Pore scale modeling and interpretation of borehole NMR logs

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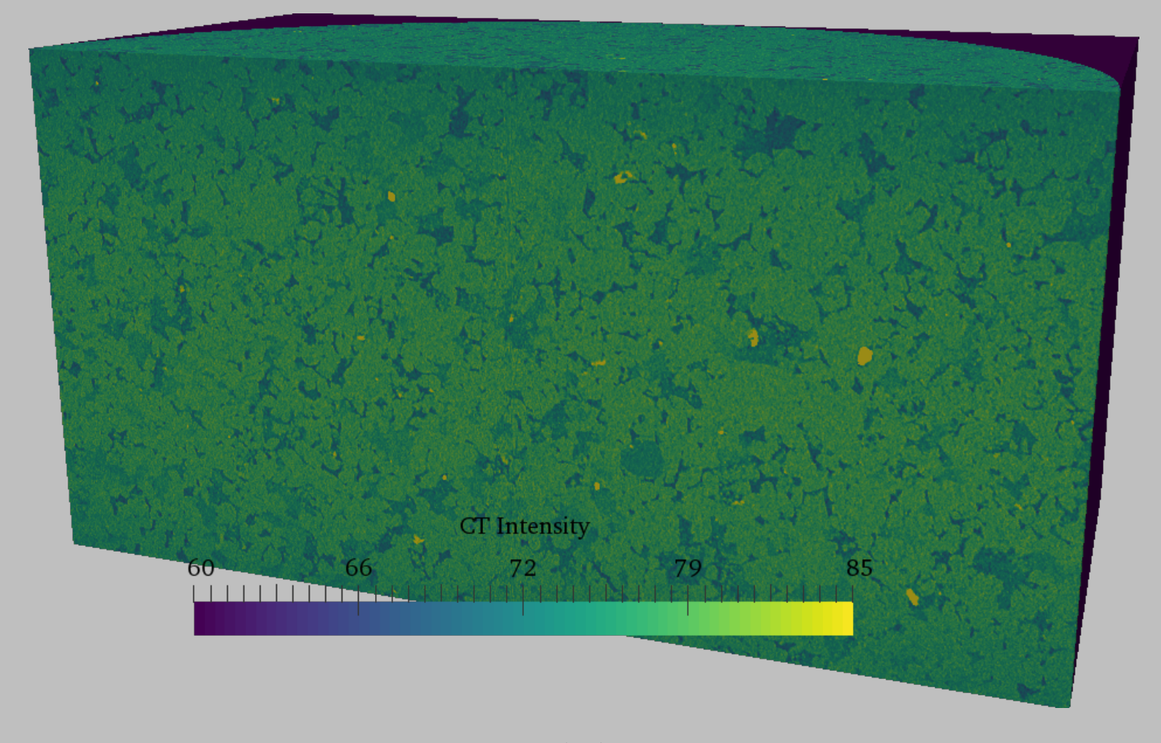
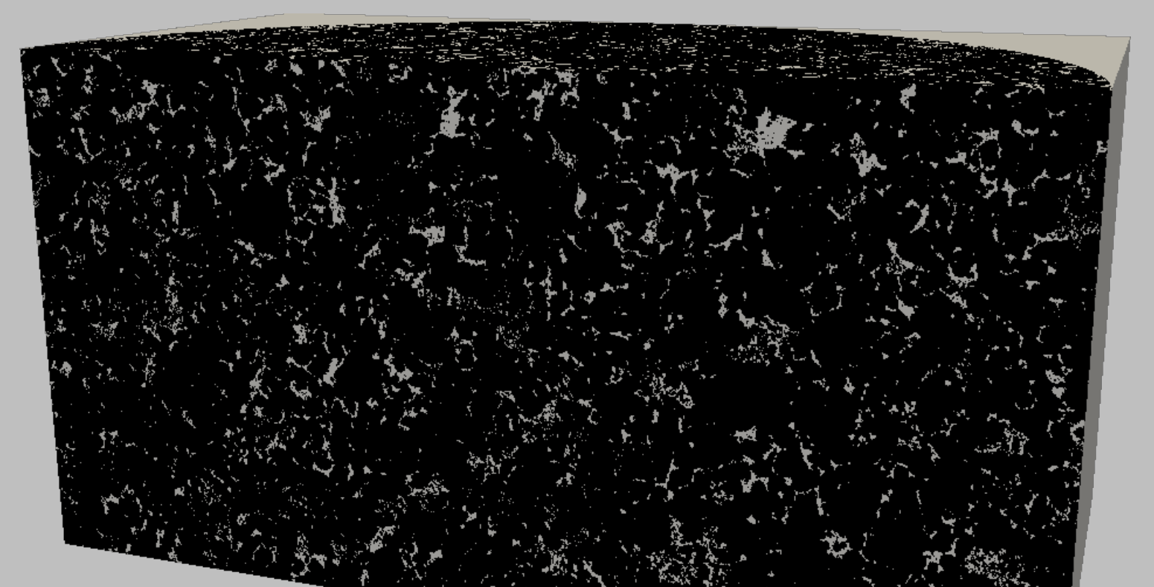
SUMMARY

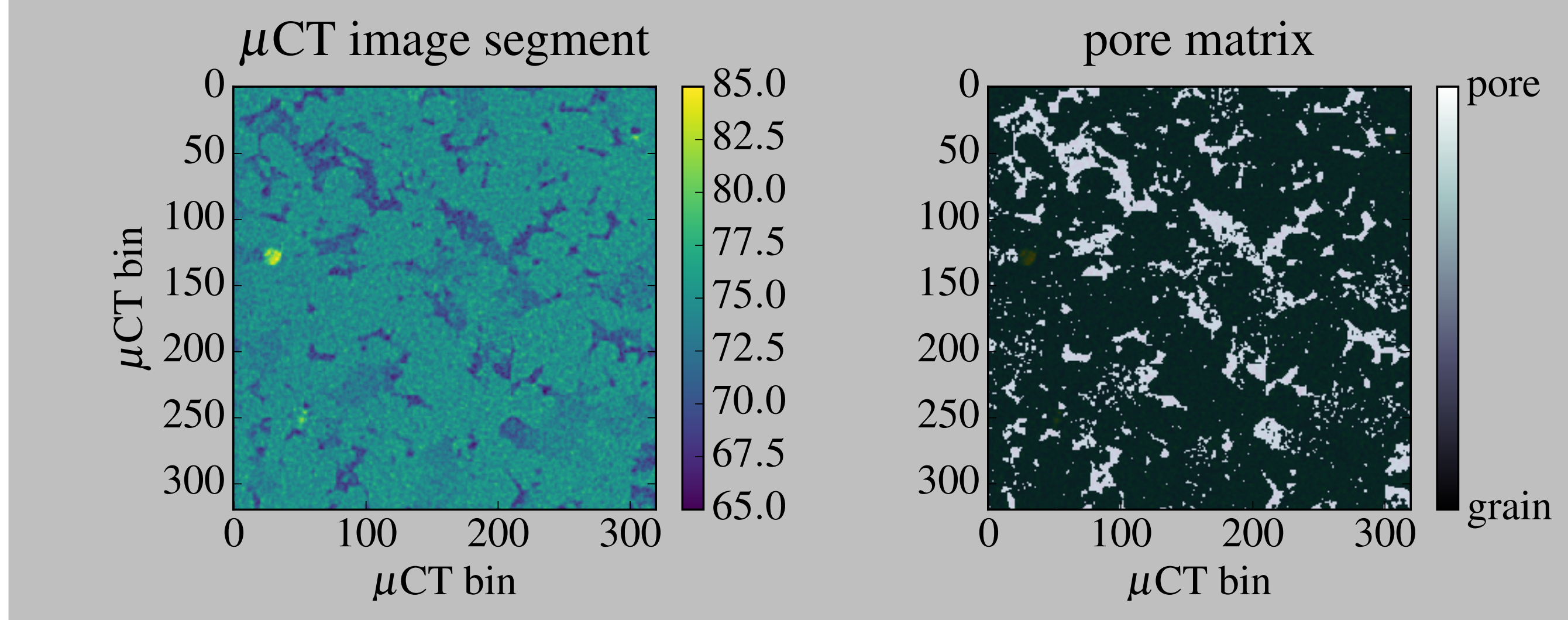
Multiphase fluid flow through porous media is of interest to the oil and gas industry and geologic carbon capture and sequestration (CCS) projects. In most of these applications, subsurface flow simulations are used to manage resources and projects by predicting responses due to driving forces such including production and injection activities. In most instances, the only practical way to model complex systems is at the continuum scale where physical (hydrologic) flow properties are aggregated over large volumes. This imposes several complications affecting model-based management. Geologic media is inherently inhomogeneous and anisotropic–properties which can be difficult to simulate accurately at large scales. Confounding this, robust measurements of relative permeability are expensive and time consuming to perform; this generally limits sampling to a few point measurements, which may or may not be characteristic. Geophysical characterization techniques are promising means by which to improve our understanding of multiphase systems. In particular nuclear magnetic resonance (NMR) methods provide signal that is directly proportional to the amount of hydrogen in pore fluids. Additionally, since NMR methods are sensitive to the surface area to volume ratio of pores, it is often possible to estimate hydraulic flow properties from the data. Borehole NMR logs provide in situ estimates of porosity and permeability, however these logs need to be calibrated in order to ensure the accuracy of the estimates. This is particularity important if more than one fluid phase are present. In this poster we compare borehole NMR measurements of multiphase systems with random walk simulations of NMR responses at the pore scale. The simulations provide a powerful interpretation tool for the data and provide insight into the fluid distribution. Additionally, anisotropy and inhomogeneity can easily be investigated in computer simulations.

PORE MATRIX FROM μCT IMAGES

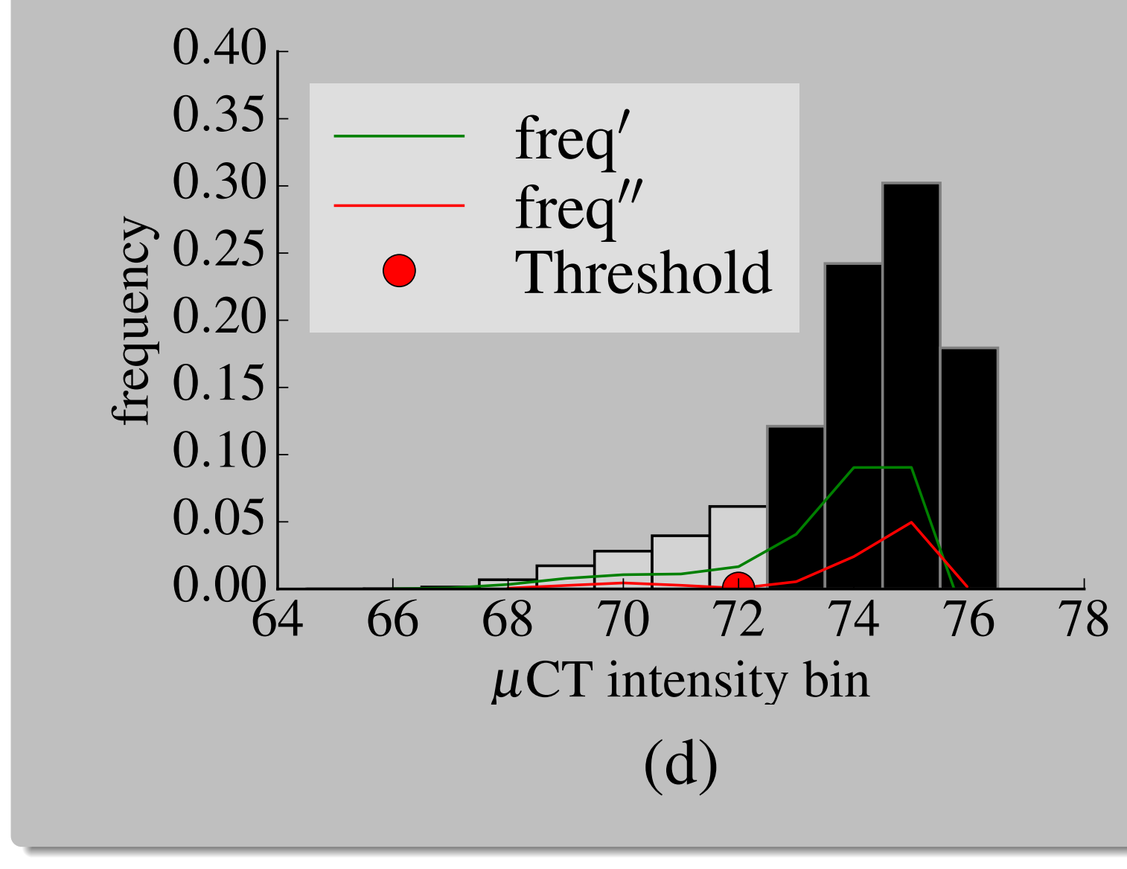


(a)

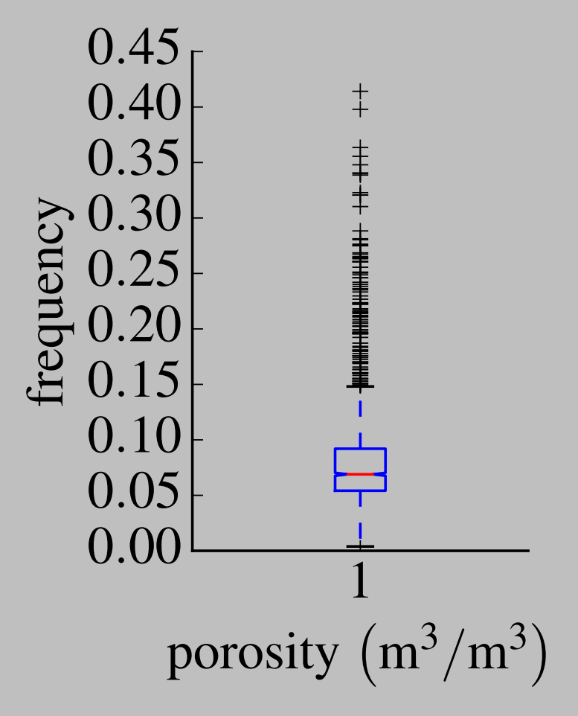

(b)



(c)



(d)



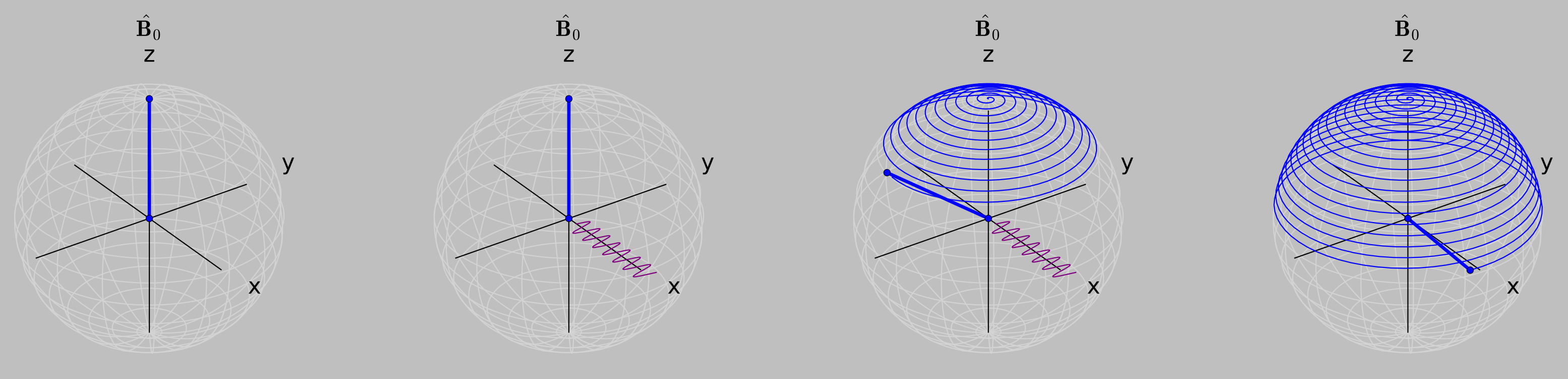
(e)

A μCT image (at 11.5 μm voxel resolution) of the Morrow B Sandstone unit is shown (a). In order to extract a pore matrix suitable for simulation (b) appropriate threshold values must be determined. Since image intensity varies throughout the volume, a global threshold value is not appropriate. Instead, subsets of the image are analysed as shown in (c,d). The 320 × 320 × 10 voxel image subset in (c) has a porosity of 9%; the porosity distribution for similar sized subsets of the while volume is shown in (e).

NMR DYNAMICS

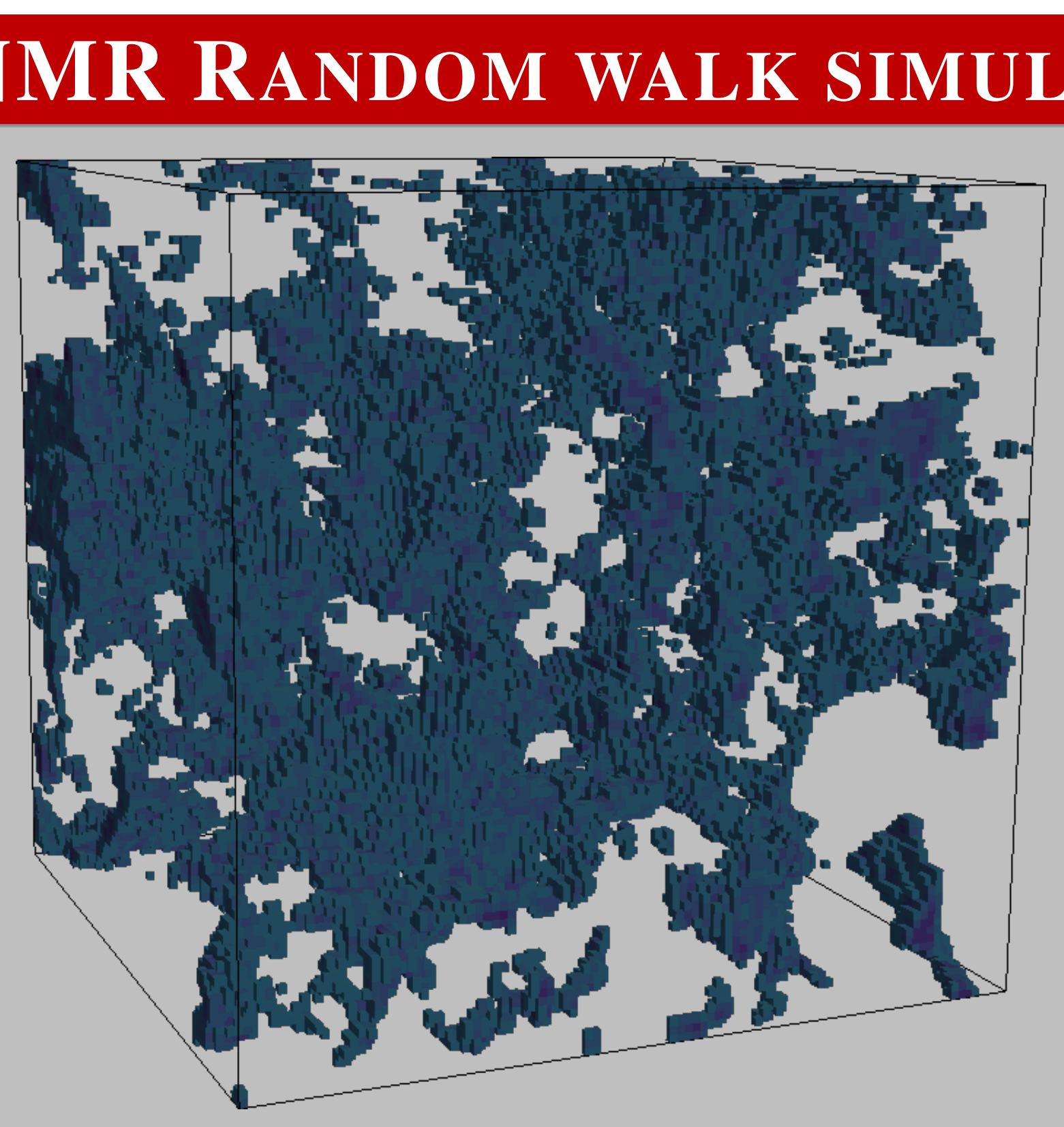
Hydrogen atoms in liquid water develop bulk magnetization moments $\mathbf{M}_N^{(0)}$ in a static magnetic field ($\mathbf{B}_0$). These moments precess at the Larmor frequency and may be tipped away from their equilibrium position using RF radiation at the same frequency. After the tipping pulse the moments decay back to equilibrium, macroscopically characterized by three parameters T_1, T_2, and T_2^* [1].

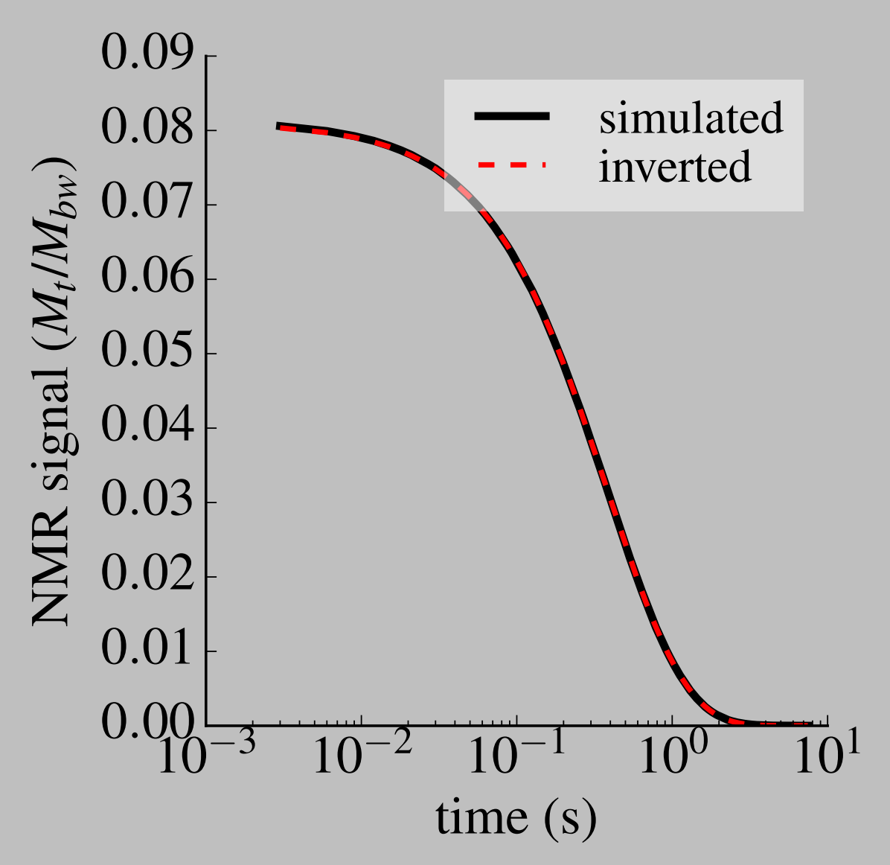
$$\begin{aligned}\mathbf{M}_N^{(0)}(\mathbf{r},T) =& 2n_{H_2O}B_0\frac{\gamma_H^2\hbar^2}{4k_BT}f(\mathbf{r})\hat{\mathbf{B}}_0\\ \mathbf{M}_N(\mathbf{r},t) =& \mathbf{M}_N^{(0)}(\mathbf{r})\left\{1-e^{-(t-\tau_p)/T_1(\mathbf{r})}+e^{-(t-\tau_p)/T_1(\mathbf{r})}\cos\left[\theta_T(\mathbf{r},\tau_p)\right]\right\}\\ &+e^{-(t-\tau_p)/T_2^*(\mathbf{r})}\times\left[\mathbf{M}_N^{(0)}(\mathbf{r})\times\hat{\mathbf{B}}_T^+(\mathbf{r},t)\right]\sin\left[\theta_T(\mathbf{r},\tau_p)\right] \qquad (1)\end{aligned}$$



Where γ_H is the gyromagnetic ratio of hydrogen, f is the porosity of the media, and n_{H_2O} is the number density of water. $\mathbf{B}_T^+$ is the corotating part of the transmitter field ($\boldsymbol{\mathcal{B}}_T$) and τ_p is the duration of the tipping pulse which together determine the tip angle θ_T. In magnetic media nuclear spins dephase causing T_2^* to dephase and deviate from T_2; refocusing CPMG pulses are used such that $T_2^* \to T_2$. In porous media the permeability can be related using, for example, the Schlumberger-Doll (SDR) equation $\kappa_{SDR} = c_p\phi_N^m T2_{2ML}^n$, where T_{2ML} is the logorithmic mean of the T_2 decay time distribution, ϕ_N is the NMR derived porosity (initial amplitude), and c_p, N, and M are tunable and lithology-dependent scaling factors determined through calibration.

NMR RANDOM WALK SIMULATION

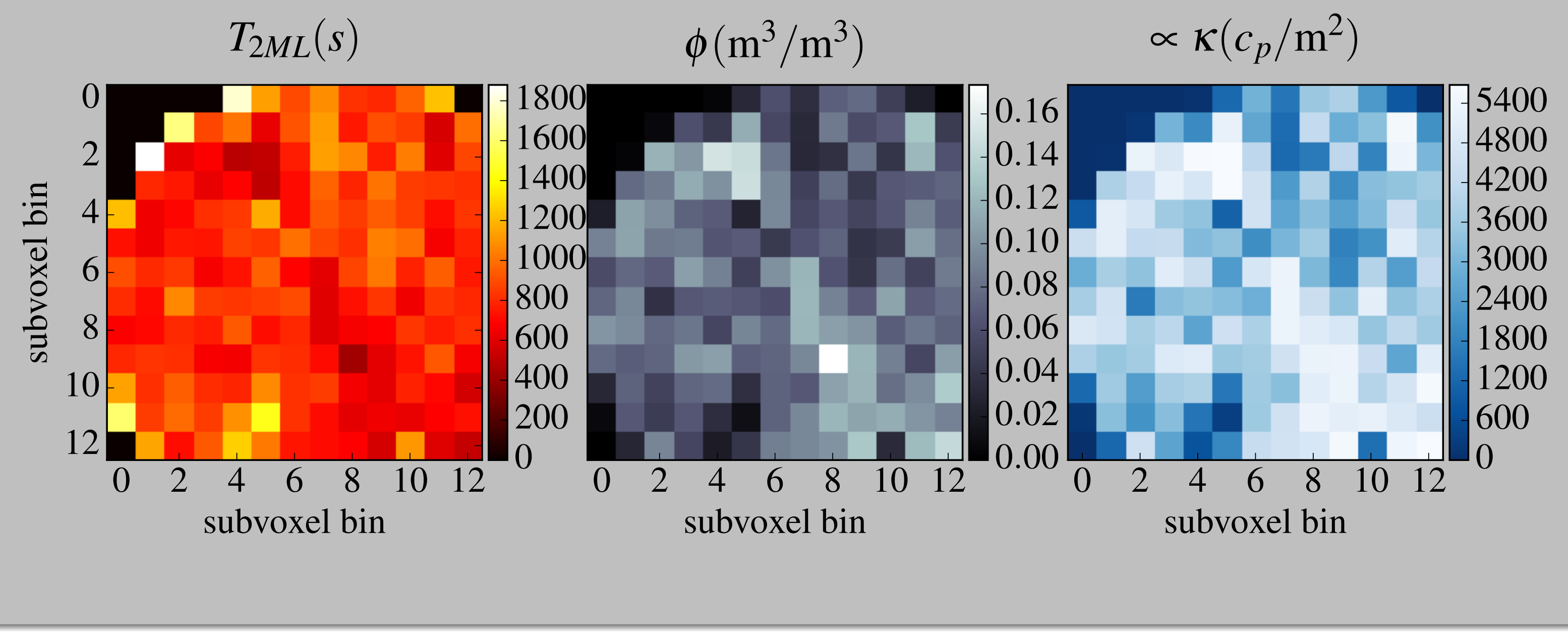

(a)



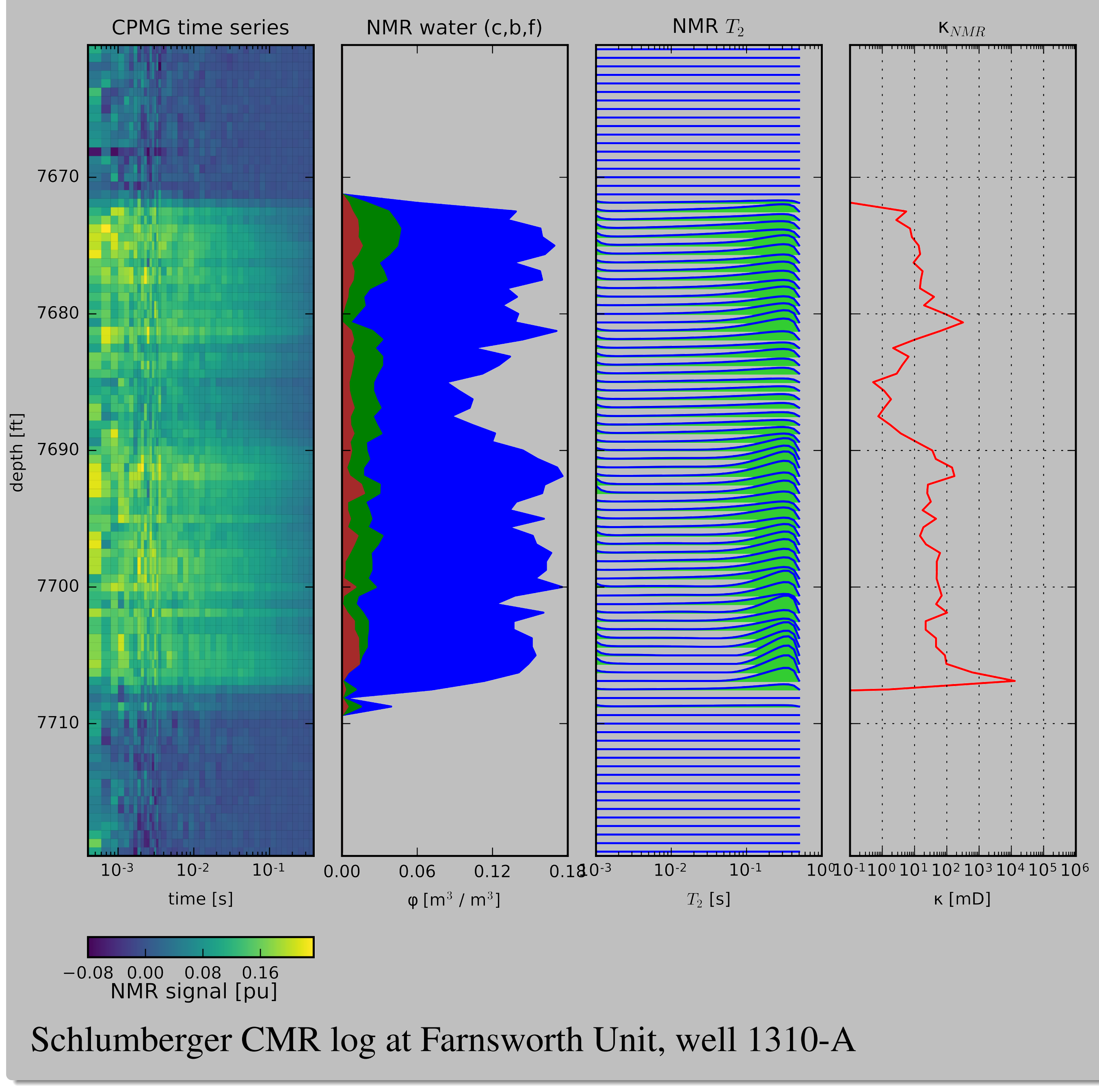
(b)

The simplified NMR equation of motion (1), as well as the SDR relation, are appropriate only on the macroscopic level and are not applicable to pore scale NMR. Instead, stochastic random walk simulations where individual spins within a pore matrix are tracked as they diffuse due to Brownian motion can be used to simulate the NMR response of media at this scale. Single phase NMR code developed by the Imperial College London (ICL) [2] was extended for multiple phases and used to perform synthetic NMR simulations on the extracted pore matrices (a), the simulated data are shown in (b) for a single subcube of 100×100×100 voxels. The simulations shown in this block are single phase; the permafrost example demonstrates the multiple phase NMR simulation capabilities.

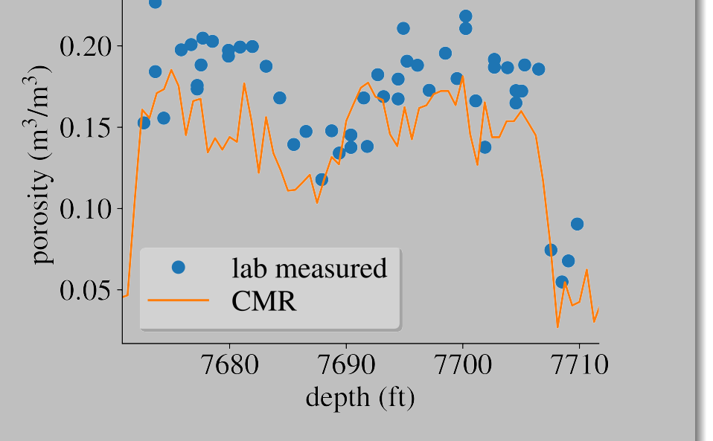
Random walk simulations of subsets of the entire image volume were similiarily generated. The results were then stiched together to form a composite simulated NMR image of the core with the pore space filled 100% with water. One slice of the synthetic NMR image is shown including estimates of NMR porosity, log mean T_2 and uncalibrated permeability.



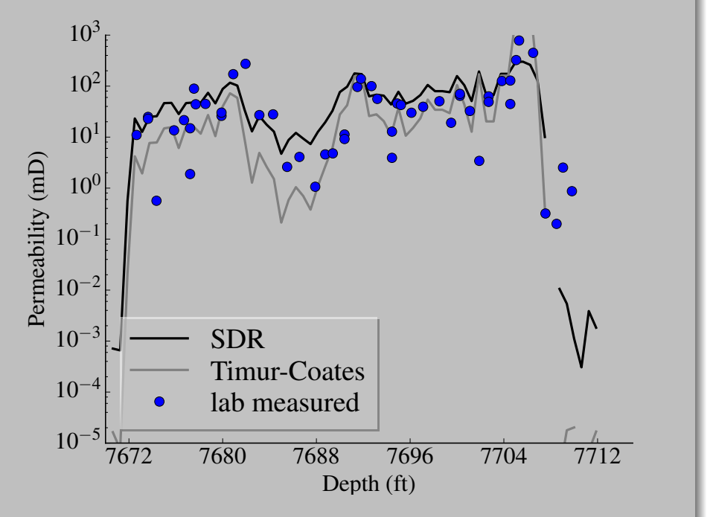
CMR LOGS



Schlumberger CMR log at Farnsworth Unit, well 1310-A



Porosity comparison of CMR data to core measurements, μ-porosity from clay content is poorly resolved in CMR logs.



CMR-derived permeability is in good agreement with core scale measurements

ACKNOWLEDGEMENTS

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