From Pore Structure to Mixing and Relative Permeability in Carbonates*

Martin J. Blunt[1], Branko Bijeljic[1], Oussama Gharbi[1], and Peyman Mostaghimi[1]

Search and Discovery Article #120039 (2012)*
Posted December 31, 2012

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG Hedberg Conference, Fundamental Controls on Flow in Carbonates, July 8-13, 2012, Saint-Cyr Sur Mer, Provence, France, AAPG©2012

[1]Department of Earth Science and Engineering, Imperial College London, UK (m.blunt@imperial.ac.uk)

Abstract

We have used synchrotron radiation to generate three-dimensional images of a variety of carbonate samples. A selection of the samples studied is shown in Figure 1 where the image resolution is approximately 8 μm and the samples have a diameter of approximately 5 mm. The images are first binarized into pore and grain. We employ a network extraction algorithm (Dong and Blunt, 2009) to determine topological properties of the pore space, such as average coordination number, as well as to produce a network for two-phase pore-scale modeling.

The study has some major limitations, of which the most significant is ignoring micro-porosity. The images do not presently have sufficient resolution to capture much of the pore space: either a higher resolution scan or a different method (such as FIB/SEM) is required. The network analysis needs to account for flow in both the larger pores and micro-porosity, which should enable a more convincing prediction of the water relative permeability (the micro-porosity is likely to be largely or completely water filled during a displacement). To validate this approach we should compare network predictions with measurements on the same core samples.

Introduction

We compute flow through central, cubic, sections of the binarized images using a standard method to solve the Stoke's equation for slow, viscous flow. We then trace streamlines through the pore space and move particles along streamlines combined with a random displacement. This approach allows us to simulate single-phase transport (Bijeljic et al. 2011).

We compute the concentration distribution in the average direction of flow as a function of time for different Peclet numbers (dimensionless ratios of advective to diffusive effects). We find a wide range of behaviour dependent on the pore structure of the carbonates – in particular, the average coordination number derived from network analysis. For the well-connected samples, (for instance Mount Gambier) we see an approximately Fickian behaviour, with the peak of the plume moving with the average flow speed and a classic, diffusive spread about this mean. However, as the pore space becomes less well connected, we observe significant channeling of the flow field. Much of the solute remains trapped in virtually stagnant regions of the pore space from which it can only escape through slow molecular diffusion. The result – for large Peclet numbers and early times – is a very dispersed profile. This is observed in sandstones, but a unique feature of carbonates emerges for the least well-connected samples, such as Portland and Indiana, with a highly anomalous behaviour, characterized by a maximum concentration that barely moves. This can be interpreted in the context of continuous time random walks: we see an approximately power-law distribution of travel times across each grid block (or between pores) with a power-law exponent less than 1, that results in a spreading that initially increases much faster than expected for a purely diffusive (Fickian) profile (Bijeljic et al. 2011). The simulations are validated against experimental NMR measurements. Figure 2 shows our computed flow field for Portland carbonate and a comparison of the predicted concentration profile with two independent measurements in the literature on the same rock type. The agreement is excellent and suggests that direct simulation on pore-space images can capture the important features of transport at the core scale.

We then use pore network modeling to study the impact of wettability and connectivity on waterflood relative permeability. Having extracted a topologically representative network of pores and throats from our binarized images, we simulate quasi-static displacement through the networks. We represent mixed-wet behaviour by varying the oil-wet fraction of the pore space. Relative permeability is strongly dependent on both the wettability and the average coordination number of the network. We generate a suite of curves that we suggest covers a likely range of behaviour encountered in different carbonates. There is a marked range of behaviour for mixed-wet systems for rocks of different connectivity: the well-connected networks see low residual saturations and high water relative permeability. For more poorly connected networks, there is considerable trapping, since the oil-wet regions of the pore space can be surrounded by water during spontaneous imbibitions. Low residual oil saturation and high water relative permeability – characteristic of oil-wet and mixed-wet media – is only observed once the medium has an oil-wet fraction greater than 0.5 and both oil and water-wet regions of the pore space are connected through the system.

Figure 3 shows an example network and predictions of waterflood relative permeability compared to measurements on a Middle Eastern reservoir sample. We assume that the rock is strongly oil-wet: all pores contacted by oil after primary drainage are assigned contact angles greater than 90°. While this is not a direct prediction, since we do not have an independent assessment of wettability and pore structure for the reservoir sample, we do capture the same generic features. The low oil relative permeability at high water

(low oil) saturation is characteristic of layer drainage, while the water, occupying the larger pore spaces, is well connected and has a high relative permeability.

Discussion and Results

This work illustrates a methodology for the study of flow and transport in carbonates. There is, of course, huge potential for future work. The transport code described could be extended to study reactive transport: here particles representing different chemical species can be moved through the pore space and react (or have some probability of reacting) when they come within a diffusion distance of each other. Heterogeneous reactions, where solute reacts with the solid in either a precipitation or dissolution reaction could also be considered with consequent changes in porosity and the flow field. This is a particularly rich topic of study, allowing a "first principles" determination of averaged reaction rates at the core scale, while rigorously accounting for local fluctuations in concentration and flow path.

Conclusions

The study has some major limitations, of which the most significant is ignoring micro-porosity. The images do not presently have sufficient resolution to capture much of the pore space: either a higher resolution scan or a different method (such as FIB/SEM) is required. The network analysis needs to account for flow in both the larger pores and micro-porosity, which should enable a more convincing prediction of the water relative permeability (the micro-porosity is likely to be largely or completely water filled during a displacement). To validate this approach we should compare network predictions with measurements on the same core samples.

References

Bijeljic, B., P. Mostaghimi and M.J. Blunt, 2011, The signature of Non-Fickian Solute Transport in complex heterogeneous porous media: Phys. Rev. Lett., 107 204502.

Dong, H., and M.J. Blunt, 2009, Pore-network extraction from micro-computerized-tomography images: Phys. Rev., E 80, 036307.

Okasha, T.M., J.J. Funk, and H.N. Rashidi, 2007, Fifty years of wettability measurements in the Arab-D Carbonate Reservoir: Middle East Oil and Gas Show and Conference, 11-14 March, Kingdom of Bahrain, SPE 105114.

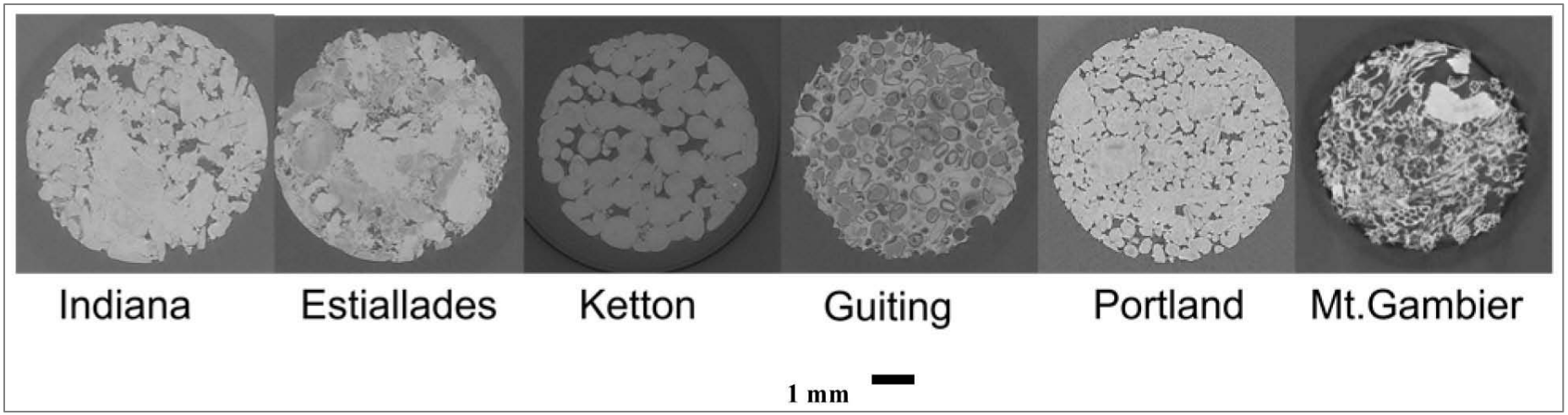

Figure 1. Two-dimensional cross-sections of three-dimensional images of the carbonates considered in this study. The image resolution is approximately 8μm. We simulate single-phase transport directly through binarized images, while we extract topologically representative networks to model two-phase flow and predict relative permeability.

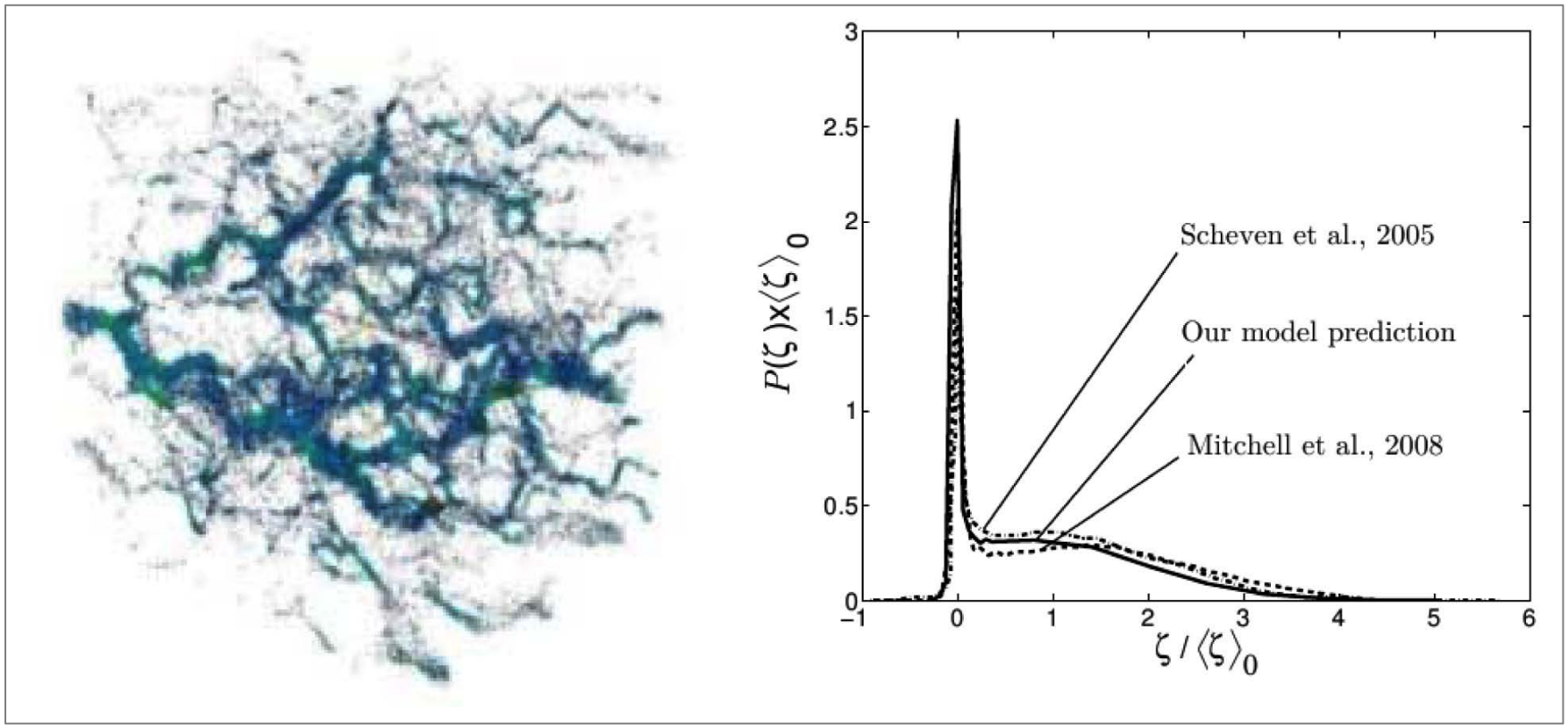

Figure 2. The left-hand image shows the flow field computed through an image of Portland limestone: the colours indicate the flow rate. Flow is highly channeled with much of the pore space being essentially stagnant; solute can only leave these domains through molecular diffusion. The right-hand plot shows the normalized concentration as a function of normalized distance along the main flow direction. Predictions are compared to two sets of experimental measurements on the same rock using NMR. The agreement with experiment is excellent, suggesting that we capture the main features of the flow field. There is an essentially immobile peak concentration and a highly dispersed leading edge of the plume, indicating highly anomalous transport. The same behaviour is predicted in other low-connectivity carbonates.

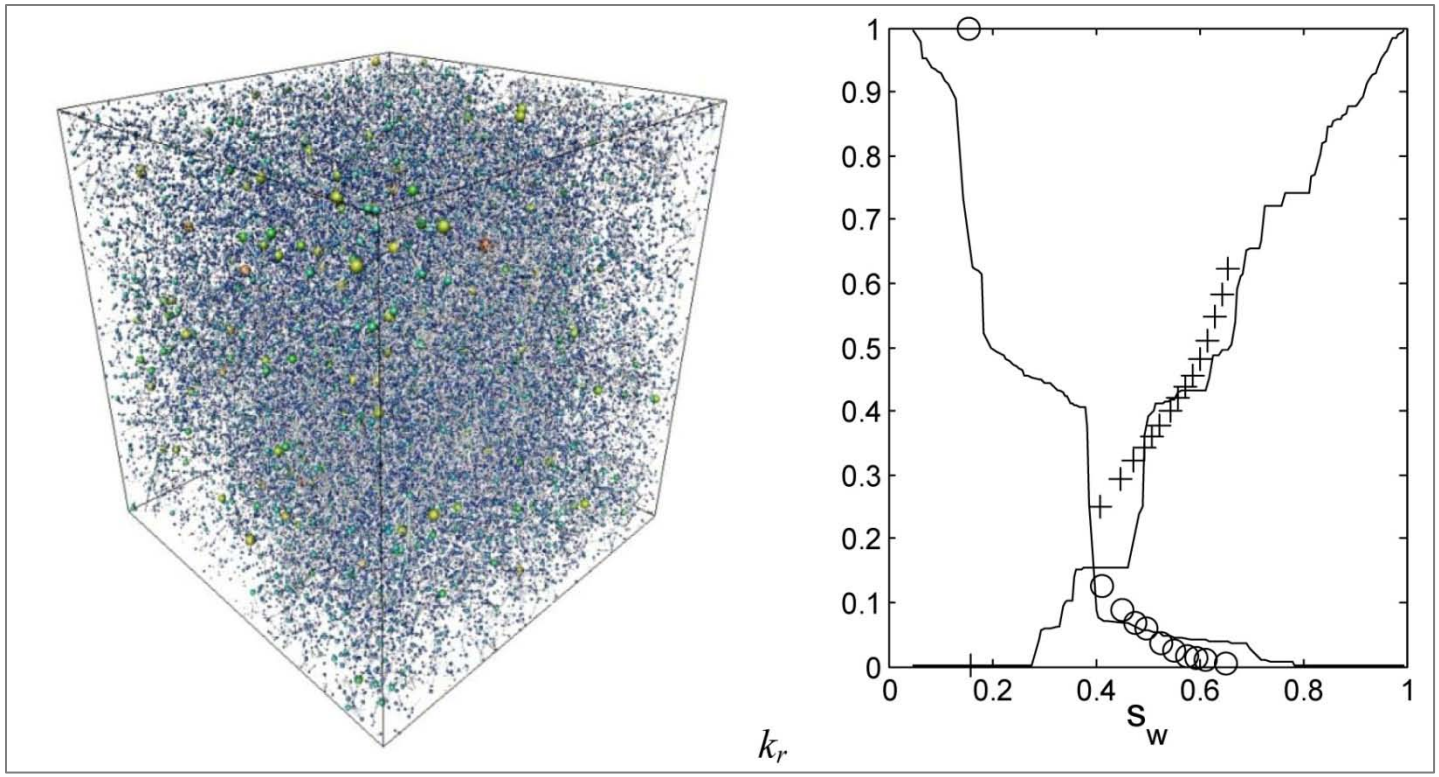

Figure 3. The left-hand image shows a network extracted from a three-dimensional image of Portland limestone: it is a topological representation of the void space partitioned into pores and throats. Quasi-static displacement is then simulated through this network and relative permeability is computed. The right-hand plot shows the computed waterflood relative permeability for a strongly oil-wet system (all the pores contacted by oil after primary drainage become oil-wet) compared to experimental measurements on a reservoir sample from the Middle East (Okasha et al. 2007). The good agreement suggests that we are able to capture the principal displacement processes observed during waterflooding. Note the low oil relative permeability at high water saturation, indicating layer drainage, and the corresponding high water relative permeability: the water occupies the larger regions of the pore space and is well connected.