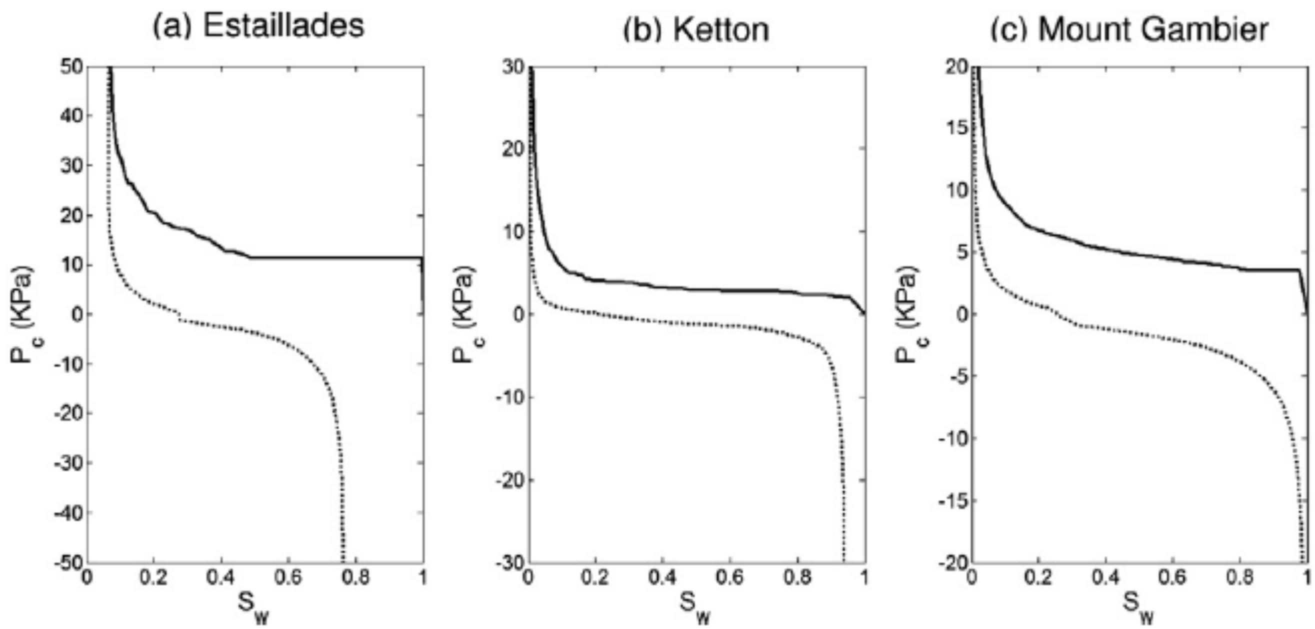




Normalized oil recovery vs. dimensionless time for very strongly water wet imbibition.

The trillion barrel question

Predicted mixed-wet capillary pressures



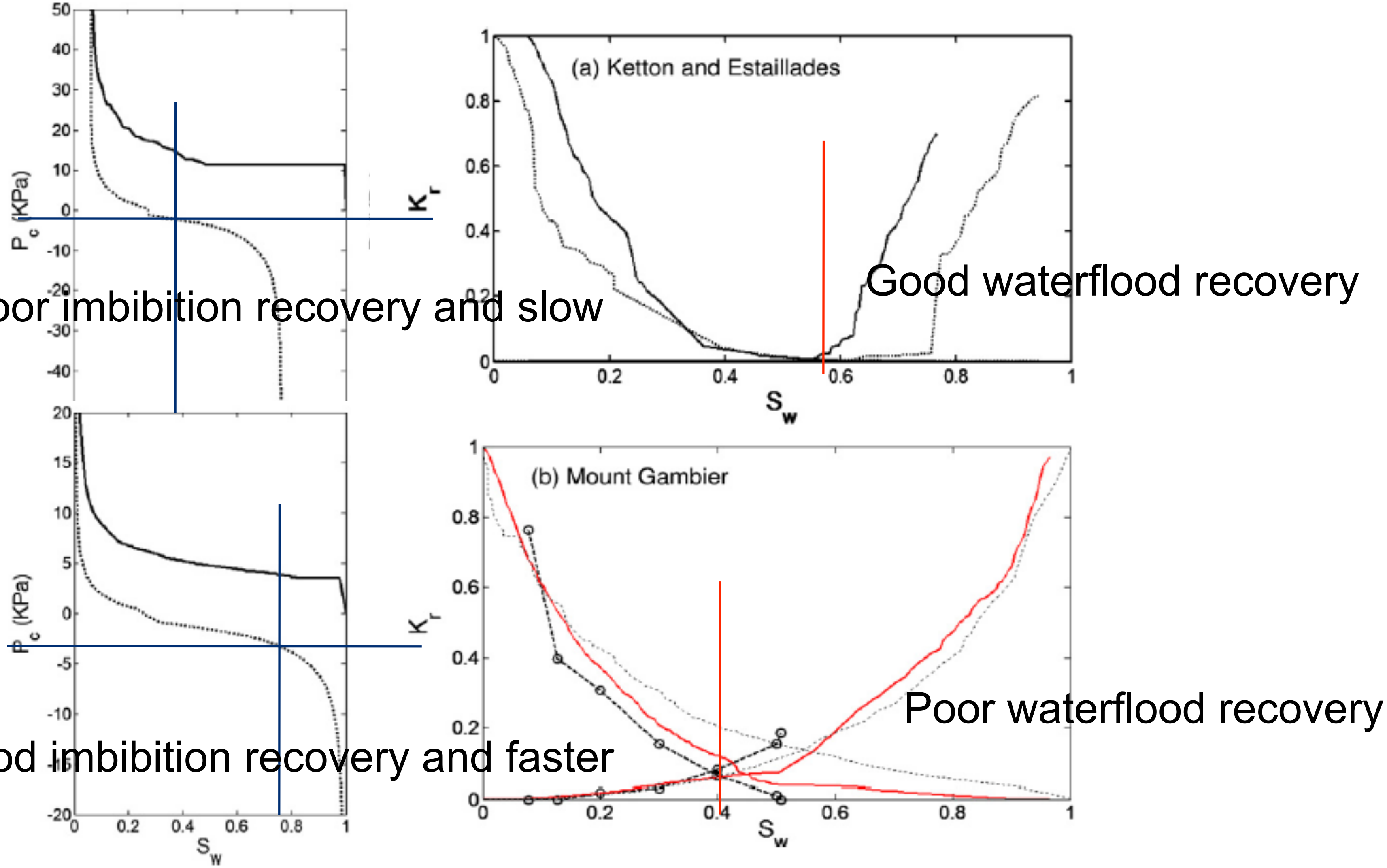
Waterflood recovery is a subtle interplay of viscous displacement (mixed-wet good) and fracture-matrix imbibition (controlled by capillary pressure and low-saturation relative permeability).

What is the best recovery strategy?

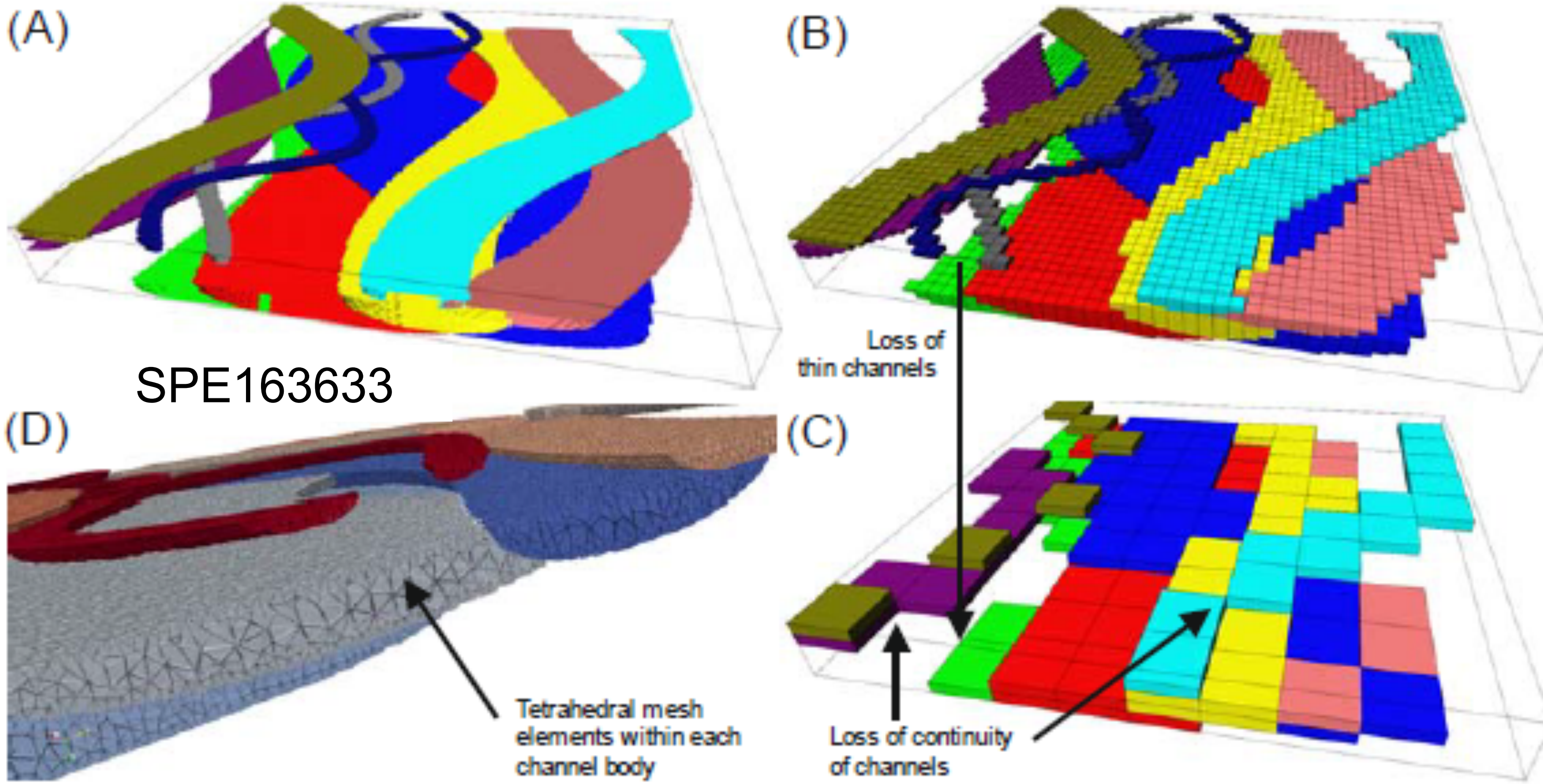
Waterflood recovery

In a fractured reservoir controlled by imbibition plus gravitational push.

Final recovery where $P_c = -\Delta\rho g h = -300\times10\times1 = -3$ kPa (say).

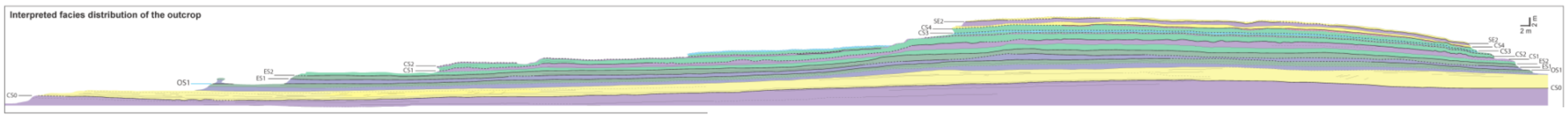


At the field scale: a vision of reservoir simulation of the future

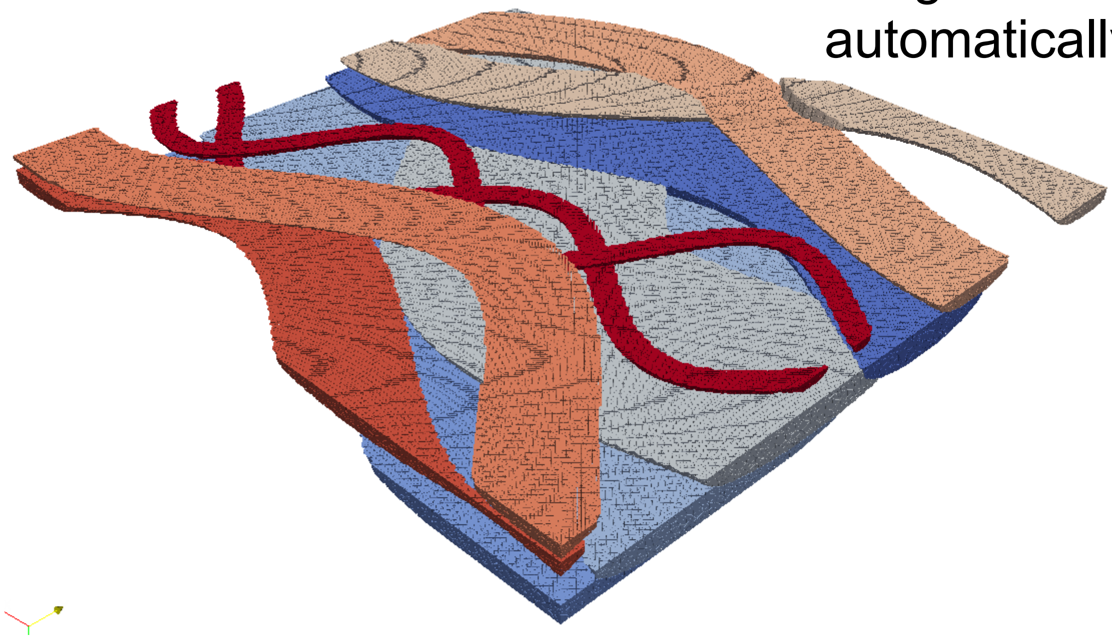


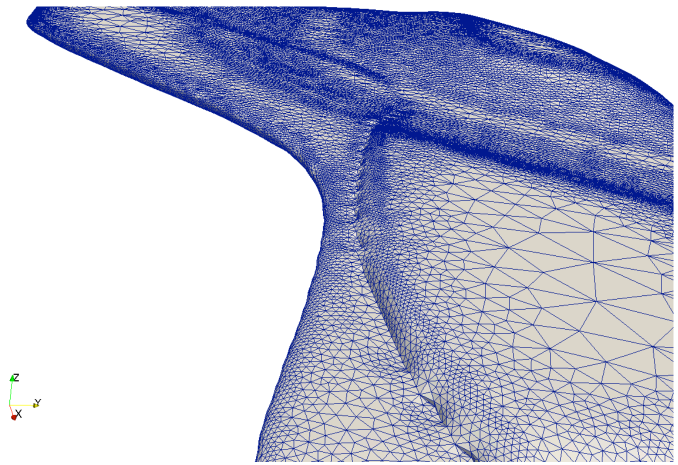
Describe the geology with hierarchical surfaces. Adaptively refined mesh within each region bounded by the surfaces. Homogeneous properties in each domain: derived from averaged pore-to-grid cell properties.

From outcrop to fine grid based on geology

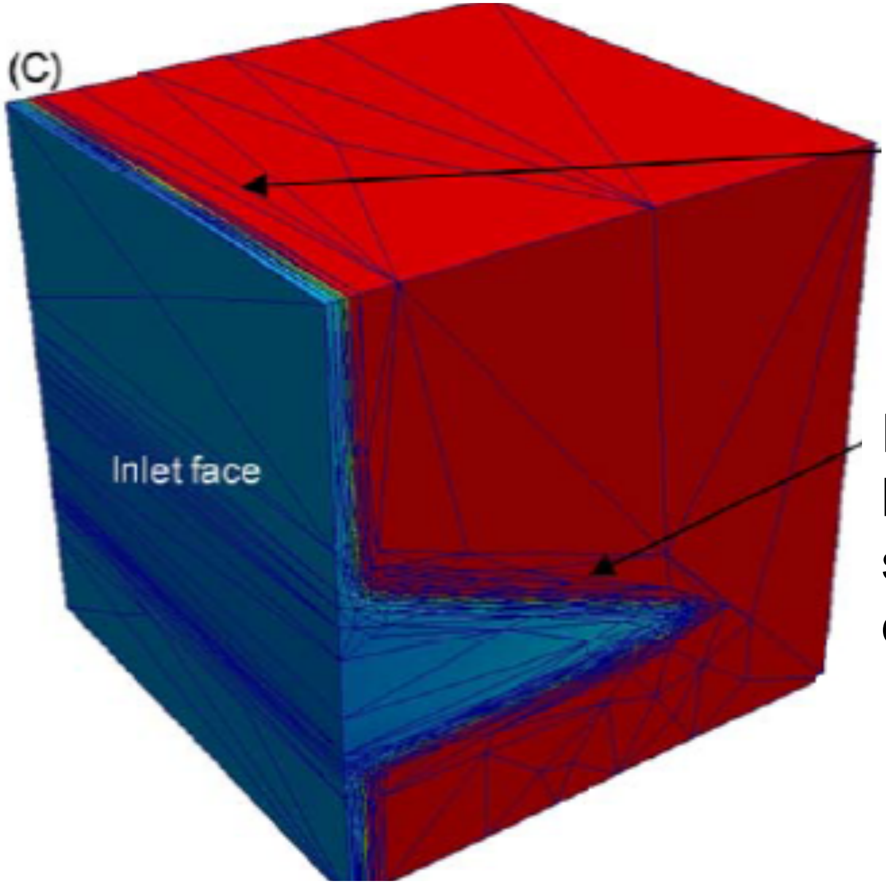


Base the structure on analogue outcrop studies and other information. Can refine the grid and follow geological structure automatically.





Reservoir simulation with unstructured adaptive meshes



Adaptively refine near the advancing front

Refine at domain boundaries with saturation discontinuities

Adaptive, unstructured mesh to capture saturation fronts accurately and efficiently. Much more accurate and faster with fewer grid cells. Working on general, high-order, parallel implementation.

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.

But…. How to we characterize and interpret the behaviour?

We are on the cusp of a revolution.

Acknowledgements

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iRock Technologies